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Residual Radioactive Contamination From Decommissioning

Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent

Final Report

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Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory Commission

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Abstract

This document is the first volume of a three-volume report to provide generic and site-specific estimates of radiation dose for exposures to residual radioactive contamination after the decommissioning of facilities licensed by the U.S. Nuclear Regulatory Commission (NRC). This first volume provides the details of the generic scenario and pathway modeling analysis. The level of detail included in this volume serves as the basis for user-friendly computer software to be developed under strict quality-assurance procedures. This volume is intended to be used as a reference to Volume 2, a full description of the computer software. Included in Volume 1 are descriptions of the scenarios, models, mathematical formulations, assumptions, and justifications of parameter selections. Volume 1 was produced after consideration of public comments received on the January 1990 review draft. The generic modeling addresses residual radioactive contamination inside buildings and in soils. For buildings, two scenarios are presented to relate volume and surface contamination levels to estimates of the annual total effective dose equivalent (TEDE) or the TEDE (as defined in 10 CFR 20) received during a year of exposure with the conditions defined in the scenarios. Because of concerns regarding potential ground-water contamination from residual radioactive contamination in soil, a generic water-use model was developed to permit evaluation of the annual TEDE for drinking water from wells. The generic water-use model was also used in the evaluation of multiple pathways associated with contaminated soil. The generic treatment of potentially complex ground-water systems used here provides a conservative analysis that may only indicate that additional site data and more sophisticated modeling are warranted. The scenarios, models, mathematical formulations, and selected parameter values in this volume are intended to serve as the technical basis for the NRC's derivation of screening values supporting its development of policy applied to residual radioactive contamination from decommissioning.

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Executive Summary

The three volumes of this document describe a generic modeling analysis of the potential radiation doses resulting from unrestricted release of slightly radioactive material in buildings and soil following decommissioning of licensed facilities. This first volume contains detailed information on the generic scenario and modeling analysis as the basis for user-friendly computer software to be developed under strict quality-assurance procedures. This document is intended to be used as a reference to the user's manual for the software (Volume 2) and has been revised in light of the public comments received on the January 1990 draft. The information in this document is intended to serve as the technical basis for the U.S. Nuclear Regulatory Commission's (NRC's) derivation of screening values supporting its development of policy on residual radioactive contamination from decommissioning. A user's manual for the software version of the modeling analysis and a sensitivity analysis of parameter values used in the analysis will be documented and distributed as two additional volumes.

The radiation exposure scenario analysis addresses the major exposure pathways of direct exposure to penetrating radiation, and inhalation and ingestion of radioactive materials. The modeling analysis is used to estimate the annual total effective dose equivalent (TEDE), or the TEDE (as defined in 10 CFR 20 [56 FR 23360-23474, 1991]) received during a year of scenario exposure, to an average individual in a population group exposed to residual radioactive material after decommissioning. The input parameters for each exposure pathway and scenario are selected in a prudently conservative (not worst-case) manner to estimate the likely radiation dose to an individual in a limited population group exposed to residual radioactive contamination. A prudently conservative generic approach is necessary so that it is more likely that the calculations will produce overestimates than underestimates of the potential dose an individual in the general public may receive.

For unrestricted release of buildings, two independent scenarios are provided: building renovation for volume sources of residual radioactive contamination and building occupancy for surface sources of residual radioactive contamination. In order to accommodate site-specific conditions, the computer software containing the modeling analysis will be designed to permit simple modifications of the scenario assumptions, including the exposure durations, intake rates, or concentrations in various pathway media.

For unrestricted use of land, two scenarios are included that rely on a generic water-use model. The first scenario considers drinking water from a well and accounts for the total radionuclide inventory at the site, in the soil, and in building materials that potentially may be demolished and disposed of onsite as buried rubble. The drinking water scenario relates the annual TEDE to the total inventory of residual radioactivity in soil. The second scenario considers residential use of land, including use of ground water for drinking and irrigation of farm products. The residential scenario includes a combination of the following exposure pathways: inhalation, external exposure, drinking water ingestion, soil ingestion, and agricultural food product ingestion.

Because of the generic treatment of potentially complex ground-water systems, the water-use modeling and parameter selection are intentionally conservative. This means that the estimated annual TEDE for the drinking water and residential scenarios may only indicate when additional site data or more sophisticated modeling are warranted. Modifications can be made to the scenarios for contaminated land to better account for site-specific soil contamination using the software developed for this effort.

Finally, appendixes are provided to this report to summarize the general responses to comments received on the January 1990 (Kennedy and Peloquin 1990) draft version of this final report, and to support information and databases in the modeling analysis.

Foreword

by
Nuclear Regulatory Commission (NRC) Staff

NRC licensees who need to decontaminate lands and structures to acquire unrestricted use of their property must have criteria to determine "how clean is clean enough" in the process of decommissioning. In making such an ascertainment, the NRC must first determine that public health, safety, and the environment are protected by ensuring that the total dose to an individual in the public from licensed operations is less than the public dose limit of 100 mrem/y. However, the NRC has set the goal for public doses attributable to residual contamination after decommissioning at a fraction of the public dose limit. In practice, decommissioning costs (as measured in terms of the cost of returning the lands and structures to unrestricted use) are balanced against the benefits of averting adverse health effects (as measured by dose reduction resulting from decontamination). The estimate of dose reduction is accomplished by first judging the potential future uses of the lands and structures as described by scenarios and then evaluating associated levels of radioactivity through modeling equations to arrive at a reasonable expectation of doses. The modeling and scenarios can become extremely complicated, depending on the level of detail required. Detailed modeling may often be beyond the technical and financial capabilities of a large number of licensees--especially for those licensees with limited scope and budgetary resources.

The purpose of this three-volume report is to provide generic and site-specific dose conversion factors for residual radioactivity that may be applied to a screening analysis to determine whether more detailed cost-benefit analyses must be performed. Briefly, Volume 1 presents the scenarios, models, mathematical formulations, assumptions, justification of parameter choices, and responses to comments from the January 1990 draft report published for comment. Volume 2 of this report is a micro-computer-based program, complete with a user's manual, tables of the generic dose conversion factors, example calculations developed to facilitate analyses, and computer code listing. The NRC staff plans to have the computer software distributed by the Energy Science and Technology Software Center, Oak Ridge National Laboratory, P.O. Box 1020, Oak Ridge, TN 37831-1020, telephone (615) 576-2606. Availability and instructions for procurement of the computer software will be announced in the Federal Register. Volume 3 is composed of sensitivity analyses of parameters used in the modeling and a comparison with previously used guidance, e.g., Regulatory Guide 1.86 (NRC 1974). These volumes will be published sequentially as they are developed.

All of over 22,000 NRC and NRC Agreement State licensees may use these dose conversion factors. In preparation for the development of release criteria to be used for decontamination of decommissioned lands and structures, the NRC has contracted the work in this report. This report will provide much of the technical basis for translating residual radioactivity into annual dose--measured in total effective dose equivalent.

The scenarios used are prudently conservative but not necessarily bounding or "worst case." Selection of a prudently conservative scenario requires a great deal of professional judgment and common sense. The intent is to account for the vast majority of potential uses of lands and structures and to overestimate the most probable annual dose while discounting a small fraction of highly unlikely uses that would result in higher doses. For example, a small fraction of higher doses could be imagined because of aberrant behavior or unpredictable and highly unlikely circumstances. The alternative was to use scenarios that would yield an upper limit on doses (i.e., bounding or "worst case") and would

unnecessarily limit the usefulness of the resulting release criteria without providing significantly increased benefits to the public health, the public safety, or the environment. Hence, the dose conversion factors in this report are judged to be higher than (i.e., overestimate) the most probable annual dose but may be lower than (i.e., underestimate) the bounding annual dose.

There is flexibility in the application of the modeling contained in this report. For example, if increased accuracy or realism of the screening dose conversion factors are desired, then with adequate justification the generic (default) parameter values may be replaced with site-specific parameters. Within the modeling framework of this report, such a substitution of parameters would lead to site-specific derived dose conversion factors. The site-specific dose conversion factors may then replace the generic dose conversion factors in the screening analysis.

Beyond the modeling and scope of this report, it is possible that a licensee may find it necessary to provide customized, site-specific modeling and optimization of radiation protection in accordance with the principles of maintaining exposures as low as reasonably achievable (ALARA) for decommissioning or the termination of a license. In such cases, some to none of the modeling framework in this report may be applicable. The hierarchy of the approaches for establishing dose conversion factors applied to residual radioactive contamination is illustrated in the following figure (page xvii).

As mentioned above, a draft of this report was issued for comment in early 1990. The summary of comments received on that draft and the NRC staff responses and resolutions are presented in Appendix A of this final report. This report is one part of a larger program the NRC staff has underway to provide information and guidance for the implementation of release criteria for the decommissioning of lands and structures. For example, NUREG/CR-5849, "Manual for Conducting Radiological Surveys in Support of License Termination" (Berger 1992), provides information on acceptable measurement and survey techniques and procedures. It is emphasized that the information in this report was developed for a screening application to the decommissioning of lands and structures and was not intended for other uses.

The NRC staff anticipates the need may arise to revise this report from time to time. Accordingly, comments noting suggested changes within the intended scope of this report are welcome and should be submitted in writing to the NRC Project Manager. The NRC Project Manager for this report may be contacted at the following address:

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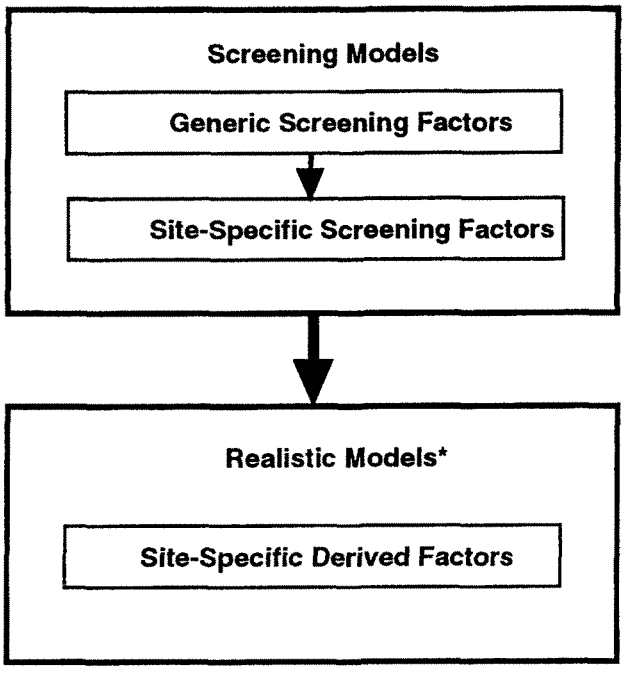
Hierarchy of Modeling Approaches



*Site-specific modeling in this box is outside the framework of modeling in this report.

NUREG/CR-5512 Modeling

Acknowledgments

This report represents the cumulative efforts of many individuals who contributed to its development, production, and publication over the past three years. We greatly appreciate the guidance, assistance, technical review, and encouragement provided by Dr. Donald A. Cool, Dr. R. A. Meck, Ms. Christine Daily, and the staff of the U.S. Nuclear Regulatory Commission (NRC); Dr. Marsha Sheppard of Atomic Energy of Canada Limited; Dr. Keith Eckerman of Oak Ridge National Laboratory; Dr. Charlie Yu of Argonne National Laboratory; Dr. David Layton and Dr. Lynn Anspaugh of Lawrence Livermore National Laboratory; Dr. Wayne Hansen of Los Alamos National Laboratory; and Mr. Jack Corley. We also would like to thank Jim Weber, Don Hanley, Joe Soldat, Gene Schreckhise, Dan Strom, Bill Templeton, Charlie Cole, Charlie Kincaid, David Baker, Paul Stansbury, Lissa Sawyer, Sandi Shindle, Rebecca Kennedy, plus all of the production team at Pacific Northwest Laboratory (PNL).

As a special note, the authors would like to gratefully mention the influence of the late Ed Watson (PNL) on this effort. In the late 1970s, under a previous NRC project designed to document the "Technology, Safety and Costs of Decommissioning," Ed was instrumental in forming the professional attitudes of the authors regarding the potential effects of exposure to residual radioactive contamination. His influence continued through the 1980s during the development of the "Allowable Residual Contamination Level" method for decommissioning U.S. Department of Energy facilities at the Hanford Site. Ed's influence has continued through the present work, and he is warmly remembered and sorely missed.

1 Introduction

The U.S. Nuclear Regulatory Commission (NRC) currently regulates the release of slightly radioactive property for unrestricted use through existing staff criteria. These NRC staff criteria are in two forms: 1) acceptable volumetric concentrations of source material in soil, provided in pCi/g first reported in the *Federal Register* in 1981 (46 FR 52061-3, 1981), and 2) acceptable levels of surface contamination, provided in units of dpm/100 cm^2 for average, maximum, and removable contamination conditions defined in Regulatory Guide 1.86 (NRC 1974). Both of these NRC staff criteria for release of slightly radioactive material have limitations. The criteria for volumetric concentrations in soil, for instance, are limited to the uranium and thorium chains of radionuclides and are applicable only to current contamination resulting from past operations. The NRC staff criteria governing surface contamination, although appropriate for all radionuclides, are often difficult to apply because of the wide variation in surface and volumetric contamination conditions and the varying mixture of radionuclides usually found in many licensed facilities. In addition, the values found in both sets of criteria are not consistent with the revised dosimetry system recommended by the International Commission on Radiological Protection (ICRP) in Publications 26 (1977), 30 (1979-1988), and 48 (1986), and provided by the U.S. Environmental Protection Agency (EPA) in Federal Guidance Report No. 11 (Eckerman, Wolbarst, and Richardson 1988).

To alleviate this situation, the NRC is developing a revised license termination policy to ensure an adequate and consistent level of protection for the public. As described in the Foreword, the revised policy will use models to form the basis for a screening analysis of the potential public doses from decommissioned lands and structures.

As a contribution to the development of revised guidance by the NRC, staff at the Pacific Northwest Laboratory (PNL) began the development in 1987 of a radiation exposure scenario/pathway modeling analysis to translate residual radioactive contamination levels into potential radiation doses to the public. The use of computerized models to conduct public dose assessments is typically necessary because of an inability to directly determine doses from numerous potential environmental pathways over long periods of time. The use of generic models and relatively simple data sets has become common for setting standards and regulations. For example, the NRC low-level radioactive waste regulations in 10 CFR 61 (1990) were developed with the use of generic models and data (Oztunali et al. 1981).

Historically, environmental-transfer and pathway-assessment models have been developed to consider a variety of different situations involving radioactive materials. Pathway-assessment models are commonly applied for radioactive waste management, accident assessment, and environmental impact statements. Example references involving various aspects of environmental radiological assessment include publications by Soldat and Harr (1971), the NRC (1977), the International Atomic Energy Agency (IAEA 1982), Till and Meyer (1983), Kennedy and Napier (1983), the National Council on Radiation Protection and Measurement (NCRP 1984), McKenzie et al. (1985), Kennedy et al. (1987), Strenge, Bander, and Soldat (1987), Napier et al. (1988), T. L. Gilbert et al. (1989), and O'Neal and Lee (1990). This report is largely based on these and numerous other previous pathway-assessment and data-collection efforts.

The development of models for screening to demonstrate compliance with environmental standards is the subject of Commentary No. 3 published by the National Council on Radiation Protection and Measurements (NCRP 1986). The NCRP presented three levels of screening for determining compliance with the regulations of the Clean Air Act, 40 CFR 61, National Emission Standards for Hazardous Air Pollutants; Standards for Radionuclides (50 FR 5190, 1985). In the NCRP approach, Level I applies the simplest models, including a high degree of conservatism with few parameter or data requirements. Levels II and III require additional site-specific data to reduce the modeling conservatism. If the user of the NCRP method shows compliance using the Level I models and data, then no further calculations are necessary. If the Level I results exceed the standards, the model user must apply the Level II and III

models until compliance is determined. If the efforts fail at all levels, the NCRP recommends the use of professional assistance in radiological assessment to determine how to proceed (NCRP 1986).

This three-volume report provides information on the generic pathway/scenario analysis model used to derive the potential annual total effective dose equivalent (TEDE), or the TEDE as defined in 10 CFR 20 (56 FR 23360-23474, 1991) received during a year of scenario exposure, by an average individual in a given population group exposed to residual radioactive contamination. Volume 1 presents the detailed scenarios, models, mathematical formulations, assumptions, selected parameter values, and general responses to comments from the January 1990 comment draft. Volume 1 contains the level of detail needed to develop microcomputer-based, user-friendly software under strict quality-assurance procedures and is intended to be used as a reference to Volume 2. Volume 2 describes the software, including a user's manual, tables of generic unit-concentration annual TEDEs, example calculations developed to facilitate analyses, and the computer code listing. Volume 3 contains the results of a sensitivity analysis of parameter values used in the modeling and a comparison of the results with previously used guidance, e.g., Regulatory Guide 1.86 (NRC 1974). Volumes 2 and 3 will be published sequentially.

The methodology described in this report to calculate doses is consistent with the recommendations of the ICRP in Publication Nos. 26 (1977), 30 (1979-1988), and 48 (1986). The mathematical models described in this report are intended to be used for two levels of screening. The first level of screening relies on the use of default values for all parameter values and is intended to produce generic dose estimates that are unlikely to be exceeded at real sites. The degree of conservatism associated with the models and data is difficult to determine for a generic analysis. For the first level of screening, efforts have generally been made to select models that represent a variety of generic conditions and parameter values that lie within the distributions of reported or expected values (i.e., parameter values that are not at the extremes of the ranges). When this approach applies, the model and data selections are referred to as being "prudently conservative." The exceptions to this general approach are the model and data selections associated with the water-use model to account for potential ground-water contamination. For the water-use model, the model and parameter selections have been made in an intentionally conservative manner and are so noted in the text. For the first level of screening, portions of the modeling analysis are intentionally conservative. As a result, the annual TEDEs calculated using the default parameter values should provide an overestimate of the actual dose that individuals might receive. The second level of screening is accomplished using the computer software described in Volume 2, with the input of site-specific data to reduce the conservatism of the result and produce a more realistic estimate of site-specific conditions. This approach should produce results that will serve as an adequate basis for the development of generic screening criteria and should also be useful in determining when more detailed site-specific assessments or modifications to the generic scenarios are required. The models, pathways, scenarios, and parameters given here will be documented as a computer program in the next volume in this series. The computer program will enable the users to make simple modifications to the analysis to better consider site-specific conditions.

As with the NCRP screening models, the NRC will allow the application of a third level of screening to produce a more site-specific result. This third level would employ models and data that are carefully chosen to match the complex conditions at a specific site. Further discussion of this third level of screening is beyond the scope of this study.

To support the first two levels of this screening analysis, decisions have been made to define the scenarios, pathways, and default parameter values. Although these decisions are intended to focus the use of the models to address residual radioactive contamination in buildings and on land, they also limit the broader application of the models to more complex situations. These complex situations include sites with buried sources (as would be found at waste disposal sites), sites with existing ground-water plumes, sites with complex ground-water systems, and sites with the potential for high concentrations of indoor radon. For these situations, a more comprehensive site-specific modeling analysis should be performed within the third level of screening.

Two scenarios for residual radioactive materials in buildings are needed to adequately describe the potential contamination conditions found at actual facilities. These two scenarios account for 1) building renovation (subsurface or volume sources) and 2) normal building occupancy (surface contamination sources). Estimates of the potential dose from a subsurface inventory in the building renovation scenario are important to account for residual inventories of difficult-to-measure alpha-emitters or beta-emitters. The building occupancy scenario is intended to depict the situation where the residual inventory is present as a layer of surface contamination.

Two scenarios that rely on a generic water-use model are included for unrestricted use of land. The first scenario only considers drinking water from a ground-water source and accounts for the total radionuclide inventory at the site, in the soil, or in building materials that potentially may be demolished and disposed of onsite as buried rubble. The drinking water scenario is included to permit a comparison with the EPA drinking water standards. The drinking water scenario relates the annual TEDE in mrem per pCi (and μSv per Bq) of residual radioactive materials in soil. The second scenario considers residential use of land, including use of ground water for drinking and irrigation of farm products. The residential scenario relates the annual TEDE in units of mrem per pCi/g (and μSv per Bq/g) of soil. Because of the generic treatment of potentially complex ground-water systems, the water-use modeling is intentionally conservative. This means that the annual TEDE for the drinking water and residential scenarios may only indicate when additional site data or more sophisticated modeling are warranted. Using the software developed for this effort, again, modifications can be made to the scenarios for contaminated land to better account for site-specific soil contamination.

The purpose of this volume is to describe fully and document the scenarios, pathways, mathematical formulations, assumptions, and parameter values included in the generic analysis. Section 2 describes the basic methodology and nomenclature, including basic dosimetry definitions and listings of the notation used throughout the report. Section 3 describes the building renovation and building occupancy scenarios with a description of the conceptual models, time frames, and exposure pathways included and excluded from the analysis. Section 4 describes the generic water-use model and its application to the drinking water scenario. Section 5 describes the residential scenario, with a detailed description of the numerous agricultural pathways included in the analysis. Section 6 describes the selected parameter values used as defaults in the scenario analysis, including the basic dosimetry, radioactive decay, ground-water, and agricultural pathway parameters and data. Section 7 briefly describes the application of the information in this volume as it relates to Volumes 2 and 3 in the series. Finally, a series of appendixes are provided that include a summary of the comments received on the January 1990 draft version of this final report, extended nomenclature and methodology, the special ^{14}C and ^{3}H agricultural pathway models, and supplemental data.

2 Methodology and Nomenclature

This section contains information needed to understand the mathematical notation used in the building and soil scenario models. Definitions of dose and dose rate terms are provided in Section 2.1. The standard mathematical and operator notations used throughout the report are provided in Section 2.2. Appendix B contains extended nomenclature and methodology supporting this section, including the methods used for radioactive decay calculations.

2.1 Dosimetry Definitions

Because the purpose of this report is to provide the mathematical models and formulations needed to estimate radiation doses from residual radioactive contamination, it is important to understand the dosimetry terminology used. In most cases, terminology consistent with 10 CFR 20 (56 FR 23360-23474, 1991) is used. Additional definitions are supplied in the Glossary.

Dose or "radiation dose" - A generic term that means absorbed dose, dose equivalent, effective dose equivalent, committed dose equivalent, committed effective dose equivalent, or total effective dose equivalent, as defined below.

Absorbed dose - The energy imparted by ionizing radiation per unit mass of irradiated material. The units of absorbed dose are the rad and the gray (Gy).

Dose equivalent (H_T) - The product of the absorbed dose in tissue, quality factor, and all other necessary modifying factors at the location of interest. The units of dose equivalent are the rem and sievert (Sv).

Effective dose equivalent (H_E) - The sum of the products of the dose equivalent to the organ or tissue (H_T) and the weighting factors (w_T) applicable to each of the body organs or tissues that are irradiated ($H_E = \Sigma w_T H_T$).

Committed dose equivalent ($H_{T,50}$) - The dose equivalent to organs or tissues of reference (T) that will be received from an intake of radioactive material by an individual during the 50-year period following intake.

Committed effective dose equivalent ($H_{E,50}$) - The sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated (by internally deposited radionuclides) and the committed dose equivalent to these organs or tissues ($H_{E,50} = \Sigma w_T H_{T,50}$).

Total effective dose equivalent (TEDE) - The sum of the deep dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures).

Deep dose equivalent (H_d) - Applied to external whole-body exposure, H_d is the dose equivalent at a tissue depth of 1 cm (1000 mg/cm^2). (Note: for this generic application, the TEDE is calculated using the external effective dose equivalent, provided in dose conversion factors from EPA, as described in Section 6.)

Annual total effective dose equivalent (annual TEDE) - The total effective dose equivalent (TEDE) received during a year of scenario exposure. The duration of exposure for each pathway is determined by the scenario considered and need not be 8766 h/y. For example, an individual may reside or work at a contaminated site for only a fraction of the year.

In general, the results produced by the scenarios considered in this report are expressed as annual TEDEs to denote that a year of scenario exposure has been considered. This notation is used to ensure the definition and use of consistent units for all of the scenario and pathway equations in this report.

2.2 Symbol Nomenclature

The mathematical models described in this report involve many equations with numerous parameters. Because of the complexity of the equations, a system of nomenclature has been developed to represent symbols used for the parameters. This system of nomenclature is summarized in this section for ease of reference to understand the mathematical formulations that follow. Parameters are defined again when they are first used within each section. The system of nomenclature includes a definition of units used to permit a full dimensional analysis.

The parameter definitions are divided into three parts: dosimetric parameters (Table 2.1), subscripted parameters (Table 2.2), and parameters without subscripts (Table 2.3). In general, terms beginning with "D" are dose or dose rate factors; "TEDE" are annual total effective dose equivalents; "AF" are ingestion-pathway committed effective dose equivalent factors; "C" are concentrations (per unit mass, volume, or area), or total activity of a radionuclide, as appropriate; and "λ" are radioactive decay rate constants. General subscripts encountered include "i" or "j" for parent or decay-chain-member radionuclides; "s" for soil; "w" for water; and "v" for food crops (agricultural pathways).

In addition to the parameters listed in the tables, a special notation is used for radioactive decay calculations. Decay operators are represented by A{}, S{}, R{}, and G{}, as defined in Appendix B:

A{} = changes in parent and progeny activities or concentrations over time (i.e., radioactive decay and ingrowth)

S{} = time integrals of activity or concentration

R{} = accumulation of deposited activity over a time period

G{} = deposition, accumulation, and time-integration of a constant deposition rate (used for deposition from irrigation water onto plants).

The operations are performed on an initial array of chain member activities or concentrations for a specific time period. For example, the decay calculation is represented as follows:

$$A\{C_*, t_*\} \tag{2.1}$$

where A{} = the operation of decay calculation (in appropriate units)

C_* = the array of chain member activities or concentrations (in appropriate units)

t_* = time period over which the decay occurs (in time units).

Table 2.1 Dosimetry parameters

Symbol	Definition
Agricultural water-use dose factors	
AF_{dj}	Dose contribution from drinking water contaminated by radionuclide j, expressed as committed effective dose equivalent per unit average concentration of radionuclide j in water (mrem per pCi/L for a year of residential scenario)
AF_{fj}	Dose contribution from aquatic food products contaminated by radionuclide j in water, expressed as committed effective dose equivalent per unit average concentration of radionuclide j in water (mrem per pCi/L for a year of residential scenario)
AF_{sj}	Dose contribution from agricultural products contaminated by radionuclide j in soil, expressed as committed effective dose equivalent per unit initial concentration of radionuclide j in soil at the start of a growing season (mrem per pCi/g for a year of residential scenario)
AF_{wj}	Dose contribution from agricultural products contaminated by irrigation with ground water for radionuclide j, expressed as committed effective dose equivalent per unit average concentration of radionuclide j in water (mrem per pCi/L for a year of residential scenario)
Dose factors for building renovation scenario	
$DEXB_i$	External dose for parent radionuclide i for one renovation work period in 1 year (mrem)
DGB_i	Committed effective dose equivalent from ingestion for parent radionuclide i for one renovation work period in 1 year (mrem)
DHB_i	Committed effective dose equivalent from inhalation for parent radionuclide i for one renovation work period in 1 year (mrem)
$TEDEB_i$	Annual total effective dose equivalent for parent radionuclide i (mrem for renovation work in a year, with an initial inventory in units of pCi/g)
$TEDEB_{iSI}$	Annual total effective dose equivalent for parent radionuclide i (μSv for renovation work in a year, with an initial inventory in units of Bq/g)
$TEDEB_m$	Annual total effective dose equivalent for the mixture of radionuclides (mrem for renovation work in a year, with an initial inventory in units of pCi/g)
Dose factors for building occupancy scenario	
$DEXO_i$	External dose for parent radionuclide i for 1 year of building occupancy (mrem)
DGO_i	Committed effective dose equivalent from ingestion for parent radionuclide i for 1 year of building occupancy (mrem)

Table 2.1 Dosimetry parameters (Continued)

Symbol	Definition
DHO_i	Committed effective dose equivalent from inhalation for parent radionuclide i for 1 year of building occupancy (mrem)
$TEDEO_i$	Annual total effective dose equivalent for parent radionuclide i (mrem for a year of building occupancy, with an initial inventory in units of dpm/100 cm^2)
$TEDEO_{iSI}$	Annual total effective dose equivalent for parent radionuclide i (μSv for a year of building occupancy, with an initial inventory in units of Bq/100 cm^2)
$TEDEO_m$	Annual total effective dose equivalent for a mixture of radionuclides (mrem for a year of building occupancy, with an initial inventory in units of dpm/100 cm^2)
Dose factors for drinking water scenario (for year of highest TEDE)	
$HOCDE_i$	Highest annual organ committed dose equivalent for parent radionuclide i from ingestion of drinking water (mrem for a year of drinking water with an initial inventory in units of pCi)
$HOCDE_{iSI}$	Highest annual organ committed dose equivalent for parent radionuclide i from ingestion of drinking water (μSv for a year of drinking water with an initial inventory in units of Bq)
$HOCDE_m$	Highest annual organ committed dose equivalent for a mixture of radionuclides m from ingestion of drinking water (mrem for a year of drinking water with an initial inventory in units of pCi)
$HOCDE_{mSI}$	Highest annual organ committed dose equivalent for a mixture of radionuclides m from ingestion of drinking water (μSv for a year of drinking water with an initial inventory in units of Bq)
$TEDED_i$	Annual total effective dose equivalent for the drinking water scenario for parent radionuclide i (mrem for a year of drinking water, with an initial inventory in units of pCi)
$TEDED_{iSI}$	Annual total effective dose equivalent for the drinking water scenario for parent radionuclide i (μSv for a year of drinking water, with an initial inventory in units of Bq)
$TEDED_m$	Annual total effective dose equivalent for the drinking water scenario for a mixture of radionuclides m (mrem for a year of drinking water, with an initial inventory in units of pCi)
Dose factors for residential scenario (for year of highest annual TEDE)	
DAR_i	Committed effective dose equivalent from ingestion of aquatic foods for parent radionuclide i (mrem for a year of residential scenario)
$DEXR_i$	External dose for parent radionuclide i (mrem for a year of residential scenario)
DGR_i	Committed effective dose equivalent from ingestion for intake of home-grown food and animal products for parent radionuclide i (mrem for a year of residential scenario)

Table 2.1 Dosimetry parameters (Continued)

Symbol	Definition
DHR_i	Committed effective dose equivalent from inhalation of airborne soil and house dust for parent radionuclide i (mrem for a year of residential scenario)
DSR_i	Committed effective dose equivalent from ingestion of soil for parent radionuclide i (mrem for a year of residential scenario)
DWR_i	Committed effective dose equivalent from ingestion of drinking water and irrigated food for parent radionuclide i (mrem for a year of residential scenario)
$TEDER_i$	Annual total effective dose equivalent for parent radionuclide i (mrem for a year of residential scenario, with an initial inventory in units of pCi/g)
$TEDER_{iSI}$	Annual total effective dose equivalent for parent radionuclide i (μSv for a year of residential scenario, with an initial inventory in units of Bq/g)
$TEDER_m$	Annual total effective dose equivalent for a mixture of radionuclides m (mrem for a year of residential scenario with an initial inventory in units of pCi/g)
General dose factors for description of implicit progeny handling	
DF_i	Internal or external factor for the parent radionuclide i as taken from the database (in appropriate units for the dose factor type)
DF_j	Internal or external dose factor for the short-lived radionuclide j as taken from the database (in appropriate units for the dose factor type)
DFC_i	Internal or external combined dose factor for the parent radionuclide i (in appropriate units for the dose factor type)
Basic dose factors from database (after units conversion)	
$DFER_j$	External dose rate factor for radionuclide j from contamination uniformly distributed in the top 15 cm of residential soil or building material (mrem/h per pCi/g)
$DFES_j$	External dose rate factor for radionuclide j from contamination uniformly distributed on surfaces (mrem/h per dpm/100 cm^2)
DFG_j	Committed effective dose equivalent from ingestion of radionuclide j (mrem per pCi ingested)
DFH_j	Committed effective dose equivalent from inhalation for radionuclide j from contaminated air (mrem per pCi inhaled)
DFO_{jo}	Committed dose equivalent to organ o from ingestion of radionuclide j (mrem per pCi ingested)

Table 2.2 Subscripted parameter summary

Parameter	Number of subscripts	Order of subscripts	Description
A	3		Concentration of radionuclides for the current year per initial unit concentration of parent radionuclide i in soil
		1	s - soil (pCi/g per pCi/g) w - water (pCi/L per pCi/g)
		2	t - current year
		3	i - parent j - chain member (1 for parent, >1 for progeny)
A_d	1		Area of land contaminated in the drinking water scenario (m^2)
A_j	1		Activity of radionuclide j (pCi)
A_r	1		Area of land contaminated in the residential scenario (m^2)
A_{tj}	2		Concentration of radionuclide j present at the beginning of the current 1-year exposure period, t, per initial concentration of parent radionuclide i (pCi/g per pCi/g in soil)
AF (see Table 2.1)			
B	2		Concentration factor for uptake of a radionuclide from soil to edible parts of a plant (pCi/kg dry-weight plant per pCi/kg dry-weight soil)
		1	i - parent radionuclide j - chain member (1 for parent, >1 for progeny)
		2	f - forage crop g - stored grain crop h - stored hay crop v - food crop
BA	2		Bioaccumulation factor for transfer of activity from water to edible parts of fish (pCi/kg wet-weight fish per pCi/L water)
		1	i - parent radionuclide j - chain member (1 for parent, >1 for progeny)
		2	f - aquatic foods (fish)

Table 2.2 Subscripted parameter summary (Continued)

Parameter	Number of subscripts	Order of subscripts	Description
C	2		Activity or concentration in a medium
		1	b - medium is building renovation material (pCi/g)
			k - medium is box k of water-use model
			o - medium is building surface material (dpm/100 cm^2)
			r - medium is residential soil (pCi/g)
			s - medium is soil (pCi/g)
			t - total activity in soil (pCi)
			w - medium is water (pCi/L)
			v - medium is vegetation (pCi/g dry-weight plant)
			1 - total activity in box 1 of water-use model (pCi)
			2 - total activity in box 2 of water-use model (pCi)
			3 - total activity in box 3 of water-use model (pCi)
		2	i - parent radionuclide
			j - chain member (1 for parent, >1 for progeny)
			C - carbon-14
			H - tritium
C	4		Activity or concentration factor for transfer from a contaminating medium (e.g., soil or water) to a receiving medium of consumption (e.g., soil, food, or water)
		1	Contaminating medium (units of denominator of C)
			s - medium is soil (pCi/g or total pCi for the drinking water scenario)
			r - root uptake from irrigation to the soil path (pCi/L)
			w - medium is water (pCi/L)
		2	Recieving medium (units of numerator of C)
			a - animal product (pCi/kg wet weight)
			f - forage crop (pCi/kg wet weight)
			g - stored grain crop (pCi/kg wet weight)
			h - stored hay crop (pCi/kg wet weight)
			s - soil (pCi/kg dry-weight soil)
			v - food crop (pCi/kg wet weight)
			w - drinking water (pCi/L)
		3	i - parent radionuclide
			j - chain member (radionuclide, parent or progeny)
			C - carbon-14
			H - tritium

Table 2.2 Subscripted parameter summary (Continued)

Parameter	Number of subscripts	Order of subscripts	Description
C	4	4	c - evaluated at time of general feed consumption by animals d - animal ingestion of dirt (soil) at time of forage consumption f - evaluated at point when animals begin consuming forage h - evaluated at point when harvesting of food begins p - evaluated at point when people start consuming the food s - evaluated at point when animals start consuming stored food t - evaluated for the year t, or at any time t w - evaluated over time of water consumption by animals y - evaluated for a 1-year time period
C_{soil}			Ratio of the ^{14}C concentration in soil eaten by animal to the initial concentration of ^{14}C in the soil, with units conversion from grams to kilograms (g/kg)
CR_v			Effective concentration ratio between soil and plant type v (pCi/g dry-weight plant per pCi/g dry-weight soil)
d_{pj}	2		Fraction of radionuclide p transitions that result in production of radionuclide j (dimensionless)
d_s	1		Density of agricultural soil (g/cm^3)
DEXB, DEXO, DEXR (see Table 2.1)			
DF, DFC, DFER, DFES, DFEV, DFG, DFH (see Table 2.1)			
DGB, DGO, DGR (see Table 2.1)			
DHB, DHO, DHR (see Table 2.1)			
DSR, DWR (see Table 2.1)			
F	2		Transfer coefficient relating daily intake in animal feed or ingested soil to concentration in edible animal product
		1	a - food type (animal product)
		2	j - chain member (radionuclide, parent, or progeny)

Table 2.2 Subscribed parameter summary (Continued)

Parameter	Number of subscripts	Order of subscripts	Description
f_r	1		Fraction of water removed from Box 3 that is deposited on the surface layer by irrigation
f	1		1 - surface-soil layer, box 1 2 - unsaturated-soil layer, box 2
f	2		Fraction, by weight, of carbon or hydrogen in a medium (dimensionless)
		1	C - carbon H - hydrogen
		2	a - medium is an animal product d - medium is soil (dirt) f - medium is fresh forage g - medium is stored grain h - medium is stored hay v - medium is food crop
H	1		Assumed thickness of soil layers for water-use model(m)
		1	1 - surface-soil layer, box 1 2 - unsaturated-soil layer, box 2
J_i			Number of radionuclides in decay chain for parent radionuclide i
K	2		Coefficient in chain decay equations (pCi•d)
		1	n - precursor chain members j - current chain member
		2	j - current chain member
Kd	2		Partition coefficient for radionuclide i, defined by element and box (mL/g)
		1	Water-use model box 1 - surface-soil, box 1 2 - unsaturated layer, box 2
		2	Radionuclide index i - parent radionuclide j - chain member radionuclide (parent or progeny)
L	3		Rate constant for movement of radionuclides between boxes of the water-use model (d^{-1})
		1	1 - transfer from box 1 2 - transfer from box 2
		2	2 - transfer to box 2 3 - transfer to box 3
		3	i - parent radionuclide j - chain member radionuclide (1 for parent or >1 for progeny)

Table 2.2 Subscribed parameter summary (Continued)

Parameter	Number of subscripts	Order of subscripts	Description
ML	1		Plant soil mass-loading factor for transfer from soil to plants (pCi/kg dry-weight plant per pCi/kg dry-weight soil)
		1	f - forage crops g - stored grain crops h - stored hay crops v - food crops
n	1		The porosity of the soil layers (dimensionless)
		1	1 - surface-soil layer, box 1 2 - unsaturated-soil layer, box 2
N_d			Number of short-lived progeny for which contributions are to be included with the parent radionuclide dose factors
N_v			Total number of food products considered in the diet
P	1		Soil areal density
		1	s - areal soil density in agricultural areas (kg dry-weight soil/m^2) d - floor dust-loading for residential scenario (g/m^2)
PPTF	4		Partial pathway transfer factors (PPTFs) providing activity time integral in a food type (pCi•y/unit receiving medium per unit initial activity in a contaminating medium)
		1	Receiving medium a - animal product type v - food crop type
		2	Contaminating medium s - soil w - water
		3	Parent radionuclide index i - parent radionuclide C - carbon-14 H - tritium
		4	Progeny radionuclide index j - chain member (1 for parent, >1 for progeny) "blank" - 4th subscript not used for carbon-14 or tritium
PF	3		Pathway transfer factors (PFs) providing intake (pCi) by humans per unit initial concentration in a medium
		1	s - medium is soil w - medium is water
		2	i - parent radionuclide
		3	j - chain member (1 for parent, >1 for progeny)

Table 2.2 Subscripted parameter summary (Continued)

Parameter	Number of subscripts	Order of subscripts	Description
Q	1		Consumption rate by animal
		1	d - animal ingestion of soil (dirt) (kg dry-weight soil per kg dry-weight forage)
			f - forage crop (kg wet-weight forage/d)
			g - stored grain crop (kg wet-weight grain/d)
			h - stored hay crop (kg wet-weight hay/d)
			w - water (L/d)
	2		Amount of radionuclide present (units proportional to atoms)
		1	1 - medium is surface-soil (box 1)
			2 - medium is unsaturated zone (box 2)
			3 - medium is ground-water aquifer (box 3)
			m - general medium
		2	1 - parent radionuclide
			2 - first progeny radionuclide (chain member 2)
			3 - second progeny radionuclide (chain member 3)
			i - parent radionuclide
			j - chain member (1 for parent, >1 for progeny)
r	1		Fraction of initial deposition retained on the plant from irrigation water
		1	f - forage crop
			g - stored grain crop
			h - stored hay crop
			v - food crop
R	4		Deposition rate from irrigation water to a medium
		1	Deposition pathway
			w - water to plant surfaces or soil
		2	Medium receiving deposition
			f - forage crop type
			g - stored grain crop
			h - stored hay crop
			s - soil
			v - food crop
		3	Radionuclide index
			i - parent radionuclide
			j - chain member (1 for parent, >1 for progeny)
		4	Period of deposition
			g - crop-growing period
			f - animal-foraging period

Table 2.2 Subscripted parameter summary (Continued)

Parameter	Number of subscripts	Order of subscripts	Description
RF	1		Resuspension factor (m^{-1})
		1	o - building occupancy scenario
			r - indoor activity for residential scenario
R_t	2		Retardation factor (dimensionless)
		1	1 - surface-soil layer, box 1
			2 - unsaturated-soil layer, (box 2)
		2	j - current chain member
SA	3		Specific activity equivalence factors for carbon and tritium
		1	s - medium is soil
			T - normalized to total activity
			w - medium is water
		2	a - animal product
			v - crop
		3	C - carbon-14
			H - tritium
t	1		Time period (d)
		1	b - time spent in building renovation work
			d - water intake period for drinking water scenario
			f - fish intake period for residential scenario
			g - time spent gardening for residential scenario
			i - time spent indoors for residential scenario
			o - time spent in building occupancy
			r - time of residential scenario
			x - time spent outdoors for residential scenario
			y - 1 year

Table 2.2 Subscripted parameter summary (Continued)

Parameter	Number of subscripts	Order of subscripts	Description
t	2		Time period (d)
		1	c - consumption period by humans
			f - feeding period for animals producing animal product a
			g - crop-growing period
			h - time between harvest and consumption by humans
			t - total elapsed time for a period
			w - consumption period for animals drinking contaminated water
		2	a - animal product
			b - building renovation scenario
			d - drinking water scenario
			f - forage crop
			g - gardening period (used only with first subscript t)
			g - stored grain crop (used only with first subscript g or f)
			h - stored hay crop
			o - building occupancy scenario
			r - residential scenario
			s - stored feed (hay or grain)
			v - food crop
T	1		Translocation factor of activity from plant surfaces to edible parts of the plant (dimensionless)
		1	f - forage crop
			g - stored grain crop
			h - stored hay crop
			v - food crop
TEDEB, TEDED, TEDEO, TEDER (see Table 2.1)			
U	1		Ingestion rate of foods or water by humans
		1	a - animal product (kg/y)
			f - aquatic food, fish (kg/y)
			v - food crop (kg/y)
			w - drinking water (L/d)
V	1		Volumetric breathing rate (m^3/h)
		1	b - building renovation scenario
			g - residential scenario, gardening
			r - residential scenario, indoors
			o - building occupancy scenario
			s - standard rate used as the basis for the inhalation dose factors (DHF_j)
			x - residential scenario, outdoors

Table 2.2 Subscripted parameter summary (Continued)

Parameter	Number of subscripts	Order of subscripts	Description
V_{dd}			Volume of water used for domestic purposes during a year of drinking water scenario (L)
V_{dr}			Volume of water used for domestic purposes during a year of residential scenario (L)
V_{Id}			Volume of water infiltrating through contaminated area in a year for the drinking water scenario water-use model (L)
V_{Ir}			Volume of water infiltrating through contaminated area in a year for the residential scenario water-use model (L)
V_{irr}			Volume of water used for irrigation during a year of residential scenario (L)
V_{sw}			Volume of water in the surface-water pond used in production of aquatic foods (L)
V_{Td}			Total aquifer volume for the drinking water scenario (L)
V_{Tr}			Total aquifer volume for the residential scenario (L)
w	1		removal rate constant for the water-use models (d^{-1})
		1	d - drinking water scenario r - residential scenario
W	1		Factor to convert plant concentrations from a dry-weight basis to a wet-weight basis (kg dry-weight plant per kg wet-weight plant)
		1	f - forage crop g - stored grain crop h - stored hay crop v - food crop
x	1		Fraction of animal feed or water intake that is contaminated, defined for each animal type
		1	f - forage g - stored grain h - stored hay w - water

Table 2.2 Subscripted parameter summary (Continued)

Parameter	Number of subscripts	Order of subscripts	Description
Y	1		Yield of crop (kg wet weight per m^2)
		1	f - forage crop
			g - stored grain crop
			h - stored hay crop
			v - food crop
θ	1		Volumetric water content for a soil layer (dimensionless)
		1	1 - surface-soil layer
			2 - unsaturated-soil layer
ρ	1		Bulk density for a soil layer (g/mL)
		1	1 - surface-soil layer
			2 - unsaturated-soil layer
λ_{nj}			Decay rate constant for transition of radionuclide n to radionuclide j (d^{-1})
λ	2		Rate constant (d^{-1})
		1	w - removal by weathering from plant surfaces
			e - effective (sum of removal and decay rate constants)
			r - radiological decay
		2	i - parent radionuclide
			j - chain member (1 for parent, >1 for progeny)
			n - chain member
			"blank" - not dependent on radionuclide

Table 2.3 Unsubscripted parameters

Symbol	Definition
A	Area of land under irrigated agricultural production (m^2)
CDB	Dust-loading for building renovation work (g/m^3)
CDG	Dust-loading for gardening activities (g/m^3)
CDI	Dust-loading for indoor exposure periods (g/m^3)
CDO	Dust-loading for outdoor exposure periods (g/m^3)
DIET	Fraction of annual diet derived from home-grown foods (dimensionless)
DL	Annual dose limit for evaluation of the potential for adverse impacts (mrem)
F	Dilution flow in the ground-water aquifer (L)
GB	Effective transfer rate for ingestion of loose dust transferred from building surfaces to hands and mouth during building renovation work (g/h)
GO	Effective transfer rate for ingestion of removable surface activity transferred from surfaces to hands and mouth during building occupancy (m^2/h)
GR	Effective transfer rate for ingestion of soil and dust transferred to the mouth during the residential scenario (g/d)
H^*	Absolute humidity (L/m^3)
i	Index of parent radionuclide
j	Index of current chain member position in decay chain
k	Proportionality constant to convert from activity units to atom units, dependent on the activity units used, equal for all radionuclides ($k = 1$ when activity is given in Bq and λ_{rj} in inverse seconds)
I	Infiltration rate (m/y)
IR	Annual average application rate of irrigation water ($L/m^2 \cdot d$)
M	Number of parent radionuclides in the mixture
QT	Total activity factor for irrigated land (pCi per pCi/g)

Table 2.3 Unsubscripted parameters (Continued)

Symbol	Definition
SFI	Shielding factor by which external dose rate is reduced during periods of indoor residence (dimensionless)
SFO	Optional shielding factor by which external dose rate is reduced during periods of outdoor residence (dimensionless)
SH	Moisture content of soil (L/kg)

The units of the decay operator are the same as those of the initial activity or concentration array. The asterisk subscript represents possibilities defined for activities or concentrations (parameters C in Table 2.2) and time (parameter t in Table 2.2). The time integral of activity or concentration, S{}, must be evaluated in several of the models. The nomenclature of this operator is the same as that for the decay operator, A{}:

$$S\{C_*,t_*\} \tag{2.2}$$

where $S\{\}$ = the operation of time-integration calculation (in appropriate units)

C_* = the array of chain member activities (in appropriate units)

t_* = time period over which the integration is performed (in time units).

Units of the resulting operation are the product of the activity or concentration units and the time units. For example, evaluation of a time integral of activity in pCi for a time period in days would provide results in units of pCi•d.

The operator for evaluation of the concentration in a medium after accumulation of constantly depositing activity is represented as

$$R\ \{R_*,t_*\} \tag{2.3}$$

where $R\{\}$ = the operation of the deposition, accumulation calculation (in appropriate units)

R_* = the array of chain member constant deposition rates (in appropriate units per unit time)

t_* = time period over which the deposition at a constant rate occurs (in time units).

Units of the resulting operation are the same as the receiving medium units, which are the units of the deposition rate multiplied by time. For example, if the deposition rate is defined as pCi/d per kg of plant and time units are in days, then the resulting units are pCi/kg of plant. Note that the time units for the deposition rate and the time parameter must be the same (or a time units conversion factor must be applied to the result).

The deposition, accumulation, and time-integration operator is needed for processes involving deposition (via irrigation water) for the residential scenario. This operator is used to evaluate the activity or concentration in a

medium after deposition for a period of time. The deposition, accumulation, and time-integration operator is represented as:

$$G\{R_*,t_*\} \tag{2.4}$$

where $G\{\}$ = the operation of the deposition, accumulation, and time-integration calculation (in appropriate units)

R_* = the array of chain members with constant deposition rates (in appropriate units per unit time)

t_* = the time period over which the deposition, accumulation, and time-integration calculation is performed (in time units).

Units of the resulting operation are the product of the activity or concentration-per-time units and the square of the time units. For example, evaluation of a time integral of deposition rate in pCi/day for a time period in days would provide results with units of pCi•d. Note that the resulting units are the same as those for the single time-integral of activity or concentration. The deposition, accumulation, and time-integration operator results may be divided by the integration time period to give an average concentration or activity over the period.

A summary of the various uses of the decay and time-integral operators used in this report is given in Table 2.4. The table provides references to specific equations in Appendix B and to the form of the exponential term in the equations. Each application involves use of a summation equation that includes the product of coefficients multiplied by an exponential term as follows:

$$(\text{Operator Value})_j = \sum_{n=1}^{J} (\text{Coefficient})_n \ (\text{Exponential Term})_n \tag{2.5}$$

Where the subscript, j, refers to a chain member and the subscript, n, refers to all precursor radionuclide positions in the decay chain. The form of the exponential term depends on the application (as indicated in Table 2.4).

Using the indicated equations, specific equations for the operators can be developed. Examples of generation of specific equations from the general equations are given in Appendix B.

The drinking water scenario involves a special application of the decay and time-integral operators. This application involves generation of a solution to the three-box water-use model. Details of the water-use model applications are provided in Section 4 (drinking water scenario) and Section 5 (residential scenario). A summary of the operator notation for the water-use model is given in Table 2.5. The drinking water scenario application uses the basic equations including removal terms in Equations (B.15 to B.18). The residential scenario application is described in Section B.7.

Table 2.4 Summary of operator notation equations

Operator	Summation Equation	Coefficient Equations	Exponential Term	Calculation
$A\{C_*,t_*\}$	B.2	B.3-B.5	$\exp(-\lambda_{rj}\, t_*)$	Decay for a time period
$A_e\{C_*,t_*\}$	B.15	B.16-B.18	$\exp(-\lambda_{ej}\, t_*)$	Decay with removal for a time period
$S\{C_*,t_*\}$	B.2	B.3-B.5	$[1-\exp(-\lambda_{rj}\, t_*)]/\lambda_{rj}$	Time integral over a time period
$S_e\{C_*,t_*\}$	B.15	B.16-B.18	$[1-\exp(-\lambda_{ej}\, t_*)]/\lambda_{ej}$	Time integral with removal over a time period
$R\{R_*,t_*\}$	B.2	B.3-B.5	$[1-\exp(-\lambda_{rj}\, t_*)]/\lambda_{rj}$	Deposition and accumulation of a constant deposition rate over a time period
$R_e\{R_*,t_*\}$	B.15	B.16-B.18	$[1-\exp(-\lambda_{ej}\, t_*)]/\lambda_{ej}$	Deposition and accumulation of a constant deposition rate with removal over a time period
$G\{R_*,t_*\}$	B.2	B.3-B.5	$\{t-[1-\exp(-\lambda_{rj}\, t_*)]/\lambda_{rj}\}/\lambda_{rj}$	Deposition, accumulation, and time-integration of a constant deposition rate over a time period
$G_e\{R_*,t_*\}$	B.15	B.16-B.18	$\{t-[1-\exp(-\lambda_{ej}\, t_*)]/\lambda_{ej}\}/\lambda_{ej}$	Deposition, accumulation, and time-integration of a constant deposition rate with removal over a time period

As an example of the use of the decay operator, the concentration of radionuclide j in building materials after decay during the renovation work period, t_{tb}, is calculated from the initial concentration in building materials, C_{bj}, and is written

$$A\{C_{bj},t_{tb}\} \tag{2.6}$$

The time integral of the concentration in building material of radionuclide j over this period is written

$$S\{C_{bj},\, t_{tb}\} \tag{2.7}$$

Table 2.5 Summary of water-use model operator notation equations

Operator	Summation Equation	Coefficient Equations	Exponential Term	Calculation
$A_{dk}\{C_*,t_*\}$	B.15	B.16-B.18	$\exp(-\lambda_{ej} t_*)$	Decay for a time period in drinking water scenario water-use model box k
$A_{rk}\{C_*,t_*\}$		(see Section B.7)		Decay with removal for a time period in residential scenario water-use model box k
$S_{dk}\{C_*,t_*\}$	B.15	B.16-B.18	$[1-\exp(-\lambda_{ej} t_*)]/\lambda_{ej}$	Time integral over a time period in drinking water scenario water-use model box k
$S_{rk}\{C_*,t_*\}$		(see Section B.7)		Time integral with removal over a time in residential scenario water-use model box k

Multiple applications of the decay or time-integral operations are represented as nested symbols. For example, the decay of radionuclide j concentration in soil, for a time t_{tb}, followed by a time integration for a period t_y, is represented as follows:

$$S\{A\{C_{sj},t_{tb}\},\ t_y\} \tag{2.8}$$

The decay operator notation can be expanded using equations given in Appendix B. The expansion will result in one equation for each chain member, giving the desired parameter value as indicated for the specific operator. For example, Equation (2.6) can be written for a two-membered decay chain as two equations, one for the parent and one for the first progeny.

The explicit equations are as follows:

for the parent,

$$C_{b1}(t_{tb}) = C_{b1}(0)\ e^{-\lambda_{r1}t_{tb}} \tag{2.9}$$

and for the first progeny,

$$C_{b2}(t_{tb}) = \frac{\lambda_{r2}d_{12}C_{b1}(0)}{\lambda_{r2} - \lambda_{r1}}\ e^{-\lambda_{r1}t_{tb}} + \left[C_{b2}(0) - \frac{\lambda_{r2}d_{12}C_{b1}(0)}{\lambda_{r2} - \lambda_{r1}}\right] e^{-\lambda_{r2}t_{tb}} \tag{2.10}$$

where $C_{b1}(t_{tb})$ = concentration of parent radionuclide in building material evaluated at time t_{tb} (activity units)

$C_{b2}(t_{tb})$ = concentration of first progeny radionuclide in building material evaluated at time t_{tb} (activity units)

$C_{b1}(0)$ = initial concentration of parent radionuclide in building material (activity units)

$C_{b2}(0)$ = initial concentration of first progeny radionuclide in building material (activity units)

λ_{r1} = radioactive decay rate constant for the parent radionuclide (d^{-1})

λ_{r2} = radioactive decay rate constant for the progeny radionuclide (d^{-1})

d_{12} = the fraction of parent radionuclide transitions that result in production of progeny radionuclide (dimensionless)

t_{tb} = duration of the renovation period

and other terms are as previously defined.

The time-integral operator notation can also be expanded directly from Equations (2.9) and (2.10) by integrating the expressions over time between 0 and t_{tb}. Noting that, for any radionuclide j,

$$\int_0^{t_{tb}} e^{-\lambda_{rj}t}\, dt = \frac{[1 - e^{\lambda_{rj}t_{tb}}]}{\lambda_{rj}} \tag{2.11}$$

the results are as follows for the parent radionuclide:

$$\int_0^{t_{tb}} C_{b1}(t)\, dt = C_{b1}(0)\left[1 - e^{-\lambda_{r1}t_{tb}}\right] / \lambda_{r1} \tag{2.12}$$

and for the first progeny,

$$\int_0^{t_{tb}} C_{b2}(t)\, dt = \left[\frac{\lambda_{r2}d_{12}C_{b1}(0)}{\lambda_{r2} - \lambda_{r1}}\left[1 - e^{-\lambda_{r1}t_{tb}}\right] / \lambda_{r1}\right] + \left[C_{b2}(0) - \frac{\lambda_{r2}d_{12}C_{b1}(0)}{\lambda_{r2} - \lambda_{r1}}\right]\left[1 - e^{-\lambda_{r2}t_{tb}}\right] / \lambda_{r2} \tag{2.13}$$

3 Scenario Descriptions for the Release of Buildings

Currently, there are estimated to be over 22,000 NRC and NRC Agreement State licensees that will eventually apply for license termination. There is a significant diversity in the types of buildings and building materials to be released after decommissioning. For example, licensed facilities range from commercial nuclear power reactors to research laboratories at universities and industrial plants. Because licensed facilities are in commercial use, it is unlikely that continuous exposure (i.e., 24 h/d) could occur after license termination. Therefore, the conceptual basis of the generic scenarios identified for the release of buildings assumes continued commercial use of a building (not residential use). This assumption is considered to be prudently conservative, while continuous exposure would be the worst case.

Two exposure scenarios are defined for buildings: building renovation and normal building occupancy. The building renovation scenario, in Section 3.1, accounts for an average volume (subsurface) concentration of radionuclides in building walls, floors, and ceilings. The building occupancy scenario, in Section 3.2, accounts for radionuclides in a thin surface layer, with a small fraction being removable. Building renovation represents relatively short-term exposures to disturbed sources, while building occupancy represents long-term chronic exposure to low levels of loose contamination. This dual-scenario approach permits the calculation of generic annual TEDEs for volume and surface sources of residual radioactive materials. This approach should help develop screening levels for well-defined situations, permit consideration of site-specific conditions using alternative parameter assignments, and assist in determining when more detailed site-specific data, models, and assessments are required. Additional information regarding specific parameter values used for the analysis is provided in Section 6.

3.1 Building Renovation Scenario

At the time of license termination, it is likely that decontamination operations will have effectively eliminated (or significantly reduced) removable surface sources of residual radioactive contamination. It is also likely that, at some point, buildings will require renovation and, ultimately, they will be demolished. During renovation or demolition, surface and volume sources will be disturbed, creating loose contamination. This loose contamination can produce higher concentrations of radionuclides in the air or on surfaces than the levels in an undisturbed building.

Renovation conditions serve as the prudently conservative basis for this scenario analysis. The differences between renovation and demolition are difficult to predict, but both can likely be represented by the same conceptual model. For some conditions, demolition may represent a worst-case situation; in others, renovation may be the worst case. For example, the exposure duration for demolition may exceed the duration of renovation. Whereas demolition may be rather remote, involving the use of heavy wrecking equipment, renovation may involve work indoors with direct contact with residual radioactive materials.

The work activities associated with building renovation will likely be quite varied, ranging from heavy construction to light finish work. Figure 3.1 shows a variety of expected activities, including removal of a portion of a concrete structure, creating loose surface contamination. Other renovation activities, such as carpentry, plumbing, or painting, will likely be less rigorous, but they are assumed to occur with an elevated amount of loose surface contamination. Figure 3.1 illustrates the modeling basis for the renovation scenario pathways, which account for all four expected activities. The following sections describe the scenario time frame, the potential exposure pathways (describing both those that are included and excluded from the analysis), and the mathematical formulations needed to describe the renovation scenario exposure pathways.

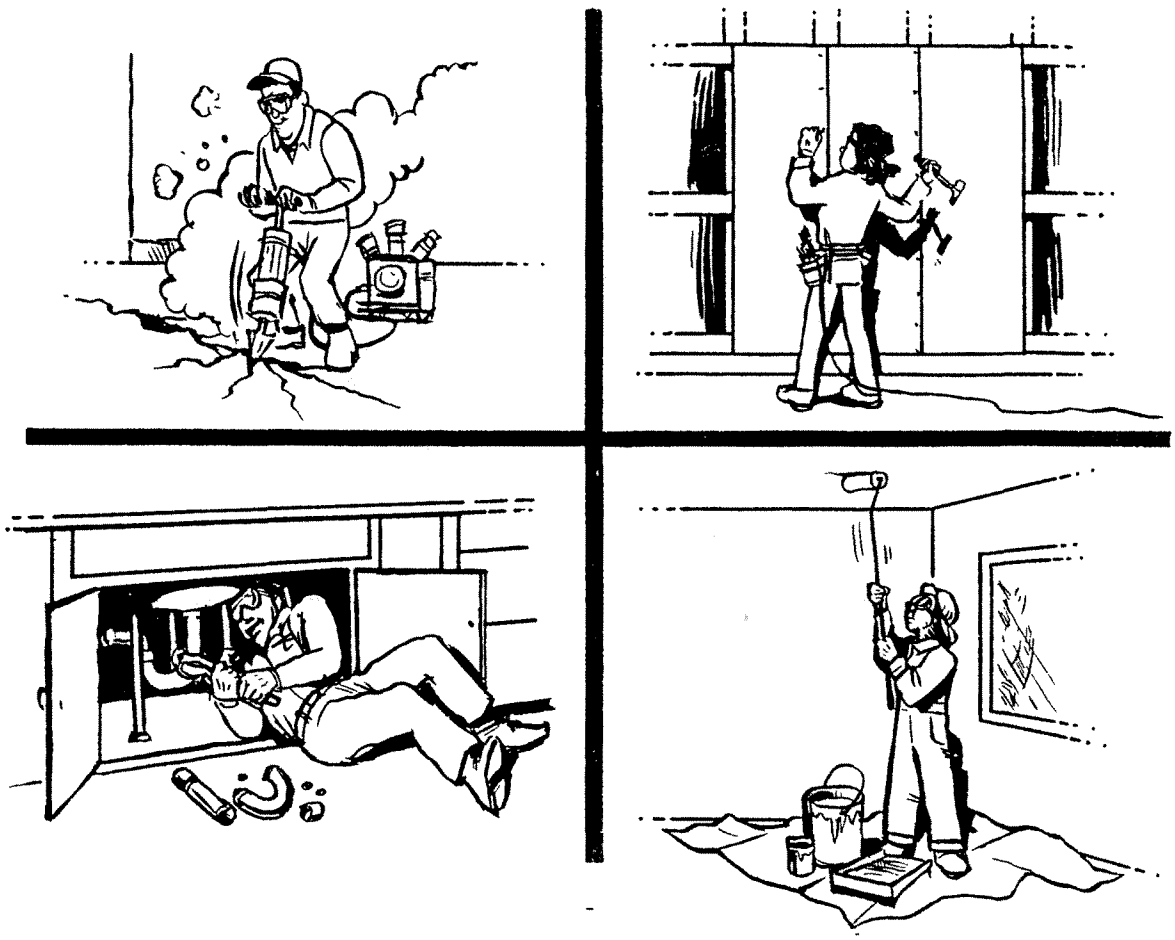


Figure 3.1 Potential activities within the building renovation scenario

3.1.1 Time Frame for Building Renovation Scenario

The time frame for exposure for the building renovation scenario is illustrated in Figure 3.2. Although building renovation may occur at any time after license termination, this study assumes that it occurs immediately after release of the building, before additional radioactive decay takes place. The workers are assumed to be involved in only one renovation operation during the year.

The top portion of Figure 3.2 shows an exact description of exposure to a decaying source during renovation. The dark lines indicate exposure for 8 h/d, 5 d/wk over the total exposure period. The lower part of Figure 3.2 shows the mathematical representation of the exact solution using the exposure duration and the mean activity level. The mean activity level is evaluated using the activity time-integral, S{} (discussed in Section 2), divided by the duration of the renovation. This formulation of mean activity level is used in each of the exposure pathway mathematical formulations.

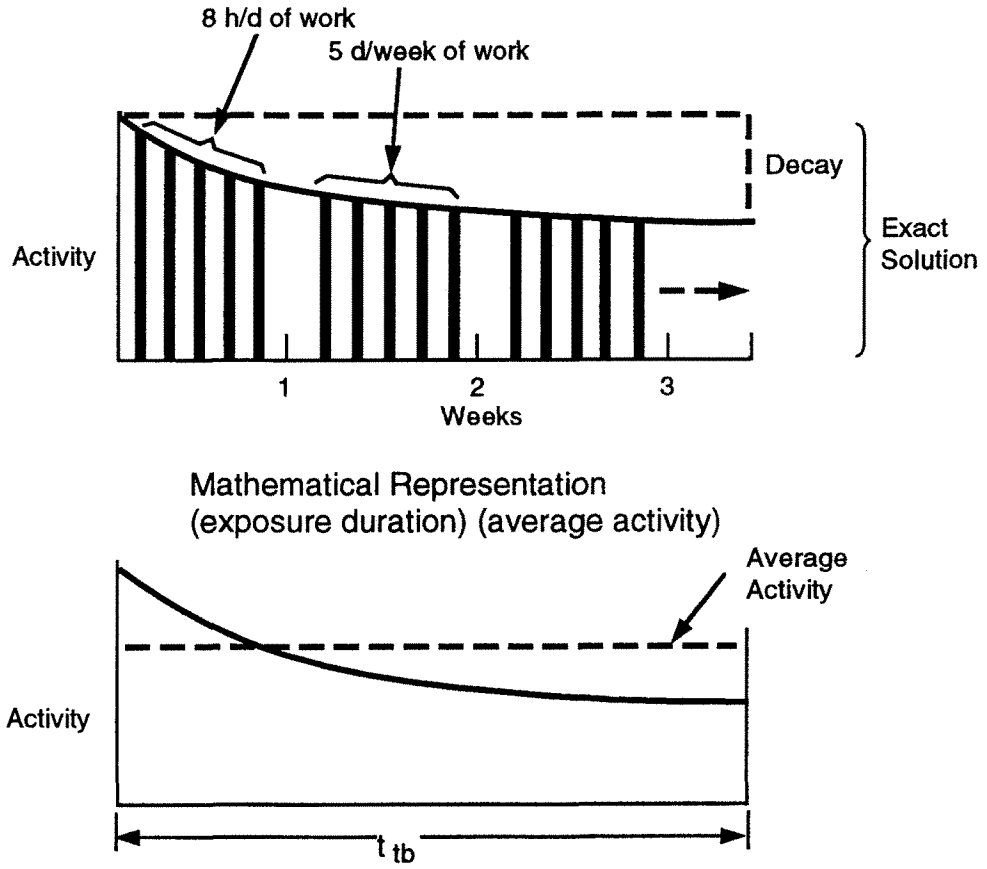


Figure 3.2 Building renovation time frame

3.1.2 Exposure Pathways for Building Renovation Scenario

As can be inferred from Figure 3.1, numerous potential exposure pathways can be identified during building renovation. Although the potential pathways may be quite numerous, some will produce greater radiation dose than others. The potential pathways are shown in the following list, with those selected for analysis shown in bold type.

- **external exposure to penetrating radiation from volume sources**
- **inhalation of airborne radioactive dust**
- **inadvertent ingestion of loose surface contamination**
- external exposure from submersion in airborne radioactive dust
- internal contamination from puncture wounds during building renovations

- dermal absorption of radionuclides
- inhalation of the indoor radon aerosol.

The exposure pathways selected for analysis in the building renovation scenario include external exposure to penetrating radiation from volume sources, inhalation of airborne dust, and inadvertent ingestion of dust. The selection of these pathways, along with the selection of prudently conservative parameter values, provides a balanced analysis for each of the following:

- photon-emitters, through the external exposure pathway
- alpha-emitters, through the inhalation exposure pathway
- beta-emitters, through inadvertent ingestion of "loose" surface contamination.

The four potential pathways identified above but not included in this analysis are external exposure during submersion in airborne radioactive dust, internal contamination from puncture wounds, dermal absorption, and inhalation of radon aerosol. Reasons for excluding these four pathways are provided below.

Air submersion can be an important pathway to consider when evaluating the potential consequences of airborne plumes from accidents at nuclear facilities. However, numerous previous studies for decommissioning have concluded that external doses from air submersion are trivial compared with external doses from surface or volume sources (Schneider and Jenkins 1977; Smith, Konzek, and Kennedy 1978; Oak et al. 1980). Thus, air submersion doses are not included in the scenarios considered in this study.

Similarly, internal exposures from puncture wounds or from dermal absorption may be important when evaluating sources of exposure to workers in licensed nuclear facilities. But most dose assessments using these pathways are retrospective (after-the-fact) and rely on bioassay results to help establish the magnitude of internal deposition that occurred for a specific situation. The frequency of occurrence of puncture wounds, although unpredictable, is assumed to be low considering the exposure pathways involved. Dermal absorption may be important for only a few radionuclides, most notably ^{3}H. To help account for dermal absorption of ^{3}H, the ICRP increased the inhalation dose factors by 50%. The doses that could result from dermal absorption for other radionuclides are assumed to be low compared with inhalation and ingestion. Thus, internal doses from puncture wounds and dermal absorption are not included in this scenario.

Under some conditions, inhalation of radon aerosol from the uranium decay chain can be a significant pathway. The concentration of indoor radon is a complex function of the quantity of uranium and decay chain members present, the building design, and the air exchange rate with outdoor air. In addition, indoor radon may be present from naturally occurring concentrations of uranium decay chain members, not just residual radioactive contamination from licensed activities. Because of the site-specific nature of the indoor radon aerosol and because the EPA has developed separate regulations for indoor radon, no attempt is made to model exposure from the indoor radon aerosol for this study.

A further justification for excluding these four pathways stems from the intent to produce a set of prudently conservative (not worst-case) generic screening scenarios. Additional pathways can be included, as necessary, in site-specific ALARA evaluations using site-specific data.

3.1.3 External Dose

The external dose is evaluated for renovation work lasting for a specified exposure duration (t_b) in the year, occurring over a specified renovation work period (t_{tb}). The concepts involved in the external dose calculation for the building renovation scenario are described in the following word equation:

$$\begin{aligned}[\text{External Dose}] = &[\text{Exposure Duration for Renovation}] \\ &\times [\text{Volume Source Dose Rate Factor}] \\ &\times [\text{Average Concentration of Radionuclides} \\ &\quad \text{in Building Material}]\end{aligned} \tag{3.1}$$

The external dose calculation involves evaluation of the average concentration of radionuclides in building material over the period of exposure. The amount of a radionuclide present at any time is evaluated as the solution to the following differential equation (quantities expressed in atoms):

$$\frac{d\,C_{bj}}{dt} = \sum_{n=1}^{j-1} d_{nj}\,\lambda_{rj} C_{bn} - \lambda_{rj} C_{bj} \tag{3.2}$$

where C_{bj} = concentration of radionuclide j present in building material at time t (pCi/g)

C_{bn} = concentration of precursor radionuclide n present in building material at time t (pCi/g)

d_{nj} = fraction of radionuclide n transitions that result in production of radionuclide j.

λ_{rj} = radioactive decay constant for radionuclide j (d^{-1}).

The average concentration of a radionuclide in building material is evaluated as the time integral of the solution to Equation (3.2) as follows:

$$\bar{C}_{bj} = \frac{1}{t_{tb}} \int_0^{t_{tb}} C_{bj}\,dt \tag{3.3}$$

where $\bar{C}_{bj}$ is the average concentration of radionuclide j in building material over the period of renovation work (pCi/g), and t_{tb} is the duration of the renovation period (d).

The mathematical formulation for calculating external dose for the building renovation scenario is given by the following equation:

$$DEXB_i = 24\ t_b \sum_{J=1}^{J_i} \left(DFER_j\ S\left\{C_{bj}, t_{tb}\right\} / t_{tb} \right) \tag{3.4}$$

where $DEXB_i$ = external dose from the specified renovation work duration for the decay chain with parent radionuclide i (mrem for renovation during 1 year)

$DFER_j$ = external dose rate factor for exposure to a volume source of radionuclide j, compatible with the volume source intent of the building renovation scenario, as described in Section 6 (mrem/h per pCi/g)

t_b = exposure duration for renovation period (d)

$S\{C_{bj}, t_{tb}\}$ = time-integral operator used to develop the average concentration of radionuclide j in building material over the renovation period (pCi•d/g for renovation during 1 year)

C_{bj} = initial concentration of radionuclide j in building material (pCi/g)

t_{tb} = duration of the renovation period (d)

J_i = number of radionuclides in the decay chain for parent radionuclide i

24 = unit conversion factor (h/d).

The time integral of concentration in building material is evaluated for each chain member. For the parent radionuclide of a decay chain, the time integral is equivalent to the following expression:

$$S\left\{C_{b1}, t_{tb}\right\} = \left\{ C_{b1}(0) \left[1 - e^{-\lambda_{r1} t_{tb}} \right] / \lambda_{r1} \right\} \tag{3.5}$$

where λ_{r1} is the radioactive decay constant for the parent radionuclide (first chain member) (d^{-1}), $C_{b1}(0)$ is the initial concentration of parent radionuclide in building material (pCi/g), and other terms are as previously defined.

When the decay chain contains progeny radionuclides, the decay operator provides an array of results, one value for each chain member. The time-integral value for the parent radionuclide is given by Equation (3.5). The value for the first progeny is given by the following equation:

$$S\left\{C_{b2}, t_{tb}\right\} = \left\{ \frac{C_{b1}(0) d_{12} \lambda_{r2}}{\left(\lambda_{r2} - \lambda_{r1}\right)} \left(1 - e^{-\lambda_{r1} t_{tb}}\right) / \lambda_{r1} + \left[C_{b2}(0) - \frac{d_{12} \lambda_{r2} C_{b1}(0)}{\lambda_{r2} - \lambda_{r1}} \right] \left(1 - e^{-\lambda_{r2} t_{tb}}\right) / \lambda_{r2} \right\} \tag{3.6}$$

where λ_{r2} is the radioactive decay constant for the first progeny radionuclide (second chain member), C_{b2} is the value of C_{bj} for the second chain member, and other terms are as previously defined. See Section 2 and Appendix B for a discussion of the decay operator notation and example generation of equations corresponding to Equations (3.5)

and (3.6) for additional progeny. A detailed discussion of the selection of parameter values for calculating the external dose during building renovation is provided in Section 6.

3.1.4 Inhalation Dose for Renovation

The concepts involved in calculating the committed effective dose equivalent (CEDE) for inhalation for the building renovation scenario are described in the following word equation:

$$\begin{aligned}[\text{CEDE for Inhalation}] = {} & [\text{Exposure Duration for Renovation}] \\ & \times [\text{Volumetric Breathing Rate}] \\ & \times [\text{Airborne Dust-Loading Factor}] \\ & \times [\text{Inhalation Dose Factor}] \\ & \times [\text{Average Concentration of Radionuclides in BuildingMaterial}]\end{aligned} \tag{3.7}$$

The mathematical formulation for calculating inhalation dose for the building renovation scenario is given by

$$DHB_i = 24\ t_b\ V_b\ CDB \sum_{j=1}^{J_i} DFH_j\ S\{C_{bj},\ t_{tb}\}/t_{tb} \tag{3.8}$$

where DHB_i = CEDE for inhalation for parent radionuclide i for the specified renovation work period (mrem for renovation work in 1 year)

CDB = dust-loading factor in air for renovation work (g/m^3)

DFH_j = inhalation CEDE factor for radionuclide j (mrem per pCi inhaled)

V_b = volumetric breathing rate for building renovation work (m^3/h)

and other terms are as previously defined. A detailed discussion of the airborne dust model and parameter values selected for calculating the inhalation dose during building renovation is provided in Section 6.

3.1.5 Ingestion Dose for Renovation

The final pathway considered for the building renovation scenario is inadvertent ingestion of dust generated during renovation activities. The concepts involved in calculating the CEDE for the inadvertent ingestion are described in the following word equation:

$$\begin{aligned}[\text{CEDE for Ingestion}] = {} & [\text{Exposure Duration for Renovation}] \\ & \times [\text{Effective Transfer Rate for Ingestion}] \\ & \times [\text{Ingestion Dose Factor}] \\ & \times [\text{Average Concentration of Radionuclides in Loose Dust}]\end{aligned} \tag{3.9}$$

The mathematical formulation for calculating ingestion dose for the building renovation scenario is given by

$$DGB_i = 24\ t_b\ GB \sum_{j=1}^{J_i} DFG_j\ S\left\{C_{bj},\ t_{tb}\right\}/t_{tb} \tag{3.10}$$

where DGB_i = ingestion CEDE for parent radionuclide i for renovation work (mrem for renovation work in 1 year)

GB = effective transfer rate for ingestion of loose dust transferred from building surfaces, to hands, to mouth (g/h of work)

DFG_j = ingestion CEDE factor for radionuclide j (mrem per pCi ingested)

and other terms are as previously defined. A detailed discussion of the parameter values selected for calculating ingestion dose during building renovation is provided in Section 6.

3.1.6 Annual TEDE for the Building Renovation Scenario

The annual TEDE for the building renovation scenario is evaluated as the sum of the contributions from the three exposure pathways, as shown in the following word equation:

$$\begin{aligned}[\text{Annual TEDE for Renovation}] = {} & [\text{External Dose}] \\ & + [\text{CEDE for Inhalation}] \\ & + [\text{CEDE for Ingestion}]\end{aligned} \tag{3.11}$$

The mathematical formulation for calculating the annual TEDE for the building renovation scenario is

$$TEDEB_i = DEXB_i + DHB_i + DGB_i \tag{3.12}$$

where $TEDEB_i$ is the TEDE for parent radionuclide i (in mrem for renovation work in 1 year) and other terms are as previously defined.

When mixtures of radionuclides are considered, the total dose for the building renovation scenario is evaluated as the sum of the dose from each decay chain:

$$TEDEB_m = \sum_{i=1}^{M} \left(DEXB_i + DHB_i + DGB_i\right) \tag{3.13}$$

where $TEDEB_m$ is the TEDE for the mixture of radionuclides (in mrem for renovation work in 1 year), M is the number of parent radionuclides in the mixture, and other terms are as previously defined.

When the initial concentration is expressed in Bq/g and the result is expressed in μSv, the evaluation is performed as above, except that the unit conversion factor is required, as follows:

$$TEDEB_{iSI} = 270.3\ TEDEB_i \tag{3.14}$$

where $TEDEB_{iSI}$ is the annual TEDE for parent radionuclide i (in μSv for renovation work in 1 year), and the constant 270.3 is a unit conversion factor, relating μSv/Bq to mrem/pCi.

3.2 Building Occupancy Scenario

At many facilities, the residual radioactive inventory will be associated with surface sources. Because surface decontamination operations may not remove all of the surface sources, a scenario describing surface contamination must be considered. For this analysis, the building occupancy scenario accounts for potential exposure to both fixed and removable thin-layer or surface-contamination sources. This assumption is a conservative representation of residual radioactive contamination that will bound the dose rates from volume sources, when equal initial activities are assumed. That is, for an equal activity in surface and volume sources, the dose rate from surface sources will exceed the dose rate from volume sources because of self-shielding. A further discussion of the selection of external dose rate factors is provided in Section 6.2.1. This scenario is used to derive the surface contamination annual TEDE.

The conceptual model used for the building occupancy scenario defined for this study is shown in Figure 3.3. Quite simply, an individual is assumed to occupy a commercial facility in a passive manner without deliberately disturbing surface sources of residual contamination. This means that the levels of "loose" contamination are likely to be substantially less than those encountered in the building renovation scenario. The following sections describe the scenario time frame, the potential exposure scenarios (those that are included and excluded from the analysis), and the mathematical formulations needed to describe the exposure pathways in the building occupancy scenario.

3.2.1 Time Frame of Building Occupancy Scenario

The building occupancy scenario involves chronic exposure to an individual for a full work year in a commercial facility. The time frame for exposures is shown in Figure 3.4. Although occupancy of a building may occur at any time after license termination, for this study occupancy is assumed to begin immediately after release of the building, before significant radioactive decay occurs. Except for exposure duration, Figures 3.2 and 3.4 are identical, showing both the exact and mathematical representation of exposure to a radioactive source. For building renovation, the exposure duration will likely be a fraction of a work year, and for building occupancy, it will likely be a full work year. As in the building renovation scenario, the average activity per unit area is evaluated using the time-integral operator, S{} (discussed in Section 2 and Appendix B), divided by the duration of the building occupancy period.

3.2.2 Exposure Pathways

As with the building renovation scenario, numerous potential exposure pathways can be identified during building occupancy. The potential pathways are shown in the following list, with those selected for analysis shown in bold type:

- **external exposure to penetrating radiation from surface sources**

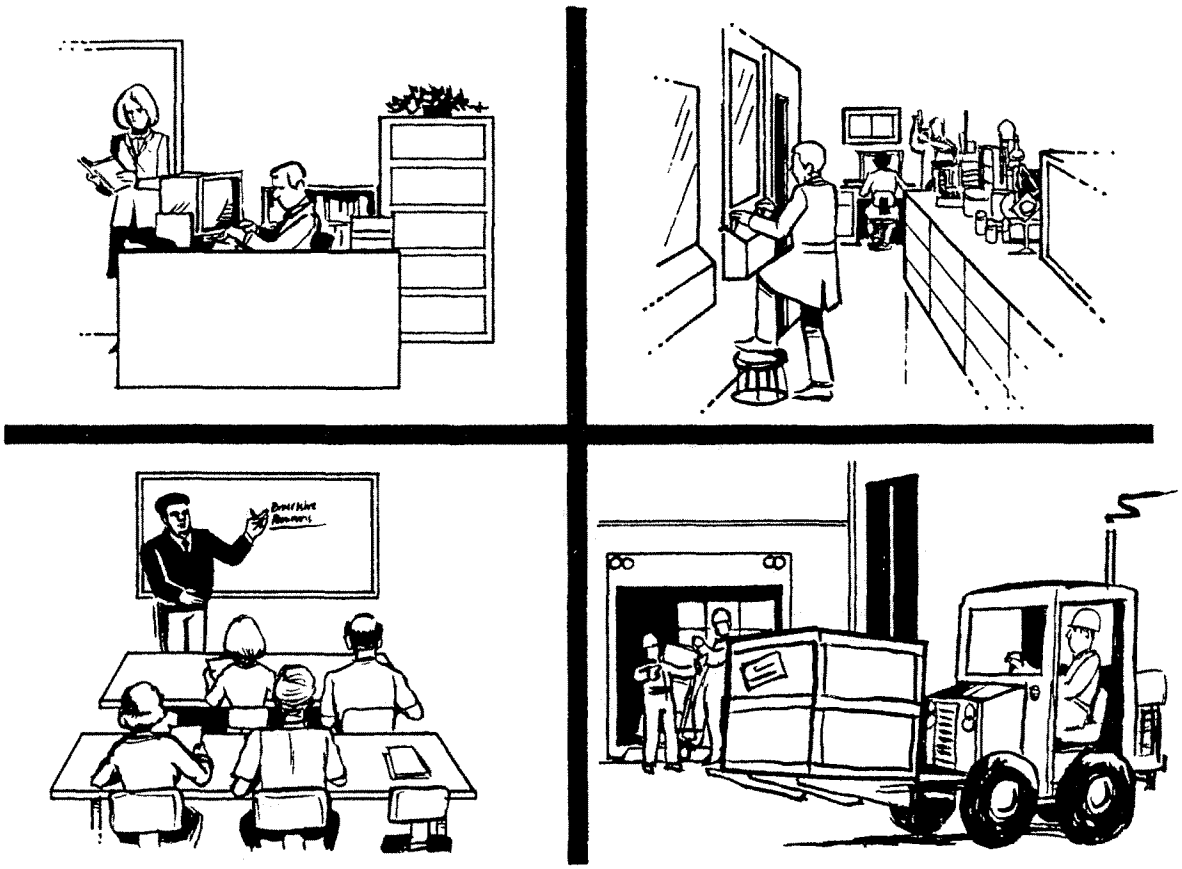


Figure 3.3 Potential activities within the building occupancy scenario

- **inhalation of resuspended surface contamination**
- **inadvertent ingestion of surface contamination**
- external exposure during submersion in airborne radioactive dust
- internal contamination from puncture wounds inflicted by contaminated surfaces
- dermal absorption of radionuclides
- inhalation of indoor radon aerosol.

The exposure pathways selected for analysis in the building occupancy scenario include external exposure to penetrating radiation from surface sources, inhalation of resuspended surface contamination, and inadvertent ingestion of surface contamination. The selection of these pathways, with prudently conservative parameter values, provides a balanced analysis for

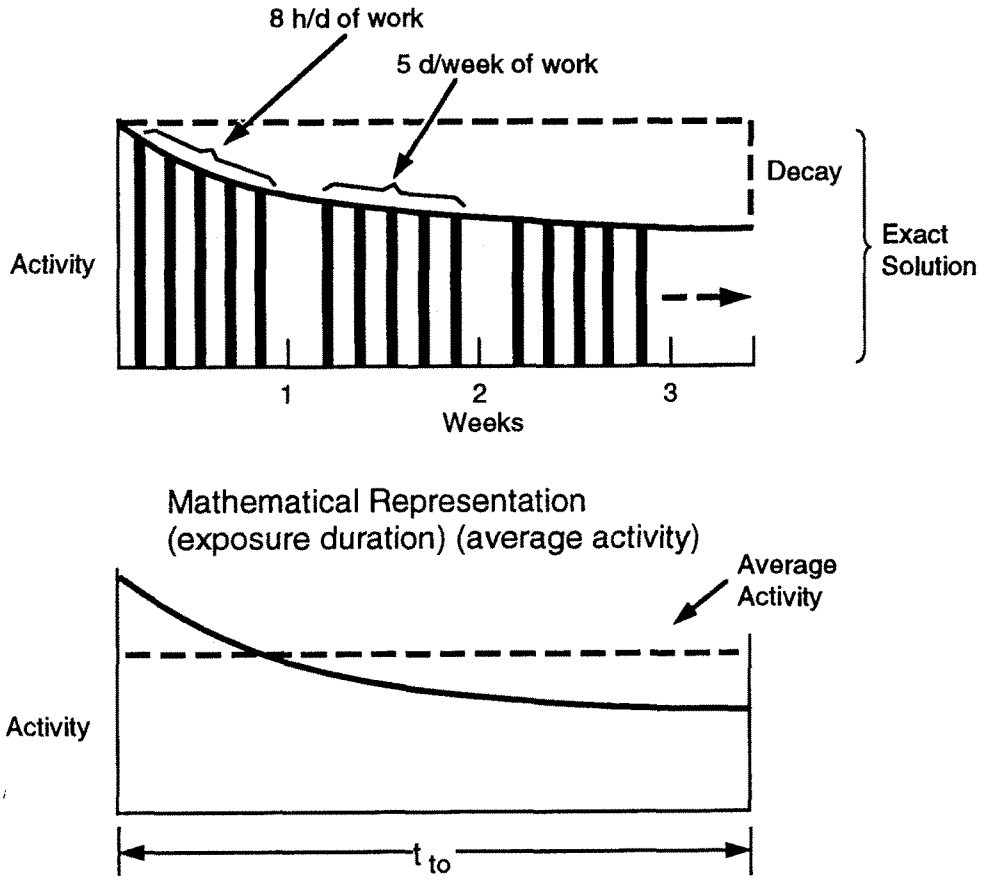


Figure 3.4 Building occupancy time line

- photon-emitters, through the external exposure
- alpha-emitters, through the inhalation exposure pathway
- beta-emitters, through the inadvertent ingestion pathway.

The potential pathways identified above but not included in this analysis are external exposure during submersion in airborne radioactive dust, internal contamination from puncture wounds, dermal absorption, and inhalation of the indoor radon aerosol. The justification for eliminating these pathways is the same as provided in Section 3.1.2 for the building renovation scenario. In addition, airborne contamination levels for air submersion are likely to be quite low during occupancy compared with renovation, further reducing the potential importance of air submersion. Puncture wounds from contaminated surfaces are even less likely for building occupancy because there are no construction-related activities. As with the building renovation scenario, additional pathways can be included, as necessary, in site-specific ALARA evaluations using site-specific data.

3.2.3 External Dose for Building Occupancy

The concepts involved in the external dose calculation for the building occupancy scenario are described in the following word equation:

$$\begin{aligned}[\text{External Dose}] = {} & [\text{Exposure Duration for Occupancy}] \\ & \times [\text{Surface Source Dose Rate Factor}] \\ & \times [\text{Average Surface Activity per Unit Area}]\end{aligned} \tag{3.15}$$

The mathematical formulation for calculating external dose for the building occupancy scenario is given by

$$DEXO_i = 24\, t_o \sum_{j=1}^{J_i} DFES_j\, S\left\{C_{oj}, t_{to}\right\}/t_{to} \tag{3.16}$$

where $DEXO_i$ = external dose for parent radionuclide i (mrem for 1 year of building occupancy)

$DFES_j$ = external dose rate factor for radionuclide j, for exposure from contamination uniformly distributed on surfaces, compatible with the surface-source intent of the building occupancy scenario, as described in Section 6 (mrem/h per dpm/100 cm^2)

C_{oj} = initial activity per unit area for radionuclide j on building surfaces (dpm/100 cm^2)

$S\{C_{oj}, t_{to}\}$ = time-integral operator used to develop the radionuclide j activity over the exposure period t_{to} (dpm•d/100 cm^2)

t_{to} = length of the occupancy period (d)

t_o = time that exposure occurs during the 1-year building occupancy period (d)

24 = unit conversion factor (h/d).

The formulation is similar to the external dose formulation in Equation (3.4), with the exception that for the building occupancy scenario, surface sources instead of volume sources are considered. The time-integral of activity, $S\{C_{oj}, t_{to}\}$, is evaluated for parent radionuclides, as discussed in Section 2 and Appendix B and illustrated in sample equations for parent and first progeny for the building renovation scenario (see Equations [3.5] and [3.6]). A detailed discussion of parameter values for calculating the external dose during building occupancy is provided in Section 6.

3.2.4 Inhalation Dose for Building Occupancy

Inhalation exposure is evaluated for residual material resuspended from building surfaces. The concepts involved in calculating the inhalation CEDE are described in the following word equation:

[CEDE for Inhalation] = [Exposure Duration for Occupancy]
× [Resuspension Factor for Surface Contamination]
× [Volumetric Breathing Rate] (3.17)
× [Inhalation Dose Factor]
× [Average Surface Activity per Unit Area].

The mathematical formulation for calculating inhalation dose for the building occupancy scenario is given by

$$DHO_i = 45.05 \left[24\, t_o\right] RF_o\, V_o \sum_{j=1}^{J_i} DFH_j\, S\left\{C_{oj},\, t_{to}\right\} / t_{to} \tag{3.18}$$

where DHO_i = CEDE for inhalation for parent radionuclide i (mrem for 1 year of building occupancy)

RF_o = resuspension factor for building occupancy (m^{-1})

DFH_j = inhalation CEDE factor for radionuclide j, as described in Section 6 (mrem per pCi inhaled)

45.05 = unit conversion factor (pCi/m^2 per dpm/100 cm^2)

24 = unit conversion factor (h/d)

V_o = volumetric breathing rate for building occupancy (m^3/h)p12000

and other terms are as previously defined. A detailed discussion of the resuspension model and the parameter values selected for calculating the inhalation dose during building occupancy is provided in Section 6.

3.2.5 Ingestion Dose for Building Occupancy

The concepts involved in calculating the CEDE for inadvertent ingestion are described in the following word equation:

[CEDE for Ingestion] = [Exposure Duration for Occupancy]
× [Effective Transfer Rate for Ingestion]
× [Ingestion Dose Factor] (3.19)
× [Average Surface Activity per Unit Area].

The mathematical formulation for calculating ingestion dose for the building occupancy scenario is given by

$$DGO_i = 45.05 \left[24\, t_o\right] GO \sum_{j=1}^{J_i} DFG_j\, S\left\{C_{oj},\, t_{to}\right\} / t_{to} \tag{3.20}$$

where DGO_i = CEDE for ingestion for parent radionuclide i (mrem for 1 year of building occupancy)

GO = effective transfer rate for ingestion of removable surface contamination transferred from surfaces, to hands, then to mouth for the building occupancy scenario (m^2/h)

DFG_j = ingestion CEDE for radionuclide j, as described in Section 6 (mrem per pCi ingested)

45.05 = unit conversion factor (pCi/m^2 per dpm/100 cm^2)

24 = unit conversion factor (h/d)

and other terms are as previously defined.

A discussion of the parameter values selected for calculating ingestion dose during building occupancy is provided in Section 6.

3.2.6 Annual TEDE for the Building Occupancy Scenario

The annual TEDE for the building occupancy scenario is evaluated as the sum of the contributions from the three exposure pathways, as shown in the following word equation:

$$\begin{aligned}\text{[Annual TEDE for Occupancy]} = {} & \text{[External Dose]} \\ & + \text{[CEDE for Inhalation]} \\ & + \text{[CEDE for Ingestion].}\end{aligned} \tag{3.21}$$

The mathematical formulation for calculating the annual TEDE for the building occupancy scenario is

$$TEDEO_i = DEXO_i + DHO_i + DGO_i \tag{3.22}$$

where $TEDEO_i$ is the annual TEDE for radionuclide i (in mrem for 1 year of building occupancy) and the other terms are as previously defined.

When mixtures of radionuclides are considered, the annual TEDE for the building occupancy scenario is evaluated as the sum of the annual TEDE from each decay chain:

$$TEDEO_m = \sum_{i=1}^{M} \left(DEXO_i + DHO_i + DGO_i\right) \tag{3.23}$$

where $TEDEO_m$ is the annual TEDE for the mixture of radionuclides (in mrem for 1 year of building occupancy) and other terms are as previously defined.

When initial activity per unit area is defined in units of Bq/100 cm^2, the following equation is used to evaluate the annual TEDEO values in μSv:

$$TEDEO_{iSI} = 600\ TEDEO_i \tag{3.24}$$

where $TEDEO_{iSI}$ is the annual TEDE for the parent radionuclide i (in μSv for a year of building occupancy), and the constant 600 is a unit conversion factor (μSv/Bq per mrem/dpm).

4 Drinking Water Scenario

The drinking water scenario (presented schematically in Figure 4.1) models the dose to persons whose sole exposure is from drinking ground water that contains radionuclides leached from surface soil, as determined by a generic water-use model. This scenario is included to permit a comparison with the drinking water standards of the EPA. The individual exposed via drinking water is assumed to obtain all of his or her drinking water from the contaminated aquifer over a period of 1 year, with a constant ingestion rate. The concentration of radionuclides in the ground water is taken as an annual average value based on the total activity of a radionuclide, or mixture of radionuclides, that is in the ground water during the year of exposure. The time frame for the drinking water scenario is shown in Figure 4.2. The concentration of a radionuclide or mixture of radionuclides in ground water will conceptually be a function of the physical and chemical properties of the radionuclides, soil, and ground-water system. Figure 4.3 is a simple representation of how the concentration of two radionuclides (shown as "a" and "b") in ground water may vary with time. It is important, therefore, to account for time-dependent behavior in the generic water-use model.

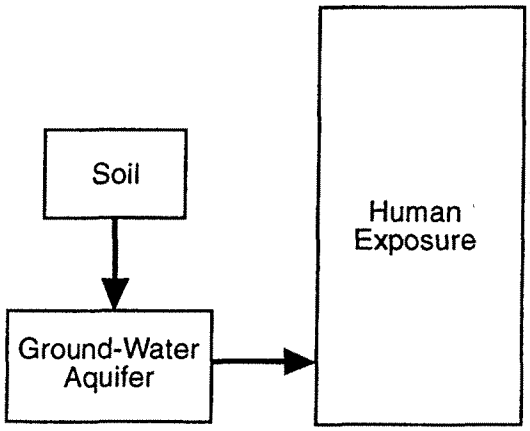


Figure 4.1 Drinking water dose pathway

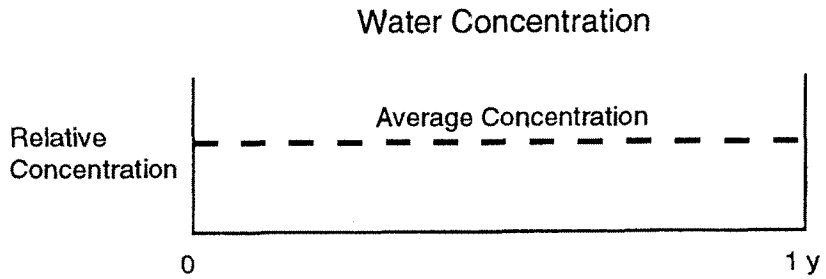


Figure 4.2 Time frame for drinking water scenario

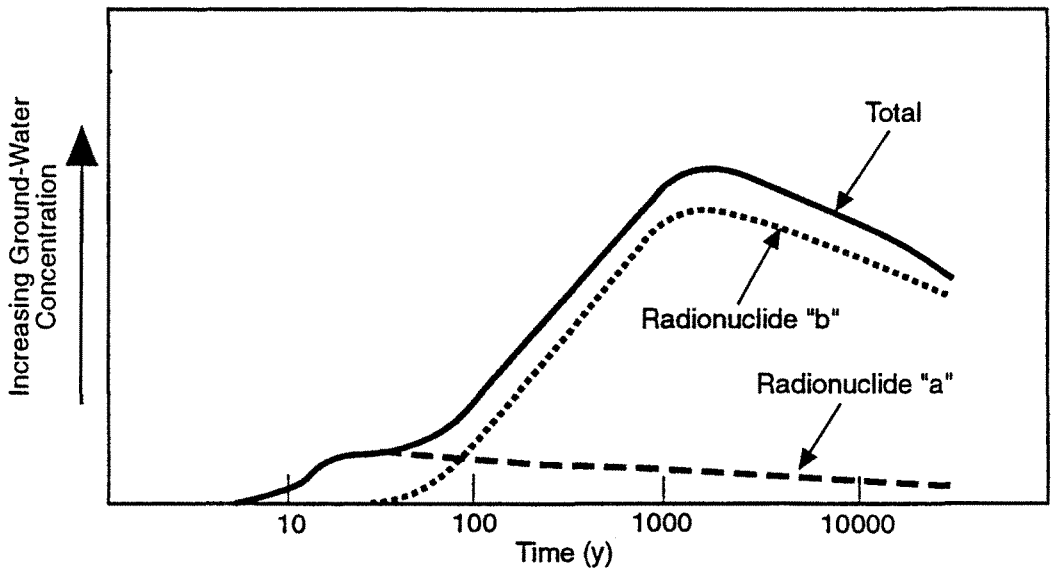


Figure 4.3 Example of time dependence of ground-water concentration

This section discusses the three-box water-use model used to estimate time-dependent ground-water concentrations and the methods used to calculate annual TEDE for the drinking water scenario.

4.1 Water-Use Model

This section describes the method used to evaluate the ground-water concentration as a function of time in order to determine the maximum dose (and year of maximum dose) for the drinking water scenario. The initial activity in surface soils or in buildings that may be left as buried rubble onsite is defined at the time the land is released for public use.

4.1.1 Characteristics of Water-Use Model Suitable for Screening

Residual radioactive contamination in soil has the potential to contaminate ground water in either the saturated or unsaturated zones. The primary mechanisms controlling potential ground-water contamination include infiltration and leaching, transport through the unsaturated zone, and transport through the saturated zone. Many additional characteristics of the site influence these mechanisms, including precipitation rates, the land's surface properties, soil properties, the chemical nature of the radioactive contamination, spatial distributions of the contamination, and advection/retardation in the aquifer. More complete discussions of ground water can be found in Freeze and Cherry (1979), Isherwood (1981), and Wilson and Miller (1979). Previous efforts by the NRC have established a family of models that have fairly broad application to matters related to waste management. These models include those by Goode et al. (1986); Konikow and Bredehoeft (1978); Tracy (1982); Codell, Key, and Whelan (1982); and Codell (1984).

The wide variability of physical and chemical conditions that potentially influence ground water, and the dependence on many parameters that may have a coupled dependency, make it difficult to model ground-water systems. In

addition, a conceptual model of a ground-water system is only an approximation of reality and may not represent all of the behavior of that system. The cost of site characterization, model selection, and model validation may be prohibitive if a trivial source of contamination exists. Because of the system's potential variability, its modeling uncertainty, and the costs of collecting and modeling the data, generic modeling generally encourages the use of worst-case (overly conservative) predictions of the ground-water system's responses. The existence of site data may allow the use of more realistic and sophisticated models, but the data may be point values (in both location and time) and may still not appropriately represent the actual system being modeled.

A middle ground between costly site-characterization and overly conservative generic modeling may be the use of simple, generic screening models for estimating drinking water concentrations with the use of data and assumptions that should be readily available for any site. The purpose of the generic screening modeling conducted for this document is to derive concentration values in an aquifer from residual radioactive materials in soil in a conservative manner that will indicate when additional site-specific data or modeling sophistication are warranted. It is recognized that the results may be prohibitive for all but trivial cases. However, it is also recognized that the types of data and assumptions used in the generic screening approach should be easily obtained for any given site so that some site-specific modifications may be possible.

The modeling approach developed for the onsite disposal of radioactive wastes (Goode et al. 1986) is potentially applicable to residual radioactive soil contamination. Goode et al. (1986) provide a discussion of a methodology for estimating the potential contamination of ground water by materials disposed in soils by licensees. Their methodology includes the formulation of a conceptual model, representation of the conceptual model mathematically, estimation of conservative parameters, and prediction of receptor concentrations. Conservative models, assumptions, and parameter selections (i.e., those that are likely to overestimate the receptor concentration) are used for their methodology because of the need to ensure that underestimates of the potential consequences do not occur. When valid site data exist, they recommend that more realistic parameters and models should be used to refine the predictions. In an appendix, Goode et al. (1986) provide an overview of the types of mathematical models that should be considered when developing a detailed evaluation of potential waste disposal impacts on ground-water resources.

4.1.2 Three-Box Water-Use Model

For the soil scenarios, a conservative method of estimating the concentration of radionuclides in a ground-water aquifer is to use a simple leach-rate model accounting for total water use. Leach rates are dependent on the chemical properties of the radionuclides and soil and the rate of local water movement. For this water-use model, it was assumed that radionuclides would be transferred to the ground water because of contact with infiltrating water (i.e., as a function of the solubility of material in water with no retardation in soils). To account for potential *saturated* and *unsaturated* conditions, a three-box compartmental model is used for this study to estimate the transfer of activity from the surface to the ground-water aquifer over time.

A conceptual representation of the three-box water-use model for the drinking water scenario is shown in Figure 4.4. This figure shows the three boxes and indicates the flow of water through the system with infiltration being the driving force for transfer from the surface soil to the ground-water aquifer. The following assumptions are implied by the model:

- Initial radioactivity is contained within the top layer (box 1).
- The unsaturated-soil layer (box 2) and the aquifer (box 3) are initially free of contamination.
- The vertical saturated hydraulic conductivity is greater than the infiltration rate.

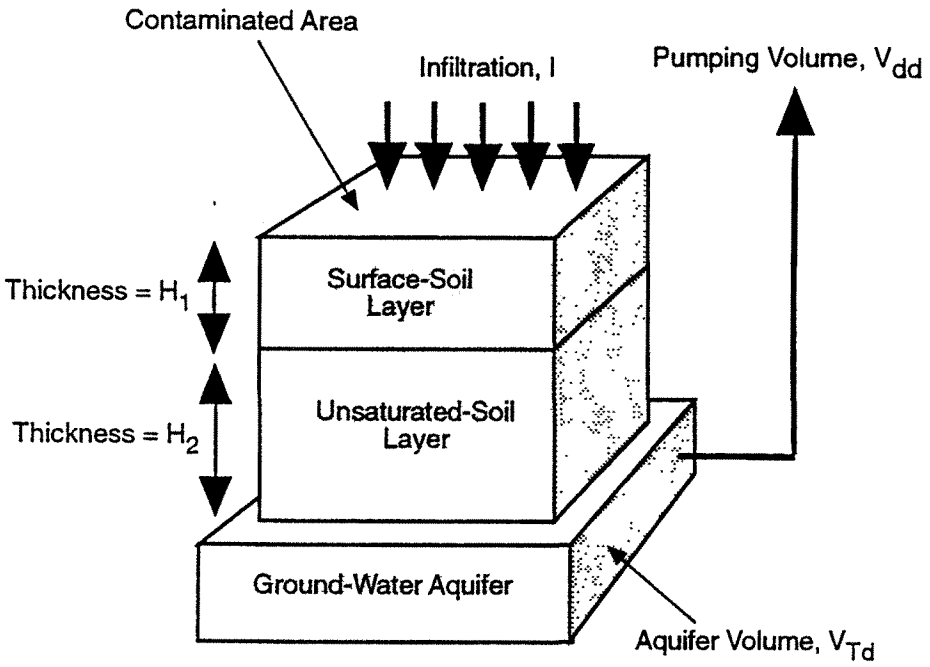


Figure 4.4 Conceptual representation of the drinking water scenario water-use model

- There is no retardation in the aquifer.
- The activity in the aquifer is diluted by the volume of water in the aquifer.
- The volume of water in the aquifer volume is considered to be the greater of the following: 1) the volume of infiltrating water or 2) the volume of water used for domestic purposes.
- The infiltration volume is the product of the infiltration rate and the area of land contaminated.
- Water is removed from the aquifer at a constant rate during all years of interest in the analysis.

The initial activity is assumed to be contained within the first soil layer as a reasonable approach for a generic water-use model. While some sites may exist that have contamination spread through all layers and even into the aquifer, these cases should be evaluated on a site-specific basis, rather than by using this generic model.

The annual volume of water in the aquifer is defined as the greater of two volumes: 1) the volume of water pumped annually for domestic uses or 2) the volume of water infiltrating through the surface-soil layer during one year. This definition is used to avoid the unrealistic case that can result when the area of contaminated land is large. For cases involving large areas of contamination, the annual volume of infiltrating water can exceed the annual volume of water required to meet domestic water demands. Without the above definition of aquifer water volume, the concentration in

the aquifer would unrealistically increase over the concentration in the unsaturated-soil layer because the volume of water delivering the contaminant to the aquifer (i.e., the volume of infiltrating water) would be greater than the volume of the water in the aquifer.

The assumption regarding the vertical saturated hydraulic conductivity means that the soil conditions will allow water to move vertically downward at least as fast as the infiltration rate (expressed as distance per year).

Figure 4.5 represents the movement of material in the simple three-box leach model. Box 1 in the figure represents the initial inventory in a surface layer, with removal of material by either radioactive decay (λ parameters) or leaching (L parameters) into box 2, an unsaturated zone. The initial quantity of material in box 1, $C_{1i}(0)$ is defined for each radionuclide of interest in total activity, pCi. The initial quantity of material in boxes 2, $C_{2i}(0)$, and 3, $C_{3i}(0)$, are both zero. The material in box 2 is transferred to the aquifer (box 3). The material in box 3 is removed by pumping to provide domestic water for an individual. The material in box 3 is used to determine the annual average concentration in the ground-water system. The ground-water concentration is evaluated for the year in which the dose via a scenario reaches a maximum, with consideration of the ingrowth of decay progeny.

The human exposure pathway from the three-box water-use model for the drinking water scenario is illustrated in Figure 4.1. Exposure via ingestion of drinking water originates directly from box 3 of the three-box water-use model (the ground-water aquifer). The concentration of radionuclides in the aquifer (box 3) is evaluated as the quotient of the activity in box 3 (the aquifer) and the annual volume of water in the aquifer.

4.1.3 Equations for Radionuclide Transfer in Soil Using the Water-Use Model

Figure 4.5 includes a simple representation of a three-member radionuclide decay chain. In this representation, each radionuclide has its own radioactive decay constant and transfer rate constant between boxes. Evaluation of the year in which the maximum annual TEDE occurs requires that annual TEDEs be calculated over a number of years until all radionuclides have reached a maximum annual activity in the third box. The following discussion gives the mathematical description of the three-box water-use model for the drinking water scenario where no irrigation recycling occurs; the irrigation recycling is included in the water-use model for the residential scenario, as described in Section 5.6.6.

The equations consider decay chain members produced in each of the boxes from precursor radionuclides. The amounts of each chain member (parameter C) are represented as the total activity present. This representation is made for consistency with the operation of the chain decay equations described below and in Appendix B. The concepts involved in accounting for the quantity of radionuclide j in box 1 at time t are described in the word equation below:

$$\begin{aligned}[\text{Rate of Change of j in Box 1 at Time t}] = {} & [\text{Production of j from Decay of Precursor n at Time t}] \\ & - [\text{Removal of j from Box 1 by Decay at Time t}] \\ & - [\text{Removal of j from Box 1 by Leaching at Time t}].\end{aligned} \quad (4.1)$$

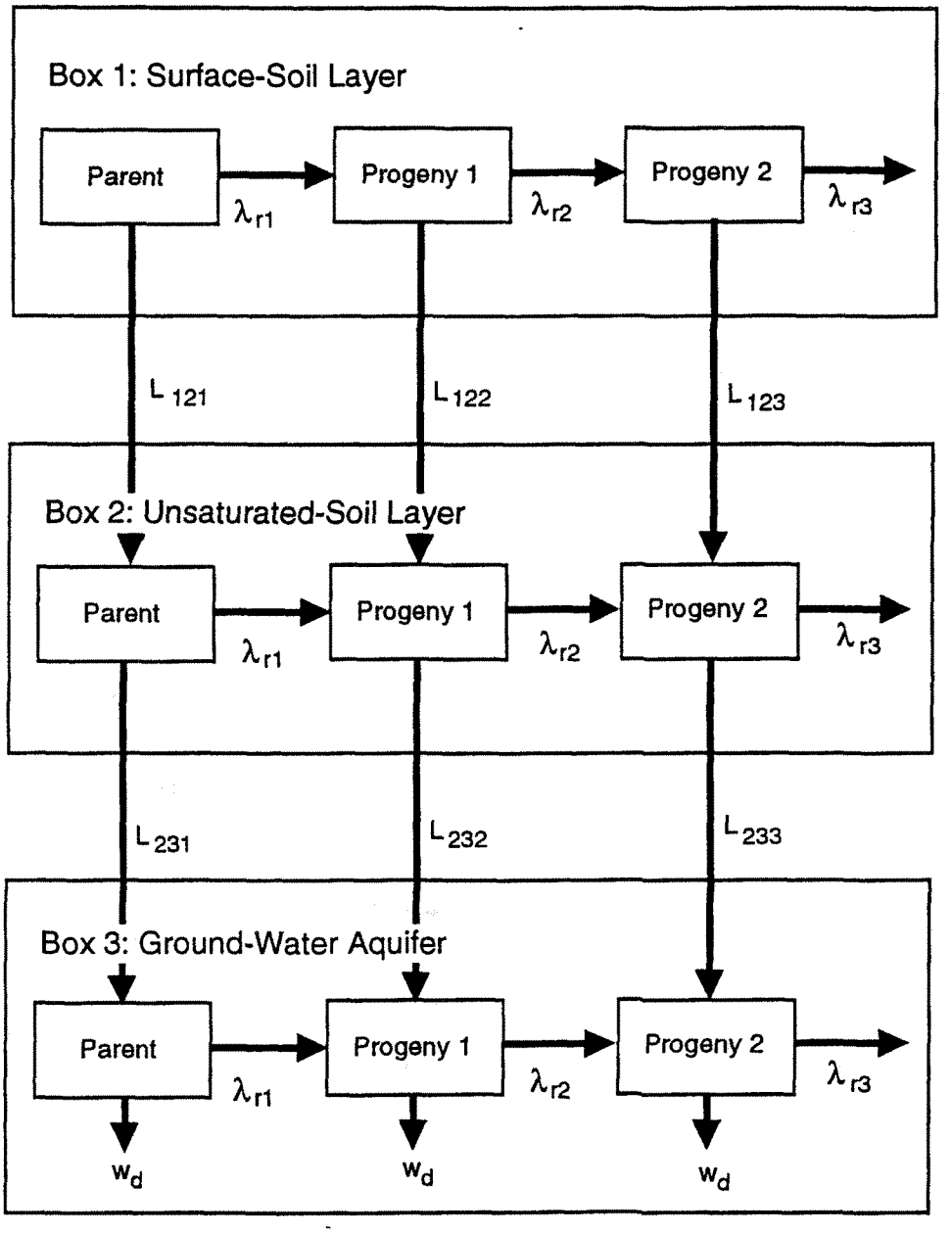


Figure 4.5 Three-box water-use model for the drinking water scenario

The basic differential equation for box 1 has the following form, accounting for original quantities and for radioactive decay (λ terms), and the rate of leaching (L term):

$$\frac{dC_{1j}}{dt} = \lambda_{rj} \sum_{n=1}^{j-1} d_{nj} C_{1n} - \left(\lambda_{rj} + L_{12j}\right) C_{1j} \tag{4.2}$$

where C_{1j} = activity of radionuclide j in box 1 at time t (pCi)

C_{1n} = activity of precursor radionuclide n in box 1 at time t (pCi)

j = index of current chain member position in decay chain

n = index of precursor chain members in decay chain ($n < j$)

L_{12j} = rate constant for movement of radionuclide j from box 1 to box 2 (d^{-1})

d_{nj} = fraction of radionuclide n transitions that result in production of radionuclide j (dimensionless)

λ_{rj} = decay rate constant for decay of radionuclide j (d^{-1}).

For box 2, the concepts involved in accounting for the quantity of radionuclide j at time t are described in the word equation shown below:

[Rate of Change of j in Box 2 at Time t] = [Production of j from Decay of Precursor n at Time t]
+ [Transfer of j by Leaching from Box 1 at Time t]
- [Removal of j from Box 2 by Decay at Time t]
- [Removal of j from Box 2 by Leaching at Time t]. (4.3)

For box 2, the basic differential equation accounts for not only original quantities, radioactive decay, and leaching, but also for quantities entering from box 1:

$$\frac{dC_{2j}}{dt} = \lambda_{rj} \sum_{n=1}^{j-1} d_{nj} C_{2n} + L_{12j} C_{1j} - \left(\lambda_{rj} + L_{23j}\right) C_{2j} \tag{4.4}$$

where C_{2j} = activity of radionuclide j in box 2 at time t (pCi)

C_{2n} = activity of precursor radionuclide n in box 2 at time t (pCi)

L_{23j} = rate constant for movement of radionuclide j from box 2 to box 3 (d^{-1})

and other terms are as defined above.

For box 3, the concepts involved in accounting for the quantity of radionuclide j at time t are described in the word equation shown below:

[Change in j in Box 3 at Time t] = [Production of j from Decay of Precursor n at Time t]
+ [Transfer of j by Leaching from Box 2 at Time t]
- [Removal of j from Box 3 by Decay at Time t]
- [Removal of j from Box 3 by Pumping at Time t]. (4.5)

The differential equation for box 3 is similar to box 2:

$$\frac{dC_{3j}}{dt} = \lambda_{rj} \sum_{n=1}^{j-1} d_{nj} C_{3n} + L_{23j} C_{2j} - \lambda_{rj} C_{3j} - w_d C_{3j} \quad (4.6)$$

where C_{3j} = activity of radionuclide j in box 3 at time t (pCi)

C_{3n} = activity of precursor radionuclide n in box 3 at time t (pCi)

w_d = rate constant for pumping of water from the aquifer for the drinking water scenario (d^{-1})

and other terms are as defined above. The summation term in each of the above equations is evaluated for only those terms for which a transition occurs.

The rate constants for movement between compartments are evaluated as follows. The leach rate from the surface layer is

$$L_{12j} = \frac{I}{H_1 \theta_1 Rt_{1j} 365.25} \quad (4.7)$$

where I = the infiltration rate (m/y)

H_1 = the assumed thickness of the surface-soil layer containing the residual radioactive material (m)

θ_1 = volumetric water content of the surface-soil layer (dimensionless)

Rt_{1j} = retardation factor for movement of radionuclide j from the surface-soil layer to the unsaturated-soil layer (dimensionless)

365.25 = unit conversion factor (d/y). (Note: a year is represented in this study as 365.25 d to include a correction for leap year so that exact hand calculations may be performed.)

The volumetric water content for the surface-soil layer can be expressed in terms of the total porosity and saturation ratio as follows:

$$\theta_1 = n_1 f_1 \tag{4.8}$$

where n_1 is the total porosity of the surface-soil layer (dimensionless) and f_1 is the saturation ratio for the surface-soil layer (dimensionless).

The retardation factor is calculated from the partition coefficient for the radionuclide in the surface-soil layer, the bulk density of the surface-soil layer, and the total porosity as follows:

$$Rt_{1j} = 1 + \frac{Kd_{1j}\ \rho_1}{n_1} \tag{4.9}$$

where Kd_{1j} is the partition coefficient for radionuclide j in the surface-soil layer (mL/g) and ρ_1 is the bulk density of surface-soil layer (g/mL). Evaluation of the retardation factor is based on the total porosity, n_1, rather than the volumetric water content, θ_1, for conservatism because the total porosity, and thus all sorption sites, comes into play as the pulses of moisture move through the surface and the unsaturated layers.

The leach rate from the second layer is defined as follows:

$$L_{23j} = \frac{I}{H_2\ \theta_2\ Rt_{2j}\ 365.25} \tag{4.10}$$

where θ_2 = volumetric water content of the unsaturated-soil layer (dimensionless)

Rt_{2j} = retardation factor for movement of radionuclide j from the unsaturated-soil layer to the aquifer (dimensionless)

H_2 = the assumed thickness of the second layer (m)

and the other parameters are as previously defined.

The volumetric water content for the unsaturated-soil layer can be expressed in terms of the total porosity and saturation ratio as follows:

$$\theta_2 = n_2 f_2 \tag{4.11}$$

where n_2 is the total porosity of the unsaturated-soil layer (dimensionless) and f_2 is the saturation ratio for the unsaturated-soil layer (dimensionless).

The retardation factor is calculated from the partition coefficient for the radionuclide in the unsaturated-soil layer, the bulk density of the unsaturated-soil layer, and the volumetric water content, as follows:

$$Rt_{2j} = 1 + \frac{Kd_{2j}\ \rho_2}{n_2} \tag{4.12}$$

where Kd_{2j} is the partition coefficient for radionuclide j in the unsaturated-soil layer (mL/g) and ρ_2 is the bulk density of unsaturated-soil layer (g/mL).

The annual average water concentration taken from the ground-water aquifer is evaluated assuming that all of the radionuclide activity that reaches the aquifer is diluted in the total volume of water in the aquifer. This calculation is represented by the time integral of activity in box 3 divided by the dilution volume and the time period. For the first year after release of the site, the average water concentration of a radionuclide in a decay chain is given as follows:

$$C_{swjt} = \frac{1}{V_{Td}\, t_y} \int_o^t C_{3j}(t)\,dt = S_{d3}\left\{C_{kj},\, t_y\right\} / \left[V_{Td}\, t_y\right] \tag{4.13}$$

where C_{swjt} = average annual water concentration factor for radionuclide j for the year of exposure, t, per unit activity of parent radionuclide i in soil at time zero (pCi/L per pCi in soil)

$S_{d3}\{C_{kj},t_y\}$ = time-integral operator notation for the drinking water scenario used to develop the time integral of activity of radionuclide j in the aquifer (box 3) over a time period t_y of 365.25 d per unit activity of parent radionuclide i in soil at time zero (pCi•d per pCi in soil)

C_{kj} = array of activities of each radionuclide j in each box k at the start of the current year t per unit activity of parent radionuclide i in soil at time zero (pCi per pCi in soil)

$C_{3j}(t)$ = array of activities of each radionuclide j in the aquifer (box 3) as a function of time over the period of integration (pCi per pCi in soil)

k = index on boxes in the three-box water-use model

t_y = averaging time period over 1 year (d)

V_{Td} = total volume of water in the aquifer, constant during a 1-year period (L).

The total water volume in the aquifer or dilution volume, V_{Td}, is taken to be the greater of the volume pumped for domestic uses during a year or the annual volume of infiltrating water. The annual volume of infiltrating water is related to the infiltration rate and the contaminated area as follows:

$$V_{Id} = I\, A_d\, 1000 \cdot 1 \tag{4.14}$$

where V_{Id} = annual infiltration volume through the contaminated area (L)

A_d = area of contaminated land defined for the drinking water scenario (m^2)

1000 = unit conversion factor (L/m^3)

1 = time period for infiltration (y)

and other terms are as previously defined. The dilution volume (V_{Td}) must be no less than the infiltration volume. Use of a smaller volume would represent concentration of radionuclides between the surface layer and the aquifer, which is unrealistic.

The pumping rate constant, w_d, is evaluated as a fractional removal rate with the total volume removed during a year being set to the volume of water pumped for domestic uses, V_{dd} (L). The pumping rate constant can be expressed as follows:

$$w_d = \left[\frac{\text{Fractional Removal}}{\text{y}}\right]\left[\frac{\text{y}}{365.25\ \text{d}}\right] \tag{4.15}$$

where 365.25 is the units conversion factor (d/y). The fractional removal is the fraction of the total water volume, V_{Td}, removed per year. The fractional removal can be expressed as follows:

$$\text{Fractional Removal} = \frac{V_{dd}}{V_{Td}} \tag{4.16}$$

where V_{dd} = volume of water used for domestic purposes during a year (y) and other terms are as previously defined. Note that when the total volume is equal to the pumping volume (i.e., the infiltration volume is less than the pumping volume), then the fractional removal is 1.

The evaluation of average radionuclide concentration in ground water for time periods beyond the first year is made by application of the decay equations as described in Appendix B. Explicit equations for the decay operator notation, $S_{d3}\{\}$, are presented in Section B.6.

4.2 Calculation of Annual TEDE

Calculation of the annual TEDE involves multiplying the ingestion rate by the ingestion dose rate factor, and then multiplying that product by the average concentration of radionuclides in ground water for 1 year:

$$\begin{aligned}[\text{TEDE for Drinking Water}] = {} & [\text{Water Ingestion Rate}] \\ & \times [\text{Ingestion Period}] \\ & \times [\text{Ingestion Dose Factor}] \\ & \times [\text{Average Concentration of Radionuclides in Water for 1 Year}].\end{aligned} \tag{4.17}$$

In mathematical notation, this equation is

$$TEDED_i = U_w\, t_d\, C_{ti} \sum_{j=1}^{J_i} C_{swjt}\, DFG_j \tag{4.18}$$

where $TEDED_i$ = TEDE for radionuclide i for the drinking water scenario (mrem for a year of drinking water scenario with inventory in pCi in soil)

C_{ti} = total activity of parent radionuclide i in soil at time zero (pCi)

C_{swjt} = average annual water concentration factor for radionuclide j for the year of exposure, t, per unit activity of parent radionuclide i in soil at time zero (pCi/L per pCi in soil)

DFG_j = CEDE for ingestion of radionuclide j (mrem per pCi ingested)

U_w = amount of contaminated drinking water ingested during the drinking water exposure period (L/d)

t_d = period over which drinking water is consumed (days for a year of drinking water scenario).

The average concentration of a radionuclide in water for the year of interest is represented in Equation (4.18) as the product of C_{ti} and C_{swjt}. The average annual water concentration factor (C_{swjt}) is evaluated as described below in this section and in Appendix B.

For periods longer than 1 year, the annual average concentration of radionuclides in the ground water is evaluated using the three-box model for each year of the analysis until the maximum value of $TEDED_i$ is found. For radionuclide decay chains, the analysis is continued until all members of the chain have reached a peak concentration and have begun to decrease.

For mixtures of radionuclides, the annual TEDE is evaluated for the year in which the sum of doses from all radionuclides in the inventory is a maximum. This calculation is as follows:

$$TEDED_m = \sum_{i=1}^{M} TEDED_i \tag{4.19}$$

The year in which the maximum dose is obtained will vary by parent radionuclide. For a mixture of radionuclides, the year of the maximum dose may be different than the year of maximum dose for individual radionuclides. It is, therefore, necessary to evaluate Equation (4.19) for the mixture for each year rather than simply using the $TEDED_i$ values for the maximum years of individual decay chains.

When the activity is in units of Bq, the following equation is used to evaluate the TEDED value in μSv:

$$TEDED_{iSI} = 270.3\ TEDED_i \tag{4.20}$$

where $TEDED_{iSI}$ is the annual TEDE for radionuclide i (μSv for a year of drinking water scenario with initial inventory in units of Bq in soil) and 270.3 is a unit conversion factor (to convert from mrem/pCi to μSv/Bq).

In addition to evaluation of the annual TEDE from drinking water, the highest committed dose equivalent to any organ is determined. The highest organ committed dose equivalent (HOCDE) is evaluated for the year in which the annual TEDE is a maximum value. The calculation of the highest organ committed dose equivalent is performed by repeated application of the following equation for each organ (based on Equation [4.18]) and selection of the highest value that results:

$$HOCDE_i = U_w\ t_d\ C_{ti} \sum_{j=1}^{J_i} C_{swjt}\ DFO_{jo} \tag{4.21}$$

where $HOCDE_i$ = highest organ committed dose equivalent for radionuclide i from ingestion of drinking water (mrem per year of drinking water scenario for inventory in pCi)

DFO_{jo} = committed dose equivalent to organ o from radionuclide j from ingestion (mrem per pCi ingested)

and other terms are as previously defined. Equation (4.21) is evaluated for all organs (subscript o) and the highest value for $HOCDE_i$ represents the result of the analysis.

The highest organ dose for a mixture is calculated by summing the contributions from all parent radionuclides and chain members contributing to each organ dose. The highest dose is not evaluated from the previously calculated $HOCDE_i$ values because each radionuclide will likely have a different organ associated with its highest organ committed dose equivalent. It is necessary, therefore, to sum all dose contributions across radionuclides in the mixture before the organ receiving the highest dose can be determined. The highest effective organ dose for a mixture of radionuclides is evaluated by repeated application of the following equation and selection of the highest dose result:

$$HOCDE_m = U_w\ t_d\ C_{ti} \sum_{i=1}^{M} \sum_{j=1}^{J_i} C_{swjt}\ DFO_{jo} \tag{4.22}$$

where $HOCDE_m$ is the highest organ committed dose equivalent for a mixture of radionuclides (mrem per year of drinking water scenario for inventory in pCi) and other terms are as previously defined.

Conversion of HOCDE values to units of μSv/y of drinking water scenario for initial activity in Bq in soil is performed using Equation (4.20) with HOCDE values in place of the corresponding TEDED value.

Criteria and algorithms for finding the year of maximum dose will be established during the software development and reported in Volume 2.

5 Residential Scenario

As with residual radioactive materials in buildings, contaminated soil from licensed operations can exist in a wide diversity of conditions. For example, radionuclides in soil can originate from intentional disposal, accidental spills, or long-term accumulation of material deposited from airborne releases during plant operation. The complexity of the environmental setting also influences the potential pathways and components that may need to be considered in modeling human exposures. Therefore, the conceptual model for residual soil contamination must be broad enough to account for many different, and potentially complex, pathways and conditions. Figure 5.1 shows a variety of potential exposure situations that can result from soil contamination. These potential situations range from simply inhaling air that contains resuspended contaminated soil to ingesting drinking water from a contaminated well or fish from contaminated surface water, or a variety of plant and animal products that may be grown in the contaminated soil. For this generic screening analysis, the radiation doses resulting from contaminated soil are described by the residential scenario. The following sections introduce the concepts used in the residential scenario, the approach for evaluating doses from complex agricultural pathways, the mathematical formulations needed to model concentrations and radionuclide transfer in the agricultural pathways, and the calculation of the annual TEDE for the residential scenario.

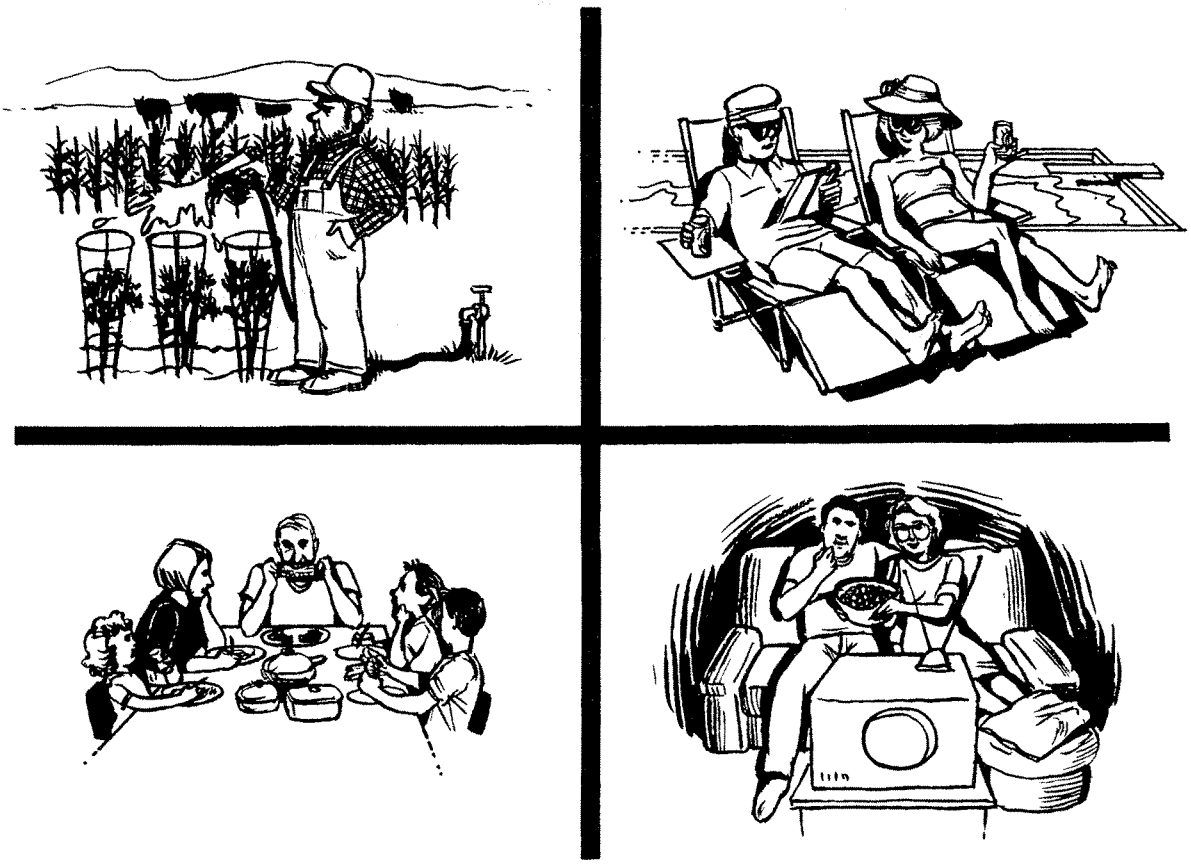


Figure 5.1 Potential activities within the residential scenario

5.1 Residential Scenario: Concepts and Assumptions

The residential scenario defines the potential pathways that can be used to estimate human radiation exposures resulting from residual radioactive contamination in soil. For this scenario, the residual radioactive materials are assumed to be contained in a surface-soil layer on property that can be used for residential and light farming activities. The following sections describe the scenario time frame, the potential exposure pathways (describing both those that are included and those excluded from the analysis), and the radionuclide inventory and transfer associated with agricultural pathways.

5.1.1 Time Frame for the Residential Scenario

The time frame for the residential scenario must potentially account for continuous exposure to multiple exposure pathways during a year; however, the time frame for each pathway during the year can vary significantly. For example, ingestion of agricultural foods may be dependent on the growing season, and the duration of external and inhalation exposure may be limited to account for time spent away from home. For the agricultural pathways, the time frame must account for the change in radionuclide concentrations in various media during holdup and consumption periods after harvest. More complete descriptions of the time frames for the agricultural pathway are given in Sections 5.3 and 5.4. As with the scenarios for release of buildings, the time-dependent concentrations of residual radioactive contamination are evaluated using exposure durations and average concentrations, as appropriate for each pathway. Again, the average concentrations are described using the concentration time-integral operator, $S\{\}$ or $S_{rk}\{\}$ (as discussed in Section 2 and Appendix B), divided by the duration of the exposure period. A detailed discussion of the selection of parameter values for calculating dose from residual soil contamination is provided in Section 6.

5.1.2 Exposure Pathways for the Residential Scenario

As can be inferred from Figure 5.1, numerous potential exposure pathways can be identified for residual radioactive contamination in soil. The potential importance of these pathways depends on several factors, including the nature and distribution of the contamination (i.e., surface or subsurface sources), the radionuclides (i.e., their chemical and physical properties), and the environmental setting (i.e., a humid or arid, warm or cold climate). The potential pathways for human exposure are shown in the following list, with those selected for analysis shown in bold type:

- **external exposure to penetrating radiation from volume soil sources while outdoors**
- **external exposure to penetrating radiation from volume soil sources while indoors**
- external exposure to soil tracked indoors (surface source)
- external exposure to penetrating radiation from submersion in airborne radioactive soil
- external exposure from swimming and shoreline activities associated with a contaminated surface-water source
- **inhalation exposure to resuspended soil while outdoors**
- **inhalation exposure to resuspended soil while indoors**
- **inhalation exposure to resuspended surface sources of soil tracked indoors**
- inhalation of the radon aerosol while outdoors

- inhalation of the radon aerosol while indoors
- **direct ingestion of soil**
- **inadvertent ingestion of soil tracked indoors**
- **ingestion of drinking water from a ground-water source**
- **ingestion of plant products grown in contaminated soil**
- **ingestion of plant products irrigated with contaminated ground water**
- **ingestion of animal products grown onsite (i.e., after the animals ingest contaminated drinking water, plant products, and soil)**
- ingestion of drinking water from a contaminated surface-water source
- **ingestion of fish from a contaminated surface-water source**
- internal contamination from puncture wounds
- dermal absorption of radionuclides.

In addition, within these major pathways there may be several mechanisms for establishing a concentration of radionuclides in a specific medium. For example, food crops can be contaminated by direct root uptake from soil, deposition of resuspended soil on plant surfaces, deposition of radionuclides in irrigation water on plant surfaces, and "rainsplash" (deposition of soil on plant surfaces splashed from rainfall or irrigation). This screening analysis includes direct root uptake, deposition of resuspended radionuclides from soil, and deposition of radionuclides in irrigation water. Rainsplash is not included. The potential importance of rainsplash is related to the type of crop, soil properties, and intensity of the rainfall (or irrigation) events. For some situations, the quantity of material on plant leaves from rainsplash may equal or exceed deposition by other mechanisms. Although rainsplash is not included in this analysis, it is compensated for by assuming that there is no removal of deposited material from plant surfaces during food preparation and through inclusion of a direct soil-ingestion pathway. These assumptions form the prudently conservative basis for the agricultural pathways of the residential scenario. Figure 5.2 shows the relationship of soil contamination to plant and animal products in the agricultural pathways. Note that Figure 5.2 accounts for resuspension of soil contamination in the air and migration of radionuclides in soil to a ground-water source used for irrigation of land and drinking by animals.

The exposure pathways selected for analysis in the residential scenario (shown in bold type in the list above) include external exposure to volume soil sources (for exposures outdoors and indoors), inhalation of resuspended soil (for exposures outdoors and indoors), inhalation of resuspended surface sources of soil tracked indoors, inadvertent ingestion of surface sources of soil (indoors and outdoors, based on the total quantity of soil ingested), ingestion of drinking water from a ground-water source, ingestion of plant products grown in contaminated soil (using irrigation water from the ground-water source), ingestion of animal products grown onsite (after the animals ingest contaminated drinking water, plant products, and soil), and ingestion of fish from a contaminated surface-water source. This set of pathways, along with the selection of prudently conservative parameter values, provides a balanced analysis for

- photon-emitters, through the external exposure pathway

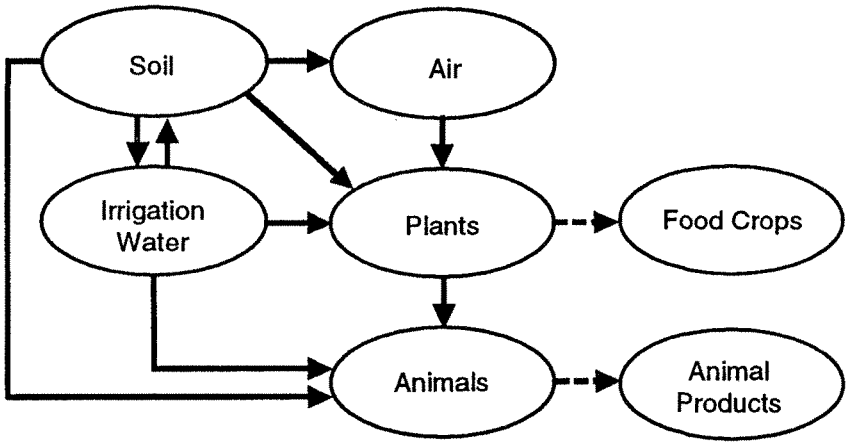


Figure 5.2 Relationship of soil contamination to agricultural pathways

- alpha-emitters, through the inhalation exposure pathway, and
- beta-emitters, through ingestion.

As described in Section 4 and Appendix B, time-dependent concentrations of radionuclides in ground water from surface-soil sources are estimated using a generic three-box water-use model that accounts for leaching of radionuclides.

It should be noted that there are numerous potential exposure pathways that are not included in this generic analysis, although they may be important under some circumstances. Air submersion, internal exposure from puncture wounds, dermal absorption, and inhalation of the radon aerosol are eliminated for the same reasons described in Sections 3.1.2 and 3.2.2 for buildings.

Although direct ingestion of soil is often considered by the EPA in generic situations (EPA 1989), it is an activity typically associated with children and constitutes a worst-case assessment. For purposes of this generic study, it is assumed that everyone inadvertently ingests some soil using assumptions about the total quantity of soil that may be ingested. Additionally, direct soil ingestion by animals is included in the pathway analysis.

Several of the pathways associated with surface-water runoff (i.e., drinking by man and farm animals, irrigation, and external exposure from swimming or shoreline activities) are not included in this study. As with the ground-water pathway, migration of radionuclides from surface soil to surface water is dependent on many conditions that are difficult to capture in a generic model. These conditions include the climate (amount of rainfall), features of the surrounding terrain (distance to the affected surface water and land use), leachability (or solubility) of specific radionuclides, surface-soil erosion rates, and sediment formation. In arid parts of the country, rainfall may move large amounts of soil in a short amount of time (through flash floods). However, evaluation of flash flood events would likely provide a worst-case, not a prudently conservative, analysis. In general, increased dilution occurs with increased distance from an environmental source; therefore, exposures to materials at the contaminated site are likely to exceed those that result from radionuclide migration to the nearby vicinity. Furthermore, the water-use model used in this study does not account for removal of radionuclides through surface runoff and assumes limited dilution in an aquifer of limited size (as described in Section 6). Thus, the water-use model is considered to be a conservative and simple

model when compared with a real situation. Finally, because of the poor quality of most surface water in the United States, it is rarely used directly (without treatment) for drinking by humans. Treating drinking water lowers the concentrations of certain radionuclides. Thus, the potential doses resulting from drinking surface water are assumed to be generally bounded by the drinking water pathway and the water-use model included in this screening analysis.

To produce a more complete set of pathways for the first and second levels of screening, ingestion of fish raised in contaminated water is included in the residential scenario. The concentrations of radionuclides in the fish are determined using a simple bioaccumulation factor and the time-dependent concentration of radionuclides in the surface water. Rather than developing a special surface-water concentration model, the surface-water concentration is determined from the overall water-use model applied to the residential scenario.

The modeling details for the residential scenario exposure pathways are shown in Figure 5.3. This figure serves as a master figure and shows each of the environmental media, exposure pathway models, unit dose factors, and pathway doses used to construct the annual TEDE for the residential scenario. The major media are air (from resuspended soil), soil, and water. The water concentrations and soil concentrations for each year of the model analysis are determined using the water-use model. Boxes are included in Figure 5.3 showing the exposure pathways with a reference to the sections of this report that contain descriptions of the model formulations. The exposure pathways shown in double boxes are described by additional figures that show the details of the pathway analysis and linkages to this master figure. Finally, specific equation numbers are shown in Figure 5.3 to help identify the mathematical formulations used at key points in the exposure pathway analysis.

5.2 Steps for Calculating Annual Dose from Agricultural Pathways

As discussed in the previous section, agricultural pathways for estimating doses from residual radioactive contamination in surface soil are quite complex. In addition to direct uptake by the roots of plants, radionuclides deposited from resuspended soil in air and those deposited in irrigation water can provide additional mechanisms for establishing radionuclide concentrations in plant and animal products. As Figure 5.4 shows, the process of estimating the annual TEDE for the agricultural pathways can be broken into seven steps. The first three steps are used to estimate radionuclide concentrations per unit concentration in soil (dry weight) or water, in plant or animal material, and in food products (using partial pathway transfer factors [PPTFs]). The fourth step is used to estimate the intake of activity from all agricultural pathways as a function of unit concentration in soil (using pathway factors [PFs]). The fifth step is used to account for the dose per unit concentration in soil for root uptake, resuspension or irrigation (using agricultural dose factors [AFs]). The sixth step is used to account for the radionuclide inventory and the CEDE for ingestion of all agricultural foods, and the seventh step is used to account for the annual TEDE by summing over all exposure pathways considered in the residential scenario.

The equations in the following sections describe calculation of the PPTFs for initial unit activity of a parent radionuclide in soil or water. For these calculations, all progeny radionuclides are assumed to have zero initial activity. This convention provides an estimate of PPTFs related to the initial activity of the parent (independent of any assumptions about progeny activities) that can be used in conjunction with measured or estimated activities for a particular site. By calculating PPTF values normalized to the activity present at the beginning of a year, the PPTF values can be applied to any year in the future by multiplying the PPTF values by the activities of the parent and progeny radionuclides present at the beginning of the future year. Contributions from progeny that may be present at the site initially and for each year in the calculation are evaluated using PPTF values for a series of decay chains, each starting with a progeny in the chain as the parent. This is shown by the double-lined boxes in Figure 5.5, which shows the calculations for a decay chain with four members. The example analysis shows a series of four decay chains, one for each chain member as the parent of a shorter chain. In each chain, the decay and progeny in-growth calculations for each

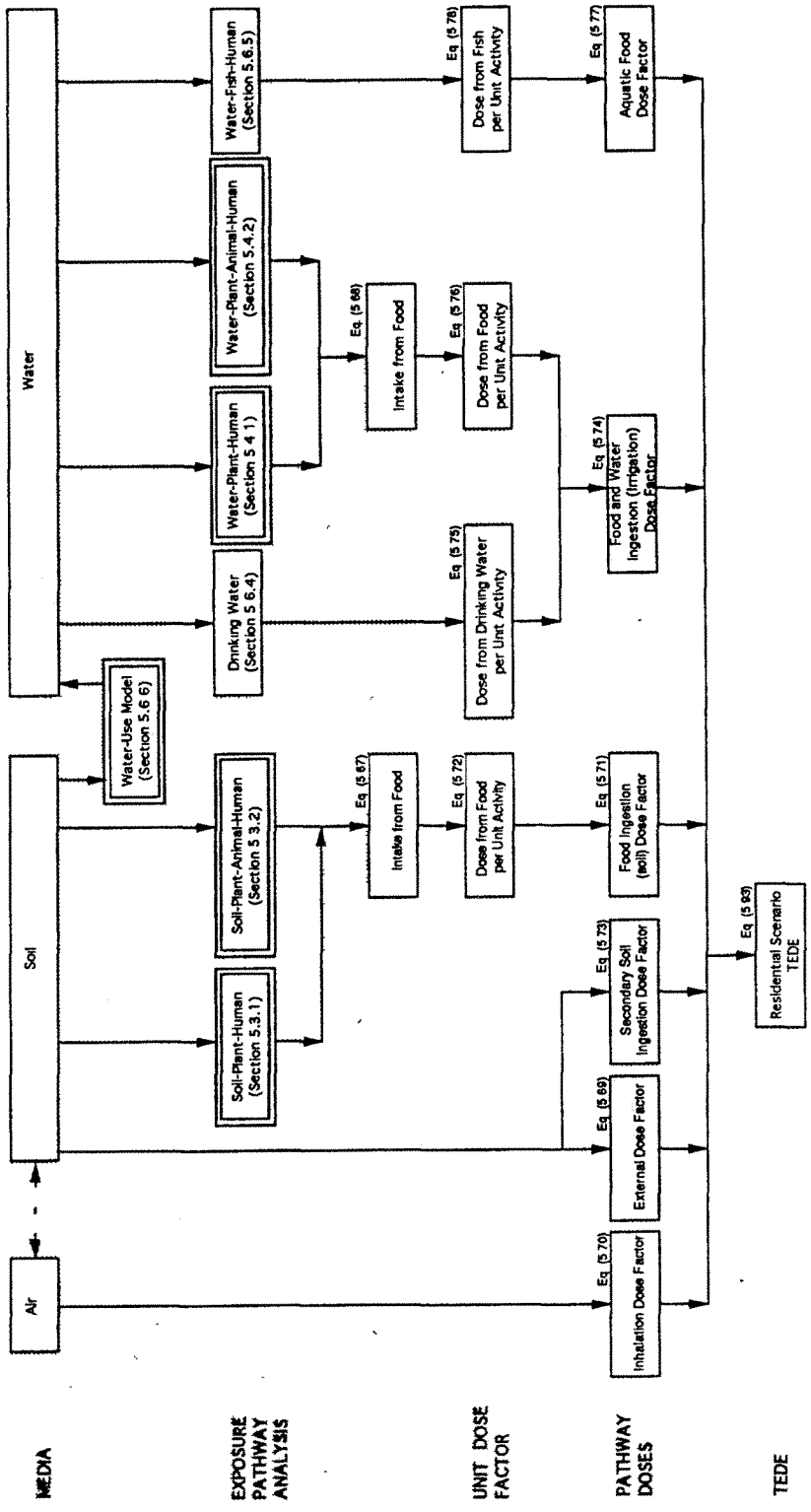


Figure 5.3 Modeling details for the residential scenario exposure pathways

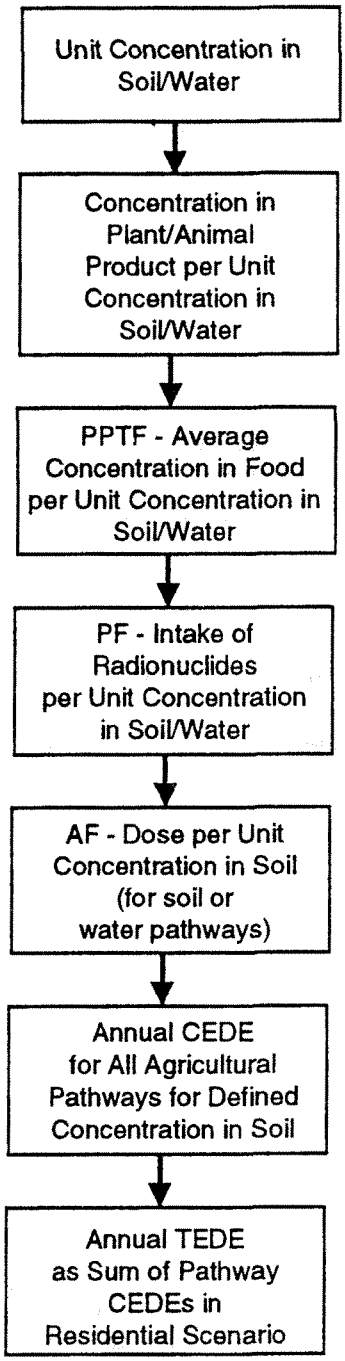


Figure 5.4 Process for estimating annual TEDEs for the agricultural pathways

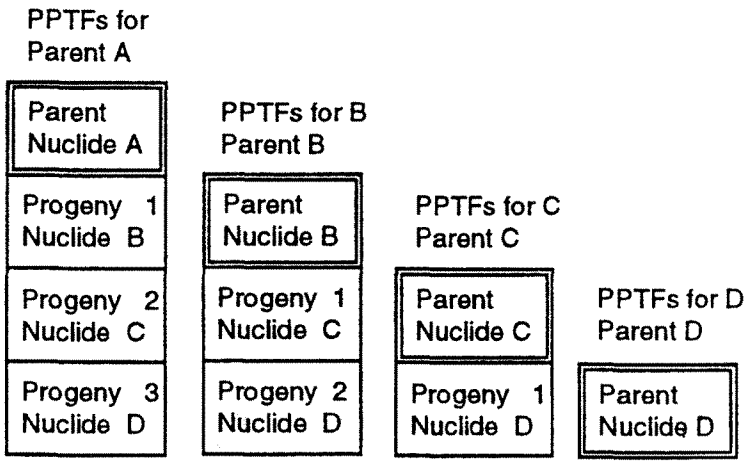


Figure 5.5 PPTF analysis for decay chain radionuclides

year of analysis result in an estimate of the activity of each chain member. Progeny in-growth is shown in Figure 5.5 by the single boxes. The total activity of each chain member at the end of a year is found by summing the activities of each chain member over each of the shorter chains. For example, the activity of radionuclide C present at the end of a year of analysis is the sum of the activity produced by decay of parent B in the decay chain with parents A and B, plus the activity of radionuclide C as a parent remaining after the year of radioactive decay.

Special cases for selected radionuclides are also considered for evaluation of unit TEDE values when secular equilibrium is assumed to occur. The progeny activities for the secular equilibrium cases are determined from the decay chain branching data.

The PPTF evaluations in the following sections relate initial activities in each medium (or average activity in ground water) to the human intake of radionuclides. These analyses are performed for a "current" 1-year period. The doses for future years are evaluated from these "current" year PPTF values, using estimates of initial activity in each medium for the future year. This process is discussed in Section 5.6.6.

The following sections describe the comprehensive models and mathematical formulations used to calculate doses for the agricultural pathways associated with air deposition of resuspended soil, root uptake, and deposition in irrigation water. The transfer of activity from soil to plants includes two pathways: deposition of resuspended particles onto plant surfaces and uptake of activity directly from soil via roots. Both of these transfer mechanisms are included in the models to estimate radionuclide concentrations in plants grown in contaminated soil. The uptake via roots is based on use of concentration ratios between plant and soil. A similar model is used for the resuspension pathway. A plant soil mass-loading parameter is defined that relates the transfer of activity deposited from resuspended soil onto the plant. This approach eliminates the need to define dose parameters based on unit activity in air, as was done in the January 1990 issue of NUREG/CR-5512 (Kennedy and Peloquin 1990). The models used for this pathway are defined in Section 5.3.

5.3 Concentrations and Transfer Factors for Resuspension and Root Uptake From Soil

This section discusses evaluation of PPTFs for the following three pathways: the soil-plant-human pathway, the soil-stored feed-animal-human pathway, and the soil-forage feed-animal-human pathway.

5.3.1 Soil-Plant-Human Pathway

An overview of the modeling processes included in the soil-plant-human pathway is shown in Figure 5.6. The bold box in this figure relates to the double-lined box in master Figure 5.3, showing the overall modeling details for the residential scenario. As shown in Figure 5.6, three significant processes are accounted for in this pathway: 1) calculation of the concentration of radionuclides in plants at the time of harvest (accounting for root uptake and deposition from resuspended soil), 2) calculation of the concentration at the start of the consumption period (accounting for radioactive decay during holdup), and 3) calculation of the time integral of activity in consumed food (calculation of the partial pathway transfer factor for the soil-plant-human pathway). Equation numbers are included in Figure 5.6 to help identify the specific mathematical formulations used in the models. Figure 5.6 also shows linkages to the other significant processes needed to estimate the annual TEDE for the residential scenario. The double-lined boxes in Figure 5.6 show linkages to the other pathways considered in the residential scenario.

The transfer of radionuclides from soil to plants is evaluated for an initial unit concentration of a parent radionuclide in the soil at the start of the growing period. The assumptions for the soil-to-food-crop pathway are as follows:

- Parent radionuclide concentration in soil is defined at the start of the crop-growing period.
- The plant concentration for each decay chain member radionuclide is in equilibrium with the soil concentration at all times.
- The concentration of radionuclides in edible parts of the plant at the end of the first growing period (i.e., first crop) is used as the harvest concentration. Multiple harvesting of plant crops is not addressed.
- The harvested crops are held for a short holdup time before being consumed by humans. The concentration at harvest is reduced by radioactive decay during the holdup time.
- The consumption period by an individual for plant food crops is taken to be 1 year. Radioactive decay during the consumption period is accounted for in the intake calculation.

Figure 5.7 illustrates the change in relative concentration in soil and plants (v) as a function of time. The concentrations of parent radionuclides in soil and food decrease with time because of radioactive decay. The relative concentrations in Figure 5.7 have similar shapes because the plant concentration is assumed to be in constant equilibrium with the soil concentration.

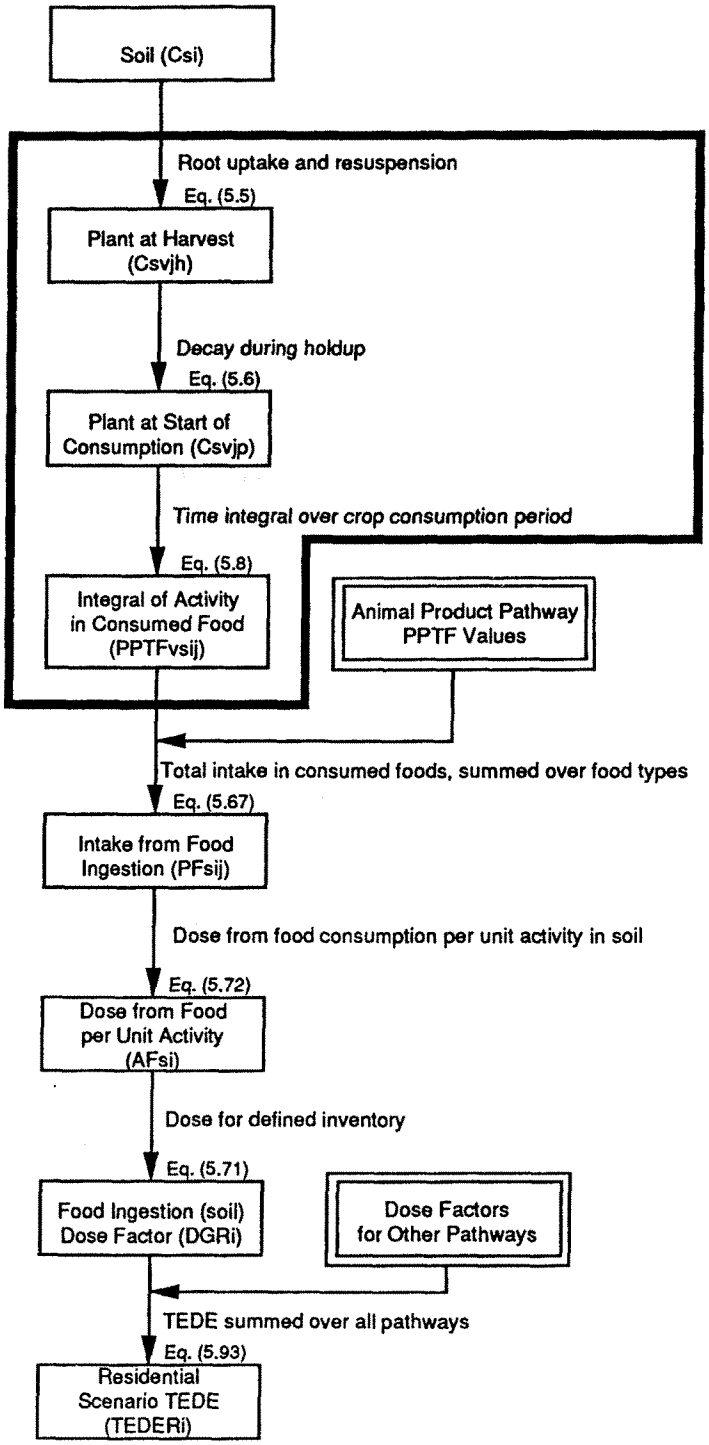


Figure 5.6 Soil-plant-human pathway

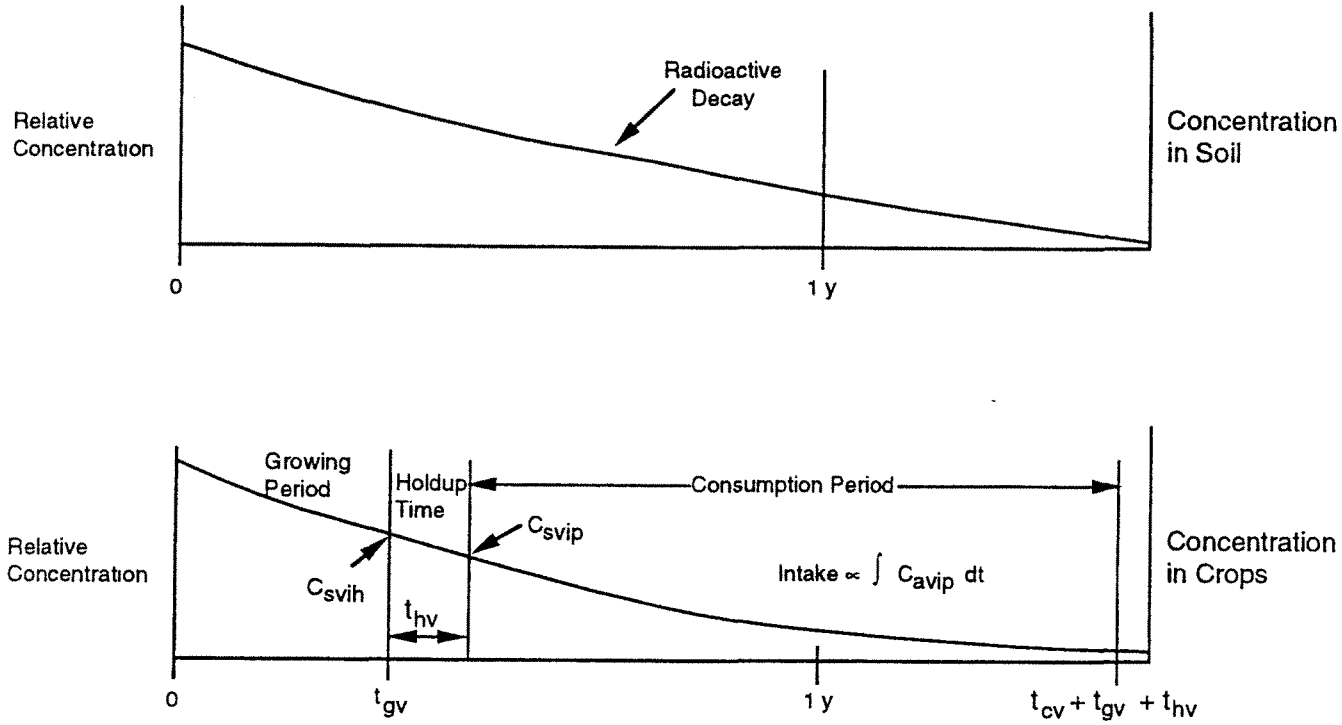


Figure 5.7 Change in relative concentrations over time for soil and plant crops from root uptake

The differential equation defining the change of radionuclide concentration in soil is represented as follows:

$$\frac{dC_{sj}}{dt} = \sum_{n=1}^{j-1} d_{nj}\,\lambda_{rj}\,C_{sn} - \lambda_{rj}\,C_{sj} \tag{5.1}$$

where C_{sj} = concentration of radionuclide j in soil during the growing period (pCi/g dry soil)

C_{sn} = concentration of radionuclide n in soil during the growing period (pCi/g dry soil)

d_{nj} = decay branching fraction for transitions of radionuclide n to radionuclide j (dimensionless)

λ_{rj} = decay rate constant for radionuclide j (d^{-1}).

The solution to the above equation is evaluated using the decay equations described in Appendix B. The solution to Equation (5.1) can be written as follows:

for the parent (j=1),

$$C_{s1}(t) = C_{s1}(0)\,e^{-\lambda_{r1}t} \tag{5.2}$$

and for the first progeny (J=2),

$$C_{s2}(t) = \frac{d_{12}\lambda_{r2}C_{s1}(0)}{\lambda_{r2} - \lambda_{r1}} e^{-\lambda_{r1}t} + \left[C_{s2}(0) - \frac{d_{12}\lambda_{r2}C_{s1}(0)}{\lambda_{r2} - \lambda_{r1}}\right] e^{-\lambda_{r2}t} \quad (5.3)$$

where $C_{s1}(0)$, $C_{s2}(0)$, $C_{s1}(t)$, and $C_{s2}(t)$ represent the initial concentration of a radionuclide in soil and the concentration at time t, respectively.

The solutions shown by Equations (5.2) and (5.3) can be represented in decay operator notation as follows:

$$A\{C_{sj}, t\} \quad (5.4)$$

where $A\{C_{sj},t\}$ = decay operator notation for evaluation of chain member radionuclide concentrations in soil after decay for a time period t (pCi/g dry soil).

This notation is used extensively in the following presentation of models for the agricultural pathways. Details of the decay operator equations are given in Appendix B with a sample application showing the generation of Equations (5.2) and (5.3) in Section B.2.2.

The concentration factors for parent and progeny radionuclides in edible parts of the plant at the time of harvest are evaluated by the following equation:

$$C_{svjh} = 1000 \left(ML_v + B_{jv}\right) W_v A\left\{C_{sj}, t_{gv}\right\} / C_{si}(0) \quad (5.5)$$

where C_{svjh} = concentration factor for radionuclide j in plant v at harvest from an initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight plant per pCi/g dry-weight soil)

B_{jv} = concentration factor for uptake of radionuclide j from the soil in plant v (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

ML_v = plant soil mass-loading factor for resuspension of soil to plant type v (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

W_v = dry-weight-to-wet-weight conversion factor for plant v (kg dry-weight plant per kg wet-weight plant)

$A\{C_{sj},t_{gv}\}$ = decay operator notation used to develop the concentration of radionuclide j in soil at the end of the crop-growing period, t_{gv} (pCi/g dry weight soil)

C_{sj} = concentration of radionuclide j in soil during the growing period (pCi/g dry-weight soil)

$C_{si}(0)$ = initial concentration of parent radionuclide i in soil (pCi/g dry-weight soil)

t_{gv} = growing period for food crop v (d)

1000 = unit conversion factor (g/kg).

The plant soil mass-loading factor represents transfer of activity from soil to plants via resuspension and deposition. This approach has been suggested by Martin and Bloom (1980) and Pinder and McLeod (1989) for estimating radionuclide concentrations in plants for cases in which the root uptake pathway is not significant. Numerical values for the plant soil mass-loading factor are discussed in Section 6.

Equation (5.5) contains the ratio of two concentration parameters: C_{sj} in the decay operator and $C_{si}(0)$ in the denominator. This ratio represents normalization of plant concentration to unit initial concentration of parent radionuclide in soil. The concentration of decay-chain-member radionuclide j (C_{sj}) is evaluated from the initial concentration of parent radionuclide i using decay equations given in Appendix B and represented in Equation (5.5) by the decay operator, A{}.

The radionuclide concentration in the plant undergoes radioactive decay during the holdup period following harvest according to the following equation:

$$C_{svjp} = A\left\{C_{svjh},\ t_{hv}\right\} \tag{5.6}$$

where C_{svjp} = concentration factor for radionuclide j after decay during the holdup period (to the start of the consumption period) for plant v, for initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight plant per pCi/g dry-weight soil)

$A\{C_{svjh}, t_{hv}\}$ = decay operator notation used to develop the concentration factor for radionuclide j after decay during the holdup period (to the start of the consumption period) for plant v, for initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight plant per pCi/g dry-weight soil)

t_{hv} = holdup time between harvest and human consumption of food crop v (d).

Equation (5.6) may be expressed for the parent radionuclide (j=1) as follows:

$$C_{sv1p} = C_{sv1h}\ e^{-\lambda_{r1}\ t_{hv}} \tag{5.7}$$

where C_{sv1p} = concentration factor for the parent radionuclide (first member of the decay chain) after decay during the holdup period for plant v, for an initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight plant per pCi/g dry-weight soil)

C_{sv1h} = concentration factor for the parent (first member of the decay chain) in plant v at harvest for an initial unit concentration of the parent radionuclide in soil (pCi/kg wet-weight plant per pCi/g dry-weight soil)

and other terms are as previously defined.

Consumption is assumed to occur over an extended time period, t_{cv}. The time integral of concentration in the food crop, $S\{C_{svjp}, t_{cv}\}$, is evaluated between the start of consumption, defined by the growing period and minimum holdup time, and the end of consumption, as defined for each type of plant. The time integral of radionuclide concentration in a plant over the consumption period t_{cv}, which is equivalent to the PPTF, is evaluated as follows:

$$PPTF_{vsij} = S\left\{C_{svjp},\ t_{cv}\right\} / 365.25 \tag{5.8}$$

where $PPTF_{vsij}$ = partial pathway transfer factor for plant v, for radionuclide j as a progeny of radionuclide i, for unit initial concentration of parent radionuclide i in soil (pCi•y/kg wet-weight plant per pCi/g dry-weight soil for a year of residential scenario)

$S\{C_{svjp},t_{cv}\}$ = time-integral operator used to develop the concentration time-integral factor for radionuclide j over the consumption period of plant v for the soil pathway, for initial unit concentration of parent radionuclide i in soil (pCi•d/kg wet-weight plant per pCi/g dry-weight soil for a year of residential scenario)

t_{cv} = consumption period of plant v by humans (d for a year of residential scenario)

365.25 = unit conversion factor (d/y).

The PPTF expression in Equation 5.8 can be expanded using expressions for the time-integral operator notation as follows:

for the parent,

$$PPTF_{vs11} = \frac{C_{sv1p}}{365.25}\left[\frac{1-e^{-\lambda_{r1}t_{cv}}}{\lambda_{r1}}\right] \tag{5.9}$$

and for the first progeny (j=2),

$$PPTF_{vs12} = \frac{1}{365.25}\left[\frac{d_{12}\lambda_{r2}C_{sv1p}}{(\lambda_{r2}-\lambda_{r1})}\left(\frac{1-e^{-\lambda_{r1}t_{cv}}}{\lambda_{r1}}\right) + \left(C_{sv2p} - \frac{d_{12}\lambda_{r2}C_{sv1p}}{\lambda_{r2}-\lambda_{r1}}\right)\left(\frac{1-e^{-\lambda_{r2}t_{cv}}}{\lambda_{r2}}\right)\right] \tag{5.10}$$

where $PPTF_{vs11}$ = PPTF value for the parent radionuclide, i=j=1 (pCi• y/kg wet-weight plant per pCi/g dry-weight soil for a year of residential scenario)

$PPTF_{vs12}$ = PPTF value for the first progeny (j=2), for unit initial concentration of parent radionuclide, i=1 (pCi• y/kg wet-weight plant per pCi/g dry-weight soil for a year of residential scenario)

and other terms are as previously defined. The time-integral operator notation is defined in Section B.1.1 and derived in Section B.3.

5.3.2 Animal Products Contaminated by Soil Sources

This section describes the calculation of the PPTF values for the soil-stored feed-animal-human pathway and the soil-forage feed-animal-human pathway. An overview of the modeling processes included in the soil-plant-animal-human

pathway is shown in Figure 5.8. The bold box in this figure relates to the double-lined box in master Figure 5.3, showing the overall modeling details for the residential scenario. As shown in Figure 5.8, three significant processes are accounted for in this pathway: 1) calculation of the concentration of radionuclides in plants used for animal forage, hay, or grain at the time of harvest (accounting for root uptake and deposition from resuspended soil), 2) calculation of the concentration in forage, stored hay, stored feed, and soil at the start of the animal feeding period (accounting for radioactive decay), and 3) calculation of the time integral of activity over all animal intake routes (calculation of the PPTF for the soil-plant-animal-human pathway). Equation numbers are included in Figure 5.8 to help identify the specific mathematical formulations used in the models. Figure 5.8 also shows linkages to the other significant processes needed to estimate the annual TEDE for the residential scenario. The double-lined boxes in Figure 5.8 show linkages to the other pathways considered in the residential scenario.

The assumptions for the pathways are as follows:

- Parent radionuclide concentration in soil is defined at the start of the crop growing period.
- Fresh forage crops are eaten by the animal continuously (starting at time zero) over the entire feeding period of the animal.
- Stored feed crops are eaten continuously during a feeding period offset by the stored feed crop's growing period (i.e., feeding begins at crop harvest).
- The harvested crops (fresh and stored) are immediately available for feeding to animals. (No holdup period is used.)
- A representative mix of fresh and stored feeds is assumed for each type of animal product, constant over the feeding period. These are described in Section 6.
- Stored feeds may consist of hay and/or grain.
- Instantaneous equilibrium occurs between the radionuclide concentration in the soil and the concentration in the plants (fresh forage and stored feed plants).
- Instantaneous equilibrium occurs between daily intake in the feed and radionuclide concentrations in the animal products.
- Animal products are harvested (e.g., milked, slaughtered, or eggs gathered) continuously over the feeding period and then distributed for human consumption.
- The human consumption period is equal in length to the feeding period for each animal product type, offset by the time between harvest and consumption.
- Decay during the holdup time between animal product harvest and consumption by humans is evaluated.

5.3.2.1 Soil-Stored Hay-Animal-Human Pathway

Figure 5.9 illustrates the variation of the relative parent radionuclide concentration in soil, stored hay plants, and animals as a function of time. In this pathway, the stored hay plants are contaminated by resuspension and root uptake from soil. Radionuclide concentrations in stored hay plants from soil uptake are evaluated using Equation (5.7). The

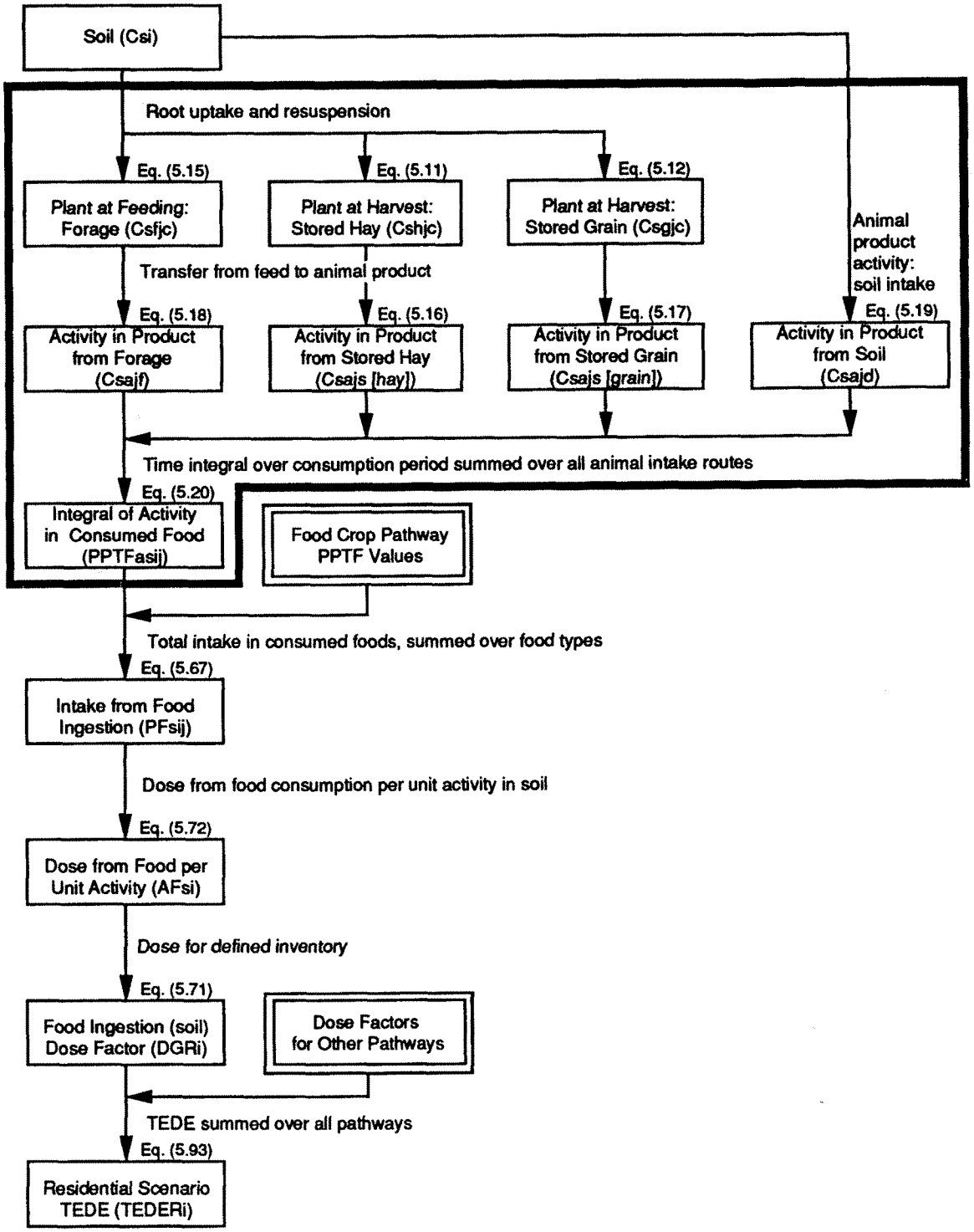


Figure 5.8 Soil-plant-animal-human pathway

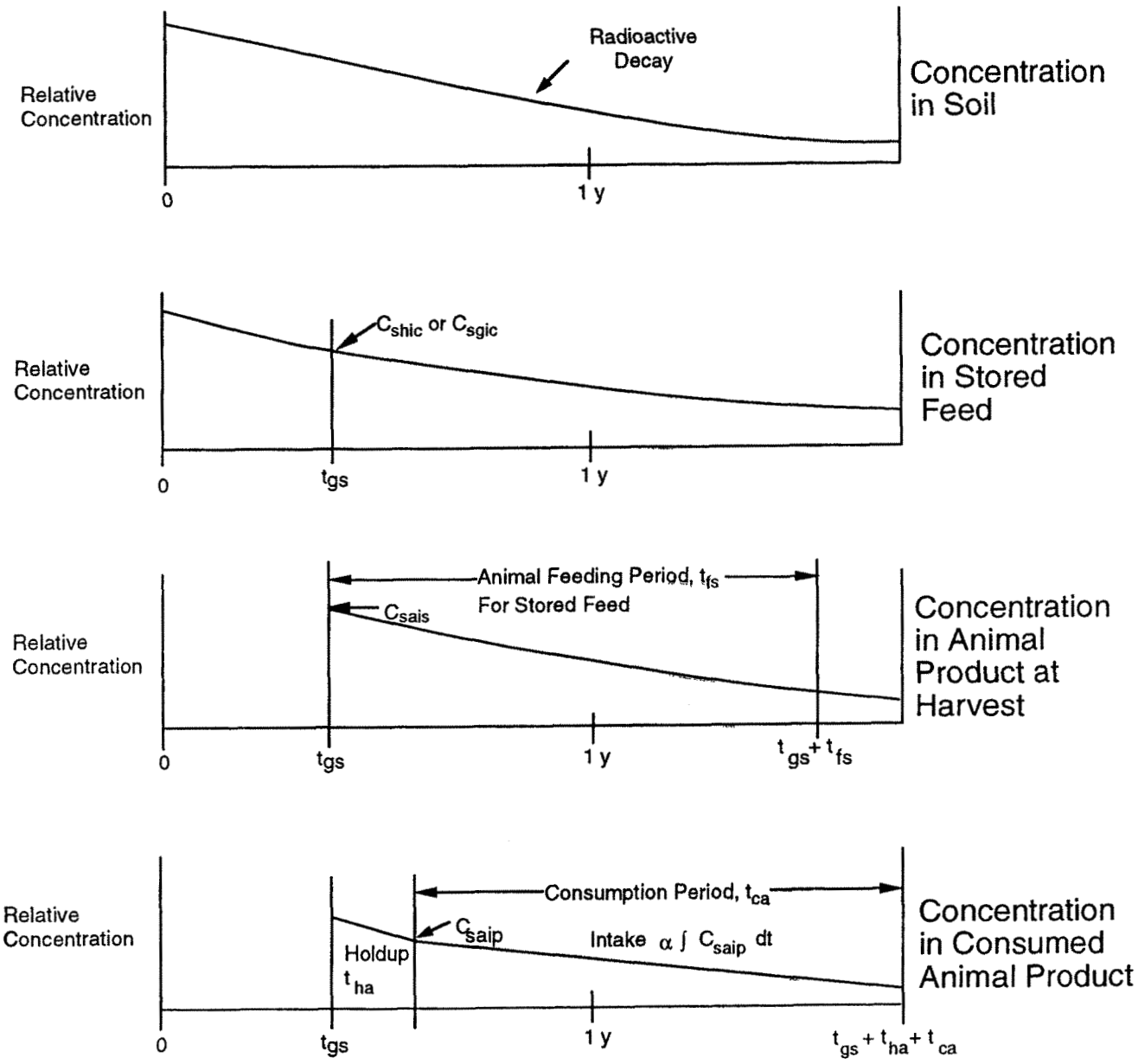


Figure 5.9 Change in relative concentrations over time for soil, stored feed, animal products, and human foods from the root-uptake pathway

appropriate stored hay crop parameters are used. The radionuclide concentration in stored hay from resuspension and root uptake from soil is evaluated as follows based on equilibrium with the concentration in soil:

$$C_{shjc} = 1000 \left(ML_h + B_{jh}\right) W_h \, A\left\{C_{sj}, t_{gh}\right\} / C_{si}(0) \tag{5.11}$$

where C_{shjc} = concentration factor for radionuclide j in stored hay crop h at time of initial feeding to animals from an initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight plant per pCi/g dry-weight soil)

B_{jh} = concentration factor for uptake of radionuclide j from the soil in stored hay crop h (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

ML_h = plant soil mass-loading factor for resuspension of soil onto hay plant h (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

W_h = dry-weight-to-wet-weight conversion factor for stored hay crop h (kg dry-weight hay per kg wet-weight hay)

$A\{C_{sj},t_{gh}\}$ = decay operator notation used to develop the concentration of radionuclide j in soil at the end of the hay-crop growing season, t_{gh} (pCi/g dry-weight soil)

C_{sj} = concentration of radionuclide j in soil during the growing period (pCi/g dry-weight soil)

$C_{si}(0)$ = initial concentration of parent radionuclide i in soil at start of growing period (pCi/g dry-weight soil)

t_{gh} = growing period for stored hay crop h (d)

1000 = unit conversion factor (g/kg)

and other terms are as previously defined.

For stored hay, the concentration is defined at the time of crop harvest (see Equation [5.11]), which is also assumed to be the time at which feeding to animals begins (i.e., there is assumed to be no holdup between feed harvest and start of feeding).

5.3.2.2 Soil-Stored Grain-Animal-Human Pathway

The evaluations for radionuclide concentrations in stored grain are analogous to those for stored hay, as defined in the previous section. The equation for radionuclide concentration at the beginning of the feeding period is evaluated using Equation (5.11) with the subscript "h" (for hay) replaced by "g" (for grain). The resulting equation for radionuclide concentration in stored grain from resuspension and root uptake from soil is evaluated as follows, based on equilibrium with the concentration in soil:

$$C_{sgjc} = 1000\left(ML_g + B_{jg}\right) W_g \, A\left\{C_{sj}, t_{gg}\right\} / C_{si}(0) \tag{5.12}$$

where C_{sgjc} = concentration factor for radionuclide j in stored grain crop g at time of initial feeding to animals from an initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight plant per pCi/g dry-weight soil)

B_{jg} = concentration factor for uptake of radionuclide j from the soil into stored grain crop g (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

ML_g = plant soil mass-loading factor for resuspension of soil onto grain plant g (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

W_g = dry-weight-to-wet-weight conversion factor for stored grain crop g (kg dry-weight grain per kg wet-weight grain)

$A\{C_{sj},t_{gg}\}$ = decay operator notation used to develop the concentration of radionuclide j in soil at the end of the crop-growing season, t_{gg} (pCi/g dry-weight soil)

t_{gg} = growing period for stored grain crop g (d)

1000 = unit conversion factor (g/kg)

and other terms are as previously defined.

For stored grain, the concentration is defined at the time of crop harvest (see Equation [5.12]), which is also assumed to be the time at which feeding to animals begins (i.e., there is assumed to be no holdup between feed harvest and start of feeding).

5.3.2.3 Soil-Forage Feed-Animal-Human Pathway

Figure 5.10 illustrates the variation of the relative parent radionuclide concentration in soil, fresh forage plants, and animals as a function of time. In this pathway, fresh forage consumed by animals is contaminated by resuspension and root uptake from soil. The animal product activity from the forage crop pathway is proportional to the soil concentration at all times during the feeding period. This is because of the assumptions of equilibrium between soil and forage plant and between forage plant intake and animal product. The animal is assumed to consume the fresh forage continuously over the grazing period with no delay time between harvest and feeding.

The concentration in forage consumed by the animal (at any time) is evaluated as follows:

$$C_{sfjt} = 1000 \left(ML_f + B_{jf}\right) W_f \, A\left\{C_{sj}, t\right\} / C_{si}(0) \qquad (5.13)$$

where C_{sfjt} = concentration factor for radionuclide j in fresh forage crop f at time t, from an initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight plant per pCi/g dry-weight soil)

B_{jf} = concentration factor for uptake of radionuclide j from the soil in fresh forage crop f (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

ML_f = plant soil mass-loading factor for resuspension of soil onto forage plant f (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

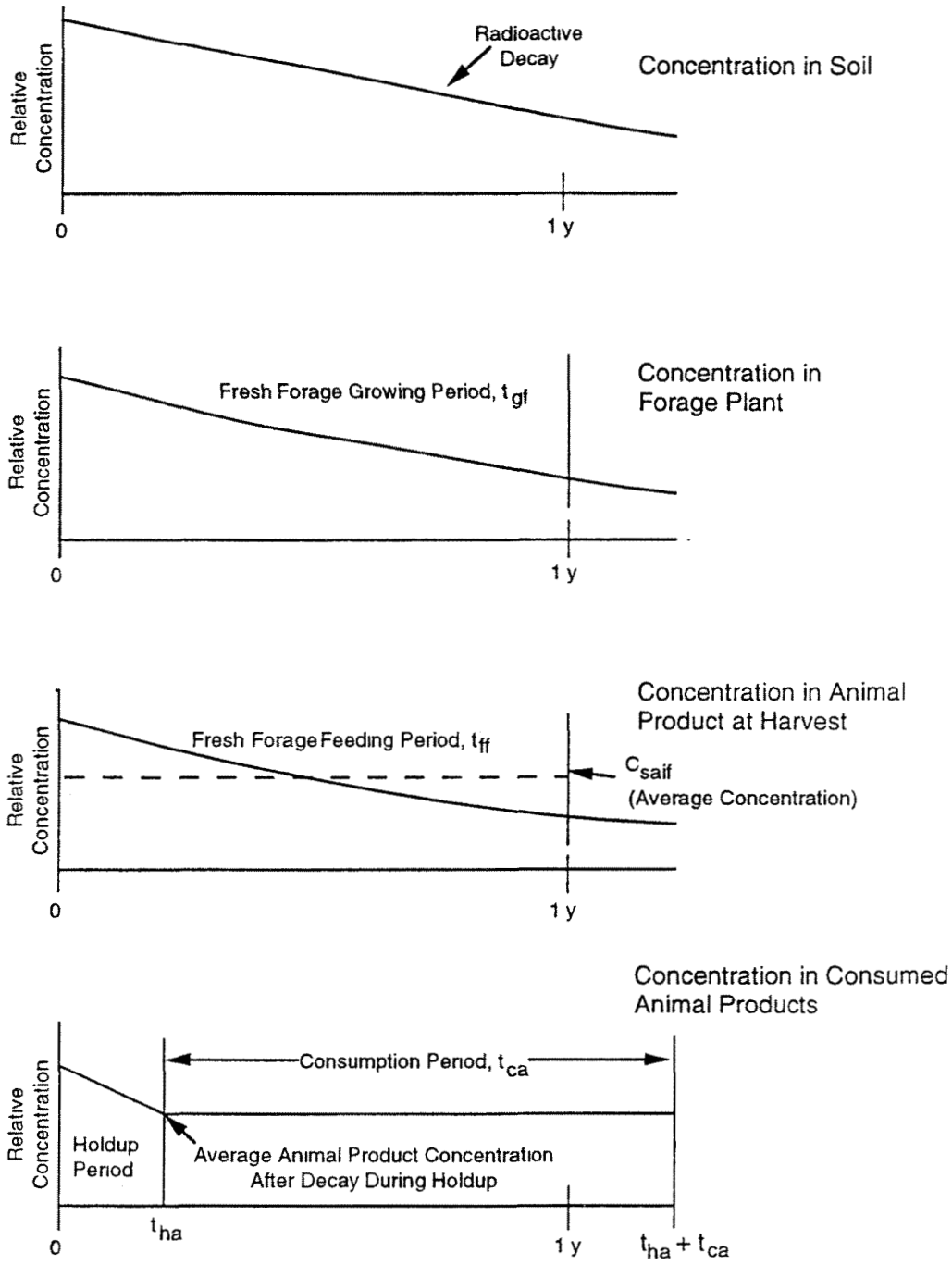


Figure 5.10 Changes in relative concentrations over time for soil, fresh feed, animal products, and human foods from the root uptake pathway

W_f = dry-weight-to-wet-weight conversion factor for fresh forage crop f (kg dry-weight forage per kg wet-weight forage)

$A\{C_{sj},t\}$ = decay operator notation used to develop the concentration of radionuclide j in soil at time t during the feeding period for fresh forage crop f (pCi/g dry-weight soil)

t = any point in time during the fresh-forage feeding period (d)

and other terms are as previously defined. Equation (5.13) provides the fresh forage concentration as a function of time during the fresh forage feeding period, t_{ff}. The integral of this equation divided by the feeding period provides the average plant concentration over the feeding period. The integral of the forage plant concentration over the feeding period can be expressed in operator notation as follows:

$$\int_0^{t_{ff}} C_{sfjt}\,dt = \int_0^{t_{ff}} A\{C_{sj},t\}\,dt = S\{C_{sj},t_{ff}\} \tag{5.14}$$

where terms are as previously defined. Using this expression and dividing by the feeding period, t_{ff}, the average plant concentration is evaluated as follows:

$$C_{sfjc} = 1000\left(ML_f + B_{jf}\right) W_f\, S\left\{C_{sj},t_{ff}\right\} / \left[t_{ff}\, C_{si}(0)\right] \tag{5.15}$$

where C_{sfjc} = average concentration factor for radionuclide j in fresh forage crop f over the feeding period at time of animal consumption of forage from an initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight plant per pCi/g dry-weight soil)

$S\{C_{sj}, t_{ff}\}$ = concentration time-integral factor for radionuclide j in soil over the feeding period, t_{ff} (pCi•d/g dry-weight soil)

t_{ff} = feeding period for forage crop f (d)

and other terms are as previously defined.

5.3.2.4 Calculation of PPTFs for Animal Products Contaminated by Soil

The animal product concentration factor is proportional to the plant concentration factor. The animal product concentration factor for stored hay intake is

$$C_{sajs(hay)} = F_{aj}\, Q_h\, x_h\, C_{shjc} \tag{5.16}$$

For stored grain the animal concentration factor is

$$C_{sajs(grain)} = F_{aj}\, Q_g\, x_g\, C_{sgjc} \tag{5.17}$$

and for fresh forage the average animal product concentration factor is

$$C_{sajf} = F_{aj}\ Q_f\ x_f\ C_{sfjc} \tag{5.18}$$

where $C_{sajs(hay)}$ = concentration factor for animal product a, at initial time of feeding of stored hay for radionuclide j for initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight hay [or pCi/L for milk] per pCi/g dry-weight soil)

$C_{sajs(grain)}$ = concentration factor for animal product a, at initial time of feeding of stored grain for radionuclide j for initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight grain [or pCi/L for milk] per pCi/g dry-weight soil)

C_{sajf} = average concentration factor for animal product a, over time period of feeding of fresh forage for radionuclide j for initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight animal product [or pCi/L for milk] per pCi/g dry-weight soil)

F_{aj} = transfer coefficient that relates daily intake in animal feed and ingested soil to the concentration of radionuclide j in an animal product a (pCi/L per pCi/d for milk or pCi/kg wet-weight animal product per pCi/d for other animal products)

Q_f = consumption rate of fresh forage by the animal (kg wet-weight plant/d)

Q_g = consumption rate of stored grain by the animal (kg wet-weight plant/d)

Q_h = consumption rate of stored hay by the animal (kg wet-weight plant/d)

x_f = fraction of animal forage intake that is contaminated (dimensionless)

x_g = fraction of animal stored grain intake that is contaminated (dimensionless)

x_h = fraction of animal stored hay intake that is contaminated (dimensionless)

and other terms are as previously defined. Note that the concentration factors for stored feeds are evaluated at the time of initial feeding to animals; for forage crops, the factor represents an average over the feeding (grazing) period. This difference is important to the evaluation of the PPTF contribution from each pathway (see Equation [5.20]).

Animals on fresh forage may also take in soil while grazing. The amount of soil ingested is assumed to be a constant fraction of the fresh forage intake rate, Q_f, expressed per kg dry weight. The average concentration in animal products from intake during the feeding period is evaluated in the same way as the average feed intakes of Equations (5.15) and (5.18):

$$C_{sajd} = 1000\ F_{aj}\ Q_d\ W_f\ Q_f\ x_f\ S\left\{C_{sj},\ t_{ff}\right\}/\left[t_{ff}\ C_{si}(0)\right] \tag{5.19}$$

where C_{sajd} = average concentration factor for animal product a, over the fresh forage feeding period for soil ingestion by animals for radionuclide j for initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight animal product per pCi/g dry-weight soil)

Q_d = soil intake as a fraction of forage intake for the animal (kg dry-weight soil per kg dry-weight forage)

and other terms are as previously defined. The ratio of S{} to time represents the average concentration of soil-contaminated crops for plant material taken in by the animal over the feeding or grazing period.

To evaluate the PPTF from animal products for the soil pathway, the animal product concentration at time of human consumption is estimated as the sum of contributions from the two feed types and soil. First, the decay between harvest and consumption by humans is evaluated for the average animal product concentration for each feed type, and then the total intake by humans is evaluated. For the forage pathway and soil ingestion, the total intake is calculated as the product of average concentrations multiplied by the time period of intake (consumption period). For the stored feed pathways, the total intake is evaluated as a time integral using the time-integral operator:

$$PPTF_{asij} = \left[S\left\{ A\left\{ C_{sajs(hay)}, t_{ha} \right\}, t_{ca} \right\} + S\left\{ A\left\{ C_{sajs(grain)}, t_{ha} \right\}, t_{ca} \right\} + A\left\{ C_{sajf}, t_{ha} \right\} t_{ca} + A\left\{ C_{sajd}, t_{ha} \right\} t_{ca} \right] / 365.25 \quad (5.20)$$

where $PPTF_{asij}$ = partial pathway transfer factor for animal product a, for radionuclide j as a progeny of radionuclide i for an initial unit concentration of parent radionuclide i in soil (pCi•y/L for milk and pCi•y/kg for other animal products per pCi/g dry-weight soil for a year of residential scenario)

$A\{C_{sajs(hay)},t_{ha}\}$ = decay operator notation used to develop the concentration factor for radionuclide j in animal product a, from stored-hay intake after decay during holdup (t_{ha}) for initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight animal product per pCi/g dry-weight soil)

$A\{C_{sajs(grain)},t_{ha}\}$ = decay operator notation used to develop the concentration factor for radionuclide j in animal product a, from stored grain intake after decay during holdup (t_{ha}) for initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight animal product per pCi/kg dry-weight soil)

$A\{C_{sajf},t_{ha}\}$ = decay operator notation used to develop the concentration factor for radionuclide j in animal product a, from fresh forage intake after decay during holdup (t_{ha}) for initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight animal product per pCi/g dry-weight soil)

$A\{C_{sajd},t_{ha}\}$ = decay operator notation used to develop the concentration factor for radionuclide j in animal product a, from soil ingestion while grazing, after decay during holdup (t_{ha}) for initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight animal product per pCi/g dry-weight soil)

$S\{A\{\}, t_{ca}\}$ = time-integral operator notation used to develop the concentration time-integral factor for radionuclide j in animal product a, over the consumption period by humans for initial unit concentration of parent radionuclide i in soil (pCi•d/kg per pCi/g dry-weight soil for a year of residential scenario)

t_{ca} = consumption period for animal product a (d for a year of residential scenario)

t_{ha} = holdup time for animal product a between harvest and consumption by humans (d)

365.25 = unit conversion factor (d/y).

A description of nested operator notation (e.g., S{A{}}) is given in Section 2.2, and an example case is described in Section 5.4.1.3.

5.4 Concentrations and Transfer Factors for Irrigation Water as the Contaminating Medium

Use of contaminated water in sprinkler-type irrigation systems results in deposition of radionuclides directly onto plant surfaces or to the soil with subsequent resuspension and plant uptake and transfer to edible parts of the plant. The contaminated plant can then be eaten by humans or animals, resulting in the same exposure pathways as defined above for air and soil. Material deposited on soil may also be ingested directly by animals while grazing. Using the average water concentrations provided by the water-use model, evaluations are made for each year that doses are to be evaluated.

5.4.1 Food Crops Contaminated by Irrigation Water

Two pathways are used for estimating radionuclide transfer from irrigation water to food crops: deposition directly onto plant leaves (the irrigation water-plant-human pathway) and deposition onto soil with uptake via roots to food crops (the irrigation water-soil-plant-human pathway). An overview of the modeling processes included in the water-plant-human pathway and the water-soil-plant-human pathway is shown in Figure 5.11. The bold box in this figure relates to the double-lined box in master Figure 5.3, showing the overall modeling details for the residential scenario. As shown in Figure 5.11, three significant processes are accounted for in this pathway: 1) calculation of the deposition of radionuclides onto plants and soil with calculation of the concentration at the time of harvest, 2) calculation of the concentration in plants at the time of harvest (accounting for root uptake and for radioactive decay during holdup), and 3) calculation of the time integral of activity over all food consumption routes (calculation of the PPTF for these pathways). Equation numbers are included in Figure 5.11 to help identify the specific mathematical formulations used in the models. Figure 5.11 also shows linkages to the other significant processes needed to estimate the annual TEDE for the residential scenario. The double-lined boxes in Figure 5.11 show linkages to the other pathways considered in the residential scenario.

The assumptions for evaluation of these pathways are as follows:

- The concentration of radionuclides in irrigation water is constant over the year of irrigation (i.e., an average water concentration is used).
- Material deposited on plant surfaces is removed at a constant weathering half-time.
- Radionuclide concentrations in soil from deposition are immediately in equilibrium with radionuclide concentrations in edible portions of the plants grown in the soil.
- Harvested plants are held for a short period of time (holdup time) before being consumed by humans.

5.4.1.1 Irrigation Water-Plant-Human Pathway

Figure 5.12 illustrates the variation over time of the relative parent radionuclide concentration in irrigation water, growing plants, and consumed plants for the water-plant-human pathway. The concentration in water is constant over the year of exposure. The concentration in plants increases as material is deposited onto plant surfaces and is incorporated into edible parts of the plant. After harvest of the food crop, the concentration decays during the holdup time

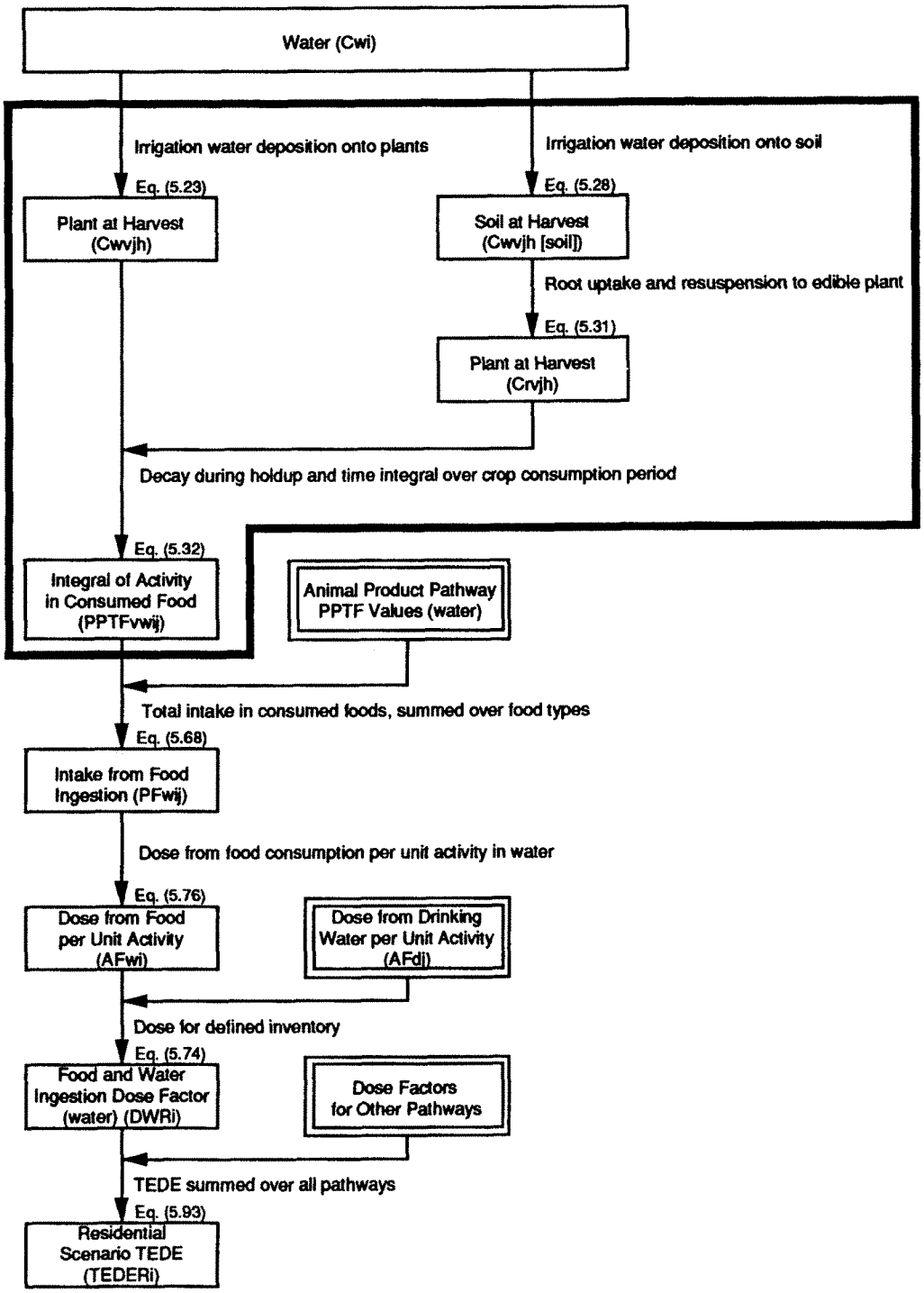


Figure 5.11 Water-plant-human pathway and water-soil-plant-human pathway

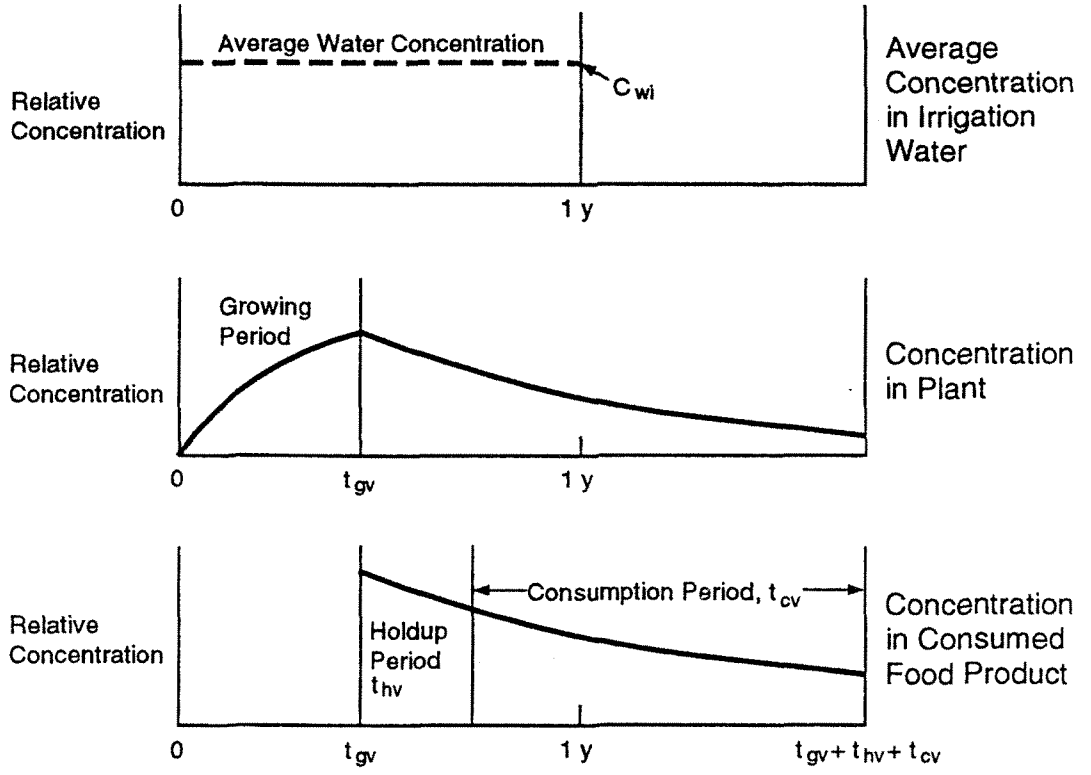


Figure 5.12 Changes in relative concentrations over time for irrigation water, plants, and human food from deposition of irrigation water onto plant surfaces

before the crop is consumed. During the consumption period, t_{cv}, the concentration continues to change. The PPTF for the year is evaluated as the time integral of the radionuclide concentrations in the food crop over the consumption period.

The change in radionuclide concentration in plants from irrigation deposition is described by the following general differential equation for each chain member:

$$\frac{dC_{wvjt}}{dt} = R_{wvjg} + \sum_{n=1}^{j-1} d_{nj}\lambda_{rj}C_{wvnt} - \left(\lambda_{rj} + \lambda_{w}\right) C_{wvjt} \qquad (5.21)$$

where C_{wvjt} = concentration of radionuclide j in plant type v at time t during the growing period from application of irrigation water per unit average concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

C_{wvnt} = concentration of radionuclide n in plant type v at time t during the growing period from application of irrigation water per unit average concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

R_{wvjg} = average deposition rate of radionuclide j to edible parts of plant v from application of irrigation water per unit average concentration of parent radionuclide i in water (pCi/d•kg wet-weight plant per pCi/L water)

d_{nj} = decay branching fraction for transitions of radionuclide n to radionuclide j (dimensionless)

λ_{rj} = decay rate constant for radionuclide j (d^{-1})

λ_w = rate constant for loss of activity from plant surfaces due to weathering (d^{-1}).

The constant average rate of deposition of radionuclide j to plants is evaluated as follows:

$$R_{wvjg} = IR\ r_v\ T_v / Y_v \left[C_{wj} / C_{wi} \right] \tag{5.22}$$

where R_{wvjg} = average deposition rate of radionuclide j to edible parts of plant v from application of irrigation water per unit average concentration of parent radionuclide *i* in water (pCi/d•kg wet-weight plant per pCi/L water)

C_{wi} = average annual concentration of parent radionuclide *i* in irrigation water over the current annual period (pCi/L water)

C_{wj} = average annual concentration of radionuclide j in irrigation water over the current annual period (pCi/L water)

IR = average annual application rate of irrigation water (L/m^2•d)

r_v = fraction of initial deposition (in water) retained on the plant (pCi retained per pCi deposited)

T_v = translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant (pCi in edible plant part per pCi retained)

Y_v = yield of plant v (kg wet-weight plant/m^2).

The deposition rate to plants, R_{wvjg}, is constant over the irrigation period because the concentration in water is constant (at the average value for C_{wj}). The evaluation of agricultural pathways is performed for 1 year of irrigation practice, normalized to initial unit concentration of the parent radionuclide in the irrigation water. All progeny are assumed to have zero concentration in water (i.e., $C_{wj} = 0.0, j \neq i$). The contributions from the progeny radionuclides are included in PPTF values calculated for each progeny as a parent of a decay chain. This convention is described in Section 5.2. With use of this convention, the PPTF values can be applied to any year of irrigation, as indicated in Sections 5.5 and 5.6.4. The ratio of radionuclide concentrations in water is included to indicate the source of activity units (pCi) and to provide consistency with other equations for radionuclide transfer to plants (e.g., Equation [5.5]).

The concentration factor for each radionuclide in edible parts of plants at the time of harvest is evaluated as the solution to Equation (5.21). The concentration factors can be written as follows using the deposition, accumulation with removal operator notation:

$$C_{wvjh} = R_e\left\{R_{wvjg},\ t_{gv}\right\} \tag{5.23}$$

where C_{wvjh} = concentration factor for radionuclide j in plant v at harvest from deposition onto plant surfaces for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

t_{gv} = growing period for plant v (d)

$R_e\{R_{wvjg},t_{gv}\}$ = deposition, accumulation operator used to develop the concentration factor for radionuclide j in plant v at harvest from deposition onto plant surfaces for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water).

Equation (5.23) applies to all members of the decay chain including the parent.

The deposition, accumulation operator notation can be expanded using equations of Section B.1 and B.4 to give the explicit equations for the parent and progeny radionuclide concentrations in the plant at harvest. The equations are as follows:

for the parent,

$$C_{wv1h} = R_{wv1g}\left[\frac{1-e^{-\lambda_{e1}t_{gv}}}{\lambda_{e1}}\right] \tag{5.24}$$

and for the first progeny (j=2),

$$C_{wv2h} = \left[\frac{d_{12}\lambda_{r2}R_{wv1g}}{(\lambda_{e2}-\lambda_{e1})}\left(\frac{1-e^{-\lambda_{e1}t_{gv}}}{\lambda_{e1}}\right)\right. + \left.\left(R_{wv2g} - \frac{d_{12}\lambda_{r2}R_{wv1g}}{\lambda_{e2}-\lambda_{e1}}\right)\left(\frac{1-e^{-\lambda_{e2}t_{gv}}}{\lambda_{e2}}\right)\right] \tag{5.25}$$

where C_{wv1h} = concentration factor for parent radionuclide in plant v at harvest from deposition onto plant surfaces for an average unit concentration of parent in water (i=j=1), (pCi/kg wet-weight plant per pCi/L water)

C_{wv2h} = concentration factor for the first progeny radionuclide (j=2) in plant v at harvest from deposition onto plant surfaces for an average unit concentration of parent in water, (pCi/kg wet-weight plant per pCi/L water)

λ_{e1} = effective weathering and decay constant for the parent radionuclide (j=1) evaluated as the sum of the weathering rate constant, λ_w, and the radioactive decay constant, λ_{r2} (d^{-1})

λ_{e2} = effective weathering and decay constant for radionuclide 2 (second chain member) evaluated as the sum of the weathering rate constant, λ_w, and the radioactive decay constant, λ_{r2} (d^{-1})

and other terms are as previously defined for parent radionuclide (subscript 1) and first progeny (subscript 2) radionuclide.

5.4.1.2 Irrigation Water-Soil-Plant-Human Pathway

Figure 5.13 illustrates the variation with time of the relative parent radionuclide concentration in irrigation water, growing plants, and consumed plants for the water-soil-plant-human pathway. For this pathway, the concentration in plants results from resuspension and root uptake of radionuclides in irrigation water applied to the soil. As before, the radionuclide concentration in water is constant over the year of exposure. Radionuclides that enter the soil via irrigation water accumulate with time and are assumed to be contained in the top 15-cm soil layer. This activity will consequently be available for root uptake. The radionuclide concentration in plants is assumed to be in constant equilibrium with the radionuclide concentration in soil. The radionuclide concentration in plants at harvest will change during the holdup period before the plant is consumed by humans. The total radionuclide intake during the

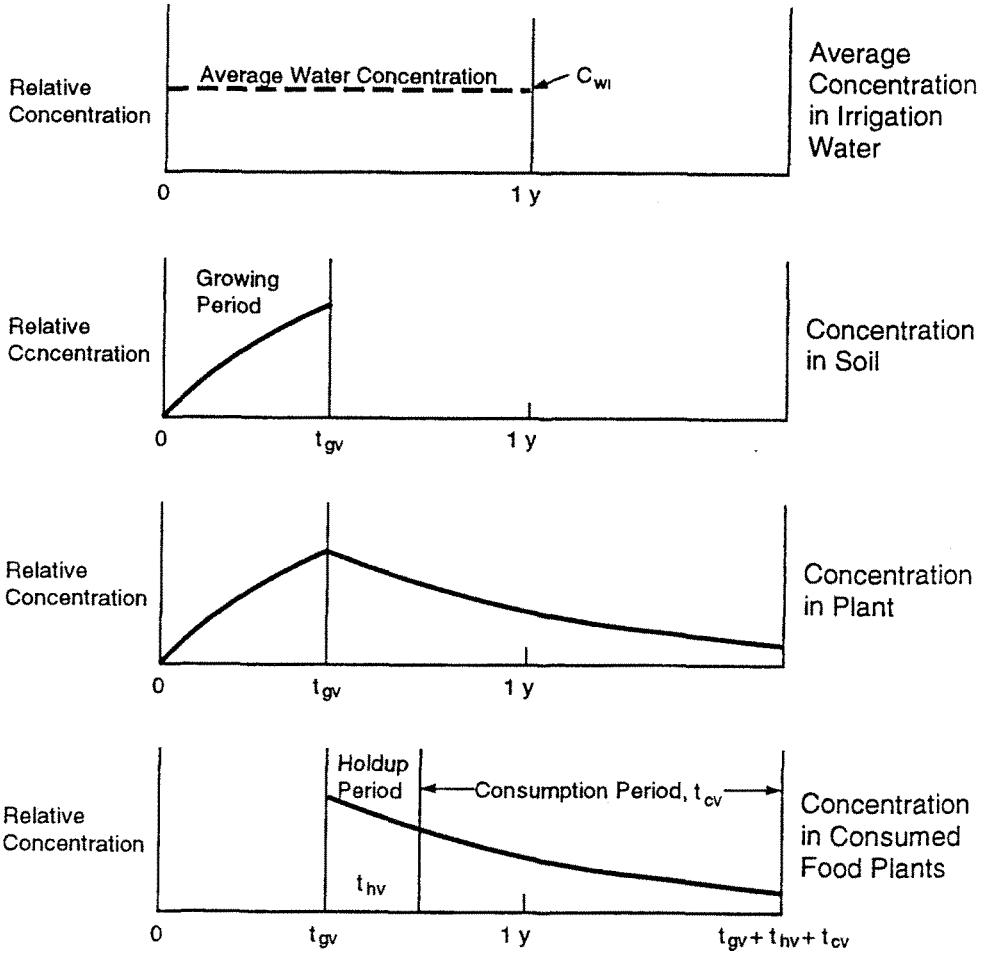


Figure 5.13 Change in relative concentrations over time for irrigation water, soil, plants, and human foods from deposition of irrigation water on soil with subsequent root uptake

consumption period is evaluated as the time integral of concentration in the plant over the consumption period, starting with the plant concentration at the beginning of the period (after decay during holdup).

The transfer is modeled in a manner analogous to that for deposition directly onto plants, as described in Section 5.4.1.1. The concentration in soil at the end of the growing period is evaluated as the solution to the following differential equation for concentration of a radionuclide in soil. Because the concentration of radionuclides in plants is assumed to be continuously in equilibrium with the concentration in soil, the concentration in crops at the end of the growing season is proportional to the soil concentration at the end of the growing season.

The change in radionuclide concentration in soil from irrigation deposition is described by the following general differential equation for each chain member:

$$\frac{d\,C_{wsjt}}{dt} = R_{wsjg} + \sum_{n=1}^{j-1} d_{nj}\,\lambda_{rj}\,C_{wsnt} - \lambda_{rj}\,C_{wsjt} \tag{5.26}$$

where C_{wsjt} = concentration of radionuclide j in soil at time t during the growing period for an average unit concentration of parent radionuclide i in water (pCi/kg dry-weight soil per pCi/L water)

C_{wsnt} = concentration of radionuclide n in soil at time t during the growing period for an average unit concentration of parent radionuclide i in water (pCi/kg dry-weight soil per pCi/L water)

R_{wsjg} = average deposition rate of radionuclide j to soil from application of irrigation water onto soil during the growing period for an average unit concentration of parent radionuclide i in water (pCi/d•kg dry-weight soil per pCi/L water)

and other terms are as previously defined.

The average deposition rate of radionuclide j to soil is evaluated as follows:

$$R_{wsjg} = IR / P_s \left[C_{wj} / C_{wi}\right] \tag{5.27}$$

where R_{wsjg} = average deposition rate of radionuclide j to soil from irrigation water application onto soil during the growing period for an average unit concentration of parent radionuclide i in water (pCi/d•kg dry-weight soil per pCi/L water)

C_{wj} = average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water)

C_{wi} = average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water)

IR = annual average application rate of irrigation water (L/m^2•d)

P_s = areal soil density (kg dry weight soil/m^2).

The contribution from irrigation to radionuclide concentration in soil at the time of harvest of plant v is evaluated as follows using the deposition, accumulation operator notation:

$$C_{wvjh(soil)} = R\left\{R_{wsjg},\ t_{gv}\right\} \tag{5.28}$$

where $C_{wvjh(soil)}$ = concentration factor for radionuclide j in soil at harvest time for plant v for an average unit concentration of parent radionuclide i in water (pCi/kg dry-weight soil per pCi/L water)

$R\{R_{wsjg},t_{gv}\}$ = deposition, accumulation operator used to develop the concentration factor for radionuclide j in soil at the time of harvest of plant v for an average unit concentration of parent radionuclide i in water (pCi/kg dry-weight soil per pCi/L water)

and other terms are as previously defined.

Equation (5.28) can be expanded using operator notation defined in Section B.1 and B.4 to give an explicit equation for the parent and first progeny radionuclide concentration factors in soil at the end of the plant-growing season. The equations are as follows:

for the parent,

$$C_{wv1h(soil)} = R_{ws1g}\left[\frac{1-e^{-\lambda_{r1}t_{gv}}}{\lambda_{r1}}\right] \tag{5.29}$$

and for the progeny (j=2),

$$C_{wv2h(soil)} = \left[\frac{d_{12}\lambda_{r2}R_{ws1g}}{(\lambda_{r2}-\lambda_{r1})}\left(\frac{1-e^{-\lambda_{r1}t_{gv}}}{\lambda_{r1}}\right)\right] + \left[R_{ws2g} - \frac{d_{12}\lambda_{r2}R_{ws1g}}{\lambda_{r2}-\lambda_{r1}}\right]\left[\frac{1-e^{-\lambda_{r2}t_{gv}}}{\lambda_{r2}}\right] \tag{5.30}$$

where terms are as previously defined for parent radionuclide (subscript 1) and first progeny radionuclide (subscript 2).

The concentration of radionuclides in edible portions of plants at the time of harvest is evaluated from the concentration of radionuclides in soil at the time of harvest. The evaluation is made using the soil-to-plant concentration factor as follows:

$$C_{rvjh} = \left(ML_v + B_{jv}\right) W_v\ C_{wvjh(soil)} \tag{5.31}$$

where C_{rvjh} = concentration factor for radionuclide j in plant v at time of harvest resulting from resuspension and root uptake for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

B_{jv} = concentration factor for uptake of radionuclide j from soil in plant v (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

ML_v = plant soil mass-loading factor for resuspension of soil to edible plant parts for plant v (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

W_v = factor for conversion of mass of plant v from a dry-weight to a wet-weight basis (kg dry-weight plant per kg wet-weight plant)

and other terms are as previously defined. Equations (5.28) and (5.31) apply to all members of the decay chain including the parent.

5.4.1.3 Calculation of PPTFs for Food Crops Contaminated by Irrigation Water

The PPTFs for food crops are calculated starting with the radionuclide concentration in plants at harvest, as evaluated using Equations (5.23) and (5.31). The harvest concentration first undergoes decay for a holdup time before initial consumption by humans. The total intake by humans is then evaluated as the time integral of the radionuclide concentration in food crops during the consumption period, t_{cv}. As a conservative assumption, removal of radionuclides by washing during food preparation is not considered. The contributions from each pathway (direct deposition of irrigation water onto plants and deposition onto soil with resuspension and root uptake) are summed to give a total PPTF:

$$PPTF_{vwij} = \left[S\left\{ A\left\{ C_{wvjh},\ t_{hv} \right\},\ t_{cv} \right\} + S\left\{ A\left\{ C_{rvjh},\ t_{hv} \right\}, t_{cv} \right\} \right] / 365.25 \tag{5.32}$$

where $PPTF_{vwij}$ = partial pathway transfer factor for the irrigation pathway for plant v, for radionuclide j as a progeny of radionuclide i for an average unit concentration of parent radionuclide i in water (pCi•y/kg wet-weight plant per pCi/L in water for a year of residential scenario)

$A\{C_{wvjh},t_{hv}\}$ = decay operator notation used to develop the concentration factor for radionuclide j in plant v (as a result of deposition onto plants) at time of human consumption after holdup (t_{hv}) for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

$A\{C_{rvjh},t_{hv}\}$ = decay operator notation used to develop the concentration factor for radionuclide j in plant v (as a result of root uptake) at time of human consumption after holdup (t_{hv}) for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

$S\{A\{\},t_{cv}\}$ = time-integral operator notation used to develop the concentration time-integral factor for radionuclide j over the consumption period of plant v for the irrigation water pathway for an average unit concentration of parent radionuclide i in water (pCi•d/kg wet-weight plant per pCi/L water for a year of residential scenario)

t_{cv} = consumption period of plant v by humans (d for 1 y of residential scenario)

t_{hv} = holdup time between harvest and consumption of plant v (d)

365.25 = unit conversion factor (d/y).

The decay operator notation in Equation (5.32) can be expanded for specific radionuclides in the decay chain using the formulas of Appendix B for radioactive chain decay. As an illustration of this expansion for nested operators, consider the second term on the right side of Equation (5.32) for food crops contaminated by the root uptake and resuspension

pathways. The starting point in the evaluation is the activity of each chain member in the plant at the time of harvest, given by the parameter C_{rvjh} of Equation (5.31). The concentration of the parent after decay during the holdup period can be expressed as follows:

$$C_{rv1p}(t_{hv}) = C_{rv1h}(t_{gv})\, e^{-\lambda_{r1} t_{hv}} \tag{5.33}$$

where $C_{rv1p}(t_{hv})$ is the concentration factor for the parent radionuclide in plant v at the start of the consumption period (pCi/kg wet-weight plant per pCi/L water) and other terms are as previously defined. The activity of the first progeny radionuclide (j=2) in the plant at the start of consumption is given by the following expression:

$$C_{rv2p}(t_{hv}) = \frac{d_{12}\,\lambda_{r2}\,C_{rv1h}(t_{gv})}{\lambda_{r2} - \lambda_{r1}}\, e^{-\lambda_{r1} t_{hv}} + \left[C_{rv2h}(t_{gv}) - \frac{d_{12}\,\lambda_{r2}\,C_{rv1h}(t_{gv})}{\lambda_{r2} - \lambda_{r1}} \right] e^{-\lambda_{r2} t_{hv}} \tag{5.34}$$

where $C_{rv1h}(t_{gv})$ and $C_{rv2h}(t_{gv})$ represent the initial concentrations of the parent and first progeny radionuclide in plant v at the start of the decay period (holdup period), and $C_{rv2p}(t_{hv})$ represents the concentrations after decay for the holdup period. The integral evaluation, indicated by the time-integral operator S{}, is applied to the results of Equations (5.33) and (5.34). The expression can be written as follows for the parent radionuclide:

$$\int_{t_{hv}}^{t_{hv} + t_{cv}} C_{rv1p}(t)\,dt = C_{rv1p}(t_{hv}) \left[\frac{1 - e^{-\lambda_{r1} t_{cv}}}{\lambda_{r1}} \right] \tag{5.35}$$

where the result is the time integral of the concentration factor for parent radionuclide i in plant v over the consumption period (pCi•d/kg wet-weight plant per pCi/L water) and other terms are as previously defined. The time integral for the first progeny radionuclide (j=2) in the plant over the consumption period is given by the following expression:

$$\int_{t_{hv}}^{t_{hv}+ t_{cv}} C_{rv2p(t)dt} = \frac{d_{12}\,\lambda_{r2}\,C_{rv1p}(t_{hv})}{\lambda_{r2} - \lambda_{r1}} \left[\frac{1 - e^{-\lambda_{r1} t_{cv}}}{\lambda_{r1}} \right] + \left[C_{rv2p}(t_{hv}) - \frac{d_{12}\,\lambda_{r2}\,C_{rv1p}(t_{hv})}{\lambda_{r2} - \lambda_{r1}} \right] \cdot \left[\frac{1 - e^{-\lambda_{r2} t_{cv}}}{\lambda_{r2}} \right] \tag{5.36}$$

where the result represents the concentration time integral of the first progeny radionuclide in plant v over the consumption period and other terms are as previously defined with subscripts 1 and 2 for parent and first progeny, respectively.

5.4.2 Animal Products Contaminated by Irrigation Water

This section discusses seven pathways involving the consumption of animal products by humans, each beginning with irrigation water as the source of radionuclides; three involve irrigation water directly applied to animal feed (stored hay, stored grain, and fresh forage) and three involve irrigation water applied to soil and thence to plants (evaluated

again for stored hay, stored grain, and fresh forage feed). The seventh pathway involves animals drinking the irrigation water. An overview of the modeling processes included in the water-plant-animal-human pathway and the water-soil-plant-animal-human pathway is shown in Figure 5.14. The bold box in this figure relates to the double-lined box in master Figure 5.3, showing the overall modeling details for the residential scenario. As shown in Figure 5.14, four significant processes, and numerous subprocesses, are accounted for in this pathway: 1) calculation of the deposition of radionuclides onto plants used to feed animals and soil with calculation of the concentration at the time of feeding or harvest, 2) calculation of the concentration in plants at the time of harvest, accounting for root uptake and for radioactive decay during holdup, 3) calculation of the concentration in animal products from animal ingestion of forage, stored hay, stored grain, and water, and 4) calculation of the time integral of activity for human ingestion of animal products over the consumption period (calculation of the PPTF for these pathways). Equation numbers are included in Figure 5.14 to help identify the specific mathematical formulations used in the models. Figure 5.14 also shows linkages to the other significant processes needed to estimate the annual TEDE for the residential scenario. The double-lined boxes in Figure 5.14 show linkages to the other pathways considered in the residential scenario.

The assumptions for evaluation of these pathways are as follows:

- The concentration of radionuclides in irrigation water (and animal drinking water) is constant over the year of irrigation (i.e., an average water concentration is used).
- Material deposited onto plant surfaces is removed at a constant weathering half-time.
- Radionuclide concentrations in soils are continuously in equilibrium with radionuclide concentrations in edible portions of the plants grown in the soil.
- Animals take in soil while grazing. The intake amount is a constant fraction of the forage intake rate, Q_f.
- Stored feeds are used for animal feed as soon as they are harvested. Feeding continues after harvest during the stored-feed feeding period.
- The concentration in animal products is immediately in equilibrium with the concentration in intake (feed, water, and soil).
- Animal products are harvested (e.g., milked, slaughtered, or eggs gathered) continuously over the feeding period and then distributed for human consumption.
- The harvested animal products are held for a short time before being consumed by humans.

Animal products may be contaminated when the animal eats crops (forage or stored feeds) produced using contaminated irrigation water. Each of these crop types may be contaminated by direct deposition of water onto leaves, or from deposition onto soil with uptake via roots and resuspension. These routes of animal feed contamination are described below.

5.4.2.1 Irrigation Water-Forage-Animal-Human Pathway

Figure 5.15 illustrates the variation with time of the relative parent radionuclide concentration in irrigation water, forage plants, animal products, and consumed plants for the water-forage plant-animal-human pathway. As before, the

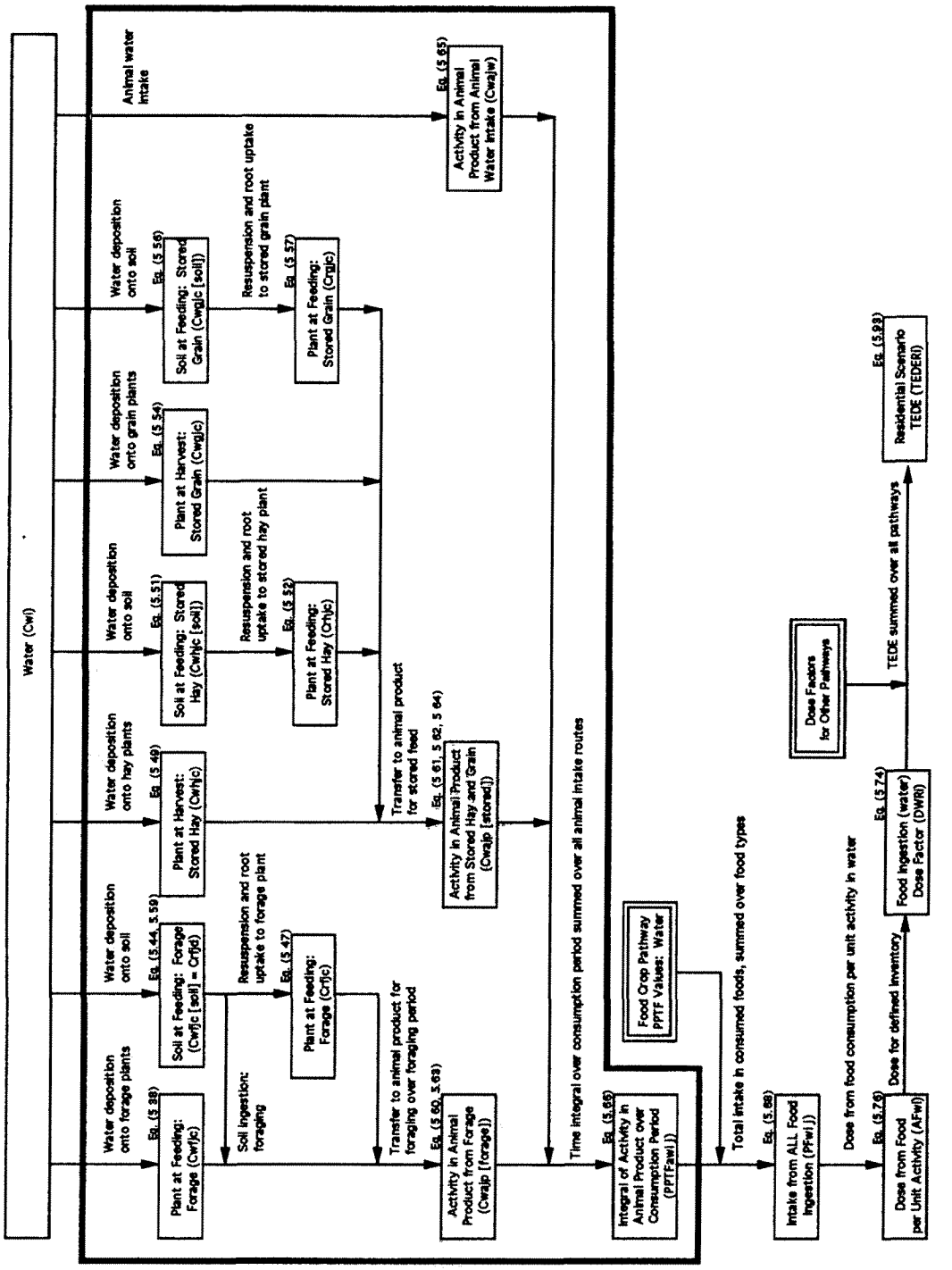


Figure 5.14 Water-plant-animal-human pathway and water-soil-plant-animal-human pathway

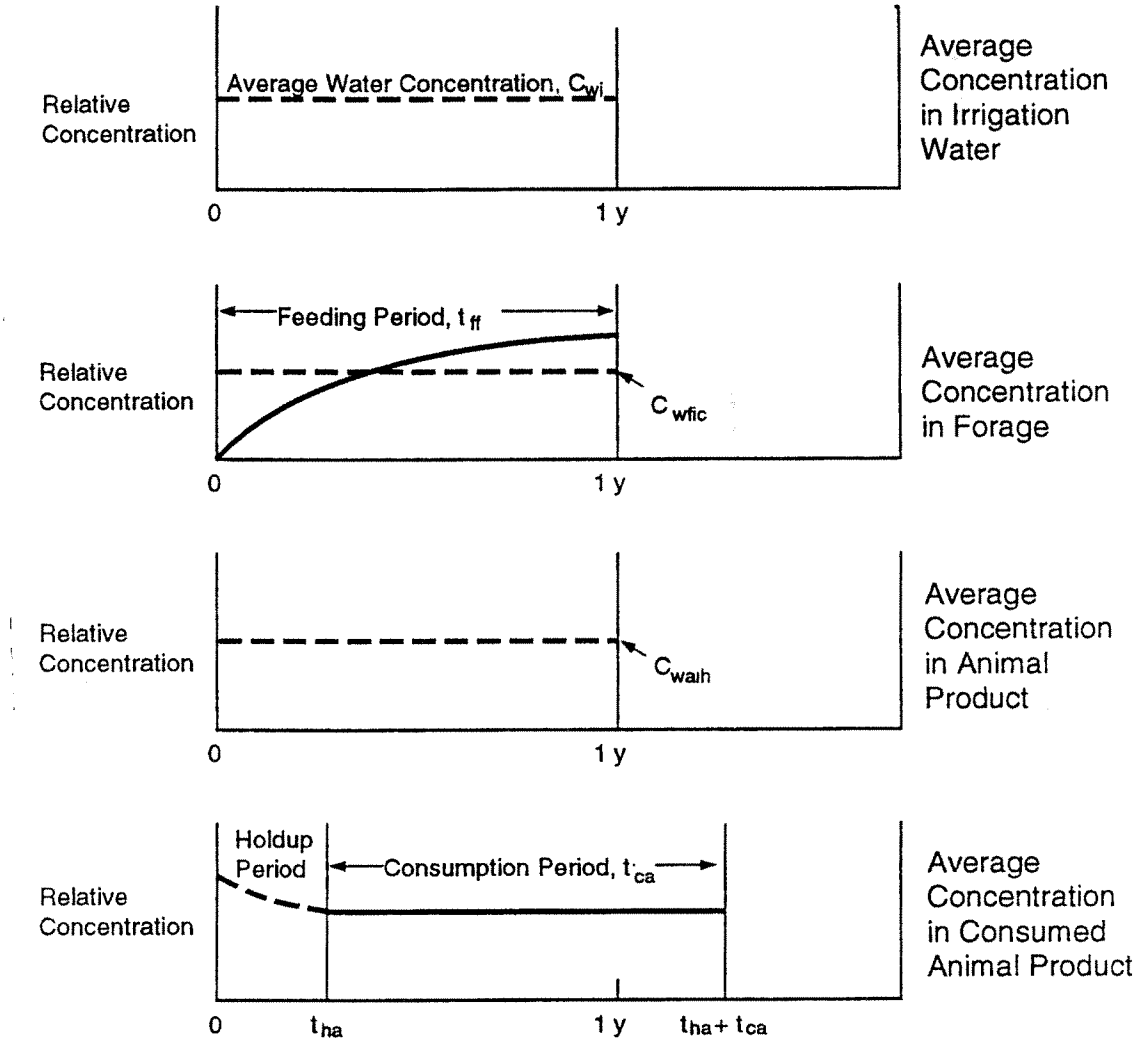


Figure 5.15 Change in relative concentrations over time for irrigation water, forage, animal products, and human foods from deposition of irrigation water on animal forage

water concentration is constant over the year of exposure. The differential equation defining the radionuclide concentration in forage plants is the same as Equation (5.21) for food crops. The constant deposition rate of radionuclide j to forage plants is evaluated according to Equation (5.22) with parameters defined for the forage crop:

$$R_{wfjf} = IR\ r_f\ T_f / Y_f \left[C_{wj} / C_{wi}\right] \tag{5.37}$$

where R_{wfjf} = average deposition rate of parent radionuclide j to forage crop f from application of irrigation water during the feeding period for an average unit concentration of parent radionuclide i in water (pCi/d•kg wet-weight plant per pCi/L water)

C_{wi} = average annual concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water)

C_{wj} = average annual concentration of radionuclide j in irrigation water over the current annual period (pCi/L water)

IR = annual average application rate of irrigation water ($L/m^2 \cdot d$)

r_f = fraction of initial deposition of radionuclides in water retained on the plant (pCi retained per pCi deposited)

T_f = translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant (pCi in edible plant part per pCi retained)

Y_f = yield of forage crop f (kg wet-weight plant/m^2).

The concentration of radionuclides in forage feed is evaluated as an average over the consumption period because the animals are assumed to graze continuously over the consumption period. The evaluation of the average radionuclide concentration in forage involves integrating the concentration in the plants over the time period, and then dividing the result by the feeding period. This average value is then used to estimate the concentration of radionuclides in the animal product. Evaluating the radionuclide concentration in plants involves the solution to Equation (5.21) for deposition, accumulation, and time integration of the resulting plant concentration, C_{wfjc}. The general solution is indicated in operator notation as follows:

$$C_{wfjc} = G_e \left\{R_{wfjf},\ t_{ff}\right\} / t_{ff} \tag{5.38}$$

where C_{wfjc} = average concentration factor for radionuclide j in forage crop f at time of animal consumption from direct deposition onto plant surfaces for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

t_{ff} = period of feeding of forage crop f (d)

$G_e\{R_{wfjf}, t_{ff}\}$ = operator notation used to develop the deposition, accumulation, and time integration of the concentration of radionuclide j in forage crop f over the animal forage consumption period for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

and other terms are as previously defined. The operator $G_e\{\}$ represents the deposition, accumulation, and time integration of the concentration over the forage-feeding period with continuous deposition and weathering.

For parent and first progeny radionuclides, the concentrations in forage plants from direct deposition onto plant surfaces are represented by the following two equations:

for the parent radionuclide,

$$C_{wf1c} = R_{wf1f} \left\{t_{ff} - \left[1 - e^{-\lambda_{e1} t_{ff}}\right] / \left(\lambda_{e1}\right)\right\} / \left(t_{ff}\, \lambda_{e1}\right) \tag{5.39}$$

and for decay-chain-member radionuclides, noting that the average concentration and deposition rate for the progeny in irrigation water are zero,

$$C_{wf2c} = \frac{d_{12}\lambda_{r2}R_{wf1f}}{\lambda_{r2} - \lambda_{r1}}\left[t_{ff} - \frac{1 - e^{-\lambda_{e1}t_{ff}}}{\lambda_{e1}}\right] / (\lambda_{e1}t_{ff}) - \frac{d_{12}\lambda_{r2}R_{wf1f}}{\lambda_{r2} - \lambda_{r1}}\left[t_{ff} - \frac{1 - e^{-\lambda_{e2}t_{ff}}}{\lambda_{e2}}\right] / (\lambda_{e2}t_{ff}) \quad (5.40)$$

where the terms are as previously defined with subscripts 1 and 2 referring to the parent and first progeny in the decay chain, respectively.

As described above and in Section B.5, the deposition, accumulation and time-integral operator, $G_e\{\}$, involves two steps: solution of the differential equation for plant concentration, Equation (5.21), followed by a time integration over the period of interest. The solution to the differential equation is equivalent to the deposition-accumulation operator, $R_e\{\}$, for accumulation with removal. The solution can be written for a parent radionuclide for any time t as follows:

$$C_{wf1t} = R_{wf1f}\left[\frac{1 - e^{-\lambda_{e1}t}}{\lambda_{e1}}\right] \quad (5.41)$$

where C_{wf1t} = concentration factor for the parent radionuclide in forage crop f at any time t after beginning of irrigation deposition for an average unit concentration of parent radionuclide in water (pCi/kg wet-weight plant per pCi/L water)

and other terms are as previously defined. The average concentration factor is evaluated as the time integral of plant concentration divided by the forage-crop feeding period. This calculation can be represented in operator notation as follows:

$$C_{wfjc} = \frac{1}{t_{ff}}\int_0^{t_{ff}} R_e\{R_{wfjf}, t\}dt = \frac{1}{t_{ff}}G_e\{R_{wfjf}, t_{ff}\} \quad (5.42)$$

where terms are as previously defined. Evaluation of this equation for the parent and first progeny is shown above in Equation (5.39) and (5.40).

5.4.2.2 Irrigation Water-Soil-Forage-Animal-Human Pathway

Figure 5.16 illustrates the time variation of the relative parent radionuclide concentration in water, soil, forage plants, animal products, and food eaten by humans for the water-soil-forage-animal-human pathway. Radionuclides that enter the soil via irrigation water are assumed to be contained in the top 15-cm soil layer (i.e., the top box of the three-box water-use model described in Section 5.6.6 and Appendix B). This activity will be available for immediate root uptake and resuspension to forage plants. The differential equation describing the change in radionuclide concentration in soil from irrigation deposition is given by Equation (5.26). The average deposition rate to soil is evaluated as follows (as in Equation [5.27]):

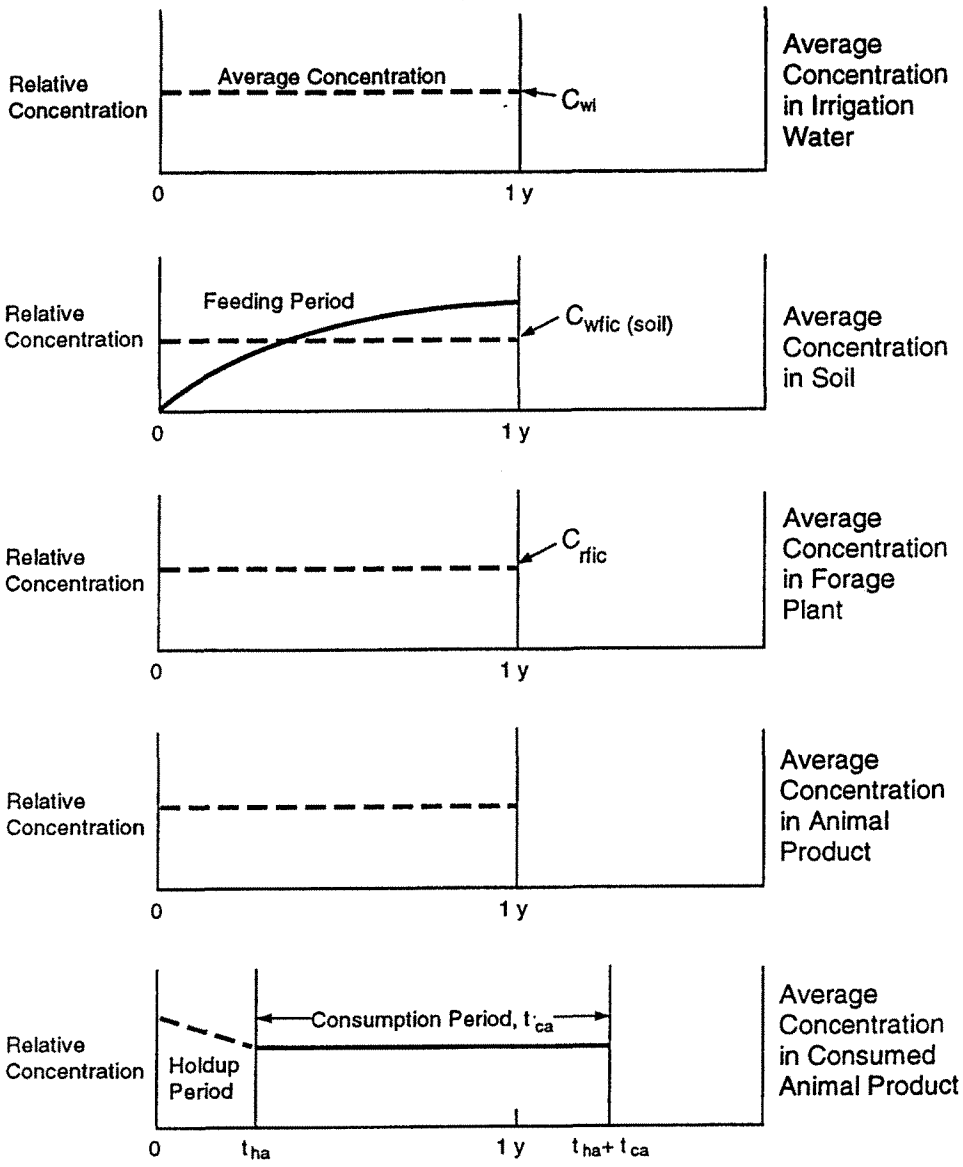


Figure 5.16 Change in relative concentrations over time for irrigation water, soil, forage, animal products, and human foods from deposition of irrigation water on soil with subsequent resuspension and root uptake to forage plants

$$R_{wsjf} = IR / P_s \left[C_{wj} / C_{wi}\right] \tag{5.43}$$

where R_{wsjf} = average deposition rate of radionuclide j to soil from irrigation water application onto the soil during the feeding period for an average unit concentration of parent radionuclide i in water (pCi/d•kg dry-weight soil per pCi/L water)

C_{wi} = average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water)

C_{wj} = average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water)

IR = annual average application rate of irrigation water (L/m^2•d)

P_s = areal soil density (kg dry-weight soil/m^2).

The radionuclide concentration in forage plants (averaged over the animal feeding period) from irrigation-water deposition and uptake from soil by forage plants is evaluated from the average soil concentration. The general equation using the deposition, accumulation, and time integration notation is

$$C_{wfjc(soil)} = G\left\{R_{wsjf}, t_{ff}\right\} / t_{ff} \tag{5.44}$$

where $C_{wfjc(soil)}$ = average concentration factor for radionuclide j in soil at time of animal consumption of forage crop f for an average unit concentration of parent radionuclide i in water (pCi/kg dry- weight soil per pCi/L water)

$G\{R_{wsjf},t_{ff}\}$ = operator notation used to develop the deposition, accumulation, and time integration of the concentration of radionuclide j in soil over the animal consumption period of forage crop f for an average concentration of parent radionuclide i in water (pCi/kg dry-weight soil per pCi/L water)

and other terms are as previously defined.

Explicit equations can be written for the parent radionuclide as follows:

$$C_{wf1c(soil)} = R_{ws1f}\left\{t_{ff} - \left[1 - e^{-\lambda_{r1} t_{ff}}\right] / \lambda_{r1}\right\} / \left(\lambda_{r1}\, t_{ff}\right) \tag{5.45}$$

and for the first progeny radionuclides,

$$\begin{aligned} C_{wf2c(soil)} = {} & \frac{d_{12}\,\lambda_{r2}\,R_{ws1f}}{\lambda_{r2} - \lambda_{r1}}\left[t_{ff} - \frac{1 - e^{-\lambda_{r1} t_{ff}}}{\lambda_{r1}}\right] / \left(\lambda_{r1} t_{ff}\right) \\ & - \frac{d_{12}\,\lambda_{r2}\,R_{ws1f}}{\lambda_{r2} - \lambda_{r1}}\left[t_{ff} - \frac{1 - e^{-\lambda_{r2} t_{ff}}}{\lambda_{r2}}\right] / \left(\lambda_{r2} t_{ff}\right) \end{aligned} \tag{5.46}$$

where terms are as previously defined, with subscripts 1 and 2 referring to the parent and first progeny in the decay chain, respectively.

The average concentration of radionuclides in forage during the forage-feeding period is evaluated from the average concentration of radionuclides in soil over the feeding period. The evaluation is made using the forage plant concentration factor as follows:

$$C_{rfjc} = \left(ML_f + B_{jf}\right) W_f \, C_{wfjc\,(soil)} \tag{5.47}$$

where C_{rfjc} = average concentration factor for radionuclide j in forage crop f at time of forage feeding, resulting from resuspension and root uptake from soil for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight forage per pCi/L water)

B_{jf} = concentration factor for uptake of radionuclide j from soil in forage crop f (pCi/kg dry-weight forage per pCi/kg dry-weight soil)

ML_f = plant soil mass-loading factor for resuspension of soil to forage plant f (pCi/kg dry-weight forage per pCi/kg dry soil)

W_f = factor for conversion of mass of forage crop f from a dry-weight to a wet-weight basis (kg dry- weight forage per kg wet-weight forage)

and C_{wfjc} is as previously defined. Equation (5.47) applies to all members of the decay chain including the parent.

5.4.2.3 Irrigation Water-Stored Hay-Animal-Human Pathway

Figure 5.17 illustrates the time variation of relative parent radionuclide concentration in irrigation water, stored hay plants, animal products, and food eaten by humans for the water-stored hay-animal-human pathway. For this pathway, the radionuclide concentration in stored hay is derived from radionuclides in irrigation water deposited on stored hay plant surfaces. The concentration at stored hay harvest is evaluated for a constant deposition rate of radionuclides from irrigation water onto the hay crop. Loss by weathering from plant surfaces is considered. The stored hay is fed to the animal over a feeding period that begins immediately after harvest and continues for the feeding period. The differential equation describing the change in radionuclide concentration in stored hay plants from irrigation deposition is analogous to Equation (5.21). The average deposition rate of radionuclide j to stored hay plants is evaluated as follows (per Equation [5.22]):

$$R_{whjg} = IR \; r_h \; T_h / Y_h \left[C_{wj} / C_{wi}\right] \tag{5.48}$$

where R_{whjg} = average deposition rate of radionuclide j to stored hay crop h from irrigation water application for an average unit concentration of parent radionuclide i in water (pCi/d•kg wet-weight plant per pCi/L water)

C_{wi} = average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water)

C_{wj} = average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water)

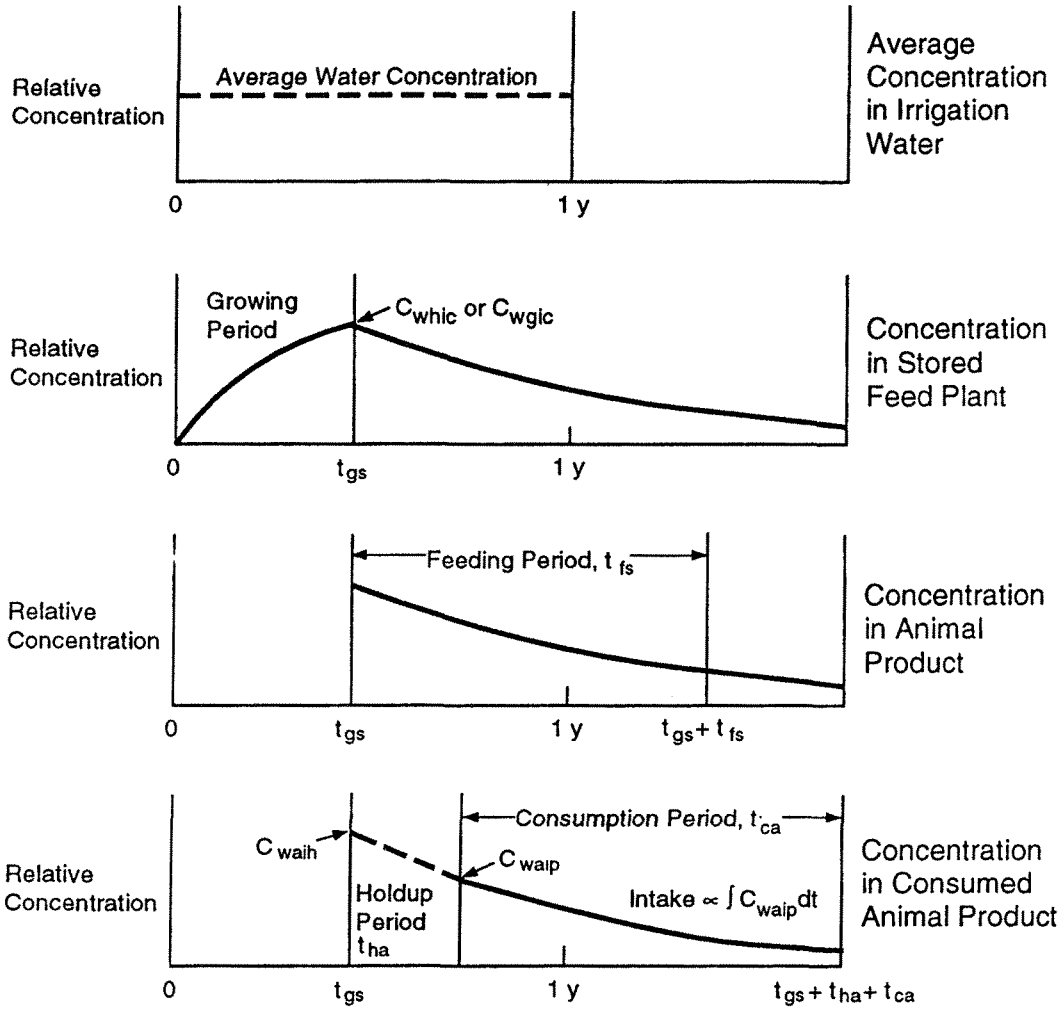


Figure 5.17 Change in relative concentrations over time for irrigation water, stored feed, animal products, and human food from deposition of irrigation water on stored feed plants

IR = annual average application rate of irrigation water ($L/m^2 \cdot d$)

r_h = fraction of initial deposition of radionuclides in water retained on plant h (pCi retained per pCi deposited)

T_h = translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant (pCi in edible plant parts per pCi retained)

Y_h = yield of stored hay crop h (kg wet-weight plant/m^2).

The concentration of radionuclides in stored hay crops from deposition onto plant surfaces at the time of animal initial feeding is evaluated using Equation (5.23) with parameters defined for stored hay plants:

$$C_{whjc} = R_e\left\{R_{whjg},\ t_{gh}\right\} \tag{5.49}$$

where C_{whjc} = concentration factor for radionuclide j in stored hay crop h at initial time of consumption by animal, from deposition onto plant surfaces for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

t_{gh} = growing period of stored hay type h (d)

$R_e\{R_{whjg},t_{gh}\}$ = deposition, accumulation operator notation used to develop the concentration factor for radionuclide j in stored hay crop h at the initial time of harvest, from irrigation water deposition onto plants for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

and other terms are as previously defined. Explicit equations for the parent and first progeny have the same form as the example equations shown in Section 5.4.1.1 (Equations [5.24] and [5.25]. A detailed description of the operator notation is given in Section 2 and Appendix B.

5.4.2.4 Irrigation Water-Soil-Stored Hay-Animal-Human Pathway

As with the water-soil-food crop-human pathway, the deposition from irrigation water is assumed to transfer to soil with subsequent uptake via resuspension and through roots to plants. Figure 5.18 illustrates the time variation of relative parent radionuclide concentrations for this pathway. The differential equation describing the time rate of change of radionuclide concentrations in soil is given by Equation (5.26). The constant deposition rate for a radionuclide to soil is evaluated according to Equation (5.27) with parameters defined for stored hay plants. The deposition rate of radionuclides to soil is evaluated as follows:

$$R_{wsjg} = IR / P_s \left[C_{wj} / C_{wi}\right] \tag{5.50}$$

where R_{wsjg} = average deposition rate of radionuclide j to soil from irrigation water application onto the soil during the crop-growing period for stored hay for an average unit concentration of parent radionuclide i in water (pCi/d•kg dry-weight soil per pCi/L water)

C_{wi} = average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water)

C_{wj} = average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water)

IR = annual average application rate of irrigation water (L/m^2•d)

P_s = areal soil density (kg dry-weight soil/m^2).

The concentration of radionuclides in soil at the time of stored hay crop harvest (beginning of feed consumption by animals) is evaluated as the solution to Equation (5.26) with the deposition rate defined by Equation (5.50) as follows:

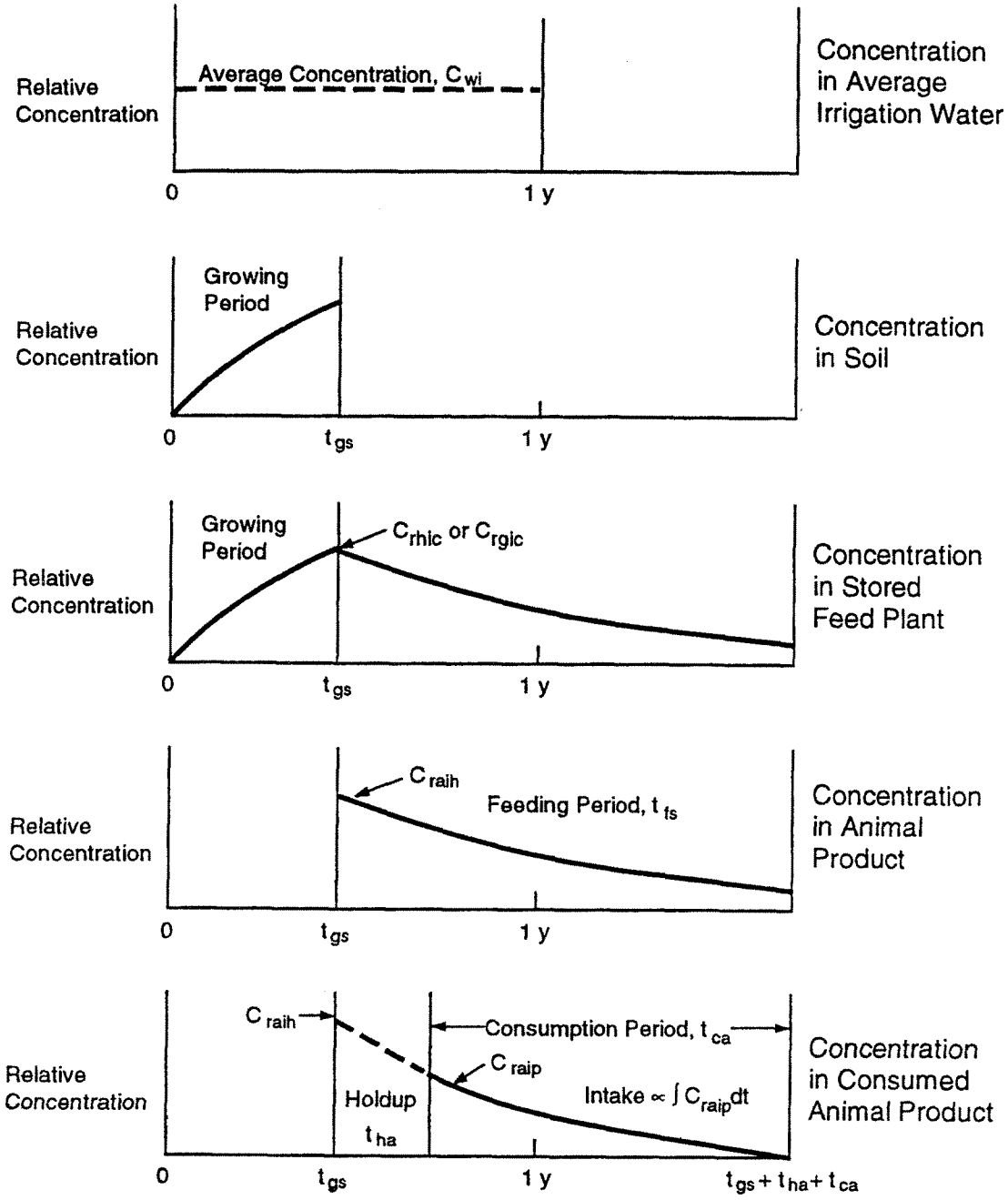


Figure 5.18 Change in relative concentrations over time for irrigation water, soil, stored feed, animal products, and human foods from deposition of irrigation water on soil with subsequent resuspension and root uptake by stored feed crops

$$C_{whjc(soil)} = R\left\{R_{wsjg},\ t_{gh}\right\} \tag{5.51}$$

where $C_{whjc(soil)}$ = concentration factor for chain member j in soil at time of initial animal consumption of stored hay crop h, for an average concentration of parent radionuclide in water (pCi/kg dry-weight soil per pCi/L water)

t_{gh} = growing period of stored hay crop h (d)

$R\{R_{wsjg},t_{gh}\}$ = deposition, accumulation operator used to develop the concentration factor for chain member j in soil at time of initial animal consumption of stored hay crop h, for an average concentration of parent radionuclide in water (pCi/kg dry-weight soil per pCi/L water)

and other terms are as previously defined. Explicit equations for the parent and first progeny can be written in a similar manner as shown in the example equations of Section 5.4.1.2 (Equations [5.29] and [5.30]).

The concentration of radionuclides in stored hay plants at the time of harvest (initial feeding to animals) is evaluated from the concentration of radionuclides in soil at the time of harvest. The evaluation is made using the stored hay crop concentration factor as follows:

$$C_{rhjc} = \left(ML_h + B_{jh}\right) W_h\ C_{whjc(soil)} \tag{5.52}$$

where C_{rhjc} = concentration factor for radionuclide j in stored hay crop h at time of initial feeding to animals (harvest), resulting from root uptake and resuspension for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

B_{jh} = concentration factor for uptake of radionuclide j from soil in stored hay crop h (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

ML_h = plant soil mass-loading factor for resuspension of soil to stored hay plant h (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

W_h = factor for conversion of mass of stored hay crop h from a dry-weight to a wet-weight basis (kg dry-weight hay per kg wet-weight hay)

and other terms are as previously defined. Equation (5.52) applies to all members of the decay chain for parent radionuclide i, including the parent.

5.4.2.5 Irrigation Water-Stored Grain-Animal-Human Pathway

This exposure pathway is analogous to the pathway involving stored hay described in Section 5.4.2.3. The time variation of relative parent radionuclide concentration in irrigation water, stored grain plants, animal products, and food eaten by humans for this pathway is as shown in Figure 5.17. The concentration of radionuclides in stored grain plants at harvest is evaluated assuming a constant deposition rate of radionuclides from irrigation water onto the grain crop during the growing season. Loss of activity from plant surfaces by weathering is considered. The stored grain is fed to the animals over a feeding period that begins immediately after harvest and continues for the feeding period.

The time rate of change of radionuclide concentration in stored grain plants is as described by Equation (5.21) for deposition onto food crop plants. The average deposition rate of radionuclides from irrigation water to plants is described by Equation (5.48) with subscript "h" for hay replaced by subscript "g" for grain, as follows:

$$R_{wgjg} = IR\ r_g\ T_g / Y_g \left[C_{wj} / C_{wi}\right] \tag{5.53}$$

where R_{wgjg} = average deposition rate of radionuclide j to stored grain crop g from irrigation water application for an average unit concentration of parent radionuclide i in water (pCi/d•kg wet-weight plant per pCi/L water)

C_{wi} = average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water)

C_{wj} = average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water)

IR = annual average application rate of irrigation water (L/m^2•d)

r_g = fraction of initial deposition of radionuclides in water retained on grain plant g (pCi retained on plants per pCi deposited)

T_g = translocation factor for transfer of radionuclides from plant surfaces to edible parts of grain plant g (pCi in edible plant parts per pCi retained on plant)

Y_g = yield of stored grain crop g (kg wet-weight plant/m^2 of land)

The concentration of radionuclides in stored grain crops from deposition onto plant surfaces at the time of animal consumption is evaluated by using Equation (5.23) but with parameters defined for stored grain plants:

$$C_{wgjc} = R_e \left\{R_{wgjg}, t_{gg}\right\} \tag{5.54}$$

where C_{wgjc} = concentration factor for radionuclide j in stored grain crop g at initial time of animal consumption, from deposition onto grain plant surfaces for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

t_{gg} = growing period of stored grain type g (d)

$R_e\{R_{wgjg}, t_{gg}\}$ = deposition, accumulation operator representing the concentration factor for radionuclide j in stored grain crop g at the initial time of harvest, from deposition of irrigation water onto plants for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

and other terms are as previously defined. Explicit equations for the parent and first progeny radionuclides can be written as shown in the example equations in Section 5.4.1.1 (Equations [5.24] and [5.25]).

5.4.2.6 Irrigation Water-Soil-Stored Grain-Animal-Human Pathway

This exposure pathway is analogous to the pathway involving stored hay described in Section 5.4.2.4. The time variation of relative parent radionuclide concentration in irrigation water, soil, stored grain plants, animal products, and food eaten by humans for this pathway is as shown in Figure 5.18. The differential equation describing the time rate of change of radionuclide concentrations in soil is given by Equation (5.26). The constant deposition rate for a radionuclide to soil is evaluated according to Equation (5.27) with parameters defined for stored grain plants:

$$R_{wsjg} = IR / P_s \left[C_{wj} / C_{wi} \right] \tag{5.55}$$

where R_{wsjg} = average deposition rate of radionuclide j to soil from irrigation water application for an average unit concentration of parent radionuclide i in water (pCi/d•kg dry-weight soil per pCi/L water)

C_{wi} = average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water)

C_{wj} = average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water)

IR = annual average application rate of irrigation water (L/m^2•d).

The concentration of radionuclides in soil at the time of stored grain crop harvest is evaluated using Equation (5.51) with parameters defined for the stored grain feed type as follows:

$$C_{wgjc\,(soil)} = R\left\{ R_{wsjg}, t_{gg} \right\} \tag{5.56}$$

where $C_{wgjc(soil)}$ = concentration factor for radionuclide j in soil at time of initial animal consumption of stored grain crop g, from irrigation water applied to soil for an average unit concentration of parent radionuclide i in water (pCi/kg dry-weight soil per pCi/L water)

t_{gg} = growing period of stored grain type g (d)

$R\{R_{wsjg}, t_{gg}\}$ = deposition, accumulation operator representing the concentration factor for radionuclide j in soil at time of initial animal consumption of stored grain crop g, from irrigation water applied to soil for an average unit concentration of parent radionuclide i in water (pCi/kg dry-weight soil per pCi/L water)

and other terms are as previously defined.

The concentration of radionuclides in stored grain plants from resuspension and root uptake at the time of harvest (initial feeding to animals) is evaluated from the concentration of radionuclides in soil at the time of harvest. The evaluation is made using Equation (5.52) with parameters defined for the stored grain crop as follows:

$$C_{rgjc} = \left[ML_g + B_{jg} \right] W_g C_{wgjc\,(soil)} \tag{5.57}$$

where C_{rgjc} = concentration factor for radionuclide j in stored grain crop g at time of initial feeding to animals (harvest), resulting from resuspension and root uptake for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

B_{jg} = concentration ratio for uptake of radionuclide j from soil in stored grain crop g (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

ML_g = plant soil mass-loading factor for resuspension of soil to stored grain plant g (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

W_g = factor for conversion of mass of stored grain crop g from a dry-weight to a wet-weight basis (kg dry-weight grain per kg wet-weight grain)

and other terms are as previously defined. Equation (5.57) applies to all members of the decay chain including the parent.

5.4.2.7 Irrigation Water-Soil-Animal-Human Pathway

This pathway results from animal ingestion of soil while grazing on fresh forage. The differential equation for the soil concentration given in Equation (5.26) applies to this pathway. Animal intake of soil while grazing is evaluated for a constant deposition rate to soil. The amount of soil ingestion by the animal is evaluated as a constant fraction of the animal intake of forage over the forage-feeding period. The deposition onto soil is evaluated as defined in Equation (5.43) and is represented as follows:

$$R_{wsjf} = IR \,/\, P_s\left[C_{wj}/C_{wi}\right] \tag{5.58}$$

where R_{wsjf} is the average deposition rate of radionuclide j to soil from irrigation water application onto soil during forage-feeding period for an average unit concentration of parent radionuclide i in water (pCi/d•kg dry-weight soil per pCi/L water) and other terms are as previously defined.

The average concentration in soil eaten by animals over the forage period is evaluated as the time integral of the soil concentration over the forage-feeding period, divided by the feeding period. The average soil concentration is evaluated according to Equation (5.44) using terms for ingestion of soil by animals:

$$C_{rfjd} = G\left\{R_{wsjf},\, t_{ff}\right\} / t_{ff} \tag{5.59}$$

where C_{rfjd} = average concentration factor for radionuclide j in soil eaten by animals during the forage period for crop f for an average unit concentration of parent radionuclide i in water (pCi/kg dry-weight soil per pCi/L water)

$G\{R_{wsjf},t_{ff}\}$ = operator notation used to develop the deposition, accumulation, and time integral of the transfer rate to soil for radionuclide j over the forage-feeding period for an average unit concentration of parent radionuclide i in water (pCi•d/kg dry-weight soil per pCi/L water)

and other terms are as previously defined. Explicit equations can be written for the parent and first progeny radionuclides as shown in Section 5.4.2.2 (Equations [5.45] and [5.46]).

5.4.2.8 Calculation of PPTFs for Animal Products Contaminated by Irrigation Water

The PPTFs for animal products involve summation of contributions for animal intake of forage crops (including soil ingestion), stored feed crops, and water (feeding contaminated irrigation water directly to animals). The concentration of radionuclides in forage crops (determined by Equations [5.38], [5.47], and [5.59]) are average concentrations over the feeding period. The radionuclide concentration in animal products is assumed to be in equilibrium with animal intake of these plant concentrations at all times during the feeding period. The concentration in animal products is, therefore, also constant (average) over the feeding period, evaluated as follows:

$$C_{wajh\,(forage)} = F_{aj}\, Q_f\, x_f \left[C_{wfjc} + C_{rfjc} + Q_d\, W_f\, C_{rfjd}\right] \tag{5.60}$$

where $C_{wajh(forage)}$ = average concentration at time of fresh forage intake by animal product a, for radionuclide j, for irrigation water pathway for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight animal product per pCi/L water)

F_{aj} = transfer factor that relates the concentration in an edible animal product a, to the daily intake in animal feed (stored, fresh forage, soil, or water) (pCi/L per pCi/d for milk, and pCi/kg wet-weight animal product per pCi/d for other animal products)

Q_d = fractional soil intake of fresh forage intake (kg dry-weight soil per kg dry-weight forage)

Q_f = consumption rate of fresh forage by the animal (kg wet-weight plant/d)

x_f = fraction of forage intake that is contaminated

and other terms are as previously defined.

The concentration of radionuclides in stored feed crops (determined in Equations [5.49], [5.52], [5.54], and [5.57]) represents the concentration at the beginning of the animal feeding period. The concentration in animal product at the beginning of the feeding period (instantaneous equilibrium between feed and animal product) is evaluated as the sum of the contributions from the direct deposition to plants and the root-uptake pathways:

$$C_{wajc\,(stored)} = F_{aj}\left[Q_h\, x_h\left(C_{whjc} + C_{rhjc}\right) + Q_g\, x_g\left(C_{wgjc} + C_{rgjc}\right)\right] \tag{5.61}$$

where $C_{wajc(stored)}$ = concentration factor at beginning of stored feed intake by animal product a, for radionuclide j, for irrigation water pathway for an initial unit concentration of parent radionuclide i in water (pCi/kg wet-weight animal product per pCi/L water)

Q_h = consumption rate of stored hay by the animal (kg wet-weight plant/d)

Q_g = consumption rate of stored grain by the animal (kg wet-weight plant/d)

x_h = fraction of stored hay intake that is contaminated

x_g = fraction of stored grain intake that is contaminated

and other terms are as previously defined.

The animal product concentration at the beginning of the feeding period (time of harvest) is equal to $C_{wajc(stored)}$:

$$C_{wajh\,(stored)} = C_{wajc\,(stored)} \tag{5.62}$$

The radionuclide concentration at harvest in animal products will change during the holdup period between harvest and consumption by humans. The change is represented as follows for the forage pathway:

$$C_{wajp\,(forage)} = A\left\{C_{wajh\,(forage)},\ t_{ha}\right\} \tag{5.63}$$

and for the stored-feed pathway,

$$C_{wajp\,(stored)} = A\left\{C_{wajh\,(stored)},\ t_{ha}\right\} \tag{5.64}$$

where $C_{wajp(forage)}$ = average concentration factor over the consumption period by humans of animal product a, for radionuclide j, for irrigation water pathway via forage crops for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight animal product per pCi/L water)

$C_{wajp(stored)}$ = concentration factor at initial time of consumption by humans of animal product a, for radionuclide j, for irrigation water pathway via stored feed crops for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight animal product per pCi/L water)

$A\{C_{wajh(forage)}, t_{ha}\}$ = decay operator notation used to develop the average concentration factor over the consumption period by humans of animal product a, for radionuclide j, for irrigation water pathway via forage crops for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight animal product per pCi/L water)

$A\{C_{wajh(stored)}, t_{ha}\}$ = decay operator notation used to develop the concentration factor at initial time of consumption period by humans of animal crop a, for radionuclide j, for irrigation water pathway via stored feed crops for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight animal product per pCi/L water)

and other terms are as previously defined.

The contribution to animal product concentration from animal intake of irrigation water over the consumption period is evaluated as follows:

$$C_{wajw} = F_{aj}\ Q_w\ x_w\left[C_{wj}/C_{wi}\right] \tag{5.65}$$

where C_{wajw} is the average concentration factor from animal ingestion of water at the time of harvest of animal product v for animal ingestion of water for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight animal product per pCi/L water), Q_w is the consumption rate of water by the animal (L/d), and x_w is the fraction of water intake that is contaminated.

The total PPTF for animal products is evaluated as follows:

$$PPTF_{awij} = \left[t_{ca}\ C_{wajp\,(forage)} + S\{C_{wajp\,(stored)}, t_{ca}\} + t_{ca}\ A\left\{C_{wajw}, t_{ha}\right\}\right]/365.25 \quad (5.66)$$

where $PPTF_{awij}$ = partial pathway transfer factor for irrigation pathway for animal product a, for radionuclide j as a progeny of radionuclide i, for an average unit concentration of parent radionuclide i in water (pCi•y/kg wet-weight animal product per pCi/L water for a year of residential scenario)

$A\{C_{wajw}, t_{ha}\}$ = decay operator notation used to develop the concentration factor for animal product a for an average unit concentration of parent radionuclide i in water from animal intake of water at the time of consumption by humans for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight animal product per pCi/L water)

$S\{\}$ = time-integral operator used to develop the concentration factor for radionuclide j concentration in animal product v over the consumption period by humans for an average unit concentration of parent radionuclide i in water (pCi•d/kg wet-weight animal product per pCi/L water)

t_{ca} = consumption period of animal product a by humans (d for a year of residential scenario)

and other terms are as previously defined.

5.5 Calculation of Pathway Transfer Factors

The PFs include the daily consumption rate of specific foods in an individual's diet and the radionuclide concentration in those foods as determined by the PPTFs. The PFs are evaluated for unit concentration in soil at the beginning of the growing season and unit concentration in irrigation water averaged over the year of exposure.

The PF for initial unit concentration of a parent radionuclide in soil is evaluated as follows:

$$PF_{sij} = \sum_{v=1}^{N_v} U_v\ PPTF_{vsij} + \sum_{a=1}^{N_a} U_a\ PPTF_{asij} \quad (5.67)$$

where PF_{sij} = agricultural pathway transfer factor for radionuclide j as a progeny of radionuclide i per unit initial concentration of parent radionuclide i in soil (pCi ingested per pCi/g dry-weight soil for a year of residential scenario)

$PPTF_{vsij}$ = partial pathway transfer factor for food crop type v, radionuclide j as a progeny of radionuclide i, for unit average concentration of parent radionuclide i in soil (pCi•y/kg wet-weight food per pCi/g dry-weight soil for a year of residential scenario)

$PPTF_{asij}$ = partial pathway transfer factor for animal product type a, radionuclide j as a progeny of radionculide i, for unit average concentration of parent radionuclide i in soil (pCi•y/kg wet-weight food per pCi/g dry-weight soil for a year of residential scenario)

N_a = number of animal products considered in the diet

N_v = number of food crops considered in the diet

U_a = ingestion rate of animal product type a by an individual (kg wet-weight/y)

U_v = ingestion rate of food crop type v by an individual (kg wet-weight/y).

A similar expression is used to evaluate the PFs for unit average concentration of a parent radionuclide in irrigation water:

$$PF_{wij} = \sum_{v=1}^{N_v} U_v \, PPTF_{vwij} + \sum_{a=1}^{N_a} U_a \, PPTF_{awij} \tag{5.68}$$

where PF_{wij} = agricultural pathway transfer factor for radionuclide j as a progeny of radionuclide i per unit average concentration of parent radionuclide i in water (pCi ingested per pCi/L water for a year of residential scenario)

$PPTF_{vwij}$ = partial pathway transfer factor for food crop type v, radionuclide j as a progeny of radionuclide i, for unit average concentration of parent radionuclide i in water (pCi•y/kg wet-weight food per pCi/L water for a year of residential scenario)

$PPTF_{awij}$ = partial pathway transfer factor for animal product type a, radionuclide j as a progeny of radionuclide i, for unit average concentration of parent radionuclide i in water (pCi•y/kg wet-weight food per pCi/L water for a year of residential scenario)

and other terms are as previously defined. The food types and annual consumption rates are given in Section 6.

5.6 Calculation of Total Dose From Pathways for the Residential Scenario

Computing the dose for the agricultural pathways (ingestion) involves using the information provided by computation of the PPTFs and PFs. The TEDE for the residential scenario (designated as "TEDER") is obtained by adding the dose rates from the five primary pathways: external exposure, inhalation exposure, ingestion exposure without irrigation, ingestion exposure with contaminated irrigation water, and secondary soil ingestion.

5.6.1 External Dose for the Residential Scenario

For external exposure, the residential exposure scenario involves an individual who spends time at home--receiving exposure indoors, in leisure outdoors, and in gardening activities outdoors--and away from home, during which no exposure is received. The starting time for the scenario (when the unit concentration in soil is defined) is assumed to be at the start of the gardening season during the year of license termination. The external dose, designated "DEXR," involves the pathways to human exposure shown in Figure 5.19.

The external dose contribution is calculated as the sum of exposure during indoor and outdoor activities (i.e., gardening exposure + indoor exposure + outdoor exposure):

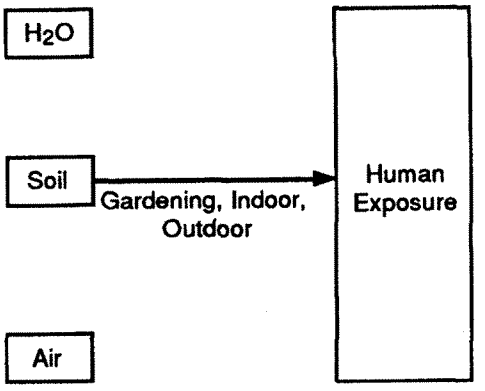


Figure 5.19 Residential scenario external dose pathway

$$DEXR_i = \left[24\left(t_g/t_{tg}\right) SFO\ C_{si} \sum_{j=1}^{J_i} S\left\{A_{stj},\ t_{tg}\right\} DFER_j\right] + \left[24\left(t_x/t_{tr}\right) SFO\ C_{si} \sum_{j=1}^{J_i} S\left\{A_{stj},\ t_{tr}\right\} DFER_j\right] + \left[24\left(t_i/t_{tr}\right) SFI\ C_{si} \sum_{j=1}^{J_i} S\left\{A_{stj},\ t_{tr}\right\} DFER_j\right] \quad (5.69)$$

where $DEXR_i$ = external dose from 1 year of residential scenario exposure to radionuclide i in soils (mrem for a year of residential scenario)

$DFER_j$ = external dose rate factor for radionuclide j for exposure to contamination uniformly distributed in the top 15 cm of residential soil (mrem/h per pCi/g)

A_{stj} = concentration factor for radionuclide j in soil at the beginning of the current annual exposure period per initial unit concentration of parent radionuclide i in soil at time of site release (pCi/g per pCi/g)

C_{si} = concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil)

SFI = shielding factor by which external dose rate is reduced during periods of indoor residence (dimensionless)

SFO = shielding factor by which external dose rate is reduced during periods of outdoor residence and gardening (dimensionless)

J_i = number of explicit members of the decay chain for parent radionuclide i

$S\{A_{stj},t_{tr}\}$ = time-integral operator used to develop the concentration time integral of radionuclide j for exposure over a 1-year period per unit initial concentration of parent radionuclide i in soil (pCi•d/g per pCi/g dry-weight soil)

$S\{A_{stj},t_{tg}\}$ = time-integral operator used to develop the concentration time integral of radionuclide j for exposure outdoors over one gardening season during 1-year period per unit initial concentration of parent radionuclide i in soil (pCi•d/g per pCi/g dry-weight soil)

t_g = time during the gardening period that the individual spends outdoors gardening (d for a year of residential scenario)

t_i = time in the 1-year exposure period that the individual spends indoors (d for a year of residential scenario)

t_x = time in the 1-year exposure period that the individual spends outdoors, other than gardening (d for a year of residential scenario)

t_{tg} = total time in the gardening period (d)

t_{tr} = total time in the residential exposure period (d)

24 = unit conversion factor (h/d).

The concentration time-integral factors, S{}, are evaluated for all radionuclides in a decay chain. The factors represent the time integral of concentration during the exposure period of interest.

The concentration factor, A_{stj}, defines the concentration of each radionuclide in soil in a decay chain at the beginning of the current year of the dose evaluation. The concentration includes material initially present in the soil, plus material that has migrated to ground water and been redeposited onto the farmland soil by irrigation with the contaminated water during the previous year. Evaluation of the concentration factor is described in Section 5.6.6.

5.6.2 Inhalation Dose for the Residential Scenario

Inhalation of resuspended soil dust (designated "DHR") also involves the three periods of exposure used for the external dose pathway (above), i.e., gardening, outdoor activities, and indoor activities. The indoor component includes contributions from material blown into the house (mass-loading method) and soil tracked into the house and suspended (resuspension factor method), as indicated in Figure 5.20 and the following expression:

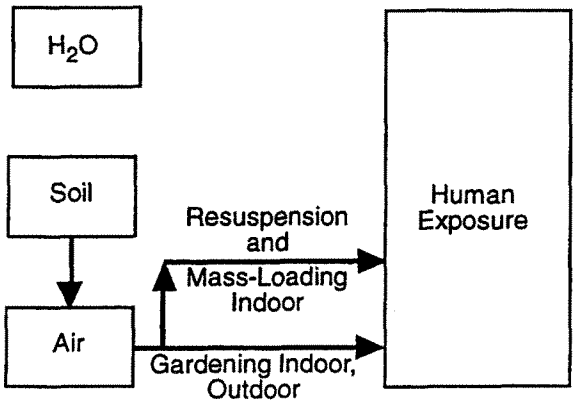


Figure 5.20 Residential scenario inhalation dose pathways

$$DHR_i = \left[24\ V_g \left(t_g/t_{tg}\right) CDG\ C_{si} \sum_{j=1}^{J_i} S\left\{A_{stj},\ t_{tg}\right\} DFH_j\right] + \left[24\ V_x \left(t_x/t_{tr}\right) CDO\ C_{si} \sum_{j=1}^{J_i} S\left\{A_{stj},\ t_{tr}\right\} DFH_j\right] + \left[24\ V_r \left(t_i/t_{tr}\right)\left(CDI + P_d RF_r\right) C_{si} \sum_{j=1}^{J_i} S\left\{A_{stj},\ t_{tr}\right\} DFH_j\right] \quad (5.70)$$

where DHR_i = inhalation committed effective dose equivalent from 1 year of residential activity (mrem for a year of residential scenario)

V_g = volumetric breathing rate for time spent gardening (m^3/h)

CDI = dust-loading for indoor exposure periods (g/m^3)

V_r = volumetric breathing rate for time spent indoors (m^3/h)

CDO = dust-loading for outdoor exposure periods (g/m^3)

CDG = dust-loading for gardening activities (g/m^3)

V_x = volumetric breathing rate for time spent outdoors (m^3/h)

DFH_j = inhalation committed effective dose equivalent factor for radionuclide j for exposure to contaminated air (in units of mrem per pCi inhaled)

P_d = indoor dust-loading on floors (g/m^2)

RF_r = indoor resuspension factor (m^{-1})

and other terms are as previously defined. A discussion of dust-loadings and resuspension is provided in Section 6. Evaluation of the concentration factor, A_{stj}, is described in Section 5.6.6.

5.6.3 Ingestion Dose for the Residential Scenario

This section describes the calculation of ingestion dose from agricultural products grown in contaminated soil and from secondary ingestion of soil. The pathway that involves ingestion of crops and animal products from deposition of resuspended soils on plant surfaces and root uptake (designated "DGR") is shown in Figure 5.21. The contribution to dose from this pathway is evaluated as follows:

$$DGR_i = C_{si}\ DIET \sum_{j=1}^{J_i} A_{stj}\ AF_{sj} \tag{5.71}$$

where DGR_i = ingestion committed effective dose equivalent from a 1-year intake of home-grown food and animal products (mrem for a year of residential scenario)

DIET = fraction of annual diet derived from home-grown foods (dimensionless)

AF_{sj} = committed effective dose equivalent factor for ingestion of agricultural product per unit concentration of radionuclide j in soil at the beginning of a growing season (mrem per pCi/g for a year of residential scenario)

C_{si} = initial concentration of parent radionuclide in soil at the time of release of the site, i.e., the start of growing season for the first year (pCi/g)

and other terms are as previously defined.

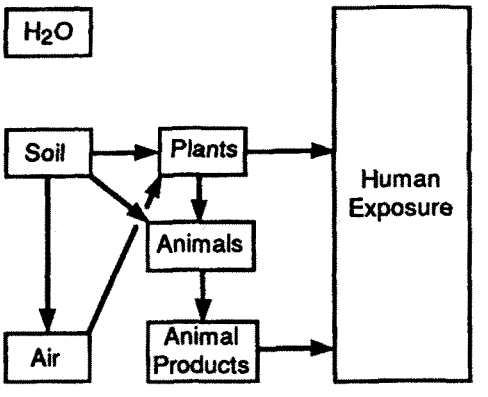


Figure 5.21 Residential scenario ingestion dose pathway for plants and animal products contaminated from soil

The agricultural product ingestion factor for soil (AF_{si}) is calculated from pathway transfer factors as follows:

$$AF_{si} = \sum_{j=1}^{J_i} PF_{sij}\ DFG_j \tag{5.72}$$

where PF_{sij} is the pathway transfer factor for agricultural products for soil for radionuclide j as a progeny of radionuclide i (pCi ingested per pCi/g dry-weight soil for a year of residential scenario) and DFG_j is the ingestion CEDE factor for radionuclide j (mrem per pCi ingested). Equation (5.72) is written to be applied to parent radionuclides (thus the subscript "i"). For progeny radionuclides of Equation (5.71), the AF_{sj} value is evaluated for progeny radionuclides as if for a parent of its own decay chain.

The dose from secondary (inadvertent) ingestion of soil or house dust is included in the residential scenario analysis. This pathway is shown in Figure 5.22. The individual is assumed to ingest soil at a constant rate over the duration of the scenario, t_{tr}. The dose is evaluated as follows:

$$DSR_i = GR\ C_{si} \sum_{j=1}^{J_i} DFG_j\ S\{A_{stj}, t_{tr}\} \tag{5.73}$$

where DSR_i = committed effective dose equivalent for radionuclide i from ingestion of soil (mrem for 1 year of residential scenario)

GR = effective transfer rate for ingestion of soil and dust transferred to the mouth (g/d)

$S\{A_{stj}, t_{tr}\}$ = time-integral operator used to develop the radionuclide j concentration in soil, over the residential exposure period for a unit initial concentration of parent radionuclide i in soil at the time of site release (pCi•d/g per pCi/g for 1 year of residential scenario)

and other terms are as previously defined.

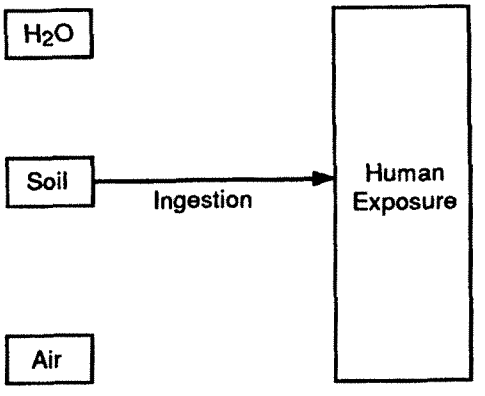


Figure 5.22 Residential scenario soil ingestion dose pathway

5.6.4 Irrigation and Drinking Water Dose for the Residential Scenario

The contribution to the ingestion dose from the use of contaminated ground water (designated "DWR") is represented in Figure 5.23. It is evaluated for drinking water and ingestion of irrigated foods, as follows:

$$DWR_i = C_{si}\left[\sum_{j=1}^{J_i} A_{wtj}\, AF_{dj} + DIET \sum_{j=1}^{J_i} A_{wtj}\, AF_{wj}\right] \tag{5.74}$$

where DWR_i = committed effective dose equivalent for radionuclide i for ingestion of drinking water and irrigated food from a 1-year intake (mrem for 1 year of residential scenario)

C_{si} = initial concentration of radionuclide i in soil at the time of site release (pCi/g)

AF_{dj} = committed effective dose equivalent factor for ingestion of drinking water per unit average concentration of radionuclide j (as a parent radionuclide) in water (mrem per pCi/L for 1 year of residential scenario)

AF_{wj} = committed effective dose equivalent factor for radionuclide j per unit average concentration of radionuclide j (as a parent radionuclide) in ground water used for irrigation for the current 1-year period (mrem per pCi/L for 1 year of residential scenario)

A_{wtj} = average concentration factor for radionuclide j in water over the current 1-year exposure period per initial unit concentration of parent radionuclide i in soil at time of site release (pCi/L water per pCi/g soil)

and other terms are as previously defined.

The average water concentration factor, A_{wtj}, is evaluated according to the water-use model described in Section 5.6.6. The water concentration is based on the initial radionuclide concentration in soil, C_{si}, as used in the inhalation and external dose equations. Therefore, the ingestion dose is on the same concentration basis as the other dose values.

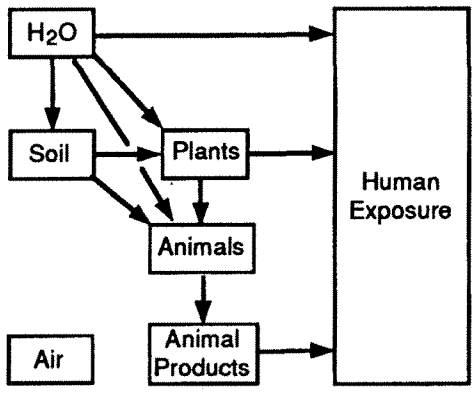


Figure 5.23 Residential scenario ingestion dose from use of contaminated ground water

The drinking water ingestion factor is calculated as follows:

$$AF_{dj} = U_w \, DFG_j \, t_d\left(C_{wj}/C_{wj}\right) \tag{5.75}$$

where U_w = daily intake of drinking water (L/d)

t_d = duration of water intake period (d for 1 year of residential scenario)

and other terms are as previously defined. The concentration ratio, C_{wj}/C_{wj} (equal to 1), indicates normalization to unit average concentration in water over the year of the residential scenario. The concentration is defined for radionuclide j as a parent radionuclide, consistent with the definition of AF_{dj}. The duration of water intake defines the amount of the individual's intake that comes from the ground-water well.

The agricultural product ingestion factor for irrigation of crops is calculated from pathway transfer factors as follows:

$$AF_{wi} = \sum_{j=1}^{J_i} PF_{wij} \, DFG_j \tag{5.76}$$

where PF_{wij} is the pathway transfer factor for agricultural products for irrigation for radionuclide j as a progeny of radionuclide i (pCi ingested per pCi/L for 1 y of residential scenario) and other terms are as previously defined.

5.6.5 Aquatic Food Ingestion Dose for the Residential Scenario

Ingestion of fish grown in contaminated surface waters is included as a potential exposure pathway for the residential scenario as shown in Figure 5.24. The following assumptions are made in evaluation of the dose from this pathway:

- The fish are grown in a surface-water pond of constant volume.
- The concentration of radionuclides in the surface water is equal to the concentration in the ground-water aquifer.
- The volume of the aquifer (for dilution of activity) includes the volume of the surface-water pond.
- The fish are harvested and eaten continually during the year.
- The radionuclide concentration in the fish is proportional to the radionuclide concentration in water, as determined by the bioaccumulation factor.

The dose from this pathway is based on the average annual water concentration as defined for the water-use model (see Section 5.6.6) and represented by the parameter C_{wj} for radionuclide j. The annual dose from ingestion of aquatic foods is calculated as follows:

$$DAR_i = C_{s1} \sum_{j=1}^{J_i} A_{wtj} \, AF_{fj} \tag{5.77}$$

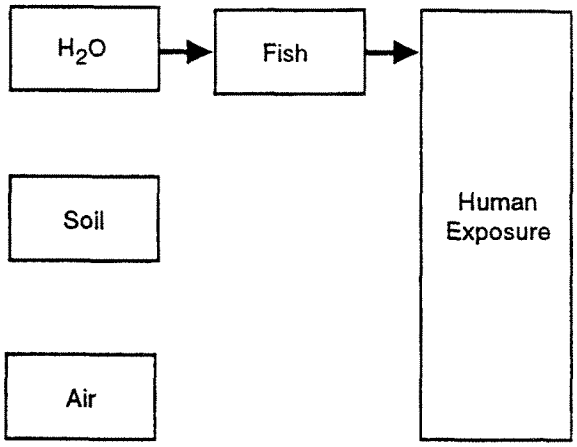


Figure 5.24 Residential scenario ingestion dose from use of contaminated ground water to grow fish in a surface-water pond

where DAR_i = ingestion committed effective dose equivalent from a 1-year intake of aquatic foods (mrem for 1 year of residential scenario)

C_{si} = initial concentration of parent radionuclide in soil at the time of site release (pCi/g dry-weight soil)

A_{wtj} = average concentration factor for radionuclide j in water over the current 1-year exposure period per initial unit concentration of parent radionuclide i in soil at time of site release (pCi/L per pCi/g dry-weight soil)

AF_{fj} = committed effective dose equivalent factor for ingestion of aquatic foods per unit average concentration of radionuclide j (as a parent radionuclide) in water (mrem per pCi/L for 1 year of the residential scenario)

and other terms are as previously defined.

The aquatic food ingestion factor for water (AF_{fj}) is calculated as follows:

$$AF_{fj} = U_f \, t_f \, DFG_j \, BA_{jf} \left(C_{wj} / C_{wj} \right) / 365.25 \tag{5.78}$$

where U_f = ingestion rate of aquatic foods produced in contaminated surface water (kg/y)

BA_{jf} = bioaccumulation factor for radionuclide j in aquatic foods (pCi/kg wet-weight aquatic food per pCi/L water)

C_{wj} = average annual concentration of radionuclide j (as a parent radionuclide) in water (pCi/L)

t_f = duration of fish consumption period (d)

365.25 = units conversion factor (d/y)

and other terms are as previously defined. The ratio of concentrations of radionuclide j (as a parent radionuclide of its own chain) in water is included for consistency with representations given for other pathways, showing normalization of the concentration to the average concentration of the parent for a decay chain.

5.6.6 Water-Use Model for the Residential Scenario

This section describes the water-use model for the residential scenario and methods for evaluation of the concentration factors for soil, A_{stj}, and water, A_{wtj}. A conceptual representation of the water-use model for the residential scenario is shown in Figure 5.25. Residual radioactive contamination is assumed to be in a surface-soil layer (15-cm thick) above an unsaturated-soil layer (1-m thick), which is above a water table that feeds a surface-water pond. Activity in the surface-soil layer leaches through the unsaturated-soil layer to the aquifer. Water in the aquifer is removed from a well for application to the surface-soil layer via irrigation and for domestic uses (i.e., drinking water). The irrigation water application represents a recycling pathway from the aquifer to the surface-soil layer. The concentration of radionuclides in the surface-water pond is assumed to be the same as the concentration in the aquifer at all times. The water-use model is a three-box model similar to the water-use model described for the drinking water scenario in Section 4. The primary differences between the two models are that the residential scenario model includes a surface-water pond and recycling of activity from the aquifer to the surface-soil layer. Figure 5.25 shows the

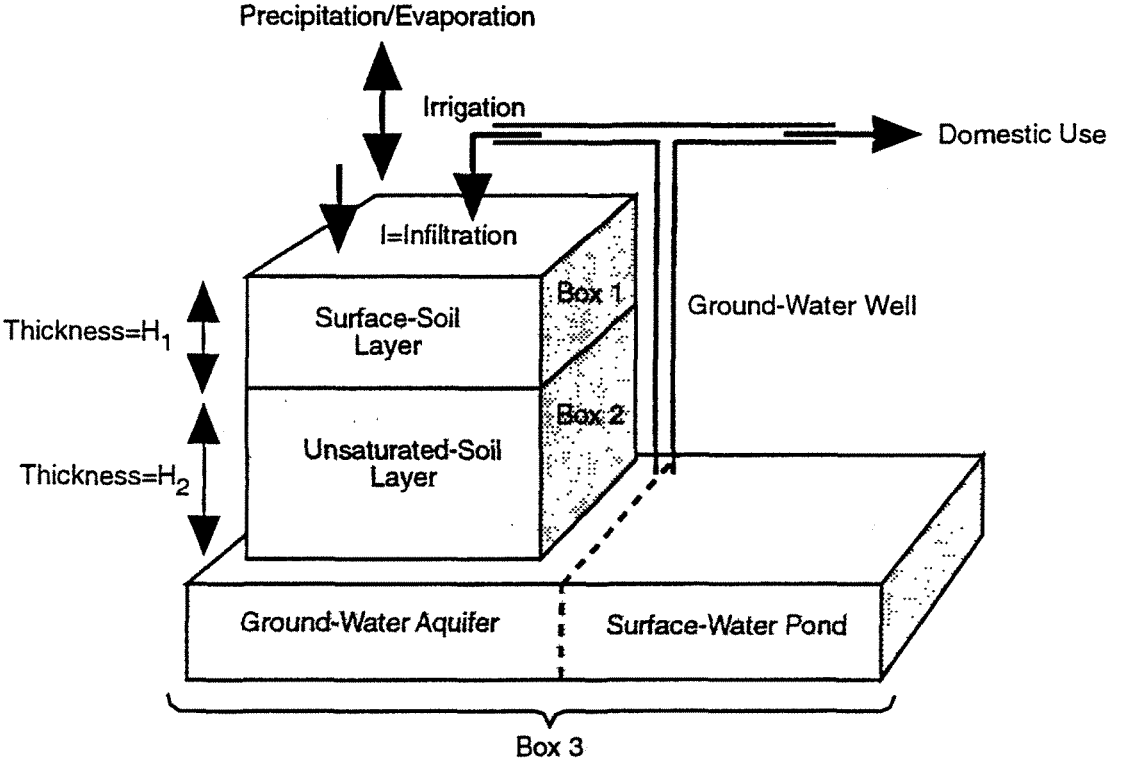


Figure 5.25 Concept representations of the residential scenario water-use model

three boxes and indicates the flow of water through the system with infiltration being the driving force for transfer from the surface soil to the ground-water aquifer. The model implies the following assumptions:

- Initial radioactivity is contained within the top layer (box 1).
- The unsaturated-soil layer (box 2) and the aquifer (box 3) are initially free of contamination.
- The vertical saturated hydraulic conductivity is greater than the infiltration rate.
- The infiltration volume is the product of the infiltration rate and the area of land contaminated.
- There is no retardation in the aquifer.
- The activity in the aquifer is diluted by the total volume of water in the aquifer.
- The radionuclide concentrations in all parts of the aquifer (including the surface-water pond) are the same: radionuclides entering box 3 are immediately uniformly mixed with the total volume of water in the aquifer.
- The total volume of water in the aquifer is constant at all times during the year.

The volume of water in the aquifer is considered to be the greater of the following: 1) the volume of infiltration water or 2) the sum of the volume of water removed annually for domestic uses and irrigation, plus the volume of the surface-water pond. The volume of infiltrating water is considered to be the product of infiltration rate, area of land irrigated, and infiltration period.

- The entire contaminated area is assumed to be irrigated and under cultivation.
- Water is removed from the aquifer at a constant rate during the year to meet the needs of irrigation and domestic water uses. The water removed is immediately replaced with uncontaminated water.
- Water is removed from the aquifer at a constant rate during all years of interest in the analysis.
- Radionuclides not removed during a year remain in the aquifer and contribute to the initial radionuclide concentration for the next annual period.
- Activity in the irrigation water is assumed to be deposited in the surface-soil layer (box 1).
- The water infiltration rate is a fraction of the total water application rate (i.e., the sum of the irrigation application rate and the annual precipitation rate).
- Evaporative losses remove only water from the system (i.e., surface soil and surface-water pond): radionuclides are not lost by evaporation.

To provide a realistic conceptual model, the volume of water in the aquifer is defined as the greater of two volumes: 1) the volume of infiltration water or 2) the volume in the surface water pond, plus the volume pumped annually for domestic and irrigation uses. This definition avoids any unrealistic case in which the volume of infiltrating water exceeds the total volume of water in the pond plus the volume of water pumped. Not using such a definition would lead to an unrealistic increase of aquifer water concentration over the concentration of the water in the unsaturated-soil layer (the source of the radionuclides reaching the aquifer).

The assumption regarding the vertical saturated hydraulic conductivity means that the soil conditions will allow water to move vertically downward at least as fast as the infiltration rate (expressed as distance per year).

Irrigation is assumed to occur continuously during a year, even during non-growing periods. This approach has been selected for simplicity for the screening model and may or may not provide conservative results, depending on the radionculides involved.

The residential scenario water-use model can be described mathematically as a three-box model shown schematically in Figure 5.26. This figure is a diagram of the water-use model showing irrigation recycling and domestic use transfers from the ground-water aquifer. The figure also includes representation of a three-member decay chain. Equations for this water-use model are similar to the equations for the drinking water scenario, but are repeated here (with slight modification for recycling) for completeness. Recycling occurs as a result of water being removed from box 3 and used to irrigate surface soil (box 1), such as in a garden, for food production.

The water-use model is used in the residential scenario to determine the change in surface soil and aquifer concentration with time, starting with the initial activity of each radionuclide in soil at the time of site release. The process of dose evaluation for food (farm products and fish) and water-ingestion pathways, as illustrated in Figure 5.27, is evaluated sequentially, year-by-year.

The initial activity in the surface-soil layer is the starting parameter in the calculation. The dose from soil pathways is evaluated using unit dose factors for soil multiplied by the initial activity for the initial year. Unit dose factors for soil, AF_{si}, are evaluated using Equation (5.72). The average water concentration is evaluated using the water-use model. The dose from water pathways (Equations [5.74] and [5.77]) is evaluated using the average water concentration over the first year, multiplied by unit dose factors for water. The unit dose factors for water include the farm product dose factors (AF_{wi}, in Equation [5.76]), the drinking water unit dose factors (AF_{dj}, in Equation [5.75]), and the aquatic food unit dose factors (AF_{fj}, in Equation [5.78]).

The equations for the water-use model account for decay chain members produced in each of the boxes from precursor radionuclides and the transfer of each chain member between boxes and from box 3 for domestic use (drinking) and irrigation (recycling to surface soil of box 1). The amounts of each chain member are represented as the total activity present. The concepts involved in accounting for the quantity of radionuclide j in box 1 at time t are described in the word equation below:

$$\begin{aligned}[\text{Rate of Change of j in Box 1 at Time t}] = {} & [\text{Deposition of j from Irrigation Water}] \\ & + [\text{Production of j from Decay of Precursor n at Time t}] \\ & - [\text{Removal of j from Box 1 by Decay at Time t}] \\ & - [\text{Removal of j from Box 1 by Leaching at Time t}].\end{aligned} \tag{5.79}$$

The basic differential equation for box 1 has the following form, accounting for original quantities for irrigation deposition (w term), radioactive decay (λ terms), and rate of leaching (L term):

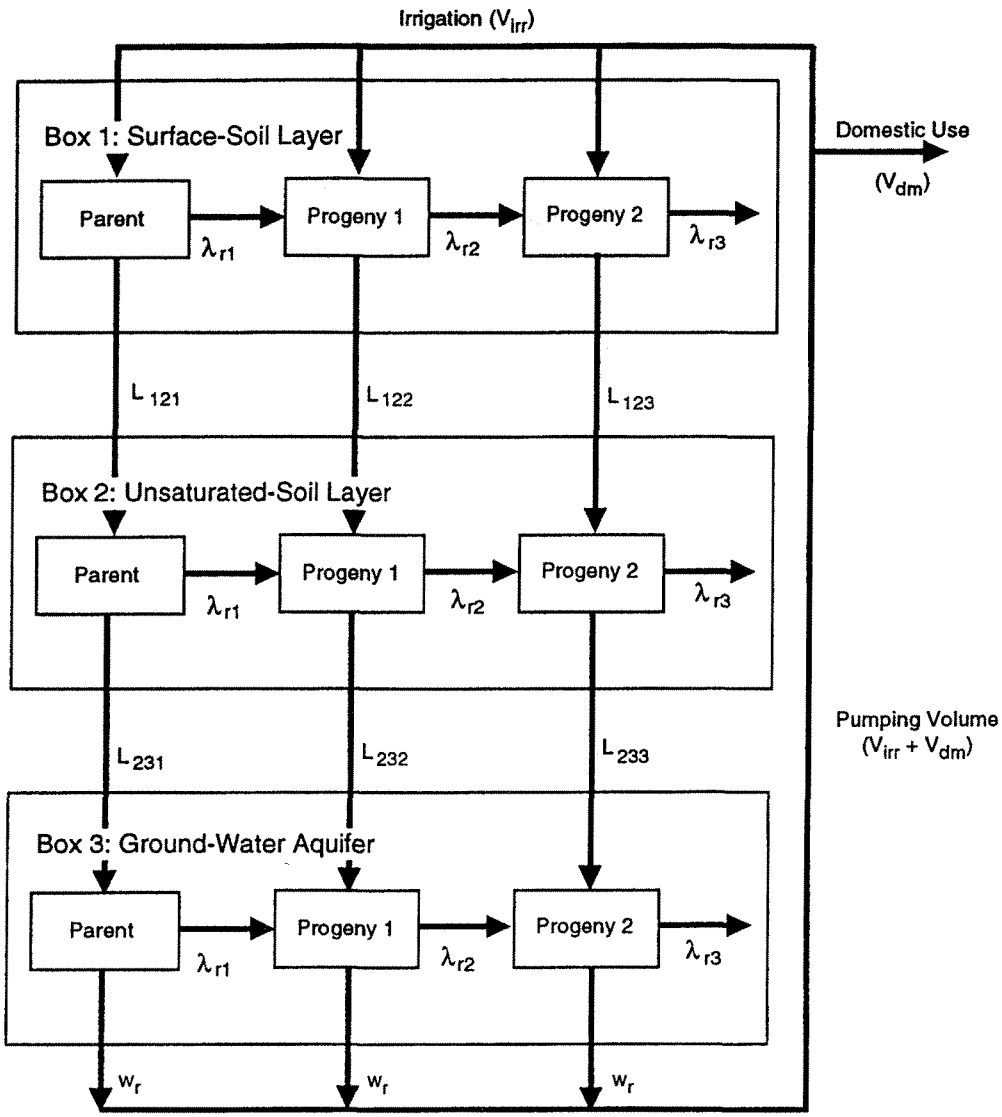
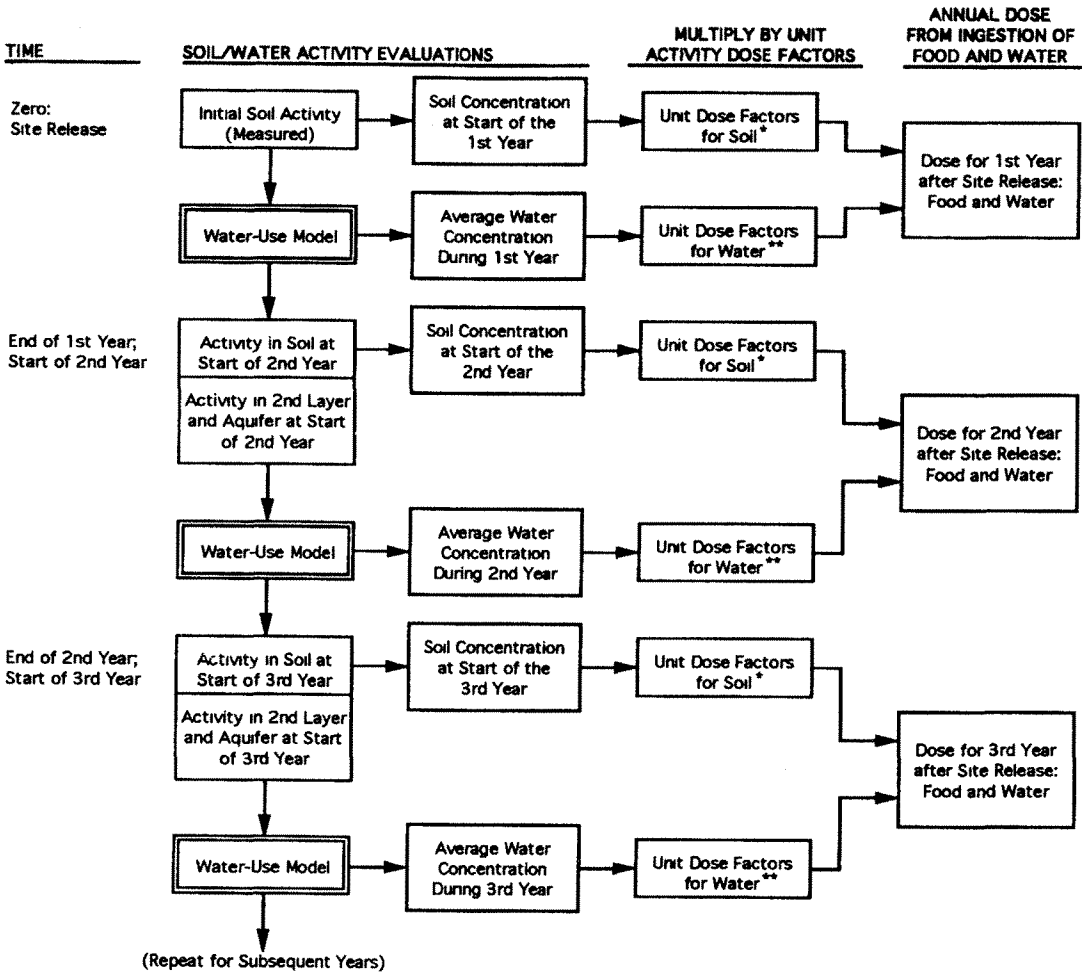


Figure 5.26 Residential three-box water-use model



* Unit dose factors for soil are AF_{Si} [Equation (5.72)]
** Unit dose factors for water are AF_{Wi} [Equation (5.76)], AF_{dj} [Equation (5.75)], and AF_{fj} [Equation (5.78)]

Figure 5.27 Annual sequence of analyses

$$\frac{dC_{1j}}{dt} = F_r\, w_r\, C_{3j} + \lambda_{rj} \sum_{n=1}^{j-1} d_{nj}\, C_{1n} - \left(\lambda_{rj} + L_{12j}\right) C_{1j} \tag{5.80}$$

where C_{1j} = total activity of radionuclide j in box 1 at time t (pCi)

C_{3j} = total activity of radionuclide j in box 3 at time t (pCi)

F_r = fraction of water removed from box 3 that is deposited on the surface layer (box 1) by irrigation

w_r = removal rate constant for pumping of water from box 3 (d^{-1})

j = index of current chain-member position in decay chain

n = index of precursor chain members in decay chain ($n < j$)

C_{1n} = total activity of precursor radionuclide n in box 1 at time t (pCi)

L_{12j} = rate constant for movement of radionuclide j from box 1 to box 2 (d^{-1})

d_{nj} = fraction of transitions of radionuclide n that result in production of radionuclide j (dimensionless)

λ_{rj} = decay rate constant for decay of radionuclide j (d^{-1}).

For box 2, the concepts involved in accounting for the quantity of radionuclide j at time t are described in the word equation shown below:

[Rate of Change of j in Box 2 at Time t] = [Production of j from Decay of Precursor n at Time t]
+ [Transfer of j by Leaching from Box 1 at Time t]
- [Removal of j from Box 2 by Decay at Time t]
- [Removal of j from Box 2 by Leaching at Time t]. (5.81)

The basic differential equation for box 2 can be written as follows:

$$\frac{dC_{2j}}{dt} = \lambda_{rj} \sum_{n=1}^{j-1} d_{nj} C_{2n} + L_{12j} C_{1j} - \left(\lambda_{rj} + L_{23j}\right) C_{2j} \quad (5.82)$$

where C_{2j} = activity of radionuclide j in box 2 at time t (pCi)

C_{2n} = activity of precursor radionuclide n in box 2 at time t (pCi)

L_{23j} = rate constant for movement of radionuclide j from box 2 to box 3 (d^{-1})

and other terms are as previously defined.

For box 3, the concepts involved in accounting for the quantity of radionuclide j at time t are described in the word equation shown below:

[Rate of Change of j in Box 3 at Time t] = [Production of j from Decay of Precursor n at Time t]
+ [Transfer of j by Leaching from Box 2 at Time t]
- [Removal of j from Box 3 by Decay at Time t]
- [Removal of j from Box 3 by Pumping at Time t]. (5.83)

The basic differential equation for box 3 can be written as follows:

$$\frac{dC_{3j}}{dt} = \lambda_{rj}\sum_{n=1}^{j-1} d_{nj}\, C_{3n} + L_{23j}C_{2j} - \lambda_{rj}C_{3j} - w_r\, C_{3j} \tag{5.84}$$

where C_{3j} = activity of radionuclide j in box 3 at time t (pCi)

C_{3n} = activity of precursor radionuclide n in box 3 at time t (pCi)

and other terms are as defined above.

The summation term in each of the above equations is evaluated for only those terms for which a transition occurs (depending on the decay scheme for the decay chain). The rate constants for movement between compartments are evaluated using the same equations as defined for the drinking water scenario water-use model (see Equations [4.7] through [4.12]).

The recycling of activity from the aquifer to the surface soil is defined by the first term on the right side of Equations (5.79) and (5.80). The pumping-rate constant, w_r, is evaluated for complete removal of the irrigation and domestic use water volume in a 1-year period. The rate constant is then the fractional removal of the total aquifer volume per year and is expressed as follows:

$$w_r = \frac{\text{Fractional Removal}}{y}\left(\frac{y}{365.25\ d}\right) \tag{5.85}$$

where 365.25 is the units conversion factor (d/y). The fractional removal is the fraction of total aquifer volume that is removed during a year. The volume removed is that associated with irrigation water use plus domestic use; the water in the farm pond is not removed. The fractional removal is then evaluated as follows:

$$\text{Fractional Removal} = \frac{V_{irr} + V_{dr}}{V_{Tr}} \tag{5.86}$$

where V_{irr} = volume of water used for irrigation during a 1-year period (L)

V_{dr} = volume of water used for domestic purposes during a 1-year period (L)

where V_{Tr} = total volume of water in the aquifer for dilution of activity over a 1-year period for the residential scenario (L).

The total volume of water in the aquifer is used as the dilution volume in determining the annual average water concentration. The total water volume is taken as the greater of the infiltration water volume or the sum of the water volumes used for irrigation, domestic purposes, and the surface-water pond. The infiltration volume is evaluated as follows:

$$V_{Ir} = I\ A\ 1000 \cdot 1 \tag{5.87}$$

where V_{Ir} = annual infiltration and irrigation volume through the cultivated farmland area (L)

I = infiltration rate (m/y)

A = area of land under cultivation (m^2)

1000 = unit conversion factor (L/m^3)

1 = time period for infiltration and irrigation (y).

The total volume of water in the aquifer for the residential scenario is then evaluated as follows:

$$V_{Tr} = \text{greater of: } V_{Ir} \text{ and } V_{irr} + V_{dr} + V_{sw} \tag{5.88}$$

where V_{sw} = volume of water in surface-water pond used for growing fish during a 1-year period (L)

and other terms are as previously defined.

The fraction of removal water that is applied to the surface layer is evaluated from the water usage volumes for irrigation and domestic uses as follows:

$$F_r = V_{irr} / \left(V_{irr} + V_{dr}\right) \tag{5.89}$$

The soil concentration factor for radionuclide j at the beginning of the current 1-year exposure period is represented in terms of the residential scenario water-use model operator as follows:

$$A_{stj} = A_{r1}\left\{C_{kj}, t\right\} \tag{5.90}$$

where A_{stj} = concentration factor for radionuclide j in soil at the beginning of the current 1-year exposure period per initial unit concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil per pCi/g dry-weight soil)

$A_{r1}\{\}$ = residential scenario water-use model decay operator notation used to develop the concentration factor for radionuclide j in soil at the beginning of the current 1-year exposure period per initial unit concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil per pCi/g dry-weight soil)

C_{kj} = concentration array of radionuclides (j) in box k at the time of site release (pCi/g dry-weight soil)

t = time between site release and the beginning of the current 1-year period (d).

The normalization of the concentration factor results from setting the initial concentrations in surface soil to unit concentration (pCi/g of parent radionuclide). A detailed description of the water-use operator is given in Appendix B, Section B.7).

To evaluate the water concentration factor, the total activity in the farmland soil must be determined. The initial inventory for the residential scenario is given per gram of soil (box 1), unlike the drinking water scenario, in which the initial inventory is defined as the total activity in soil. The water-use model equations involve activity independent of any normalization by mass. Therefore, the total activity present in the surface layer must be determined in order to evaluate the water concentration in the aquifer. For the first level of screening, the total activity in the soil layer (per unit activity in soil, pCi/g dry-weight soil) is calculated from the total mass of soil using the irrigated area, soil depth, and soil density as follows:

$$QT = A_r \, H_1 \, d_s \, 10^6 \tag{5.91}$$

where QT = total mass of soil in the irrigated surface-soil layer (box 1) (g dry-weight soil)

A_r = area of land contaminated for the residential scenario (m^2)

H_1 = thickness of surface-soil layer, i.e., plow depth (m)

d_s = average density of surface-soil layer (g dry-weight soil/cm^3)

10^6 = unit conversion factor (cm^3/m^3).

The average water concentration factor, A_{wtj}, is evaluated from the time integral of radionuclide activity in the aquifer (box 3), $S_{r3}\{C_{kj},t_y\}$ over the current year. The total activity in the aquifer is the product of the time integral and the total soil mass, QT, divided by the time period (1 year). This total activity is divided by the total water volume to obtain the average water concentration during the current year. The calculation of the average water concentration factor is performed as follows:

$$A_{wtj} = \frac{QT \, S_{r3}\{C_{kj}, t_y\}}{V_{Tr} \, t_y} \tag{5.92}$$

where A_{wtj} = average concentration factor for radionuclide j in ground water during a year t per initial unit concentration of parent radionuclide i at time of site release (pCi/L per pCi/g dry-weight soil)

C_{kj} = initial activity of chain member radionuclide j in water-use model box k per unit activity of parent radionuclide i at the beginning of the current year (pCi/g dry-weight soil per pCi/g dry-weight soil)

t_y = 1-year period of integration (d)

$S_{r3}\{\}$ = time-integral operator used to develop the residential scenario water-use model total aquifer activity for radionuclide j in ground water over a 1-year period per initial unit concentration of parent radionuclide i at time of site release (pCi•d/g dry-weight soil per pCi/g dry-weight soil)

and other terms are as previously defined. A detailed description of the residential scenario water-use time-integral operator is given in Section B.7.

5.7 Total Dose for Residential Scenario

The annual TEDE (designated "TEDER") for the residential scenario is evaluated as the sum of the contributions from the six exposure pathways:

$$TEDER_i = DEXR_i + DHR_i + DGR_i + DWR_i + DSR_i + DAR_i \quad (5.93)$$

where $TEDER_i$ is the annual TEDE for radionuclide i (mrem for a year of residential scenario) and other terms are as previously defined. To obtain normalized annual TEDEs, the calculations are performed with a normalized source term (i.e., 1 Bq/g or 1 pCi/g). The annual TEDE is evaluated for each year until a maximum is found.

The evaluation of the annual TEDE for the residential scenario for mixtures involves calculation of the annual TEDE summed over all radionuclides in the inventory. The year of maximum dose is the year during which this *summed* dose is maximum. The annual TEDE for a mixture can be represented as the sum of annual TEDEs from individual radionuclides:

$$TEDER_m = \sum_{i=1}^{M} TEDER_i \quad (5.94)$$

where $TEDER_m$ is the annual TEDE for the mixture of radionuclides, evaluated at the year in which the total is a maximum value (mrem for a year of residential scenario), and M is the number of radionuclides in the mixture.

The corresponding annual TEDEs in units of μSv, when inventory is given in units of Bq/g, are evaluated as follows:

$$TEDER_{iSI} = 270.3\ TEDER_i \quad (5.95)$$

where the constant 270.3 is a unit conversion factor (μSv/Bq per mrem/pCi).

6 Selected Parameter Values

As described in the previous sections, the calculation of radiation doses for the generic screening scenarios and pathways established for residual radioactive contamination in buildings and soil rely on numerous parameters and data values. These include radioactive decay data, basic dose conversion factors, media-specific concentration data, water-use model data, and data used to describe the agricultural pathways. This section explains the selection of data used in this study and justifies the selections made.

6.1 Radioactive Decay Data

Many of the models employed in the calculation of the annual TEDE require consideration of radioactive decay for radionuclide decay chains. The most notable decay chains include the multiple radionuclides in the neptunium, uranium, actinium, and thorium series. A method for handling chain decay in preparation of dose factors has been devised that is easy to implement in a computer program. This section describes the conventions developed for handling radioactive decay chains, the method for evaluation of decay with time, and the radioactive decay database.

6.1.1 Conventions for Handling Radioactive Chain Decay

The following basic conventions for handling radioactive chain progeny are defined for the calculation of annual TEDEs for residual radioactive materials:

1. A single master set of radionuclides (shown in Appendix E, Table E.1), with over 200 entries for single and multiple member decay chains, was selected by the authors for this screening model. This master set is intended to include the more significant radionuclides used by NRC licensees, including numerous short-lived radionuclides.

2. All dose values generated by the scenario analysis will be normalized to unit activity of the parent radionuclide.

3. The radiations included in the dose factor for a parent are those associated with decay of the parent, plus radiations from progeny that are always in secular equilibrium (constant ratio of activity as a function of time). For this study, radioactive decay chain members are assumed to be in secular equilibrium with parent radionuclides if they have half-lives 1) less than 9 hours *and* 2) less than one-tenth the listed parent half-life. Radiations from decay chain members that meet these criteria are included with the radiations from their parent radionuclides as *implicit* progeny in the dose factor listings. Several implicit progeny may be defined under one parent. Progeny that are not implicit are defined as *explicit*.

   The 9-hour half-life cutoff value was selected as a convenient break point. For the master listing of radionuclides considered in this study, there is a group of radionuclides (within decay chains) with half-lives just above 9 hours, but only a few with half-lives immediately below 9 hours. Use of other notation, such as the "+ I" or "+ D" found in the public comment draft version of this document (Kennedy and Peloquin 1990), is not necessary because the progeny contributions are always included (for external or internal dose factors). Thus, it makes no practical sense to define factors without such progeny contributions. For inhalation and ingestion dose factors, the entries include radiations from all radionuclides contributing to internal dose following intake of the parent (within the 50-year dose commitment period). The inclusion of such contributions is justified by recommendations of the ICRP 26 (1977) and in EPA Federal Guidance Report No. 11 (Eckerman, Wolbarst, and Richardson 1988). These contributions are included in the inhalation and ingestion dose factors to be used for the calculations.

4. For decay chains having two or more radionuclides of significant half-life that reach secular equilibrium (constant ratio of activity as a function of time), an entry is provided giving dose factors for the entire chain. Such decay chains have a long-lived parent with progeny of varying shorter half-lives. This representation is of particular value for radionuclides in the four actinide decay series (the neptunium, uranium, actinium, and thorium series). The radionuclide notation includes a "+C" to indicate that *all* progeny in the chain are included in the dose factors. Entries are included for a decay chain member with a "+C" representation when *all* progeny of the chain have half-lives less than one-tenth the half-life of the listed member.

These conventions are sufficient to define a useful and consistent method of handling radioactive decay chains for use in development of dose factors for both internal and external exposures. It should be noted, with respect to internal dose factors, that the users of the tabulated dose factors need only be concerned about the radionuclide inventory present at the time of site release; the contributions from progeny radionuclides after intake (inhalation or ingestion) are automatically included in the evaluation of the annual TEDE.

6.1.2 Decay Chain Data

The radioactive decay chain database contains decay data for the master list of radionuclides defined for this report. The decay chain representations in the database are taken from ICRP Publication 38 (ICRP 1983). The database contains a data set for each radionuclide or chain, except natural thorium and natural uranium, for which dose factors are calculated from entries for the radionuclides in the decay chain. For single-member chains (i.e., no progeny), the data set contains the radionuclide name, decay half-life, and atomic number. Decay chains having progeny also contain listings for each chain member, including the radionuclide name, decay half-life (explicit members only), atomic number, and branching information. A complete tabulation of radioactive decay chain data contained in the database is presented in Appendix E, Table E.1. The tables in Appendix E were generated from computer-readable electronic files anticipating their direct use in the user-friendly software implementing the scenario/pathway analysis for residual radioactive contamination.

The entries in the radioactive decay chain database in Table E.1 are organized by increasing atomic number and by decay chain. Within each decay chain, members follow according to their decay sequence. The treatment of progeny radionuclides as implicit or explicit is indicated in Table E.1 by the presence of a value for the radioactive half-life. Implicit radionuclides have no value for the radioactive half-life, while explicit radionuclides have the half-life listed. The table also includes a chain member position index, with the parent always having position 1. The position indices are used to indicate the decay sequence, which is necessary when branching occurs. Implicit radionuclides have no chain member position index because they are not included in the decay calculations performed by the decay processor.

As an example of definition of implicit and explicit radionuclides, consider the entry for ^{232}U. The ^{232}U chain has three explicit progeny: ^{228}Th, ^{224}Ra, and ^{212}Pb. The data set for ^{232}U contains data for all four radionuclides as explicit chain members. Another data set is included with ^{228}Th as the parent with two explicit progeny, ^{224}Ra and ^{212}Pb. A third data set is included with ^{224}Ra as the parent with one explicit progeny, ^{212}Pb. The ^{224}Ra data set also has two implicit progeny, ^{220}Rn and ^{216}Po. Note that no half-life values are given for the two implicit progeny. The ^{212}Pb data set has three implicit progeny: ^{212}Bi, ^{212}Po, and ^{208}Tl. Note that implicit progeny are listed only once in the database and are listed under the explicit radionuclide that is their immediate precursor. This method for definition of decay chain data involves some duplication of information but greatly simplifies input and usage of the decay data in the calculations performed. It permits direct consideration of a complete or partial decay chain.

The branching information listed in Appendix E defines the sequence and fraction of parent decays that result in the production of each chain member. The branching fractions defined for each member indicate the source of production of the chain member. This convention is the opposite of the usual method of defining the fractions for the parent and

an indication of the radionuclides produced by the parent decay. A chain member may be produced by one or two precursor chain members. The decay chain database in Appendix E contains the following information:

- index of the first precursor (if any) for the chain member
- fraction of first precursor decays that result in production of the chain member
- index of the second precursor (if any) for the chain member
- fraction of second precursor decays that result in production of the chain member.

The decay fractions for implicit progeny represent the *total* fraction of explicit precursor decays that result in production of the implicit progeny. The atomic number as provided in the radioactive decay database is used as a cross-reference index with other element-specific data.

6.2 Dosimetry Database

For purposes of the generic screening analysis for evaluating the annual TEDE for the building and soil scenarios, a standardized database of external dose rate conversion factors and internal CEDE factors is required. These conversion factors are obtained from existing Federal Guidance published by the EPA, implementing the recommendations of the ICRP. A complete listing of these factors is provided in Appendix E (Table E.2). Ingestion organ dose equivalents, used to determine the organ with the highest dose in the drinking water scenario (as described in Section 4), are given in Tables E.3 through E.5.(1) The following sections discuss the literature sources for the external dose rate conversion factors and the internal CEDE rate conversion factors, and additional details on their selection and use.

6.2.1 External Dose Rate Conversion Factors

The external dose rate conversions used in this study were obtained directly from the EPA Federal Guidance report No. 12 developed by Oak Ridge National Laboratory (ORNL) (Eckerman and Ryman 1992). These factors provide the external effective dose equivalent by summing the product of individual organ doses and organ weighting factors over the body organs. These factors are consistent with ICRP 26 (1977) guidance; however, they are inconsistent with the concept of deep dose equivalent, as defined by the NRC (see Appendix F, "Glossary"). For purposes of this generic study, the EPA factors are judged to be an adequate representation of the external dose because skin is not considered as one of the organs. For most radionuclides, the numerical difference between the effective dose equivalent evaluated without skin and the deep dose equivalent will be a few percent. If skin were included, the difference would likely be greater for radionuclides with low photon energies. The external dose rate conversion factors from the EPA are used to determine factors for the three source conditions used for this study: 1) infinite surface (thin-layer) contamination (for surface sources in the building occupancy scenario), 2) volume contamination in a 15-cm-thick slab source (for thin volume sources used in the building renovation scenario), and 3) volume contamination in a 15-cm-thick slab source (for surface-soil sources used in the residential scenario). A listing of the external dose conversion factors for exposure to surface and volume sources is provided in Table E.2 for the radionuclides considered in this study. These factors are in units of

- Sv/d per Bq/m^2 for external exposure to surface sources and

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(1) Please refer to the text of Appendix E for a description of the structure of these dose factor tables.

- Sv/d per Bq/m^3 for external exposure to volume sources.

As described in Sections 2 and 5, the dose rate conversion factors need to generically account for different conditions. For the building scenarios, a variety of contamination conditions could exist, including inhomogeneous distributions of residual radioactivity on building walls, ceilings, and floors, and surface or volume sources. As described in Appendix A of the 1990 review draft of this document (Kennedy and Peloquin 1990), sensitivity studies were conducted to determine the best geometries for use in a generic analysis. A sensitivity study was conducted with an arrangement of surface (disk) sources contaminated with ^{60}Co and using the ISOSHLD computer program (Engel, Greenborg, and Hendrickson 1966) to model potential external doses in a room. The room was assumed to have a fixed distance 3 m from ceiling to floor, with variable floor and ceiling areas to represent different room volumes. The dose location was assumed to be the center of the room. Figure 6.1 illustrates the potential effect of uniform and nonuniform distributions on the relative external dose rate within a room, as a function of room size (volume). For further comparison, the figure contains a line that represents the dose rate from an infinite flat plane source. The room surface results for a uniform distribution of surface contamination are based on the assumption that the same contamination level exists on all interior building surfaces (walls, floor, and ceiling). The nonuniform distribution results are intended to represent a perhaps more common situation, where the floors are more contaminated than the walls or ceiling. The nonuniform distribution results are based on walls and a ceiling that have contamination levels 50% and 10%, respectively, of the contamination level on the floor. The results show that the uniform distribution dose rates are about

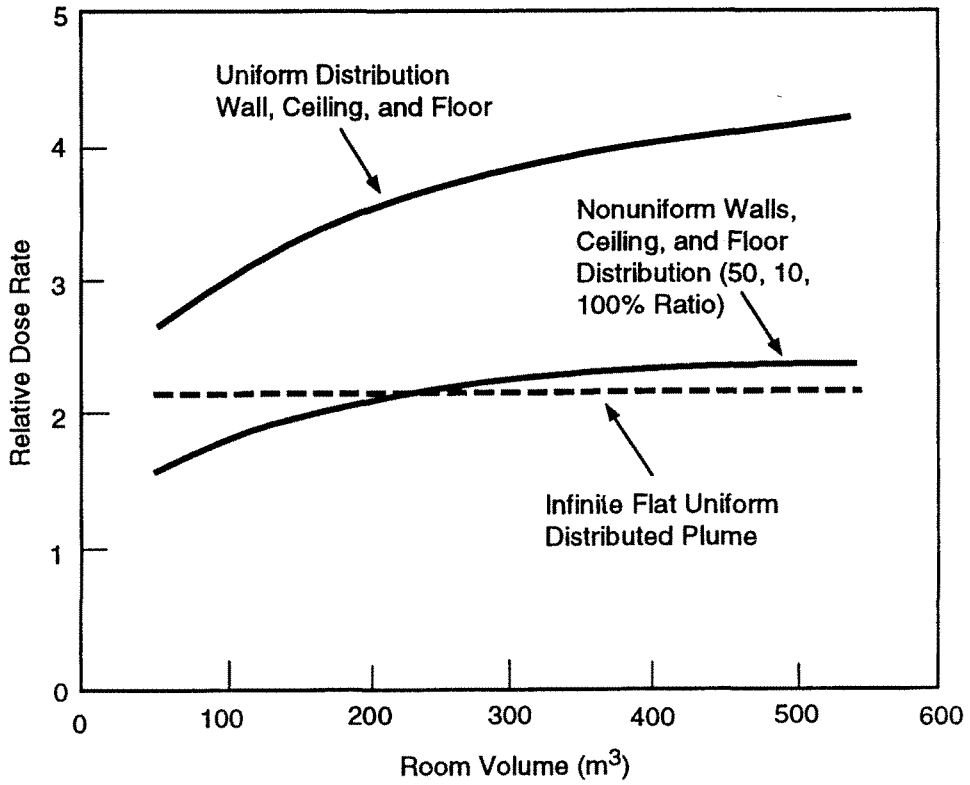

Figure 6.1 Relative external dose rate for uniform and nonuniform source distributions on interior surfaces of a room as a function of room volume

twice the dose rates from the nonuniformly distributed sources. The reason is that the contribution from the ceiling has the effect of doubling the dose rate from the floor when contamination is uniformly distributed. The contributions from the walls are minimal for medium-to-large rooms. (They are farther away from the receptor than the floor or ceiling, and thus have little contribution to the total dose.)

The results shown in Figure 6.1 indicate that external dose rate results for the infinite flat plane (with a uniform distribution of radioactive contamination) provide a good approximation of the external dose rate for rooms with nonuniform distributions of contamination levels. For reference, the two results are about equal for rooms with a volume of about 200 m^3 (a floor area of 8 x 8 m with a ceiling height of 3 m). For smaller rooms, such as most offices, the infinite flat plane result provides a conservative estimate of the potential dose rates when nonuniform contamination conditions are present. For this reason, external doses are estimated using an infinite plane source for the building occupancy scenario and an infinite slab source with a thickness of 15 cm for the building renovation scenario. These geometries are assumed to provide a prudently conservative basis for estimating external radiation doses inside contaminated rooms.

For the building renovation scenario, special consideration was given to the selection of a prudently conservative external exposure volume source configuration. With the exception of sources resulting from neutron activation, most volume activity in buildings will be limited to small areas (hot spots) or rather shallow sources (i.e., liquid spills absorbed into wall or floor surfaces). For the case of neutron activation, volume sources could extend deep into the volume of a building structure; however, these volume sources will likely be identified and removed during decontamination. The construction of most building walls and floors will likely range from thicknesses of about 10 to 30 cm. The thickness of building structural materials will place a limit on the potential thickness for volume sources. As a prudently conservative assumption, building surfaces are assumed to be represented by slab sources, of infinite extent, with a thickness of 15 cm. For external exposure calculations, this thickness will approximate an infinite thickness for alpha-emitters, beta-emitters, and x-ray or low-energy photon-emitters. For high-energy photon-emitters, a source thickness of 15 cm represents 85% of the dose rate from an infinite source as described by the sensitivity analysis for soils that follows. For contaminated soil, a sensitivity study was conducted to determine the best source geometry for estimating radiation doses in the residential scenario. Appendix A of the January 1990 comment draft (Kennedy and Peloquin 1990) report shows the external dose rates as a function of various source geometries and source areas. Figure 6.2 in this report illustrates relative external dose rates for ^{60}Co for five source thicknesses: 1, 15, and 50 cm and 1 and 2 meters for effective source areas between 10 and 10,000 m^2. The units used in the sensitivity study have been normalized to a unit activity per unit mass, and the relative dose rates are shown. As can be expected, the relative external dose rate increases as a function of source area and thickness because of an increase of the total activity present. This increase occurs over a range until an approximation to an infinite source area and thickness is reached (at a surface area of about 1,000 m^2 and a source thickness of about 0.5 m, as shown in Figure 6.2). It should be noted that the effect of increasing source thickness and area will also be a function of the photon energy associated with the radionuclides in the residual contamination. However, it should also be noted that the use of ^{60}Co in the sensitivity study, with two high-energy gammas, provides a prudently conservative basis for understanding the change in relative external dose rate as a function of source area and thickness.

As shown in Figure 6.2, the difference in the estimated external dose rate for source thicknesses of 15 cm and 1 m is about 15% over all source areas. It should be noted that the 15-cm solution can be assumed to represent sources thinner than 15-cm if part of the scenario considers plowing the land. Plowing is assumed to create a homogeneous volume source, 15-cm thick.

For this generic analysis, external doses from contaminated soil are modeled with a single source representation: a slab source, 15-cm thick, and of infinite extent. As described by the EPA (Eckerman and Ryman 1992), the volume source geometry used to calculate the external dose rate conversion factors is a slab source of infinite extent (a distance

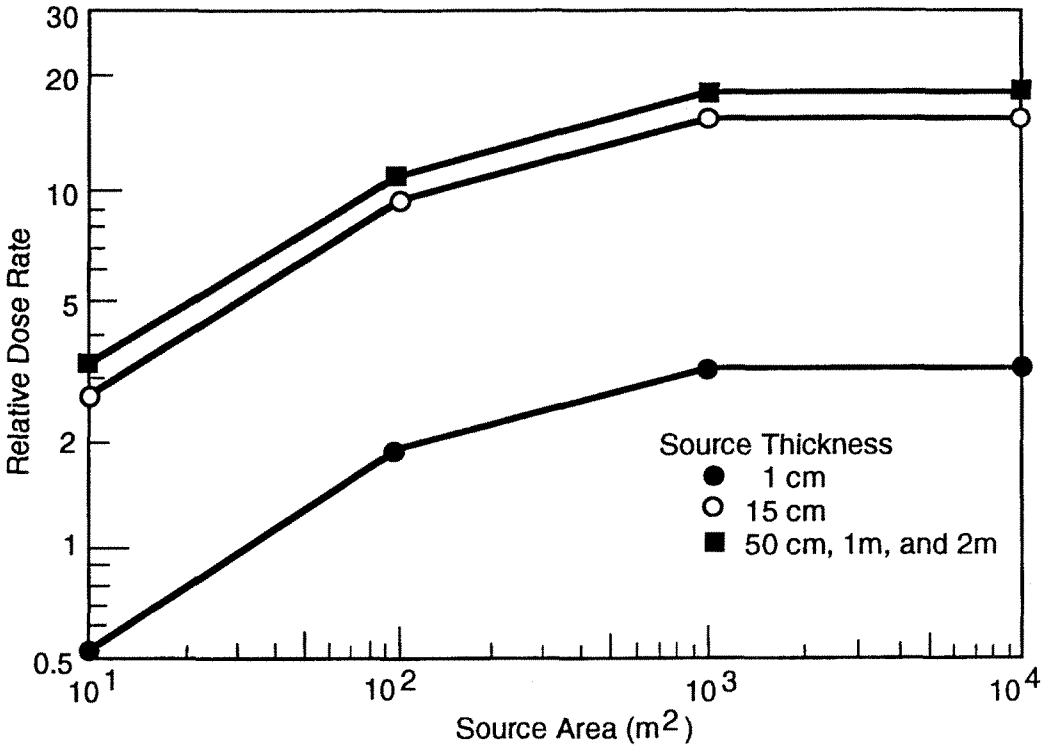

Figure 6.2 Relative external dose rate as a function of soil source area and thickness for ^{60}Co

of four mean free paths for each photon energy group). This geometry represents a prudently conservative approximation and is consistent with the soil thickness assumed for the plow layer in the agricultural pathway analysis.

The intent of this study is to produce screening values that should adequately bound most situations. When more complex situations arise, such as the presence of inhomogeneous, buried sources in soil, site-specific modeling or the use of external exposure measurements may better describe the situation and should be used instead of the simple model representations provided here.

6.2.2 Inhalation and Ingestion Dose Conversion Factors

For inhalation and ingestion of radioactive materials, unit CEDE conversion factors are obtained from EPA Federal Guidance Report No. 11 (Eckerman, Wolbarst, and Richardson 1988). This Federal Guidance Report supersedes previous Federal Radiation Council (FRC) guidance and, in addition to listing CEDE conversion factors per unit intake, it presents values for derived annual limits on intake (ALIs) and derived air concentrations (DACs). The unit CEDE conversion factors for inhalation and ingestion from the EPA references are included in Table E.2 in Appendix E for the radionuclides considered in this study. These factors are in units of Sv/Bq inhaled or ingested. Ingestion organ dose equivalents for the drinking water scenario are listed in Tables E.3 through E.5. These internal dose conversion factors are based on the recommendations of the ICRP in Publication 30 (1979-1988). For plutonium and related elements, the factors include the revised ICRP recommendations concerning metabolic data found in Publication 48 (1986). The dose conversion factors in EPA Federal Guidance Report No. 11 are intended for general use in assessing average individual committed doses in any population that can be characterized by Reference Man, as described by the ICRP (1975).

6.2.3 Dose and Dose Rate Factor Working Units

The dose and dose rate factors provided in the dosimetric files by the EPA are presented in units different from those needed for the scenario analyses. Conversion of the factors to the desired units, consistent with the units described in Sections 3, 4, and 5, is performed using unit conversion factors presented in this section.

Estimates of external doses from exposure to direct penetrating radiation require the use of dose rate conversion factors that are given in units of mrem/h per pCi/g (and μSv/h per Bq/g) for soil or volume contamination in a building, or mrem/h per dpm/100 cm^2 (and μSv/h per Bq/100 cm^2) for surface contamination in a building. Table 6.1 lists the unit conversion factors used to convert the basic dose rate factors in the EPA data files (Table E.2) to the desired units for this study.

Table 6.1 Unit conversion factors for external dose

Units of EPA database parameter	Multiply by	To obtain value in units
Sv/d per Bq/m^2	6.944E+03	mrem/h per dpm/100 cm^2
Sv/d per Bq/m^2	4.167E+06	μSv/h per Bq/100 cm^2
Sv/d per Bq/m^3	2.505E+08	mrem/h per pCi/g
Sv/d per Bq/m^3	6.771E+10	μSv/h per Bq/g

The conversion factors of Table 6.1 are determined as follows:

$$6.944E+3 \frac{\left[\frac{\text{mrem}}{\text{h}} \frac{100\,\text{cm}^2}{\text{dpm}}\right]}{\left[\frac{\text{Sv}}{\text{d}} \frac{\text{m}^2}{\text{Bq}}\right]} = \left[\frac{(100)\ 100\ \text{cm}^2}{\text{m}^2}\right]\left(\frac{1\ \text{Bq}}{\text{dps}}\right)\left(\frac{1\ \text{dps}}{60\ \text{dpm}}\right)\left(\frac{10^5\ \text{mrem}}{\text{Sv}}\right)\left(\frac{1\ \text{d}}{24\ \text{h}}\right) \tag{6.1}$$

$$4.167E+6 \frac{\left[\frac{\mu\text{Sv}\ 100\ \text{cm}^2}{\text{h}}\right]}{\left[\frac{\text{Sv}\ \text{m}^2}{\text{d}}\right]} = \left(\frac{10^6\ \mu\text{Sv}}{\text{Sv}}\right)\left(\frac{1\ \text{d}}{24\ \text{h}}\right)\left[\frac{(100)\ 100\ \text{cm}^2}{\text{m}^2}\right] \tag{6.2}$$

$$2.505E+8 \frac{\left[\frac{\text{mrem}}{\text{h}} \frac{\text{g}}{\text{pCi}}\right]}{\left[\frac{\text{Sv}}{\text{d}} \frac{\text{m}^3}{\text{Bq}}\right]} = \left(\frac{1.625E+6\ \text{g}}{\text{m}^3}\right)\left(\frac{0.037\ \text{Bq}}{\text{pCi}}\right)\left(\frac{10^5\ \text{mrem}}{\text{Sv}}\right)\left(\frac{1\ \text{d}}{24\ \text{h}}\right) \quad (6.3)$$

$$6.771E+10 \frac{\left[\frac{\mu\text{Sv}\ \text{g}}{\text{h}}\right]}{\left[\frac{\text{Sv}\ \text{m}^3}{\text{d}}\right]} = \left(\frac{1.625E+6\ \text{g}}{\text{m}^3}\right)\left(\frac{10^6\ \mu\text{Sv}}{\text{Sv}}\right)\left(\frac{1\ \text{d}}{24\ \text{h}}\right) \quad (6.4)$$

The inhalation CEDE conversion factors for exposure to contaminated air are provided in units of mrem per pCi inhaled (and μSv per Bq inhaled).

Table 6.2 lists unit conversion factors used to convert the basic dose rate factors in the EPA data file to the desired units for this study.

Table 6.2 Unit conversion factors for inhalation dose factors

Units of EPA database parameter	Multiply by	To obtain value in units
Sv per Bq	3.700E+03	mrem per pCi inhaled
Sv per Bq	1.000E+06	μSv per Bq inhaled

The conversion factors of Table 6.2 are determined as follows:

$$3.700E+3 \frac{\left[\frac{\text{mrem}}{\text{pCi}}\right]}{\left[\frac{\text{Sv}}{\text{Bq}}\right]} = \left(\frac{10^5\ \text{mrem}}{\text{Sv}}\right)\left(\frac{0.037\ \text{Bq}}{\text{pCi}}\right) \quad (6.5)$$

$$1.000E+6 \left[\frac{\mu\text{Sv}}{\text{Sv}}\right] = \left(\frac{10^6\ \mu\text{Sv}}{\text{Sv}}\right) \quad (6.6)$$

Ingestion of radionuclides can occur through several pathways, including ingestion of agricultural crops, ingestion of drinking water, and secondary ingestion of removable contamination in buildings. Secondary ingestion occurs when removable radioactive contamination found on facility surfaces is transferred from a surface to hands, foodstuffs, cigarettes, or other items that enter the mouth. Doses for ingestion pathways are estimated using ingestion CEDE conversion factors obtained from EPA Federal Guidance Report No. 11 (Eckerman, Wolbarst, and Richardson 1988), shown in Table E.2. These dose conversion factors are converted to units of mrem per pCi and μSv per Bq ingested, using

unit conversion factors given in Table 6.3. These unit conversion factors are used for the organ-specific dose factors (for the drinking water scenario), as well as for the CEDE factors.

Table 6.3 Unit conversion factors for ingestion dose factors

Units of starting database parameter	Multiply by	To obtain value in units
Sv per Bq	3.700E+03	mrem per pCi ingested
Sv per Bq	1.000E+06	μSv per Bq ingested

The conversion factors of Table 6.3 are determined in the same manner as described above in Equations (6.5) and (6.6) for the conversion factors of Table 6.2.

6.2.4 Dose Factors for Decay Chains

The basic internal and external dose factors used to calculate the annual TEDEs are taken directly from the dose factor files provided by ORNL. However, special consideration has been given to radioactive decay chains having short-lived progeny following a parent, or for cases in which equilibrium of progeny is assumed, as described in Section 6.1.1.

Radiations from short-lived progeny are assigned to the parent radionuclide immediately preceding the short-lived radionuclide. When short-lived progeny contributions are included, the dose factor for the parent is evaluated using the following expression:

$$DFC_i = DF_i + \sum_{j=1}^{N_d} DF_j F_j \tag{6.7}$$

where DFC_i = combined dose factor (internal or external) for the parent radionuclide i, in appropriate units for the dose factor type

DF_i = dose factor for the parent radionuclide as taken from the database, in appropriate units for the dose factor type

N_d = number of short-lived progeny for which contributions are to be included with the parent radionuclide dose factors, as defined by criteria of Section 6.1.1

j = index of short-lived progeny to be included

DF_j = dose factor for the short-lived radionuclide j, as taken from the database, in appropriate units for the dose factor type

F_j = the fraction of parent transitions that result in production of short-lived radionuclide j.

The progeny transition fractions, F_j, are provided in column 2 of Tables E.2 through E.5.

6.3 Media-Specific Considerations for Exposure Scenarios

The annual TEDEs produced by the scenario analysis are based on the dose rate and CEDE conversion factors described in Section 6.1 and pathway-specific assumptions and parameters, including exposure durations, quantities inhaled or ingested, and media concentrations. This section describes the media-specific considerations used to produce concentrations and doses for inhalation, secondary ingestion, ingestion of agricultural foods, and ingestion or agricultural use of ground water.

6.3.1 Air Concentrations for Inhalation

Evaluation of CEDE for inhalation is performed using equations of the following general form:

$$\begin{aligned}[\text{CEDE for Inhalation}] = {} & [\text{Exposure Duration for Scenario}] \\ & \times [\text{Volumetric Breathing Rate}] \\ & \times [\text{Airborne Dust-Loading}] \\ & \times [\text{Inhalation Dose Factor}] \\ & \times [\text{Mean Activity Level}].\end{aligned} \tag{6.8}$$

The concentration of respirable dust in the air will vary depending upon a variety of factors, including the physical condition (such as the particle size) of the material being handled, the quantity of the material present, and the building ventilation or wind conditions. For this study, concentrations of respirable dust in the air are estimated using mass-loading factors and resuspension factors.

Perhaps the simplest method of estimating air concentrations is to use mass-loading factors. For this method, the average air concentration is defined in terms of g/m^3 of air. This concentration is converted to units of activity using the concentration of the source material. Although dust-loading in itself is not a topic that is widely studied or reported in the literature, topics related to dust-loading are reported, including concentrations of particles, aerosols, and total suspended particulates (TSP). The field of air pollution has the greatest amount of relevant literature, including representative entries in several leading reference books (MaGill, Holden, and Ackley 1956; Stern 1968; U.S. Department of Health, Education, and Welfare [HEW] 1969; Lillie 1970; and Hinton et al., 1986). In addition, health hazard evaluation reports listed in the *Energy Research Abstracts* sometimes contain data for indoor or outdoor concentrations of particles for specific industrial settings. Additional information can be found in the *Air Pollution Control Association Journal* for specific situations.

For indoor dust, 29 CFR 1910.1000 (1990) provides the regulatory limits authorized by the Occupational Safety and Health Administration (OSHA), Department of Labor. The 8-hour time-weighted-average (TWA) value allowed for dust ranges from 5 to 15 mg/m^3. The value for total dust is 15 mg/m^3, but is reduced to 10 mg/m^3 for certain compounds. The respirable fraction of dust is regulated at 5 mg/m^3. Other dusts have specific concentration limits based on their harmful characteristics. Cadmium and crystalline quartz silica are the most restrictive, with limits of 0.02 and 0.05 mg/m^3. Other dusts have limits up to 5 mg/m^3. The American Conference of Governmental Industrial Hygienists

(ACGIH 1987) recommends threshold limit values (TLVs) of 10 mg/m^3 of total dust. This limit is for a "normal workday" and does not apply for short periods of exposure to high concentrations.

For this analysis, the radioactive concentrations in indoor air for the building renovation and residential scenarios have been assumed to be 10^{-4} and $5 \times 10^{-5} g/m^3$, respectively. This range is a fraction of the maximum total dust limits, representing longer-term average concentrations and accounting for airborne dust from nonradioactive sources. This range provides a prudently conservative estimate of actual radioactive dust-loadings in the workplace or household, and serves as an adequate basis for the first-level generic screening analysis.

For outdoor air concentrations, a number of references provide information for a wide variety of situations. In *Air Pollution, Vol. I* (Stern 1968), measurements from the National Air Sampling Network for urban stations are summarized for the period 1957-1963. Chemical analysis for suspended particles (soot and ash) of 14,494 urban and 3,114 nonurban samples in the United States yielded a geometric mean of 98 $\mu g/m^3$, with a maximum of 1706 $\mu g/m^3$. Information in *Air Quality Criteria for Particulate Matter* (HEW 1969) indicated that

> ...average suspended particle mass concentrations range from about 10 $\mu g/m^3$ in remote nonurban areas to about 60 $\mu g/m^3$ near urban locations. In urban areas, averages range from 60 $\mu g/m^3$ to 220 $\mu g/m^3$, depending on the size of the city and its industrial activity.

The *Air Pollution Handbook* (MaGill, Holden, and Ackley 1956) reported that suspended particles in the atmosphere of a number of communities in the United States can range from 100 $\mu g/m^3$ to 1000 or 2000 $\mu g/m^3$. The London smog disaster of December 1952 had concentrations of soot and ash particles that were more than 4000 $\mu g/m^3$ for 6 days with a reported 4000-fold increase over the normal death rate during that period.

Measurements of suspended dust were made at the Bikini Atoll in an effort to determine potential inhalation exposures from plutonium-contaminated soil (Shinn, Homan, and Robinson 1989). Background dust concentrations of 21 $\mu g/m^3$ and sea spray concentrations of 34 $\mu g/m^3$ were measured. The highest suspended dust concentrations measured were for tilling a bare field and were 136 $\mu g/m^3$.

Upper and lower limits of airborne-soil mass-loadings as a function of particle size were estimated for the Hanford Site near Richland, Washington (Sehmel 1975; 1977a; 1984). The volume distributions were for wind erosion, without mechanical disturbance, for a semi-arid climate. For particle sizes less than 10 μm, the upper limit for mass-loading was estimated to be about 700 $\mu g/m^3$. For particle diameters, larger than 10 μm, the upper limit for mass-loading was 232,000 $\mu g/m^3$. The effect of mechanical disturbances is to create somewhat higher localized air concentrations than for wind erosion alone. For comparison, relatively clean air has a dust-loading of about 20 $\mu g/m^3$ (Sehmel 1977b); a dust-loading of 110,000 $\mu g/m^3$ is barely tolerable for breathing (Stewart 1964); and the dust concentration measured in a dust devil (whirlwind) is approximately 5 g/m^3 (Sinclair 1976).

Previous efforts have been made to determine a long-term average dust-loading for purposes of radiation dose assessment. A 1973 study assessed the potential environmental impacts of the interim storage of commercial high-level wastes in a retrievable surface storage (Soldat et al. 1973). This high-level waste assessment used an average atmospheric dust-loading of 100 $\mu g/m^3$ as being a typical annual average dust-loading. In 1975, Anspaugh et al. suggested the use of 100 $\mu g/m^3$ for predictive purposes. This value was partly based on measurements for 30 nonurban locations with arithmetic averages from 9 to 70 $\mu g/m^3$ (Anspaugh et al. 1975).

For the residential scenario, long-term average outdoor dust-loadings are assumed to be 1×10^{-4} g/m^3 (100 $\mu g/m^3$), consistent with the value selected by previous studies. Short-term gardening activities are likely to produce localized, elevated dust-loadings. To account for this possibility, the dust-loading for gardening is assumed to be 5×10^{-4} g/m^3

(500 $\mu g/m^3$). These dust-loadings are within the ranges established from literature sources and should result in a prudently conservative first-level generic screening analysis.

For the building occupancy scenario and indoor exposure to house dust in the residential scenario, the resuspension factor method is used. For this method, the average airborne concentration is a function of a resuspension factor and the surface contamination level, as follows:

$$c = S_f S_A \tag{6.9}$$

where c = average airborne concentration (pCi/m^3 or Bq/m^3)

S_f = resuspension factor (m^{-1})

S_A = activity per unit area (pCi/m^2 or Bq/m^2).

The typical ranges for reported resuspension factors, as shown in Table 6.4 is from about 10^{-11} to 10^{-4} m^{-1}.

To apply a resuspension factor analysis, there must be a reasonably uniform level of removable surface contamination, as would be found for soil contamination conditions. The IAEA suggested an indoor resuspension factor of 5×10^{-5} m^{-1} (IAEA 1970). This factor was intended to apply to operating nuclear facilities. Inside buildings after decontamination operations, it is unlikely that significant removable surface contamination would be present. This value is within the range of resuspension factors cited by Sehmel (1980) for activities conducted within rooms. For the building occupancy scenario of this study, a lower value of 10^{-6} is used because surfaces are assumed to be cleaned of easily removable contamination at the time of license termination. This value provides a prudently conservative basis for the generic analysis of the building occupancy scenario. For the residential scenario, the IAEA-suggested indoor resuspension factor value of 5×10^{-5} m^{-1} is used because the airborne material is largely soil tracked into the house.

For this analysis, the inhalation CEDEs are calculated using an assumed particle size distribution of 1-μm average median aerodynamic diameter (AMAD). A listing of the assumed inhalation classes that were selected to provide a prudently conservative estimate of the potential inhalation dose, as calculated using the ICRP lung model, is shown in Table E.6 of Appendix E. In most cases, the inhalation class selection will maximize the potential inhalation dose. For plutonium, the inhalation class selection represents the most common chemical form that will likely be encountered in environmental situations.

Local annual averaged dust-loadings may be higher or lower than the values assumed in this study, depending on soil and wind conditions.

6.3.2 Secondary Ingestion Rates

Ingestion of removable surface contamination inside buildings after transfer to hands, foods, or other items entering the mouth is referred to as secondary ingestion. This pathway can be of importance for beta-emitters and is included in the building renovation and building occupancy scenarios to provide a balanced set of pathways for evaluation. The ingestion CEDE conversion factors are used to evaluate secondary ingestion in the scenario analysis. The secondary ingestion doses for building renovation and building occupancy are described in Section 3. The equations for secondary ingestion are of the general form of Equation (6.10):

Table 6.4 Reported resuspension information

Condition, author, and reference	Resuspension factor range (m^{-1})	Comments
Wind Stress		
Stewart (1964)	2×10^{-11} to 8×10^{-9}	Bare soil, ^{91}Y aqueous chloride.
Stewart (1964)	9×10^{-8} to 1×10^{-7}	^{210}Po as oxide.
Stewart (1964)	9×10^{-8} to 5×10^{-7}	U_3O_8.
Anspaugh et al. (1974)	1×10^{-4} to 1×10^{-9}	Time-dependent model for plutonium in soil.
Sehmel (1980)	9×10^{-11} to 3×10^{-4}	Literature review.
Shinn, Homan, and Hofmann (1986)	1.8×10^{-13} to 6.1×10^{-10}	Nevada Test Site, plutonium aerosols.
Garland and Pattenden (1990)	$< 2 \times 10^{-9}$ $< 5 \times 10^{-10}$	Nuclear weapon test debris: 13 years after deposition 22 years after deposition.
Garland and Pattenden (1990)	3.6×10^{-9} to 4.9×10^{-8}	Chernobyl ^{137}Cs deposition: initial factor, reduce by 0.23 to 0.64 within the first year.
Vegetation		
Healy and Fuquay (1959)	2.9×10^{-8} to 6×10^{-7}	Fluorescent powder.
Stewart (1964)	3×10^{-8} to 5×10^{-5}	U_3O_8.
Mechanical Disturbances		
Stewart (1964)	1.5×10^{-6} to 3×10^{-4}	Plutonium.
Sehmel (1974)	4.8×10^{-5} to 1.1×10^{-2}	ZnS, per disturbance.
Sehmel (1977a)	1×10^{-5} to 2×10^{-4}	ZnS, per disturbance.
Sehmel (1980)	1×10^{-10} to 4×10^{-2}	Literature review.
Indoor Buildings		
IAEA (1970)	5×10^{-5}	Surface contamination.
Sehmel (1980)	1×10^{-6} to 2×10^{-2} 2×10^{-4} to 4×10^{-2} 2×10^{-5} to 1.5×10^{-2}	Walking. Vigorous sweeping. Fan.

$$\begin{aligned}[\text{CEDE for Ingestion}] = &[\text{Exposure Duration for Scenario}] \\ &\times [\text{Effective Transfer Rate for Ingestion}] \\ &\times [\text{Ingestion Dose Factor}] \\ &\times [\text{Mean Volume Activity}].\end{aligned} \tag{6.10}$$

To estimate the secondary ingestion effective transfer rate, a literature survey was conducted. Previous dose evaluations for ingestion of loose surface contamination have been directed toward chronic occupational exposure situations (Dunster 1962; Gibson and Wrixon 1979; Healy 1971; Kennedy et al. 1981). Additional studies have been conducted in estimating the quantities of lead contamination that could be ingested by different age groups (Sayre et al. 1974; Lepow et al. 1975; Walter, Yankel, and Von Lindern 1980; Gallacher et al. 1984; LaGoy 1987). A summary of the referenced surface contamination ingestion data is given in Table 6.5. A review of previous work on secondary ingestion pathways indicates that no quantitative data for radioactive materials are available. Because of this lack of data, previous dose estimates for secondary ingestion have relied on assumed effective transfer rates. Quantitative data for ingestion of lead by children indicate that they may ingest 11 to 50 mg of lead from hand surfaces with a frequency of up to 10 times per day (Sayre et al. 1974; Lepow et al. 1975; Walter, Yankel, and Von Lindern 1980; Gallacher et al. 1984; LaGoy 1987). The total quantity ingested per day by children may range upward from about 0.1 g.

For our analysis, adult workers are assumed to ingest less removable contamination than children, and renovation workers are assumed to ingest at a higher rate than workers who have routine occupancy. To estimate the potential radiation doses resulting from secondary ingestion, adult renovation workers are assumed to ingest 10 mg of loose surface contamination per hour of exposure. Workers during routine building occupancy are assumed to ingest surface loose contamination at a lesser rate because of the general reduction of removable surface contamination in the building. The assumed secondary ingestion effective transfer rate for building occupancy is the loose surface contamination associated with an area of 10^{-4} m^2 per hour of exposure. These assumed values are within the range of values reported in the literature for secondary ingestion. In general, the most soluble form of each element was assumed to maximize the calculated ingestion dose, as shown by the assumed f_1 values in Table E.6 of Appendix E. These assumptions should form a conservative basis for the first-level generic screening analysis.

Evaluation of the dose from ingestion of soil for the residential scenario requires an estimate of the average daily intake of soil by an individual. Considerable uncertainty (and variability) exists in estimating values for soil intake. Also, most experiments designed to estimate effective transfer rates for soil ingestion have been directed toward children. Early estimates of soil ingestion rates were based largely on observations of mouthing behavior and measurements of soil on hands (LaGoy 1987). Calabrese and Stanek (1991) have recently reviewed and reported on attempts to estimate soil ingestion rates experimentally by measuring tracer metal concentrations in soil and feces. Table 6.6 lists effective transfer rates for soil ingestion reported in literature cited by Calabrese and Stanek (1991), plus other studies as identified in the table.

Calabrese and Stanek (1991) reviewed four major studies of soil ingestion rates (Binder, Sokal, and Maughan [1986], Calabrese et al. [1989], Davis et al. [1990], and Van Wijnen, Clausing, and Brunekreef [1990]). They concluded, based on an evaluation of experimental design and statistics related to tracer detection, that the quantitative results of the Binder and Van Wijnen studies were questionable. The other two studies were concluded to be of value and indicate that soil intake by children is generally less than 100 mg/d (except for children who exhibit unusual soil ingestion habits).

Table 6.5 Referenced surface-contamination ingestion data

Author and reference	Reported ingestion rate or other value	Comments
Dunster (1962)	10^{-3} m^2/d	Chronic ingestion of MPC_w values of ^{226}Ra, ^{90}Sr, and ^{210}Pb to derive permissible levels of skin contamination.
Gibson and Wrixon (1979)	10^{-3} m^2/d	Chronic ingestion. No data available to improve Dunster's model (MPC_w analysis).
Healy (1971)	10^{-4} m^2/h	Chronic ingestion during 8 h for workers, 24 h for members of the public. These are arbitrary assumptions in an effort to account for presumed higher intake by children--2.4 E-3 m^2/d.
Kennedy et al. (1981)	10^{-4} m^2/h	Chronic ingestion of removable surface contamination on transportation containers. Dose estimates for both workers and members of the public (2000 h/y exposure).
Sayre et al. (1974)	0.018 m^2 of dust on hands (children)	Dirt-hand-mouth ingestion route by children for intake of lead dust. Measurement of the amount of lead dust on children's hands compared with the level present on surfaces in a house.
Lepow et al. (1975)	0.1 g/d (children)	"Hands-in-mouth" exposure route is the principal cause of excessive lead ingestion. Mean measured weight on children's hands was 11 mg. Assuming a mouthing frequency of 10 times/d for small children yields an estimate of 0.1 g of dirt ingested/d.
Walter, Yankel, and Von Lindern (1980)	Age-dependent	Secondary risk factors for lead ingestion were found to be age-dependent. Household dustiness is a factor for ages 2 years and under; soil lead is a factor for ages 2 to 7 years.
Gallacher et al. (1984)	10^{-3} to 3 x 10^{-3} m^2/h (children)	Data comparing environmental and hand contamination of lead on children's hands was equivalent by 20 to 50 mg. This level was estimated to equal about 1 E-3 to 3 E-3 m^2 at the level present in outdoor areas.

The 1990 study by Calabrese et al. is the only reported study in which adult soil intake rates were measured (mean intake range was 5-77 mg/d depending on the tracer used in the evaluation). Based largely on this study and the belief that the adult soil ingestion rate would be less than that for small children (the age examined by most other studies), a soil ingestion rate of 50 mg/d (0.05 g/d) was selected as a reasonably conservative value for the residential scenario. This parameter selection should provide a prudently conservative basis for the first-level generic screening analysis.

Table 6.6 Referenced secondary soil ingestion rates

Author and reference	Reported ingestion rate (mg/d)	Age	Comments
National Academy of Science (1980)	day20	Adult	Suggested value for adults (estimated).
Lepow et al. (1975)	100	Child	Estimated from mouthing and measurements of soil on hands.
Hawley (1985)	66 30-160	Adult Child	Estimated values. Estimated values.
Binder, Sokal, and Maughan (1986)	130	Child	Arithmetic mean using tracers (Al and Si).
Calabrese et al. (1989)	9-40	Child	Median measured values using tracers (Al, Si, and Y) with food ingestion taken into account.
Davis et al. (1990)	39-82	Child	Mean measured values using tracers (Al and Si).
Calabrese et al. (1990)	5-77	Adult	Mean measured values using tracers (Al, Si, Y, and Zr) with food ingestion taken into account.
Van Wijnen, Clausing, and Brunekreef (1990)	0-90	Child	Geometric mean values using tracers (Al, Ti, and acid-insoluble residue) for children in daycare centers.
Van Wijnen, Clausing, and Brunekreef (1990)	30-200	Child	Geometric mean values using tracers (Al, Ti, and acid-insoluble residue) for children in campgrounds.
EPA (1991)	200 100	Child Adult	Values selected for use in exposure analyses for individuals in an agricultural setting.
EPA (1991)	50	Adult	Value selected for use in exposure analyses for individuals in an industrial setting.

6.4 Water-Use Model Data

This section discusses the parameter values selected for implementation of the three-box water-use model for the drinking water and residential scenarios.

Selection of 0.18 m/y as the infiltration rate determined for humid areas should provide a bounding assumption because many sites are located in areas of lower annual rainfall. This value was obtained from the waste management literature (Oztunali et al. 1981), and the same value is used for both scenarios. The application of irrigation water is relevant to arid areas and is necessary to supplement a lack of precipitation. The total infiltration for such areas is therefore expected to be approximately the same as for humid areas that do not involve irrigation. Also, selection of 0.3 as the porosity of the soil is intended to provide a bounding analysis. The irrigation rate is set to 76 cm/y (about 30 in./y) or 2.08 $L/m^2 \cdot d$. This is a representative value sufficient to produce most crops.

The partition coefficients are used to develop the leach-rate constants between the surface-soil layer, the unsaturated-soil layer, and the aquifer. Sheppard and Thibault (1990) have suggested values for solid/liquid partition coefficients for several elements and for four types of soil: sand, loam, clay, and organic. Sand soil was characterized as mineral soils with >70% sand-sized particles. Clay soil was characterized as mineral soils with >35% clay-sized particles. Loam soils had approximately even distributions of sand-, clay-, and silt-sized particles, or consisted of up to 80% silt-sized particles. Soils with >30% organic matter were classified as organic soils and were either peat or muck soils, or the litter horizon of mineral soils. A set of partition coefficients was presented in Sheppard and Thibault (1990), based on either experimental values from the literature or derived from soil-to-plant concentration ratio data. For this study, experimental values are used, when available. The smallest partition coefficients (over all four types of soils) were selected, which represents the most mobile prediction. For the remainder of the elements, partition coefficients have been estimated from soil-to-plant concentration ratios as defined for leafy vegetables (essentially whole plant values), using the following correlation (Thibault, Sheppard, and Smith 1990) for sand soils:

$$\ln\left(Kd_{ki}\right) = 2.11 - 0.56 \ln\left(B_{iv}/4\right) \tag{6.11}$$

where Kd_{ki} = partition coefficient for radionuclide i in soil layer k (mL/g)

B_{iv} = concentration ratio for vegetative parts of the plant v (dry-weight basis) for radionuclide i

4 = factor for conversion of B_{iv} values from dry-weight to wet-weight basis.

The value for k is either 1 (for the surface-soil layer) or 2 (for the unsaturated-soil layer). The B_{iv} values were taken from the transfer factor database described in Section 6.5. It should be noted that the coefficient to the concentration ratio logarithm term (-0.56) is taken from Thibault, Sheppard, and Smith (1990) and was incorrectly printed as -0.5 in Sheppard and Thibault (1990).[a]

The partition coefficients (Kd_{ki}) resulting from the above selection methods are listed in Table 6.7, which was prepared from computer-readable electronic files, anticipating their direct use in user-friendly software implementing the scenario/pathway analysis. It should also be noted that a single value for Kd_{ki} is defined for each element to be used for both soil layers for the first level of screening analysis.

The use of the simple three-box water-use model with these conservative default parameter values provides a conservative estimate of the potential concentrations that could be present in ground-water systems from residual radioactive contamination in soil. This approach is intentionally adopted to ensure that the first-level generic screening produces conservative results.

(a) Confirmed by personal communication with Dr. Marsha Sheppard by D. L. Strenge on May 19, 1992.

Table 6.7 Partition coefficients (Kd_{id}) for the water-use model

Element	Partition Coefficient	Basis*	Element	Partition Coefficient	Basis*
H	0.0E+0	M	Sb	4.5E+1	E
Be	2.4E+2	R	Te	1.4E+2	R
C	6.7E+0	C	I	1.0E+0	E
F	8.7E+1	R	Xe	0.0E+0	M
Na	7.6E+1	R	Cs	2.7E+2	E
P	8.9E+0	R	Ba	5.2E+1	R
S	1.4E+1	R	La	1.2E+3	R
Cl	1.7E+0	R	Ce	5.0E+2	E
K	1.8E+1	R	Pr	2.4E+2	R
Ca	8.9E+0	R	Nd	2.4E+2	R
Sc	3.1E+2	R	Pm	2.4E+2	R
Cr	3.0E+1	E	Sm	2.4E+2	R
Mn	5.0E+1	E	Eu	2.4E+2	R
Fe	1.6E+2	E	Gd	2.4E+2	R
Co	6.0E+1	E	Tb	2.4E+2	R
Ni	4.0E+2	E	Ho	2.4E+2	R
Cu	3.0E+1	R	W	1.0E+2	R
Zn	2.0E+2	E	Re	1.4E+1	R
As	1.1E+2	R	Os	1.9E+2	R
Se	1.4E+2	R	Ir	9.1E+1	R
Br	1.4E+1	R	Au	3.0E+1	R
Kr	0.0E+0	M	Hg	1.9E+1	R
Rb	5.2E+1	R	Tl	3.9E+2	R
Sr	1.5E+1	E	Pb	2.7E+2	E
Y	1.9E+2	R	Bi	1.2E+2	R
Zr	5.8E+2	R	Po	1.5E+2	E
Nb	1.6E+2	R	Rn	0.0E+0	M
Mo	1.0E+1	E	Ra	5.0E+2	E
Tc	1.0E - 1	E	Ac	4.2E+2	R
Ru	5.5E+1	E	Th	3.2E+3	E
Rh	5.2E+1	R	Pa	5.1E+2	R
Pd	5.2E+1	R	U	1.5E+1	E
Ag	9.0E+1	E	Np	5.0E+0	E
Cd	4.0E+1	E	Pu	5.5E+2	E
In	3.9E+2	R	Am	1.9E+3	E
Sn	1.3E+2	R	Cm	4.0E+3	E
Sb	4.5E+1	E	Cf	5.1E+2	R

* Values for partition coefficients are based on: M - Assumed to be mobile; R - Calculated from concentration ratios using Equation (6.11); C - Experimental data from Sheppard, Sheppard, and Amiro (1991); or E - Experimental data from Sheppard and Thibault (1990).

6.5 Agricultural Pathway Data

Specific values used for parameters in the agricultural product equations were taken from the literature, when possible, or developed for the specific models of this study, when necessary. The parameter values used and their sources are described below.

6.5.1 Animal Feed Intake Rates

The intake rates are all expressed as kg wet weight of plant per day during a 1-year period. For grains, the intake is based on the weight of the grain. The intake rates are given in Table 6.8.

Table 6.8 Animal feed and water intake rates

Intake media	Intake rate (kg wet weight/d)*			
	Beef	Poultry	Milk	Eggs
Fresh forage	27	0.13	36	0.13
Stored hay	14	-	29	-
Stored grain	3	0.09	2	0.09
Water	50	0.3	60	0.3

*References cited in text.

The feed intake rates for beef are based on a total daily intake of 12 kg (dry weight) per day (IAEA 1982), with 25% of this being in the form of forage, 50% as stored hay, and 25% as stored grains. The stored hay intake is based on a fresh plant water content of 78%, and the stored grain intake is based on a water content of 9% at harvest (Till and Meyer 1983). The milk cow intake rates are based on a total daily intake of 16 kg (dry weight) per day (IAEA 1982), with 50% of this being in the form of fresh forage, 40% as stored hay, and 10% as stored grain. Both forage and hay plants are assumed to have a water content of 78%. For poultry, the intakes are based on a total daily dry-weight intake of 0.11 kg (Ng, Colsher, and Thompson 1982), with 25% of this being fresh forage and 75% being stored grains. The fresh forage component is included because the residential situation could involve poultry allowed to range free.

Evaluation of the wet-weight intake rates is performed using the dry-weight intake rate, the percent intake by feed type, and the percent water content in the feed of interest for the animal type as follows:

$$(\text{Wet-Weight Intake Rate}) = \frac{(\text{Dry-Weight Intake Rate})\ (\text{Percent Intake})}{(100\text{-Percent Water Content})} \qquad (6.12)$$

The water intake requirements by beef animals is set to 50 L/d and for milk cows to 60 L/d (NRC 1977, Napier et al. 1988). Altman and Dittmer (1974) also report that cows drink approximately 60 L/d. The water intake rate for poultry is set to 0.3 L/d (Napier et al. 1988).

All of the feed and water intake rates represent total intake by the animal. For cases in which uncontaminated feed is used to supplement the feed produced onsite, these values may be reduced to represent only the contaminated feed intake. This reduction is represented in the equations of Section 5 and Appendixes C and D by the contaminated feed

fraction parameters: x_f (fresh forage), x_h (stored hay), x_g (stored grain), and x_w (water). The default values for these feed fractions are set to 1.0, representing total intake being derived from contaminated sources.

The intake rate of soil by animals during grazing is quite variable and depends on seasonal factors and the behavior of specific animals. For cattle, the intake rate can vary from 1% to 18% of the dry-matter intake (data summarized by Thorton and Abrahams 1983), based on studies of grazing animals in Britain and New Zealand. One study reported by Fries (1982 and 1987), indicated that cattle in areas where grazing can occur during the entire year ingest about 6% of dry-matter intake as soil. Simmons, Linsley, and Jones (1979) suggest that soil can contribute 4% of the dry matter consumed by cows. Free-range poultry are expected to take in even more soil because of their need to supply sand to their gizzards. Thorne (1984) suggested a value of 10% of dry-matter intake be used for poultry, although no data are available to support that figure. Based on the above information and the suggestions of Thorne (1984), the default soil intake for cattle (beef and milk cows) is set to 5% of dry-matter intake. For poultry (poultry and egg hens), the intake value is set to 10% of dry-matter intake.

6.5.2 Plant Soil Mass-Loading Factor

The transfer of activity from soil to plants is represented by two pathways: root uptake and resuspension to plant surfaces. These pathways are included in equations of Section 5 through the concentration ratio, B_{iv}, and plant soil mass-loading factor, ML_v, respectively. The plant soil mass-loading factor measures the amount of soil on plants. Evaluation of the plant soil mass-loading factor is based on data from the literature for systems in which transfer is expected to be dominated by the resuspension pathway. (Concentration ratio values are presented in Section 6.5.9.) Note that the plant soil mass-loading factor is not a function of radionuclide because the controlling mechanism is assumed to be transfer of soil.

The dominant pathway depends mainly on the radionuclide and the ability of plants to take in the radionuclide via roots. For radionuclides that are easily taken in via roots, the root uptake pathway will dominate and the concentration ratio value will control the transfer from soil to plant. For radionuclides that are not readily taken in by plant roots (e.g., radionuclides that are bound to the soil), the resuspension pathway will dominate and the plant soil mass-loading factor will control the transfer from soil to plant.

Citing data from monitoring studies at the Nevada Test Site, Martin and Bloom (1980) suggest that 99% of the transfer of plutonium from soil to plants occurs via the resuspension route. Pinder et al. (1990) also found that plutonium resuspension was about an order of magnitude more important for transfer from soil to corn grains at the Savannah River Site. Estimation of plant concentrations for cases where resuspension dominates can be represented as follows:

$$C_{vi} = C_{si}\, ML_v \tag{6.13}$$

where C_{vi} = concentration of parent radionuclide i in food crop v in equilibrium with activity in soil (pCi/g dry plant)

C_{si} = concentration of parent radionuclide i in soil (pCi/g dry soil)

ML_v = plant mass-loading factor for plant type v (g dry soil/g dry plant).

The appropriate value for the plant soil mass-loading factor, as applied in Equation (6.13), includes consideration of translocation of activity in soil from plant surfaces to edible parts of the plant.

Martin and Bloom (1980) suggest that the estimation of activity on plants can be described by an effective concentration ratio that includes both routes of transfer. This approach can also be represented by Equation (6.13) if the mass-loading factor is replaced by the effective concentration ratio, as follows:

$$C_{vi} = C_{si}\, CR_v \tag{6.14}$$

where CR_v is the effective concentration ratio for transfer of material from soil to plants (pCi/g dry plant per pCi/g dry soil).

The effective concentration ratio and the plant mass-loading factor are equivalent for systems in which resuspension dominates the transfer from soil to plants. Table 6.9 provides a summary of reported values for the plant soil mass-loading factor, and Table 6.10 summarizes data on effective concentration ratios. The values presented show a considerable variation, ranging between a low of 0.0011 and a high of 0.26. A default value for the plant soil mass-loading factor of 0.1 is selected. Even though this value is more than a factor of two less than the highest reported values, it is believed to represent a prudently conservative estimate of resuspension transfer from soil to edible parts of plants. The reported values of plant soil mass-loading represent soil adhered to plant surfaces, and do not necessarily include the translocation of activity to edible parts of plants. Therefore, selection of a default value less than the maximum values is appropriate.

A review of concentration ratio values for elements of interest in the present study (Section 6.5.9) indicates that several radionuclides have reported values greater than the effective concentration ratios and plant mass-loading factors given in Tables 6.9 and 6.10. This suggests that the effective concentration ratio method (using data cited in the two tables) should not be based solely on plant mass-loading factors. In keeping with the desire to provide a prudently conservative analysis, the radionuclide concentration in edible parts of plants is evaluated as the sum of contributions from root uptake and resuspension: the pathways are not lumped into one effective concentration ratio. The summation over the two pathways is indicated in Equation (5.5) (and other equations of Section 5) as the sum of ML_v and B_{jv}.

6.5.3 Holdup Times

The time between harvest and consumption of each food product is based on values suggested by the NRC (1977) for a maximally exposed individual for food crops and beef. A nominal minimum time of 1 day is assigned to the other animal products, as indicated in Table 6.11.

6.5.4 Exposure Period/Animal Feeding Times

Because the animal products are assumed to be harvested continuously, the animal feeding is made to coincide (in length) with the human consumption period. Also, the residential scenario is to provide the dose for a 1-year period. For these reasons, the animal feeding times and human consumption periods are set to 1 year (365.25 days) for all food products.

6.5.5 Crop-Growing Periods

The growing periods for food crops and animal-fed crops are based on suggestions by Soldat and Harr (1971), Kennedy et al. (1987), and Napier et al. (1988). The values used for the crop-growing periods are given in Table 6.12. These values represent the time to produce one crop and may not be the same as the growing season, during which multiple crops may be harvested.

Table 6.9 Summary of plant mass-loading data*

Plant conditions	Reported values (g soil/g dry plant)	References
Bush beans	0.03 - 0.06	White, Hakonson, and Ahlquist (1981)
Squash (<2 m above soil)	0.14 - 0.26	White, Hakonson, and Ahlquist (1981)
Squash (>2 m above soil)	0.03 - 0.04	White, Hakonson, and Ahlquist (1981)
Broccoli	0.01	McLeod, Pinder, and Watts (1984)
Cabbage	0.0011	McLeod, Pinder, and Watts (1984)
Lettuce	0.26	McLeod, Pinder, and Watts (1984)
Turnips	0.032	McLeod, Pinder, and Watts (1984)
Sunflowers	0.0026	Pinder and McLeod (1988)
Tobacco	0.0021	McLeod et al. (1984)
Tomato plants	0.017	Dreicer et al. (1984)
Meadow vegetation	0.018 (mean) 0.25 (max)	Arthur and Alldredge (1982)
English pastures	0.07	Green and Dodd (1988)
English pastures	0.05 - 0.20	Sumerling, Dodd, and Green (1984)

*Data cited by Pinder and McLeod (1989)

Table 6.10 Summary of effective concentration ratio data

Radionuclide	Reported values	Units	References
^{241}Am	0.23, 0.19	g soil/g plant	Gilbert, Engel, and Anspaugh (1989)
$^{239}Pu+^{240}Pu$	0.17, 0.18	g soil/g plant	Gilbert, Engel, and Anspaugh (1989)
^{137}Cs	0.15	g soil/g plant	Gilbert, Engel, and Anspaugh (1989)
Plutonium	0.1	g soil/g plant	Martin and Bloom (1980)

6.5.6 Translocation Fraction from Leaves to Edible Parts

The translocation fraction is the fraction of activity deposited on plant surfaces that reaches the edible parts of the plant. The values used are those recommended by the NRC (1977) and Napier et al. (1988). A value of 1.0 is used for leafy vegetables, grasses, and hay, and a factor of 0.1 is used for other plant types.

Table 6.11 Holdup time for food consumption*

Food product	Holdup time (d)
Leafy vegetables	1
Other vegetables	14
Fruit	14
Grains	14
Beef	20
Poultry	1
Milk	1
Eggs	1

*Based on information in Soldat and Harr (1971) and NRC (1977).

Table 6.12 Minimum crop-growing periods*

Crop type		period (d)
Leafy vegetables		45
Other vegetables		90
Fruit		90
Grains		90
Beef:	forage	30
	stored hay	45
	stored grain	90
Poultry:	forage	30
	stored hay	45
	stored grain	90
Milk cows:	forage	30
	stored hay	45
	stored grain	90
Eggs:	forage	30
	stored hay	45
	stored grain	90

*Based on information in Soldat and Harr (1971), Kennedy et al. (1987), and Napier et al. (1988).

6.5.7 Crop Yields

Values for crop yields are adapted from Shor, Baes, and Sharp (1982); Strenge, Bander, and Soldat (1987); and Napier et al. (1988). The animal feed crop yields are defined by standing biomass for estimation of interception fraction and for the plant concentration calculation. The recommended crop yield values for animal products are provided in Table 6.13, and crop yield values for food crops are given in Table 6.14.

Table 6.13 Crop yields for animal products (kg wet weight/m^2)*

Crop type	Beef	Poultry	Milk	Eggs
Fresh forage	1.5	1.0	1.5	1.0
Stored hay	1.0	1.0	1.0	1.0
Stored feed	1.0	1.0	1.0	1.0

*Based on information in Shor, Baes, and Sharp (1982), Strenge, Bander, and Soldat (1987), and Napier et al. (1988).

Table 6.14 Crop yields for food crops (kg wet weight/m^2)*

Food crop	Yield
Leafy vegetables	2.0
Other vegetables	4.0
Fruit	2.0
Grains	1.0

*Based on information in Shor, Baes, and Sharp (1982), Strenge, Bander, and Soldat (1987), and Napier et al. (1988).

6.5.8 Consumption and Intake Parameters for Humans

The internal dose received by an individual for a particular pathway is directly proportional to the amount of the contaminated medium taken in by the individual. Inhalation dose is dependent on the volumetric breathing rate, and ingestion dose is dependent on the rate of intake of food products and water.

Ingestion of drinking water is evaluated for a daily intake rate of 2 L/d, as suggested by the EPA (1989). This value represents the 90th percentile daily drinking water ingestion rate as tap water, including uses in cooking and for beverages prepared using tap water (coffee, tea, etc.). Use of this value provides a conservative basis for the first-level generic screening analysis.

The intake rates for food products defined for the agricultural pathways are based on data collected during the Nationwide Food Consumption Survey (Pao et al. 1985; U.S. Department of Agriculture 1983). This study involved the collection of 3-day food intake data for about 36,000 individuals in the 48 contiguous states. The data were collected over a period of 1 year (April 1977 through March 1978) and are, therefore, representative of average intakes and include seasonal variations of intake for the food categories. The Nationwide Food Consumption Survey identified several hundred classes of food, selected to include the major types of food in the diet of the general population. Higley and Strenge (1988) condensed the data to 18 food groups and reported mean and median intake values for each group. The present analysis used mean values from these 18 food groups, supplemented by data from Pao et al. (1985), to obtain the mean daily ingestion rates for the eight food groups used in this study. The eight food groups were selected to be representative of food products that would be produced on a farm for home consumption and, therefore, do not include foods such as fish, oils, and sugars. Higley and Strenge (1988) reported only one value for vegetables, rather than the desired breakdown by leafy and other vegetables. The Pao et al. (1985) data were reviewed to determine the leafy vegetable mean intake rate, which was then subtracted from the Higley and Strenge (1988) vegetable value to obtain the "other" vegetable intake rate. The daily ingestion rates for the eight food products are given in Table 6.15.

6.5.9 Agricultural Pathway Transfer Factors

The transfer factor database contains several parameters defined for each element that are used in the agricultural pathway models, plus a partition coefficient that is used in the ground-water analysis. The transfer factors include the

Table 6.15 Daily ingestion rates for foods

Food type	Individual annual consumption rate	Units
Leafy vegetables	11	kg/y
Other vegetables	51	kg/y
Fruit	46	kg/y
Grain	69	kg/y
Beef	59	kg/y
Poultry	9	kg/y
Milk	100	L/y
Eggs	10	kg/y

soil-to-plant concentration factor for each food crop (leafy vegetables, other vegetables, fruit, and grain) and the animal product transfer factors (beef meat, poultry meat, cow milk, and chicken eggs).

The selection of values for the soil-to-plant concentration factors was based on the following hierarchy. The primary reference was the compilation of the International Union of Radioecologists (IUR 1989). For parameter values not defined in that report, the compilation of Baes et al. (1984b) was used. Finally, for californium (not included in Baes et al. 1984b), the values were taken from Strenge, Bander, and Soldat (1987). Table 6.16 gives the values for

Table 6.16 Soil-to-plant concentration factors

Element/atomic number	Soil-to-plant concentration factors (pCi/kg dry weight per pCi/kg soil) Leafy vegetables	Root vegetables	Fruit	Grain
H 1	(-)*	(-)*	(-)*	(-)*
Be 4	1.0E-2	1.5E-3	1.5E-3	1.5E-3
C 6	7.0E-1	7.0E-1	7.0E-1	7.0E-1
N 7	3.0E+1	3.0E+1	3.0E+1	3.0E+1
F 9	6.0E-2	6.0E-3	6.0E-3	6.0E-3
Na 11	7.5E-2	5.5E-2	5.5E-2	5.5E-2
Mg 12	1.0E+0	5.5E-1	5.5E-1	5.5E-1
Si 14	3.5E-1	7.0E-2	7.0E-2	7.0E-2
P 15	3.5E+0	3.5E+0	3.5E+0	3.5E+0
S 16	1.5E+0	1.5E+0	1.5E+0	1.5E+0
Cl 17	7.0E+1	7.0E+1	7.0E+1	7.0E+1
Ar 18	(-)**	(-)**	(-)**	(-)**
K 19	1.0E+0	5.5E-1	5.5E-1	5.5E-1
Ca 20	3.5E+0	3.5E-1	3.5E-1	3.5E-1
Sc 21	6.0E-3	1.0E-3	1.0E-3	1.0E-3
Cr 24	7.5E-3	4.5E-3	4.5E-3	4.5E-3
Mn 25	5.6E-1	1.5E-1	5.0E-2	2.9E-1
Fe 26	4.0E-3	1.0E-3	1.0E-3	1.0E-3
Co 27	8.1E-2	4.0E-2	7.0E-3	3.7E-3
Ni 28	2.8E-1	6.0E-2	6.0E-2	3.0E-2
Cu 29	4.0E-1	2.5E-1	2.5E-1	2.5E-1
Zn 30	1.4E+0	5.9E-1	9.0E-1	1.3E+0
Ga 31	4.0E-3	4.0E-4	4.0E-4	4.0E-4
As 33	4.0E-2	6.0E-3	6.0E-3	6.0E-3
Se 34	2.5E-2	2.5E-2	2.5E-2	2.5E-2
Br 35	1.5E+0	1.5E+0	1.5E+0	1.5E+0
Kr 36	(-)**	(-)**	(-)**	(-)**
Rb 37	1.5E-1	7.0E-2	7.0E-2	7.0E-2
Sr 38	1.6E+0	8.1E-1	1.7E-1	1.3E-1
Y 39	1.5E-2	6.0E-3	6.0E-3	6.0E-3
Zr 40	2.0E-3	5.0E-4	5.0E-4	5.0E-4
Nb 41	2.0E-2	5.0E-3	5.0E-3	5.0E-3
Mo 42	2.5E-1	6.0E-2	6.0E-2	6.0E-2
Tc 43	4.4E+1	1.1E+0	1.5E+0	7.3E-1

Table 6.16 Soil-to-plant concentration factors (Continued)

Element/atomic number	Soil-to-plant concentration factors (pCi/kg dry weight per pCi/kg soil)			
	Leafy vegetables	Root vegetables	Fruit	Grain
Ru 44	5.2E-1	2.0E-2	2.0E-2	5.0E-3
Rh 45	1.5E-1	4.0E-2	4.0E-2	4.0E-2
Pd 46	1.5E-1	4.0E-2	4.0E-2	4.0E-2
Ag 47	2.7E-4	1.3E-3	8.0E-4	1.0E-1
Cd 48	5.5E-1	1.5E-1	1.5E-1	1.5E-1
In 49	4.0E-3	4.0E-4	4.0E-4	4.0E-4
Sn 50	3.0E-2	6.0E-3	6.0E-3	6.0E-3
Sb 51	1.3E-4	5.6E-4	8.0E-5	3.0E-2
Te 52	2.5E-2	4.0E-3	4.0E-3	4.0E-3
I 53	3.4E-3	5.0E-2	5.0E-2	5.0E-2
Xe 54	(-)**	(-)**	(-)**	(-)**
Cs 55	1.3E-1	4.9E-2	2.2E-1	2.6E-2
Ba 56	1.5E-1	1.5E-2	1.5E-2	1.5E-2
La 57	5.7E-4	6.4E-4	4.0E-3	4.0E-3
Ce 58	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Pr 59	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Nd 60	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Pm 61	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Sm 62	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Eu 63	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Gd 64	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Tb 65	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Dy 66	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Ho 67	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Er 68	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Hf 72	3.5E-3	8.5E-4	8.5E-4	8.5E-4
Ta 73	1.0E-2	2.5E-3	2.5E-3	2.5E-3
W 74	4.5E-2	1.0E-2	1.0E-2	1.0E-2
Re 75	1.5E+0	3.5E-1	3.5E-1	3.5E-1
Os 76	1.5E-2	3.5E-3	3.5E-3	3.5E-3
Ir 77	5.5E-2	1.5E-2	1.5E-2	1.5E-2
Au 79	4.0E-1	1.0E-1	1.0E-1	1.0E-1
Hg 80	9.0E-1	2.0E-1	2.0E-1	2.0E-1
Tl 81	4.0E-3	4.0E-4	4.0E-4	4.0E-4
Pb 82	5.8E-3	3.2E-3	9.0E-3	4.7E-3
Bi 83	3.5E-2	5.0E-3	5.0E-3	5.0E-3
Po 84	2.5E-3	9.0E-3	4.0E-4	4.0E-4
Rn 86	(-)**	(-)**	(-)**	(-)**
Ra 88	7.5E-2	3.2E-3	6.1E-3	1.2E-3
Ac 89	3.5E-3	3.5E-4	3.5E-4	3.5E-4
Th 90	6.6E-3	1.2E-4	8.5E-5	3.4E-5
Pa 91	2.5E-3	2.5E-4	2.5E-4	2.5E-4

Table 6.16 Soil-to-plant concentration factors (Continued)

Element/atomic number	Soil-to-plant concentration factors (pCi/kg dry weight per pCi/kg soil) Leafy vegetables	Root vegetables	Fruit	Grain
U 92	1.7E-2	1.4E-2	4.0E-3	1.3E-3
Np 93	1.3E-2	9.4E-3	1.0E-2	2.7E-3
Pu 94	3.9E-4	2.0E-4	4.5E-5	2.6E-5
Am 95	5.8E-4	4.1E-4	2.5E-4	5.9E-5
Cm 96	3.0E-4	2.4E-4	1.5E-5	2.1E-5
Cf 98	1.0E-2	1.0E-2	1.0E-2	1.0E-2

* Concentration factors for ^{3}H are not needed because a special model is used to determine ^{3}H uptake in plants.

** Noble gas radionuclides are not assumed to be taken up by plants.

soil-to-plant concentration factors used in the present analysis. All soil-to-plant concentration factors are based on unit dry weight of plant. The IUR report (1989) provided values for several plant types. The values were combined by the food crop and animal feed crop types defined for the present study (Table 6.12). The values were combined using a weighted geometric mean formula, with the weights being the number of observation data values for each data value in the IUR report. The compilation by Baes et al. (1984a) provided soil-to-plant concentration factors for vegetative parts and for reproductive parts of the plant. The values for vegetative parts were used for leafy vegetables, forage, and hay, and the values for reproductive parts were used for other vegetables, fruit, grain, and stored animal feed (other than hay).

The soil-to-plant concentration factors are defined in terms of dry weight of plants, but are converted to wet weight values for use in the agricultural models. The dry-to-wet-weight conversion factors given in Table 6.17 are from Till and Meyer (1983). These values apply to the edible parts of plants and may differ from the whole-plant values used in the interception fraction calculation (Section 6.5.2).

The primary source of animal product transfer factors was Napier et al. (1988). Additional values were found in Baes et al. (1984b) for beef and milk. Values for poultry and eggs were difficult to obtain and came primarily from Napier et al. (1988), who took them largely from Ng, Colsher, and Thompson (1982). However, there were several elements for which no information was available. For these elements, transfer factors for poultry and eggs were calculated from data for similar elements in the periodic chart. Values for transfer factors used for the present analysis are given in Table 6.18.

The deposition of contaminated irrigation water on plant surfaces may result in contamination of plants used for food and animal feed. The fraction of deposited activity that is retained on plant surfaces is given by the interception fraction. A value of 0.25 is used for all plant types as recommended by the NRC (1977).

Table 6.17 Dry-to-wet-weight conversion factors

Plant type		Conversion factor
Leafy vegetables		0.2
Other vegetables		0.25
Fruit		0.18
Grain		0.91
Beef	Forage	0.22
	Stored hay	0.22
	Stored grain	0.91
Poultry	Forage	0.22
	Stored hay	0.22
	Stored grain	0.91
Milk	Forage	0.22
	Stored hay	0.22
	Stored grain	0.91
Eggs	Forage	0.22
	Stored hay	0.22
	Stored grain	0.91

6.6 Aquatic Food Pathway Data

Evaluation of dose from the aquatic food pathway requires definition of the consumption rate of aquatic foods, the volume of the surface-water pond, and the bioaccumulation factors for transfer of activity from water to edible parts of fish for elements of interest.

The consumption rate of aquatic foods is expressed as the mass of fish consumed during 1 year of the residential scenario. The EPA (1989) has published a value of 2.37 kg/y (6.5 g/d) for use in exposure assessments for the general population, with intake being from recreational and commercial harvests of marine and freshwater finfish and shellfish. Rupp, Miller, and Baes (1980) summarized consumption rates of fish by region in the United States and also provided U.S. averages. They reported that over 85% of the population eat no freshwater fish. They further report that the U.S. freshwater fish consumption rate is 1.87 kg/y at the 90th percentile; 8.39 at the 99th percentile; and 57.68 as a maximum observed value. The highest 90th percentile value reported was 2.63 kg/y for the West South Central region (Arkansas, Louisiana, Oklahoma, and Texas), and the highest 99th percentile value was 10.03 for the East South Central region (Alabama, Kentucky, Mississippi, and Tennessee). These percentiles are based on the entire population, including those individuals who eat no fish. Because the current scenario involves a resident who is assumed to eat freshwater fish from an available supply, a prudently conservative estimate of annual intake is selected as the 99th percentile value for the highest regional rate, which is 10 kg/y. This represents approximately the 93rd percentile for those individuals who eat freshwater fish within the region.

The volume of the surface-water pond is selected to represent the volume of water necessary to raise enough fish to provide the annual consumption for one individual. Water requirements for raising fish depend on the type of fish and the aquaculture practices used by the resident. For example, if the fish are left to eat natural foods in the pond, a large volume of water will be needed to sustain the food necessary for the fish throughout the entire food chain. On the

Table 6.18 Animal product transfer factors

Element		Animal product transfer factors, wet-weight basis			
		Beef (d/kg)	Poultry (d/kg)	Milk (d/L)	Eggs (d/kg)
H	1	(-)**	(-)**	(-)**	(-)**
Be	4	1.0E-3	4.0E-1	9.0E-7	2.0E-2
C	6	(-)**	(-)**	(-)**	(-)**
N	7	7.5E-2	1.0E-1*	2.5E-2	8.0E-1*
F	9	1.5E-1	1.0E-2*	1.0E-3	2.0E+0*
Na	11	5.5E-2	1.0E-2	3.5E-2	2.0E-1
Mg	12	5.0E-3	3.0E-2*	4.0E-3	1.6E+0
Si	14	4.0E-5	2.0E-1*	2.0E-5	8.0E-1*
P	15	5.5E-2	1.9E-1	1.5E-2	1.0E+1
S	16	1.0E-1	9.0E-1*	1.5E-2	7.0E+0*
Cl	17	8.0E-2	3.0E-2	1.5E-2	2.0E+0*
Ar	18	(-)***	(-)***	(-)***	(-)***
K	19	2.0E-2	4.0E-1*	7.0E-3	7.0E-1*
Ca	20	7.0E-4	4.4E-2	1.0E-2	4.4E-1
Sc	21	1.5E-2	4.0E-3	5.0E-6	3.0E-3*
Cr	24	5.5E-3	2.0E-1*	1.5E-3	8.0E-1*
Mn	25	4.0E-4	5.0E-2	3.5E-4	6.5E-2
Fe	26	2.0E-2	1.5E+0	2.5E-4	1.3E+0
Co	27	2.0E-2	5.0E-1	2.0E-3	1.0E-1
Ni	28	6.0E-3	1.0E-3	1.0E-3	1.0E-1
Cu	29	1.0E-2	5.1E-1	1.5E-3	4.9E-1
Zn	30	1.0E-1	6.5E+0	1.0E-2	2.6E+0
Ga	31	5.0E-4	3.0E-1*	5.0E-5	8.0E-1*
As	33	2.0E-3	8.3E-1	6.0E-5	8.0E-1*
Se	34	1.5E-2	8.5E+0	4.0E-3	9.3E+0
Br	35	2.5E-2	4.0E-3	2.0E-2	1.6E+0
Kr	36	(-)***	(-)***	(-)***	(-)***
Rb	37	1.5E-2	2.0E+0	1.0E-2	3.0E+0
Sr	38	3.0E-4	3.5E-2	1.5E-3	3.0E-1
Y	39	3.0E-4	1.0E-2	2.0E-5	2.0E-3
Zr	40	5.5E-3	6.4E-5	3.0E-5	1.9E-4
Nb	41	2.5E-1	3.1E-4	2.0E-2	1.3E-3
Mo	42	6.0E-3	1.9E-1	1.5E-3	7.8E-1
Tc	43	8.5E-3	3.0E-2	1.0E-2	3.0E+0
Ru	44	2.0E-3	7.0E-3	6.0E-7	6.0E-3
Rh	45	2.0E-3	5.0E-1*	1.0E-2	1.0E-1*
Pd	46	4.0E-3	3.0E-4	1.0E-2	4.0E-3
Ag	47	3.0E-3	5.0E-1*	2.0E-2	5.0E-1*
Cd	48	5.5E-4	8.4E-1	1.0E-3	1.0E-1
In	49	8.0E-3	3.0E-1*	1.0E-4	8.0E-1*

Table 6.18 Animal product transfer factors (Continued)

Element	Animal product transfer factors, wet-weight basis			
	Beef (d/kg)	Poultry (d/kg)	Milk (d/L)	Eggs (d/kg)
Sn 50	8.0E-2	2.0E-1*	1.0E-3	8.0E-1*
Sb 51	1.0E-3	6.0E-3	1.0E-4	7.0E-2
Te 52	1.5E-2	8.5E-2	2.0E-4	5.2E+0
I 53	7.0E-3	1.8E-2	1.0E-2	2.8E+0
Xe 54	(-)***	(-)***	(-)***	(-)***
Cs 55	2.0E-2	4.4E+0	7.0E-3	4.9E-1
Ba 56	1.5E-4	8.1E-4	3.5E-4	1.5E+0
La 57	3.0E-4	1.0E-1	2.0E-5	9.0E-3
Ce 58	7.5E-4	1.0E-2	2.0E-5	5.0E-3
Pr 59	3.0E-4	3.0E-2	2.0E-5	5.0E-3
Nd 60	3.0E-4	4.0E-3	2.0E-5	2.0E-4
Pm 61	5.0E-3	2.0E-3	2.0E-5	2.0E-2
Sm 62	5.0E-3	4.0E-3	2.0E-5	7.0E-3
Eu 63	5.0E-3	4.0E-3	2.0E-5	7.0E-3
Gd 64	3.5E-3	4.0E-3*	2.0E-5	7.0E-3*
Tb 65	4.5E-3	4.0E-3	2.0E-5	7.0E-3
Dy 66	5.5E-3	4.0E-3*	2.0E-5	7.0E-3*
Ho 67	4.5E-3	4.0E-3	2.0E-5	7.0E-3
Er 68	4.0E-3	4.0E-3*	2.0E-5	7.0E-3*
Hf 72	1.0E-3	6.0E-5*	5.0E-6	2.0E-4*
Ta 73	6.0E-4	3.0E-4*	3.0E-6	1.0E-3*
W 74	4.5E-2	2.0E-1*	3.0E-4	8.0E-1*
Re 75	8.0E-3	4.0E-2*	1.5E-3	4.0E-1*
Os 76	4.0E-1	1.0E-1*	5.0E-3	9.0E-2*
Ir 77	1.5E-3	5.0E-1*	2.0E-6	1.0E-1*
Au 79	8.0E-3	5.0E-1*	5.5E-6	5.0E-1*
Hg 80	2.5E-1	1.1E-2	4.5E-4	2.0E-1*
Tl 81	4.0E-2	3.0E-1*	2.0E-3	8.0E-1*
Pb 82	3.0E-4	2.0E-1*	2.5E-4	8.0E-1*
Bi 83	4.0E-4	1.0E-1*	5.0E-4	8.0E-1*
Po 84	3.0E-4	9.0E-1*	3.5E-4	7.0E+0*
Rn 86	(-)***	(-)***	(-)***	(-)***
Ra 88	2.5E-4	3.0E-2*	4.5E-4	2.0E-5
Ac 89	2.5E-5	4.0E-3	2.0E-5	2.0E-3
Th 90	6.0E-6	4.0E-3	5.0E-6	2.0E-3
Pa 91	1.0E-5	4.0E-3	5.0E-6	2.0E-3
U 92	2.0E-4	1.2E+0	6.0E-4	9.9E-1
Np 93	5.5E-5	4.0E-3	5.0E-6	2.0E-3
Pu 94	5.0E-7	1.5E-4	1.0E-7	8.0E-3
Am 95	3.5E-6	2.0E-4	4.0E-7	9.0E-3

Table 6.18 Animal product transfer factors (Continued)

Element	Animal product transfer factors, wet-weight basis			
	Beef (d/kg)	Poultry (d/kg)	Milk (d/L)	Eggs (d/kg)
Cm 96	3.5E-6	4.0E-3	2.0E-5	2.0E-3
Cf 98	5.0E-3	4.0E-3	7.5E-7	2.0E-3

* Transfer factors derived from data for similar elements.
** Transfer factors for ^{3}H and ^{14}C are not needed because special models for transfer in animals are used for these two radionuclides.
*** Noble gases are assumed not to be transferred to animal products.

other hand, if the resident feeds the fish supplemental food, the water volume requirement will be much less. Data provided by Bardach, Ryther, and McLarney (1972) indicate that the mean production rate of catfish for pond culture is about 2600 kg/y per ha of pond area. This should be considered to be a maximum production rate involving a commercial operation using large ponds, with the production representing total fish weight. The area of pond needed to produce the annual ingestion amount of 10 kg/y (edible) can be estimated as follows:

$$\text{Pond Area} = (10 \text{ kg/y}) / [(0.6 \text{ edible fraction}) (2600 \text{ kg/y/ha})] = 0.0064 \text{ ha} \quad (6.15)$$

or 64 m^2, where the edible fraction of catfish is taken to be a nominal value of 0.6 (Bardach, Ryther, and McLarney 1972). This area represents a very small pond in which the fish are provided their feeding requirements. No information is available on fish production rates in farm pond systems in which the fish are totally dependent on aquatic biota produced within the pond ecosystem. For the present analysis, the pond is taken to be 10 times the minimum pond size for cultured ponds, with a water depth assumed to be 2 m. This pond depth will provide protection for aquatic species from temperature extremes plus allow light penetration needed to support the ecosystem. With these assumptions, the volume of water needed for production of the annual fish consumption amount is 1300 m^3 or 1.3×10^6 L.

The transfer of activity from water to edible parts of fish is based on bioaccumulation factors defined for each element of interest. The bioaccumulation factor is the ratio of radionuclide concentration in fish to the radionuclide concentration in water. Table 6.19 lists the default values for bioaccumulation factors. The primary reference for these values is a compilation of recommended freshwater fish bioaccumulation factors by Poston and Klopfer (1988), supplemented by data from Strenge, Peloquin, and Wehlan (1986). The latter reference contains bioaccumulation factors for freshwater fish as used in the NRC computer program LADTAP II in support of NRC Regulatory Guide 1.109 (NRC 1977).

6.7 Summary of Parameters That May Vary and Default Value Assignments

The mathematical formulations contained in Sections 2 through 5 of this report contain numerous parameters that have been identified for each exposure scenario and pathway. Most of these parameters can have a significant range, and the selection of specific values is an important part of the generic evaluation of radiation doses from residual radioactive material. This section summarizes by scenario the model parameters that may vary and provides the assigned default values. The default values are used to generate the first-level screening unit concentration annual

Table 6.19 Fish bioaccumulation factors (BA_{jf}) for the residential scenario

Element	Bioaccumulation Factor	Basis*	Element	Bioaccumulation Factor	Basis*
H	1.0E+0	A	Sn	3.0E+3	B
Be	2.0E+0	B	Sb	2.0E+2	A
C	4.6E+3	B	Te	4.0E+2	B
N	1.5E+5	B	I	5.0E+2	A
F	1.0E+1	B	Cs	2.0E+3	B
Na	1.0E+2	A	Ba	2.0E+2	A
P	7.0E+4	A	La	2.5E+1	B
S	7.5E+2	B	Ce	5.0E+2	B
Cl	5.0E+1	B	Pr	2.5E+1	B
K	1.0E+3	B	Nd	2.5E+1	B
Ca	4.0E+1	B	Pm	2.5E+1	B
Sc	1.0E+2	A	Sm	2.5E+1	B
Cr	2.0E+2	B	Eu	2.5E+1	B
Mn	4.0E+2	A	Gd	2.5E+1	B
Fe	2.0E+3	A	Tb	2.5E+1	B
Co	3.3E+2	A	Ho	2.5E+1	B
Ni	1.0E+2	A	W	1.2E+3	B
Cu	5.0E+1	B	Re	1.2E+2	B
Zn	2.5E+3	A	Os	1.0E+1	B
As	1.0E+2	B	Ir	1.0E+1	B
Se	1.7E+2	B	Au	3.3E+1	B
Br	4.2E+2	B	Hg	1.0E+3	B
Rb	2.0E+3	B	Pb	1.0E+2	B
Sr	5.0E+1	A	Bi	1.5E+1	B
Y	2.5E+1	B	Po	5.0E+2	B
Zr	2.0E+2	A	Ra	7.0E+1	A
Nb	2.0E+2	A	Ac	2.5E+1	B
Mo	1.0E+1	A	Th	1.0E+2	A
Tc	1.5E+1	A	Pa	1.1E+1	B
Ru	1.0E+2	A	U	5.0E+1	A
Rh	1.0E+1	B	Np	2.5E+2	A
Pd	1.0E+1	B	Pu	2.5E+2	A
Ag	2.3E+0	B	Am	2.5E+2	A
Cd	2.0E+2	B	Cm	2.5E+2	A
In	1.0E+5	B	Cf	2.5E+1	B

*Values for fish bioaccumulation factors are based on: A - Poston and Klopfer (1988), B - Strenge, Peloquin, and Whelan (1986).

TEDEs in Volume 2 of this report. The parameters are described using the consistent symbol nomenclature defined in Section 2.1. Users of the screening model software will substitute site-specific values for the default values identified in this section, when they can justify doing so.

6.7.1 Parameters for the Building Renovation Scenario

Table 6.20 lists the parameters that may vary for the pathway analysis described in Section 3.1 for the building renovation scenario. Because this is a relatively simple scenario, only five parameters that may vary have been defined. The first two parameters (t_b and t_{tb}) are the time parameters for the scenario used for all exposure pathways. The next two parameters (V_b and CDB) define the volumetric breathing rate and the average airborne dust-loading in air during renovation work (described in Section 6.3.1), respectively. The final parameter (GB) is the effective transfer rate for ingestion of loose dust, described in Section 6.3.2, in units of g/h.

The time parameters, t_b and t_{tb}, are needed to define the extent of exposure during the renovation period. The exposure is evaluated using the time integral of activity over the renovation period to determine the mean activity level of each radionuclide or decay chain. These parameters could vary from a very short time period to a full year, depending on the type of building encountered and the type of renovation activity considered. An attempt has been made to assign prudently conservative default values for these parameters. The actual time spent on the renovation job (t_b) is assumed to be about 25% of a work year, 500 h or 20.83 d. The total duration of the renovation period (t_{tb}) is also assumed to be about 25% of a calendar year, or 90 calendar days. The combination of these parameter values provides a prudently conservative basis for the first-level screening analysis.

6.7.2 Parameters for the Building Occupancy Scenario

Table 6.21 lists the parameters that may vary for the pathway analysis described in Section 3.2 for the building occupancy scenario. Again, because this is a relatively simple scenario, only five parameters that may vary have been

Table 6.20 Building renovation scenario parameters that may vary and generic default values

Parameter symbol	Default	Units	Description/comments
t_b	20.83	d/y	The time on the job (converted to effective 24-h days) during the renovation period is based on working 40-h weeks over a 90-d period.
t_{tb}	90.	d	The duration of the renovation period is set to 3 months during the year.
V_b	1.2	m^3/h	The volumetric breathing rate is set to the ICRP "light activity" value as an average for the 8-h renovation work day.
CDB	1.E-4	g/m^3	The average dust-loading in air during renovation work activities, as described in Section 6.3.1.
GB	1.E-2	g/h	The effective transfer rate for ingestion of loose dust during building renovation, as described in Section 6.3.2.

Table 6.21 Building occupancy scenario parameters that may vary and generic default values

Parameter symbol	Default	Units	Description/comments
t_o	83.33	d/y	The time in the building (converted to effective 24-h days) during the occupancy period is based on working 40-h weeks (or 2000 h) over the year.
t_{to}	365.25	d	The duration of the occupancy period is set to 1 year, representing continuous use.
V_o	1.2	m^3/h	The volumetric breathing rate is set to the ICRP "light activity" value as an average for the 8-h renovation work day.
RF_o	1.E-6	m^{-1}	The resuspension factor during the occupancy period, as described in Section 6.3.1.
GO	1.E-4	m^2/h	The secondary ingestion transfer rate of removable surface activity during building occupancy, as described in Section 6.3.2.

defined. These parameters are parallel to the parameters identified for the building renovation scenario because similar exposure pathways are used. The first two parameters (t_o and t_{to}) are the time parameters for the scenario used for all exposure pathways. The next two parameters (V_o and RF_o) define the volumetric breathing rate and the resuspension factor during the building occupancy scenario (described in Section 6.3.1), respectively. The final parameter (GO) is the secondary ingestion transfer rate of removable surface activity, described in Section 3.2.5, in units of m^2/h.

The time parameter t_{to} is needed to determine the time integral of activity over the building occupancy period. This time integral is used to determine the mean activity level of each radionuclide or decay chain. These parameters could vary from a very short time period to a full year, depending on how many hours per year an employee is assumed to spend in the office or room during the year. The actual time spent on the job (t_o) is assumed to be 100% of a work year, 2000 h or 83.33 d. This parameter selection is prudently conservative when compared with continuous exposure for a full year (8766 h). The total duration of the occupancy period (t_{to}) is also assumed to be 100% of a calendar year, or 365.25 d, including a correction for leap year so that exact hand calculations may be performed using the equations contained in this report.

6.7.3 Parameters for the Drinking Water Scenario

Table 6.22 summarizes the parameters that may vary for the drinking water scenario. This table lists 10 different parameters, most of which are used in the water-use model described in Section 4.1. Again, an attempt has been made to select values that will result in a prudently conservative (not worst-case) analysis. Only two of the parameters shown in Table 6.22 are not related to the water-use model. These are the drinking water ingestion period, t_d (assumed to be a full year or 365.25 d), and the drinking water ingestion rate, U_w (assumed to be 2.0 L/d).

Eight parameters in Table 6.22 that may vary are identified with the water-use model. The first two are used to define the thickness of the top two boxes in the model. These boxes represent the surface soil (H_1) and the unsaturated zone (H_2). For this analysis, the top box is assumed to be 15-cm thick, or the same thickness assumed for the plow layer in

Table 6.22 Drinking water scenario parameters that may vary and generic default values

Parameter symbol	Default	Units	Description/comments
t_d	365.25	d/y	The drinking water ingestion period is based on continuous use.
U_w	2.0	L/d	Drinking water ingestion rate.
H_1	0.15	m	The thickness of surface-soil layer is set to equal the assumed plow layer.
H_2	1.0	m	The thickness of unsaturated zone.
n_1	0.3	-	The porosity of surface-soil associated with only partially compacted soils, as described in Oztunali et al. (1981).
n_2	0.3	-	The porosity of unsaturated zone, assumed to equal the porosity of the surface-soil.
f_1	1.0	-	Saturation ratio for the surface-soil layer.
f_2	1.0	-	Saturation ratio for the unsaturated-soil layer.
V_{dd}	91250	L	The annual dilution flow is set to the volume of water used by an individual for all domestic purposes during the year, as defined in Miller (1980).
I	0.18	m/y	Infiltration rate based on the high end of the range of infiltration rates determined for humid areas of the United States (Oztunali et al. 1981).
A_d	507	m^2	Area of contaminated site.
Kd_{1i}	Table 6.7	-	Surface soil partition coefficient, as described in Section 6.4.
Kd_{2i}	Table 6.7	-	Subsurface soil partition coefficient, assumed to be the same as the surface soil partition coefficient, as described in Section 6.4.

the agricultural pathway analysis and the same thickness for which external dose factors are defined for the residential scenario. The unsaturated zone is assumed to be 1-m thick. The next parameters represent the porosities of the top two boxes in the three-box water-use model (n_1 and n_2). For this study, the porosity for the top two boxes is assigned a single value of 0.3. This value was selected from the low-level waste management literature as being representative of surface soil that is in a partially compacted condition, as described in Oztunali et al. (1981). The annual dilution flow (V_{dd}) is set equal to the volume of water used by an individual for all purposes during the year, as defined by Miller (1980). This volume is taken to be 91,250 L, of which 2 L/d (or about 730 L/y) is used for drinking. The infiltration rate (I) is based on the high end of the range of infiltration rates determined for humid areas of the United States

(Oztunali et al. 1981). The default value for area of the contaminated site, A_d, is calculated from the pumping volume and the infiltration rate, based on the relationship given by Equation (4.14). Finally, partition coefficients (Kd_{1i} and Kd_{2i}) are derived using the methods described in Section 6.4. Although it may be likely that surface and subsurface-soils will be different, for the generic model analysis, a single set of partition coefficients has been identified for use in both soil layers. The use of the simple three-box water-use model with these conservative default parameter values provides a conservative estimate of the potential concentrations that could be present from residual radioactive contamination in soil. This conservative approach is intentionally adopted to ensure that the first-level screening produces conservative results.

These assumed values allow a generic analysis without attempting to account for site-specific conditions. As noted earlier, it is intended that users of the software (produced and documented in Volume 2 of this report) substitute, whenever possible, site-specific values for default values identified for this scenario to better account for site-specific conditions.

6.7.4 Parameters for the Residential Scenario

The most complicated scenario included in this analysis is the residential scenario. This scenario accounts for future use of contaminated land and includes leaching of radionuclides through the soil into the ground water, with redeposition on the land surface through irrigation. This scenario defines conditions for an individual who resides most of the year onsite and is involved in outdoor gardening activities. The time and pathway assumptions may not be representative of other lifestyles, such as suburban living, where the individual may spend less time outdoors and more time away from home. However, these assumptions are assumed to provide a conservative, complete pathway analysis. The scenario is described in a manner that permits enough pathway flexibility to accommodate modification into a suburban scenario by changing certain default parameters. Table 6.23 lists the parameters that may vary for the residential scenario. Several of the parameters, and their default values, are discussed in other sections of this report. Only those parameters that are not discussed elsewhere are described in this section.

The first four parameters define the times that the individual spends during the year involved in various activities around a house constructed on the land. They account for time spent indoors (t_i), outdoors (t_x), gardening (t_g), and the total time in the year (t_{tr}). Again, the hours of exposure for each of the time categories have been converted to effective days for unit consistency. The default exposure times are 200 d for t_i, 70.83 d for t_x, 4.17 d for t_g, and 365.25 d for t_{tr}.

For the external exposure pathway, two shielding factors have been defined for indoor (SFI) and outdoor (SFO) exposures. These factors are assumed to provide a correction for shielding by either building materials or clean cover soil, when justified. Although these factors should be dependent on the photon energy, single factors across all photon energies are used in this study to match the generic nature of the other simplifying assumptions made in the external dose analysis. The shielding factor afforded by the house is dependent on the type of house construction and the nature of the contaminated soil (i.e., the source thickness, size, and depth of clean cover soil). Previous studies have considered shielding factors associated with the atmospheric deposition of radioactive material from passing plumes after accidental airborne releases (Aldrich, Ericson, and Johnson 1978; Kocher 1978; Jensen 1985). Estimated shielding factors from these studies range from about 0.02 to 0.7, with the majority of the values reported from 0.04 to about 0.4 (Aldrich, Ericson, and Johnson 1978). The situation being modeled in this study is a bit different than a nuclear accident analysis because the dose is from contaminated soil around the house without plume deposition on the roof of the house. For this reason, a shielding factor of 0.33 is used for SFI. Although the shielding factor for outdoor exposures may vary, for this study it is assumed to be 1.0, representing surface-soil contamination with no clean soil cover.

Table 6.23 Residential scenario parameters that may vary and generic default values

Parameter symbol	Default	Units	Description/comments
t_i	200	d/y	Time in the 1-year exposure period that the individual spends indoors (effective days).
t_x	70.83	d/y	Time in the 1-year exposure period that the individual spends outdoors (effective days).
t_g	4.17	d/y	Time in the 1-year exposure period that the individual spends gardening (effective days).
t_{tr}	365.25	d	Total time in the 1-year exposure period.
SFI	0.33	-	Indoor shielding factor.
SFO	1.0	-	Outdoor shielding factor.
P_d	4.E-1	g/m^2	Floor dust-loading.
RF_r	5.E-5	m^{-1}	Resuspension factor for indoor dust, discussed in Section 6.3.1.
CDI	5.E-5	g/m^3	Air dust-loading indoors, discussed in Section 6.3.1.
CDO	1.E-4	g/m^3	Air dust-loading outdoors, discussed in Section 6.3.1.
CDG	5.E-4	g/m^3	Air dust-loading gardening, discussed in Section 6.3.1.
V_r	1.2	m^3/h	Volumetric breathing rate while indoors, based on the ICRP "light activity" value as an average for time spent indoors.
V_x	1.2	m^3/h	Volumetric breathing rate while outdoors, based on the ICRP "light activity" value as an average for time spent outdoors.
V_g	1.2	m^3/h	Volumetric breathing rate while gardening, based on the ICRP "light activity" value as an average for time spent gardening.
GR	5.E-2	g/d	Soil ingestion transfer rate for the residential scenario, as discussed in Section 6.3.2.
U_w	2	L/d	Drinking water ingestion rate.
H_1	0.15	m	The thickness of surface-soil layer is set to equal the assumed plow layer.
H_2	1.0	m	The thickness of unsaturated zone.

Table 6.23 Residential scenario parameters that may vary and generic default values (Continued)

Parameter symbol	Default	Units	Description/comments
n_1	0.3	-	The porosity of surface-soil associated with only partially compacted soils, described in Oztunali et al. (1981).
n_2	0.3	-	The porosity of unsaturated zone, assumed to equal the porosity of the surface-soil.
f_1	1.0	-	Saturation ratio for the surface-soil layer.
f_2	1.0	-	Saturation ratio for the unsaturated-soil layer.
V_{dr}	91,250	L	Volume of water removed from the ground-water aquifer per year for domestic uses.
V_{irr}	*	L	Volume of water removed from the ground-water aquifer per year for irrigation use, based on the irrigation rate.
V_{sw}	1.3E+6	L	Volume of water in the surface-water pond used to grow fish for the aquatic food ingestion pathway.
I	0.18	m/y	Infiltration rate based on the high end of the range of infiltration rates for humid areas of the United States (Oztunali et al. 1981).
Kd_{1i}	Table 6.7	-	Surface-soil partition coefficient, described in Section 6.4.
Kd_{2i}	Table 6.7	-	Unsaturated-soil partition coefficient, assumed to be the same as the surface-soil partition coefficient, described in Section 6.4.
A_r	2500	m^2	Area of land cultivated.
IR	2.08	$L/m^2 \cdot d$	Irrigation water application rate, corresponding to 76 cm/y.
P_s	240	kg/m^2	Soil areal density of surface plow layer.
DIET	0.25	-	Fraction of diet from garden.
U_v	11	kg/y	Human diet of leafy vegetables, discussed in Section 6.5.8.
	51	kg/y	Human diet of other vegetables, discussed in Section 6.5.8.
	46	kg/y	Human diet of fruits, discussed in Section 6.5.8.
	69	kg/y	Human diet of grains, discussed in Section 6.5.8.
U_a	59	kg/y	Human diet of beef, discussed in Section 6.5.8.
	9	kg/y	Human diet of poultry, discussed in Section 6.5.8.
	100	L/y	Human diet of milk, discussed in Section 6.5.8.

Table 6.23 Residential scenario parameters that may vary and generic default values (Continued)

Parameter symbol	Default	Units	Description/comments
	10	kg/y	Human diet of egg, discussed in Section 6.5.8.
U_f	10	kg/y	Human diet of fish, discussed in Section 6.6.
t_{cv}	365.25	d	Food consumption period for leafy vegetables, discussed in Section 6.5.4.
	365.25	d	Food consumption period for other vegetables, discussed in Section 6.5.4.
	365.25	d	Food consumption period for fruits, discussed in Section 6.5.4.
	365.25	d	Food consumption period for grains, discussed in Section 6.5.4.
t_{ca}	365.25	d	Food consumption period for beef, discussed in Section 6.5.4.
	365.25	d	Food consumption period for poultry, discussed in Section 6.5.4.
	365.25	d	Food consumption period for milk, discussed in Section 6.5.4.
	365.25	d	Food consumption period for eggs, discussed in Section 6.5.4.
t_{hv}	1	d	Holdup period for leafy vegetables, discussed in Section 6.5.3.
	14	d	Holdup period for other vegetables, discussed in Section 6.5.3.
	14	d	Holdup period for fruits, discussed in Section 6.5.3.
	14	d	Holdup period for grains, discussed in Section 6.5.3.
t_{ha}	20	d	Holdup period for beef, discussed in Section 6.5.3.
	1	d	Holdup period for poultry, discussed in Section 6.5.3.
	1	d	Holdup period for milk, discussed in Section 6.5.3.
	1	d	Holdup period for eggs, discussed in Section 6.5.3.
t_{gv}	45	d	Minimum growing period for leafy vegetables, discussed in Section 6.5.5.
	90	d	Minimum growing period for other vegetables, discussed in Section 6.5.5.
	90	d	Minimum growing period for fruits, discussed in Section 6.5.5.
	90	d	Minimum growing period for grains, discussed in Section 6.5.5.
t_{gf}	30	d	Minimum growing period for forage consumed by beef cattle, discussed in Section 6.5.5.
	30	d	Minimum growing period for forage consumed by poultry, discussed in Section 6.5.5.
	30	d	Minimum growing period for forage consumed by milk cows, discussed in Section 6.5.5.
	30	d	Minimum growing period for forage consumed by layer hens, discussed in Section 6.5.5.

Table 6.23 Residential scenario parameters that may vary and generic default values (Continued)

Parameter symbol	Default	Units	Description/comments
t_{gg}	90	d	Minimum growing period for stored grain consumed by beef cattle, discussed in Section 6.5.5.
	90	d	Minimum growing period for stored grain consumed by poultry, discussed in Section 6.5.5.
	90	d	Minimum growing period for stored grain consumed by milk cows, discussed in Section 6.5.5.
	90	d	Minimum growing period for stored grain consumed by layer hens, discussed in Section 6.5.5.
t_{gh}	45	d	Minimum growing period for stored hay consumed by beef cattle, discussed in Section 6.5.5.
	45	d	Minimum growing period for stored hay consumed by poultry, discussed in Section 6.5.5.
	45	d	Minimum growing period for stored hay consumed by milk cows, discussed in Section 6.5.5.
	45	d	Minimum growing period for stored hay consumed by layer hens, discussed in Section 6.5.5.
r_v	0.25	-	Interception fraction for water deposition for leafy vegetables, discussed in Section 6.5.9.
	0.25	-	Interception fraction for water deposition for other vegetables, discussed in Section 6.5.9.
	0.25	-	Interception fraction for water deposition for fruits, discussed in Section 6.5.9.
	0.25	-	Interception fraction for water deposition for grains, discussed in Section 6.5.9.
r_f	0.25	-	Interception fraction for water deposition for forage consumed by beef cattle, discussed in Section 6.5.9.
	0.25	-	Interception fraction for water deposition for forage consumed by poultry, discussed in Section 6.5.9.
	0.25	-	Interception fraction for water deposition for forage consumed by milk cows, discussed in Section 6.5.9.
	0.25	-	Interception fraction for water deposition for forage consumed by layer hens, discussed in Section 6.5.9.
r_g	0.25	-	Interception fraction for water deposition for stored grain consumed by beef cattle, discussed in Section 6.5.9.
	0.25	-	Interception fraction for water deposition for stored grain consumed by poultry, discussed in Section 6.5.9.

Table 6.23 Residential scenario parameters that may vary and generic default values (Continued)

Parameter symbol	Default	Units	Description/comments
	0.25	-	Interception fraction for water deposition for stored grain consumed by milk cows, discussed in Section 6.5.9.
	0.25	-	Interception fraction for water deposition for stored grain consumed by layer hens, discussed in Section 6.5.9.
r_h	0.25	-	Interception fraction for water deposition for stored hay consumed by beef cattle, discussed in Section 6.5.9.
	0.25	-	Interception fraction for water deposition for stored hay consumed by poultry, discussed in Section 6.5.9.
	0.25	-	Interception fraction for water deposition for stored hay consumed by milk cows, discussed in Section 6.5.9.
	0.25	-	Interception fraction for water deposition for stored hay consumed by layer hens, discussed in Section 6.5.9.
T_v	1.0	-	Translocation factor for leafy vegetables, described in Section 6.5.6.
	0.1	-	Translocation factor for other vegetables, described in Section 6.5.6.
	0.1	-	Translocation factor for fruits, described in Section 6.5.6.
	0.1	-	Translocation factor for grains, described in Section 6.5.6.
T_f	1.0	-	Translocation factor for forage consumed by beef cattle, described in Section 6.5.6.
	1.0	-	Translocation factor for forage consumed by poultry, described in Section 6.5.6.
	1.0	-	Translocation factor for forage consumed by milk cows, described in Section 6.5.6.
	1.0	-	Translocation factor for forage consumed by layer hens, described in Section 6.5.6.
T_g	0.1	-	Translocation factor for stored grain consumed by beef cattle, described in Section 6.5.6.
	0.1	-	Translocation factor for stored grain consumed by poultry, described in Section 6.5.6.
	0.1	-	Translocation factor for stored grain consumed by milk cows, described in Section 6.5.6.
	0.1	-	Translocation factor for stored grain consumed by layer hens, described in Section 6.5.6.
T_h	1.0	-	Translocation factor for stored hay consumed by beef cattle, described in Section 6.5.6.
	1.0	-	Translocation factor for stored hay consumed by poultry, described in Section 6.5.6.

Table 6.23 Residential scenario parameters that may vary and generic default values (Continued)

Parameter symbol	Default	Units	Description/comments
	1.0	-	Translocation factor for stored hay consumed by milk cows, described in Section 6.5.6.
	1.0	-	Translocation factor for stored hay consumed by layer hens, described in Section 6.5.6.
x_f	1.0	-	Fraction of contaminated forage consumed by beef cattle, described in Section 6.5.1.
	1.0	-	Fraction of contaminated forage consumed by poultry, described in Section 6.5.1.
	1.0	-	Fraction of contaminated forage consumed by milk cows, described in Section 6.5.1.
	1.0	-	Fraction of contaminated forage consumed by layer hens, described in Section 6.5.1.
x_g	1.0	-	Fraction of contaminated stored grain consumed by beef cattle, described in Section 6.5.1.
	1.0	-	Fraction of contaminated stored grain consumed by poultry, described in Section 6.5.1.
	1.0	-	Fraction of contaminated stored grain consumed by milk cows, described in Section 6.5.1.
	1.0	-	Fraction of contaminated stored grain consumed by layer hens, described in Section 6.5.1.
x_h	1.0	-	Fraction of contaminated stored hay consumed by beef cattle, described in Section 6.5.1.
	1.0	-	Fraction of contaminated stored hay consumed by poultry, described in Section 6.5.1.
	1.0	-	Fraction of contaminated stored hay consumed by milk cows, described in Section 6.5.1.
	1.0	-	Fraction of contaminated stored hay consumed by layer hens, described in Section 6.5.1.
x_w	1.0	-	Fraction of contaminated water consumed by beef cattle, described in Section 6.5.1.
	1.0	-	Fraction of contaminated water consumed by poultry, described in Section 6.5.1.
	1.0	-	Fraction of contaminated water consumed by milk cows, described in Section 6.5.1.
	1.0	-	Fraction of contaminated water consumed by layer hens, described in Section 6.5.1.
Y_v	2.0	kg/m^2	Crop yields for leafy vegetables, described in Section 6.5.7.
	4.0	kg/m^2	Crop yields for other vegetables, described in Section 6.5.7.

Table 6.23 Residential scenario parameters that may vary and generic default values (Continued)

Parameter symbol	Default	Units	Description/comments
	2.0	kg/m^2	Crop yields for fruits, described in Section 6.5.7.
	1.0	kg/m^2	Crop yields for grains, described in Section 6.5.7.
Y_f	1.0	kg/m^2	Crop yields for forage consumed by beef cattle, described in Section 6.5.7.
	1.0	kg/m^2	Crop yields for forage consumed by poultry, described in Section 6.5.7.
	1.5	kg/m^2	Crop yields for forage consumed by milk cows, described in Section 6.5.7.
	1.0	kg/m^2	Crop yields for forage consumed by layer hens, described in Section 6.5.7.
Y_g	1.0	kg/m^2	Crop yields for stored grain consumed by beef cattle, described in Section 6.5.7.
	1.0	kg/m^2	Crop yields for stored grain consumed by poultry, described in Section 6.5.7.
	1.0	kg/m^2	Crop yields for stored grain consumed by milk cows, described in Section 6.5.7.
	1.0	kg/m^2	Crop yields for stored grain consumed by layer hens, described in Section 6.5.7.
Y_h	1.5	kg/m^2	Crop yields for stored hay consumed by beef cattle, described in Section 6.5.7.
	1.0	kg/m^2	Crop yields for stored hay consumed by poultry, described in Section 6.5.7.
	1.5	kg/m^2	Crop yields for stored hay consumed by milk cows, described in Section 6.5.7.
	1.0	kg/m^2	Crop yields for stored hay consumed by layer hens, described in Section 6.5.7.
W_v	0.2	-	Wet-to-dry-weight conversion factors for leafy vegetables, described in Section 6.5.9.
	0.25	-	Wet-to-dry-weight conversion factors for other vegetables, described in Section 6.5.9.
	0.18	-	Wet-to-dry-weight conversion factors for fruits, described in Section 6.5.9.
	0.91	-	Wet-to-dry-weight conversion factors for grains, described in Section 6.5.9.

Table 6.23 Residential scenario parameters that may vary and generic default values (Continued)

Parameter symbol	Default	Units	Description/comments
W_f	0.22	-	Wet-to-dry-weight conversion factors for forage consumed by beef cattle, described in Section 6.5.9.
	0.22	-	Wet-to-dry-weight conversion factors for forage consumed by poultry, described in Section 6.5.9.
	0.22	-	Wet-to-dry-weight conversion factors for forage consumed by milk cows, described in Section 6.5.9.
	0.22	-	Wet-to-dry-weight conversion factors for forage consumed by layer hens, described in Section 6.5.9.
W_g	0.91	-	Wet-to-dry-weight conversion factors for stored grain consumed by beef cattle, described in Section 6.5.9.
	0.91	-	Wet-to-dry-weight conversion factors for stored grain consumed by poultry, described in Section 6.5.9.
	0.91	-	Wet-to-dry-weight conversion factors for stored grain consumed by milk cows, described in Section 6.5.9.
	0.91	-	Wet-to-dry-weight conversion factors for stored grain consumed by layer hens, described in Section 6.5.9.
W_h	0.22	-	Wet-to-dry-weight conversion factors for stored hay consumed by beef cattle, described in Section 6.5.9.
	0.22	-	Wet-to-dry-weight conversion factors for stored hay consumed by poultry, described in Section 6.5.9.
	0.22	-	Wet-to-dry-weight conversion factors for stored hay consumed by milk cows, described in Section 6.5.9.
	0.22	-	Wet-to-dry-weight conversion factors for stored hay consumed by layer hens, described in Section 6.5.9.
Q_f	27	kg/d	Animal feed intake rates for forage consumed by beef cattle, described in Section 6.5.1.
	0.13	kg/d	Animal feed intake rates for forage consumed by poultry, described in Section 6.5.1.
	36	kg/d	Animal feed intake rates for forage consumed by milk cows, described in Section 6.5.1.
	0.13	kg/d	Animal feed intake rates for forage consumed by layer hens, described in Section 6.5.1.
Q_g	3	kg/d	Animal feed intake rates for stored feed consumed by beef cattle, described in Section 6.5.1.
	0.09	kg/d	Animal feed intake rates for stored feed consumed by poultry stored feed, described in Section 6.5.1.
	2	kg/d	Animal feed intake rates for stored feed consumed by milk cows, described in Section 6.5.1.

Table 6.23 Residential scenario parameters that may vary and generic default values (Continued)

Parameter symbol	Default	Units	Description/comments
	0.09	kg/d	Animal feed intake rates for stored feed consumed by layer hens, described in Section 6.5.1.
Q_h	14	kg/d	Animal feed intake rates for stored hay consumed by beef cattle, described in Section 6.5.1.
	0	kg/d	Animal feed intake rates for stored hay consumed by poultry, described in Section 6.5.1.
	29	kg/d	Animal feed intake rates for stored hay consumed by milk cows, described in Section 6.5.1.
	0	kg/d	Animal feed intake rates for stored hay consumed by layer hens, described in Section 6.5.1.
Q_w	50	L/d	Water intake rates for beef cattle, described in Section 6.5.1.
	0.3	L/d	Water intake rates for poultry, described in Section 6.5.1.
	60	L/d	Water intake rates for milk cows, described in Section 6.5.1.
	0.3	L/d	Water intake rates for layer hens, described in Section 6.5.1.
Q_d	0.02	-	Beef cattle soil-intake fractions (forage diet, dry-weight), described in Section 6.5.1.
	0.1	-	Poultry soil-intake fractions (forage diet, dry-weight), described in Section 6.5.1.
	0.02	-	Milk cow soil-intake fractions (forage diet, dry-weight), described in Section 6.5.1.
	0.1	-	Layer hen soil-intake fractions (forage diet, dry-weight), described in Section 6.5.1.
BA_{if}	Table 6.19	-	Fish bioaccumulation factors, wet-weight basis, discussed in Section 6.6.
B_{jv}	Table 6.16	-	Vegetation concentration factors, dry-weight basis, described in Section 6.5.9.
F_{aj}	Table 6.18	d/kg	Animal product transfer factors, wet-weight basis, described in Section 6.5.9.

A potentially significant pathway of inhalation exposure is resuspension of contaminated soil tracked indoors. This pathway is dependent on the floor dust-loading (P_d) and the resuspension factor. Indoor dust-loadings may vary over a wide range and are dependent on a number of factors. A representative value from recent literature for indoor dust is 0.4 g/m^2 of floor surface.[a] The resuspension factor used in this analysis for estimating indoor air concentrations is discussed in Section 6.3.1.

The parameters used to determine the ground-water concentration using the three-box water-use model are generally the same as those described for the drinking water scenario. The significant exception is the method used for estimating the annual dilution flow (F) within the aquifer (box 3). As shown in Table 6.23, F is evaluated from the irrigation rate (IR), the area under irrigation (A), and assumed domestic use of land. The residential scenario is based on the assumption that 2500 m^2 of land are under irrigation at an irrigation rate of 2.08 L/m^2•d, or 76 cm/y. This irrigation rate is within a range of potential irrigation rates for various crops in the western United States. The Specific Information on the Terrestrial Environmental (SITE) database referenced by Baes et al. (1984b) shows the geographic distribution of estimated annual average irrigation rates across the country. While a large percentage of the United States is not irrigated at all, a prudently conservative exposure scenario will include irrigation. This is a significant pathway for contamination in ground water to reach food products and surface soil. Baes et al. (1984a) show a few very dry areas with irrigation rates in excess of 100 cm/y; however, this value would be overly conservative because it is the maximum listed. A large geographical percentage of the drier western states irrigates at a rate of 70-85 cm/y; the default value of 76 cm/y selected for this study falls within this range. Although the default value is conservative when compared with the annual irrigation rates in the eastern United States, it is representative of the rates in the western United States. This default value is adopted to ensure that the irrigation pathway in the residential scenario produces conservative first-level generic screening results. The total volume of water needed for irrigation is about 1.9×10^7 L. The volume of water needed for domestic purposes is 91,250 L, and the volume of the surface-water pond is 1.3×10^6 L. The total aquifer size is the sum of these three water volumes, or 2.0×10^7 L.

Summaries of the default parameter values for the ^{14}C and ^{3}H agricultural models are shown in Tables 6.24 and 6.25, respectively. The ^{14}C model and default parameter values are described in Appendix C, and the ^{3}H model and default parameter values are described in Appendix D.

The pathway and default parameter selections for the residential scenario have been made to model typical conditions that could be encountered at most sites across the United States. They are selected to provide a conservative estimate of the potential radiation doses that could result from residual radioactive contamination in soil. This approach is adopted to ensure that the first-level generic screening produces conservative results.

(a) Based on personal communication from Dr. D. W. Layton, Lawrence Livermore National Laboratory (November 27, 1991), regarding his recent literature review of the amounts of dust/dirt on the floors of homes. Dr. Layton stated that the 0.4 g dust/m^2 represents a geometric mean of the values found in his literature review.

Table 6.24 ^{14}C model residential scenario parameters that may vary and generic default values*

Parameter symbol	Default	Units	Description/comments
f_{Ca}	0.24	-	Fraction of carbon in beef cattle.
	0.20	-	Fraction of carbon in poultry.
	0.07	-	Fraction of carbon in milk cows.
	0.15	-	Fraction of carbon in layer hens.
f_{Cf}	0.09	-	Fraction of carbon in forage: beef cattle.
	0.09	-	Fraction of carbon in forage: poultry.
	0.09	-	Fraction of carbon in forage: milk cows.
	0.09	-	Fraction of carbon in forage: layer hens.
f_{Cg}	0.4	-	Fraction of carbon in stored grain: beef cattle.
	0.4	-	Fraction of carbon in stored grain: poultry.
	0.4	-	Fraction of carbon in stored grain: milk cows.
	0.4	-	Fraction of carbon in stored grain: layer hens.
f_{Ch}	0.09	-	Fraction of carbon in stored hay: beef cattle.
	0.09	-	Fraction of carbon in stored hay: poultry.
	0.09	-	Fraction of carbon in stored hay: milk cows.
	0.09	-	Fraction of carbon in stored hay: layer hens.
f_{Cs}	0.03	-	Fraction of soil that is carbon.
SA_{aTC}	1.0	-	Specific activity equivalence: beef cattle.
	1.0	-	Specific activity equivalence: poultry.
	1.0	-	Specific activity equivalence: milk cows.
	1.0	-	Specific activity equivalence: layer hens.

*Details of the ^{14}C model for the agricultural pathways are provided in Appendix C.

Table 6.25 ^{3}H model residential scenario parameters that may vary and generic default values*

Parameter symbol	Default	Units	Description/comments
H^*	0.008	L/m^3	Absolute humidity.
SH	0.1	L/kg	Moisture content of soil.
SA_{svH}	1.0	-	Tritium equivalence: plant/soil.
SA_{wvH}	1.0	-	Tritium equivalence: plant/water.
SA_{TaH}	1.0	-	Tritium equivalence: animal product/intake.
f_{Hv}	0.1	-	Fraction of hydrogen: leafy vegetables.
	0.1	-	Fraction of hydrogen: other vegetables.
	0.1	-	Fraction of hydrogen: fruit.
	0.068	-	Fraction of hydrogen: grains.
f_{Hf}	0.1	-	Fraction of hydrogen in forage: beef cattle.
	0.1	-	Fraction of hydrogen in forage: poultry.
	0.1	-	Fraction of hydrogen in forage: milk cows.
	0.1	-	Fraction of hydrogen in forage: layer hens.
f_{Hg}	0.068	-	Fraction of hydrogen in stored grain: beef cattle.
	0.068	-	Fraction of hydrogen in stored grain: poultry.
	0.068	-	Fraction of hydrogen in stored grain: milk cows.
	0.068	-	Fraction of hydrogen in stored grain: layer hens.
f_{Hh}	0.10	-	Fraction of hydrogen in stored hay: beef cattle.
	0.10	-	Fraction of hydrogen in stored hay: poultry.
	0.10	-	Fraction of hydrogen in stored hay: milk cows.
	0.10	-	Fraction of hydrogen in stored hay: layer hens.
f_{Ha}	0.10	-	Fraction of hydrogen in beef cattle.
	0.10	-	Fraction of hydrogen in poultry.
	0.11	-	Fraction of hydrogen in milk cows.
	0.11	-	Fraction of hydrogen in layer hens.
f_{Hs}	0.011	-	Fraction of soil that is hydrogen based on a soil moisture content (SH) of 0.1.

*Details of the ^{3}H model for the agricultural pathways are provided in Appendix D.

7 Discussion

The models and equations presented in this volume provide a method for calculation of radiation doses from residual radioactive contamination in buildings and soil. Four scenarios are included. For buildings, the scenarios cover the building renovation and building occupancy conditions, as described in Section 3. For soils, a generic water-use model, described in Sections 4 and 5, is used to provide time-dependent concentrations of radionuclides in water used for drinking and/or irrigation. The two scenarios for soils included are the drinking water scenario described in Section 4 and the residential scenario, as described in Section 5. The residential scenario is used to estimate doses from residual radioactivity in soil, including use of ground water for drinking, irrigation of farm products, and for obtaining fish from a surface pond. The selected parameter values and a summary of parameters that may vary are presented in Section 6. This section discusses the generic modeling approach, the generic scenarios and their limitations, and the potential applications of the models and methods.

7.1 Generic Modeling Approach

The generic modeling evaluation relies on a radiation exposure scenario analysis, including the major exposure pathways of direct exposure to penetrating radiation, inhalation, and ingestion. The modeling analysis is used to derive the annual TEDE to an average individual in a population exposed to residual radioactive material after decommissioning. The input parameters for each exposure pathway and scenario are selected to provide a prudently conservative estimate of the potential annual radiation dose. The parameters generally do not represent average conditions for all individuals exposed; however, they were not selected to perform a worst-case (overly conservative) analysis of the potential radiation dose to a maximally exposed individual. Rather, the parameters were chosen from documented sources and previous analyses on the basis of the professional judgment of the study contributors. Although the dose estimates produced may be overestimations in some cases, they are considered to be generally more realistic than the large overestimations produced by analysis of bounding cases. It is possible that for a few situations, the parameters chosen could lead to an underestimate of the annual TEDE.

The exception to this approach is the generic water-use analysis considered in this study. To estimate ground-water concentrations, a simple three-box, leach-rate model was developed using parameters and assumptions from literature sources. In this analysis, geometric mean partition coefficients (Kd's) data for the most mobile form of each element were obtained from literature sources, for those elements for which data existed. Where literature data were not available, Kd's were estimated using soil-to-plant concentration ratios as defined for leafy vegetables using a conservative correlation for soils. In a similar manner, infiltration rate and porosity values were selected based on the high end of the range of infiltration rates and porosities determined for humid areas of the United States. The ground-water parameter values and concentration equations selected for this analysis provide a conservative analysis of potential ground-water concentrations.

Generic screening modeling evaluations, similar to the one described in this document, have become a rather common approach to setting risk-based radiation protection standards. They are useful in evaluating a wide variety of conditions; however, they often have limitations that need to be recognized. Models are intended to be an approximation of reality. Because of data limitations or lack of knowledge, generic modeling sometimes oversimplifies actual conditions and may not account for important physical or chemical processes. When this occurs, or when it is suspected, attempts are made to use conservative assumptions and parameter selections to ensure that potential adverse consequences are overestimated. That is, where detailed knowledge is unavailable, an intentional error is introduced to provide a greater margin for safety. The results obtained by overestimating the adverse consequences may not be very useful because they may lead to prohibitive expenses for cleanup to meet regulatory requirements. However, for

simple cases where trivial contamination exists, compliance reached by generic screening modeling is beneficial because it eliminates unwarranted regulation and expense while not significantly affecting public health and safety.

For more complex situations, where a wide variation of contamination levels, radionuclide mixtures, and physical/chemical properties exist, generic models and data sets may not produce a very convincing assurance of compliance. When complex conditions occur, site-specific data should be used, if possible, and modifications to the generic approach should be made to account for the actual conditions. For example, direct measurements of radiation fields and their variation provide more meaningful information than generic attempts to model dose rates from contamination levels (i.e., actual measurements may obviate the need to model). A dilemma occurs when the costs of characterizing a site escalate beyond the basic demolition and waste disposal costs. The tendency in this situation may be to comply with a more restrictive generic limit than to attempt a full site characterization and compliance with a site-specific limit. However, a carefully conducted and documented optimization/ALARA evaluation may be used to help justify the adoption of site-specific derived levels, as described in the Foreword.

7.2 Generic Scenarios

For residual contamination in buildings, this document provides scenarios and mathematical formulations to derive annual TEDE factors that account for both potential building renovation (accounting for volume contamination sources) and routine building occupancy (accounting for surface contamination sources). These two scenarios were developed in an attempt to account for questions about the relative importance of volume versus surface activity and fixed versus removable contamination. For many alpha- and beta-emitting radionuclides, direct survey measurements may only account for surface activity because of self-shielding. Surface measurement methods may not detect subsurface sources, and significant inventories of radioactive material may be missed. Surface contamination that is fixed (i.e., not easily removed by smearing) at the time of release may become removable with time. Loose surface contamination may result in additional radiation exposure pathways and higher estimated radiation doses, as described by scenarios and parameter values defined in this document. Because unrestricted release is considered, it cannot be assumed that subsurface sources or fixed contamination will remain that way after license termination. The two scenarios identified for buildings attempt to account for this potential situation. No attempt was made to model indoor radon concentrations that may result from residual ^{226}Ra in buildings.

Residual radioactive soil contamination may be in a thin or thick soil layer, reside on the surface or be stabilized under a clean soil layer, cover a large or small area, and consist of many different radionuclides or mixtures of radionuclides. The scenarios and mathematical formulations contained in this volume relate to surface soils and are based on a scenario analysis that combines exposure pathways for inhalation, external exposure, ingestion of contaminated drinking water, and ingestion of soil and agricultural food products, including fish from a pond. The residential scenario was intentionally developed in a conservative manner to account for potential residential and light agricultural activities. It is recognized that, for sites located in industrial or urban areas, the potential for even light agricultural activities may be remote. Again, no attempt was made to model the indoor radon aerosol concentrations that could result from residual ^{226}Ra soil contamination.

The wide variability of physical and chemical conditions that potentially influence ground water, and the dependence on many parameters that may have a coupled dependency, make it difficult to model ground-water systems. In addition, a conceptual model of a ground-water system may not represent all the behavior of that system. Generic attempts at modeling ground-water systems generally encourage the use of overly conservative parameters, assumptions, and models. As a result, most generic modeling attempts have little meaning when compared with a real system. The existence of site-specific data may encourage a site-specific modeling effort, but such data are relatively costly to obtain, may be point values (both in time and location), and may not appropriately represent the actual system being modeled.

The purpose of the generic modeling in this document is to derive an aquifer concentration from residual radioactive materials in soil (or in building materials that may ultimately be buried as rubble onsite) in a conservative manner to permit screening and to indicate when additional site data or modeling sophistication are warranted. This approach is not intended for broader applications such as application to buried sources, disposed wastes, or sites with a history of spills contaminating soil deeper than 15 cm. Rather, it is intended to support the development of screening values, as described in the Foreword.

7.3 Applications

The annual doses estimated using these scenarios are to be used to provide an indication of the potential for license termination of a site by comparison of the calculated doses to a dose limit (to be set by NRC policy). The comparison can be made in two ways: by simply using precalculated TEDE screening factors, defining the concentration of each radionuclide that equals the dose limit, or through site-specific calculations relating measured residual concentrations to annual dose. The equations in this report are incorporated into a computer program that can perform both of these types of calculations. The program, to be documented in Volume 2, will also allow modifications to the scenario calculations to be performed using site-specific parameters defined by a user, as described in Section 6. For both methods, the user must have an estimate of the radionuclide inventory present.

Annual TEDE screening factors for the full set of radionuclides of interest will be calculated per unit activity of each parent radionuclide and provided in Volume 2 of this report. For sites that are well described by the set of default parameters identified in this volume, an indication of potential impacts can be made using these derived unit annual TEDE screening factors. For any scenario, the following evaluation can be made:

$$\text{Dose Ratio} = \sum_{i=1}^{M} C_{mi}\ \text{TEDE}_i/\text{DL} \tag{7.1}$$

where Dose Ratio = indicator of impact for the mixture of radionuclides at the site for a scenario of interest (dimensionless)

C_{mi} = inventory of radionuclide i in the medium m upon which the scenario is based (pCi/medium)

TEDE_i = annual TEDE per unit activity of radionuclide i in the medium for the scenario of interest (mrem per pCi/medium) for a year of scenario exposure

DL = annual dose limit for evaluation of the potential for adverse impacts (mrem).

When site-specific parameter values are available, the computer program will allow a second-level screening analysis to be made using these parameter values instead of the default values identified in Section 6. Under this mode of operation, the program will provide an estimate of the total dose from the user-defined mixture of radionuclides for each scenario of interest. The results from this analysis, in the form of annual TEDEs, are compared to the dose limit as follows:

$$\text{Dose Ratio} = TEDE_m/DL \tag{7.2}$$

where $TEDE_m$ is the annual TEDE for the mixture of radionuclides in the medium for the scenario of interest (mrem) for a year of scenario exposure and DL is as previously defined.

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Appendix A

NRC Staff and Technical Responses to Comments on NUREG/CR-5512 - Residual Radioactive Contamination from Decommissioning: Technical Basis for Translating Contamination Levels to Annual Dose, Draft Report for Comment - January 1990

Appendix A

NRC Staff and Technical Responses to Comments on NUREG/CR-5512 - Residual Radioactive Contamination from Decommissioning: Technical Basis for Translating Contamination Levels to Annual Dose, Draft Report for Comment - January 1990

During January 1990, the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC) issued for public comment a draft report prepared by the Pacific Northwest Laboratory (PNL) entitled *Residual Radioactive Contamination From Decommissioning: Technical Basis for Translating Contamination Levels to Annual Dose*, NUREG/CR-5512 (Kennedy and Peloquin 1990). This appendix contains a summary of the comments received during the public comment period, with a description of the responses provided and the modifications that were made to the final report. Comments included are those from the six public comment letters received as well as those from NRC staff. Public comment letters are available from the NRC Public Document Room, Washington, D.C. 20555, telephone number 301-634-3273, under reference citation 55 FR 6137, February 21, 1990. Public commenters are listed in Table A.1. The comments have been organized in six major areas: 1) Policy Issues and Regulatory Perspective, 2) Measurements and Survey Considerations, 3) Textual Errors and Editorial Improvements, 4) Technical Considerations, 5) Model Verification, and 6) Other Issues. Of the 246 comments received, the majority (over 100 comments) came from the technical community regarding the pathway analysis, scenario descriptions, mathematical models, and dosimetric methods.

Table A.1 List of public commenters

Docket no.	Commenter
1	Fuel Cycle Facilities Forum
2	Nuclear Management and Resources Council (NUMARC)
3	Oak Ridge National Laboratory (ORNL)
4	Argonne National Laboratory (ANL)
5	Department of Energy (DOE)
6	Los Alamos National Laboratory (LANL)

A further breakdown of the technical comments has been provided in specific technical areas of concern. About 25 comments were received that provided background or general information and by their informational nature required no response. The following sections describe the general types of comments received in each area and provide specific summary questions and responses in the areas of greatest interest. In developing the summary questions, several related questions were often combined so that an overall response could be provided. The response under each comment indicates the nature of changes that were made in this final report as a result of the comment.

Several of the comments appeared to misunderstand the intended purpose of the generic screening levels (expressed as radioactivity or concentration thereof) and the modeling framework in the draft report. As of August 1992, generic radiological criteria for decommissioning have not been established by the NRC. However, for illustrative purposes one can hypothetically consider the case where such criteria could be related to annual dose. Then, under this hypothesis, application of generic screening levels can be illustrated with a flow diagram of a three-layered hierarchy for criteria that might be used for release after decontamination and decommissioning (Figure A.1). Continuing with this hypothesis in a general sense, the shaded area of Figure A.1, labeled "Generic Screening Levels," corresponds to the levels obtained by dividing an annual dose criterion in mrem TEDE/y by the appropriate dose conversion factors in the tables from Volume 2 of this report. This is the same hierarchy illustrated in the Foreword under "Hierarchy of Modeling Approaches." As also mentioned in the Foreword, the next stratum in the hierarchy applies the modeling framework contained in this final report to derive site-specific dose conversion factors--and, in turn, release levels. These site-specific derived levels are determined by inserting appropriately justified site-specific parameter values into the modeling analysis using the user-friendly software documented in Volume 2 of this report. Finally, the last stratum of release criteria is derived from technically defensible site-specific models, which incorporate site-specific parameter values and data. This last stratum is not generically applicable and is beyond the scope of this report. It should be noted that with adequate justification it is possible to obtain unrestricted use (i.e., release) from any of the three modeling strata.

A.1 Policy Issues and Regulatory Perspective

About 30 comments were received concerning various aspects of the NRC policy on residual radioactivity. NUREG/CR-5512 is only a part of a general information base being developed for use by the NRC for consideration of regulatory activities necessary to implement decommissioning of facilities, lands, and structures. Other studies are underway or have been completed (e.g., NUREG/CR-5849, "Manual for Conducting Radiological Surveys in Support of License Termination" [Berger 1992]). The results of these studies, in conjunction with the resolution of policy issues, will permit the development of appropriate regulations allowing the unrestricted use of, and termination of licenses for, decommissioned nuclear facilities.

Responses to additional summary comments are included below:

Comment 1: Collective dose needs to be discussed to assure that affected groups of individuals will not be subjected to unacceptably large doses.

Response: For purposes of the draft report, there was no consideration of collective dose. This was because the intent of the report was focused on individual dose conversion factors and the technical development of models and methods for translating contamination levels to dose for radionuclides in buildings or land.

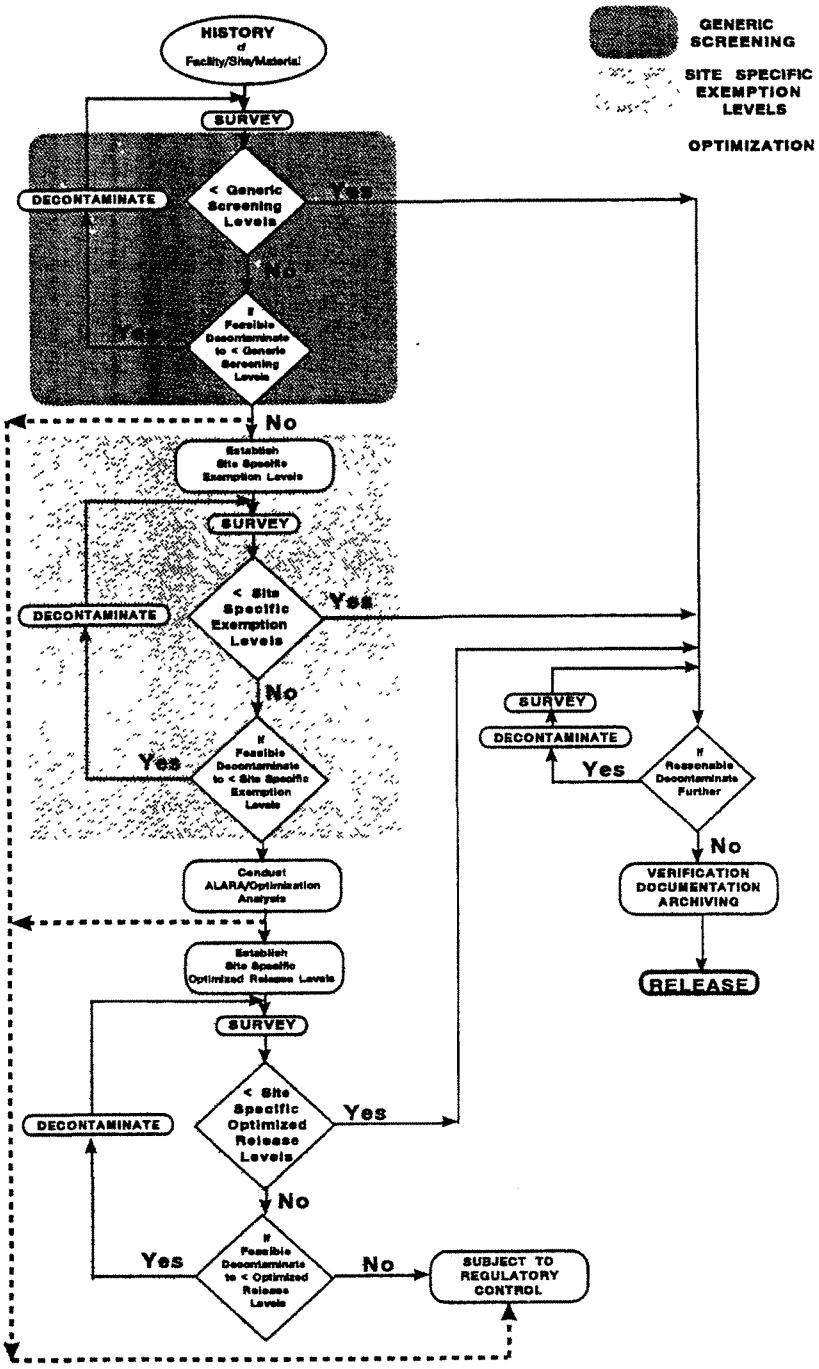

Figure A.1 Hypothetical flow diagram for release criteria

Comment 2: Is there some average number for acceptable dose that one can assign in some plausible manner?

Response: The scope of this report is limited to providing the technical basis and calculational methods for deriving dose conversion factors. Through an enhanced participatory rulemaking, the NRC will determine radiological criteria for decommissioning appropriate to protect both the public health and safety and the environment.

Comment 3: How do the recently modified risk conversion factors in the National Research Council's BIER V (1990) report affect the values shown in draft NUREG/CR-5512?

Response: There is no attempt to convert from dose to risk in the draft NUREG/CR-5512. No changes were made to the final report due to this comment.

Comment 4: Dose values like 5 μR/h at 1 m are often quoted by NRC staff in relation to release criteria. In practice, NRC inspectors typically will place the meter a lot closer (sometimes in contact) with items being surveyed. Is there a way to look at the relationship between a reading at one meter and a contact dose reading for these release criteria?

Response: The value of 5 μR/h at 1 m approximates 10 mrem/y for the external exposure pathway, assuming a 2000 h/y exposure period. However, direct measurement of the external exposure pathway does not account for the contributions to annual TEDE from the ingestion and inhalation pathways. The response to this comment is more appropriately a policy issue because the decision to allow direct measurements is not part of the technical basis found in NUREG/CR-5512 and references to direct measurements have been removed from the final report. However, as previously stated in the Foreword, a separate report (NUREG/CR-5849 [Berger 1992]) has been prepared to discuss survey methods and alternatives. Based on that report and the rulemaking on radiological criteria for decommissioning, guidance regarding appropriate measurement methods will be included in the release criteria.

Comment 5: Explain an apparent discrepancy with the 5 μR/h release criteria. A conversion of 5 μR/h, with continuous exposure for 8760 h/y, gives a dose value of about 31 mrem/y, not 10 mrem/y.

Response: As stated in the previous response, the value of 5 μR/h at 1 m approximates 10 mrem/y for the external exposure pathway, assuming a 2000 h/y exposure period. Implementation of direct measurements of external pathway exposures is beyond the scope of this report. Guidance will be provided in a Regulatory Guide.

Comment 6: How were values for radium in lands and the indoor radon aerosol derived?

Response: Values for radium in lands were calculated on the technical basis described in the report. No modeling was conducted for the indoor radon aerosol—on the basis that geological and architectural variations are so great that generic modeling is not feasible and that direct measurement of the indoor radon aerosol is preferred. A footnote will be included in the appropriate tables in Volume 2 to remind the user that the indoor radon aerosol has not been modeled in the calculations. Comment number 8 in Section A.4.4 also addresses indoor radon.

Comment 7: If annual dose limits other than 10 mrem/y are adopted, will the estimated concentration criteria simply scale, or is the calculation more complicated?

Response: The values in Volume 2 of NUREG/CR-5512 will show the dose conversion factors resulting from a unit concentration of radioactivity for residual contamination in buildings or lands. The level of residual radioactive contamination associated with any dose limit is a simple calculation; namely, divide the dose by the dose conversion factor to get the corresponding concentration or quantity of radioactivity. Thus, the dose conversion factors simply scale from one dose criterion to another. However, as of August 1992, radiological criteria for decommissioning have not been established, and they may or may not be expressed in terms of a dose criterion in the final form.

Comment 8: An explanation of why there are large differences in the derived contamination levels relating to 10 mrem/y needs to be developed to provide users an understanding of how a range of values by several orders of magnitude for different radionuclides could result.

Response: The range of levels is derived from the potential of each radionuclide to deliver dose through several pathways in the scenario analysis. This means that a combination of pathways is considered, not just external exposure, because the annual TEDE is used. The dose conversion factor values for inhalation or ingestion of alpha-emitters or beta-emitters for some scenarios are more limiting (i.e., unit concentrations result in similar doses). The relative radiotoxicity of a radionuclide is directly related to types and energies of their emissions as well as the dominant pathway of exposure.

Comment 9: When Regulatory Guide 1.86 (NRC 1974) was developed, the NRC found that limits set on the basis of dose alone resulted in some very large allowable concentrations. At that time, it was decided to put a cap or limit on the numbers because decontamination to lower levels is easy to implement (i.e., you don't have to live with 100 million dpm of tritium—you would clean it up!). A cap should be placed on the screening levels to add credibility to the overall effort.

Response: The technical basis document was developed in a consistent manner for all radionuclides. The decision whether to cap higher values for tritium, or to group similar radionuclides, or even to consider other special factors would be a policy decision beyond the intent of the technical basis report. As indicated in Figure A.1, as a matter of good practice the licensee should consider whether simple decontamination practices would be effective at levels below the release criteria, e.g., wiping a wall with a damp cloth. No changes were made to the final report due to this comment.

A.2 Measurements and Survey Considerations

About 12 detailed comments on draft NUREG/CR-5512 were submitted regarding various aspects of radiation detection. While there was some overlap in the comments, the primary concern expressed was whether the residual radionuclide concentrations derived would be detectable using current field-survey methods. Other commenters wanted to know if the scenario-specific dose conversion factors were to be applied as maximum or average values, how to estimate the radioactive decay period for compliance estimates, and whether building-surface contamination should be combined with soil contamination. The section contains a general summary of these comments with detailed responses and indicates changes made for the final document.

Comment 1: For many mixtures of radionuclides, there will be difficulties in verifying compliance with a fraction of the public dose limit, like 10 mrem/y, when using field instrumentation. Potential problems were cited

for mixtures of uranium using information from the Formerly Utilized Site Remedial Action Project (FUSRAP) program. Additionally, it may be impractical to accurately measure an external exposure rate increment from soil of less than 2 μR/h when the range of natural background varies from about 5 to 10 μR/h. At other sites, variability in measurements may be as much (or more) than 10 mrem/y.

Response: Although radiation detection problems at low dose exposures are likely to be encountered, measures to ensure compliance are possible through the definition of adequate survey protocols. This may mean the use of laboratory analyses to establish environmental levels if direct measurements in the field are not reliable. No change was made to the final document because of this comment. However, because this is an important concern, a separate document, NUREG/CR-5849 (Berger 1992), has been developed concerning the design of radiation survey methods for residual radioactive contamination.

Comment 2: Calibration differences at low exposure rates may also make it difficult, at best, to draw intercomparisons between data measured with different instruments. This may mean that exposure rate measurements are reliable only in demonstrating that no statistical excess exists.

Response: Again, the role of external exposure rate measurements within a survey may only be of a confirmatory nature. Further consideration of instrument selection and survey protocol design for residual radioactivity has been developed and documented separately in NUREG/CR-5849 (Berger 1992). No change was made to the final document because of this comment.

Comment 3: There is a need to resolve some confusion regarding characterization of the concentration of radioactive materials at a site and verification of modeling methods.

Response: Characterization of the concentration of radioactive materials at a site consists of technically sound sampling of lands and structures with the appropriate instrumentation with the aim of using the data to summarize the character of the site. This procedure is described in the companion document on surveys and instrumentation that is under development. Model verification is a quality-assurance check that the modeling equations are applied and calculated accurately. The computer models and calculations in Volumes 2 and 3 of this document have been checked by hand calculations and comparisons with other modeling approaches have been made under strict quality-assurance procedures. No changes were made to the final report because of this comment.

Comment 4: For surface-contamination in buildings, the staff from Oak Ridge National Laboratory report a minimum alpha detection level of 3 cpm per 100 cm_2. This level is sufficiently low so that detection of alpha surface contamination should pose no problem.

Response: Information on the proper choice of instrumentation and survey protocols is available (NUREG/CR-5849 [Berger 1992]). Radiation surveys conducted within buildings are significantly different from environmental surveys. However, at low dose rates there may be problems that require the careful choice of instrumentation and design of survey protocols for proper characterization. No change was made to the final report because of this comment.

Comment 5: The scenarios and models used attempt to estimate doses in a realistic manner but include a high degree of conservatism when the uncertainties are large. In the case of the external dose, measurements are probably faster than modeling and may provide a better estimation of long-term hazard.

Response: Site-specific analyses may be required when the simple screening approach fails. External measurements, if done in an appropriate manner, may provide a more accurate estimate of the overall dose from the external exposure pathway. However, external measurements need to be included with modeled estimates of dose from inhalation and ingestion to calculate the annual TEDE. The release criteria will address the potential role of external exposure measurements.

Comment 6: Provide an expanded discussion of the intent of the final survey and what a licensee must do to convince the NRC that the contamination levels or dose limits are met.

Response: A separate document, NUREG/CR-5849 (Berger 1992), has been developed to discuss potential survey methods and alternatives. The complexity of the procedures will depend on the nature of the source term and the characteristics of the site. For example, if a licensee dealing with sealed sources can verify that the integrity of the sources has not been breached, the verification of appropriate disposal of these sources may be sufficient to justify a simple survey. Other sites involving volume contamination in buildings or soils, with highly variable mixtures or intensities, may require sophisticated measurements and statistical analysis as part of the final survey. No major changes were made to this final report due to this comment.

Comment 7: Before the analysis can be evaluated, a reviewer must clearly understand how the "technical basis" is to be used. For example, are the calculated values averages over some unit area or are they maximum concentrations? At what decay time should the calculations be performed? Are the doses from the indoor surface contamination pathway to be combined with the soil pathway?

Response: Figure A.1 illustrates the role of the levels with respect to the hierarchy of criteria for release. Further consideration of how the values will be applied and related to radiation surveys will be developed and documented separately. This documentation will include a discussion of averaging for purposes of compliance determination. Generally, the calculations should be performed at the decay time considered for release of a site, unless additional ingrowth of radioactive decay progeny would increase the potential doses. Delayed entry of radionuclides into drinking water is also considered in the revised model. Finally, the only situation for which adding indoor surface contamination to outdoor soil contamination was considered was the drinking water scenario. For this scenario, an accounting of the total inventory should be made if the building could be demolished and rubble disposed of onsite (thus adding to the soil inventory). For more complicated situations, additional site-specific modeling may be warranted.

Comment 8: What about the use of smear samples for measuring removable contamination?

Response: Historically, a vital part of survey methods has been the use of smear samples to measure removable contamination. From a practical point of view, it makes sense to leave as little removable material on surfaces as possible; however, in a modeling analysis, future conditions regarding the removable fraction are difficult to determine. Given oxidative and other destructive processes and enough time, all materials deteriorate and contamination could become removable. Therefore, all contamination is considered removable.

A.3 Textual Errors and Editorial Improvements

More than 30 comments were submitted regarding various textual errors or suggesting editorial improvements to the final report. There was a good deal of overlap in the comments received on textual errors and internal inconsistencies, while the editorial comments varied. These comments were considered in developing the final report; however, because of the other significant modifications that have been made, it is not appropriate to provide a detailed response to each comment here. Instead, this section contains a general summary of the more significant comments and responses and indicates the types of changes that were made for the final document.

Comment 1: Several comments were received regarding units or unit conversions. Inconsistencies or errors in selected table headings, equations, or text were noted. For example, p. 2.45 was missing a unit for soil thickness (m); conversions in activity (pCi to Bq) or dose units (mrem to Sv) were questioned in a number of places; and the units used in some equations were in error.

Response: In preparing the final report, careful attention has been paid to the use of units. In addition to looking for typographical errors, dimensional analyses and programming verification of the basic equations were used to identify inconsistencies. Careful use of notation and an explanation of the derivation of constants have been added to Volume 1. As a result, numerous changes were made to properly account for the units of all equations, calculations, and tables.

Comment 2: Several comments were received regarding literature references. In some cases, additional references were suggested; in other cases, the use of references or the format of references was questioned.

Response: In preparing the final report, the authors consulted additional references in several areas, including existing pathway analysis models, regulations developed by other Federal agencies, and basic research information in the open literature. Additional references and their contributions to the revised analysis have been added to the text in several places.

Comment 3: Several comments regarding the format and content of the tables of TEDE conversion factors and scenario results were received. Some comments called for the use of expanded titles to eliminate the need for some of the footnotes, while other comments called for the creation of additional footnotes to better describe the calculations.

Response: Each of the comments on the format and content of the tables was considered and consistent modifications were made. Expanded titles and more complete footnotes have been developed to better communicate both the calculational process and the final results found in the tables in Volume 2.

Comment 4: One comment called for restructuring the document to include a separate section for each pathway. In this manner, additional details in the calculational procedure could be presented.

Response: The structure of the draft report was developed to provide a balance between the pathways and scenarios in the analysis. It is not only important to understand how the dose conversion factor is calculated for each pathway, but also to understand the relationship of each pathway to each scenario. Additional graphics have been added to Volume 1 to better describe the conceptual models, time frames, and connections among the basic elements of the modeling analysis. For clarity, the final report has been expanded into three volumes with greatly elaborated detail, as described in the Introduction to Volume 1.

Comment 5: All assumptions that go into analyses of various scenarios should be documented in a manner that will allow a licensee to ascertain if the generic treatment applies. This will also permit easy modifications when the generic treatment fails.

Response: The final report has a greatly expanded section on the assumptions and details of the modeling.

A.4 Technical Considerations

About 100 comments were received dealing with the technical details contained in draft NUREG/CR-5512. These comments have been sorted into seven categories: 1) Radioactive Chain Decay Methods, 2) External Dose Rate Calculations, 3) Water-Use and the Drinking Water Scenarios, 4) Models, 5) Data Selections, 6) Other Pathways and Scenarios, and 7) Airborne Dust-Loadings. This section summarizes the significant comments and responses and indicates the types of changes that were made in the final report for each category of technical comment.

A.4.1 Radioactive Chain Decay Methods

About 25 comments were submitted concerning the radioactive chain decay methods in draft NUREG/CR-5512. Many of the comments focused on the notation used for expressing decay chains in equilibrium or the practice of normalizing the dose conversion factors to a unit activity of the parent plus progeny. As a result of the comments, several changes were made to the final report. Several commenters provided specific examples of how to better express the results. The following general comments and responses summarize the significant points of concern raised during the public review and the modifications that have been made to the final report.

Comment 1: A number of commenters recommended against the approach used to provide unit dose conversion (and scenario) factors normalized to unit activity of parents plus progeny in equilibrium. The comments indicated that it would be confusing to users to include the activity of progeny with the parents and recommended providing all factors normalized to a unit of activity of parent only.

Response: All of the dose conversion factor presentations and calculations have been revised to be normalized to a unit of activity of the parent only (without consideration of the activity of progeny). Separate listings will be provided for progeny so that users of the report may calculate doses for any parent/progeny mixture not in secular equilibrium.

Comment 2: A number of commenters addressed the +I notation found in the draft version of NUREG/CR-5512. Most indicated that, in any dose assessment, it was reasonable to assume that short-lived progeny are in equilibrium with the parent, if all dose conversion factors are normalized to a unit activity of the parent.

Response: The notation for the entire report has been modified. For decay chains in secular equilibrium, the radiations included in the dose conversion factor for a parent are those associated with decay of the parent plus radiations from progeny. For the final report, secular equilibrium is defined for progeny having half-lives of less than 9 hours and also having half-lives less than 10% of the half-life of the parent. The use of +I notation is no longer necessary because the contributions from the progeny are always included (for external or internal dose conversion factors). For inhalation and ingestion dose conversion factors, the entries include radiations from all radionuclides contributing to internal dose, including progeny ingrowth, following intake of the parent (within the 50-year dose commitment

period). The inclusion of such contributions is defined precisely by recommendations of the International Commission on Radiological Protection (ICRP) in Publication 30 (1979-1988).

Comment 3: In addition to the +I notation, several commenters addressed the +D notation found in draft NUREG/CR-5512. The problem arises when the half-life of the progeny, although shorter than the parent, is still quite long. In this case, it would be tempting to include the progeny with the parent (as the +D notation indicated), but it would also be wrong for the majority of cases. A good example is ^{93}Zr+D, where the parent is very long-lived and the progeny (^{93m}Nb) has a half-life of 16 years. It is not likely that the progeny will reach full equilibrium with the parent by the time decisions are needed on release of a decommissioned site. Eliminating the use of the +D notation forces users who make dose assessments to make conscious decisions about the state of equilibrium in radioactive decay chains.

Response: As with the +I notation, the notation for the entire report has been modified. The use of the +D notation is no longer needed because the radiations included in the dose conversion factor for a parent are those associated with decay of the parent plus radiations from progeny that are always in secular equilibrium. For all other cases, when the progeny are longer-lived than the parent or when the half-life of the progeny (although shorter than the parent) is still quite long, separate entries are provided for both the parent and the progeny. For the final report, secular equilibrium is assumed for progeny with half-lives that are both less than 9 hours and less than 10% of the half-life of the parent. For decay chains having two or more progeny radionuclides that reach secular equilibrium (constant ratio of activity as a function of time), a new +C (C for chain decay) entry is provided, giving dose conversion factors for the entire chain. These decay chains have a long-lived parent with progeny of varying shorter half-lives. This representation is of particular value for radionuclides in the four actinide decay series (neptunium, uranium, actinium, and thorium). The entry name in the table will include +C to indicate that all progeny in the chain are included in the dose conversion factors. An extended discussion has been provided in the final report summarizing the notation for entries in the final dose conversion factor tables.

Comment 4: Several commenters cited examples in which the calculation of dose conversion factors involving parent/progeny relationships were in error in draft NUREG/CR-5512. Examples included ^{93}Zr/^{93}Nb, ^{90m}Y/^{90}Y, and decay chains involving the U series.

Response: As part of the revision to the final report, a carefully defined Software Requirements Specification was developed as part of the internal quality-assurance documentation for the design of the software used to generate the scenario analysis for residual radioactive contamination. One of the requirements specifies the details of the radioactive decay chain analysis. A second requirement specifies the database supporting the calculations. These requirements were identified to ensure that the software performed all calculations in accordance with the modified approach to chain decay. Additional quality-assurance testing was conducted as part of the software development, including cases that used the comments and examples of cases in which the previous calculations contained errors.

Comment 5: Fuel cycle facilities downstream of a mine and mill process increasingly refined uranium (i.e., uranium separated from its progeny). Radioactive decay for the uranium chain would predict that a very small fraction of ^{226}Ra (the parent of ^{222}Rn) would be created relative to the parent uranium within 500 years, because of the long half-life of the uranium. Thus, residual contamination levels of refined uranium should not produce significant levels of ^{226}Ra in soils. This means that the use of dose conversion factors for the full chain is too conservative.

Response: The use of the entire uranium chain for specific situations involving refined uranium is not appropriate. For this reason, separate listings of parents and progeny are provided in the final document so that an accounting can be made of the non-secular equilibrium conditions that may exist at the time of decommissioning. In addition, the drinking water and residential scenarios are now time-dependent so that the peak dose conversion factor value and year can be determined for chain decay situations.

Comment 6: The draft version of NUREG/CR-5512 does not include ^{198}Au, although the use of this radionuclide is licensed by the NRC.

Response: This radionuclide has been added to the master radionuclide listing.

A.4.2 External Dose Rate Calculations

There were about 30 comments received during the public comment period on the external exposure pathway of draft NUREG/CR-5512. The comments questioned specific aspects of the calculational method, various aspects of the sensitivity study (in Appendix A of the draft), the need to calculate a deep dose equivalent, and the comparisons with other external dose rate calculations found in the literature. The following general comments and responses summarize the significant issues raised during the public review, and the modifications that have been included in the final report.

Comment 1: The external dose rate factors used in the draft report are provided for 1 cm in body tissue, referred to as the deep dose equivalent. A more appropriate method of calculation provides an organ-weighted effective dose equivalent, which can be directly added to the committed effective dose equivalent calculated for internal exposures from inhalation and ingestion of radionuclides.

Response: In this final report, a change has been made to use effective dose equivalent from external exposures, consistent with the method recommended by this commenter. The method for estimating external doses is discussed in Section 6.

Comment 2: Several commenters stated that a different method of producing external dose rate estimates should be developed. The commenters indicated that: 1) the ISOSHLD code used for the draft was not documented well enough (a complete listing of the data library should be included), 2) a better description of the annihilation radiation calculations was needed, 3) accounting for bremsstrahlung was not needed, especially if the neutron dose is ignored, and 4) errors in the use of discrete energy groups as found in ISOSHLD can occur (especially for low-energy photons).

Response: In response to these comments, the use of ISOSHLD has been replaced with the use of a database of external dose rate factors contained in a Federal Guidance Report developed by the U.S. Environmental Protection Agency (Eckerman, Wolbarst, and Richardson 1988). Standardized source configurations from the Federal Guidance report are used in the scenario analysis for both surface contamination and contamination to an effective depth. The source geometries are either an infinite plane or an infinite slab. External doses were calculated for specific organs, taking into account the structure of the human body so that an effective dose equivalent is obtained. The effective dose equivalent (dose from external sources) can be added to the internal committed effective dose equivalent from ingestion and/or inhalation so that the TEDE is obtained.

Comment 3: There are many discrepancies between the external dose rate factors in the draft report and the factors found in DOE/EH-0070, *External Dose Rate Conversion Factors for Calculation of Dose to the Public* (DOE 1988).

Response: These discrepancies should be minimized in the final report because both listings of external dose rate factors provide the effective dose equivalent and both were developed by staff at Oak Ridge National Laboratory. Additional comparisons with other modeling approaches were made, as discussed in Volumes 2 and 3.

Comment 4: Several commenters discussed the potential role of backscatter in the external dose rate calculations. It was noted that the ISOSHLD code does not include backscatter calculations, and thus produces serious underestimation of the exposure. It was also noted that the source-receptor relationship for various work situations may require backscatter if the individual is located near a wall in a room.

Response: The generic nature of the calculations (i.e., one simple generic model used to estimate external doses for all scenarios) indicated that the method of calculation needed to be prudently conservative, without introducing additional modeling detail. Although backscatter may be important in some situations, so may the size of the room, the distribution of contamination (on the floor, walls, and ceiling), and the type of building or building materials encountered. It was determined that the simple model could not account for all possible levels of site-specific detail. Consequently, backscattering was not considered in this revised document.

Comment 5: Several commenters addressed the details found in Appendix A ("External Exposure Modeling Sensitivity Studies") of the January 1990 draft (Kennedy and Peloquin 1990). There was concern about using a tissue-equivalent cylinder of 5-cm radius to approximate whole body dose. The curves in Figure A.1 of the January 1990 draft were challenged as being incorrect (i.e., the energy-specific exposure rate curves should not be parallel for various source areas). One commenter indicated that omitting backscatter in the sensitivity studies (and dose conversion factors) would underestimate the potential dose, while a second commenter indicated that the use of an infinite plane source to model a contaminated room would lead to an overestimation of the dose. It was also noted that, for a generic study, it was not appropriate to develop more detailed methods for analysis of contaminated rooms.

Response: The original intent of Appendix A was to provide a discussion of the selection of source geometry configurations used in the scenario analysis. The 5-cm-radius sphere of tissue was a simple ISOSHLD representation that would indicate the relationship between point sources and small-to-large-radius disk sources. As a result of these comments and the degree of confusion that Appendix A appears to have caused, and because the method of external dose rate calculations has been revised, most of the information in that Appendix no longer applies and has been eliminated from the final report. Section 6 of Volume 1 of the final report includes an expanded discussion of the use of Federal Guidance Report external dose conversion factors and a discussion of the use of infinite plane or slab sources for the standard geometries.

Comment 6: One commenter indicated that the external dose conversion factors used in the draft report do not agree closely with those found in Regulatory Guide 1.109 (NRC 1977) and the database for 10 CFR 61 (within factors of 2 to 3), while a second commenter indicated that this range shows excellent agreement, given the different methods for estimating external exposure. A third commenter found the comparisons to be not particularly illuminating because similar methods have been used in all compilations developed in this country.

Response: It is recognized that different methods are used in the final report than in the draft; hence, such comparisons may not be technically correct. However, there is still merit in providing comparisons with the other pathway analysis studies found in the literature because such comparisons are relative bench marks with which past evaluations may be re-examined. These comparisons will be revised and will be included in Volume 3.

Comment 7: There needs to be an expanded discussion, with additional detail, describing how the external dose conversion factors were calculated. Specifically, a more detailed comparison with the methods of Regulatory Guide 1.109 (NRC 1977) needs to be provided in the comparison so that the reader may perform hand calculations to verify the table values.

Response: A revised method of external dose rate estimates has been provided with an expanded discussion of how the Federal Guidance Report database (Eckerman and Ryman 1992) was applied in the final report. It is beyond the scope of this final report to fully describe the calculational approach used in Regulatory Guide 1.109 or any other literature source; however, a comparison of the final results is useful.

A.4.3 Water-Use Model and the Drinking Water Scenario

About 14 detailed comments were received concerning various aspects of the water-use model and the drinking water scenario found in the draft version of NUREG/CR-5512. The commenters questioned the need for the scenario, identified an error in the mathematical representation, and questioned the completeness of the scenarios concerning other uses of surface or ground water. The following comments and responses summarize the significant points of concern raised during the public review and highlight the modifications that have been included in the final report.

Comment 1: The authors have recognized the extremely uncertain nature of a generic analysis for the ground-water pathway; however, the generic analysis is so uncertain (when compared to any specific site) that it is meaningless for purposes of this report. Because of the uncertainty, this analysis and the drinking water scenario should be deleted from the report.

Response: The water-use model and the drinking water scenario are needed for completeness in the consideration of exposures for years beyond the time of decommissioning. In several places in the draft text, the authors have clearly recognized the limitations of a generic analysis and the fact that simple models oversimplify the actual conditions encountered at a particular site. The model and parameter values in this report are useful in establishing generic screening values. As illustrated in Figure A.1, the intent of the modeling exercise (as stated in Section 5.2 of the January 1990 draft NUREG/CR-5512) was to derive an aquifer concentration from residual radioactive materials in a conservative manner that would indicate when additional site data or modeling sophistication were warranted. The approach is not intended for broader applications. The model is constructed in a manner that will allow users to modify simple parameters (i.e., partition coefficients, infiltration rates, soil thickness, porosity, etc.) to better account for site-specific conditions. The option also exists within the NRC policy to use a much more sophisticated method for conducting a site-specific analysis, if needed. The final report contains an expanded discussion of the water-use model that clarifies the intent of the modeling analysis.

Comment 2: It would seem that the NRC should demand that licensees provide enough site-specific information to allow site-specific determinations of the importance of the drinking water pathway instead of attempting a generic analysis.

Response: The intent was to provide a conservative screening value that would eliminate the need for costly data collection and reporting when trivial conditions exist. Numerous licensees have sealed sources or short half-lived materials for which simple survey data (that are compared to generic inventory numbers) would be sufficient to prove that no problem exists. Also, see response to Comment 1 above. No change was made to the final report because of this comment.

Comment 3: The water-use model correctly uses the total inventory in the calculations; however, a clear purpose for the approach needs to be stated. The users need to be warned about the site-specific nature of potential ground-water contamination problems and that the analysis is based on a unit of activity (1 pCi and 1 Bq).

Response: An expanded discussion of the limitations of the water-use model has been provided to repeat the purpose of the approach and caution users about the uncertainties associated with the analysis. In Volume 2, the table of annual TEDE results has been modified to more clearly describe the units.

Comment 4: The water-use model assumes that elements are leached as determined by the partition coefficient, with no retardation, under conditions of continuous saturation. These are unlikely assumptions that should be replaced with more realistic ones.

Response: The water-use model was modified by the addition of an unsaturated zone with a depth of 1 m, to add realism and flexibility. Nonetheless, it is difficult to define a robust generic water-use model that does not contain conservative or unlikely assumptions compared with any real site or data. Again, the intent of the modeling exercise was to derive an aquifer concentration from residual radioactive materials in a conservative manner that would indicate when additional site data or modeling sophistication would be warranted. This approach is not intended for broader applications; however, it does permit the use of alternative parameters or models for conducting site-specific analyses. The NRC plans to continue to research ground-water modeling in an effort to provide alternatives to this approach.

Comment 5: The simple modeling of the ground water for use as drinking water ignores potential use of water for irrigation. The draft text states that this is done to avoid accounting for the inventory twice. If leaching of radionuclides is subtracted from the surface-soil concentration, a proper accounting of the inventory can be made. The residential scenario would also be more realistic if leaching is included in the modeling.

Response: Based on this comment and the review of the draft report, the residential scenario has been revised to include the use of ground water for irrigation and drinking, and the use of surface water for raising fish, as described in Section 5. The time-dependent ground-water radionuclide concentration is calculated using the three-box water-use model. This model includes simple leaching of radionuclides through soil and the unsaturated zone, with no retardation. The significant difference in the operation of the water-use model between the drinking water and residential scenarios is the annual flow assumed in the aquifer and surface pond (box 3). For the drinking water scenario, the flow is assumed to be the quantity of water used during a year by an individual for all purposes, including drinking, as discussed in Section 6. For the residential scenario, the flow is determined by the volume of water used for irrigation, plus the volume in the surface pond, plus the volume used by an individual for all other purposes (the same volume as used in the drinking water scenario). These changes were made to add realism to the generic scenario and to provide a more complete consideration of the potential behavior of radionuclides in soil.

Comment 6: A dimensional analysis of the ground-water equations in Appendix B indicates an error in the definition of λ_L. The correct equation should read:

$$\lambda_L = kI/(Hn) \qquad (B.10)$$

Response: The generic water-use model used in the January 1990 draft report was a draft screening model provided by the National Council on Radiation Protection and Measurement (NCRP). It had been reviewed by the NCRP authors prior to publication of the January 1990 draft. A few weeks after publication, the error in the definition of λ_L was discovered in both the NCRP draft and our January 1990 draft. While the generic model has been replaced with the new three-box model, this formulation is still used, in a corrected form, for estimation of λ_L. Revised nomenclature has been used, as shown in Section 4.

Comment 7: The time-dependence of the TEDE should be accounted for in the modeling, especially the water-use modeling.

Response: For building scenarios, the annual TEDE is conservatively calculated on the basis of the exposure that occurs during the first year after license termination. For a screening analysis, this is an appropriate approximation because of the projected short life of a building compared to the time needed to reach equilibrium conditions for long-lived radionuclide chains. To account for the ingrowth of progeny from parent radionuclides in non-equilibrium chain decay, the user should perform a site-specific calculation based on the appropriate ratios of the radionuclides of interest. For residual radioactive contamination in soil, the revised water-use model has been calculated arbitrarily to determine a peak dose conversion factor up to 10,000 years. The credibility of model predictions for the distant future is quite low. The modeling assumptions concerning the physics and chemistry of the land, water, and carrier of the radionuclides, as well as assumptions of climatic stability, are associated with uncertainties that become greatly increased in the context of even a few hundred years. However, it should be recalled that only the long-lived radionuclides persist in these long time-frames, and that the levels of residual radioactive contamination of the long-lived radionuclides considered here are probably comparable to natural background.

Comment 8: At the bottom of page 2.34, there is a potentially misleading statement regarding the EPA's drinking water standards. The dose limit of 4 mrem for whole body or any organ in the interim drinking water standards applies only to man-made, beta/gamma-emitting radionuclides. In particular, the present drinking water standard of 5 pCi/L for radium and 15 pCi/L for all alpha-emitters, exclusive of uranium and radon, do not correspond to annual doses of 4 mrem. Thus, it is potentially misleading to present similar results for alpha and beta/gamma-emitting radionuclides in Tables 2.4 and 3.4. This mistake appears more explicitly on page 5.5.

Response: The dose conversion factors in Sections 2 and 3 are needed independent of doing a comparison with the EPA drinking water standards. Clearly, this comment is correct and a modified discussion is needed. The text in Sections 4 and 7 has been appropriately modified.

Comment 9: The 2-L/d drinking water consumption rate is too high. The EPA Office of Radiation Programs currently is using a value of 1.4 L/d for the drinking water scenario.

Response: The 2-L/d drinking rate may be a high value for use in a site-specific analysis. However, the intent in this scenario is to conservatively model drinking water consumption and provide a generic evaluation that can be used to determine when a more site-specific analysis should be performed. While the general intent of the scenario analysis in the document is to provide a prudently conservative estimate of the potential radiation doses, the wide range of variables and parameters to model has compelled a relatively conservative approach for the drinking water scenario and the water-use modeling. An expanded discussion has been added to explain the rationale for this scenario. In addition, the 1.4-L/d value is for an average individual and may not provide a prudently conservative analysis.

Comment 10: Paragraph 2 on page B.14 states that modified annual TEDE factors can be obtained by simply multiplying the TEDE factor in Table 3.4 by the modified parametric value and then dividing by the previously assumed parameter value. This is incorrect because the TEDE factors do not have linear relationships with most of the parameters listed in Equations (B.9) and (B.10).

Response: The paragraph and concepts have been modified appropriately based on this comment.

Comment 11: What assurance is there that the drinking water scenario is sufficiently conservative that it won't give a "false positive" (or low dose) reading?

Response: The water-use model has been extensively reviewed by both PNL and NRC geohydrologists. After an extensive literature search, the authors selected a set of parameter values for the calculations consistent with the prudently conservative approach. As mentioned above, the doses were calculated for an arbitrary period of up to 10,000 years. While it is possible that a scenario could be developed that would result in higher doses, it is assumed that the modeling and parameter selection are sufficiently conservative and will result in appropriate screening values for all but highly unlikely cases. In addition, the scenario considered an individual who consumes 2 L/d of water from the ground-water source. Several commenters held that a more reasonable consumption rate would be about 1 to 1.5 L/d. Based on this (and other) comments, the discussion of the water-use model and the drinking water scenario were expanded appropriately.

A.4.4 Models

About 20 comments were received on the details of the pathway analysis models used in the draft NUREG/CR-5512. The comments included concerns over the use of specific data or assumptions, details about the surface contamination conditions in the building occupancy scenario, accommodation of sources below the top 15 cm of soil, and the need for models describing other situations. The following comments and responses summarize the significant issues raised during the public review, and the modifications that have been made to the final report.

Comment 1: In general, the screening approach is difficult to apply when the many site-specific variables are considered. Screening levels, depending on the scenarios selected and parameters used, can be extremely conservative for many applications and radionuclides; but they can also result in underestimates of dose in selected cases. Site-specific modeling forces the users to consider the major parameters and allows flexibility of site-specific analysis that is easily verified by the regulators.

Response: The screening approach was selected because there are numerous licensees that handle rather small quantities of materials and have relatively trivial problems. These sites may not have the resources to conduct site-specific analyses and should not be required to do so. For more sites that do not meet the screening levels, site-specific applications derived within the modeling framework of this report may

be used; or more detailed models and data can be applied. It is difficult to predict in advance whether a generic modeling analysis will produce a more or less conservative result than a site-specific analysis. However, by using prudently conservative assumptions and data selections, it is unlikely that the doses for many sites will be underestimated. This approach has not been changed in the final report.

Comment 2: The draft report claims that the purpose is to calculate the likely radiation doses to average individuals. This is a general philosophy of dose assessment that should be endorsed. Too often decisions are made on the basis of worst-case estimates of dose, which have virtually no chance of being experienced by any individuals.

Response: The final report continues to be based on a prudently conservative analysis of the dose to average, not maximally, exposed individuals. No changes have been made to the text because of this comment.

Comment 3: It is important to emphasize the objective of the modeling exercise. By selecting prudently conservative modeling assumptions, instead of worst case, the doses may be underestimates for some situations.

Response: The section describing the intent of the modeling analysis was reviewed and expanded. For example, it is not reasonable to expect that all structures will become residences (e.g., reactor containment buildings). However, many could continue with some kind of laboratory or industrial application (e.g., laboratory space at a university). Discussions of the study basis and the modeling approach were reviewed and expanded appropriately.

Comment 4: It is difficult to interpret the methodology and data well enough to recreate the effective dose equivalent factors in the draft report using the GENII system. A clear explanation of how the calculations were performed is needed.

Response: For the final report, a careful analysis of the models, data, and calculational methods was performed and the use of the GENII software was discontinued. As a result, a software requirements specification was developed as part of the quality-assurance process of establishing a new computer code. This specification serves as the basis of a separate user-friendly computer program contained in Volume 2. This computer program can be used to recreate the scenarios and values found in this final document and produce dose conversion factor results for any mixture of radionuclides. The software also allows the user to make simple changes to the scenarios and data to better fit a simple site. Furthermore, all equations and parameter values necessary to hand-calculate annual TEDEs are provided in Volume 1 of this report.

Comment 5: The inhalation and secondary ingestion models used in the building occupancy (surface activity) scenario contain errors in converting from surface activity to mass activity. The models for these pathways need to be corrected and revised calculations need to be performed.

Response: A careful dimensional analysis was conducted, and the errors were identified and corrected for the final report. In summary, to convert from surface activity to mass activity in air for the building occupancy scenario, a resuspension factor of 10^{-6} m^{-1} is used. To convert from loose surface activity to mass activity for ingestion, an ingestion rate of 10^{-4} m^2/h is used.

Comment 6: The residential surface-soil scenario is of limited use for sites with contamination or wastes buried deeper than 15 cm. Accommodation of sources of radioactivity deeper than 15 cm is needed in the models.

Response: The intent of the basic analysis is to provide generic screening levels and the modeling framework for deriving site-specific levels. These screening levels will aid the identification of cases where more detailed site-specific analyses are warranted. Clearly, for sites with subsurface sources, additional modeling detail may be needed to determine compliance. Also, the models are intended for simple surface-soil contamination cases and not onsite waste disposal or residual contamination within 1 m of the saturated zone, where other more appropriate performance assessment models and data sets are needed.

Comment 7: Inhalation dose conversion factors should be supplied for each solubility class, and ingestion dose conversion factors should be supplied for each f_1 value provided by the ICRP.

Response: The base-line calculations in the final document are made using assumptions about the inhalation solubility and f_1 values that will produce limiting results because the intent is to provide a screening analysis. The initial user-friendly computer software package developed to support this document will be done in the same manner. Future enhancements to the software will consider expanding the flexibility of the code to allow users to modify the inhalation solubility and f_1 selections to match known conditions.

Comment 8: One commenter indicated that the indoor radon aerosol should be considered for residual uranium and thorium in building materials because in many cases the radon will be the limiting pathway for uranium and thorium contamination. A second commenter stated that a generic model for the indoor radon aerosol would produce uncertain results because the design of a future building and its ventilation would be entirely conjectural.

Response: The NRC believes that it is more practical in terms of accuracy and economics to appropriately measure the indoor radon aerosol than to model it. The broad range of geological and architectural environments would lead to generic indoor radon models that would be extremely conservative for a large fraction of cases. The NRC will include criteria for indoor radon for measurements in the interim criteria for unrestricted release. No changes were made to the modeling approach because of this comment.

Comment 9: Equation (2.5) on page 2.43 of the draft presents a rather formidable-looking model for estimating the concentration of radionuclides in vegetation. In particular, the distinction of the last two terms seems unnecessary for a generic modeling exercise.

Response: This modeling approach for the residential scenario using this equation has been revised for the final report, eliminating the contribution from the last term (uptake from deep layers of soil). The revised approach accounts for uptake by roots from soil; deposition of resuspended soil on leaves; deposition and uptake of irrigation water by plants; uptake from plants, soil, and water by animals; and uptake of water, soil, plant crops, animal products, fish, soil, and air by man. A discussion of the modified approach for the residential scenario is found in Section 5.

Comment 10: If the inhalation rate is included in the dose conversion factor listed in Table 2.2, then the text must be appropriately modified.

Response: The inhalation rate is included as a separate parameter that may vary in the analysis for each scenario. The dose conversion factors are taken directly from Eckerman, Wolbarst, and Richardson (1988) in units of dose per unit intake. The text has been carefully reviewed and appropriately modified.

Comment 11: The value of zero for soil uptake for ^{3}H and ^{14}C should be verified and the specific form of ^{3}H should be stated.

Response: The models have been modified to include uptake of ^{3}H and ^{14}C from soil, as discussed in Appendices C and D. The ^{3}H is assumed to be HTO.

A.4.5 Data Selections

Seven comments on draft NUREG/CR-5512 were received dealing with the details of data or parameter selections supporting the modeling analysis. Some commenters generally questioned the overly conservative nature of specific data or parameter selections, while others requested a more conservative approach in selected areas. The following general comments and responses summarize the significant issues raised during the public review, and the modifications that have been made to the final report.

Comment 1: Several commenters stated that parameters were selected to provide a reasonable (not worst-case) estimate of the radiation dose conversion factor to an average member of a population. However, many of the assumptions and data used are not reasonable and represent the worst case. For example, it is assumed that the entire inventory of radionuclides will go into drinking water; there is no retardation in radionuclide transport in ground-water systems; and in some cases maximum individual consumption rates versus average consumption rates are used. These assumptions and data selections are extremely conservative and unreasonable.

Response: As discussed in Section 6 of the final report, an attempt has been made to identify the potential range for all data or parameter values, and to select parameter values within (not at the extreme) of these ranges. The notable exception is the drinking water pathway, where a simple method of estimating the ground-water concentration (ignoring retardation), combined with 2-L/d consumption of drinking water, is used. The major difference for this pathway between the residential and drinking water scenarios is the volume of water in the aquifer used to estimate the water concentration (i.e., because of irrigation and surface water, the residential scenario requires more water and thus provides more dilution for the radionuclides). Because less dilution is used in the drinking water scenario, the results will be more conservative than the drinking water pathway in the residential scenario. The results of this scenario provide a basis for determining when additional site-specific details or modeling are needed. Volume 1 of the final report contains an expanded discussion of the water-use model and the intent of the drinking water scenario. Because the other assumptions and parameters are within their potential ranges defined by literature values (as discussed in Section 6), no other changes have been made to the final report.

Comment 2: The choice of input parameters generally provides assurance that a conservative analysis has been conducted so that the dose limits are never exceeded. A sensitivity study needs to be conducted to assure that the estimates are conservative.

Response: The basic premise of the entire modeling analysis is to perform a prudently conservative analysis, not a worst-case analysis. The reason for this approach is that the calculated dose conversion factors are expected to be reasonably bounding in the large majority of cases. The discussion of the study basis and the modeling approach were reviewed and expanded appropriately.

Comment 3: The choice of shielding factors for the indoor residence part of the residential scenario, as discussed at the top of page 3.24 of the draft, is somewhat subjective. The most important variable is whether

shielding inside a single-family house is considered or whether the structure is more substantial (i.e., a school, factory, apartment, or office building). From the literature, a higher shielding factor of 0.7 (instead of 0.33) would be reasonable for this analysis.

Response: The choice of a shielding factor for the indoor-exposure conditions in the residential scenario is indeed somewhat subjective. As explained in the draft text, the range of potential shielding factors in the literature is from about 0.2 to 0.6, with the majority of data within a range of 0.02 to 0.4. The choice of a factor as high as 0.7 exceeds the range identified in the literature. For this reason, no change has been made to the residential-scenario indoor-shielding factor for the final report.

Comment 4 The leach-rate factors from Oztunali et al. (1981) refer to low-level radioactive wastes and may not be applicable for other types of wastes, including contaminated soils.

Response: Leach-rate factors and other information pertaining to the ground-water pathway can vary over a wide range, depending on site- and radionuclide-specific conditions. As discussed in Section 4, the purpose of the water-use model was to help determine which cases pose a trivial potential for ground-water contamination and which cases need to be further evaluated. The leach-rate values found in recent literature or derived using the soil-to-plant ratios (as discussed in Section 6) have been used instead of those found in Oztunali et al. (1981).

Comment 5: A better description of the solubility of radionuclides for the ingestion and inhalation pathways needs to be developed for the residential scenario. Was the most conservative solubility (i.e., the one leading to the largest radiation dose) used for each pathway for conservatism, even though it is chemically contradictory to model the same radionuclide as both soluble and insoluble simultaneously?

Response: An expanded discussion of the inhalation solubility classes and the f_1 factors has been provided for the final text. In general, the worst-case solubility has been assumed for the inhalation and ingestion pathways for the dose estimates using information found in EPA Federal Guidance Report No. 11 (Eckerman, Wolbarst, and Richardson 1988), even though this may seem contradictory. The exception is for plutonium, where a solubility class and uptake fraction more representative of environmental plutonium is used. The objective of this report is to derive generic screening levels as opposed to providing a precise kinetic model. This prudently conservative approach is intended to compensate for large uncertainties in the knowledge of the long-term interactions between the environment and radionuclides--either alone or in a spectrum of chemical carriers. For sites where the detailed environmental chemistry of specific elements is well known, future enhancements to the user-friendly software, described in Volume 2, will allow the user to specify the inhalation class and f_1. No change beyond a modified discussion has been made to the final document.

Comment 6: The external dose rate conversion factors listed in Table 2.1 of the draft were converted from data in Table D.4 using an apparent soil density of 2.42 g/cm^3. This density is too high for soils.

Response: In the January 1990 draft, the density of concrete was assumed to be 2.4 g/cm^3. In the revised report, the soil density used in the calculations is 1.625 g/cm^3 (using the number of significant figures provided in Eckerman, Wolbarst, and Richardson 1988). The software design requirements were written to include this value in the modified method of determining external radiation exposures, and the text has been revised.

A.4.6 Other Pathways and Scenarios

There were 10 comments on draft NUREG/CR-5512 that involved other potential radiation exposure pathways or scenarios. The comments indicated that water pathways (including irrigation of agricultural land and ingestion of foods harvested from aquatic environments) should be included; the comments also encouraged inclusion of indoor radon exposure pathways in addition to a more detailed discussion of intruder events. The following comments and responses summarize the significant points raised during the public review and the modifications that have been made to the final report.

Comment 1: Several commenters specifically addressed potential water pathways that were not considered in the draft report. These included irrigation of land using contaminated ground water and ingestion of aquatic foods from surface streams potentially contaminated by surface runoff. One commenter indicated that this omission would make the data in the tables of the report of limited use, while another indicated that omission of the water pathways was justified because these pathways are site-specific.

Response: The pathways included in the generic analysis were those directly associated with exposure to contaminated soil sites. As previously noted, the residential scenario was modified to include use of ground water for drinking and irrigation and ingestion of fish from a surface pond. Surface runoff was assumed to be a secondary pathway in a generic analysis because it relies too strongly on site-specific conditions and requires processes that result in additional dilution before exposure can occur at a distance from the contaminated site. It is recognized that this pathway may be important for very large sites and for acute (flash flood) events at arid sites; however, a complete analysis would require a more detailed set of models, with the inclusion of additional data that may not be representative of a variety of generic situations. A revised description of the basis for the modeling has been included, but no other modifications have been made to the final report.

Comment 2: A potential pathway of importance that was omitted is direct ingestion of contaminated soil. This can be an important pathway for exposures of children who are prone to eat a lot of dirt while playing outdoors; however, it is hard to include in an analysis of the potential dose to adults. There are radionuclides for which direct ingestion of soil may play a role. This is particularly the case for radionuclides for which the root uptake factor from soil to plants may be very low. This pathway should be included for adults only in conjunction with ingestion of foods contaminated via root uptake.

Response: Children who eat contaminated soil do not constitute an appropriate critical population for the purposes of developing generic screening criteria. In recognition of the potential importance of this pathway, secondary ingestion of removable contamination was included in the building renovation and building occupancy scenarios, and soil deposition on plant surfaces after resuspension or irrigation was included in the residential scenario. The final report has been modified to include secondary ingestion of soil by an adult (using a lower ingestion) and by animals. The inclusion of soil ingestion is supported by an expanded review of the literature. The scenario descriptions were modified to better explain the rationale, but no modifications were made to the scenario analysis.

Comment 3: Two commenters referred to contamination on food crops by mechanisms other than root uptake. The first indicated that lack of rain-drop splash may produce nonconservative answers for some elements like cesium. A second commenter indicated removal of radionuclides on plant surfaces (deposited from radionuclides in soil resuspended in the air) should be included to reduce the doses from ingestion.

Response: For the food pathway within the residential scenario, the crops are assumed to be contaminated by both root uptake and deposition of radionuclides in irrigation water or in soils that are resuspended. Washing of produce to cause removal of some of the deposited material on the surface was not assumed. In this manner, the analysis was designed to compensate for the potential ingestion of material on plant surfaces, without adding deposition or removal mechanisms. In addition, secondary ingestion of soil by adults has been added to compensate for not including rain-drop splash. The scenario descriptions were modified to better explain the rationale, and the inclusion of the soil-ingestion pathway was made to further bound the potential effect of rain-drop splash.

Comment 4: The report should provide more detailed discussion on how to account for intruder events in performing dose assessments.

Response: The concept of intruders applies to sites that are still under regulatory control. A classic example is for licensed low-level-waste disposal sites. Intruder analyses can occur either during or after a period of institutional control. For sites containing residual radioactivity, the concept of an intruder is difficult to define since the release is intended for unrestricted use by any person, for all times. The discussion of scenario selection was expanded for the final draft, but no modifications were made to the scenario analysis specifically to address intruders.

A.4.7 Airborne Dust-Loadings

As a result of the public review of draft NUREG/CR-5512, 10 comments were received concerning the choice of airborne dust-loadings in the scenario analysis. The comments included concerns about sources of data, the potential use of a respirable fraction to reduce the effective air concentrations, individual data selections for indoor and outdoor dust-loadings, and the potential relationship between resuspended dust- and mass-loading models. The following comments and responses summarize both the significant issues raised during the public review and the modifications that have been made to the final report.

Comment 1: One commenter generally questioned the determination of dust-loadings from the literature, requesting an explanation of why different indoor dust-loadings were assumed for the building occupancy and residential scenarios. In some cases, the commenter noted, although the values seem reasonable when compared to the reference by Anspaugh et al. (1974), the supporting justification does not.

Response: The discussion of dust-loadings found in Section 6 has been revised to consider additional literature sources. The conclusions of Anspaugh et al. (1974) were reviewed as part of this revised discussion. It was assumed that the building occupancy scenario would include both office buildings and buildings used for light industrial activities; thus, a higher dust-loading than just for the residential scenario was used. The revised discussion in Section 6 provides an expanded rationale for the selection of dust-loadings; however, no other modifications were made to the report based on this comment.

Comment 2: The amounts of suspended dust in air assumed in exposure scenarios are reasonably conservative; dust-loadings three times higher than those used would be unrealistically high. However, all dust-loadings use a respirable fraction of 1.0. Literature values report that only about 30% of the suspended dust would be in the respirable range below 10 μm. All inhaled dust concentrations should be reduced to about 0.3 of the values used to account for the respirable fraction.

Response: The respirable fraction of airborne dust is highly variable (but seldom 1.0) and will depend on many factors. The mass-loading approach for estimating airborne dust concentrations was selected because

of its ease of application and because it required fewer assumptions and modeling steps than other methods. Variability in the dust-loading is accounted for by assuming a single average mass-loading factor for the duration of similar activities during the scenario. Dust-loadings were assigned within the expected range of values and a respirable fraction of 1.0 was assumed to provide conservatism. A discussion of the selection of mass-loading factors has been revised; however, no other change has been made to the final document because of this comment.

Comment 3: The indoor dust-loading was assumed to be 10% of the average value outdoors. While the indoor level in an undisturbed house may be less because of the availability of surfaces onto which airborne dust may deposit, human activity in the house (e.g., vacuuming or sitting in padded chairs) may increase indoor dust-loadings. An increase by a factor of two to five in the airborne dust-loading would be appropriate.

Response: The indoor dust-loading was assumed to be equal to the previously reported EPA value for indoor dust shown in their threshold limit values (TLVs). This value is within the range of values that appear in the literature shown in the discussion in Section 6. For the residential scenario, an additional source of indoor airborne dust has been added from resuspended soil tracked indoors. Because the intent of the analysis is to provide a prudently conservative (not worst-case) analysis of the potential dose, no changes to the assumed indoor dust-loading have been made for the final report. An expanded discussion of the selection of dust-loadings, including additional literature values, is included in Section 6.

Comment 4: One commenter asked if it was reasonable that gardening will be five times as dusty as the ambient outdoor air, while a second commenter noted that higher dust concentrations while gardening seemed reasonable. A third commenter suggested that all dust values be rounded up to the nearest order of magnitude.

Response: The expanded discussion of potential dust-loadings in Section 6 discusses the rationale for assuming an elevated dust-loading while gardening. Because the values selected are within the potential ranges for dust-loadings associated with the activities defined for the scenarios, no changes are made to the data selections.

Comment 5: The consideration of only respirable dust for dosimetric purposes makes sense for determining lung dose. To best determine the effective dose equivalent, however, the non-respirable particle sizes should be considered because they will contribute to the overall effective dose.

Response: The ICRP task group's lung model, used in the estimation of radiation doses from inhalation, does account for materials that are removed from the nose and shallow lung compartments and then transferred to the stomach. In addition, all of the scenarios defined in the generic analysis account for ingestion dose, either through secondary ingestion or direct ingestion of food products, drinking water, or soil. Ingestion of large-particle (non-respirable) material in the air concentration, beyond the normal operation of the ICRP lung model, was not included in the final report. However, it is believed that the assumption that the respirable fraction is 1.0 is sufficiently conservative to account for the dose attributable to ingested particles.

Comment 6: The conclusions of Anspaugh et al. (1974) are not used in Appendix B of the draft, even though a mass-loading model is used. The effort to fit the mass-loading model to the data on resuspension factors seems rather weak, given the wide range of resuspension factors reported in the literature.

Perhaps it would make more sense to simply use mass-loading factors from the literature and eliminate the discussion of resuspension factors.

Response: Part of the reason for including a discussion of resuspension models is to recognize that they may be used as an alternative to the methods used in this analysis. Based on an expanded literature survey of potential dust-loading information, an expanded discussion has been included in Section 6; however, no modifications have been made to the data selections or dose conversion factor analysis.

Comment 7: For the building renovation scenario, an average atmospheric dust-loading of 10^{-4} g/m^3 was assumed. According to the paper by Anspaugh et al. (1974), this dust-loading corresponds to the average background value outdoors. Dust-loadings during building renovation could be considerably greater than the average dust-loading outdoors--this means that the potential doses for this scenario may be underestimated.

Response: Although the short-term dust-loadings may be higher, the intent was to select an average value that would be appropriate for the entire 500 hours of building renovation. The indoor dust-loading would be controlled by a number of factors, including the type and effectiveness of the building ventilation system. For this reason, no changes have been made to the assumed dust-loading for the building renovation scenario for the final report. No changes were made to the final report based on this comment.

Comment 8: Does the EPA have standards for residential surface soils indoors and air concentrations for leaf deposition as shown in Table 3.5?

Response: A careful review of Table 3.5 of the draft showed two typographical errors involving dust-loadings. The first was the yardwork dust value shown for the residential scenario. The table shows an incorrect value of 1×10^{-5} g/m^3. The correct value is 1×10^{-4} g/m^3. The second error was an air-concentrations value of 5×10^{-5} g/m^3 from air-to-leaf disposition in the residential scenario (Table 3.5). The correct value for this parameter is 1×10^{-4} g/m^3, the same value as used for yardwork dust.

A.5 Model Verification

A total of 16 comments were submitted regarding verification of the model analysis supporting draft NUREG/CR-5512. The commenters requested expanded documentation of computer model intercomparisons and provided feedback on the initial comparisons of model results that were based on the draft and made independently based on the draft. Most of the commenters either requested a model comparison study with the RESRAD computer code developed by the U.S. Department of Energy (DOE) or reported on initial comparison efforts using the RESRAD computer code. The following comments and responses summarize the significant issues raised during the public review, and the modifications that have been made to the final report.

Comment 1: Provide a description of how the models were verified by comparisons with other computer codes and with experimental data correlating contamination levels with external dose.

Response: Attempts to verify operation of the models with hand calculations and comparisons with other modeling studies were made and documented in several places in the draft report. These included comparisons of the basic pathway dose conversion factors and comparisons of the scenario results. For the final report, hand calculations have been repeated under strict quality-assurance procedures as

described in an internal software validation, verification, and testing plan. The quality-assurance procedures included the development of a software-specifications manual that was carefully reviewed to match the mathematical formulations in Volume 1 of the final report. Furthermore, Volume 1 of the final report contains all the mathematical formulations necessary for the user to perform independent hand calculations. Upon completion of the user-friendly computer software supported by Volume 1, a modeling comparison will be conducted with relevant scenarios using other computerized software, including the RESRAD code developed for DOE and IMPACTS-BRC developed for NRC.

Comment 2: A comment from DOE recommended a cooperative interagency research effort to support the criteria. The effort could be in the development and verification of the computer codes and their mathematical models. To verify the models, DOE recommends that several NRC staff select a scenario for soil-contamination criteria and attempt an analysis with both RESRAD and the NRC methods to determine which is more desirable.

Response: There have been interagency discussions regarding potential joint research projects that could be conducted to evaluate the models and methods for translating residual contamination levels to annual dose. Staff from the NRC have agreed to participate in a joint project with DOE to collect experimental data from a contaminated facility and to relate surface-contamination levels to external dose rates. These data should be useful in future model-verification studies. Additional model intercomparisons will be conducted to evaluate the operation of the models supporting this document. No changes were made to the final report because of this comment.

Comment 3: One commenter found the comparisons with Regulatory Guides 1.109 and 1.86 (NRC 1977 and 1974) to be useful and commented that the "now versus then" agreement was very good. A second commenter indicated that there was no basis for these comparisons because Regulatory Guide 1.86 was based on measurement, not potential dose considerations; this commenter went on to suggest further comparisons that might be more meaningful.

Response: Although the existing Regulatory Guides and the methods used for this report have a different basis, a comparison is useful to help indicate the impact of the revisions. As stated in response to Comment 1 above, PNL will conduct an extended modeling comparison with relevant scenarios using other methods and include these comparisons in a separate volume supporting this document.

Comment 4: One commenter reported initial results obtained using the RESRAD computer program. The commenter indicated that the models and pathways of exposure generally compare with those considered by RESRAD; however, some differences do occur. The commenter indicated that RESRAD contains more conservatism and a different ground-water model, but that ground water is so site-specific that both approaches should be used with caution. A second commenter indicated that the RESRAD code is more user-friendly than the methods contained in draft NUREG/CR-5512.

Response: As previously noted, an expanded modeling analysis is planned and formal documentation of the methods and models used to generate this report will be provided in Volume 3. Perhaps it is not surprising that the RESRAD code produced initial results that are more conservative than the models used in this analysis because this analysis was intended to produce prudently conservative (not worst-case) results. However, a full comparison needs to be completed before any conclusions can be made. Finally, the computerized method and models used in the draft report were simply listed in an appendix; they were not made publicly available for testing during the review. Thus, complete comparisons using anything except hand calculations were not possible. Attempts will be made to ensure that the

final software is user-friendly and documented in an understandable manner; however, no changes were made to the final report because of this comment.

Comment 5: A set of five detailed comments was submitted concerning an initial comparison with RESRAD completed by DOE. The first two comments outlined the comparison using 100 pCi/g of plutonium isotopes. The results with zero decay were quite close; RESRAD produced 3.7 mrem/y versus 2.6 mrem/y using the results for this study. The commenters also discussed the problem of radioactive decay and the ingrowth of ^{241}Am at different times. When an attempt was made to conduct a comparison with 15 years of decay, one commenter noted, RESRAD continued to produce 3.7 mrem/y, while the results of this study, including daughter ingrowth, produced 54 mrem/y. Another commenter indicated that there was some confusion about how to perform the calculations using the dose conversion factors in the draft report. This commenter also indicated that not including soil-removal mechanisms would lead to greatly different results.

Response: Major revisions to the modeling approach have been made. Instead of listing the scenario dose conversion factors as the total activity of parent plus daughters, as was done in the draft, the final report lists the factors by activity of the parent alone. This change should clarify the factors and make them simpler to use. Comparisons at different decay periods are possible by simply using the mixtures representing different equilibrium conditions present at different times. As previously stated, a sensitivity study and model comparison is documented in Volume 3 of this report.

A.6 Other Issues

The final category of comments included six comments that did not fit into the other categories. One commenter indicated that the document should include an analysis of contaminated piping or other equipment that may be left in place for reuse. A second commenter indicated that the analysis in the draft would be of little use because it did not include key radionuclides in the uranium and thorium decay chains (i.e., $^{220/222}Rn$, $^{212/214}Po$, ^{214}Pb, ^{214}Bi, and ^{208}Tl). A set of comments questioned the scenario results and indicated that their application to the FUSRAP and the Uranium Mill Tailings Remedial Action Project (UMTRAP) sites might be limited. The following general comments and responses summarize the significant issues raised and the modifications that have been made to the final report.

Comment 1: Piping and other components are not considered in draft NUREG/CR-5512. If this document and the revised NRC policy are to replace Regulatory Guide 1.86 as a basis for determining criteria for unrestricted release, piping and components should be included. It is not adequate to assume that all slightly contaminated components would be removed. For example, slightly contaminated systems might remain in the facility if it were converted into a fossil-fueled power plant.

Response: Any unusual contamination left in place requires NRC approval. Such approval could be given to justify a specific request after the NRC evaluates the pathway analysis submitted by the licensee. Recycle or reuse of contaminated equipment, including piping or other components that may be left in place, will be the subject of a separate, future NRC technical report. However, volume contamination was included in the building renovation scenario and an accounting of the total inventory left onsite was included in the water-use scenario. No changes were made to the final report because of this comment.

Comment 2: Many residual radioactivity sites contain materials contaminated with uranium, thorium, and radium. This document will have limited utility for these sites because essential radionuclides (such as $^{220/222}Rn$, $^{212/214}Po$, ^{214}Pb, and ^{208}Tl) are omitted.

Response: With the exception of radon gas, the radionuclides mentioned in the comment have very short half-lives (from a fraction of a second to about 30 minutes). They were all included as implicit daughters in equilibrium with longer-lived parents in the draft report. For the final report, the format of the information has been changed and the explanation of the role of decay progeny has been expanded to make the information more useful. The major exception is the omission of a special model for radon in buildings. This omission is justified, however, because of the potential complexity in modeling the indoor radon aerosol and the intent to produce generic models and scenarios. Indoor radon aerosol modeling would also be of limited usefulness when compliance with EPA standards can be made using measurements. No further changes were made to the final report because of this comment.

Comment 3: Two commenters requested a verification that the surface-contamination (building occupancy) scenario is more restrictive than the volume-contamination (building renovation) scenario, and requested a basis for the conclusion.

Response: An expanded discussion of the two scenarios has been provided; however, the two scenarios consider different situations. It is not correct to assume that the surface scenario provides the more restrictive limits (i.e., for beta and alpha sources, volume contamination may be more important than surface contamination). No further change was made to the final document because of this comment.

Comment 4: The comparison-to-standards section should be expanded to include a comparison with the proposed EPA guidance on transuranic elements in soil.

Response: A comparison with the proposed EPA guidance was intentionally omitted because the standards are not in final form. No change has been made to the final report because of this comment.

Comment 5: The scenario analysis is limited to NRC-licensed facilities. With modifications, the information should be applicable to most types of facilities. For FUSRAP, UMTRAP, and DOE surplus facilities, measurements of the radiological conditions would be necessary to apply the methodology.

Response: The generic analysis should permit consideration of any type of facility, as long as detailed information concerning the radionuclide inventory is developed. This information should be available from a detailed radiological survey conducted for a site prior to release. No change is made to the final document based on this comment.

A.7 References

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Appendix B

Extended Nomenclature and Methodology

Appendix B

Extended Nomenclature and Methodology

This appendix is an extension to the nomenclature and methodology described in Section 2 of this report. The details presented in this appendix explain the nomenclature and methodology needed for a complete evaluation of the annual total effective dose equivalent (TEDE) from residual radioactive contamination. Section B.1 provides the basic radioactive decay equations for cases with and without removal by loss processes (e.g., weathering from plant surfaces). Section B.2 illustrates use of the decay equations (operators $A\{\}$, and $A_e\{\}$) for evaluating the change in activity or concentration over a time period. Derivations of basic equations are shown for decay with removal. Equivalence between the decay operator notation and the original Bateman equations is demonstrated. The evaluation of time integrals (operators $S\{\}$ and $S_e\{\}$) is demonstrated in Section B.3 based on the basic form of equations for decay over a time period. Section B.4 presents a derivation of equations for deposition accumulation (operators $R\{\}$ and $R_e\{\}$) for evaluation of an activity or concentration at the end of the accumulation period. The deposition accumulation equations are extended to give the time integral of activity or concentration over a deposition period (operators $G\{\}$ and $G_e\{\}$) in Section B.5. The solution to the water-use model for the drinking water scenario (operators $A_{dk}\{\}$ and $S_{dk}\{\}$) is demonstrated in Section B.6 based on the basic decay equations given in Section B.1 for decay with removal, and Section B.3 for the time integral of decay with removal. Finally, the solution to the water-use model for the residential scenario is described in Section B.7 (operators $A_{rk}\{\}$ and $S_{rk}\{\}$).

B.1 Radionuclide Decay Calculations

The mathematical description of radioactive decay processes was first described by Bateman (1910) in the form of equations giving the amount (in atoms) of each decay chain member present as a function of time. These equations are defined for a chain of radionuclides without branching and with 100% transition from each chain member to the next chain member. The initial amount of chain member present at time zero is represented in the equations.

Skrable et al. (1974) extended the Bateman equations to consider cases involving a constant independent rate of production of each chain member and removal mechanisms other than radioactive transitions. They also indicated how to use their equations to represent radioactive decay sequences involving branching. When branching occurs, the amount of each chain member present at a given time is evaluated as the sum of contributions from each branch of the decay sequence, a method suggested by Friedlander and Kennedy (1955). The equations as presented are similar to the original Bateman equations, with expansion of the exponential terms to include the independent rate of production of each chain member. The expansions represent the time integral of production at a constant rate.

Scherpelz and Desrosiers (1980) have described a recurrence formula based on the work of Hamawi (1971) that can be used to evaluate radioactive chain decay. Their method provides the Bateman equations when expanded and condensed. They also indicate that the time integral of the amount of each chain member can be evaluated by replacing the exponential term by the integral form of the exponential term. The replacement is applied in the equations presented for radioactive decay calculations described in this report.

The forms of radioactive decay equations described by Skrable et al. (1974) and Scherpelz and Desrosiers (1980) are defined for radioactive decay in sequences without branching. Branching can be accounted for by multiple applications of the equations and summing appropriately. Also, both equation sets can be used to account for loss or removal of each chain member by processes other than radioactive decay.

An alternate form of the radioactive decay equations has been developed and implemented in computer programs at Pacific Northwest Laboratory (Strenge, Hendrickson, and Watson 1971; Strenge and Watson 1973; Strenge, Watson, and Houston 1975; Houston, Strenge, and Watson, 1976; Napier, Peloquin, and Strenge 1986; Napier et al. 1988; Strenge et al. 1990). The equations for this alternate form differ from those presented by the other authors discussed above in that the solution for radioactive decay chains with branching is included explicitly in the representations: no addition of contributions from multiple applications for branches is necessary. This alternate form is used as the basis for radioactive decay calculations defined in this report, including evaluations for the three-box water-use model.

B.1.1 General Decay Equations

The radioactive decay process occurs in a random manner that may be described mathematically. When a parent radionuclide i undergoes a transition to a progeny radionuclide (or stable isotope), the quantity of the parent remaining in a medium m after a time period t is written as:

$$C_{mi}(t) = C_{mi}(0)\, e^{-\lambda_{ri} t} \tag{B.1}$$

where $C_{mi}(t)$ = the activity of a radionuclide i at time t in a medium m (pCi)

$C_{mi}(0)$ = the activity of a radionuclide at time zero in a medium m (pCi)

λ_{ri} = radiological decay constant for radionuclide i (d^{-1}).

By defining the source of production (i.e., the parent radionuclides) for each chain member, the decay equations can be used to evaluate chains with multiple branching in a single pass through the system of equations. The general form of the decay equation for the jth member of a decay chain, using the notation defined for this study, is as follows:

$$C_{mj}(t) = \lambda_{rj} \sum_{n=1}^{j} K_{jn}\, e^{-\lambda_{rn} t} \tag{B.2}$$

where $C_{mj}(t)$ = quantity of chain member j at time t in medium m (pCi)

λ_{rj} = decay constant of radionuclide j (d^{-1})

λ_{rn} = decay constant of radionuclide n (d^{-1})

K_{jn} = coefficient for term n for chain member j (pCi•d).

As Equation (B.2) indicates, the solution for the jth member is the sum of j terms, with an exponential component for each member of the decay chain. The coefficients (K_{jn}) are determined by the decay chain data (half-lives and branching fraction) and by the initial amount of the precursor radionuclides present at the start of the time period. The amount of each radionuclide is expressed in activity units (e.g., pCi).

Evaluation of the coefficients is performed starting with the first member and proceeding sequentially through the chain. The number of coefficients needed for a given chain member is equal to the position of the member in the chain. For example, the third chain member requires three coefficients. The coefficient for the first chain member is equal to the activity present at the start of the decay period divided by the radionuclide decay rate constant:

$$K_{11} = \frac{C_{m1}(0)}{\lambda_{r1}} \tag{B.3}$$

The coefficients for other chain members are evaluated using the following equations:

$$K_{jn}(n=1 \text{ to } j-1) = \frac{\sum_{p=n}^{j-1} d_{pj}\,\lambda_{rp}\,K_{pn}}{\lambda_{rj} - \lambda_{rn}} \tag{B.4}$$

and

$$K_{jj} = \frac{C_{mj}(0)}{\lambda_{rj}} - \sum_{n=1}^{j-1} K_{jn} \tag{B.5}$$

where d_{pj} is the fraction of radionuclide p transitions that result in production of radionuclide j (dimensionless) and other terms are as previously defined. This generic representation of the radioactive decay process allows transition and branching from any chain member to any member lower in the chain. In practice, it is only necessary to include terms in the equation for which the branching fractions (d_{pj}) are non-zero.

An alternate form of Equation (B.2), for the amount of each chain member present after a time period t, can be derived by combining Equations (B.2) through (B.5) and separating the term for the last chain member (j). The result is as follows:

$$C_{mj}(t) = C_{mj}(0)\,e^{-\lambda_{rj}t} + \lambda_{rj} \sum_{n=1}^{j-1} K_{jn}\left(e^{-\lambda_{rn}t} - e^{-\lambda_{rj}t}\right) \tag{B.6}$$

This form of the radioactive decay equation is similar to (but still different from) the representations used by Skrable et al. (1974) and Scherpelz and Desroisers (1980) in that the formulation involves the difference of exponentials. Either of the above representations can be evaluated for a radioactive decay chain that has no branching to obtain the original Bateman (1910) equations. In so doing, all decay fractions (d_{pj}) in which the indices differ by more than one (e.g., d_{13}) are set to zero. For chain members beyond the first two, the evaluation involves some algebraic manipulations to collapse terms to the form in Bateman's representation. This process is demonstrated in Section B.2.

The operator notation used to designate decay for a time period is as follows:

$$A\{C_*,t_*\} \tag{B.7}$$

where A{} = the operation of decay of activity in a medium for a time period (units same as C_* units)

C_* = the array of initial concentrations in a medium (activity or concentration units, e.g. pCi, pCi/g, pCi/kg)

t_* = time period for evaluation of concentration (d).

The above equations define the method used to evaluate the amount of a chain member present after a specified time period, t. Another important calculation needed for the dose calculations of this report is the time integral over a specified time period. Inspection of Equations (B.2) through (B.5) reveals that the time parameter, t, appears only in the exponential term of Equation (B.2). This allows the time integral to be evaluated as the integral of the sum of exponential terms. By replacing each exponential expression in Equation (B.2) with the time integral of the exponential evaluated between time zero and time t, the time integral of activity of each chain member can be determined. Details of this procedure are given in Section B.3. This substitution is represented as follows:

$$e^{-\lambda_{rn}t} \text{ is replaced by } \left(1 - e^{-\lambda_{rn}t}\right)/\lambda_{rn} \tag{B.8}$$

The substitution indicated by Equation B.8 allows evaluation of the time integral of the amount of a radionuclide present over a time period. The time units of the time integral correspond to those used for t. The units of t must also be the inverse of the units for λ_{rn}.

The operator notation used to designate the time integral for a time period is as follows:

$$S\{C_*,t_*\} \tag{B.9}$$

where S{} = the operation of time integration of activity in a medium for a time period (units of C_* multiplied by units of t_*), and other terms are as previously defined.

Another application of the decay equations is to evaluate the concentration in a medium after deposition and accumulation at a constant rate for a period of time. This application is needed in evaluation of the activity in soil from irrigation water deposition. The derivation of equations for deposition accumulation are presented in Section B.4. The resulting forms of the equations are very similar to Equations (B.2) through (B.4). The equations may be represented by replacing the initial radionuclide activities, $C_{mj}(0)$, in Equations (B.2), (B.3), and (B.5) with the corresponding constant deposition rates, R_{mj}. Also, the exponential term is replaced as follows:

$$e^{-\lambda_{rn}t} \text{ is replaced by } \frac{1 - e^{-\lambda_{rn}t}}{\lambda_{rn}} \tag{B.10}$$

The derivation of equations for deposition at a constant rate is presented in Section B.4. The deposition, accumulation operator notation representing these calculations is as follows:

$$R\{R_*,t_*\} \tag{B.11}$$

where $R\{\}$ = the operation of deposition accumulation for deposition at a constant rate (units of R_* multiplied by units of t_*, e.g., pCi/g dry-weight soil)

R_* = the array of constant deposition rates for each chain member (units of activity per day per unit mass of receiving medium, e.g., pCi/d•g dry-weight soil)

t_* = time period for evaluation of concentration (d).

The fourth application of the decay equations is for evaluation of a deposition, accumulation, and time integration of a constant input rate by irrigation. Equations for this application can be evaluated as the time integral of the for the deposition accumulation at a constant rate, with integration over the period from 0 to t. The integration step involves integration of the term on the right side of Equation (B.10), as described in Section B.5. The final form for Equation (B.2) is then written by replacing the exponential terms as follows:

$$e^{-\lambda_{rn}t} \text{ is replaced by } \left[t - \left(1 - e^{-\lambda_{rn}t}\right)/\lambda_{rn}\right]/\lambda_{rn} \tag{B.12}$$

The deposition, accumulation, and time-integral evaluation also involves replacement of the initial radionuclide quantities, $C_{mj}(0)$, with the constant deposition rates, R_{mj}, as demonstrated in Section B.4.

The operator notation representing deposition, accumulation, and time integration is as follows:

$$G\{R_*,t_*\} \tag{B.13}$$

where $G\{\}$ = the operation of deposition, accumulation, and time integration for a time period (units of R_* times squared units of t_*)

R_* = the array of constant deposition rates for each chain member (units of activity per day per unit mass of receiving medium, e.g., pCi/d•g dry-weight soil)

t_* = time period for evaluation (d).

B.1.2 Equations for Decay with Removal

In the soil scenarios, the agricultural pathway models require consideration of radioactive decay in a system where other removal mechanisms may also be occurring. For example, the activity on plant surfaces is subject to loss by weathering processes. To evaluate the activity in plants at the end of a growing season, this weathering loss must be considered when performing the decay calculations.

The equations for decay with removal are similar to the equations for decay without removal, i.e., Equations (B.2), (B.3), (B.4), and (B.5). The difference is in use of an effective rate constant in place of the decay constant in specific parts of the equations. The effective rate constant is the sum of the decay constant and the removal rate constant:

$$\lambda_{ej} = \lambda_{rj} + \lambda_w \tag{B.14}$$

where λ_{ej} is the effective rate constant (d^{-1}), and λ_w is the removal rate constant (d^{-1}), shown here as the weathering rate constant.

The equations for decay and loss are given as follows, based on Equations (B.2), (B.3), (B.4), and (B.5):

$$C_{mj}(t) = \lambda_{rj} \sum_{n=1}^{j} K_{jn} e^{-\lambda_{en} t} \tag{B.15}$$

$$K_{11} = \frac{C_{m1}(0)}{\lambda_{r1}} \tag{B.16}$$

$$K_{jn}(n=1 \text{ to } j-1) = \frac{\sum_{p=n}^{j-1} d_{pj} \lambda_{rp} K_{pn}}{\lambda_{ej} - \lambda_{en}} \tag{B.17}$$

$$K_{jj} = \frac{C_{mj}(0)}{\lambda_{rj}} - \sum_{n=1}^{j-1} K_{jn} \tag{B.18}$$

The derivation of these equations is demonstrated in Section B.2 for the first two decay chain members. Equations (B.15) through (B.18) can be combined to obtain an alternate expression comparable to Equation (B.6), as follows:

$$C_{mj}(t) = C_{mj}(0) e^{-\lambda_{ej} t} + \lambda_{rj} \sum_{n=1}^{j-1} K_{jn} \left(e^{-\lambda_{en} t} - e^{-\lambda_{ej} t} \right) \tag{B.19}$$

Equations (B.14) through (B.18) also represent the evaluations for the deposition, accumulation operator and for the deposition, accumulation and time-integration operator, when appropriate substitution is made for the exponential terms. The substitutions parallel those indicated by Equations (B.8), (B.10), and (B.12).

For the time-integral equations (see Section B.3.1), the exponential term of Equation (B.15) is replaced with its integral form as follows:

$$e^{-\lambda_{en} t} \text{ is replaced by } \left[1 - e^{-\lambda_{en} t}\right] / \lambda_{en} \tag{B.20}$$

This substitution is also used for the deposition accumulation calculation with removal as described in Section B.4.1. For the deposition, accumulation and time-integration (see Section B.5.1), the exponential term of Equation (B.15) is replaced as follows:

$$e^{-\lambda_{en}t} \text{ is replaced by } \left[t - \left(1 - e^{-\lambda_{en}t}\right)/\lambda_{en}\right]/\lambda_{en} \tag{B.21}$$

The decay with removal calculation is represented by the decay operator as follows:

$$A_e\{C_*, t_*\} \tag{B.22}$$

where $A_e\{\}$ represents the operation of radioactive decay with removal using an effective removal rate constant, λ_{en}, and other terms are as previously defined. The time integral with removal is represented similarly:

$$S_e\{C_*, t_*\} \tag{B.23}$$

where $S_e\{\}$ represents the operation of the time integration with removal using an effective removal rate constant. The deposition accumulation with removal calculation is indicated by the following operator notation:

$$R_e\{R_*, t_*\} \tag{B.24}$$

where $R_e\{\}$ represents the operation of deposition, accumulation, with removal and other terms are as previously defined.

The time-integration with removal is represented as follows:

$$G_e\{R_*, t_*\} \tag{B.25}$$

where $G_e\{\}$ represents the operation of deposition, accumulation, and time-integration with removal, using an effective removal rate constant.

B.1.3 Decay Equation Units

The equations provided in this section for evaluation of the amount of each chain member present after a time period have been defined for radionuclide amounts defined in units of activity (e.g., pCi) present at the start of the time period. However, in comparing equations in this report with those of the original Bateman (1910) publication, a conversion between activity and atoms must be made. The basic relationship between the two units is as follows:

$$\text{Activity (transitions/time)} = \text{Rate Constant (1/time)} \times \text{Atoms.} \tag{B.26}$$

The conversion from activity units to units proportional to atoms is performed as the inverse of the above equation, as follows:

$$Q_{mj}(t) = kC_{mj}(t)/\lambda_{rj} \tag{B.27}$$

where $Q_{mj}(t)$ = atoms of radionuclide j present in medium m at the start of the period (atoms)

$C_{mj}(t)$ = activity of radionuclide j present in medium m at time t (activity units)

k = constant of proportionality to relate activity units to atom units.

The numerical value for k depends on the choice of activity and time units employed. For activity in Bq and time in seconds, the value for k is 1.0, because 1 Bq is defined as 1 transition per second. However, the value for k is irrelevant to implementation of the equations because k appears in each term of the equation being converted and can be cancelled.

B.2 Radioactive Decay Operators

This section demonstrates correctness and use of the decay equations for decay over a time period, with and without removal processes (operators A{} and A_e{}). The derivation of the equations for decay with removal (Equations [B.14] through [B.18]) are presented in Section B.2.1 as the solution of the basic differential equation for decay. In Section B.2.2 the basic equations for decay without removal are expanded to demonstrate their equivalence with the original Bateman (1910) equations.

B.2.1 Decay Operator with Removal A_e{}

The change in activity or concentration of a radionuclide in a medium with removal can be written as follows:

$$\frac{dC_{mj}}{dt} = \sum_{n=1}^{j-1} d_{nj}\lambda_{rj}C_{mn} - (\lambda_w + \lambda_{rj})\, C_{mj} \qquad \text{(B.28)}$$

where C_{mj} = concentration of radionuclide chain member j in medium m (pCi)

C_{mn} = concentration of precursor radionuclide chain member n in medium m (pCi)

λ_{rj} = radioactive decay rate constant for radionuclide j (d^{-1})

λ_w = rate constant for loss of activity from a medium (d^{-1})

d_{nj} = fraction of precursor radionuclide n transitions that result in production of radionuclide chain member j (dimensionless).

The solution to Equation (B.28) will be derived for the parent and first progeny radionuclides. Equation (B.28) can be written in terms of these chain members as follows, for the parent (j=1):

$$\frac{dC_{m1}}{dt} = -\lambda_{e1}C_{m1} \qquad \text{(B.29)}$$

and for the first progeny (j=2),

$$\frac{dC_{m2}}{dt} = d_{12}\lambda_{r2}C_{m1} - \lambda_{e2}C_{m2} \tag{B.30}$$

where C_{m1} = concentration of parent radionuclide chain member (j=1) in medium m (pCi)

C_{m2} = concentration of first progeny radionuclide (j=2) in medium m (pCi)

d_{12} = fraction of precursor radionuclide 1 (parent) transitions that result in production of radionuclide chain member 2 (dimensionless)

λ_{e1} = rate constant for removal and decay of radionuclide 1, evaluated as the sum of λ_w and λ_{r1} (d^{-1}).

λ_{e2} = rate constant for removal and decay of radionuclide 2, evaluated as the sum of λ_w and λ_{r2} (d^{-1}).

The solution to Equation (B.29) is evaluated by first transferring terms containing the concentration of the parent radionuclide in the medium (C_{m1}) to the left side of the equation, and then multiplying by the integration factor, $e^{\lambda_{e1}t}$:

$$[dC_{m1} + \lambda_{e1}C_{m1}dt]\, e^{\lambda_{e1}t} = 0 \tag{B.31}$$

The left side of the equation can be written as a differential and then integrated to give the following expression:

$$C_{m1}\, e^{\lambda_{e1}t} = \text{Constant} \tag{B.32}$$

Evaluation of the constant of integration is performed using the condition that at t = 0, $C_{m1} = C_{m1}(0)$. The constant is given by:

$$\text{Constant} = C_{m1}(0) \tag{B.33}$$

and the final expression for the amount of parent radionuclide in a medium is given by:

$$C_{m1} = C_{m1}(0)\, e^{-\lambda_{e1}t} \tag{B.34}$$

This expression can be seen to be equivalent to the decay operator notation for the change of activity over a time period, t, as given by Equations (B.15) and (B.16).

The solution of Equation (B.30) for the first progeny radionuclide can be found by first moving terms containing the medium concentration parameter, C_{m2}, to the left side of the equation and multiplying by the integration factor. The expression of Equation (B.34) is also substituted into Equation (B.30) for the parent concentration in the medium. The result of these actions is the following expression:

$$\left[dC_{m2} + \lambda_{e2}C_{m2}dt\right] e^{\lambda_{e2}t} = d_{12}\lambda_{r2}C_{m1}(0)\, e^{(\lambda_{e2}-\lambda_{e1})t}dt \tag{B.35}$$

The left side of this equation can be written as a differential, and the whole equation can be integrated to give the following expression:

$$C_{m2}e^{\lambda_{e2}t} = \frac{d_{12}\lambda_{r2}C_{m1}(0)}{(\lambda_{e2} - \lambda_{e1})} e^{(\lambda_{e2}-\lambda_{e1})t} + \text{Constant} \quad \text{(B.36)}$$

Multiplying through by the inverse of the integrating factor gives the following expression:

$$C_{m2} = \frac{d_{12}\lambda_{r2}C_{m1}(0)}{(\lambda_{e2} - \lambda_{e1})} e^{-\lambda_{e1}t} + [\text{Constant}]\, e^{-\lambda_{e2}t} \quad \text{(B.37)}$$

The constant can be evaluated from the condition that $C_{m2} = C_{m2}(0)$ at $t = 0$. Substituting this condition into Equation (B.37) gives the following expression for the constant:

$$\text{Constant} = + C_{m2}(0) - \frac{d_{12}\lambda_{r2}C_{m1}(0)}{(\lambda_{e2} - \lambda_{e1})} \quad \text{(B.38)}$$

Substituting this expression for the constant and combining terms results in the following expression for the amount of first progeny radionuclide in the medium as a function of time:

$$C_{m2} = \frac{d_{12}\lambda_{r2}C_{m1}(0)}{(\lambda_{e2} - \lambda_{e1})} e^{-\lambda_{e1}t} + \left[C_{m2}(0) - \frac{d_{12}\lambda_{r2}C_{m1}(0)}{(\lambda_{e2} - \lambda_{e1})}\right] e^{-\lambda_{e2}t} \quad \text{(B.39)}$$

This equation is equivalent to the equations generated using the formulas for the decay operator with removal (Equations [B.14] through [B.18]). This derivation demonstrates that the solution to the decay with removal case can be written using Equations (B.14) through (B.18). Examples of equation generation using decay operator equations are given in the next section.

B.2.2 Decay Operator A{}

This section provides a demonstration that the basic decay equations (Equations [B.2] through [B.5]) are equivalent to the original Bateman (1910) equations for a decay sequence that has no branching.

Consider a four-member decay chain with initial activities (pCi) of the four members given by $C_{m1}(0)$, $C_{m2}(0)$, $C_{m3}(0)$, and $C_{m4}(0)$. The equations for each chain member can be written by inspection from Equations (B.2), (B.3), (B.4), and (B.5). For the first chain member (j=1), the equation for the activity present as a function of time is

$$C_{m1}(t) = \lambda_{r1}K_{11}e^{-\lambda_{r1}t} \quad \text{(B.40)}$$

or,

$$C_{m1}(t) = \frac{\lambda_{r1} C_{m1}(0)\, e^{-\lambda_{r1} t}}{\lambda_{r1}} = C_{m1}(0) e^{-\lambda_{r1} t} \tag{B.41}$$

For the second chain member (j=2), the equation is

$$C_{m2}(t) = \lambda_{r2}\left[K_{21}\, e^{-\lambda_{r1} t} + K_{22}\, e^{-\lambda_{r2} t}\right] \tag{B.42}$$

where K_{21} is $\frac{d_{12}\,\lambda_{r1}\,K_{11}}{\lambda_{r2} - \lambda_{r1}}$ and K_{22} is $\frac{C_{m2}(0)}{\lambda_{r2}} - K_{21}$. The final expression for $C_{m2}(t)$ is:

$$\begin{aligned} C_{m2}(t) &= \lambda_{r2}\left\{\frac{C_{m1}(0)\; d_{12}\; \lambda_{r1}}{(\lambda_{r2} - \lambda_{r1})\lambda_{r1}}\, e^{-\lambda_{r1} t} + \left[\frac{C_{m2}(0)}{\lambda_{r2}} - \frac{d_{12}\; \lambda_{r1}\; C_{m1}(0)}{(\lambda_{r2} - \lambda_{r1})\lambda_{r1}}\right] e^{-\lambda_{r2} t}\right\} \\ &= \frac{d_{12}\lambda_{r2} C_{m1}(0)}{\lambda_{r2} - \lambda_{r1}}\, e^{-\lambda_{r1} t} + \left[C_{m2}(0) - \frac{d_{12}\lambda_{r2} C_{m1}(0)}{\lambda_{r2} - \lambda_{r1}}\right] e^{-\lambda_{r2} t} \end{aligned} \tag{B.43}$$

For the third chain member (j=3), the equation is

$$C_{m3}(t) = \lambda_{r3}\left[K_{31}\, e^{-\lambda_{r1} t} + K_{32}\, e^{-\lambda_{r2} t} + K_{33}\, e^{-\lambda_{r3} t}\right] \tag{B.44}$$

The first coefficient, K_{31}, is evaluated using Equation (B.4) as follows:

$$K_{31} = \frac{\sum_{p=1}^{2} d_{p3}\; \lambda_{rp}\; K_{p1}}{\left(\lambda_{r3} - \lambda_{r1}\right)} = \frac{d_{13}\; \lambda_{r1}\; K_{11} + d_{23}\; \lambda_{r2}\; K_{21}}{\left(\lambda_{r3} - \lambda_{r1}\right)} \tag{B.45}$$

Using the previously defined expressions for K_{11} and K_{21} results in the final expression for K_{31}:

$$K_{31} = \frac{d_{13}\; C_{m1}(0)}{\left(\lambda_{r3} - \lambda_{r1}\right)} + \frac{d_{23}\; \lambda_{r2}\; d_{12}\; C_{m1}(0)}{\left(\lambda_{r3} - \lambda_{r1}\right)\left(\lambda_{r2} - \lambda_{r1}\right)} \tag{B.46}$$

The second coefficient, K_{32}, is also evaluated using Equation (B.4) as follows:

$$K_{32} = \frac{\sum_{p=2}^{2} d_{p3}\,\lambda_{rp}\,K_{p2}}{\lambda_{r3} - \lambda_{r2}} = \frac{d_{23}\,\lambda_{r2}\,K_{22}}{\lambda_{r3} - \lambda_{r2}} \tag{B.47}$$

Using the previously defined expressions for K_{22} and K_{21}, the final expression for K_{32} becomes

$$K_{32} = \frac{d_{23}\,C_{m2}(0)}{(\lambda_{r3} - \lambda_{r2})} - \frac{d_{23}\,\lambda_{r2}\,d_{12}\,C_{m1}(0)}{(\lambda_{r3} - \lambda_{r2})(\lambda_{r2} - \lambda_{r1})} \tag{B.48}$$

The third coefficient for the third chain member, K_{33}, is evaluated according to Equation (B.5) as follows:

$$K_{33} = \frac{C_{m3}(0)}{\lambda_{r3}} - \sum_{n=1}^{2} K_{3n} = \frac{C_{m3}(0)}{\lambda_{r3}} - K_{31} - K_{32} \tag{B.49}$$

Substituting the expressions for K_{31} and K_{32} into this expression gives the following equation for coefficient K_{33}:

$$\begin{aligned} K_{33} = {} & \frac{C_{m3}(0)}{\lambda_{r3}} - \frac{d_{13}\,C_{m1}(0)}{\lambda_{r3} - \lambda_{r1}} - \frac{d_{23}\,\lambda_{r2}\,d_{12}\,C_{m1}(0)}{(\lambda_{r3} - \lambda_{r1})(\lambda_{r2} - \lambda_{r1})} \\ & - \frac{d_{23}\,C_{m2}(0)}{(\lambda_{r3} - \lambda_{r2})} + \frac{d_{23}\,\lambda_{r2}\,d_{12}\,C_{m1}(0)}{(\lambda_{r3} - \lambda_{r2})(\lambda_{r2} - \lambda_{r1})} \end{aligned} \tag{B.50}$$

An important algebraic manipulation will now be demonstrated to simplify the above equation for K_{33}. Note that the numerators of the 3rd and 5th term on the right side of Equation (B.50) are the same: $[d_{23}\,\lambda_{r2}\,d_{12}\,C_{m1}(0)]$. The following identity is applied to these two terms:

$$\frac{1}{(c-b)(b-a)} - \frac{1}{(c-a)(b-a)} = \frac{1}{(c-a)(c-b)} \tag{B.51}$$

with $a \neq b$, $b \neq c$, and $a \neq c$. Applying this reduction to the 3rd and 5th terms gives the following expression (numerators omitted for simplicity):

$$\frac{1}{(\lambda_{r3} - \lambda_{r2})(\lambda_{r2} - \lambda_{r1})} - \frac{1}{(\lambda_{r3} - \lambda_{r1})(\lambda_{r2} - \lambda_{r1})} = \frac{1}{(\lambda_{r3} - \lambda_{r1})(\lambda_{r3} - \lambda_{r2})} \tag{B.52}$$

The expression for coefficient K_{33} can now be written in the simpler form:

$$K_{33} = \frac{C_{m3}(0)}{\lambda_{r3}} - \frac{d_{13}\, C_{m1}(0)}{\lambda_{r3} - \lambda_{r1}} - \frac{d_{23}\, C_{m2}(0)}{(\lambda_{r3} - \lambda_{r2})} + \frac{d_{23}\, \lambda_{r2}\, d_{12}\, C_{m1}(0)}{(\lambda_{r3} - \lambda_{r1})(\lambda_{r3} - \lambda_{r2})} \tag{B.53}$$

This type of reduction is necessary to show agreement with the Bateman form of the decay equations, as will be illustrated below. The equation for the third chain member can now be written as follows:

$$\begin{aligned} Q_{m3}(t) = &\left[\frac{d_{13}\, \lambda_{r3}\, C_{m1}(0)}{(\lambda_{r3} - \lambda_{r1})} + \frac{d_{23}\, \lambda_{r2}\, d_{12}\, \lambda_{r3}\, C_{m1}(0)}{(\lambda_{r3} - \lambda_{r1})(\lambda_{r2} - \lambda_{r1})}\right] e^{-\lambda_{r1}t} \\ &+ \left[\frac{d_{23}\, \lambda_{r3}\, C_{m2}(0)}{(\lambda_{r3} - \lambda_{r2})} - \frac{d_{23}\, \lambda_{r2}\, d_{12}\, \lambda_{r3}\, C_{m1}(0)}{(\lambda_{r3} - \lambda_{r2})(\lambda_{r2} - \lambda_{r1})}\right] e^{-\lambda_{r2}t} \\ &+ \left[C_{m3}(0) - \frac{d_{13}\, \lambda_{r3}\, C_{m1}(0)}{(\lambda_{r3} - \lambda_{r1})} - \frac{d_{23}\, \lambda_{r3}\, C_{m2}(0)}{(\lambda_{r3} - \lambda_{r2})} + \frac{d_{23}\, \lambda_{r2}\, d_{12}\, \lambda_{r3}\, C_{m1}(0)}{(\lambda_{r3} - \lambda_{r1})(\lambda_{r3} - \lambda_{r2})}\right] e^{-\lambda_{r3}t} \end{aligned} \tag{B.54}$$

For the fourth chain member (j=4), the equation is

$$C_{m4}(t) = \lambda_{r4}\left[K_{41}\, e^{-\lambda_{r1}t} + K_{42}\, e^{-\lambda_{r2}t} + K_{43}\, e^{-\lambda_{r3}t} + K_{44}\, e^{-\lambda_{r4}t}\right] \tag{B.55}$$

The first coefficient K_{41} is evaluated using Equation (B.4) as follows:

$$K_{41} = \frac{\sum_{p=1}^{3} d_{p4}\, \lambda_{rp}\, K_{p1}}{\lambda_{r4} - \lambda_{r1}} = \frac{d_{14}\, \lambda_{r1}\, K_{11} + d_{24}\, \lambda_{r2}\, K_{21} + d_{34}\, \lambda_{r3}\, K_{31}}{\lambda_{r4} - \lambda_{r1}} \tag{B.56}$$

Substituting the previous expressions for K_{11}, K_{21}, and K_{31} gives the following expression for K_{41}:

$$K_{41} = \frac{d_{14}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r1})} + \frac{d_{24}\, \lambda_{r2}\, d_{12}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r1})(\lambda_{r2} - \lambda_{r1})} + \frac{d_{34}\, \lambda_{r3}\, d_{13}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r1})(\lambda_{r3} - \lambda_{r1})} + \frac{d_{34}\, \lambda_{r3}\, d_{23}\, \lambda_{r2}\, d_{12}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r1})(\lambda_{r3} - \lambda_{r1})(\lambda_{r2} - \lambda_{r1})} \tag{B.57}$$

The second coefficient of Equation (B.55), K_{42}, is evaluated using Equation (B.4) as follows:

$$K_{42} = \frac{\sum_{p=2}^{3} d_{p4}\,\lambda_{rp}\,K_{p2}}{\lambda_{r4} - \lambda_{r2}} = \frac{d_{24}\,\lambda_{r2}\,K_{22} + d_{34}\,\lambda_{r3}\,K_{32}}{\left(\lambda_{r4} - \lambda_{r2}\right)} \tag{B.58}$$

Using the previously defined expressions for K_{22} and K_{32} gives the following equation for coefficient K_{42}:

$$\begin{aligned} K_{42} = {} & \frac{d_{24}\,C_{m2}(0)}{\left(\lambda_{r4} - \lambda_{r2}\right)} - \frac{d_{24}\,\lambda_{r2}\,d_{12}\,C_{m1}(0)}{\left(\lambda_{r4} - \lambda_{r2}\right)\left(\lambda_{r2} - \lambda_{r1}\right)} \\ & + \frac{d_{34}\,\lambda_{r3}\,d_{23}\,C_{m2}(0)}{\left(\lambda_{r4} - \lambda_{r2}\right)\left(\lambda_{r3} - \lambda_{r2}\right)} - \frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r2}\,d_{12}\,C_{m1}(0)}{\left(\lambda_{r4} - \lambda_{r2}\right)\left(\lambda_{r3} - \lambda_{r2}\right)\left(\lambda_{r2} - \lambda_{r1}\right)} \end{aligned} \tag{B.59}$$

The third coefficient of Equation (B.55), K_{43}, is evaluated using Equation (B.4) as follows:

$$K_{43} = \frac{\sum_{p=3}^{3} d_{p4}\,\lambda_{rp}\,K_{p3}}{\lambda_{r4} - \lambda_{r3}} = \frac{d_{34}\,\lambda_{r3}\,K_{33}}{\lambda_{r4} - \lambda_{r3}} \tag{B.60}$$

Using the expression for K_{33} given by Equation (B.50) (the unsimplified form) gives the following expression for K_{43}:

$$\begin{aligned} K_{43} = {} & \frac{d_{34}\,C_{m3}(0)}{\lambda_{r4} - \lambda_{r3}} - \frac{d_{34}\,\lambda_{r3}\,d_{13}\,C_{m1}(0)}{\left(\lambda_{r4} - \lambda_{r3}\right)\left(\lambda_{r3} - \lambda_{r1}\right)} \\ & - \frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r2}\,d_{12}\,C_{m1}(0)}{\left(\lambda_{r4} - \lambda_{r3}\right)\left(\lambda_{r3} - \lambda_{r1}\right)\left(\lambda_{r2} - \lambda_{r1}\right)} - \frac{d_{34}\,\lambda_{r3}\,d_{23}\,C_{m2}(0)}{\left(\lambda_{r4} - \lambda_{r3}\right)\left(\lambda_{r3} - \lambda_{r2}\right)} \\ & + \frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r2}\,d_{12}\,C_{m1}(0)}{\left(\lambda_{r4} - \lambda_{r3}\right)\left(\lambda_{r3} - \lambda_{r2}\right)\left(\lambda_{r2} - \lambda_{r1}\right)} \end{aligned} \tag{B.61}$$

The fourth coefficient of Equation (B.55), K_{44}, is evaluated using Equation (B.5) as follows:

$$K_{44} = \frac{C_{m4}(0)}{\lambda_{r4}} - \sum_{n=1}^{3} K_{4n} = \frac{C_{m4}(0)}{\lambda_{r4}} - K_{41} - K_{42} - K_{43} \tag{B.62}$$

Using the previous expressions for K_{41}, K_{42}, and K_{43} gives the following equation for K_{44}:

This equation for K_{44} contains 14 terms. Four pairs of these terms can be reduced using the identity of Equation (B.51).

$$K_{44} = \frac{C_{m4}(0)}{\lambda_{r4}} - \frac{d_{14}\, C_{m1}(0)}{\lambda_{r4} - \lambda_{r1}} - \frac{d_{24}\, \lambda_{r2}\, d_{12}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r1})(\lambda_{r2} - \lambda_{r1})}$$

$$- \frac{d_{34}\, \lambda_{r3}\, d_{13}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r1})(\lambda_{r3} - \lambda_{r1})} - \frac{d_{34}\, \lambda_{r3}\, d_{23}\, \lambda_{r2}\, d_{12}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r1})(\lambda_{r3} - \lambda_{r1})(\lambda_{r2} - \lambda_{r1})}$$

$$- \frac{d_{24}\, C_{m2}(0)}{(\lambda_{r4} - \lambda_{r2})} + \frac{d_{24}\, \lambda_{r2}\, d_{12}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r2})(\lambda_{r2} - \lambda_{r1})}$$

$$- \frac{d_{34}\, \lambda_{r3}\, d_{23}\, C_{m2}(0)}{(\lambda_{r4} - \lambda_{r2})(\lambda_{r3} - \lambda_{r2})} + \frac{d_{34}\, \lambda_{r3}\, d_{23}\, \lambda_{r2}\, d_{12}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r2})(\lambda_{r3} - \lambda_{r2})(\lambda_{r2} - \lambda_{r1})} \quad \text{(B.63)}$$

$$- \frac{d_{34}\, C_{m3}(0)}{\lambda_{r4} - \lambda_{r3}} + \frac{d_{34}\, \lambda_{r3}\, d_{13}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r3})(\lambda_{r3} - \lambda_{r1})}$$

$$+ \frac{d_{34}\, \lambda_{r3}\, d_{23}\, \lambda_{r2}\, d_{12}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r3})(\lambda_{r3} - \lambda_{r1})(\lambda_{r2} - \lambda_{r1})} + \frac{d_{34}\, \lambda_{r3}\, d_{23}\, C_{m2}(0)}{(\lambda_{r4} - \lambda_{r3})(\lambda_{r3} - \lambda_{r2})}$$

$$- \frac{d_{34}\, \lambda_{r3}\, d_{23}\, \lambda_{r2}\, d_{12}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r3})(\lambda_{r3} - \lambda_{r2})(\lambda_{r2} - \lambda_{r1})}$$

The reductions are as follows:

terms 3 and 7 become

$$\frac{d_{24}\, \lambda_{r2}\, d_{12}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r1})(\lambda_{r4} - \lambda_{r2})} \quad \text{(B.64)}$$

terms 4 and 11 become

$$\frac{d_{34}\, \lambda_{r3}\, d_{13}\, C_{m1}(0)}{(\lambda_{r4} - \lambda_{r1})(\lambda_{r4} - \lambda_{r3})} \quad \text{(B.65)}$$

terms 8 and 13 become

$$\frac{d_{34}\, \lambda_{r3}\, d_{23}\, C_{m2}(0)}{(\lambda_{r4} - \lambda_{r2})(\lambda_{r4} - \lambda_{r3})} \quad \text{(B.66)}$$

and terms 12 and 14 become

$$\frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r2}\,d_{12}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r3})(\lambda_{r3}-\lambda_{r1})(\lambda_{r3}-\lambda_{r2})} \tag{B.67}$$

At this point another algebraic identity is used to further reduce the number of terms. The following can be shown (by algebraic manipulation) to be true:

$$\frac{1}{(d-a)(c-a)(b-a)} - \frac{1}{(d-b)(c-b)(b-a)} + \frac{1}{(d-c)(c-a)(c-b)} = \frac{1}{(d-a)(d-b)(d-c)} \tag{B.68}$$

Applying this identity to terms 5 and 9 of Equation (B.63) and Equation (B.67) with $a = \lambda_{r1}$, $b = \lambda_{r2}$, $c = \lambda_{r3}$, and $d = \lambda_{r4}$ gives the following expression for the three combined terms:

$$\frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r2}\,d_{12}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r1})(\lambda_{r4}-\lambda_{r2})(\lambda_{r4}-\lambda_{r3})} \tag{B.69}$$

Then, using the identity in Equation (B.51), two terms of Equation (B.61) for K_{43} can be combined. Terms 3 and 5 of Equation (B.61) become

$$\frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r2}\,d_{12}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r3})(\lambda_{r3}-\lambda_{r1})(\lambda_{r3}-\lambda_{r2})} \tag{B.70}$$

The final equation for the fourth chain member can now be written using expressions for K_{41} (Equation [B.57]), K_{42} (Equation [B.59]), K_{43} (Equation [B.61]), and K_{44} (Equation [B.63]) together with the term reductions (Equations [B.64] through [B.67]) and Equation (B.55) as follows:

$$C_{m4}(t) = \left[\frac{d_{14}\,\lambda_{r4}\,C_{m1}(0)}{\lambda_{r4}-\lambda_{r1}} + \frac{d_{24}\,\lambda_{r2}\,d_{12}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r1})(\lambda_{r2}-\lambda_{r1})} \right.$$

$$\left. + \frac{d_{34}\,\lambda_{r3}\,d_{13}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r1})(\lambda_{r3}-\lambda_{r1})} + \frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r2}\,d_{12}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r1})(\lambda_{r3}-\lambda_{r1})(\lambda_{r2}-\lambda_{r1})} \right] e^{-\lambda_{r1}t}$$

$$+ \left[\frac{d_{24}\,\lambda_{r4}\,C_{m2}(0)}{\lambda_{r4}-\lambda_{r2}} - \frac{d_{24}\,\lambda_{r2}\,d_{12}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r2})(\lambda_{r2}-\lambda_{r1})} \right.$$

$$\left. + \frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r4}\,C_{m2}(0)}{(\lambda_{r4}-\lambda_{r2})(\lambda_{r3}-\lambda_{r2})} - \frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r2}\,d_{12}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r2})(\lambda_{r3}-\lambda_{r2})(\lambda_{r2}-\lambda_{r1})} \right] e^{-\lambda_{r2}t}$$

$$+ \left[\frac{d_{34}\,\lambda_{r4}\,C_{m3}(0)}{\lambda_{r4}-\lambda_{r3}} - \frac{d_{34}\,\lambda_{r3}\,d_{13}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r3})(\lambda_{r3}-\lambda_{r1})} \right. \qquad \text{(B.71)}$$

$$\left. - \frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r4}C_{m2}(0)}{(\lambda_{r4}-\lambda_{r3})(\lambda_{r3}-\lambda_{r2})} + \frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r2}\,d_{12}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r3})(\lambda_{r3}-\lambda_{r1})(\lambda_{r3}-\lambda_{r2})} \right] e^{-\lambda_{r3}t}$$

$$+ \left[C_{m4}(0) - \frac{d_{14}\,\lambda_{r4}\,C_{m1}(0)}{\lambda_{r4}-\lambda_{r1}} + \frac{d_{24}\,\lambda_{r2}\,d_{12}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r1})(\lambda_{r4}-\lambda_{r2})} + \frac{d_{34}\,\lambda_{r3}\,d_{13}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r1})(\lambda_{r4}-\lambda_{r3})} \right.$$

$$- \frac{d_{24}\,\lambda_{r4}\,C_{m2}(0)}{\lambda_{r4}-\lambda_{r2}} + \frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r4}\,C_{m2}(0)}{(\lambda_{r4}-\lambda_{r2})(\lambda_{r4}-\lambda_{r3})} - \frac{d_{34}\,\lambda_{r4}\,C_{m3}(0)}{\lambda_{r4}-\lambda_{r3}}$$

$$\left. - \frac{d_{34}\,\lambda_{r3}\,d_{23}\,\lambda_{r2}\,d_{12}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r1})(\lambda_{r4}-\lambda_{r2})(\lambda_{r4}-\lambda_{r3})} \right] e^{-\lambda_{r4}t}$$

The above equations for chain-member activity as a function of time include all possible branching routes in a chain. For most radionuclide decay chains, only a few branches exist with most sequences being "straight chains" without branching. The original Bateman (1910) equations were developed for the case of decay chains without branching. As a further exercise in use of the decay processor equations, the equivalence between the Bateman equations and the above equations for a four-membered chain will be demonstrated. Equations (B.41), (B.43), (B.54) and (B.71) will be modified to represent a decay chain that has no branching (for comparison with the Bateman equations). The elimination of branching is implemented through the definition of the branching fractions. All transitions from one chain member to the next chain member are described by a branching fraction equal to 1.0. All branching fractions for which the subscripts differ by more than 1 are zero. The branching fractions for the example four-membered chain have the following values:

$$d_{12} = d_{23} = d_{34} = 1.0 \tag{B.72}$$

$$d_{13} = d_{14} = d_{24} = 0.0 \tag{B.73}$$

With these definitions, the equations for the four-membered chain without branching can be written as follows:

$$C_{m1}(t) = C_{m1}(0)\, e^{-\lambda_{r1} t} \tag{B.74}$$

$$C_{m2}(t) = \frac{C_{m1}(0)\, \lambda_{r2}}{\lambda_{r2} - \lambda_{r1}} e^{-\lambda_{r1} t} + \left[C_{m2}(0) - \frac{\lambda_{r2}\, C_{m1}(0)}{\lambda_{r2} - \lambda_{r1}} \right] e^{-\lambda_{r2} t} \tag{B.75}$$

$$\begin{aligned} C_{m3}(t) = {} & \frac{\lambda_{r2}\, \lambda_{r3}\, C_{m1}(0)}{\left(\lambda_{r3} - \lambda_{r1}\right)\left(\lambda_{r2} - \lambda_{r1}\right)} e^{-\lambda_{r1} t} \\ & + \left[\frac{\lambda_{r3}\, C_{m2}(0)}{\lambda_{r3} - \lambda_{r2}} - \frac{\lambda_{r2}\, \lambda_{r3}\, C_{m1}(0)}{\left(\lambda_{r3} - \lambda_{r2}\right)\left(\lambda_{r2} - \lambda_{r1}\right)} \right] e^{-\lambda_{r2} t} \\ & + \left[C_{m3}(0) - \frac{\lambda_{r3}\, C_{m2}(0)}{\lambda_{r3} - \lambda_{r2}} + \frac{\lambda_{r2}\, \lambda_{r3}\, C_{m1}(0)}{\left(\lambda_{r3} - \lambda_{r1}\right)\left(\lambda_{r3} - \lambda_{r2}\right)} \right] e^{-\lambda_{r3} t} \end{aligned} \tag{B.76}$$

$$C_{m4}(t) = \frac{\lambda_{r3}\,\lambda_{r2}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r1})(\lambda_{r3}-\lambda_{r1})(\lambda_{r2}-\lambda_{r1})}\,e^{-\lambda_{r1}t}$$
$$+\left[\frac{\lambda_{r3}\,\lambda_{r4}\,C_{m2}(0)}{(\lambda_{r4}-\lambda_{r2})(\lambda_{r3}-\lambda_{r2})} - \frac{\lambda_{r3}\,\lambda_{r2}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r2})(\lambda_{r3}-\lambda_{r2})(\lambda_{r2}-\lambda_{r1})}\right]e^{-\lambda_{r2}t}$$
$$+\left[\frac{\lambda_{r4}\,C_{m3}(0)}{\lambda_{r4}-\lambda_{r3}} - \frac{\lambda_{r3}\,\lambda_{r4}\,C_{m2}(0)}{(\lambda_{r4}-\lambda_{r3})(\lambda_{r3}-\lambda_{r2})} + \frac{\lambda_{r3}\,\lambda_{r2}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r3})(\lambda_{r3}-\lambda_{r1})(\lambda_{r3}-\lambda_{r2})}\right]e^{-\lambda_{r3}t} \quad \text{(B.77)}$$
$$+\left[C_{m4}(0) - \frac{\lambda_{r4}\,C_{m3}(0)}{\lambda_{r4}-\lambda_{r3}} + \frac{\lambda_{r3}\,\lambda_{r4}\,C_{m2}(0)}{(\lambda_{r4}-\lambda_{r3})(\lambda_{r4}-\lambda_{r2})}\right.$$
$$\left. - \frac{\lambda_{r3}\,\lambda_{r2}\,\lambda_{r4}\,C_{m1}(0)}{(\lambda_{r4}-\lambda_{r1})(\lambda_{r4}-\lambda_{r2})(\lambda_{r4}-\lambda_{r3})}\right]e^{-\lambda_{r4}t}$$

The decay equations as originally published by Bateman (1910) in units of atoms are as follows:

chain member 1,

$$P = P_o\,e^{-\lambda_1 t} \quad \text{(B.78)}$$

chain member 2,

$$Q = \frac{\lambda_1\,P_o}{\lambda_2-\lambda_1}\,e^{-\lambda_1 t} + \left(\frac{\lambda_1\,P_o}{\lambda_1-\lambda_2} + Q_o\right)e^{-\lambda_2 t} \quad \text{(B.79)}$$

chain member 3,

$$R = \frac{\lambda_1\,\lambda_2\,P_o}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)}\,e^{-\lambda_1 t} + \left[\frac{\lambda_1\,\lambda_2\,P_o}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)} + \frac{\lambda_2\,Q_o}{\lambda_3-\lambda_2}\right]e^{-\lambda_2 t}$$
$$+\left[\frac{\lambda_1\lambda_2\,P_o}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)} + \frac{\lambda_2\,Q_o}{\lambda_2-\lambda_3} + R_o\right]e^{-\lambda_3 t} \quad \text{(B.80)}$$

chain member 4,

$$S = \frac{\lambda_1 \lambda_2 \lambda_3 P_o}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)(\lambda_4 - \lambda_1)} e^{-\lambda_1 t}$$

$$+ \left[\frac{\lambda_1 \lambda_2 \lambda_3 P_o}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)(\lambda_4 - \lambda_2)} + \frac{\lambda_2 \lambda_3 Q_o}{(\lambda_3 - \lambda_2)(\lambda_4 - \lambda_2)} \right] e^{-\lambda_2 t}$$

$$+ \left[\frac{\lambda_1 \lambda_2 \lambda_3 P_o}{(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)(\lambda_4 - \lambda_3)} + \frac{\lambda_2 \lambda_3 Q_o}{(\lambda_2 - \lambda_3)(\lambda_4 - \lambda_3)} + \frac{\lambda_3 R_o}{\lambda_4 - \lambda_3} \right] e^{-\lambda_3 t} \quad \text{(B.81)}$$

$$+ \left[\frac{\lambda_1 \lambda_2 \lambda_3 P_o}{(\lambda_1 - \lambda_4)(\lambda_2 - \lambda_4)(\lambda_3 - \lambda_4)} + \frac{\lambda_2 \lambda_3 Q_o}{(\lambda_2 - \lambda_4)(\lambda_3 - \lambda_4)} + \frac{\lambda_3 R_o}{(\lambda_3 - \lambda_4)} + S_o \right] e^{-\lambda_4 t}$$

Equations (B.74) through (B.77) can be seen by inspection to be equivalent to Equations (B.78) through (B.81), respectively, using the following nomenclature identities:

$$P = \frac{C_{m1}(t)}{\lambda_{r1}}, \; P_o = \frac{C_{m1}(0)}{\lambda_{r1}} \quad \text{(B.82)}$$

$$Q = \frac{C_{m2}(t)}{\lambda_{r2}}, \; Q_o = \frac{C_{m2}(0)}{\lambda_{r2}} \quad \text{(B.83)}$$

$$R = \frac{C_{m3}(t)}{\lambda_{r3}}, \; R_o = \frac{C_{m3}(0)}{\lambda_{r3}} \quad \text{(B.84)}$$

$$S = \frac{C_{m4}(t)}{\lambda_{r4}}, \; S_o = \frac{C_{m4}(0)}{\lambda_{r4}} \quad \text{(B.85)}$$

and

$$\lambda_i = \lambda_{ri}, \; i = 1, 2, 3, \text{ or } 4 \quad \text{(B.86)}$$

Note that expressions (B.82) through (B.86) include conversion from activity units to atom units as defined by Equation (B.27) with the constant, k, eliminated for clarity.

B.3 Time-Integral Operators

This section demonstrates the correctness of the time-integral operator notation, $S_e\{\}$ and $S\{\}$. The demonstrations involve integration of the results of the decay operators, $A_e\{\}$ and $A\{\}$, over a specific time period.

B.3.1 Time-Integral Operator with Removal, $S_e\{\}$

The time-integral operator with removal provides a solution to the integration of an activity or concentration over a specific time period. The basic equation for the activity or concentration in a medium as a function of time is given by Equation B.15. Integration of this equation over a time period is the action represented by the time-integral operator. This integration can be expressed as follows:

$$S_e\{C_{mj},t_y\} = \int_0^{t_y} A_e\{C_{mj},t\}\,dt = \int_0^{t_y} C_{mj}(t)\,dt \tag{B.87}$$

where $C_{mj}(t)$ = concentration factor for chain member radionuclide j evaluated at time t for medium m involving decay and removal (appropriate activity units, e.g., pCi/g)

t_y = example time period of integration (d)

and other terms are as previously defined. Using the expression of Equation B.15 the above equation can be integrated as follows:

$$\begin{aligned}\int_0^{t_y} C_{mj}(t)\,dt &= \int_0^{t_y} \lambda_{rj}\left[\sum_{n=1}^{j} K_{jn} e^{-\lambda_{en}t}\right]dt = \lambda_{rj}\sum_{n=1}^{j} K_{jn}\left[\int_0^{t_y} e^{-\lambda_{en}t}\,dt\right] \\ &= \lambda_{rj}\sum_{n=1}^{j} K_{jn}\left[\frac{e^{-\lambda_{en}t}}{-\lambda_{en}}\right]_0^{t_y} = \lambda_{rj}\sum_{n=1}^{j} K_{jn}\left[\frac{1 - e^{-\lambda_{en}t_y}}{\lambda_{en}}\right]\end{aligned} \tag{B.88}$$

where terms are as previously defined. The last term on the right side of Equation (B.88) can be seen by inspection to be equal to Equation B.15 with the substitution given by Expression (B.20). This demonstrates the correctness of the operator notation for $S_e\{\}$.

B.3.2 Time-Integral Operator, $S\{\}$

The correctness of the time-integral operator equations for the case without removal can be demonstrated in the same manner as shown above for the time-integral operator with removal. The starting activity or concentration is as provided by the decay operator without removal, $A\{\}$, with integration over a specified time. This integration can be expressed as follows:

$$S\{C_{mj},t_y\} = \int_0^{t_y} A\{C_{mj},t\}\,dt = \int_0^{t_y} C_{mj}(t)\,dt \tag{B.89}$$

where $C_{mj}(t)$ = concentration factor for chain member radionuclide j evaluated at time t for medium m involving decay without removal (appropriate activity units, e.g., pCi/g)

t_y = example time period of integration (d)

and other terms are as previously defined. Using the expression of Equation B.2 the above equation can be integrated as follows: the steps are analogous to Equation (B.88) with the radiological decay rate constant, λ_{rj}, replacing the decay rate constant with removal, λ_{ej}, as follows:

$$\begin{aligned}\int_0^{t_y} C_{mj}(t)\,dt &= \int_0^{t_y} \lambda_{rj}\left[\sum_{n=1}^{j} K_{jn} e^{-\lambda_{rn}t}\right]dt = \lambda_{rj}\sum_{n=1}^{j} K_{jn}\left[\int_0^{t_y} e^{-\lambda_{rn}t}\,dt\right] \\ &= \lambda_{rj}\sum_{n=1}^{j} K_{jn}\left[\frac{e^{-\lambda_{rn}t}}{-\lambda_{rn}}\right]_0^{t_y} = \lambda_{rj}\sum_{n=1}^{j} K_{jn}\left[\frac{1 - e^{-\lambda_{rn}t_y}}{\lambda_{rn}}\right]\end{aligned} \tag{B.90}$$

The last term on the right side of Equation (B.90) can be seen by inspection to be equal to Equation B.2 with the substitution given by Expression (B.8). This demonstrates the correctness of the operator notation for S{}.

B.4 Deposition, Accumulation Operators

This section demonstrates the correctness of the deposition accumulation operator notation, $R_e\{\}$ and $R\{\}$. The demonstration involves derivation of the solution to deposition at a constant rate with removal for the operator $R_e\{\}$. Correctness of the corresponding operator without removal is demonstrated by reduction of the equations for the case with removal.

B.4.1 Deposition Accumulation with Removal Operator, $R_e\{\}$

The agricultural pathway model requires evaluation of activity following deposition at a constant rate from application of irrigation water to plants and to soil. The deposition rate is constant because the concentration in the water is assumed to be represented by an annual average value, as generated from the water-use model for the residential scenario. The case of deposition to plant surfaces with removal by weathering is selected for illustration.

The change in concentration of a radionuclide on plant surfaces from deposition at a constant rate with weathering removal can be written as follows:

$$\frac{dC_{vj}}{dt} = R_{vj} + \sum_{n=1}^{j-1} d_{nj}\lambda_{rj}C_{vn} - (\lambda_w + \lambda_{rj})\,C_{vj} \tag{B.91}$$

where C_{vj} = concentration of radionuclide chain member j in plants per initial unit average concentration of parent radionuclide i in water (per Ci/kg wet-weight plant per pCi/L water)

C_{vn} = concentration of precursor radionuclide chain member n in plants per initial unit average concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

R_{vj} = constant deposition rate of radionuclide chain member j to plants from irrigation water application during the growing period for plant type v per initial unit average concentration of parent radionuclide i in water (pCi/d•kg wet-weight plant per pCi/L water)

λ_{rj} = radioactive decay rate constant for radionuclide j (d^{-1})

λ_w = rate constant for loss of material from plants (d^{-1})

d_{nj} = fraction of precursor radionuclide n transitions that result in production of radionuclide chain member j (dimensionless).

The normalization to initial average activity of the parent radionuclide is included for consistency with representations given in Section 5. The solution to Equation (B.91) will be derived for the parent and first progeny radionuclides. Equation (B.91) can be written in terms of these chain members as follows, for the parent (j=1):

$$\frac{dC_{v1}}{dt} = R_{v1} - \lambda_{e1} C_{v1} \tag{B.92}$$

and for the first progeny (j=2),

$$\frac{dC_{v2}}{dt} = R_{v2} + d_{12}\lambda_{r2} C_{v1} - \lambda_{e2} C_{v2} \tag{B.93}$$

where C_{v1} = concentration of parent radionuclide chain member (j=1) in plants per initial unit average concentration of parent radionuclide in water (pCi/kg wet-weight plant per pCi/L water)

C_{v2} = concentration of first progeny radionuclide (j=2) in plants per initial unit average concentration of parent radionuclide in water (pCi/kg wet-weight plant per pCi/L water)

d_{12} = fraction of precursor radionuclide 1 (parent) transitions that result in production of radionuclide chain member 2 (dimensionless)

λ_{e1} = rate constant for removal and decay of radionuclide 1, evaluated as the sum of λ_w and λ_{r1} (d^{-1}).

λ_{e2} = rate constant for removal and decay of radionuclide 2, evaluated as the sum of λ_w and λ_{r2} (d^{-1}).

The solution to Equation (B.92) is evaluated by first transferring terms containing the concentration of the parent radionuclide in the plant (C_{v1}) to the left side of the equation, and then multiplying by the integration factor, $e^{\lambda_{e1} t}$:

$$[dC_{v1} + \lambda_{e1} C_{v1} dt]\, e^{\lambda_{e1} t} = R_{v1}\, e^{\lambda_{e1} t}\, dt \tag{B.94}$$

The left side of the equation can be written as a differential, and the whole equation can then be integrated to give the following expression:

$$C_{v1}\, e^{\lambda_{e1} t} = \frac{R_{v1}\, e^{\lambda_{e1} t}}{\lambda_{e1}} + \text{Constant} \tag{B.95}$$

Evaluation of the constant of integration is performed using the condition that at $t = 0$, $C_{v1} = 0$ (no initial radionuclide in plant). The constant is given by

$$\text{Constant} = -\frac{R_{v1}}{\lambda_{e1}} \tag{B.96}$$

and the final expression for the amount of parent radionuclide in plants is given by

$$C_{v1} = \frac{R_{v1}}{\lambda_{e1}} \left[1 - e^{-\lambda_{e1} t}\right] \tag{B.97}$$

The solution of Equation (B.93) for the first progeny radionuclide can be found by first moving terms containing the plant concentration parameter, C_{v2}, to the left side of the equation and multiplying by the integration factor. The expression of Equation (B.97) is also substituted into Equation (B.93) for the parent concentration in the plant. The result of these actions is the following expression:

$$\left[dC_{v2} + \lambda_{e2} C_{v2} dt\right] e^{\lambda_{e2} t} = R_{v2} e^{\lambda_{e2} t} dt + \frac{d_{12} \lambda_{r2} R_{v1}}{\lambda_{e1}} \cdot \left[e^{\lambda_{e2} t} - e^{(\lambda_{e2} - \lambda_{e1}) t}\right] dt \tag{B.98}$$

The left side of this equation can be written as a differential, and the whole equation can be integrated to give the following expression:

$$C_{v2} e^{\lambda_{e2} t} = \frac{R_{v2}}{\lambda_{e2}}\, e^{\lambda_{e2} t} + \frac{d_{12} \lambda_{r2} R_{v1}}{\lambda_{e1} \lambda_{e2}}\, e^{\lambda_{e2} t} - \frac{d_{12} \lambda_{r2} R_{v1}}{\lambda_{e1} (\lambda_{e2} - \lambda_{e1})}\, e^{(\lambda_{e2} - \lambda_{e1}) t} + \text{Constant} \tag{B.99}$$

Multiplying through by the inverse of the integrating factor gives the following expression:

$$C_{v2} = \frac{R_{v2}}{\lambda_{e2}} + \frac{d_{12} \lambda_{r1} R_{v1}}{\lambda_{e1} \lambda_{e2}} - \frac{d_{12} \lambda_{r1} R_{v1}}{\lambda_{e1} (\lambda_{e2} - \lambda_{e1})}\, e^{-\lambda_{e1} t} + [\text{Constant}]\, e^{-\lambda_{e2} t} \tag{B.100}$$

The constant can be evaluated from the condition that $C_{v2} = 0$ at $t = 0$. Substituting this condition into Equation (B.100) gives the following expression for the constant:

$$\text{Constant} = -\frac{R_{v2}}{\lambda_{e2}} - \frac{d_{12}\lambda_{r2}R_{v1}}{\lambda_{e1}\lambda_{e2}} + \frac{d_{12}\lambda_{r2}R_{v1}}{\lambda_{e1}(\lambda_{e2} - \lambda_{e1})} \tag{B.101}$$

Substituting this expression for the constant and combining terms results in the following expression for the amount of first progeny radionuclide on the plant as a function of time after start of irrigation:

$$C_{v2} = \frac{R_{v2}}{\lambda_{e2}}\left[1 - e^{-\lambda_{e2}t}\right] + \frac{d_{12}\lambda_{r2}R_{v1}}{\lambda_{e1}\lambda_{e2}}\left[1 - e^{-\lambda_{e2}t}\right] - \frac{d_{12}\lambda_{r2}R_{v1}}{\lambda_{e1}(\lambda_{e2} - \lambda_{e1})}\left[e^{-\lambda_{e1}t} - e^{-\lambda_{e2}t}\right] \tag{B.102}$$

Some algebraic manipulation is required to convert Equation (B.102) to the form indicated by Equations (B.14) through (B.18) and (B.20). First, the difference of exponentials in the last term of Equation (B.102) is expanded using the following identity:

$$\frac{e^{-\lambda_{e1}t} - e^{-\lambda_{e2}t}}{\lambda_{e1}} = \frac{1 - e^{-\lambda_{e2}t}}{\lambda_{e1}} - \frac{1 - e^{-\lambda_{e1}t}}{\lambda_{e1}} \tag{B.103}$$

Application of this identity results in the following expression for Equation (B.102):

$$\begin{aligned} C_{v2} = {} & \frac{R_{v2}}{\lambda_{e2}}\left[1 - e^{-\lambda_{e2}t}\right] + \frac{d_{12}\lambda_{r2}R_{v1}}{\lambda_{e1}\lambda_{e2}}\left[1 - e^{-\lambda_{e2}t}\right] \\ & + \frac{d_{12}\lambda_{r2}R_{v1}}{\lambda_{e2} - \lambda_{e1}}\left[\frac{1 - e^{-\lambda_{e1}t}}{\lambda_{e1}}\right] - \frac{d_{12}\lambda_{r2}R_{v1}}{\lambda_{e2} - \lambda_{e1}}\left[\frac{1 - e^{-\lambda_{e2}t}}{\lambda_{e1}}\right] \end{aligned} \tag{B.104}$$

The second and last terms on the right side of this equation can be combined using the following algebraic identity:

$$\frac{1}{\lambda_{e1}}\left[\frac{1}{\lambda_{e2}} - \frac{1}{\lambda_{e2} - \lambda_{e1}}\right] = -\frac{1}{\lambda_{e2}[\lambda_{e2} - \lambda_{e2}]} \tag{B.105}$$

The final expression for the concentration of the first progeny on the plant as a function of time can now be written:

$$C_{v2} = \frac{d_{12}\lambda_{r2}R_{v1}}{\lambda_{e2} - \lambda_{e1}}\left[\frac{1 - e^{-\lambda_{e1}t}}{\lambda_{e1}}\right] + \left[R_{v2} - \frac{d_{12}\lambda_{r2}R_{v1}}{\lambda_{e2} - \lambda_{e1}}\right]\left[\frac{1 - e^{-\lambda_{e2}t}}{\lambda_{e2}}\right] \tag{B.106}$$

The equivalence can now be observed between the deposition accumulation with removal operator equations [Equations (B.14) through (B.18) and (B.20)] and Equation (B.93) for the parent and Equation (B.107) for the first progeny. Expansion of Equations (B.15) through (B.18) can be performed as demonstrated in Section B.2 for the first and second chain members. The equivalence can be seen by substitution of the constant deposition rates (R_{v1} and R_{v2}) for the initial activities ($C_{m1}$and C_{m2}) in Equations (B.16) and (B.18), and by substitution of the exponential term of Equation (B.15) by the expression indicated in Equation (B.20).

The explicit form of Equation (B.15) becomes

$$C_{mj}(t) = \lambda_{rj} \sum_{n=1}^{j} K_{jn} \left[\frac{1 - e^{-\lambda_{en} t}}{\lambda_{en}} \right] \quad \text{(B.107)}$$

The deposition, accumulation operator with removal, $R_e\{\}$, is represented by this equation with constants, K_{jn}, defined by Equations (B.16), (B.17), and (B.18).

B.4.2 Deposition, Accumulation Operator, R{}

The deposition, accumulation operator (without removal), R{}, is represented by the general decay Equations (B.2) through (B.5) with the substitution indicated in Equation (B.10). The correctness of this representation can be shown by reduction of the equations for the corresponding case with removal, as shown to be correct in Section B.4.1. The reduction is performed by observing that the effective removal rate constant, λ_{ej}, is equal to the decay rate constant, λ_{rj}, when the removal rate constant, λ_w, is zero (see Equation [B.14]). By inspection, Equation (B.107) can be seen to reduce to the following:

$$C_{mj}(t) = \lambda_{rj} \sum_{n=1}^{j} K_{jn} \left[\frac{1 - e^{-\lambda_{rn} t}}{\lambda_{rn}} \right] \quad \text{(B.108)}$$

Also, substitution of the decay rate constant for the effective removal rate constant can be seen to transform Equation (B.17) to Equation (B.4). This demonstrates that the equations for decay without removal (Equations [B.2] through [B.5]) with the substitution indicated in Equation (B.10) provide the correct representation for the deposition, accumulation operator, R{}.

B.5 Use of Deposition, Accumulation, and Time-Integral Equations

This section will show the correctness of the deposition, accumulation, and time-integration operators, $G_e\{\}$ and G{}.

B.5.1 Deposition, Accumulation, and Time-Integral with Removal Operator $G_e\{\}$

The correctness of the deposition accumulation with removal operator equations has been demonstrated in Section B.4. This section will demonstrate that time-integration of the deposition accumulation with removal operator, $R_e\{\}$, equations results in the defined equations for the deposition, accumulation, and time-integral with removal operator, $G_e\{\}$.

Integration of Equation (B.107) over time is equivalent to the calculations indicated by the deposition accumulation and time-integral operator with removal, $G_e\{\}$. Equation (B.107) can be integrated over a specific time period by integrating each term in the summation and evaluating the resulting expression between time zero and the end of the period of interest. This integration is indicated below for application of irrigation water to plants over the animal feeding period, t_{ff}. Using the nomenclature of Equation (5.38), Equation (B.107) can be expressed as follows:

$$C_{wfjc} = \left[\frac{G_e\{R_{wfjf}, t_{ff}\}}{t_{ff}}\right] = \frac{\lambda_{rj}}{t_{ff}} \sum_{n=1}^{j} K_{jn} \int_0^{t_{ff}} \left[\frac{1 - e^{-\lambda_{en} t}}{\lambda_{en}}\right] dt$$

$$= \frac{\lambda_{rj}}{t_{ff}} \sum_{n=1}^{j} K_{jn} \left[\frac{t}{\lambda_{en}} - \frac{e^{-\lambda_{en} t}}{-\lambda_{en}^2}\right]_0^{t_{ff}} \qquad \text{(B.109)}$$

$$= \frac{\lambda_{rj}}{t_{ff}} \sum_{n=1}^{j} \frac{K_{jn}}{\lambda_{en}} \left[t_{ff} - \frac{(1 - e^{-\lambda_{en} t_{ff}})}{\lambda_{en}}\right]$$

where C_{wfjc} = average concentration factor for radionuclide j in forage crop f, at time of consumption by animal, from direct deposition onto plant surfaces for an average unit concentration of parent radionuclide i in water (pCi/kg wet-weight plant per pCi/L water)

t_{ff} = period of feeding of forage crop f (d)

and other terms are as previously defined. Comparison of this expression with Equation (B.21) proves the validity of the substitution suggested in Equation (B.21). Note that in evaluation of the coefficients in Equation (B.109), K_{jn}, values for the deposition rate, R_{wfjf}, of Equation (5.38) are used in place of $C_{mj}(0)$ in Equations (B.16) and (B.18).

B.5.2 Deposition, Accumulation, and Time-Integral with Removal Operator $G_e\{\}$

The deposition, accumulation, and time-integration operator without removal, G{}, is evaluated in the same manner as indicated by Equation (B.109), except that the removal term (λ_w in λ_e) is set to zero, so that occurrences of λ_{ej} are replaced by λ_{rj}. Thus, the equations collapse to the general operator notation given by Equations (B.2) through (B.5) with the substitution indicated by Equation (B.12).

B.6 Water-Use Model for the Drinking Water Scenario

This section illustrates use of the operator equations for decay with removal to evaluate radionuclide activities in the water-use model. The example involves a two-membered decay chain applied to the drinking water scenario model (Section B.6.1). In this scenario, the water-use model has three compartments (as defined in Section 4.1), and no recycling of activity from the aquifer (box 3) to the surface (box 1) occurs. This section also shows the derivation of the equations for the parent activity in all three boxes, plus the equations for the activity of the first progeny in box 1 (Section B.6.2).

B.6.1 Demonstration of Equations for Drinking Water Water-Use Model

The primary purpose of this example is to show how the various parameters in the water-use model are applied in the operator setup. As indicated in Figure 4.3, each box of the water-use model contains compartments for each member of the decay chain. The total number of these compartments that must be accounted for in the operator

application is the product of the number of chain members and the number of boxes. For the current example, this is 6 (2 chain members times 3 boxes). These compartments are referred to in the example as "expanded chain member positions."

For each expanded chain member position, it is necessary to define all parameters required by the operator. These parameters include the radioactive decay constant, precursor indices, branching fractions, and removal rate constants. The water-use model involves transfer of activity from box 1 (surface soil) to box 2 (unsaturated-soil layer), and from box 2 to box 3 (aquifer). Removal from the aquifer is at a constant rate for all radionuclides, with total aquifer volume being removed in a 1-year period.

The steps in setting up the parameters for the operator equations are described by the following procedure using the example case. Following this description, derivation of equations for the example case will be given.

1. The expanded chain member positions are defined, and decay rate constants and radionuclide amounts are set for each expanded chain member position, as follows:

Representation	Expanded Chain Member Position	Parameter Symbol	Decay Rate Constant (d^{-1})	Radionuclide Amount (atoms)	Equivalent Notation in Section 4.1.3
Box 1, member 1	1	λ_{r1}	λ_{r1}	C_{m1}	C_{11}
Box 1, member 2	2	λ_{r2}	λ_{r2}	C_{m2}	C_{12}
Box 2, member 1	3	λ_{r3}	λ_{r1}	C_{m3}	C_{21}
Box 2, member 2	4	λ_{r4}	λ_{r2}	C_{m4}	C_{22}
Box 3, member 1	5	λ_{r5}	λ_{r1}	C_{m5}	C_{31}
Box 3, member 2	6	λ_{r6}	λ_{r2}	C_{m6}	C_{32}

Using the expanded chain member notation requires a slight modification to the definition of "precursor." Besides the standard usage to represent transition within a decay chain, there can now be transitions from one box to the next without radioactive decay. For example, radionuclide 1 in box 1 can be considered a precursor to radionuclide 1 in box 2 because leaching of radionuclide 1 from box 1 to box 2 will result in generation of radionuclide 1 in box 2, even though no radioactive decay has taken place.

2. The branching fractions and precursor indices are set for radioactive decay as follows:

Parameter Symbol	Radioactive Transition Branching Fraction From	To	Set to:	Comments
d_{12}	1	2	d_{12}	Chain member 1 to chain member 2 within box 1.
d_{23}	2	3	0.0	No transitions from chain member 2 to chain member 1.
d_{34}	3	4	d_{12}	Chain member 1 to chain member 2 within box 2.
d_{45}	4	5	0.0	No transitions from chain member 2 to chain member 1.
d_{56}	5	6	d_{12}	Chain member 1 to chain member 2 within box 3.

3. For transfer of radionuclides between boxes, rate constants and effective branching fractions must be defined. The rate constant is treated as the general removal rate constant, λ_w, as defined in Equation (B.14). The definitions of the removal rate constants are as follows:

Parameter Symbol	Compartmental Transfer Loss Rate Constant From	To	Set to:	Comments
λ_{w1}	1	3	L_{121}	Leakage of chain member 1 from box 1 to box 2.
λ_{w2}	2	4	L_{122}	Leakage of chain member 2 from box 1 to box 2.
λ_{w3}	3	5	L_{231}	Leakage of chain member 1 from box 2 to box 3.
λ_{w4}	4	6	L_{232}	Leakage of chain member 2 from box 2 to box 3.
λ_{w5}	5	-	w_d	Removal of chain member 1 from the aquifer.
λ_{w6}	6	-	w_d	Removal of chain member 2 from the aquifer.

The branching fractions associated with transfers between boxes are defined as follows:

Parameter Symbol	Compartmental Transfer Branching Fraction From	To	Set to:	Comments
d_{13}	1	3	L_{121}/λ_{r1}	Chain member 1 leakage from box 1 to box 2.
d_{24}	2	4	L_{122}/λ_{r2}	Chain member 2 leakage from box 1 to box 2.
d_{35}	3	5	L_{231}/λ_{r1}	Chain member 1 leakage from box 2 to box 3.
d_{46}	4	6	L_{232}/λ_{r2}	Chain member 2 leakage from box 2 to box 3.

Compartmental transfer branching fractions (as defined above) can be understood by inspection of the differential equations for the three-box water-use model of Section 4.1 and those for the decay processor of Section B.1.2. For example, consider transfer of chain member 2 from box 1 to box 2. This transfer is represented by the branching fraction symbol, d_{24}. This transfer appears as the second term on the right side of Equation (4.11). The net transfer rate is L_{122} times the quantity in box 1 (C_{12}). This transfer is evaluated by the operator (for decay with removal, Section B.1.2) by the term within the summation of Equation (B.17). The operator generates a term of the form $d_{24}\ \lambda_{r2}$ times a quantity (represented by the coefficient K_{pn}). For the implementation to give the correct solution to the differential equations, it is necessary that

$$L_{122} = d_{24}\ \lambda_{r2} \tag{B.110}$$

or

$$d_{24} = L_{122}/\lambda_{r2} \tag{B.111}$$

as defined in step number 3, above.

All other branching fractions are set to zero, as these (and the branching fractions identified in item 2 above) are the only transfers defined in the water-use model. Branching fractions are not needed for removal from the aquifer.

The effective removal rate constant for each compartment is defined by Equation (B.14) as the sum of the removal rate constant and the radioactive decay rate constant as follows:

Parameter Symbol	Removal from Compartment Number	Set to:	Comments
λ_{e1}	1	$L_{121} + \lambda_{r1}$	Chain member 1 in box 1.
λ_{e2}	2	$L_{122} + \lambda_{r2}$	Chain member 2 in box 1.
λ_{e3}	3	$L_{231} + \lambda_{r1}$	Chain member 1 in box 2.
λ_{e4}	4	$L_{232} + \lambda_{r2}$	Chain member 2 in box 2.
λ_{e5}	5	$w_d + \lambda_{r1}$	Chain member 1 in box 3.
λ_{e6}	6	$w_d + \lambda_{r2}$	Chain member 2 in box 3.

The following discussion will illustrate how the above definitions are used in the general decay equations with removal (Equations [B.14] through [B.18]) to evaluate results for the water-use model of the drinking water scenario. The equation derivations are first performed using the nomenclature of the general decay equations, and then the substitutions of parameters as described above are made to show the final form of the equations. All derivations are shown for evaluation of the amount of a radionuclide present as a function of time, representative of the processor notation $A_{dk}\{C_*,t_*\}$, where k represents the box of interest in the three-box water-use model.

Radionuclide 1 in Box 1: Expanded Chain Member Position 1

The activity of chain member 1 remaining in box 1 at time t is evaluated according to Equations (B.15) and (B.16) as follows:

$$C_{m1}(t) = \lambda_{r1} K_{11}\, e^{-\lambda_{e1} t} \tag{B.112}$$

or

$$C_{m1}(t) = C_{m1}(0)\, e^{-\lambda_{e1} t} \tag{B.113}$$

where terms follow the standard nomenclature and λ_{e1} is as defined in item 3 above.

Radionuclide 2 in Box 1: Expanded Chain Member Position 2

The activity of chain member 2 remaining in box 1 at time t is evaluated according to Equation (B.15) as follows:

$$C_{m2}(t) = \lambda_{r2}\left[K_{21}\, e^{-\lambda_{e1} t} + K_{22}\, e^{-\lambda_{e2} t}\right] \tag{B.114}$$

Coefficient K_{21} is evaluated using Equation (B.17) as follows:

$$K_{21} = \frac{\sum_{p=1}^{1} d_{p2}\lambda_{rp} K_{p1}}{\lambda_{e2} - \lambda_{e1}} = \frac{d_{12}\lambda_{r1} K_{11}}{\lambda_{e2} - \lambda_{e1}} \tag{B.115}$$

and

$$K_{11} = \frac{C_{m1}(0)}{\lambda_{r1}} \tag{B.116}$$

Then, K_{21} is written as:

$$K_{21} = \frac{d_{12} C_{m1}(0)}{\lambda_{e2} - \lambda_{e1}} \tag{B.117}$$

where terms follow the standard nomenclature and λ_{e2} is as defined in item 3 above.

Coefficient K_{22} is evaluated using Equation (B.18) as follows:

$$K_{22} = \frac{C_{m2}(0)}{\lambda_{r2}} - \sum_{n=1}^{1} K_{2n} = \frac{C_{m2}(0)}{\lambda_{r2}} - K_{21} \tag{B.118}$$

and

$$K_{22} = \frac{C_{m2}(0)}{\lambda_{r2}} - \frac{d_{12} C_{m1}(0)}{\lambda_{e2} - \lambda_{e1}} \tag{B.119}$$

The activity of chain member 2 at time t can now be written as

$$C_{m2}(t) = \frac{d_{12} \lambda_{r2} C_{m1}(0)}{\lambda_{e2} - \lambda_{e1}} e^{-\lambda_{e1} t} + \left[C_{m2}(0) - \frac{d_{12} \lambda_{r2} C_{m1}(0)}{\lambda_{e2} - \lambda_{e1}} \right] e^{-\lambda_{e2} t} \tag{B.120}$$

Radionuclide 1 in Box 2: Expanded Chain Member Position 3

The activity of chain member 1 remaining in box 2 at time t is evaluated according to Equation (B.15) as follows:

$$C_{m3}(t) = \lambda_{r3} \left[K_{31} e^{-\lambda_{e1} t} + K_{32} e^{-\lambda_{e2} t} + K_{33} e^{-\lambda_{e3} t} \right] \tag{B.121}$$

Coefficient K_{31} is evaluated using Equation (B.17) as follows:

$$K_{31} = \frac{\sum_{p=1}^{2} d_{p3} \lambda_{rp} K_{p1}}{\lambda_{e3} - \lambda_{e1}} = \frac{d_{13} \lambda_{r1} K_{11}}{\lambda_{e3} - \lambda_{e1}} + \frac{d_{23} \lambda_{r2} K_{21}}{\lambda_{e3} - \lambda_{e1}} \tag{B.122}$$

Substituting previous expressions for K_{11} and K_{21} into Equation (B.122) gives the following expression for coefficient K_{31}:

$$K_{31} = \frac{d_{13} C_{m1}(0)}{\lambda_{e3} - \lambda_{e1}} + \frac{d_{23} \lambda_{r2} d_{12} C_{m1}(0)}{(\lambda_{e3} - \lambda_{e1})(\lambda_{e2} - \lambda_{e1})} \tag{B.123}$$

This expression can be further reduced by noting that the branching fraction d_{23} is zero, as indicated in item 2 above. Equation (B.123) then reduces to the following:

$$K_{31} = \frac{d_{13} C_{m1}(0)}{\lambda_{e3} - \lambda_{e1}} \tag{B.124}$$

The second coefficient in Equation (B.121) is evaluated using Equation (B.17) as follows:

$$K_{32} = \frac{\sum_{p=2}^{2} d_{p3} \lambda_{rp} K_{p2}}{\lambda_{e3} - \lambda_{e2}} = \frac{d_{23} \lambda_{r2} K_{22}}{\lambda_{e3} - \lambda_{e2}} \tag{B.125}$$

However, as before, the branching fraction d_{23} is zero and K_{32} is also zero. The expression for K_{33} is evaluated using Equation (B.18) as follows:

$$K_{33} = \frac{C_{m3}(0)}{\lambda_{r3}} - \sum_{n=1}^{2} K_{3n} = \frac{C_{m3}(0)}{\lambda_{r3}} - K_{31} - K_{32} \tag{B.126}$$

Using the previous expression for K_{31}, the following expression for K_{33} is obtained:

$$K_{33} = \frac{C_{m3}(0)}{\lambda_{r3}} - \frac{d_{13} C_{m1}(0)}{\lambda_{e3} - \lambda_{e1}} \tag{B.127}$$

The amount of radionuclide 1 in box 2 can now be written as follows:

$$C_{m3}(t) = \frac{d_{13} \lambda_{r3} C_{m1}(0)}{\lambda_{e3} - \lambda_{e1}} e^{-\lambda_{e1} t} + \left[C_{m3}(0) - \frac{d_{13} \lambda_{r3} C_{m1}(0)}{\lambda_{e3} - \lambda_{e1}} \right] e^{-\lambda_{e3} t} \tag{B.128}$$

This expression can be rewritten by substituting the definition for parameter d_{13} from the table in item 3 above ($d_{13} = L_{121}/\lambda_{r1}$ and $\lambda_{r3} = \lambda_{r1}$) to give the following equation:

$$C_{m3}(t) = \frac{L_{121} C_{m1}(0)}{\lambda_{e3} - \lambda_{e1}} e^{-\lambda_{e1} t} + \left[C_{m3}(0) - \frac{L_{121} C_{m1}(0)}{\lambda_{e3} - \lambda_{e1}} \right] e^{-\lambda_{e3} t} \tag{B.129}$$

Radionuclide 2 in Box 2: Expanded Chain Member Position 4

The amount of chain member 2 remaining in box 2 at time t is evaluated according to Equation (B.15) as follows:

$$C_{m4}(t) = \lambda_{r4}\left[K_{41}\, e^{-\lambda_{e1}t} + K_{42}\, e^{-\lambda_{e2}t} + K_{43}\, e^{-\lambda_{e3}t} + K_{44}\, e^{-\lambda_{e4}t}\right] \tag{B.130}$$

Coefficient K_{41} is evaluated using Equation (B.17) as follows:

$$K_{41} = \frac{\sum_{p=1}^{3} d_{p4}\lambda_{rp}K_{p1}}{\lambda_{e4} - \lambda_{e1}} \tag{B.131}$$

and

$$K_{41} = \frac{d_{14}\lambda_{r1}K_{11}}{\lambda_{e4} - \lambda_{e1}} + \frac{d_{24}\lambda_{r2}K_{21}}{\lambda_{e4} - \lambda_{e1}} + \frac{d_{34}\lambda_{r3}K_{31}}{\lambda_{e4} - \lambda_{e1}} \tag{B.132}$$

Using previous expressions for K_{11}, K_{21}, and K_{31}, and noting that d_{14} is zero, the following equation for K_{41} is obtained:

$$K_{41} = \frac{d_{24}\lambda_{r2}d_{12}C_{m1}(0)}{\left(\lambda_{e4} - \lambda_{e1}\right)\left(\lambda_{e2} - \lambda_{e1}\right)} + \frac{d_{34}\lambda_{r3}d_{13}C_{m1}(0)}{\left(\lambda_{e4} - \lambda_{e1}\right)\left(\lambda_{e3} - \lambda_{e1}\right)} \tag{B.133}$$

Coefficient K_{42} is evaluated using Equation (B.17) as follows:

$$K_{42} = \frac{\sum_{p=2}^{3} d_{p4}\lambda_{rp}K_{p2}}{\lambda_{e4} - \lambda_{e2}} = \frac{d_{24}\lambda_{r2}K_{22}}{\lambda_{e4} - \lambda_{e2}} + \frac{d_{34}\lambda_{r3}K_{32}}{\lambda_{e4} - \lambda_{e2}} \tag{B.134}$$

Using previous expressions for K_{22} and noting that K_{32} is zero, the following equation for K_{42} is obtained:

$$K_{42} = \frac{d_{24}C_{m2}(0)}{\lambda_{e4} - \lambda_{e2}} - \frac{d_{24}\lambda_{r2}d_{12}C_{m1}(0)}{\left(\lambda_{e4} - \lambda_{e2}\right)\left(\lambda_{e2} - \lambda_{e1}\right)} \tag{B.135}$$

Coefficient K_{43} is evaluated using Equation (B.17) as follows:

$$K_{43} = \frac{\sum_{p=3}^{3} d_{p4}\lambda_{rp}K_{p3}}{\lambda_{e4} - \lambda_{e3}} = \frac{d_{34}\lambda_{r3}K_{33}}{\lambda_{e4} - \lambda_{e3}} \tag{B.136}$$

Using previous expression for K_{33}, the following equation for K_{43} is obtained:

$$K_{43} = \frac{d_{34} C_{m3}(0)}{\lambda_{e4} - \lambda_{e3}} - \frac{d_{34} \lambda_{r3} d_{13} C_{m1}(0)}{\left(\lambda_{e4} - \lambda_{e3}\right)\left(\lambda_{e3} - \lambda_{e1}\right)} \tag{B.137}$$

The final coefficient for radionuclide 2 in box 2 is evaluated using Equation (B.18):

$$K_{44} = \frac{C_{m4}(0)}{\lambda_{r4}} - K_{41} - K_{42} - K_{43} \tag{B.138}$$

Using the previous expressions for K_{41}, K_{42}, and K_{43}, coefficient K_{44} can be written as follows:

$$\begin{aligned} K_{44} = {} & \frac{C_{m4}(0)}{\lambda_{r4}} - \frac{d_{24} \lambda_{r2} d_{12} C_{m1}(0)}{\left(\lambda_{e4} - \lambda_{e1}\right)\left(\lambda_{e2} - \lambda_{e1}\right)} \\ & - \frac{d_{34} \lambda_{r3} d_{13} C_{m1}(0)}{\left(\lambda_{e4} - \lambda_{e1}\right)\left(\lambda_{e3} - \lambda_{e1}\right)} - \frac{d_{24} C_{m2}(0)}{\lambda_{e4} - \lambda_{e2}} \\ & + \frac{d_{24} \lambda_{r2} d_{12} C_{m1}(0)}{\left(\lambda_{e4} - \lambda_{e2}\right)\left(\lambda_{e2} - \lambda_{e1}\right)} - \frac{d_{34} C_{m3}(0)}{\lambda_{e4} - \lambda_{e3}} \\ & + \frac{d_{34} \lambda_{r3} d_{13} C_{m1}(0)}{\left(\lambda_{e4} - \lambda_{e3}\right)\left(\lambda_{e3} - \lambda_{e1}\right)} \end{aligned} \tag{B.139}$$

Four terms on the right side of Equation (B.139) can be combined using the algebraic identity of Equation (B.51): terms 2 and 5 become

$$\frac{d_{24} \lambda_{r2} d_{12} C_{m1}(0)}{\left(\lambda_{e4} - \lambda_{e1}\right)\left(\lambda_{e4} - \lambda_{e2}\right)} \tag{B.140}$$

terms 3 and 7 become

$$\frac{d_{34} \lambda_{r3} d_{13} C_{m1}(0)}{\left(\lambda_{e4} - \lambda_{e1}\right)\left(\lambda_{e4} - \lambda_{e3}\right)} \tag{B.141}$$

Substituting these expressions into Equation (B.139) and using expressions for K_{41}, K_{42}, K_{43}, and K_{44} in Equation (B.130), the amount of radionuclide 2 in box 2 at time t can be written as follows:

$$C_{m4}(t) = \left[\frac{d_{24}\lambda_{r2}d_{12}\lambda_{r4}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e1})(\lambda_{e2}-\lambda_{e1})} + \frac{d_{34}\lambda_{r3}d_{13}\lambda_{r4}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e1})(\lambda_{e3}-\lambda_{e1})}\right] e^{-\lambda_{e1}t}$$

$$+ \left[\frac{d_{24}\lambda_{r4}C_{m2}(0)}{\lambda_{e4}-\lambda_{e2}} - \frac{d_{24}\lambda_{r2}d_{12}\lambda_{r4}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e2})(\lambda_{e2}-\lambda_{e1})}\right] e^{-\lambda_{e2}t}$$

$$+ \left[\frac{d_{34}\lambda_{r4}C_{m3}(0)}{\lambda_{e4}-\lambda_{e3}} - \frac{d_{34}\lambda_{r3}d_{13}\lambda_{r4}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e3})(\lambda_{e3}-\lambda_{e1})}\right] e^{-\lambda_{e3}t} \qquad \text{(B.142)}$$

$$+ \left[C_{m4}(0) + \frac{d_{24}\lambda_{r2}d_{12}\lambda_{r4}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e1})(\lambda_{e4}-\lambda_{e2})} - \frac{d_{24}\lambda_{r4}C_{m2}(0)}{\lambda_{e4}-\lambda_{e2}}\right.$$

$$\left. + \frac{d_{34}\lambda_{r3}d_{13}\lambda_{r4}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e1})(\lambda_{e4}-\lambda_{e3})} - \frac{d_{34}\lambda_{r4}C_{m3}(0)}{\lambda_{e4}-\lambda_{e3}}\right] e^{-\lambda_{e4}t}$$

Substitution of expressions for d_{24} and d_{13} from item 3 above ($d_{24} = L_{122}/\lambda_{r2}$ and $d_{13} = L_{121}/\lambda_{r1}$), d_{34} from item 2 above ($d_{34} = d_{12}$), and λ_{r3}, and λ_{r4} from item 1 above, into Equation (B.142) gives the following equation for the amount of radionuclide 2 in box 2 as a function of time:

$$C_{m4}(t) = \left[\frac{L_{122}d_{12}\lambda_{r2}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e1})(\lambda_{e2}-\lambda_{e1})} + \frac{d_{12}L_{121}\lambda_{r2}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e1})(\lambda_{e3}-\lambda_{e1})}\right] e^{-\lambda_{e1}t}$$

$$+ \left[\frac{L_{122}C_{m2}(0)}{\lambda_{e4}-\lambda_{e2}} - \frac{L_{122}d_{12}\lambda_{r2}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e2})(\lambda_{e2}-\lambda_{e1})}\right] e^{-\lambda_{e2}t}$$

$$+ \left[\frac{d_{12}\lambda_{r2}C_{m3}(0)}{\lambda_{e4}-\lambda_{e3}} - \frac{d_{12}L_{121}\lambda_{r2}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e3})(\lambda_{e3}-\lambda_{e1})}\right] e^{-\lambda_{e3}t} \qquad \text{(B.143)}$$

$$+ \left[C_{m4}(0) + \frac{L_{122}d_{12}\lambda_{r2}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e1})(\lambda_{e4}-\lambda_{e2})} - \frac{L_{122}C_{m2}(0)}{\lambda_{e4}-\lambda_{e2}}\right.$$

$$\left. + \frac{d_{12}L_{121}\lambda_{r2}C_{m1}(0)}{(\lambda_{e4}-\lambda_{e1})(\lambda_{e4}-\lambda_{e3})} - \frac{d_{12}\lambda_{r2}C_{m3}(0)}{\lambda_{e4}-\lambda_{e3}}\right] e^{-\lambda_{e4}t}$$

Radionuclide 1 in Box 3: Expanded Chain Member Position 5

The activity of chain member 1 remaining in box 3 at time t is evaluated according to Equation (B.15) as follows:

$$C_{m5}(t) = \lambda_{r5}\left[K_{51}\, e^{-\lambda_{e1}t} + K_{52}\, e^{-\lambda_{e2}t} + K_{53}\, e^{-\lambda_{e3}t} + K_{54}\, e^{-\lambda_{e4}t} + K_{55}\, e^{-\lambda_{e5}t}\right] \tag{B.144}$$

Coefficient K_{51} is evaluated using Equation (B.17) as follows:

$$K_{51} = \frac{\sum_{p=1}^{4} d_{p5}\lambda_{rp}K_{p1}}{\lambda_{e5} - \lambda_{e1}} = \frac{d_{15}\lambda_{r1}K_{11}}{\lambda_{e5} - \lambda_{e1}} + \frac{d_{25}\lambda_{r2}K_{21}}{\lambda_{e5} - \lambda_{e1}} + \frac{d_{35}\lambda_{r3}K_{31}}{\lambda_{e5} - \lambda_{e1}} + \frac{d_{45}\lambda_{r4}K_{41}}{\lambda_{e5} - \lambda_{e1}} \tag{B.145}$$

The branching fractions d_{15} and d_{25} are zero because there is no direct transfer from box 1 to box 3. Also, the branching fraction d_{45} is zero because there is no production of radionuclide 1 from radionuclide 2. With these simplifications, and use of the previous expression for K_{13}, Equation (B.145) can be reduced to the following:

$$K_{51} = \frac{d_{35}\lambda_{r3}K_{31}}{\lambda_{e5} - \lambda_{e1}} = \frac{d_{35}\lambda_{r3}d_{13}C_{m1}(0)}{\left(\lambda_{e5} - \lambda_{e1}\right)\left(\lambda_{e3} - \lambda_{e1}\right)} \tag{B.146}$$

The second coefficient of Equation (B.144), K_{52}, is evaluated using Equation (B.17) as follows:

$$K_{52} = \frac{\sum_{p=2}^{4} d_{p5}\lambda_{rp}K_{p2}}{\lambda_{e5} - \lambda_{e2}} = \frac{d_{25}\lambda_{r2}K_{22}}{\lambda_{e5} - \lambda_{e2}} + \frac{d_{35}\lambda_{r3}K_{32}}{\lambda_{e5} - \lambda_{e2}} + \frac{d_{45}\lambda_{r4}K_{42}}{\lambda_{e5} - \lambda_{e2}} \tag{B.147}$$

Because K_{32}, d_{25}, and d_{45} are zero (as before), the expression reduces to zero:

$$K_{52} = 0 \tag{B.148}$$

The third coefficient of Equation (B.144), K_{53}, is evaluated using Equation (B.17) as follows:

$$K_{53} = \frac{\sum_{p=3}^{4} d_{p5}\lambda_{rp}K_{p3}}{\lambda_{e5} - \lambda_{e3}} = \frac{d_{35}\lambda_{r3}K_{33}}{\lambda_{e5} - \lambda_{e3}} + \frac{d_{45}\lambda_{r4}K_{43}}{\lambda_{e5} - \lambda_{r3}} \tag{B.149}$$

As before, d_{45} is zero and the expression reduces to the following:

$$K_{53} = \frac{d_{35} C_{m3}(0)}{\lambda_{e5} - \lambda_{e3}} - \frac{d_{35} \lambda_{r3} d_{13} C_{m1}(0)}{\left(\lambda_{e5} - \lambda_{e3}\right)\left(\lambda_{e3} - \lambda_{e1}\right)} \tag{B.150}$$

The fourth coefficient of Equation (B.144), K_{54}, is evaluated using Equation (B.17) as follows:

$$K_{54} = \frac{\sum_{p=4}^{4} d_{p5} \lambda_{rp} K_{p4}}{\lambda_{e5} - \lambda_{e4}} = \frac{d_{45} \lambda_{r4} K_{44}}{\lambda_{e5} - \lambda_{e4}} \tag{B.151}$$

As before, d_{45} is zero and K_{54} reduces to zero:

$$K_{54} = 0 \tag{B.152}$$

The last coefficient of Equation (B.144), K_{55}, is evaluated using Equation (B.18) as follows:

$$K_{55} = \frac{C_{m5}(0)}{\lambda_{r5}} - K_{51} - K_{52} - K_{53} - K_{54} \tag{B.153}$$

Using the previous expressions for the first four coefficients of Equation (B.144) gives the following expression for K_{55}:

$$\begin{aligned} K_{55} = \frac{C_{m5}(0)}{\lambda_{r5}} &- \frac{d_{35} \lambda_{r3} d_{13} C_{m1}(0)}{\left(\lambda_{e5} - \lambda_{e1}\right)\left(\lambda_{e3} - \lambda_{e1}\right)} + 0 \\ &- \frac{d_{35} C_{m3}(0)}{\lambda_{e5} - \lambda_{e3}} + \frac{d_{35} \lambda_{r3} d_{13} C_{m1}(0)}{\left(\lambda_{e5} - \lambda_{e3}\right)\left(\lambda_{e3} - \lambda_{e1}\right)} + 0 \end{aligned} \tag{B.154}$$

Using the algebraic identity of Equation (B.51), the second and fourth terms for K_{55} can be combined to give the following expression:

$$\frac{d_{35} \lambda_{r3} d_{13} C_{m1}(0)}{\left(\lambda_{e5} - \lambda_{e1}\right)\left(\lambda_{e5} - \lambda_{e3}\right)} \tag{B.155}$$

The activity of radionuclide 1 in box 3 as a function of time can now be written from Equation (B.144) and the above expressions for the coefficients as follows:

$$C_{m5}(t) = \frac{d_{35}\lambda_{r3}d_{13}\lambda_{r5}C_{m1}(0)}{(\lambda_{e5} - \lambda_{e1})(\lambda_{e3} - \lambda_{e1})} e^{-\lambda_{e1}t}$$

$$+ \left[\frac{d_{35}\lambda_{r5}C_{m3}(0)}{\lambda_{e5} - \lambda_{e3}} - \frac{d_{35}\lambda_{r3}d_{13}\lambda_{r5}C_{m1}(0)}{(\lambda_{e5} - \lambda_{e3})(\lambda_{e3} - \lambda_{e1})}\right] e^{-\lambda_{e3}t} \quad \text{(B.156)}$$

$$+ \left[C_{m5}(0) - \frac{d_{35}\lambda_{r5}C_{m3}(0)}{\lambda_{e5} - \lambda_{e3}} + \frac{d_{35}\lambda_{r3}d_{13}\lambda_{r5}C_{m1}(0)}{(\lambda_{e5} - \lambda_{e1})(\lambda_{e5} - \lambda_{e3})}\right] e^{-\lambda_{e5}t}$$

Using expressions for d_{13} and d_{35} from item 3 above ($d_{13} = L_{121}/\lambda_{r1}$ and $d_{35} = L_{231}/\lambda_{r1}$), and $\lambda_{r5} = \lambda_{r3} = \lambda_{r1}$, the final expression for the amount of radionuclide 1 in box 3 can be expressed as follows:

$$C_{m5}(t) = \frac{L_{231}\, L_{121}\, C_{m1}(0)}{(\lambda_{e5} - \lambda_{e1})(\lambda_{e3} - \lambda_{e1})} e^{-\lambda_{e1}t}$$

$$+ \left[\frac{L_{231}\, C_{m3}(0)}{\lambda_{e5} - \lambda_{e3}} - \frac{L_{231}\, L_{121}\, C_{m1}(0)}{(\lambda_{e5} - \lambda_{e3})(\lambda_{e3} - \lambda_{e1})}\right] e^{-\lambda_{e3}t} \quad \text{(B.157)}$$

$$+ \left[C_{m5}(0) - \frac{L_{231}\, C_{m3}(0)}{\lambda_{e5} - \lambda_{e3}} + \frac{L_{231}\, L_{121}\, C_{m1}(0)}{(\lambda_{e5} - \lambda_{e1})(\lambda_{e5} - \lambda_{e3})}\right] e^{-\lambda_{e5}t}$$

Further modifications could be made to the above equation by substituting the following expressions for terms in the denominators of the coefficient terms:

$$\lambda_{e3} - \lambda_{e1} = \lambda_{r1} + L_{231} - \lambda_{r1} - L_{121} = L_{231} - L_{121} \quad \text{(B.158)}$$

$$\lambda_{e5} - \lambda_{e3} = \lambda_{r1} + w_d - \lambda_{r1} - L_{231} = w_d - L_{231} \quad \text{(B.159)}$$

Making these substitutions in Equation (B.157) can be done, but will not result in a simpler expression. The important point to note from Equations (B.158) and (B.159) is that each term must be non-zero, implying that the leakage rate constants must not be the same between any two boxes:

$$L_{121} \neq L_{231} \text{ and } L_{231} \neq w_d \quad \text{(B.160)}$$

Radionuclide 2 in Box 3: Expanded Chain Member Position 6

Details of the derivation of equations for this case are not presented. The derivations are performed in a manner similar to the previous cases. The final result of the derivation is given in the following equation for the amount of radionuclide 2 in box 3 as a function of time:

$$
\begin{aligned}
C_{m6}(t) = &\left[\frac{L_{232}\, L_{122}\, d_{12}\, \lambda_{r2}\, C_{m1}(0)}{(\lambda_{e6} - \lambda_{e1})(\lambda_{e4} - \lambda_{e1})(\lambda_{e2} - \lambda_{e1})} \right. \\
&\left. + \frac{L_{232}\, d_{12}\, \lambda_{r2}\, L_{121}\, C_{m1}(0)}{(\lambda_{e6} - \lambda_{e1})(\lambda_{e4} - \lambda_{e1})(\lambda_{e3} - \lambda_{e1})} + \frac{d_{12}\, \lambda_{r2}\, L_{231}\, L_{121}\, C_{m1}(0)}{(\lambda_{e6} - \lambda_{e1})(\lambda_{e5} - \lambda_{e1})(\lambda_{e3} - \lambda_{e1})} \right] e^{-\lambda_{e1} t} \\
&+ \left[\frac{L_{232}\, L_{122}\, C_{m2}(0)}{(\lambda_{e6} - \lambda_{e2})(\lambda_{e4} - \lambda_{e2})} - \frac{L_{232}\, L_{122}\, d_{12}\, \lambda_{r2}\, C_{m1}(0)}{(\lambda_{e6} - \lambda_{e2})(\lambda_{e4} - \lambda_{e2})(\lambda_{e2} - \lambda_{e1})} \right] e^{-\lambda_{e2} t} \\
&+ \left[\frac{L_{232}\, d_{12}\, \lambda_{r2}\, C_{m3}(0)}{(\lambda_{e6} - \lambda_{e3})(\lambda_{e4} - \lambda_{e3})} - \frac{L_{232}\, d_{12}\, \lambda_{r2}\, L_{121}\, C_{m1}(0)}{(\lambda_{e6} - \lambda_{e3})(\lambda_{e4} - \lambda_{e3})(\lambda_{e3} - \lambda_{e1})} \right. \\
&\left. + \frac{d_{12}\, \lambda_{r2}\, L_{231}\, C_{m3}(0)}{(\lambda_{e6} - \lambda_{e3})(\lambda_{e5} - \lambda_{e3})} - \frac{d_{12}\, \lambda_{r2}\, L_{231}\, L_{121}\, C_{m1}(0)}{(\lambda_{e6} - \lambda_{e3})(\lambda_{e5} - \lambda_{e3})(\lambda_{e3} - \lambda_{e1})} \right] e^{-\lambda_{e3} t} \\
&+ \left[\frac{L_{232}\, C_{m4}(0)}{\lambda_{e6} - \lambda_{e4}} + \frac{L_{232}\, L_{122}\, d_{12}\, \lambda_{r2}\, C_{m1}(0)}{(\lambda_{e6} - \lambda_{e4})(\lambda_{e4} - \lambda_{e1})(\lambda_{e4} - \lambda_{e2})} - \frac{L_{232}\, L_{122}\, C_{m2}(0)}{(\lambda_{e6} - \lambda_{e4})(\lambda_{e4} - \lambda_{e2})} \right. \\
&\left. + \frac{L_{232}\, d_{12}\, \lambda_{r2}\, L_{121}\, C_{m1}(0)}{(\lambda_{e6} - \lambda_{e4})(\lambda_{e4} - \lambda_{e1})(\lambda_{e4} - \lambda_{e3})} - \frac{L_{232}\, d_{12}\, \lambda_{r2}\, C_{m3}(0)}{(\lambda_{e6} - \lambda_{e4})(\lambda_{e4} - \lambda_{e3})} \right] e^{-\lambda_{e4} t}
\end{aligned}
\tag{B.161}
$$

$$+\left[\frac{d_{12}\lambda_{r2}C_{m5}(0)}{\lambda_{e6}-\lambda_{e5}}-\frac{d_{12}\lambda_{r2}L_{231}C_{m3}(0)}{(\lambda_{e6}-\lambda_{e5})(\lambda_{e5}-\lambda_{e3})}+\frac{d_{12}\lambda_{r2}L_{231}L_{121}C_{m1}(0)}{(\lambda_{e6}-\lambda_{e5})(\lambda_{e5}-\lambda_{e1})(\lambda_{e5}-\lambda_{e3})}\right]e^{-\lambda_{e5}t}$$

$$+\left[C_{m6}(0)-\frac{L_{232}C_{m4}(0)}{\lambda_{e6}-\lambda_{e4}}-\frac{d_{12}\lambda_{r2}C_{m5}(0)}{\lambda_{e6}-\lambda_{e5}}+\frac{L_{232}L_{122}C_{m2}(0)}{(\lambda_{e6}-\lambda_{e2})(\lambda_{e6}-\lambda_{e4})}+\frac{L_{232}d_{12}\lambda_{r2}C_{m3}(0)}{(\lambda_{e6}-\lambda_{e3})(\lambda_{e6}-\lambda_{e4})}\right.$$

$$+\frac{d_{12}\lambda_{r2}L_{231}C_{m3}(0)}{(\lambda_{e6}-\lambda_{e3})(\lambda_{e6}-\lambda_{e5})}-\frac{L_{232}L_{122}d_{12}\lambda_{r2}C_{m1}(0)}{(\lambda_{e6}-\lambda_{e1})(\lambda_{e6}-\lambda_{e2})(\lambda_{e6}-\lambda_{e4})}$$

$$\left.-\frac{L_{232}d_{12}\lambda_{r2}L_{121}C_{m1}(0)}{(\lambda_{e6}-\lambda_{e1})(\lambda_{e6}-\lambda_{e3})(\lambda_{e6}-\lambda_{e4})}-\frac{d_{12}\lambda_{r2}L_{231}L_{121}C_{m1}(0)}{(\lambda_{e6}-\lambda_{e1})(\lambda_{e6}-\lambda_{e3})(\lambda_{e6}-\lambda_{e5})}\right]e^{-\lambda_{e6}t}$$

As mentioned above, the operator equations have a limitation caused by the form of the denominator to Equation (B.17): $\lambda_{ej} - \lambda_{en}$. Because the difference between the two rate constants appears in the denominator, the rate constants must be unequal. This condition is met for all radionuclide chains (unequal half-lives) and all transfers between boxes (unequal rate constants for transfer out of boxes 1 and 2 for the drinking water scenario).

The activity in each box after a time period for the water-use model of the drinking water scenario is represented as follows:

$$A_{dk}\{C_*, t_*\} \tag{B.162}$$

where $A_{dk}\{\}$ represents the operator for the activity after a time period in the drinking water water-use model with results given for box k, C_* is the array of initial activities or concentrations of all radionuclides in all boxes of the water-use model (in pCi/medium), and t is a time period of interest. The units of $A_{dk}\{\}$ are the same as the units of C_*. Note that the results of the operator are defined for one box at a time by subscript k (replaceable by 1, 2, or 3). The particular radionuclide of interest is represented by the subscript given on the activity or concentration array, C_*. For example, the results for radionuclide j in box 3 (aquifer) after a time t_y are represented as

$$A_{d3}\{C_{kj}, t_y\} \tag{B.163}$$

Here, the input activity array includes activities of all radionuclides through radionuclide j of the decay chain in all boxes k of the water-use model. The time-integral operator for the drinking water water-use model is represented similarly:

$$S_{dk}\{C_*, t_*\} \tag{B.164}$$

where $S_{dk}\{\}$ represents the operation of time integration over a time period, t_*, in the water-use model with results given for box k, and other terms are as previously defined. The deposition, accumulation, and time-integration

operations, R{} and G{}, are not needed for the water-use model because none of the evaluations needed to implement the water-use model involves deposition.

The operator notation can be related to the equations defined in this section for the activity of each radionuclide present in each box of the drinking water scenario water-use model. The sample case used to illustrate generation of the equations involved a two-membered decay chain. Therefore, each box of the water-use model will have two numerical values generated from application of the decay operator. For example, the notation for the first box given above, $A_{d1}\{C_{kj},t_y\}$, represents two numerical values: one for the parent and one for the progeny radionuclide. There will also be a total of six numerical values associated with the total solution: two values for each of the three boxes. These are related to previous equations as follows:

Chain Member	Water-use Model Box	Reference Equation	Expression
1	1	B.113	$A_{d1}\{\} = C_{m1}(t_y)$
2	1	B.120	$A_{d1}\{\} = C_{m2}(t_y)$
1	2	B.129	$A_{d2}\{\} = C_{m3}(t_y)$
2	2	B.143	$A_{d2}\{\} = C_{m4}(t_y)$
1	3	B.157	$A_{d3}\{\} = C_{m5}(t_y)$
2	3	B.161	$A_{d3}\{\} = C_{m6}(t_y)$

B.6.2 Solution to Water-Use Model for the Drinking Water Scenario

This section presents the derivation of the solution to the drinking water scenario water-use model differential equations. The solution is also compared to the decay operator equations (defined in Section B.1) as illustrated for a sample case in Section B.6.1. The differential equations for the water-use model are as follows (repeated from Section 4.1.3):

for box 1 (surface-soil layer),

$$\frac{dC_{1j}}{dt} = \sum_{n=1}^{j-1} d_{nj}\lambda_{rj} C_{1n} - \left(\lambda_{rj} + L_{12j}\right) C_{1j} \qquad \text{(B.165)}$$

for box 2 (unsaturated-soil layer),

$$\frac{dC_{2j}}{dt} = \sum_{n=1}^{j-1} d_{nj}\lambda_{rj} C_{2n} + L_{12j} C_{1j} - \left(\lambda_{rj} + L_{23j}\right) C_{2j} \qquad \text{(B.166)}$$

and for box 3 (aquifer),

$$\frac{dC_{3j}}{dt} = \sum_{n=1}^{j-1} d_{nj}\lambda_{rj} C_{3n} + L_{23j} C_{2j} - \left(\lambda_{rj} + w_d\right) C_{3j} \quad \text{(B.167)}$$

where C_{1j} = activity of radionuclide j in box 1 at time t (pCi)

C_{2j} = activity of radionuclide j in box 2 at time t (pCi)

C_{3j} = activity of radionuclide j in box 3 at time t (pCi)

C_{1n} = activity of radionuclide n as a precursor to radionuclide j in box 1 at time t (pCi)

C_{2n} = activity of radionuclide n as a precursor to radionuclide j in box 2 at time t (pCi)

C_{3n} = activity of radionuclide n as a precursor to radionuclide j in box 3 at time t (pCi)

j = index of current chain member position in decay chain

n = index of precursor chain members in decay chain (n<j)

L_{12j} = rate constant for movement of radionuclide j from box 1 to box 2 (d^{-1})

L_{23j} = rate constant for movement of radionuclide j from box 2 to box 3 (d^{-1})

w_d = rate constant for pumping of water from the aquifer (d^{-1})

d_{nj} = fraction of radionuclide n transitions that result in production of radionuclide j

λ_{rj} = decay rate constant for radioactive decay of radionuclide j (d^{-1}).

The solution to these differential equations will be demonstrated for the parent and first progeny radionuclides in box 1, and for the parent radionuclides in boxes 2 and 3. The differential equation for the parent radionuclide in box 1 can be written as follows from Equation (B.165):

$$\frac{dC_{11}}{dt} = -\left(\lambda_{r1} + L_{121}\right) C_{11} \quad \text{(B.168)}$$

Combining terms containing C_{11}, and multiplying by the integration factor $e^{(\lambda_{r1} + L_{121})t}$, gives the following equation:

$$\left(dC_{11}\right) e^{\left(\lambda_{r1} + L_{121}\right)t} + \left(\lambda_{r1} + L_{121}\right) C_{11} e^{\left(\lambda_{r1} + L_{121}\right)t} dt = 0 \quad \text{(B.169)}$$

This can be written as a differential as follows:

$$\frac{d\left[C_{11}\, e^{(\lambda_{r1} + L_{121})t}\right]}{dt} = 0 \tag{B.170}$$

The integral form can be written as follows:

$$C_{11}\, e^{(\lambda_{r1} + L_{121})t} = \text{Constant} \tag{B.171}$$

and

$$C_{11} = \text{Constant}\; e^{-(\lambda_{r1} + L_{121})t} \tag{B.172}$$

Using the initial condition of $C_{11} = C_{11}(0)$ at t=0, the constant is evaluated as equal to $C_{11}(0)$. Then, the activity of parent radionuclide in box 1 as a function of time is expressed as follows:

$$C_{11}(t) = C_{11}(0)\; e^{-(\lambda_{r1} + L_{121})t} \tag{B.173}$$

(Note: this equation is equivalent to Equation [B.113] with $\lambda_{r1} + L_{121} = \lambda_{e1}$ and $C_{11} = C_{m1}$.)

The differential equation for the first progeny in box 1 is as follows:

$$\frac{dC_{12}}{dt} = d_{12}\, \lambda_{r2}\, C_{11} - \left(\lambda_{r2} + L_{122}\right) C_{12} \tag{B.174}$$

Arranging terms containing C_{12} on the left side of the equation, substituting the expression for C_{11} from Equation (B.173), and multiplying by the integrating factor $e^{(\lambda_{r2} + L_{122})t}$ results in the following expression:

$$\frac{d\left[C_{12}\, e^{(\lambda_{r2} + L_{122})t}\right]}{dt} = d_{12}\lambda_{r2}\, C_{11}(0)\; e^{\left[(\lambda_{r2} + L_{122}) - (\lambda_{r1} + L_{121})\right]t} \tag{B.175}$$

The integral expression is as follows:

$$C_{12}(t) = \frac{d_{12}\lambda_{re}\, C_{11}(0)\; e^{-(\lambda_{r1} + L_{121})t}}{\left(\lambda_{r2} + L_{122}\right) - \left(\lambda_{r1} + L_{121}\right)} + \text{Constant}\; e^{-(\lambda_{r2} + L_{122})t} \tag{B.176}$$

Using the condition that $C_{12} = C_{12}(0)$ at $t = 0$, the constant is evaluated as follows:

$$\text{Constant} = C_{12}(0) - \frac{d_{12}\lambda_{r2}\, C_{11}(0)}{\left(\lambda_{r2} + L_{122}\right) - \left(\lambda_{r1} + L_{121}\right)} \tag{B.177}$$

The final expression for the amount of the first progeny radionuclide in box 1 is then

$$C_{12}(t) = \frac{d_{12}\lambda_{r2}\, C_{11}(0)\, e^{-\left(\lambda_{r1} + L_{121}\right)t}}{\left(\lambda_{r2} + L_{122}\right) - \left(\lambda_{r1} + L_{121}\right)} + \left[C_{12}(0) - \frac{d_{12}\lambda_{r2}\, C_{11}(0)}{\left(\lambda_{r2} + L_{122}\right) - \left(\lambda_{r1} + L_{121}\right)}\right] e^{-\left(\lambda_{r2} + L_{122}\right)t} \tag{B.178}$$

(Note: This expression is equivalent to Equation [B.120] with $C_{12} = C_{m2}$, and $\lambda_{r2} + L_{122} = \lambda_{e2}$.)

The differential equation for the activity of parent radionuclide in box 2 is written as follows from Equation (B.166):

$$\frac{dC_{21}}{dt} = L_{121}\, C_{11} - \left(\lambda_{r1} + L_{231}\right)C_{21} \tag{B.179}$$

Arranging terms containing C_{21} on the left side of the equation, substituting the expression for C_{11} from Equation (B.173), and multiplying by the integrating factor $e^{(\lambda_{r1} + L_{231})t}$ results in the following expression:

$$\frac{dC_{21}\, e^{\left(\lambda_{r1} + L_{231}\right)t}}{dt} = L_{121}\, C_{11}(0)\, e^{\left[\left(\lambda_{r1} + L_{231}\right) - \left(\lambda_{r1} + L_{121}\right)\right]t} \tag{B.180}$$

The integral expression is as follows:

$$C_{21} = \frac{L_{121}\, C_{11}(0)\, e^{-\left(\lambda_{r1} + L_{121}\right)t}}{\left(\lambda_{r1} + L_{231}\right) - \left(\lambda_{r1} + L_{121}\right)} + \text{Constant}\; e^{-\left(\lambda_{r1} + L_{231}\right)t} \tag{B.181}$$

Using the condition that $C_{21} = C_{21}(0)$ at t=0, the constant is evaluated as follows:

$$\text{Constant} = C_{21}(0) - \frac{L_{121}\, C_{11}(0)}{\left(\lambda_{r1} + L_{231}\right) - \left(\lambda_{r1} + L_{121}\right)} \tag{B.182}$$

The final expression for the amount of parent radionuclide in box 2 is then

$$C_{21}(t) = \frac{L_{121}\, C_{11}(0)\, e^{-(\lambda_{r1} + L_{121})t}}{(\lambda_{r1} + L_{231}) - (\lambda_{r1} + L_{121})} + \left[C_{21}(0) - \frac{L_{121}\, C_{11}(0)}{(\lambda_{r1} + L_{231}) - (\lambda_{r1} + L_{121})} \right] e^{-(\lambda_{r1} + L_{231})t} \quad \text{(B.183)}$$

(Note: This expression is equivalent to Equation [B.129] with $C_{21} = C_{m3}$ and $\lambda_{r1} + L_{231} = \lambda_{e3}$ and previous substitutions as indicated for Equations [B.173] and [B.178].)

The differential equation for the amount of the parent radionuclide in box 3 is written as follows from Equation (B.167):

$$\frac{dC_{31}}{dt} = L_{231}\, Q_{21} - (\lambda_{r1} + w_d)\, Q_{31} \quad \text{(B.184)}$$

Arranging terms containing C_{31} on the left side of the equation, substituting the expression for C_{21} from Equation (B.183), and multiplying by the integration factor $e^{(\lambda_{r1} + w_d)t}$ results in the following expression:

$$\frac{d\left[C_{31}\, e^{(\lambda_{r1} + w_d)t}\right]}{dt} = \frac{L_{231}\, L_{121}\, C_{11}(0)\, e^{\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{121})\right]t}}{(\lambda_{r1} + L_{231}) - (\lambda_{r1} + L_{121})} + L_{231}\, C_{21}(0)\, e^{\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})\right]t} - \frac{L_{231}\, L_{121}\, C_{11}(0)\, e^{\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})\right]t}}{(\lambda_{r1} + L_{231}) - (\lambda_{r1} + L_{121})} \quad \text{(B.185)}$$

As before, the integral of this expression can be written as follows:

$$C_{31}(t) = \frac{L_{231} L_{121} C_{11}(0) e^{-(\lambda_{r1} + L_{121})t}}{\left[(\lambda_{r1} + L_{231}) - (\lambda_{r1} + L_{121})\right]\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{121})\right]}$$

$$+ \frac{L_{231} C_{21}(0) e^{-(\lambda_{r1} + L_{231})t}}{(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})} \qquad \text{(B.186)}$$

$$- \frac{L_{231} L_{121} C_{11}(0) e^{-(\lambda_{r1} + L_{231})t}}{\left[(\lambda_{r1} + L_{231}) - (\lambda_{r1} + L_{121})\right]\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})\right]} + \text{Constant } e^{-(\lambda_{r1} + w_d)t}$$

The constant can be evaluated from the condition that $C_{31} = C_{31}(0)$ at t=0, as follows:

$$\text{Constant} = C_{31}(0) - \frac{L_{231} C_{21}(0)}{(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})}$$

$$- \frac{L_{231} L_{121} C_{11}(0)}{\left[(\lambda_{r1} + L_{231}) - (\lambda_{r1} + L_{121})\right]\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{121})\right]} \qquad \text{(B.187)}$$

$$+ \frac{L_{231} L_{121} C_{11}(0)}{\left[(\lambda_{r1} + L_{231}) - (\lambda_{r1} + L_{121})\right]\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})\right]}$$

This expression can be reduced using the algebraic identity defined in Equation (B.51) with $a = \lambda_{r1} + L_{121}$, $b = \lambda_{r1} + L_{231}$, and $c = \lambda_{r1} + w_d$. The expression for the constant becomes

$$\text{Constant} = C_{31}(0) - \frac{L_{231} C_{21}(0)}{(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})}$$

$$+ \frac{L_{231} L_{121} C_{11}(0)}{\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{121})\right]\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})\right]} \qquad \text{(B.188)}$$

Substituting this expression into Equation (B.186) results in the following equation for the amount of parent radionuclide in box 3 as a function of time:

$$C_{31}(t) = -\frac{L_{231} L_{121} C_{11}(0)\, e^{-(\lambda_{r1} + L_{121})t}}{\left[(\lambda_{r1} + L_{231}) - (\lambda_{r1} + L_{121})\right]\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{121})\right]} + \left\{\frac{L_{231} C_{21}(0)}{(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})} - \frac{L_{231} L_{121} C_{11}(0)}{\left[(\lambda_{r1} + L_{231}) - (\lambda_{r1} + L_{121})\right]\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})\right]}\right\} e^{-(\lambda_{r1} + L_{231})t}$$

$$+ \left\{C_{31}(0) - \frac{L_{231} C_{21}(0)}{(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})} + \frac{L_{231} L_{121} C_{11}(0)}{\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{121})\right]\left[(\lambda_{r1} + w_d) - (\lambda_{r1} + L_{231})\right]}\right\} e^{-(\lambda_{r1} + w_d)t} \quad \text{(B.189)}$$

(Note: This equation is equivalent to Equation [B.157] with $C_{31} = C_{m5}$ and $\lambda_{r1} + w_d = \lambda_{e5}$ and previous substitutions as indicated for Equations [B.173], [B.178], and [B.183].)

B.7 Water-Use Model for the Residential Scenario

The water-use model for the residential scenario, as described in Section 5.6.6, is very similar to the water-use model for the drinking water scenario, with one major exception. The residential scenario involves recycling of activity from the aquifer (box 3) to the surface-soil layer (box 1). This recycling pathway causes a number of complications in the equations for calculating the activity in each box as a function of time. The decay operator equations can not be applied directly to solve the problem, as was possible for the simpler drinking water scenario water-use model. General methods for solving the recycling case have been published based on matrix algebra with the aid of computers in generating numerical solutions to specific cases. A method for solving the three-box water-use model with recycling is provided in the discussion that follows.

The three-box ground-water model for a parent and a single radioactive progeny can be solved numerically using the method of Birchall and James (1989). To apply this method, consider the representation of the three-box model presented in Figure B.1. This figure illustrates the three-box model for the residential scenario with recycling from box 3 to box 1 for a two-membered decay chain. Application of the Birchall and James method requires defining the matrices to represent the system. Table B.1 illustrates the methods for establishing the system matrix [R]. The [R] matrix is given by the portion of the table within the double lines. The column labeled "Out" contains additional removal rate terms that do not appear as input to any of the Q_{ij} compartments; these terms appear below as "further reductions" in the [A] matrix (Birchall and James 1989). Note that quantities are represented in units of atoms for this application. Conversion between atom units and activity units is performed on the result according to Equation (B.26).

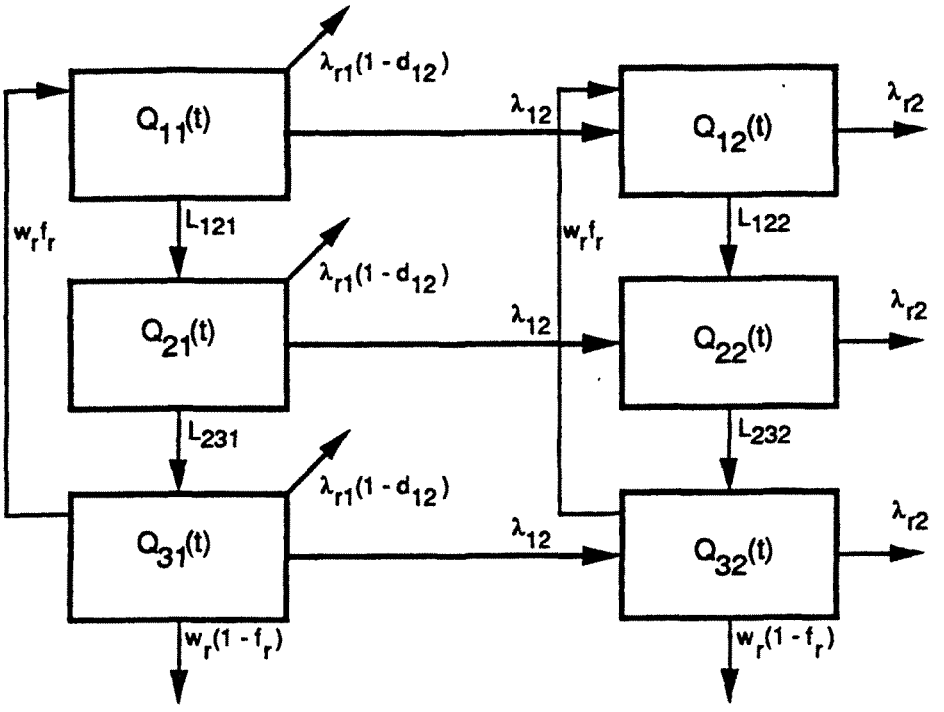

Figure B.1 Residential scenario three-box water-use model

Table B.1 System matrix generation table

matrix [R]		To: $Q_{11}(t)$	$Q_{21}(t)$	$Q_{31}(t)$	$Q_{12}(t)$	$Q_{22}(t)$	$Q_{32}(t)$	Out
From:	$Q_{11}(t)$	$Q_{11}(0)$	L_{121}		λ_{12}			$\lambda_{r1}(1\text{-}d_{12})$
	$Q_{21}(t)$		$Q_{21}(0)$	L_{231}		λ_{12}		$\lambda_{r1}(1\text{-}d_{12})$
	$Q_{31}(t)$	$f_r w_r$		$Q_{31}(0)$			λ_{12}	$\lambda_{r1}(1\text{-}d_{12}) + w_r(1\text{-}f_r)$
	$Q_{12}(t)$				$Q_{12}(0)$	L_{122}		λ_{r2}
	$Q_{22}(t)$					$Q_{22}(0)$	L_{232}	λ_{r2}
	$Q_{32}(t)$				$f_r w_r$		$Q_{32}(0)$	$\lambda_{r2} + w_r(1\text{-}f_r)$

From the matrix [R] is formed the matrix [A] with reductions along the diagonal as shown above. Note that many of the terms along the diagonal simplify, since $\lambda_{r1} = \lambda_{12} + \lambda_{r1}(1\text{-}d_{12})$ and $w_r = w_r f_r + w_r(1\text{-}f_r)$. The first expression is a result of the definition of the fractional decay rate constant, λ_{12}, which is equal to the product of the branching fraction, d_{12}, and the radioactive decay rate constant, λ_{r1}.

$$[A] = \begin{bmatrix} -L_{121}-\lambda_{r1} & 0 & f_r w_r & 0 & 0 & 0 \\ L_{121} & -L_{231}-\lambda_{r1} & 0 & 0 & 0 & 0 \\ 0 & L_{231} & -w_r-\lambda_{r1} & 0 & 0 & 0 \\ \lambda_{12} & 0 & 0 & -L_{122}-\lambda_{r2} & 0 & 0 \\ 0 & \lambda_{12} & 0 & L_{122} & -L_{232}-\lambda_{r2} & 0 \\ 0 & 0 & \lambda_{12} & 0 & L_{232} & -w_r-\lambda_{r2} \end{bmatrix} \quad \text{(B.190)}$$

Multiplying each element in matrix [A] by the scalar t gives:

$$[A]t = \begin{bmatrix} -(L_{121}+\lambda_{r1})t & 0 & f_r w_r t & 0 & 0 & 0 \\ L_{121}t & -(L_{231}+\lambda_{r1})t & 0 & 0 & 0 & 0 \\ 0 & L_{231}t & -(w_r+\lambda_{r1})t & 0 & 0 & 0 \\ \lambda_{12}t & 0 & 0 & -(L_{122}+\lambda_{r2})t & 0 & f_r w_r t \\ 0 & \lambda_{12}t & 0 & L_{122}t & -(L_{232}+\lambda_{r2})t & 0 \\ 0 & 0 & \lambda_{12}t & 0 & L_{232}t & -(w_r+\lambda_{r2})t \end{bmatrix} \quad \text{(B.191)}$$

Let Φ denote the eigenvalues of [A]t, $[\epsilon_1, \epsilon_2, \epsilon_3, \epsilon_4, \epsilon_5, \epsilon_6]$. Form a matrix $[\Phi]$ whose diagonal is the exponential of each eigenvalue:

$$[\Phi] = \begin{bmatrix} e^{\epsilon_1} & 0 & 0 & 0 & 0 & 0 \\ 0 & e^{\epsilon_2} & 0 & 0 & 0 & 0 \\ 0 & 0 & e^{\epsilon_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & e^{\epsilon_4} & 0 & 0 \\ 0 & 0 & 0 & 0 & e^{\epsilon_5} & 0 \\ 0 & 0 & 0 & 0 & 0 & e^{\epsilon_6} \end{bmatrix} \quad \text{(B.192)}$$

Let $[\Psi]$ denote the matrix of eigenvectors of [A]t, and $[\Psi]^{-1}$ denote its inverse. The general solution to the three-box model becomes

$$\begin{bmatrix} Q_{11}(t) \\ Q_{21}(t) \\ Q_{31}(t) \\ Q_{12}(t) \\ Q_{22}(t) \\ Q_{32}(t) \end{bmatrix} = [\Psi]\,[\Phi]\,[\Psi]^{-1} \begin{bmatrix} Q_{11}(0) \\ Q_{21}(0) \\ Q_{31}(0) \\ Q_{12}(0) \\ Q_{22}(0) \\ Q_{32}(0) \end{bmatrix} \tag{B.193}$$

While there are many commercially available programs that can solve the above equation if it contains completely numeric values and coefficients (including time), solving it symbolically requires the solution of a characteristic equation that is at least of sixth order, which cannot be done analytically.

The solution matrix expressed by Equation (B.190) is represented by the three-box operator, $A_{rk}\{C_{\bullet},t_{\bullet}\}$, when multiplied by the radioactive decay constant for the radionuclide of interest. For example, the activity of the third chain member in the first box (surface soil) after a time period, t, is given as follows:

$$A_{r1}\{C_{k3},t\} = \lambda_{r3} \cdot Q_{13}(t) \tag{B.194}$$

where $A_{r1}\{\}$ = activity of radionuclide chain member 3 in box 1 after a time period t following definition of the initial inventory (pCi/g)

C_{k3} = array of initial activities of all chain members through chain member 3 in all boxes of the water-use model (pCi/g)

λ_{r3} = radioactive decay rate constant for radionuclide chain member 3 (d^{-1}).

The time-integral operator for the residential scenario, $S_{rk}\{\}$, can be represented similarly using the numerical solution to the time integral for each radionuclide activity in the appropriate box. For example, the activity of the third chain member in the first box after a time period, t_y, is given as follows:

$$S_{r1}\{C_{k3},t_y\} = \lambda_{r3}\int_0^{t_y} Q_{13}(t)dt \tag{B.195}$$

where $S_{r1}\{\}$ = time integral of activity of radionuclide chain member 3 in box 1 after a time period, t_y, following definition of the initial inventory (pCi•d/g)

and other terms are as previously defined.

B.8 References

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Appendix C

Carbon-14 Agricultural Pathway Model

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Carbon-14 Agricultural Pathway Model

Because of its production in the nuclear fuel cycle, its long half-life, and its environmental mobility, carbon-14 has attracted significant research and modeling interest. Examples of these efforts include studies by the Nuclear Energy Agency (1980), Wirth (1982), Till and Meyer (1983), Napier et al. (1988), Sheppard, Sheppard, and Amiro (1991), and Amiro, Zhuang, and Sheppard (1991). For this study, the transfer of carbon-14 from air, soil, and water to plants is evaluated using the models for other radionuclides as described in the previous sections. The transfer from animal feed to animal products is evaluated using the specific activity models and special parameters described in this appendix.

C.1 Transfer of Carbon-14 from Soil to Plants

The transfer of carbon-14 from soil to plants is based on the concentration factor (B_{iv}) approach. The value selected for the concentration factor is critical in defining the level of conservatism in the evaluations. Recent experimental work by Sheppard, Sheppard, and Amiro (1991) has addressed the estimation of the concentration factor for edible plants (radishes and beans). For application of carbon in the form of $NaHCO_3$ to two soil types (undisturbed soils with high-organic-matter content and acidic low-organic-matter content), they derived experimental B_{iv} values of 0.7 and 1.3, on a dry weight basis for the two soils, respectively. Their experiments also suggested that most of the transfer from soil to plant was via air, rather than via root uptake. Similar experiments using labeled 2,2',5,5' tetrachlorobiphenyl (^{14}C-PCB) resulted in B_{iv} estimates of 0.014 and 0.088 for the two soils, respectively. A reasonably conservative estimate for the B_{iv} value for the residential scenario is taken to be 0.7, representing uptake in organic soils that are likely to be used for gardening.

C.2 Transfer of Carbon-14 to Animal Products

The model for carbon-14 concentration in animal products is based on the assumption that the specific activity of carbon-14 in the animal product is equal to the specific activity of carbon-14 in the animal intake as follows:

$$\text{pCi carbon-14/kg carbon in animal product} = \text{pCi carbon-14/kg carbon total intake} \qquad \text{(C.1)}$$

where the total animal intake results from the consumption of contaminated fresh forage, stored feed, soil, and water.

The partial pathway transfer factor (PPTF) for carbon-14 in animal products is estimated for soil sources as in Equation (C.2). The decay correction for holdup between harvesting of the animal product and its consumption by humans is not needed because of the long half-life of carbon-14. The time integral of activity over the intake period is represented as concentration times intake time. The equation for the soil pathway includes the ingestion of soil by grazing animals.

$$PPTF_{asC} = f_{Ca}\left[Q_f\, x_f\, C_{sfCc}\, t_{ff} + Q_d\, W_f\, Q_f\, x_f\, C_{soil}\, t_{ff} + Q_g\, x_g\, C_{sgCc}\, t_{fg} + Q_h\, x_h\, C_{shCc}\, t_{fh}\right] \quad (C.2)$$
$$t_{ca}\, SA_{TaC} / \left[\left(f_{Cf}\, Q_f\, t_{ff} + f_{Cd}\, Q_d\, W_f\, Q_f\, t_{ff} + f_{Cg}\, Q_g\, t_{fg} + f_{Ch}\, Q_h\, t_{fh}\right) 365.25\right]$$

where $PPTF_{asC}$ = partial pathway transfer factor for animal product type a, for carbon-14, for unit initial concentration of carbon-14 in soil (pCi•y/kg wet-weight per pCi/g)

f_{Ca} = fraction of carbon in animal product a (kg carbon/kg wet-weight animal product)

f_{Cf} = fraction of carbon in animal fresh forage f (kg carbon/kg wet-weight animal product)

f_{Cg} = fraction of carbon in animal stored grain g (kg carbon/kg wet-weight animal product)

f_{Ch} = fraction of carbon in animal stored hay h (kg carbon/kg wet-weight animal product)

f_{Cd} = fraction of carbon in soil (kg carbon/kg dry-weight soil)

Q_d = soil dry-weight consumption rate as a fraction of the fresh forage consumption rate by the animal (kg dry-weight soil/kg dry-weight forage)

Q_f = consumption rate of fresh forage by the animal (kg wet-weight forage/d)

Q_g = consumption rate of stored grain by the animal (kg wet-weight grain/d)

Q_h = consumption rate of stored hay by the animal (kg wet-weight hay/d)

C_{sfCc} = concentration factor for carbon-14 in fresh forage plant f at time of harvest, from unit initial concentration of carbon-14 in soil (pCi/kg wet-weight forage per pCi/g dry-weight soil)

C_{sgCc} = concentration factor for carbon-14 in stored grain plant g at time of harvest, from unit initial concentration of carbon-14 in soil (pCi/kg wet-weight grain per pCi/g dry-weight soil)

C_{shCc} = concentration factor for carbon-14 in stored hay plant h at time of harvest, from unit initial concentration of carbon-14 in soil (pCi/kg wet-weight hay per pCi/g dry-weight soil)

C_{soil} = ratio of the carbon-14 concentration in soil eaten by the animal to the initial concentration of carbon-14 in the soil, with units conversion from grams to kilograms (pCi/kg dry-weight soil per pCi/g dry-weight soil)

t_{ff} = time period over which the animal is fed fresh forage (d)

t_{fg} = time period over which the animal is fed stored grain (d)

t_{fh} = time period over which the animal is fed stored hay (d)

t_{ca} = time period over which the animal product is consumed by humans (d for a year of residential scenario)

W_f = factor for conversion of mass of forage crop from a dry-weight to a wet-weight basis (kg dry weight per kg wet weight)

SA_{TaC} = specific activity equivalence of animal product type a and the specific activity of the total fresh forage and stored feed intake (pCi carbon-14/kg carbon in animal product per pCi carbon-14/kg carbon in fresh forage, stored feed, and ingested soil)

x_f = fraction of animal is intake of forage that is contaminated (dimensionless)

x_g = fraction of animal is intake of stored grain that is contaminated (dimensionless)

x_h = fraction of animal is intake of stored hay that is contaminated (dimensionless)

365.25 = unit conversion factor (d/y).

The soil concentration term, C_{soil}, is numerically equal to the conversion factor 1000 g/kg because both soil concentrations (soil eaten and initial soil) are defined to be equal. Because carbon-14 is long-lived, the concentration in soil during the feeding period is equal to the initial carbon-14 concentration in soil.

The PPTF for animal products for carbon-14 in water is evaluated using Equation (C.2), with the subscript w replacing subscript s. Also, the animal is assumed to drink the contaminated irrigation water. All the carbon in the irrigation water is assumed to be carbon-14. Therefore, the specific activity equivalence term for animal products includes the carbon-14 intakes from fresh forage, stored feed, soil, and water and the carbon intakes of only the fresh forage, stored feed, and soil. The PPTF is evaluated as follows:

$$PPTF_{awC} = \left[f_{Ca}\left(Q_f\, x_f\, C_{wfCc}\, t_{ff} + Q_d W_f\, Q_f\, x_f\, C_{wfCd}\, t_{ff} + Q_g\, x_g\, C_{wgCc}\, t_{fg} + Q_h\, X_h\, C_{whCc}\, t_{fh} + Q_w\, x_w\, C_{wwCc}\, t_{fw}\right) t_{ca}\, SA_{TaC}\right] / \left[\left(f_{Cf}\, Q_f\, t_{ff} + f_{Cd} Q_d W_f\, Q_f\, t_{ff} + f_{Cg}\, Q_g\, t_{fg} + f_{Ch}\, Q_h\, t_{fh}\right) 365.25\right] \quad \text{(C.3)}$$

where $PPTF_{awC}$ = partial pathway transfer factor for animal product type a, for carbon-14, for unit initial concentration of carbon-14 in water (pCi•y/kg per pCi/L for a year of residential scenario)

t_{fw} = period over which animal is fed contaminated water (d)

C_{wfCc} = concentration factor for carbon-14 in fresh forage plant f at time of animal consumption per unit initial concentration of carbon-14 in water (pCi/kg wet-weight forage per pCi/L)

C_{wfCd} = concentration factor for carbon-14 in soil at the time of animal consumption of soil per unit initial concentration of carbon-14 in water (pCi/kg dry-weight soil per pCi/L)

C_{wgCc} = concentration factor for carbon-14 in stored grain plant g at time of animal consumption per unit initial concentration of carbon-14 in water (pCi/kg wet-weight grain per pCi/L)

C_{whCc} = concentration factor for carbon-14 in stored hay plant h at time of animal consumption per unit initial concentration of carbon-14 in water (pCi/kg wet-weight hay per pCi/L water)

C_{wwCc} = concentration factor for carbon-14 in water per unit initial concentration in water (added for clarity) (pCi/L per pCi/L)

x_w = fraction of animal water intake that is contaminated (dimensionless)

and other terms are as previously defined.

C.3 Special Parameters for the Carbon-14 Model for Crops and Animal Products

The model for carbon-14 uses several special parameters for which values are provided in Table C.1.

Table C.1 Carbon model parameter values*

Parameter description		Value
Fraction of animal product that is carbon:		
Beef		0.24
Poultry		0.20
Milk		0.07
Eggs		0.15
Fraction of animal feeds that is carbon:		
Beef	Forage	0.09
	Stored hay	0.09
	Stored grain	0.4
Poultry	Forage	0.09
	Stored hay	0.09
	Stored grain	0.4
Milk	Forage	0.09
	Stored hay	0.09
	Stored grain	0.4
Eggs	Forage	0.09
	Stored hay	0.09
	Stored grain	0.4
Fraction of soil that is carbon:		0.03

*Values taken from Napier et al. (1988).

C.4 References

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Appendix D

Tritium Agricultural Pathway Model

Appendix D

Tritium Agricultural Pathway Model

Tritium is a radioactive form of hydrogen with a half-life of 12.43 years. It decays to helium-3 by emission of a low-energy beta particle. Tritium uptake by man can occur by exposure to air, water, or food. Numerous research studies have investigated the environmental and pathway modeling aspects of tritium, including those by Moghissi and Carter (1973), National Council on Radiation Protection and Measurements (1979), Murphy (1986 and 1990), Johnson et al. (1988), Killough and Kocher (1988), Diabate and Strack (1990), Neil (1990), and Straume (1991). For the scenarios used in this study, a special model is used to evaluate the transfer of tritium in food chains. The concentration of tritium in each food type is assumed to have the same specific activity as the contaminating medium. This assumption is approximately valid for situations involving continuous replenishment of tritium in the medium and represents a conservative approximation for residual radioactive material in soil.

D.1 Transfer of Tritium from Soil to Plants and Animal Products

When soil is contaminated with residual tritium and no tritium from air and water is continually added to the soil, the contamination would be expected to rapidly escape from the soil or plants that had taken up this tritium. This analysis, however, conservatively assumes that the soil tritium is retained and remains available for plant uptake over time. The transfer of tritium from soil to plants is evaluated using a specific activity model for root uptake. Resuspension of soil onto plants is not considered because the specific activity model predicts plant concentrations about two orders of magnitude greater than the resuspension contribution. Also, tritium is not normally bound tightly to soil and would be expected to escape rapidly from suspended particles.

The estimation of concentration in plants from root uptake of tritium in soil assumes equilibrium between tritium in soil moisture and the plant:

$$C_{svHh} = 9\ f_{Hv}\ C_{sH}\ SA_{svH}\ 1000 / \left[S_H\ C_{sH}\right] \qquad (D.1)$$

where C_{svHh} = concentration factor for tritium in food type v from unit initial concentration of tritium in soil (pCi/kg wet-weight plant per pCi/g dry-weight soil)

f_{Hv} = fraction of hydrogen in total vegetation (kg hydrogen in plant/kg wet-weight plant)

C_{sH} = initial concentration of tritium in soil (pCi/g)

SA_{svH} = specific activity equivalence of the soil and plant (pCi/kg hydrogen in plant per pCi/kg hydrogen in soil)

S_H = moisture content of soil (kg water/kg soil)

9 = conversion from soil water to soil hydrogen based on molecular components of water (kg water in soil/kg hydrogen in soil)

1000 = units conversion factor (g/kg).

Because the half-life of tritium is long compared to the time periods considered (1 year or less), it is not necessary to model the decay of tritium concentration in plants. The partial pathway transfer factor (PPTF) for tritium in soil is evaluated as the product of the time period times the average concentration:

$$PPTF_{vsH} = C_{svHh}\, t_{cv} / 365.25 \qquad (D.2)$$

where $PPTF_{vsH}$ = partial pathway transfer factor for tritium in crop type v, per unit initial concentration of tritium in soil (pCi•y/kg wet-weight plant per pCi/g dry-weight soil for a year of residential scenario)

C_{svHh} = concentration factor for tritium in crop type v from root uptake at time of harvest for unit initial concentration of tritium in soil (pCi/kg wet-weight plant per pCi/g dry-weight soil)

t_{cv} = time period over which the crop is consumed (d for a year of residential scenario)

365.25 = unit conversion factor (d/y).

The model for tritium concentration in animal products from soil contamination is based on the assumption that the specific activity of the tritium in the animal product is equal to the specific activity of the total animal intake. For tritium, the total intake results from the consumption of contaminated fresh forage, stored feed, and soil. The total hydrogen intake considers the hydrogen contained in the fresh forage, stored feed, soil, and uncontaminated water. This is expressed as follows:

[pCi tritium/kg hydrogen in animal product] = [pCi tritium intake in fresh forage, stored feed, and soil]/[kg hydrogen intake in fresh forage, stored feed, and water] (D.3)

The forage, stored grain, and stored hay tritium concentrations are evaluated by Equation (D.1) with subscripts v and h replaced by subscripts f (g or h) and c, respectively. The ingestion of soil by the animal during the grazing period is included.

The concentration of tritium in animal products is estimated for soil sources as follows. Again, decay is not considered because of the long half-life for tritium:

$$PPTF_{asH} = f_{Ha}\left[\left(Q_f\, x_f\, C_{sfHc}\, t_{ff} + Q_g\, x_g\, C_{sgHc}\, t_{fg} + Q_h\, x_h\, C_{shHc}\, t_{fh} + 1000\, Q_f\, x_f\, Q_d\, W_f\, t_{ff}\, C_{sH}/C_{sH}\right)\right] t_{ca}\, SA_{TaH}/\left[\left(f_{Hf}\, Q_f\, t_{ff} + f_{Hd}\, Q_d\, W_f\, Q_f\, t_{ff} + f_{Hg}\, Q_g\, t_{fg} + f_{Hh}\, Q_h\, t_{fh} + Q_w\, t_{fw}/9\right) 365.25\right] \quad (D.4)$$

where $PPTF_{asH}$ = partial pathway transfer factor for animal product type a for tritium, per unit initial concentration of tritium in soil (pCi•y/kg wet-weight animal product per pCi•y/g for a year of residential scenario)

f_{Hd} = fraction of hydrogen in soil d (kg hydrogen/ kg dry-weight soil)

f_{Hf} = fraction of hydrogen in fresh forage f (kg hydrogen/kg wet-weight forage)

f_{Ha} = fraction of hydrogen in animal product a (kg hydrogen/kg wet-weight animal product)

f_{Hg} = fraction of hydrogen in stored grain g (kg hydrogen/kg wet-weight grain)

f_{Hh} = fraction of hydrogen in stored hay h (kg hydrogen/kg wet-weight hay)

Q_d = fraction of forage intake that is soil (kg dry-weight soil/kg dry-weight forage)

Q_f = consumption rate of fresh forage by the animal (kg wet-weight forage/d)

Q_g = consumption rate of stored grain by the animal (kg wet-weight grain/d)

Q_h = consumption rate of stored hay by the animal (kg wet-weight hay/d)

Q_w = consumption rate of water by the animal (kg/d)

W_f = factor for conversion of forage plant mass from a dry-weight to wet-weight basis (kg dry-weight forage/kg wet-weight forage)

9 = conversion factor for environmental water to hydrogen based on the molecular components of water (kg water/kg hydrogen)

C_{sfHc} = concentration factor for tritium in fresh forage plant f at time of consumption by animal, per unit initial concentration of tritium in soil (pCi/kg wet-weight forage per pCi/g dry-weight soil)

C_{sgHc} = concentration factor for tritium in stored grain plant g at time of consumption by animal, per unit initial concentration of tritium in soil (pCi/kg wet-weight grain per pCi/g dry-weight soil)

C_{shHc} = concentration factor for tritium in stored hay plant h at time of consumption by animal, per unit initial concentration of tritium in soil (pCi/kg wet-weight hay per pCi/g dry-weight soil)

t_{ff} = time period over which the animal is fed fresh forage (d)

t_{fg} = time period over which the animal is fed stored grain (d)

t_{fh} = time period over which the animal is fed stored hay (d)

t_{ca} = time period over which the animal product is consumed by humans (d for a year of residential scenario)

t_{fw} = time period over which the animal is fed water (d)

SA_{TaH} = specific activity equivalence of animal product type a and the specific activity of the total tritium and hydrogen intakes (pCi tritium/kg hydrogen in animal product per pCi tritium intake/total hydrogen intake)

x_f = fraction of animal is intake of forage that is contaminated (dimensionless)

x_g = fraction of animal is intake of stored grain that is contaminated (dimensionless)

x_h = fraction of animal is intake of stored hay that is contaminated (dimensionless)

1000 = unit conversion factor (g/kg).

D.2 Transfer of Tritium from Irrigation Water to Plants and Animal Products

The concentration of tritium in plants from contamination by irrigation with ground water is evaluated based on equilibrium between water and the plant's moisture concentration. For a unit initial tritium concentration in water (pCi/L) and for unit density of water (1 kg/L), the plant concentration is evaluated as follows:

$$C_{wvHh} = 9\ f_{Hv}\ C_{wH}\ SA_{wvH}/C_{wH} \qquad (D.5)$$

where C_{wvHh} = concentration factor for tritium in food type v at harvest from unit average concentration of tritium in water (pCi/kg wet-weight plant per pCi/L water)

C_{wH} = average concentration of tritium in water (pCi/L water)

f_{Hv} = fraction of hydrogen in total vegetation (kg hydrogen/kg wet-weight plant)

SA_{wvH} = specific activity equivalence of plant type v and tritium in water (pCi tritium/kg hydrogen in wet-weight plant per pCi tritium/kg hydrogen in water)

9 = conversion from environmental water to hydrogen based on molecular components of water (kg water/kg hydrogen).

The partial pathway transfer factor for food crops for tritium in water is evaluated using Equation (D.2), with the subscript w replacing subscript s:

$$PPTF_{vwH} = C_{wvHh}\, t_{cv} / 365.25 \quad \text{(D.6)}$$

where $PPTF_{vwH}$ = partial pathway transfer factor for tritium in food type v for irrigation with contaminated water, per unit average concentration of tritium in water (pCi•y/kg wet-weight plant per pCi/L water for a year of residential scenario)

C_{wvHh} = concentration factor for tritium in crop type v from root uptake at time of harvest, for unit average concentration of tritium in water (pCi/kg wet-weight plant per pCi/L water)

t_{cv} = time period over which food type v is consumed (d for a year of residential scenario)

365.25 = unit conversion factor (d/y).

The partial pathway transfer factor for tritium from water to animal products is based on tritium concentration in animal feed, evaluated by Equation (D.5) for forage crops and stored hay and grain crops. The animals are also assumed to drink contaminated water and ingest contaminated soil. The partial pathway transfer factors are calculated as follows:

$$\begin{aligned} PTF_{awH} = \Big[f_{Ha} \Big(& Q_f\, x_f\, C_{wfHc}\, t_{ff} + Q_g\, x_g\, C_{wgHc}\, t_{fg} + Q_h\, x_h\, C_{whHc}\, t_{fh} + Q_d\, W_f\, Q_f\, x_f\, C_{wfHd}\, t_{ff} \\ & + Q_w\, x_w\, C_{wwHc}\, t_{fw} \Big)\, t_{ca}\, SA_{TaH} \Big] / \Big(f_{Hf}\, Q_f\, t_{ff} + f_{Hg}\, Q_g\, t_{fg} \\ & + f_{Hh}\, Q_h\, t_{fh} + f_{Hd}\, Q_d\, W_f\, Q_f\, t_{ff} + Q_w\, t_{fw}/9 \Big)\, 365.25 \end{aligned} \quad \text{(D.7)}$$

where $PPTF_{awH}$ = partial pathway transfer factor for animal product type a for tritium, for unit average concentration of tritium in water (pCi•y/kg wet-weight animal product per pCi/L water for a year of residential scenario)

C_{wfHc} = concentration factor for tritium in fresh forage plant f at time of animal consumption, from unit average concentration of tritium in water (pCi/kg wet-weight forage per pCi/L water)

C_{wsHc} = concentration factor for tritium in stored feed plant s at time of animal consumption, from unit average concentration of tritium in water (pCi/kg wet-weight stored feed per pCi/L water)

C_{wwHc} = concentration factor for tritium in water per unit average concentration of tritium in water (added for clarity) (pCi/L per pCi/L)

C_{wfHd} = concentration factor for tritium in soil at time of animal consumption of soil per unit average concentration of tritium in water (pCi/kg dry-weight soil per pCi/L water)

SA_{TaH} = specific activity equivalence factor for tritium in animal product a (pCi tritium/kg hydrogen in animal product per total pCi tritium in fresh forage, stored feed, soil, and water/kg hydrogen in fresh forage, stored feed, soil, and water)

x_w = fraction of animal water intake that is contaminated (dimensionless)

and other terms are as previously defined. The concentration factor for tritium in soil, C_{wfHd}, is evaluated from the total deposition of tritium to soil from irrigation. The deposition rate is evaluated as per Equation (5.58). For tritium, the expression is written as follows:

$$R_{wsHf} = IR / P_s \left[C_{wH} / C_{wH} \right] \quad (D.8)$$

where R_{wsHf} = deposition rate of tritium from irrigation water to soil during the forage-feeding period per unit activity of tritium in irrigation water (pCi/d•kg dry-weight soil per pCi/L water)

IR = annual average application rate of irrigation water ($L/m^2 \cdot d$)

P_s = areal soil density (kg dry-weight soil/m^2)

C_{wH} = average concentration of tritium in water over the current 1-year period (pCi/L).

The average concentration in soil is evaluated as the deposition, accumulation and, time-integral over the forage-feeding period, divided by the forage-feeding period. Because tritium has a relatively long half-life, the average soil concentration factor can be expressed as follows

$$C_{wfHd} = R_{wsHf} \, t_{ff} / 2 \quad (D.9)$$

where terms are as previously defined.

D.3 Special Parameters for the Tritium Model for Crops and Animal Products

The tritium model for agricultural pathway transfer factors uses several special parameters. Values for these parameters were taken from Napier et al. (1988) and are given in Table D.1.

Table D.1 Tritium agricultural model parameter values*

Parameter Description		Value
Fraction of food plant that is hydrogen:		
Leafy vegetables		0.1
Other vegetables		0.1
Fruit		0.1
Grain		0.068
Fraction of animal product that is hydrogen:		
Beef		0.10
Poultry		0.10
Milk		0.11
Eggs		0.11
Fraction of animal feeds that is hydrogen:		
Beef	Forage	0.1
	Stored hay	0.1
	Stored grain	0.068
Poultry	Forage	0.1
	Stored hay	0.1
	Stored grain	0.068
Milk	Forage	0.1
	Stored hay	0.1
	Stored grain	0.068
Eggs	Forage	0.1
	Stored hay	0.1
	Stored grain	0.068
Fraction of soil that is hydrogen:		0.011**
Soil moisture content (kg/kg):		0.1

*From Napier et al. (1988).
**Evaluated as soil moisture content divided by 9.

D.4 References

Diabate, S., and S. Strack. 1990. *Doses Due to Tritium Releases by NET-Data Base and Relevant Parameters on Biological Tritium Behavior.* KfK4713, Kernforschungszentrum Karlsruhe, GmbH, Karlsruhe, Germany.

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Appendix E

Supplemental Data

Appendix E

Supplemental Data

This appendix contains supplemental data needed in the calculation of annual total effective dose equivalents (TEDEs) for the residual radioactive contamination scenarios defined in this study. The tables provided in this appendix are shown in a computer-readable form, anticipating their direct use in user-friendly software implementing the scenario/pathway analysis. The numbers of significant figures shown in each table were obtained from primary references and are included for completeness.

E.1 Contents and Units of Tables

Table E.1 contains radioactive decay data and decay-chain specifications for the listing of radionuclides considered in this study. As described in Section 6.1.2, the radioactive decay database contains information taken directly from ICRP Publication 38 (ICRP 1983). The database contains a data set for each radionuclide or chain, except for natural thorium or natural uranium, for which dose factors are calculated from the radionuclides in the decay chain. The entries are organized by increasing atomic number and by decay chain. Within each chain, members follow according to their decay sequence. Progeny radionuclides are treated as implicit or explicit, as defined in Section 6.1.1. The columns in Table E.1 include listings for 1) parent radionuclide, 2) progeny radionuclides in the chain, 3) radioactive half-life (in days), 4) position of each radionuclide in the chain, 5) branching information for the first parent of each radionuclide (index and fraction), 6) branching information for the second parent, if any, of each radionuclide (index and fraction), and 7) atomic number.

Tables E.2 through E.5 contain the standardized databases of external and internal effective dose equivalent factors, committed effective dose conversion factors, and the organ dose equivalent factors used in this generic screening analysis. These factors are obtained from recent Federal Guidance published by the EPA, implementing the recommendations of the ICRP (Eckerman, Wolbarst, and Richardson 1988; Eckerman and Ryman 1992). Entries are included for each parent radionuclide with implicit progeny immediately following the parent entry. Implicit progency are signified by an entry showing in the second column of each table.

Table E.2 lists the internal committed effective dose equivalent (CEDE) and the external effective dose equivalent factors. The columns in Table E.2 include listings for 1) radionuclide, 2) implicit progeny fraction, 3) internal committed effective dose equivalent for ingestion (Sv/Bq), 4) internal CEDE for inhalation (Sv/Bq), and 5) external effective dose equivalents for surface sources (Sv/d per Bq/m^2) and volume sources with 15-cm thickness (Sv/d per Bq/m^3). The implicit progeny fraction is the parameter F_j used in Equation (6.7) to calculate combined dose factors for parent radionuclides with implicit (short-lived) progeny.

Tables E.3 through E.5 contain ingestion organ dose equivalent factors for use in the drinking water scenario. Each table contains columns showing the radionuclide, implicit progeny fraction, and organ dose equivalent factors in units of Sv per Bq ingested. Table E.3 includes factors for adrenals, urinary bladder wall (Bld Wall), bone surface (B Surface), brain, breast, stomach wall (S Wall), and small intestine wall (SI Wall). Table E.4 includes factors for upper large intestine wall (ULI Wall), lower large intestine wall (LLI Wall), kidneys, liver, lungs, ovaries, and pancreas. Table E.5 includes factors for red bone marrow (R Marrow), skin, spleen, testes, thymus, thyroid, and uterus.

Table E.6 lists by radionuclide the inhalation translocation class and the gastrointestinal (GI) tract uptake fractions (f_1) used in this study. In most cases, the solubility class selection will maximize the potential inhalation dose. For plutonium, the solubility class represents the most common chemical form that will likely be encountered in environmental situations. For the other radionuclides, the translocation classes and GI uptake fractions are defined for the combination resulting in the highest dose.

E.2 References

Eckerman, K. F., and J. C. Ryman. 1992. *Dose Coefficients for External Exposure to Radionuclides Distributed in Air, Water, and Soil.* Federal Guidance Report No. 12, U.S. Environmental Protection Agency, Washington, D.C.

Eckerman, K. F., A. B. Wolbarst, and A. C. B. Richardson. 1988. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion.* Federal Guidance Report No. 11, EPA-520/1-88-020, U.S. Environmental Protection Agency, Washington, D.C.

International Commission on Radiation Protection (ICRP). 1983. *Radionuclide Transformations - Energy and Intensity of Emissions.* ICRP Publication 38, vol. 11-13, Pergamon Press, New York.

Table E.1 Radioactive decay data and decay chain specifications

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information: First parent Index	First parent Fraction	Second parent Index	Second parent Fraction	Atomic Number**
^{3}H		4.51E+03	1					1
^{10}Be		5.84E+08	1					4
^{14}C		2.09E+06	1					6
^{18}F		7.62E-02	1					9
^{22}Na		9.50E+02	1					11
^{24}Na		6.25E-01	1					11
^{32}P		1.43E+01	1					15
^{33}P		2.54E+01	1					15
^{35}S		8.74E+01	1					16
^{36}Cl		1.10E+08	1					17
^{40}K		4.68E+11	1					19
^{41}Ca		5.11E+07	1					20
^{45}Ca		1.63E+02	1					20
^{46}Sc		8.38E+01	1					21
^{51}Cr		2.77E+01	1					24
^{54}Mn		3.13E+02	1					25
^{56}Mn		1.07E-01	1					25
^{55}Fe		9.86E+02	1					26
^{59}Fe		4.45E+01	1					26
^{57}Co		2.71E+02	1					27
^{58}Co		7.08E+01	1					27
^{60}Co		1.93E+03	1					27
^{59}Ni		2.74E+07	1					28
^{63}Ni		3.51E+04	1					28
^{65}Ni		1.05E-01	1					28
^{64}Cu		5.29E-01	1					29

Table E.1 Radioactive decay data and decay chain specifications (Continued)

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information: First parent Index	First parent Fraction	Second parent Index	Second parent Fraction	Atomic Number**
^{65}Zn		2.44E+02	1					30
^{69m}Zn		5.73E-01	1					30
^{69}Zn				1	0.9997			
^{69}Zn		3.96E-02	1					30
^{76}As		1.10E+00	1					33
^{75}Se		1.20E+02	1					34
^{79}Se		2.37E+07	1					34
^{82}Br		1.47E+00	1					35
^{83}Br		9.96E-02	1					35
	^{83m}Kr			1	1.0000			
^{84}Br		2.21E-02	1					35
^{86}Rb		1.87E+01	1					37
^{88}Rb		1.24E-02	1					37
^{89}Rb		1.06E-02	1					37
	^{89}Sr	5.05E+01	2	1	1.0000	0	0.0000	38
^{85}Sr		6.48E+01	1					38
^{89}Sr		5.05E+01	1					38
^{90}Sr		1.06E+04	1					38
	^{90}Y	2.67E+00	2	1	1.0000	0	0.0000	39
^{91}Sr		3.96E-01	1					38
	^{91m}Y			1	0.5780			
^{91}Y		5.85E+01	2	1	1.0000	0	0.0000	39
^{90}Y		2.67E+00	1					39
^{91m}Y		3.45E-02	1					39
	^{91}Y	5.85E+01	2	1	1.0000	0	0.0000	39
^{91}Y		5.85E+01	1					39
^{92}Y		1.48E-01	1					39
^{93}Y		4.21E-01	1					39
	^{93}Zr	5.59E+08	2	1	1.0000	0	0.0000	40
	^{93m}Nb	4.97E+03	3	2	1.0000	0	0.0000	41
^{93}Zr		5.59E+08	1					40
	^{93m}Nb	4.97E+03	2	1	1.0000	0	0.0000	41
$^{93}Zr+C$		(Same data as for named radionuclide)						
^{95}Zr		6.40E+01	1					40
	^{95m}Nb	3.61E+00	2	1	0.0070	0	0.0000	41
	^{95}Nb	3.52E+01	3	2	1.0000	1	0.9930	41

Table E.1 Radioactive decay data and decay chain specifications (Continued)

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information				Atomic Number**
				First parent		Second parent		
				Index	Fraction	Index	Fraction	
^{97}Zr		7.04E-01	1					40
	^{97m}Nb			1	0.9470			
	^{97}Nb			1	0.0530			
^{93m}Nb		4.97E+03	1					41
^{94}Nb		7.41E+06	1					41
^{95m}Nb		3.61E+00	1					41
	^{95}Nb	3.52E+01	2	1	1.0000	0	0.0000	41
^{95}Nb		3.52E+01	1					41
^{97m}Nb		6.94E-04	1					41
	^{97}Nb	5.01E-02	2	1	1.0000	0	0.0000	41
^{97}Nb		5.01E-02	1					41
^{93}Mo		1.28E+06	1					42
	^{93m}Nb	4.97E+03	2	1	1.0000	0	0.0000	41
^{99}Mo		2.75E+00	1					42
	^{99m}Tc			1	0.8760			
	^{99}Tc	7.78E+07	2	1	1.0000	0	0.0000	43
^{99m}Tc		2.51E-01	1					43
	^{99}Tc	7.78E+07	2	1	1.0000	0	0.0000	43
^{99}Tc		7.78E+07	1					43
^{101}Tc		9.86E-03	1					43
^{103}Ru		3.93E+01	1					44
	^{103m}Rh	3.90E-02	2	1	0.9970	0	0.0000	45
^{105}Ru		1.85E-01	1					44
	^{105}Rh	1.47E+00	2	1	1.0000	0	0.0000	45
^{106}Ru		3.68E+02	1					44
	^{106}Rh			1	1.0000			
^{103m}Rh		3.90E-02	1					45
^{105}Rh		1.47E+00	1					45
^{103}Pd		1.70E+01	1					46
	^{103m}Rh			1	0.9997			
^{107}Pd		2.37E+09	1					46
^{109}Pd		5.59E-01	1					46
^{110m}Ag		2.50E+02	1					47
	^{110}Ag			1	0.0133			
^{111}Ag		7.45E+00	1					47
^{109}Cd		4.64E+02	1					48

Table E.1 Radioactive decay data and decay chain specifications (Continued)

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information: First parent Index	First parent Fraction	Second parent Index	Second parent Fraction	Atomic Number**
^{113m}Cd		4.97E+03	1					48
^{115m}Cd		4.46E+01	1					48
^{115}Cd		2.23E+00	1					48
	^{115m}In			1	1.0000			
^{111}In		2.83E+00	1					49
^{114m}In		4.95E+01	1					49
	^{114}In			1	0.9570			
^{115m}In		1.87E-01	1					49
^{117m}Sn		1.36E+01	1					50
^{119m}Sn		2.93E+02	1					50
^{121m}Sn		2.01E+04	1					50
	^{121}Sn	1.13E+00	2	1	0.7760	0	0.0000	50
^{121}Sn		1.13E+00	1					50
^{123}Sn		1.29E+02	1					50
^{125}Sn		9.64E+00	1					50
	^{125}Sb	1.01E+03	2	1	1.0000	0	0.0000	51
	^{125m}Te	5.80E+01	3	2	0.2280	0	0.0000	52
^{126}Sn		3.65E+07	1					50
^{126m}Sb				1	1.0000			
	^{126}Sb	1.24E+01	2	1	0.1400	0	0.0000	51
^{126}Sn+C		(Same data as for named radionuclide)						
^{124}Sb		6.02E+01	1					51
^{125}Sb		1.01E+03	1					51
	^{125m}Te	5.80E+01	2	1	0.2280	0	0.0000	52
^{126m}Sb		1.32E-02	1					51
	^{126}Sb	1.24E+01	2	1	0.1400	0	0.0000	51
^{126}Sb		1.24E+01	1					51
^{127}Sb		3.85E+00	1					51
	^{127m}Te	1.09E+02	2	1	0.1760	0	0.0000	52
	^{127}Te	3.90E-01	3	2	0.9760	1	0.8240	52
^{123m}Te		1.20E+02	1					52
^{125m}Te		5.80E+01	1					52
^{127m}Te		1.09E+02	1					52
	^{127}Te	3.90E-01	2	1	0.9760	0	0.0000	52
^{127}Te		3.90E-01	1					52
^{129m}Te		3.36E+01	1					52
	^{129}Te			1	0.6500			
	^{129}I	5.73E+09	2	1	1.0000	0	0.0000	53

Table E.1 Radioactive decay data and decay chain specifications (Continued)

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information				Atomic Number**
				First parent		Second parent		
				Index	Fraction	Index	Fraction	
^{129}Te		4.83E-02	1					52
	^{129}I	5.73E+09	2	1	1.0000	0	0.0000	53
^{131m}Te		1.25E+00	1					52
	^{131}Te			1	0.2220			
	^{131}I	8.04E+00	2	1	1.0000	0	0.0000	53
^{131}Te		1.74E-02	1					52
	^{131}I	8.04E+00	2	1	1.0000	0	0.0000	53
^{132}Te		3.26E+00	1					52
	^{132}I			1	1.0000			
^{133m}Te		3.85E-02	1					52
	^{133}Te			1	0.1300			
	^{133}I	8.67E-01	2	1	1.0000	0	0.0000	53
^{133}Te		8.65E-03	1					52
	^{133}I	8.67E-01	2	1	1.0000	0	0.0000	53
^{134}Te		2.90E-02	1					52
	^{134}I			1	1.0000			
^{125}I		6.01E+01	1					53
^{129}I		5.73E+09	1					53
^{130}I		5.15E-01	1					53
^{131}I		8.04E+00	1					53
^{132}I		9.58E-02	1					53
^{133}I		8.67E-01	1					53
^{134}I		3.65E-02	1					53
^{135}I		2.75E-01	1					53
	^{135m}Xe			1	0.1540			
^{134m}Cs		1.21E-01	1					55
	^{134}Cs	7.53E+02	2	1	1.0000	0	0.0000	55
^{134}Cs		7.53E+02	1					55
^{135}Cs		8.40E+08	1					55
^{136}Cs		1.31E+01	1					55
^{137}Cs		1.10E+04	1					55
	^{137m}Ba			1	0.9460			
^{138}Cs		2.24E-02	1					55
^{139}Ba		5.74E-02	1					56
^{140}Ba		1.27E+01	1					56
	^{140}La	1.68E+00	2	1	1.0000	0	0.0000	57
^{141}Ba		1.27E-02	1					56
	^{141}La	1.64E-01	2	1	1.0000	0	0.0000	57
	^{141}Ce	3.25E+01	3	2	1.0000	0	0.0000	58

Table E.1 Radioactive decay data and decay chain specifications (Continued)

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information				Atomic Number**
				First parent		Second parent		
				Index	Fraction	Index	Fraction	
^{142}Ba		7.36E-03	1					56
	^{142}La	6.42E-02	2	1	1.0000	0	0.0000	57
^{140}La		1.68E+00	1					57
^{141}La		1.64E-01	1					57
	^{141}Ce	3.25E+01	2	1	1.0000	0	0.0000	58
^{142}La		6.42E-02	1					57
^{141}Ce		3.25E+01	1					58
^{143}Ce		1.38E+00	1					58
	^{143}Pr	1.36E+01	2	1	1.0000	0	0.0000	59
^{144}Ce		2.84E+02	1					58
	^{144m}Pr			1	0.0178			
	^{144}Pr			1	1.0000			
^{143}Pr		1.36E+01	1					59
^{144}Pr		1.20E-02	1					59
^{147}Nd		1.10E+01	1					60
	^{147}Pm	9.58E+02	2	1	1.0000	0	0.0000	61
^{147}Pm		9.58E+02	1					61
^{148m}Pm		4.13E+01	1					61
	^{148}Pm	5.37E+00	2	1	0.0460	0	0.0000	61
^{148}Pm		5.37E+00	1					61
^{149}Pm		2.21E+00	1					61
^{151}Pm		1.18E+00	1					61
	^{151}Sm	3.29E+04	2	1	1.0000	0	0.0000	62
^{147}Sm		3.87E+13	1					62
^{151}Sm		3.29E+04	1					62
^{153}Sm		1.95E+00	1					62
^{152}Eu		4.87E+03	1					63
^{154}Eu		3.21E+03	1					63
^{155}Eu		1.81E+03	1					63
^{156}Eu		1.52E+01	1					63
^{153}Gd		2.42E+02	1					64
^{160}Tb		7.23E+01	1					65
^{166m}Ho		4.38E+05	1					67

Table E.1 Radioactive decay data and decay chain specifications (Continued)

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information				Atomic Number**
				First parent		Second parent		
				Index	Fraction	Index	Fraction	
^{181}W		1.21E+02	1					74
^{185}W		7.51E+01	1					74
^{187}W		9.96E-01	1					74
	^{187}Re	1.72E+13	2	1	1.0000	0	0.0000	75
^{187}Re		1.72E+13	1					75
^{185}Os		9.40E+01	1					76
^{191}Os		1.54E+01	1					76
^{192}Ir		7.40E+01	1					77
^{198}Au		2.70E+00	1					79
^{203}Hg		4.66E+01	1					80
^{210}Pb		8.15E+03	1					82
	^{210}Bi	5.01E+00	2	1	1.0000	0	0.0000	83
	^{210}Po	1.38E+02	3	2	1.0000	0	0.0000	84
^{212}Pb		4.43E-01	1					82
	^{212}Bi			1	1.0000			
	^{212}Po			1	0.6407			
	^{208}Tl			1	0.3593			
^{210}Bi		5.01E+00	1					83
	^{210}Po	1.38E+02	2	1	1.0000	0	0.0000	84
^{212}Bi		4.20E-02	1					83
	^{212}Po			1	0.6407			
	^{208}Tl			1	0.3593			
^{210}Po		1.38E+02	1					84
^{222}Rn		3.82E+00	1					86
	^{218}Po			1	1.0000			
	^{214}Pb			1	1.0000			
	^{214}Bi			1	1.0000			
	^{214}Po			1	0.9998			
	^{210}Pb	8.15E+03	2	1	1.0000	0	0.0000	82
	^{210}Bi	5.01E+00	3	2	1.0000	0	0.0000	83
	^{210}Po	1.38E+02	4	3	1.0000	0	0.0000	84

Table E.1 Radioactive decay data and decay chain specifications (Continued)

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information: First parent Index	First parent Fraction	Second parent Index	Second parent Fraction	Atomic Number**
^{223}Ra		1.14E+01	1					88
	^{219}Rn			1	1.0000			
	^{215}Po			1	1.0000			
	^{211}Pb			1	1.0000			
	^{211}Bi			1	1.0000			
	^{211}Po			1	0.0028			
	^{207}Tl			1	0.9972			
^{224}Ra		3.66E+00	1					88
	^{220}Rn			1	1.0000			
	^{216}Po			1	1.0000			
	^{212}Pb	4.43E-01	2	1	1.0000	0	0.0000	82
^{225}Ra		1.48E+01	1					88
	^{225}Ac	1.00E+01	2	1	1.0000	0	0.0000	89
^{226}Ra		5.84E+05	1					88
	^{222}Rn	3.82E+00	2	1	1.0000	0	0.0000	86
	^{210}Pb	8.15E+03	3	2	1.0000	0	0.0000	82
	^{210}Bi	5.01E+00	4	3	1.0000	0	0.0000	83
	^{210}Po	1.38E+02	5	4	1.0000	0	0.0000	84
$^{226}Ra+C$		(Same data as for named radionuclide)						
^{228}Ra		2.10E+03	1					88
	^{228}Ac			1	1.0000			
	^{228}Th	6.99E+02	2	1	1.0000	0	0.0000	90
	^{224}Ra	3.66E+00	3	2	1.0000	0	0.0000	88
	^{212}Pb	4.43E-01	4	3	1.0000	0	0.0000	82
^{225}Ac		1.00E+01	1					89
	^{221}Fr			1	1.0000			
	^{217}At			1	1.0000			
	^{213}Bi			1	1.0000			
	^{213}Po			1	0.9784			
	^{209}Tl			1	0.0216			
	^{209}Pb			1	1.0000			
^{227}Ac		7.95E+03	1					89
	^{223}Fr			1	0.0138			
	^{227}Th	1.87E+01	2	1	0.9862	0	0.0000	90
	^{223}Ra	1.14E+01	3	2	1.0000	1	0.0138	88
$^{227}Ac+C$		(Same data as for named radionuclide)						
^{228}Ac		2.55E-01	1					89
	^{228}Th	6.99E+02	2	1	1.0000	0	0.0000	90
	^{224}Ra	3.66E+00	3	2	1.0000	0	0.0000	88
	^{212}Pb	4.43E-01	4	3	1.0000	0	0.0000	82

Table E.1 Radioactive decay data and decay chain specifications (Continued)

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information: First parent Index	First parent Fraction	Second parent Index	Second parent Fraction	Atomic Number**
^{227}Th		1.87E+01	1					90
	^{223}Ra	1.14E+01	2	1	1.0000	0	0.0000	88
^{228}Th		6.99E+02	1					90
	^{224}Ra	3.66E+00	2	1	1.0000	0	0.0000	88
	^{212}Pb	4.43E-01	3	2	1.0000	0	0.0000	82
^{228}Th+C		(Same data as for named radionuclide)						
^{229}Th		2.68E+06	1					90
	^{225}Ra	1.48E+01	2	1	1.0000	0	0.0000	88
	^{225}Ac	1.00E+01	3	2	1.0000	0	0.0000	89
^{229}Th+C		(Same data as for named radionuclide)						
^{230}Th		2.81E+07	1					90
	^{226}Ra	5.84E+05	2	1	1.0000	0	0.0000	88
	^{222}Rn	3.82E+00	3	2	1.0000	0	0.0000	86
	^{210}Pb	8.15E+03	4	3	1.0000	0	0.0000	82
	^{210}Bi	5.01E+00	5	4	1.0000	0	0.0000	83
	^{210}Po	1.38E+02	6	5	1.0000	0	0.0000	84
^{230}Th+C		(Same data as for named radionuclide)						
^{231}Th		1.06E+00	1					90
	^{231}Pa	1.20E+07	2	1	1.0000	0	0.0000	91
	^{227}Ac	7.95E+03	3	2	1.0000	0	0.0000	89
	^{227}Th	1.87E+01	4	3	0.9862	0	0.0000	90
	^{223}Ra	1.14E+01	5	4	1.0000	0	0.0000	88
^{232}Th		5.13E+12	1					90
	^{228}Ra	2.10E+03	2	1	1.0000	0	0.0000	88
	^{228}Th	6.99E+02	3	2	1.0000	0	0.0000	90
	^{224}Ra	3.66E+00	4	3	1.0000	0	0.0000	88
	^{212}Pb	4.43E-01	5	4	1.0000	0	0.0000	82
^{232}Th+C		(Same data as for named radionuclide)						
^{234}Th		2.41E+01	1					90
	^{234m}Pa			1	0.9980			91
	^{234}Pa			1	0.0020			91
	^{234}U	8.93E+07	2	1	1.0000	0	0.0000	92
^{231}Pa		1.20E+07	1					91
	^{227}Ac	7.95E+03	2	1	1.0000	0	0.0000	89
	^{227}Th	1.87E+01	3	2	0.9862	0	0.0000	90
	^{223}Ra	1.14E+01	4	3	1.0000	0	0.0000	88
^{231}Pa+C		(Same data as for named radionuclide)						
^{233}Pa		2.70E+01	1					91
	^{233}U	5.79E+07	2	1	1.0000	0	0.0000	92
	^{229}Th	2.68E+06	3	2	1.0000	0	0.0000	90
	^{225}Ra	1.48E+01	4	3	1.0000	0	0.0000	88

Table E.1 Radioactive decay data and decay chain specifications (Continued)

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information: First parent Index	First parent Fraction	Second parent Index	Second parent Fraction	Atomic Number**
	^{225}Ac	1.00E+01	5	4	1.0000	0	0.0000	89
^{234}Pa		2.79E-01	1					91
^{232}U		2.63E+04	1					92
	^{228}Th	6.99E+02	2	1	1.0000	0	0.0000	90
	^{224}Ra	3.66E+00	3	2	1.0000	0	0.0000	88
	^{212}Pb	4.43E-01	4	3	1.0000	0	0.0000	82
^{232}U+C		(Same data as for named radionuclide)						
^{233}U		5.79E+07	1					92
	^{229}Th	2.68E+06	2	1	1.0000	0	0.0000	90
	^{225}Ra	1.48E+01	3	2	1.0000	0	0.0000	88
	^{225}Ac	1.00E+01	4	3	1.0000	0	0.0000	89
^{233}U+C		(Same data as for named radionuclide)						
^{234}U		8.93E+07	1					92
^{235}U		2.57E+11	1					92
	^{231}Th	1.06E+00	2	1	1.0000	0	0.0000	90
	^{231}Pa	1.20E+07	3	2	1.0000	0	0.0000	91
	^{227}Ac	7.95E+03	4	3	1.0000	0	0.0000	89
	^{227}Th	1.87E+01	5	4	0.9862	0	0.0000	90
	^{223}Ra	1.14E+01	6	5	1.0000	0	0.0000	88
^{235}U+C		(Same data as for named radionuclide)						
^{236}U		8.55E+09	1					92
^{237}U		6.75E+00	1					92
	^{237}Np	7.82E+08	2	1	1.0000	0	0.0000	93
	^{233}Pa	2.70E+01	3	2	1.0000	0	0.0000	91
^{238}U		1.63E+12	1					92
	^{234}Th	2.41E+01	2	1	1.0000	0	0.0000	90
	^{234}U	8.93E+07	3	2	1.0000	0	0.0000	92
	^{230}Th	2.81E+07	4	3	1.0000	0	0.0000	90
	^{226}Ra	5.84E+05	5	4	1.0000	0	0.0000	88
	^{222}Rn	3.82E+00	6	5	1.0000	0	0.0000	86
	^{210}Pb	8.15E+03	7	6	1.0000	0	0.0000	82
	^{210}Bi	5.01E+00	8	7	1.0000	0	0.0000	83
	^{210}Po	1.38E+02	9	8	1.0000	0	0.0000	84
^{238}U+C		(Same data as for named radionuclide)						
^{240}U		5.88E-01	1					92
	^{240m}Np			1	1.0000			
^{237}Np		7.82E+08	1					93
	^{233}Pa	2.70E+01	2	1	1.0000	0	0.0000	91
	^{233}U	5.79E+07	3	2	1.0000	0	0.0000	92
	^{229}Th	2.68E+06	4	3	1.0000	0	0.0000	90
	^{225}Ra	1.48E+01	5	4	1.0000	0	0.0000	88

Table E.1 Radioactive decay data and decay chain specifications (Continued)

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information				Atomic Number**
				First parent		Second parent		
				Index	Fraction	Index	Fraction	
	^{225}Ac	1.00E+01	6	5	1.0000	0	0.0000	89
^{237}Np+C		(Same data as for named radionuclide)						
^{238}Np		2.12E+00	1					93
^{239}Np		2.36E+00	1					93
^{236}Pu		1.04E+03	1					94
	^{232}U	2.63E+04	2	1	1.0000	0	0.0000	92
	^{228}Th	6.99E+02	3	2	1.0000	0	0.0000	90
	^{224}Ra	3.66E+00	4	3	1.0000	0	0.0000	88
	^{212}Pb	4.43E-01	5	4	1.0000	0	0.0000	82
^{237}Pu		4.53E+01	1					94
	^{237}Np	7.82E+08	2	1	1.0000	0	0.0000	93
	^{233}Pa	2.70E+01	3	2	1.0000	0	0.0000	91
^{238}Pu		3.20E+04	1					94
	^{234}U	8.93E+07	2	1	1.0000	0	0.0000	92
^{239}Pu		8.79E+06	1					94
^{240}Pu		2.39E+06	1					94
^{241}Pu		5.26E+03	1					94
	^{241}Am	1.58E+05	2	1	1.0000	0	0.0000	95
^{242}Pu		1.37E+08	1					94
^{243}Pu		2.07E-01	1					94
^{244}Pu		3.02E+10	1					94
	^{240}U	5.88E-01	2	1	0.9988	0	0.0000	92
	^{240}Pu	2.39E+06	3	2	1.0000	0	0.0000	94
^{241}Am		1.58E+05	1					95
^{242m}Am		5.55E+04	1					95
	^{242}Am	6.68E-01	2	1	0.9952	0	0.0000	95
	^{242}Cm	1.63E+02	3	2	0.8270	0	0.0000	96
	^{242}Pu	1.37E+08	4	2	0.1730	0	0.0000	94
	^{238}Np	2.12E+00	5	1	0.0048	0	0.0000	93
	^{238}Pu	3.20E+04	6	5	1.0000	3	1.0000	94
^{242}Am		6.68E-01	1					95
	^{242}Cm	1.63E+02	2	1	0.8270	0	0.0000	96
	^{242}Pu	1.37E+08	3	1	0.1730	0	0.0000	94
	^{238}Pu	3.20E+04	4	2	1.0000	0	0.0000	94
^{243}Am		2.70E+06	1					95
	^{239}Np	2.36E+00	2	1	1.0000	0	0.0000	93
	^{239}Pu	8.79E+06	3	2	1.0000	0	0.0000	94
^{242}Cm		1.63E+02	1					96
	^{238}Pu	3.20E+04	2	1	1.0000	0	0.0000	94
^{243}Cm		1.04E+04	1					96
	^{243}Am	2.70E+06	2	1	0.0024	0	0.0000	95

Table E.1 Radioactive decay data and decay chain specifications (Continued)

Parent radio-nuclide+	Progeny in chain	Half-life (d)*	Position in chain	Branching information				Atomic Number**
				First parent		Second parent		
				Index	Fraction	Index	Fraction	
	^{239}Np	2.36E+00	3	2	1.0000	0	0.0000	93
	^{239}Pu	8.79E+06	4	1	0.9976	3	1.0000	94
^{244}Cm		6.61E+03	1					96
	^{240}Pu	2.39E+06	2	1	1.0000	0	0.0000	94
^{245}Cm		3.10E+06	1					96
	^{241}Pu	5.26E+03	2	1	1.0000	0	0.0000	94
	^{241}Am	1.58E+05	3	2	1.0000	0	0.0000	95
^{246}Cm		1.73E+06	1					96
^{247}Cm		5.70E+09	1					96
	^{243}Pu			1	1.0000			
	^{243}Am	2.70E+06	2	1	1.0000	0	0.0000	95
	^{239}Np	2.36E+00	3	2	1.0000	0	0.0000	93
	^{239}Pu	8.79E+06	4	3	1.0000	0	0.0000	94
^{248}Cm		1.24E+08	1					96
^{252}Cf		9.64E+02	1					98
	^{248}Cm	1.24E+08	2	1	0.9691	0	0.0000	96

\+ Radionuclides with a "+C" representation use the same data as defined for the named radionuclide. The differences in the reported dose factors are due to differences in definition of initial activity for chain members. For the named radionuclide (without "+C") the progeny have zero initial activity. For the "+C" entries, the progeny have equilibrium initial activity.

* Values of radioactive half-life are given for all parent radionuclides and for all explicitly defined progeny. Blank entries signify that the radionuclide is short-lived and is considered to be an implicit progeny of the parent radionuclide.

** The atomic number is defined and used only for explicit radionuclides.

Table E.2 Internal committed effective dose equivalent and external effective dose equivalent factors

Radio-nuclide	Implicit progeny fraction	Ingestion (Sv/Bq)	Inhalation (Sv/Bq)	External	
				Surface (Sv/d per Bq/m^2)	15 cm* (Sv/d per Bq/m^3)
^{3}H		1.73E-11	1.73E-11	0.00E+00	0.00E+00
^{10}Be		1.26E-09	9.58E-08	3.56E-14	4.90E-16
^{14}C		5.64E-10	5.64E-10	1.39E-15	6.22E-18
^{18}F		3.31E-11	2.26E-11	8.73E-11	2.52E-12
^{22}Na		3.10E-09	2.07E-09	1.82E-10	5.45E-12
^{24}Na		3.84E-10	3.27E-10	3.12E-10	1.02E-11
^{32}P		2.37E-09	4.19E-09	2.51E-13	5.18E-15
^{33}P		2.48E-10	6.27E-10	3.85E-15	2.73E-17
^{35}S		1.98E-10	6.69E-10	1.45E-15	6.88E-18
^{36}Cl		8.18E-10	5.93E-09	5.81E-14	1.06E-15
^{40}K		5.02E-09	3.34E-09	1.26E-11	3.95E-13
^{41}Ca		3.44E-10	3.64E-10	0.00E+00	0.00E+00
^{45}Ca		8.55E-10	1.79E-09	3.98E-15	2.89E-17
^{46}Sc		1.73E-09	8.01E-09	1.66E-10	5.01E-12
^{51}Cr		3.98E-11	9.03E-11	2.66E-12	7.56E-14
^{54}Mn		7.48E-10	1.81E-09	7.01E-11	2.07E-12
^{56}Mn		2.64E-10	1.02E-10	1.36E-10	4.23E-12
^{55}Fe		1.64E-10	7.26E-10	0.00E+00	0.00E+00
^{59}Fe		1.81E-09	4.00E-09	9.71E-11	2.97E-12
^{57}Co		3.20E-10	2.45E-09	9.97E-12	2.29E-13
^{58}Co		9.68E-10	2.94E-09	8.20E-11	2.42E-12
^{60}Co		7.28E-09	5.91E-08	2.03E-10	6.26E-12
^{59}Ni		5.67E-11	7.31E-10	0.00E+00	0.00E+00
^{63}Ni		1.56E-10	1.70E-09	0.00E+00	0.00E+00
^{65}Ni		1.68E-10	9.32E-11	4.45E-11	1.38E-12
^{64}Cu		1.26E-10	7.48E-11	1.61E-11	4.67E-13
^{65}Zn		3.90E-09	5.51E-09	4.78E-11	1.45E-12
^{69m}Zn		3.55E-10	2.20E-10	3.56E-11	1.02E-12
^{69}Zn	0.9997	2.40E-11	1.06E-11	6.20E-14	1.02E-15
^{69}Zn		2.40E-11	1.06E-11	6.20E-14	1.02E-15
^{76}As		1.41E-09	1.01E-09	3.66E-11	1.08E-12
^{75}Se		2.60E-09	2.29E-09	3.26E-11	8.75E-13
^{79}Se		2.35E-09	2.66E-09	1.79E-15	8.60E-18
^{82}Br		4.62E-10	4.13E-10	2.20E-10	6.57E-12
^{83}Br		2.47E-11	2.41E-11	7.02E-13	1.95E-14
^{83m}Kr	1.0000	0.00E+00	0.00E+00	3.28E-14	1.40E-17
^{84}Br		4.91E-11	2.61E-11	1.38E-10	4.45E-12
^{86}Rb		2.53E-09	1.79E-09	8.04E-12	2.41E-13
^{88}Rb		4.71E-11	2.26E-11	5.14E-11	1.63E-12
^{89}Rb		2.65E-11	1.16E-11	1.65E-10	5.18E-12
^{85}Sr		5.34E-10	1.36E-09	4.32E-11	1.24E-12
^{89}Sr		2.50E-09	1.12E-08	1.96E-13	3.99E-15

Table E.2 Internal committed effective dose equivalent and external effective dose equivalent factors (Continued)

Radio-nuclide	Implicit progeny fraction	Ingestion (Sv/Bq)	Inhalation (Sv/Bq)	External	
				Surface (Sv/d per Bq/m^2)	15 cm* (Sv/d per Bq/m^3)
^{90}Sr		3.85E-08	3.51E-07	2.46E-14	3.21E-16
^{91}Sr		8.39E-10	4.49E-10	5.84E-11	1.74E-12
^{91m}Y	0.5780	1.12E-11	9.82E-12	4.52E-11	1.31E-12
^{90}Y		2.91E-09	2.28E-09	4.60E-13	1.03E-14
^{91m}Y		1.12E-11	9.82E-12	4.52E-11	1.31E-12
^{91}Y		2.57E-09	1.32E-08	4.95E-13	1.31E-14
^{92}Y		5.15E-10	2.11E-10	2.18E-11	6.54E-13
^{93}Y		1.23E-09	5.82E-10	7.87E-12	2.37E-13
^{93}Zr		4.48E-10	8.67E-08	0.00E+00	0.00E+00
^{95}Zr		1.02E-09	6.39E-09	6.24E-11	1.84E-12
^{97}Zr		2.28E-09	1.17E-09	1.50E-11	4.51E-13
^{97m}Nb	0.9470	0.00E+00	0.00E+00	6.15E-11	1.81E-12
^{97}Nb	0.0530	6.30E-11	2.24E-11	5.57E-11	1.63E-12
^{93m}Nb		1.41E-10	7.90E-09	8.11E-14	4.80E-17
^{94}Nb		1.93E-09	1.12E-07	1.32E-10	3.91E-12
^{95m}Nb		6.22E-10	6.59E-10	5.41E-12	1.41E-13
^{95}Nb		6.95E-10	1.57E-09	6.46E-11	1.90E-12
^{97m}Nb		0.00E+00	0.00E+00	6.15E-11	1.81E-12
^{97}Nb		6.30E-11	2.24E-11	5.57E-11	1.63E-12
^{93}Mo		3.64E-10	7.68E-09	4.61E-13	2.73E-16
^{99}Mo		1.36E-09	1.07E-09	1.27E-11	3.65E-13
^{99m}Tc	0.8760	1.68E-11	8.80E-12	1.04E-11	2.51E-13
^{99m}Tc		1.68E-11	8.80E-12	1.04E-11	2.51E-13
^{99}Tc		3.95E-10	2.25E-09	6.73E-15	5.79E-17
^{101}Tc		1.14E-11	4.84E-12	2.83E-11	8.03E-13
^{103}Ru		8.24E-10	2.42E-09	4.00E-11	1.15E-12
^{105}Ru		2.87E-10	1.23E-10	6.64E-11	1.94E-12
^{106}Ru		7.40E-09	1.29E-07	0.00E+00	0.00E+00
^{106}Rh	1.0000	0.00E+00	0.00E+00	1.83E-11	5.31E-13
^{103m}Rh		3.14E-12	1.38E-12	1.08E-13	1.13E-16
^{105}Rh		3.99E-10	2.58E-10	6.58E-12	1.86E-13
^{103}Pd		2.13E-10	4.24E-10	9.37E-13	1.15E-15
^{103m}Rh	.99974	3.14E-12	1.38E-12	1.08E-13	1.13E-16
^{107}Pd		4.04E-11	3.45E-09	0.00E+00	0.00E+00
^{109}Pd		5.87E-10	2.96E-10	9.69E-13	8.38E-15
^{110m}Ag		2.92E-09	2.17E-08	2.29E-10	6.85E-12
^{110}Ag	0.0133	0.00E+00	0.00E+00	3.30E-12	9.25E-14
^{111}Ag		1.37E-09	1.66E-09	2.31E-12	6.45E-14
^{109}Cd		3.55E-09	3.09E-08	1.94E-12	6.80E-15
^{113m}Cd		4.35E-08	4.13E-07	2.27E-14	2.95E-16
^{115m}Cd		4.37E-09	1.95E-08	2.02E-12	5.88E-14
^{115}Cd		1.54E-09	1.14E-09	1.99E-11	5.71E-13

Table E.2 Internal committed effective dose equivalent and external effective dose equivalent factors (Continued)

Radio-nuclide	Implicit progeny fraction	Ingestion (Sv/Bq)	Inhalation (Sv/Bq)	External	
				Surface (Sv/d per Bq/m^2)	15 cm* (Sv/d per Bq/m^3)
^{115m}In	1.0000	9.33E-11	3.59E-11	1.36E-11	3.69E-13
^{111}In		3.59E-10	2.27E-10	3.37E-11	8.73E-13
^{114m}In		4.61E-09	2.40E-08	7.90E-12	2.05E-13
^{114}In	0.9570	0.00E+00	0.00E+00	2.33E-13	6.85E-15
^{115m}In		9.33E-11	3.59E-11	1.36E-11	3.69E-13
^{117m}Sn		7.97E-10	1.17E-09	1.31E-11	2.97E-13
^{119m}Sn		3.76E-10	1.69E-09	9.01E-13	1.39E-15
^{121m}Sn		4.19E-10	3.11E-09	4.22E-13	9.11E-16
^{121}Sn		2.44E-10	1.38E-10	9.07E-15	9.02E-17
^{123}Sn		2.27E-09	8.79E-09	7.22E-13	2.02E-14
^{125}Sn		3.33E-09	4.18E-09	2.60E-11	7.88E-13
^{126}Sn		5.27E-09	2.69E-08	4.72E-12	6.82E-14
^{126m}Sb	1.0000	2.54E-11	9.17E-12	1.31E-10	3.83E-12
^{124}Sb		2.74E-09	6.80E-09	1.48E-10	4.54E-12
^{125}Sb		7.59E-10	3.30E-09	3.67E-11	1.02E-12
^{126m}Sb		2.54E-11	9.17E-12	1.31E-10	3.83E-12
^{126}Sb		2.89E-09	3.17E-09	2.40E-10	7.02E-12
^{127}Sb		1.95E-09	1.63E-09	5.84E-11	1.70E-12
^{123m}Te		1.53E-09	2.86E-09	1.23E-11	2.84E-13
^{125m}Te		9.92E-10	1.97E-09	3.12E-12	7.00E-15
^{127m}Te		2.23E-09	5.81E-09	9.73E-13	2.49E-15
^{127}Te		1.87E-10	8.60E-11	4.47E-13	1.22E-14
^{129m}Te		2.89E-09	6.47E-09	3.27E-12	7.58E-14
^{129}Te	0.6500	5.45E-11	2.42E-11	5.19E-12	1.38E-13
^{129}Te		5.45E-11	2.42E-11	5.19E-12	1.38E-13
^{131m}Te		2.46E-09	1.73E-09	1.18E-10	3.50E-12
^{131}Te	0.2220	2.44E-10	1.29E-10	3.54E-11	9.94E-13
^{131}Te		2.44E-10	1.29E-10	3.54E-11	9.94E-13
^{132}Te		2.54E-09	2.55E-09	1.97E-11	4.80E-13
^{132}I	1.0000	1.82E-10	1.03E-10	1.91E-10	5.67E-12
^{133m}Te		2.26E-10	1.17E-10	1.92E-10	5.72E-12
^{133}Te	0.1300	4.73E-11	2.49E-11	7.72E-11	2.30E-12
^{133}Te		4.73E-11	2.49E-11	7.72E-11	2.30E-12
^{134}Te		6.63E-11	3.44E-11	7.48E-11	2.12E-12
^{134}I	1.0000	6.66E-11	3.55E-11	2.18E-10	6.53E-12
^{125}I		1.04E-08	6.53E-09	3.69E-12	7.65E-15
^{129}I		7.46E-08	4.69E-08	2.23E-12	5.98E-15
^{130}I		1.28E-09	7.14E-10	1.81E-10	5.30E-12
^{131}I		1.44E-08	8.89E-09	3.24E-11	9.21E-13
^{132}I		1.82E-10	1.03E-10	1.91E-10	5.67E-12
^{133}I		2.80E-09	1.58E-09	5.15E-11	1.50E-12
^{134}I		6.66E-11	3.55E-11	2.18E-10	6.53E-12

Table E.2 Internal committed effective dose equivalent and external effective dose equivalent factors (Continued)

Radionuclide	Implicit progeny fraction	Ingestion (Sv/Bq)	Inhalation (Sv/Bq)	External	
				Surface (Sv/d per Bq/m^2)	15 cm* (Sv/d per Bq/m^3)
^{135}I		6.08E-10	3.32E-10	1.27E-10	3.94E-12
^{135m}Xe	0.1540	0.00E+00	0.00E+00	3.66E-11	1.05E-12
^{134m}Cs		1.33E-11	1.18E-11	2.24E-12	3.33E-14
^{134}Cs		1.98E-08	1.25E-08	1.31E-10	3.86E-12
^{135}Cs		1.91E-09	1.23E-09	2.87E-15	1.77E-17
^{136}Cs		3.04E-09	1.98E-09	1.80E-10	5.33E-12
^{137}Cs		1.35E-08	8.63E-09	2.46E-14	3.40E-16
^{137m}Ba	0.9460	0.00E+00	0.00E+00	5.06E-11	1.48E-12
^{138}Cs		5.25E-11	2.74E-11	1.89E-10	5.90E-12
^{139}Ba		1.08E-10	4.64E-11	3.96E-12	9.91E-14
^{140}Ba		2.56E-09	1.01E-09	1.56E-11	4.34E-13
^{141}Ba		5.65E-11	2.18E-11	7.04E-11	2.06E-12
^{142}Ba		3.01E-11	1.11E-11	8.68E-11	2.56E-12
^{140}La		2.28E-09	1.31E-09	1.86E-10	5.78E-12
^{141}La		3.74E-10	1.57E-10	3.92E-12	1.18E-13
^{142}La		1.79E-10	6.84E-11	2.12E-10	6.85E-12
^{141}Ce		7.83E-10	2.42E-09	6.37E-12	1.45E-13
^{143}Ce		1.23E-09	9.16E-10	2.41E-11	6.28E-13
^{144}Ce		5.68E-09	1.01E-07	1.75E-12	3.28E-14
^{144m}Pr	0.0178	0.00E+00	0.00E+00	1.13E-12	6.33E-15
^{144}Pr	1.0000	3.15E-11	1.17E-11	3.27E-12	9.71E-14
^{143}Pr		1.27E-09	2.19E-09	6.05E-14	9.90E-16
^{144}Pr		3.15E-11	1.17E-11	3.27E-12	9.71E-14
^{147}Nd		1.18E-09	1.85E-09	1.20E-11	2.84E-13
^{147}Pm		2.83E-10	1.06E-08	2.94E-15	2.30E-17
^{148m}Pm		2.07E-09	6.10E-09	1.69E-10	4.94E-12
^{148}Pm		2.94E-09	2.95E-09	4.73E-11	1.44E-12
^{149}Pm		1.07E-09	7.93E-10	9.80E-13	2.68E-14
^{151}Pm		8.09E-10	4.73E-10	2.72E-11	7.37E-13
^{147}Sm		5.01E-08	2.02E-05	0.00E+00	0.00E+00
^{151}Sm		1.05E-10	8.10E-09	4.34E-16	4.55E-19
^{153}Sm		8.07E-10	5.31E-10	5.37E-12	7.27E-14
^{152}Eu		1.75E-09	5.97E-08	9.53E-11	2.78E-12
^{154}Eu		2.58E-09	7.73E-08	1.02E-10	3.04E-12
^{155}Eu		4.13E-10	1.12E-08	5.10E-12	8.42E-14
^{156}Eu		2.48E-09	3.82E-09	1.07E-10	3.30E-12
^{153}Gd		3.17E-10	6.43E-09	9.13E-12	1.13E-13
^{160}Tb		1.82E-09	6.75E-09	9.32E-11	2.76E-12
^{166m}Ho		2.18E-09	2.09E-07	1.47E-10	4.23E-12
^{181}W		9.31E-11	4.09E-11	3.39E-12	3.53E-14
^{185}W		5.38E-10	2.03E-10	1.59E-14	1.99E-16
^{187}W		7.46E-10	1.67E-10	4.05E-11	1.14E-12

Table E.2 Internal committed effective dose equivalent and external effective dose equivalent factors (Continued)

Radio-nuclide	Implicit progeny fraction	Ingestion (Sv/Bq)	Inhalation (Sv/Bq)	External	
				Surface (Sv/d per Bq/m^2)	15 cm* (Sv/d per Bq/m^3)
^{187}Re		2.57E-12	1.47E-11	0.00E+00	0.00E+00
^{185}Os		6.11E-10	2.80E-09	6.07E-11	1.71E-12
^{191}Os		6.23E-10	1.13E-09	6.37E-12	1.11E-13
^{192}Ir		1.55E-09	7.61E-09	6.93E-11	1.97E-12
^{198}Au		1.14E-09	8.87E-10	3.46E-11	9.86E-13
^{203}Hg		3.09E-09	1.98E-09	2.00E-11	5.52E-13
^{210}Pb		1.45E-06	3.67E-06	2.14E-13	1.13E-15
^{212}Pb		1.23E-08	4.56E-08	1.23E-11	3.13E-13
^{212}Bi	1.0000	2.87E-10	5.83E-09	1.54E-11	4.63E-13
^{212}Po	0.6407	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{208}Tl	0.3593	0.00E+00	0.00E+00	2.58E-10	8.36E-12
^{210}Bi		1.73E-09	5.29E-08	9.06E-14	1.61E-15
^{212}Bi		2.87E-10	5.83E-09	1.54E-11	4.63E-13
^{212}Po	0.6407	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{208}Tl	0.3593	0.00E+00	0.00E+00	2.58E-10	8.36E-12
^{210}Po		5.14E-07	2.54E-06	7.16E-16	2.11E-17
^{222}Rn		0.00E+00	0.00E+00	3.41E-14	9.81E-16
^{218}Po	1.0000	0.00E+00	0.00E+00	7.67E-16	2.27E-17
^{214}Pb	1.0000	1.69E-10	2.11E-09	2.10E-11	5.78E-13
^{214}Bi	1.0000	7.64E-11	1.78E-09	1.22E-10	3.77E-12
^{214}Po	0.9998	0.00E+00	0.00E+00	7.02E-15	2.07E-16
^{223}Ra		1.78E-07	2.12E-06	1.11E-11	2.67E-13
^{219}Rn	1.000	0.00E+00	0.00E+00	4.74E-12	1.33E-13
^{215}Po	1.000	0.00E+00	0.00E+00	1.51E-14	4.30E-16
^{211}Pb	1.000	1.42E-10	2.35E-09	4.38E-12	1.26E-13
^{211}Bi	1.000	0.00E+00	0.00E+00	3.96E-12	1.10E-13
^{211}Po	0.0028	0.00E+00	0.00E+00	6.57E-13	1.94E-14
^{207}Tl	0.9972	0.00E+00	0.00E+00	3.25E-13	8.19E-15
^{224}Ra		9.89E-08	8.53E-07	8.26E-13	2.26E-14
^{220}Rn	1.000	0.00E+00	0.00E+00	3.29E-14	9.52E-16
^{216}Po	1.000	0.00E+00	0.00E+00	1.43E-15	4.21E-17
^{225}Ra		1.04E-07	2.10E-06	1.15E-12	5.09E-15
^{226}Ra		3.58E-07	2.32E-06	5.56E-13	1.42E-14
^{228}Ra		3.88E-07	1.29E-06	0.00E+00	0.00E+00
^{228}Ac	1.0000	5.85E-10	8.33E-08	8.01E-11	2.38E-12
^{225}Ac		3.00E-08	2.92E-06	1.37E-12	2.89E-14
^{221}Fr	1.000	0.00E+00	0.00E+00	2.57E-12	6.82E-14
^{217}At	1.000	0.00E+00	0.00E+00	2.61E-14	7.43E-16
^{213}Bi	1.000	1.95E-10	4.63E-09	1.14E-11	3.24E-13
^{213}Po	.9784	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{209}Tl	.0216	0.00E+00	0.00E+00	1.64E-10	4.99E-12
^{209}Pb	1.000	5.75E-11	2.56E-11	2.60E-14	3.52E-16

Table E.2 Internal committed effective dose equivalent and external effective dose equivalent factors (Continued)

Radionuclide	Implicit progeny fraction	Ingestion (Sv/Bq)	Inhalation (Sv/Bq)	External	
				Surface (Sv/d per Bq/m^2)	15 cm* (Sv/d per Bq/m^3)
^{227}Ac		3.80E-06	1.81E-03	1.36E-14	2.26E-16
^{223}Fr	0.0138	2.33E-09	1.68E-09	4.88E-12	8.74E-14
^{228}Ac		5.85E-10	8.33E-08	8.01E-11	2.38E-12
^{227}Th		1.03E-08	4.37E-06	8.94E-12	2.29E-13
^{228}Th		1.07E-07	9.23E-05	2.03E-13	3.60E-15
^{229}Th		9.54E-07	5.80E-04	7.38E-12	1.47E-13
^{230}Th		1.48E-07	8.80E-05	6.48E-14	5.52E-16
^{231}Th		3.65E-10	2.37E-10	1.60E-12	1.68E-14
^{232}Th		7.38E-07	4.43E-04	4.76E-14	2.40E-16
^{234}Th		3.69E-09	9.47E-09	7.18E-13	1.12E-14
^{234m}Pa	0.9980	0.00E+00	0.00E+00	1.32E-12	3.62E-14
^{234}Pa	0.0020	5.84E-10	2.20E-10	1.59E-10	4.65E-12
^{231}Pa		2.86E-06	3.47E-04	3.52E-12	8.30E-14
^{233}Pa		9.81E-10	2.58E-09	1.69E-11	4.45E-13
^{234}Pa		5.84E-10	2.20E-10	1.59E-10	4.65E-12
^{232}U		3.54E-07	1.78E-04	8.73E-14	4.12E-16
^{233}U		7.81E-08	3.66E-05	6.18E-14	6.25E-16
^{234}U		7.66E-08	3.58E-05	6.46E-14	1.85E-16
^{235}U		7.19E-08	3.32E-05	1.28E-11	3.24E-13
^{236}U		7.26E-08	3.39E-05	5.61E-14	9.87E-17
^{237}U		8.57E-10	9.54E-10	1.15E-11	2.40E-13
^{238}U		6.88E-08	3.20E-05	4.76E-14	4.76E-17
^{240}U		1.20E-09	6.13E-10	3.65E-13	6.58E-16
^{240m}Np	1.0000	0.00E+00	0.00E+00	2.82E-11	8.20E-13
^{237}Np		1.20E-06	1.46E-04	2.48E-12	3.59E-14
^{238}Np		1.08E-09	1.00E-08	4.57E-11	1.36E-12
^{239}Np		8.82E-10	6.78E-10	1.41E-11	3.37E-13
^{236}Pu		3.15E-07	3.91E-05	8.47E-14	1.04E-16
^{237}Pu		1.20E-10	5.33E-10	4.01E-12	7.47E-14
^{238}Pu		8.65E-07	1.06E-04	7.23E-14	6.97E-17
^{239}Pu		9.56E-07	1.16E-04	3.17E-14	1.31E-16
^{240}Pu		9.56E-07	1.16E-04	6.93E-14	6.77E-17
^{241}Pu		1.85E-08	2.23E-06	1.67E-16	2.72E-18
^{242}Pu		9.08E-07	1.11E-04	5.76E-14	5.91E-17
^{243}Pu		9.02E-11	4.44E-11	2.08E-12	3.63E-14
^{244}Pu		8.97E-07	1.09E-04	4.82E-14	3.49E-17
^{241}Am		9.84E-07	1.20E-04	2.37E-12	2.02E-14
^{242m}Am		9.50E-07	1.15E-04	2.60E-13	7.77E-16
^{242}Am		3.81E-10	1.58E-08	1.35E-12	2.30E-14
^{243}Am		9.79E-07	1.19E-04	4.62E-12	6.57E-14
^{242}Cm		3.10E-08	4.67E-06	8.25E-14	7.83E-17
^{243}Cm		6.79E-07	8.30E-05	1.08E-11	2.61E-13

Table E.2 Internal committed effective dose equivalent and external effective dose equivalent factors (Continued)

Radio-nuclide	Implicit progeny fraction	Ingestion (Sv/Bq)	Inhalation (Sv/Bq)	External	
				Surface (Sv/d per Bq/m^2)	15 cm* (Sv/d per Bq/m^3)
^{244}Cm		5.45E-07	6.70E-05	7.58E-14	5.82E-17
^{245}Cm		1.01E-06	1.23E-04	7.51E-12	1.56E-13
^{246}Cm		1.00E-06	1.22E-04	6.78E-14	5.37E-17
^{247}Cm		9.24E-07	1.12E-04	2.68E-11	7.59E-13
^{243}Pu	1.0000	9.02E-11	4.44E-11	2.08E-12	3.63E-14
^{248}Cm		3.68E-06	4.47E-04	5.18E-14	4.06E-17
^{252}Cf		2.93E-07	4.24E-05	6.23E-14	8.11E-17

* Based on a density of 1.625 x 10^6 g/m^3 (EPA 1992).

Table E.3 Ingestion organ dose equivalent factors for organ set 1

Radio-nuclide	Implicit progeny fraction	Organ name: Adrenals (Sv/Bq)	Bld wall (Sv/Bq)	B surface (Sv/Bq)	Brain (Sv/Bq)	Breast (Sv/Bq)	S wall (Sv/Bq)	SI wall
^{3}H		1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11
^{10}Be		2.42E-11	2.42E-11	2.15E-09	2.42E-11	2.42E-11	3.15E-10	7.47E-10
^{14}C		5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10
^{18}F		9.70E-12	3.23E-12	6.02E-11	7.67E-12	6.36E-12	2.87E-10	6.99E-12
^{22}Na		4.03E-09	2.83E-09	5.54E-09	2.52E-09	2.58E-09	2.93E-09	2.98E-09
^{24}Na		3.73E-10	3.01E-10	4.68E-10	2.39E-10	2.71E-10	1.18E-09	3.22E-10
^{32}P		6.55E-10	6.55E-10	7.87E-09	0.00E+00	6.55E-10	1.45E-09	1.05E-09
^{33}P		9.37E-11	9.37E-11	1.32E-09	0.00E+00	9.37E-11	1.82E-10	1.38E-10
^{35}S		9.53E-12	9.53E-12	9.53E-12	9.53E-12	9.53E-12	6.58E-11	1.36E-10
^{36}Cl		7.99E-10	7.99E-10	7.99E-10	7.99E-10	7.99E-10	1.11E-09	7.99E-10
^{40}K		5.37E-09	5.00E-09	4.88E-09	4.79E-09	4.89E-09	5.48E-09	5.02E-09
^{41}Ca		3.24E-12	2.56E-12	4.01E-09	3.86E-12	3.19E-12	5.53E-12	7.73E-12
^{45}Ca		5.36E-11	5.36E-11	5.23E-09	5.36E-11	5.36E-11	1.43E-10	2.10E-10
^{46}Sc		1.34E-10	6.06E-10	1.39E-10	2.82E-12	2.51E-10	6.83E-10	2.31E-09
^{51}Cr		6.76E-12	1.47E-11	7.86E-12	3.28E-12	7.51E-12	1.81E-11	4.68E-11
^{54}Mn		4.13E-10	3.72E-10	5.71E-10	0.00E+00	2.77E-10	4.11E-10	9.85E-10
^{56}Mn		1.76E-11	2.56E-11	1.06E-11	0.00E+00	1.76E-11	9.02E-10	1.05E-09
^{55}Fe		1.06E-10	1.00E-10	1.05E-10	1.03E-10	1.04E-10	1.08E-10	1.16E-10
^{59}Fe		1.02E-09	1.08E-09	6.61E-10	4.65E-10	7.37E-10	1.11E-09	2.09E-09
^{57}Co		1.99E-10	2.05E-10	2.12E-10	0.00E+00	1.58E-10	2.25E-10	3.41E-10
^{58}Co		5.93E-10	6.67E-10	4.07E-10	0.00E+00	4.50E-10	7.01E-10	1.25E-09
^{60}Co		8.74E-09	6.64E-09	4.81E-09	0.00E+00	5.08E-09	5.85E-09	8.18E-09
^{59}Ni		3.70E-11	3.41E-11	3.62E-11	3.56E-11	3.58E-11	4.10E-11	5.11E-11
^{63}Ni		8.50E-11	8.50E-11	8.50E-11	8.50E-11	8.50E-11	1.05E-10	1.32E-10
^{65}Ni		6.02E-12	8.55E-12	2.89E-12	4.39E-13	5.63E-12	6.18E-10	7.26E-10
^{64}Cu		1.71E-11	2.19E-11	1.39E-11	3.62E-11	1.59E-11	1.73E-10	2.13E-10
^{65}Zn		4.76E-09	4.07E-09	4.50E-09	2.85E-09	3.28E-09	3.39E-09	4.27E-09
^{69m}Zn		4.56E-11	5.90E-11	7.27E-11	3.08E-11	4.42E-11	2.68E-10	4.90E-10
^{69}Zn		4.17E-13	4.17E-13	5.18E-13	4.17E-13	4.17E-13	2.14E-10	1.09E-10
^{76}As		1.13E-10	1.32E-10	1.02E-10	8.98E-11	1.09E-10	1.36E-09	1.66E-09
^{75}Se		2.83E-09	1.59E-09	1.70E-09	9.56E-10	1.45E-09	2.18E-09	2.16E-09
^{79}Se		9.06E-10	9.06E-10	9.06E-10	9.06E-10	9.06E-10	9.70E-10	9.38E-10
^{82}Br		5.62E-10	4.83E-10	3.80E-10	2.84E-10	3.81E-10	8.29E-10	4.98E-10
^{83}Br		7.38E-12	7.34E-12	7.33E-12	7.31E-12	7.34E-12	2.97E-10	7.38E-12
^{84}Br		8.47E-12	5.86E-12	5.56E-12	4.49E-12	6.62E-12	6.82E-10	8.61E-12
^{86}Rb		2.19E-09	2.17E-09	6.86E-09	2.13E-09	2.14E-09	2.92E-09	2.17E-09
^{88}Rb		3.36E-12	2.55E-12	2.75E-12	2.33E-12	2.82E-12	7.32E-10	3.25E-12
^{89}Rb		4.71E-12	2.62E-12	4.19E-12	1.91E-12	3.38E-12	3.63E-10	4.64E-12
^{85}Sr		3.39E-10	3.00E-10	6.06E-10	0.00E+00	2.53E-10	3.09E-10	6.20E-10
^{89}Sr		2.40E-10	2.40E-10	4.81E-09	0.00E+00	2.40E-10	9.12E-10	1.41E-09

Table E.3 Ingestion organ dose equivalent factors for organ set 1 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name: Adrenals (Sv/Bq)	Bld wall (Sv/Bq)	B surface (Sv/Bq)	Brain (Sv/Bq)	Breast (Sv/Bq)	S wall (Sv/Bq)	SI wall
^{90}Sr		1.51E-09	1.51E-09	4.19E-07	0.00E+00	1.51E-09	1.75E-09	1.98E-09
^{91}Sr		2.46E-11	6.88E-11	2.02E-11	0.00E+00	3.57E-11	8.50E-10	1.75E-09
^{90}Y		1.26E-14	1.26E-14	3.67E-13	1.26E-14	1.27E-14	1.07E-09	2.55E-09
^{91m}Y		2.00E-12	2.32E-12	8.71E-13	1.97E-14	1.84E-12	4.92E-11	3.09E-11
^{91}Y		3.50E-13	1.23E-12	6.13E-12	1.20E-13	5.54E-13	6.94E-10	1.73E-09
^{92}Y		3.14E-12	5.58E-12	1.75E-12	4.65E-14	3.55E-12	1.42E-09	2.00E-09
^{93}Y		2.23E-12	6.45E-12	1.73E-12	3.46E-14	3.13E-12	1.28E-09	2.51E-09
^{93}Zr		2.95E-13	4.61E-14	9.14E-09	0.00E+00	1.97E-13	2.27E-11	5.65E-11
^{95}Zr		6.09E-11	2.43E-10	4.86E-10	0.00E+00	1.05E-10	3.57E-10	1.12E-09
^{97}Zr		4.89E-11	1.76E-10	4.55E-11	0.00E+00	8.12E-11	1.21E-09	3.39E-09
^{97m}Nb	0.9470	Note: Contribution included with parent.						
^{97}N	0.0530	3.37E-12	4.33E-12	1.60E-12	0.00E+00	3.30E-12	3.88E-10	2.96E-10
^{93m}Nb		2.52E-12	2.52E-12	5.98E-11	2.50E-12	2.57E-12	3.62E-11	8.83E-11
^{94}Nb		3.41E-10	6.05E-10	7.65E-10	0.00E+00	3.47E-10	7.71E-10	2.24E-09
^{95m}Nb		6.67E-12	2.54E-11	4.31E-11	0.00E+00	1.06E-11	2.15E-10	5.46E-10
^{95}Nb		6.79E-11	2.43E-10	2.94E-10	0.00E+00	1.07E-10	2.80E-10	9.13E-10
^{97m}Nb		6.79E-11	2.43E-10	2.94E-10	0.00E+00	1.07E-10	2.80E-10	9.13E-10
^{97}Nb		3.37E-12	4.33E-12	1.60E-12	0.00E+00	3.30E-12	3.88E-10	2.96E-10
^{93}Mo		1.31E-10	1.02E-10	1.15E-09	0.00E+00	9.96E-11	1.09E-10	1.06E-10
^{99}Mo		2.54E-11	7.46E-11	6.32E-11	0.00E+00	3.43E-11	5.14E-10	1.25E-09
^{99m}Tc		4.33E-12	4.53E-12	4.06E-12	1.82E-12	3.57E-12	7.17E-11	2.22E-11
^{99}Tc		6.04E-11	6.04E-11	6.04E-11	6.04E-11	6.04E-11	3.39E-09	1.19E-10
^{101}Tc		5.60E-13	2.86E-13	2.55E-13	9.46E-14	4.06E-13	1.50E-10	2.28E-11
^{103}Ru		1.11E-10	2.21E-10	9.63E-11	5.12E-11	1.20E-10	3.14E-10	8.51E-10
^{105}Ru		1.29E-11	2.71E-11	8.89E-12	1.27E-12	1.59E-11	4.97E-10	7.89E-10
^{106}Ru		1.46E-09	1.50E-09	1.43E-09	1.39E-09	1.44E-09	3.10E-09	5.53E-09
^{103m}Rh		3.50E-15	3.87E-15	5.29E-15	3.24E-15	8.65E-15	2.56E-11	1.60E-11
^{105}Rh		6.36E-12	1.85E-11	6.75E-12	2.74E-12	8.97E-12	1.95E-10	4.43E-10
^{103}Pd		2.97E-13	1.66E-12	2.00E-12	4.51E-14	1.58E-12	3.50E-11	1.55E-10
^{103m}Rh	0.99974	3.50E-15	3.87E-15	5.29E-15	3.24E-15	8.65E-15	2.56E-11	1.60E-11
^{107}Pd		9.91E-15	9.91E-15	1.43E-13	9.91E-15	9.91E-15	1.07E-11	2.65E-11
^{109}Pd		2.18E-13	9.02E-13	1.02E-12	9.30E-14	6.27E-13	4.84E-10	1.00E-09
^{110m}Ag		1.63E-09	1.05E-09	4.93E-10	1.00E-10	7.51E-10	1.50E-09	3.47E-09
^{110}Ag	0.0133	Note: Contribution included with parent.						
^{111}Ag		1.10E-11	1.58E-11	9.67E-12	7.33E-12	1.09E-11	4.22E-10	9.85E-10
^{109}Cd		5.89E-10	2.94E-10	3.28E-10	2.64E-10	3.10E-10	4.09E-10	5.93E-10
^{113m}Cd		3.44E-09	3.44E-09	3.44E-09	3.44E-09	3.44E-09	3.65E-09	3.94E-09
^{115m}Cd		1.79E-10	1.69E-10	1.64E-10	1.60E-10	1.66E-10	8.70E-10	1.84E-09
^{115}Cd		3.92E-11	9.57E-11	3.06E-11	8.33E-12	4.44E-11	4.65E-10	1.30E-09
^{115m}In	1.0000	2.51E-12	5.39E-12	2.19E-12	1.14E-13	3.16E-12	1.95E-10	3.04E-10
^{111}In		2.52E-11	1.14E-10	3.73E-11	2.02E-12	4.37E-11	1.59E-10	4.95E-10

Table E.3 Ingestion organ dose equivalent factors for organ set 1 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name						
		Adrenals (Sv/Bq)	Bld wall (Sv/Bq)	B surface (Sv/Bq)	Brain (Sv/Bq)	Breast (Sv/Bq)	S wall (Sv/Bq)	SI wall
^{114m}In		1.39E-10	1.51E-10	1.81E-09	1.18E-10	1.32E-10	1.15E-09	2.73E-09
^{114}In	0.9570	Note: Contribution included with parent.						
^{115m}In		2.51E-12	5.39E-12	2.19E-12	1.14E-13	3.16E-12	1.95E-10	3.04E-10
^{117m}Sn		1.16E-11	6.26E-11	4.78E-10	3.58E-12	2.39E-11	2.44E-10	6.60E-10
^{119m}Sn		9.16E-12	1.17E-11	1.82E-10	9.63E-12	1.05E-11	1.06E-10	2.61E-10
^{121m}Sn		2.89E-11	3.02E-11	6.12E-10	2.94E-11	2.95E-11	7.49E-11	1.71E-10
^{121}Sn		2.00E-13	2.00E-13	2.51E-11	2.00E-13	2.00E-13	1.29E-10	2.86E-10
^{123}Sn		3.20E-11	3.34E-11	6.62E-10	3.15E-11	3.22E-11	6.32E-10	1.50E-09
^{125}Sn		2.91E-11	9.36E-11	2.38E-10	1.03E-11	4.41E-11	1.02E-09	2.54E-09
^{126}Sn		8.92E-10	1.06E-09	5.06E-09	7.28E-10	7.96E-10	1.60E-09	4.41E-09
^{126m}Sb	1.0000	2.60E-12	1.82E-12	9.53E-13	3.21E-14	2.06E-12	2.64E-10	7.03E-11
^{124}Sb		1.30E-10	5.91E-10	1.89E-10	1.25E-11	2.30E-10	9.45E-10	2.84E-09
^{125}Sb		9.52E-11	1.85E-10	5.86E-10	4.31E-11	1.00E-10	2.97E-10	7.65E-10
^{126m}Sb		2.60E-12	1.82E-12	9.53E-13	3.21E-14	2.06E-12	2.64E-10	7.03E-11
^{126}Sb		1.89E-10	8.62E-10	2.27E-10	1.06E-11	3.53E-10	1.14E-09	3.63E-09
^{127}Sb		4.14E-11	1.82E-10	5.24E-11	3.24E-12	7.60E-11	5.62E-10	1.63E-09
^{123m}Te		1.29E-10	1.31E-10	2.41E-08	0.00E+00	1.26E-10	2.47E-10	4.90E-10
^{125m}Te		4.29E-11	4.80E-11	1.27E-08	0.00E+00	4.64E-11	1.86E-10	3.76E-10
^{127m}Te		9.75E-11	9.66E-11	2.07E-08	0.00E+00	9.74E-11	2.12E-10	4.34E-10
^{127}Te		2.97E-12	3.17E-12	6.46E-12	0.00E+00	3.00E-12	2.43E-10	3.91E-10
^{129m}Te		1.68E-10	1.75E-10	7.99E-09	0.00E+00	1.66E-10	6.27E-10	1.47E-09
^{129}Te	0.6500	6.07E-13	6.72E-13	5.40E-13	0.00E+00	6.05E-13	3.98E-10	2.74E-10
^{129}Te		1.02E-10	2.46E-10	3.24E-10	4.45E-11	1.35E-10	6.01E-10	1.51E-09
^{131}Te	0.2220	4.47E-12	5.27E-12	3.69E-12	2.18E-12	4.96E-12	6.27E-10	5.50E-10
^{131}Te		4.47E-12	5.27E-12	3.69E-12	2.18E-12	4.96E-12	6.27E-10	5.50E-10
^{132}Te		4.06E-10	4.22E-10	8.30E-10	2.86E-10	3.50E-10	5.23E-10	8.06E-10
^{132}I	1.0000	3.23E-11	2.44E-11	2.19E-11	0.00E+00	2.52E-11	6.31E-10	3.17E-11
^{133m}Tem		1.26E-11	1.20E-11	6.61E-12	2.71E-12	1.14E-11	6.55E-10	4.10E-10
^{133}Te		1.61E-12	8.93E-13	7.73E-13	4.89E-13	1.23E-12	2.39E-10	4.21E-11
^{134}Te		1.65E-11	1.57E-11	1.23E-11	9.52E-12	1.37E-11	2.34E-10	1.22E-10
^{134}I	1.0000	1.58E-11	1.04E-11	9.32E-12	0.00E+00	1.17E-11	5.49E-10	1.61E-11
^{125}I		2.52E-11	2.90E-11	6.63E-11	0.00E+00	1.45E-10	6.80E-11	3.06E-11
^{129}I		1.32E-10	1.35E-10	2.17E-10	0.00E+00	3.31E-10	2.19E-10	1.41E-10
^{130}I		7.41E-11	5.85E-11	6.12E-11	0.00E+00	7.32E-11	5.82E-10	6.86E-11
^{131}I		5.62E-11	4.08E-11	8.72E-11	0.00E+00	1.21E-10	3.06E-10	4.47E-11
^{132}I		3.23E-11	2.44E-11	2.19E-11	0.00E+00	2.52E-11	6.31E-10	3.17E-11
^{133}I		4.37E-11	3.69E-11	4.07E-11	0.00E+00	4.68E-11	5.54E-10	4.03E-11
^{134}I		1.58E-11	1.04E-11	9.32E-12	0.00E+00	1.17E-11	5.49E-10	1.61E-11
^{135}I		4.84E-11	3.56E-11	3.36E-11	0.00E+00	3.85E-11	5.41E-10	4.11E-11
^{135m}Xe	0.1540	Note: Contribution included with parent.						
^{134m}Cs		7.32E-12	6.96E-12	6.57E-12	0.00E+00	6.28E-12	1.15E-10	7.21E-12
^{134}Cs		2.32E-08	2.14E-08	1.74E-08	0.00E+00	1.72E-08	2.01E-08	2.18E-08

Table E.3 Ingestion organ dose equivalent factors for organ set 1 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name: Adrenals (Sv/Bq)	Bld wall (Sv/Bq)	B surface (Sv/Bq)	Brain (Sv/Bq)	Breast (Sv/Bq)	S wall (Sv/Bq)	SI wall
^{135}Cs		1.91E-09	1.91E-09	1.91E-09	0.00E+00	1.91E-09	1.99E-09	1.91E-09
^{136}Cs		3.47E-09	3.46E-09	2.71E-09	0.00E+00	2.65E-09	3.38E-09	3.42E-09
^{137}Cs		1.50E-08	1.41E-08	1.26E-08	0.00E+00	1.24E-08	1.39E-08	1.44E-08
^{137m}Ba	0.9460	Note: Contribution included with parent.						
^{138}Cs		1.22E-11	6.83E-12	6.47E-12	0.00E+00	8.00E-12	7.01E-10	1.06E-11
^{139}Ba		5.41E-13	5.75E-13	4.38E-13	2.59E-13	5.17E-13	6.90E-10	5.55E-10
^{140}Ba		1.20E-10	3.71E-10	5.53E-10	5.67E-11	1.59E-10	5.83E-10	1.70E-09
^{141}Ba		1.70E-12	1.03E-12	1.27E-12	1.52E-13	1.22E-12	3.94E-10	1.86E-10
^{142}Ba		3.01E-12	2.95E-12	1.24E-12	1.17E-13	2.52E-12	2.02E-10	1.11E-10
^{140}La		1.05E-10	4.50E-10	9.77E-11	2.03E-12	1.80E-10	1.09E-09	2.96E-09
^{141}La		6.36E-13	1.27E-12	6.06E-13	2.82E-14	7.07E-13	9.33E-10	1.37E-09
^{142}La		1.71E-11	2.06E-11	7.40E-12	3.36E-13	1.54E-11	8.53E-10	7.76E-10
^{141}Ce		4.55E-12	3.29E-11	2.30E-11	0.00E+00	1.11E-11	2.23E-10	5.88E-10
^{143}Ce		1.18E-11	5.57E-11	1.61E-11	0.00E+00	2.32E-11	5.61E-10	1.37E-09
^{144}Ce		8.91E-12	2.43E-11	1.28E-10	0.00E+00	1.22E-11	1.11E-09	3.71E-09
^{144m}Pr	0.0178	Note: Contribution included with parent.						
^{144}Pr	1.0000	5.20E-14	2.64E-14	1.52E-14	9.97E-16	3.38E-14	4.09E-10	9.63E-11
^{143}Pr		5.60E-19	2.65E-18	1.03E-12	7.35E-21	1.09E-18	3.61E-10	8.95E-10
^{144}Pr		5.20E-14	2.64E-14	1.52E-14	9.97E-16	3.38E-14	4.09E-10	9.63E-11
^{147}Nd		7.69E-12	4.96E-11	2.22E-11	8.19E-14	1.87E-11	3.58E-10	9.43E-10
^{147}Pm		4.23E-16	2.05E-15	2.61E-10	5.78E-17	7.45E-16	7.14E-11	1.78E-10
^{148m}Pm		1.32E-10	6.45E-10	1.74E-10	2.80E-12	2.59E-10	7.89E-10	2.59E-09
^{148}Pm		3.28E-11	1.58E-10	3.49E-11	6.04E-13	6.11E-11	9.71E-10	2.53E-09
^{149}Pm		5.35E-13	2.62E-12	9.59E-13	3.82E-15	1.02E-12	4.19E-10	9.97E-10
^{151}Pm		1.30E-11	5.84E-11	1.62E-11	9.72E-14	2.42E-11	4.19E-10	1.02E-09
^{147}Sm		0.00E+00	0.00E+00	8.59E-07	0.00E+00	0.00E+00	5.18E-10	1.29E-09
^{151}Sm		1.16E-15	8.66E-16	3.45E-10	3.14E-16	1.03E-15	2.28E-11	5.70E-11
^{153}Sm		2.21E-12	1.83E-11	8.38E-12	5.28E-15	6.91E-12	3.32E-10	8.10E-10
^{152}Eu		4.78E-10	4.29E-10	2.09E-09	1.20E-10	2.85E-10	6.42E-10	1.75E-09
^{154}Eu		4.37E-10	4.42E-10	4.46E-09	1.06E-10	2.79E-10	8.19E-10	2.23E-09
^{155}Eu		1.60E-11	3.07E-11	1.29E-09	3.78E-12	1.44E-11	1.03E-10	2.80E-10
^{156}Eu		8.30E-11	3.85E-10	1.16E-10	2.09E-12	1.52E-10	8.32E-10	2.40E-09
^{153}Gd		5.80E-12	5.07E-11	7.92E-11	4.50E-13	1.80E-11	9.86E-11	3.18E-10
^{160}Tb		7.62E-11	3.52E-10	1.57E-10	2.45E-12	1.43E-10	6.12E-10	1.88E-09
^{166m}Ho		4.74E-10	6.25E-10	2.35E-09	9.46E-11	3.48E-10	8.98E-10	2.38E-09
^{181}W		2.08E-12	2.00E-11	1.03E-11	1.19E-13	7.01E-12	3.08E-11	1.03E-10
^{185}W		3.14E-15	2.67E-14	4.90E-12	1.06E-16	8.98E-15	1.46E-10	3.61E-10
^{187}W		1.80E-11	7.31E-11	2.12E-11	1.87E-13	3.22E-11	4.29E-10	1.03E-09
^{187}Re		3.94E-13	3.94E-13	3.94E-13	3.94E-13	3.94E-13	2.21E-11	7.74E-13
^{185}Os		1.15E-10	2.69E-10	8.91E-11	0.00E+00	1.25E-10	2.85E-10	8.78E-10
^{191}Os		8.38E-12	3.78E-11	1.72E-11	0.00E+00	1.51E-11	1.90E-10	5.01E-10
^{192}Ir		1.34E-10	3.36E-10	1.11E-10	0.00E+00	1.51E-10	5.62E-10	1.57E-09

Table E.3 Ingestion organ dose equivalent factors for organ set 1 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name						
		Adrenals (Sv/Bq)	Bld wall (Sv/Bq)	B surface (Sv/Bq)	Brain (Sv/Bq)	Breast (Sv/Bq)	S wall (Sv/Bq)	SI wall
^{198}Au		3.98E-11	1.84E-10	4.06E-11	1.67E-11	5.51E-11	4.94E-10	1.15E-09
^{203}Hg		1.79E-09	1.32E-09	1.51E-09	1.16E-08	1.23E-09	1.61E-09	1.50E-09
^{210}Pb		1.25E-07	1.25E-07	2.16E-05	0.00E+00	1.25E-07	1.25E-07	1.25E-07
^{212}Pb		1.66E-09	1.71E-09	1.66E-07	0.00E+00	1.67E-09	2.93E-09	5.76E-09
^{212}Bi	1.0000	1.27E-11	1.29E-11	9.14E-12	0.00E+00	1.18E-11	1.60E-09	1.08E-09
^{212}Po	0.6407	Note: Contribution included with parent.						
^{208}Tl	0.3593	Note: Contribution included with parent.						
^{210}Bi		1.97E-11	1.97E-11	1.97E-11	0.00E+00	1.97E-11	4.65E-10	1.06E-09
^{212}Bi		1.27E-11	1.29E-11	9.14E-12	0.00E+00	1.18E-11	1.60E-09	1.08E-09
^{212}Po	0.6407	Note: Contribution included with parent.						
^{208}Tl	0.3593	Note: Contribution included with parent.						
^{210}Po		8.23E-08	8.23E-08	8.23E-08	0.00E+00	8.23E-08	8.36E-08	8.51E-08
^{222}Rn		8.23E-08	8.23E-08	8.23E-08	0.00E+00	8.23E-08	8.36E-08	8.51E-08
^{218}Po	1.0000	Note: Contribution included with parent.						
^{214}Po	1.0000	2.50E-11	2.47E-11	1.10E-09	0.00E+00	2.42E-11	8.75E-10	5.62E-10
^{214}Bi	1.0000	3.61E-12	2.25E-12	1.51E-12	0.00E+00	2.55E-12	8.65E-10	2.32E-10
^{214}Po	0.9998	Note: Contribution included with parent.						
^{223}Ra		4.23E-08	4.24E-08	2.93E-06	0.00E+00	4.23E-08	4.83E-08	5.64E-08
^{219}Rn	1.000	Note: Contribution included with parent.						
^{215}Po	1.000	Note: Contribution included with parent.						
^{211}Pb	1.000	1.91E-11	1.91E-11	1.60E-10	0.00E+00	1.91E-11	1.17E-09	5.74E-10
^{211}Bi	1.000	Note: Contribution included with parent.						
^{211}Po	0.0028	Note: Contribution included with parent.						
^{207}T	0.9972	Note: Contribution included with parent.						
^{224}Ra		2.06E-08	2.08E-08	1.59E-06	0.00E+00	2.06E-08	2.49E-08	3.03E-08
^{220}Rn	1.000	Note: Contribution included with parent.						
^{216}Po	1.000	Note: Contribution included with parent.						
^{225}Ra		3.37E-08	3.37E-08	1.78E-06	0.00E+00	3.37E-08	3.38E-08	3.41E-08
^{226}Ra		9.19E-08	9.15E-08	6.83E-06	0.00E+00	9.17E-08	9.25E-08	9.37E-08
^{228}Ra		1.58E-07	1.57E-07	5.82E-06	0.00E+00	1.57E-07	1.57E-07	1.58E-07
^{228}Ac	1.0000	1.80E-11	4.09E-11	3.01E-09	2.54E-13	2.31E-11	6.21E-10	1.12E-09
^{225}Ac		1.30E-11	7.45E-11	9.94E-08	2.44E-13	2.73E-11	5.23E-09	1.67E-08
^{221}Fr	1.000	Note: Contribution included with parent.						
^{217}At	1.000	Note: Contribution included with parent.						
^{213}Bi	1.000	4.86E-12	4.84E-12	4.45E-12	0.00E+00	4.73E-12	1.31E-09	7.46E-10
^{213}Po	0.9784	Note: Contribution included with parent.						
^{209}Tl	0.0216	Note: Contribution included with parent.						
^{209}Pb	1.000	5.37E-13	5.37E-13	2.09E-11	0.00E+00	5.37E-13	1.88E-10	2.24E-10
^{227}Ac		3.89E-10	5.33E-11	6.73E-05	1.31E-10	1.41E-10	1.96E-10	2.90E-10
^{223}Fr	0.0138	2.32E-09	2.32E-09	2.32E-09	5.44E-12	2.32E-09	2.49E-09	2.32E-09
^{228}Ac		1.80E-11	4.09E-11	3.01E-09	2.54E-13	2.31E-11	6.21E-10	1.12E-09
^{227}Th		1.30E-10	1.73E-10	6.84E-08	0.00E+00	1.40E-10	1.63E-09	4.09E-09

Table E.3 Ingestion organ dose equivalent factors for organ set 1 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name: Adrenals (Sv/Bq)	Bld wall (Sv/Bq)	B surface (Sv/Bq)	Brain (Sv/Bq)	Breast (Sv/Bq)	S wall (Sv/Bq)	SI wall
^{228}Th		2.32E-09	2.38E-09	2.37E-06	0.00E+00	2.33E-09	3.64E-09	6.07E-09
^{229}Th		4.57E-09	4.59E-09	2.38E-05	0.00E+00	4.57E-09	5.84E-09	7.84E-09
^{230}Th		6.80E-10	6.80E-10	3.60E-06	0.00E+00	6.80E-10	1.77E-09	3.41E-09
^{231}Th		3.93E-13	2.89E-12	3.17E-12	0.00E+00	1.44E-12	1.95E-10	4.54E-10
^{232}Th		1.31E-09	1.21E-09	1.85E-05	0.00E+00	1.26E-09	2.14E-09	3.56E-09
^{234}Th		1.64E-12	9.15E-12	2.08E-11	0.00E+00	3.57E-12	9.95E-10	2.55E-09
^{234m}Pa	0.9980	Note: Contribution included with parent.						
^{234}Pa	0.0020	3.72E-11	9.06E-11	2.74E-11	4.48E-13	4.99E-11	7.80E-10	1.48E-09
^{231}Pa		9.83E-11	5.06E-11	7.22E-05	1.28E-10	7.81E-11	1.25E-09	3.11E-09
^{233}Pa		1.25E-11	7.58E-11	1.02E-10	3.41E-13	2.71E-11	2.92E-10	8.02E-10
^{234}Pa		3.72E-11	9.06E-11	2.74E-11	4.48E-13	4.99E-11	7.80E-10	1.48E-09
^{232}U		8.49E-09	8.15E-09	6.63E-06	0.00E+00	8.33E-09	9.38E-09	1.12E-08
^{233}U		2.62E-09	2.62E-09	1.16E-06	0.00E+00	2.62E-09	3.74E-09	5.28E-09
^{234}U		2.58E-09	2.58E-09	1.13E-06	0.00E+00	2.58E-09	3.70E-09	5.23E-09
^{235}U		2.50E-09	2.49E-09	1.05E-06	0.00E+00	2.49E-09	3.56E-09	5.24E-09
^{236}U		2.45E-09	2.45E-09	1.07E-06	0.00E+00	2.45E-09	3.50E-09	4.95E-09
^{237}U		7.28E-12	5.18E-11	3.39E-11	0.00E+00	1.81E-11	2.75E-10	7.34E-10
^{238}U		2.31E-09	2.30E-09	1.01E-06	0.00E+00	2.31E-09	3.28E-09	4.65E-09
^{240}U		9.90E-12	3.39E-11	1.02E-11	0.00E+00	1.60E-11	8.34E-10	2.03E-09
^{240m}Np	1.0000	Note: Contribution included with parent.						
^{237}Np		2.28E-10	8.39E-11	2.72E-05	2.11E-10	1.45E-10	1.29E-09	3.13E-09
^{238}Np		2.77E-11	1.06E-10	1.77E-09	4.71E-13	4.81E-11	4.28E-10	1.13E-09
^{239}Np		7.91E-12	4.74E-11	3.59E-11	7.93E-14	1.72E-11	3.46E-10	8.76E-10
^{236}Pu		5.96E-13	2.65E-13	5.61E-08	2.80E-13	3.90E-13	1.34E-09	3.36E-09
^{237}Pu		2.44E-12	2.11E-11	7.40E-12	5.98E-15	7.07E-12	3.80E-11	1.22E-10
^{238}Pu		8.97E-14	1.54E-13	1.58E-07	8.34E-14	1.80E-13	1.28E-09	3.20E-09
^{239}Pu		8.28E-14	1.25E-13	1.76E-07	7.66E-14	1.21E-13	1.19E-09	2.99E-09
^{240}Pu		8.63E-14	1.50E-13	1.76E-07	7.91E-14	1.73E-13	1.20E-09	3.00E-09
^{241}Pu		6.58E-15	1.43E-15	3.48E-09	2.82E-15	2.79E-15	6.07E-12	1.52E-11
^{242}Pu		1.25E-13	3.84E-13	1.67E-07	7.88E-14	2.54E-13	1.14E-09	2.85E-09
^{243}Pu		3.57E-13	1.03E-12	5.71E-13	8.11E-16	5.93E-13	1.79E-10	2.88E-10
^{244}Pu		2.63E-11	1.37E-10	1.65E-07	3.03E-12	5.36E-11	1.26E-09	3.69E-09
^{241}Am		4.62E-11	2.29E-11	1.81E-05	2.25E-11	2.62E-11	1.34E-09	3.34E-09
^{242m}Am		2.59E-11	7.92E-12	1.76E-05	1.04E-11	1.22E-11	7.88E-11	2.72E-10
^{242}Am		4.10E-13	2.08E-12	1.52E-09	2.13E-14	9.38E-13	2.04E-10	4.41E-10
^{243}Am		3.04E-10	9.91E-11	1.80E-05	1.26E-10	1.41E-10	1.40E-09	3.40E-09
^{242}Cm		8.86E-12	8.92E-12	4.46E-07	8.83E-12	8.95E-12	1.43E-09	3.55E-09
^{243}Cm		1.26E-10	7.72E-11	1.23E-05	5.03E-11	6.96E-11	1.59E-09	3.96E-09
^{244}Cm		9.15E-12	8.58E-12	9.77E-06	8.69E-12	8.82E-12	1.35E-09	3.37E-09
^{245}Cm		1.23E-10	6.52E-11	1.86E-05	5.34E-11	6.80E-11	1.40E-09	3.46E-09
^{246}Cm		6.55E-11	3.07E-11	1.85E-05	3.35E-11	3.91E-11	1.30E-09	3.23E-09
^{247}Cm		4.90E-10	2.07E-10	1.70E-05	1.94E-10	2.29E-10	1.47E-09	3.66E-09

Table E.3 Ingestion organ dose equivalent factors for organ set 1 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name						
		Adrenals (Sv/Bq)	Bld wall (Sv/Bq)	B surface (Sv/Bq)	Brain (Sv/Bq)	Breast (Sv/Bq)	S wall (Sv/Bq)	SI wall
^{243}Pu	1.0000	3.57E-13	1.03E-12	5.71E-13	8.11E-16	5.93E-13	1.79E-10	2.88E-10
^{248}Cm		2.02E-08	8.13E-09	6.75E-05	9.01E-09	1.10E-08	1.73E-08	3.89E-08
^{252}Cf		1.22E-09	2.68E-09	5.84E-06	6.09E-10	1.49E-09	5.49E-09	1.63E-08

Table E.4 Ingestion organ dose equivalent factors for organ set 2

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		ULI wall	LLI wall	Kidneys	Liver	Lungs	Ovaries	Pancreas
^{3}H		1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11
^{10}Be		4.30E-09	1.29E-08	2.42E-11	2.42E-11	2.42E-11	2.42E-11	2.42E-11
^{14}C		5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10
^{18}F		7.54E-12	5.52E-12	8.36E-12	5.74E-12	6.54E-12	4.97E-12	2.91E-11
^{22}Na		2.86E-09	3.08E-09	2.84E-09	2.70E-09	2.51E-09	2.81E-09	2.83E-09
^{24}Na		3.10E-10	3.39E-10	2.98E-10	2.93E-10	2.60E-10	3.43E-10	4.37E-10
^{32}P		2.95E-09	7.24E-09	6.55E-10	6.55E-10	6.55E-10	6.55E-10	6.55E-10
^{33}P		3.50E-10	8.45E-10	9.37E-11	9.37E-11	9.37E-11	9.37E-11	9.37E-11
^{35}S		7.53E-10	2.23E-09	9.53E-12	9.53E-12	9.53E-12	9.53E-12	9.53E-12
^{36}Cl		7.99E-10	7.99E-10	7.99E-10	7.99E-10	7.99E-10	7.99E-10	7.99E-10
^{40}K		4.97E-09	5.02E-09	4.93E-09	4.95E-09	4.85E-09	5.07E-09	4.93E-09
^{41}Ca		3.19E-11	8.82E-11	3.06E-12	2.78E-12	2.84E-12	2.71E-12	3.21E-12
^{45}Ca		9.94E-10	2.80E-09	5.36E-11	5.36E-11	5.36E-11	5.36E-11	5.36E-11
^{46}Sc		4.66E-09	1.04E-08	2.84E-10	2.02E-10	4.86E-11	2.01E-09	2.60E-10
^{51}Cr		1.06E-10	2.48E-10	8.48E-12	7.01E-12	4.38E-12	4.00E-11	8.96E-12
^{54}Mn		1.35E-09	2.20E-09	3.82E-10	1.00E-09	2.29E-10	9.48E-10	3.81E-10
^{56}Mn		1.37E-09	5.40E-10	3.20E-11	2.63E-11	8.80E-12	8.53E-11	5.62E-11
^{55}Fe		1.72E-10	3.04E-10	1.03E-10	3.44E-10	1.02E-10	1.07E-10	1.04E-10
^{59}Fe		3.94E-09	8.43E-09	9.09E-10	1.54E-09	6.35E-10	1.66E-09	9.03E-10
^{57}Co		5.61E-10	1.08E-09	1.97E-10	4.65E-10	1.63E-10	2.94E-10	2.17E-10
^{58}Co		1.86E-09	3.33E-09	5.74E-10	1.01E-09	4.05E-10	1.08E-09	5.65E-10
^{60}Co		9.58E-09	1.35E-08	6.41E-09	1.28E-08	4.96E-09	7.23E-09	6.23E-09
^{59}Ni		1.16E-10	2.70E-10	3.56E-11	3.58E-11	3.50E-11	3.83E-11	3.61E-11
^{63}Ni		3.62E-10	9.18E-10	8.52E-11	8.50E-11	8.50E-11	8.50E-11	8.50E-11
^{65}Ni		9.34E-10	3.65E-10	1.06E-11	7.27E-12	2.75E-12	2.43E-11	1.80E-11
^{64}Cu		6.07E-10	7.51E-10	1.95E-11	3.71E-11	1.28E-11	4.78E-11	4.27E-11
^{65}Zn		4.23E-09	4.97E-09	3.87E-09	3.68E-09	3.08E-09	3.51E-09	3.56E-09
^{69m}Zn		1.77E-09	2.39E-09	5.16E-11	4.63E-11	3.63E-11	1.23E-10	5.92E-11
^{69}Zn	0.9997	6.16E-11	1.04E-11	4.17E-13	4.17E-13	4.17E-13	4.17E-13	4.17E-13
^{69}Zn		6.16E-11	1.04E-11	4.17E-13	4.17E-13	4.17E-13	4.17E-13	4.17E-13
^{76}As		6.55E-09	1.18E-08	3.83E-10	3.19E-10	9.83E-11	2.16E-10	1.25E-10
^{75}Se		2.24E-09	1.97E-09	7.17E-09	5.73E-09	1.66E-09	1.80E-09	4.00E-09
^{79}Se		1.10E-09	1.48E-09	1.25E-08	6.48E-09	9.06E-10	9.06E-10	3.89E-09
^{82}Br		4.85E-10	4.95E-10	4.58E-10	4.52E-10	3.84E-10	4.14E-10	5.05E-10
^{83}Br		7.38E-12	7.36E-12	7.37E-12	7.36E-12	7.35E-12	7.35E-12	7.54E-12
^{83m}Kr	1.0000	Note: Contribution included with parent.						
^{84}Br		9.16E-12	7.10E-12	9.10E-12	7.70E-12	6.99E-12	6.75E-12	2.54E-11
^{86}Rb		2.16E-09	2.17E-09	2.16E-09	2.16E-09	2.14E-09	2.14E-09	2.15E-09
^{88}Rb		3.43E-12	2.91E-12	3.41E-12	3.06E-12	2.91E-12	2.78E-12	7.56E-12
^{89}Rb		5.17E-12	3.56E-12	5.21E-12	4.07E-12	3.68E-12	3.32E-12	1.77E-11
^{85}Sr		8.69E-10	1.50E-09	2.54E-10	2.17E-10	2.06E-10	6.25E-10	2.53E-10

Table E.4 Ingestion organ dose equivalent factors for organ set 2 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		ULI wall	LLI wall	Kidneys	Liver	Lungs	Ovaries	Pancreas
^{89}Sr		7.30E-09	2.07E-08	2.40E-10	2.40E-10	2.40E-10	2.40E-10	2.40E-10
^{90}Sr		5.74E-09	1.97E-08	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09
^{91}Sr		4.88E-09	5.11E-09	5.47E-11	3.95E-11	9.81E-12	2.48E-10	5.95E-11
^{91m}Y	0.5780	3.08E-11	2.39E-11	3.92E-12	2.46E-12	1.28E-12	6.94E-12	1.12E-11
^{90}Y		1.32E-08	3.16E-08	1.26E-14	3.65E-13	1.26E-14	1.43E-14	1.26E-14
^{91m}Y		3.08E-11	2.39E-11	3.92E-12	2.46E-12	1.28E-12	6.94E-12	1.12E-11
^{91}Y		1.02E-08	3.02E-08	6.10E-13	6.17E-12	2.02E-13	3.54E-12	5.61E-13
^{92}Y		3.31E-09	1.74E-09	6.52E-12	4.53E-12	1.39E-12	1.96E-11	1.00E-11
^{93}Y		7.80E-09	8.84E-09	4.74E-12	3.52E-12	8.67E-13	2.20E-11	5.67E-12
^{93}Zr		3.34E-10	1.00E-09	1.09E-13	8.27E-14	1.15E-13	9.23E-14	1.28E-13
^{95}Zr		3.05E-09	7.81E-09	1.13E-10	7.78E-11	2.34E-11	8.16E-10	1.05E-10
^{97}Zr		1.21E-08	1.79E-08	1.10E-10	7.97E-11	1.76E-11	6.22E-10	1.07E-10
^{97}Nb	0.9470	Note: Contribution included with parent.						
^{97}Nb	0.0530	2.20E-10	4.75E-11	6.84E-12	4.36E-12	1.98E-12	1.45E-11	1.66E-11
^{93m}Nb		4.96E-10	1.47E-09	3.44E-11	2.47E-12	2.45E-12	5.77E-12	2.53E-12
^{94}Nb		5.19E-09	1.25E-08	6.95E-10	2.82E-10	1.72E-10	1.80E-09	3.73E-10
^{95m}Nb		2.59E-09	6.47E-09	1.80E-11	8.02E-12	2.82E-12	9.30E-11	1.14E-11
^{95}Nb		1.82E-09	4.00E-09	1.37E-10	8.29E-11	2.74E-11	8.05E-10	1.12E-10
^{97m}Nb		1.82E-09	4.00E-09	1.37E-10	8.29E-11	2.74E-11	8.05E-10	1.12E-10
^{97}Nb		2.20E-10	4.75E-11	6.84E-12	4.36E-12	1.98E-12	1.45E-11	1.66E-11
^{93}Mo		1.33E-10	1.81E-10	1.65E-09	1.80E-09	1.06E-10	1.27E-10	1.07E-10
^{99}Mo		5.75E-09	1.37E-08	1.77E-10	1.79E-10	1.51E-11	2.18E-10	3.84E-11
^{99m}Tc	0.8760	3.70E-11	2.54E-11	5.19E-12	4.72E-12	3.14E-12	9.75E-12	1.07E-11
^{99m}Tc		3.70E-11	2.54E-11	5.19E-12	4.72E-12	3.14E-12	9.75E-12	1.07E-11
^{99}Tc		4.05E-10	1.10E-09	6.04E-11	8.23E-11	6.04E-11	6.04E-11	6.04E-11
^{101}Tc		4.95E-12	7.57E-13	8.27E-13	5.37E-13	4.13E-13	6.29E-13	3.24E-12
^{103}Ru		2.53E-09	6.53E-09	1.31E-10	1.12E-10	7.31E-11	5.72E-10	1.28E-10
^{105}Ru		1.59E-09	1.34E-09	2.70E-11	1.92E-11	6.21E-12	9.67E-11	3.86E-11
^{106}Ru		2.47E-08	7.09E-08	1.45E-09	1.44E-09	1.42E-09	1.64E-09	1.45E-09
^{106}Rh	1.0000	Note: Contribution included with parent.						
^{103m}Rh		9.05E-12	1.45E-12	4.76E-15	4.96E-15	4.93E-15	4.02E-14	4.46E-14
^{105}Rh		1.89E-09	3.79E-09	1.06E-11	8.37E-12	3.86E-12	5.80E-11	1.12E-11
^{103}Pd		8.30E-10	2.32E-09	2.04E-11	1.13E-11	1.28E-13	4.13E-11	7.75E-13
^{103m}Rh	0.99974	9.05E-12	1.45E-12	4.76E-15	4.96E-15	4.93E-15	4.02E-14	4.46E-14
^{107}Pd		1.57E-10	4.72E-10	6.71E-12	3.47E-12	9.91E-15	9.91E-15	9.91E-15
^{109}Pd		3.53E-09	4.73E-09	6.76E-12	3.68E-12	1.49E-13	7.90E-12	8.68E-13
^{110m}Ag		5.86E-09	1.08E-08	1.50E-09	8.62E-09	8.30E-10	2.99E-09	1.64E-09
^{110}Ag	0.0133	Note: Contribution included with parent.						
^{111}Ag		5.40E-09	1.48E-08	1.24E-11	9.20E-10	8.84E-12	3.58E-11	1.27E-11
^{109}Cd		1.80E-09	4.62E-09	4.08E-08	7.38E-09	3.17E-10	3.46E-10	3.55E-10
^{113m}Cd		6.43E-09	1.25E-08	5.64E-07	9.72E-08	3.44E-09	3.44E-09	3.44E-09
^{115m}Cd		9.89E-09	2.89E-08	2.58E-08	4.47E-09	1.64E-10	1.84E-10	1.74E-10

Table E.4 Ingestion organ dose equivalent factors for organ set 2 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		ULI wall	LLI wall	Kidneys	Liver	Lungs	Ovaries	Pancreas
^{115}Cd		6.30E-09	1.50E-08	9.94E-10	2.07E-10	1.65E-11	3.17E-10	5.29E-11
^{115m}In	1.0000	5.74E-10	3.55E-10	6.04E-12	4.17E-12	1.03E-12	2.20E-11	8.38E-12
^{111}In		1.07E-09	2.01E-09	6.76E-11	4.71E-11	8.35E-12	4.15E-10	5.53E-11
^{114m}In		1.49E-08	4.36E-08	3.97E-09	1.98E-09	1.23E-10	2.49E-10	1.41E-10
^{114}In	0.9570	Note: Contribution included with parent.						
^{115m}In		5.74E-10	3.55E-10	6.04E-12	4.17E-12	1.03E-12	2.20E-11	8.38E-12
^{117m}Sn		2.90E-09	7.94E-09	2.48E-11	1.77E-11	5.50E-12	2.23E-10	2.61E-11
^{119m}Sn		1.37E-09	4.04E-09	9.34E-12	9.46E-12	9.20E-12	4.11E-11	9.95E-12
^{121m}Sn		1.14E-09	4.47E-09	2.89E-11	2.90E-11	2.90E-11	4.31E-11	2.93E-11
^{121}Sn		1.27E-09	2.36E-09	2.00E-13	2.00E-13	2.00E-13	2.00E-13	2.00E-13
^{123}Sn		8.68E-09	2.59E-08	3.24E-11	3.20E-11	3.15E-11	3.80E-11	3.23E-11
^{125}Sn		1.32E-08	3.67E-08	4.95E-11	3.65E-11	1.60E-11	2.88E-10	4.69E-11
^{126}Sn		1.57E-08	4.33E-08	8.19E-10	6.85E-10	5.99E-10	2.41E-09	7.78E-10
^{126m}Sb	1.0000	2.59E-11	7.59E-12	4.53E-12	2.77E-12	1.88E-12	5.29E-12	1.72E-11
^{124}Sb		8.85E-09	2.33E-08	2.55E-10	2.18E-10	5.40E-11	1.78E-09	2.40E-10
^{125}Sb		2.22E-09	5.79E-09	1.13E-10	2.49E-10	6.03E-11	5.24E-10	1.15E-10
^{126m}Sb		2.59E-11	7.59E-12	4.53E-12	2.77E-12	1.88E-12	5.29E-12	1.72E-11
^{126}Sb		8.48E-09	1.94E-08	3.93E-10	2.99E-10	6.85E-11	2.89E-09	3.71E-10
^{127}Sb		7.31E-09	1.96E-08	8.71E-11	7.35E-11	1.57E-11	6.14E-10	8.40E-11
^{123m}Te		1.67E-09	4.54E-09	1.20E-10	1.03E-10	1.10E-10	2.75E-10	1.29E-10
^{125m}Te		1.67E-09	4.72E-09	4.18E-11	4.23E-11	4.36E-11	1.27E-10	4.42E-11
^{127m}Te		3.07E-09	1.11E-08	9.52E-11	9.49E-11	9.62E-11	1.25E-10	9.59E-11
^{127}Te		1.17E-09	1.26E-09	3.09E-12	3.02E-12	2.89E-12	4.02E-12	3.17E-12
^{129m}Te		8.41E-09	2.47E-08	1.66E-10	1.62E-10	1.59E-10	2.41E-10	1.65E-10
^{129}Te	0.6500	1.86E-10	3.70E-11	8.84E-13	6.82E-13	4.91E-13	1.59E-12	1.91E-12
^{129}Te		1.86E-10	3.70E-11	8.84E-13	6.82E-13	4.91E-13	1.59E-12	1.91E-12
^{131m}Te		4.65E-09	8.23E-09	1.58E-10	1.24E-10	6.26E-11	7.38E-10	1.65E-10
^{131}Te	0.2220	5.26E-10	1.49E-10	7.27E-12	5.28E-12	3.39E-12	1.57E-11	1.44E-11
^{131}Te		5.26E-10	1.49E-10	7.27E-12	5.28E-12	3.39E-12	1.57E-11	1.44E-11
^{132}Te		1.87E-09	3.80E-09	3.72E-10	3.65E-10	3.30E-10	5.41E-10	3.69E-10
^{132}I	1.0000	3.32E-11	2.77E-11	3.26E-11	2.84E-11	2.64E-11	2.33E-11	7.73E-11
^{133m}Te		2.74E-10	5.66E-11	2.06E-11	1.40E-11	8.33E-12	3.68E-11	5.16E-11
^{133}Te	0.1300	9.53E-12	1.92E-12	2.09E-12	1.43E-12	1.22E-12	1.85E-12	7.48E-12
^{133}Te		9.53E-12	1.92E-12	2.09E-12	1.43E-12	1.22E-12	1.85E-12	7.48E-12
^{134}Te		7.32E-11	2.43E-11	1.77E-11	1.57E-11	1.29E-11	2.03E-11	2.91E-11
^{134}I	1.0000	1.75E-11	1.29E-11	1.75E-11	1.40E-11	1.26E-11	1.10E-11	5.39E-11
^{125}I		3.10E-11	2.97E-11	2.71E-11	2.94E-11	4.08E-11	2.93E-11	3.33E-11
^{129}I		1.42E-10	1.39E-10	1.34E-10	1.38E-10	1.65E-10	1.38E-10	1.41E-10
^{130}I		7.00E-11	6.36E-11	6.78E-11	6.40E-11	7.18E-11	5.31E-11	1.20E-10
^{131}I		4.43E-11	4.24E-11	4.51E-11	4.95E-11	1.02E-10	4.07E-11	5.98E-11
^{132}I		3.32E-11	2.77E-11	3.26E-11	2.84E-11	2.64E-11	2.33E-11	7.73E-11
^{133}I		4.08E-11	3.89E-11	3.99E-11	3.93E-11	4.53E-11	3.57E-11	5.57E-11

Table E.4 Ingestion organ dose equivalent factors for organ set 2 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		ULI wall	LLI wall	Kidneys	Liver	Lungs	Ovaries	Pancreas
^{134}I		1.75E-11	1.29E-11	1.75E-11	1.40E-11	1.26E-11	1.10E-11	5.39E-11
^{135}I		4.19E-11	3.93E-11	4.08E-11	3.82E-11	3.75E-11	3.61E-11	7.60E-11
^{135m}Xe	0.1540	Note: Contribution included with parent.						
^{134m}Cs		7.20E-12	7.11E-12	6.88E-12	6.83E-12	6.42E-12	6.48E-12	7.82E-12
^{134}Cs		2.14E-08	2.19E-08	2.01E-08	2.01E-08	1.76E-08	1.81E-08	1.94E-08
^{135}Cs		1.91E-09	1.91E-09	1.91E-09	1.91E-09	1.91E-09	1.91E-09	1.91E-09
^{136}Cs		3.29E-09	3.40E-09	3.16E-09	3.15E-09	2.62E-09	2.71E-09	3.08E-09
^{137}Cs		1.42E-08	1.44E-08	1.37E-08	1.36E-08	1.27E-08	1.29E-08	1.34E-08
^{137m}Ba	0.9460	Note: Contribution included with parent.						
^{138}Cs		1.20E-11	8.77E-12	1.16E-11	9.44E-12	8.53E-12	8.00E-12	3.56E-11
^{139}Ba		4.38E-10	9.86E-11	7.95E-13	6.02E-13	3.89E-13	1.56E-12	1.58E-12
^{140}Ba		7.75E-09	2.64E-08	1.51E-10	1.17E-10	6.63E-11	9.96E-10	1.36E-10
^{141}Ba		2.16E-10	1.15E-10	2.52E-12	1.60E-12	1.10E-12	2.86E-12	9.16E-12
^{142}Ba		9.37E-11	2.43E-11	4.97E-12	3.37E-12	1.67E-12	9.88E-12	1.33E-11
^{140}La		9.12E-09	1.75E-08	2.23E-10	1.69E-10	4.01E-11	1.34E-09	2.19E-10
^{141}La		2.46E-09	1.45E-09	1.20E-12	1.26E-12	2.72E-13	3.77E-12	1.75E-12
^{142}La		7.18E-10	1.91E-10	2.96E-11	2.08E-11	8.40E-12	6.99E-11	6.42E-11
^{141}Ce		2.99E-09	8.64E-09	1.19E-11	1.96E-11	1.43E-12	1.08E-10	1.23E-11
^{143}Ce		5.71E-09	1.17E-08	2.79E-11	2.18E-11	3.82E-12	2.12E-10	2.97E-11
^{144}Ce		2.22E-08	6.64E-08	1.30E-11	6.91E-10	6.52E-12	6.98E-11	1.30E-11
^{144m}Pr	0.0178	Note: Contribution included with parent.						
^{144}Pr	1.0000	1.78E-11	9.68E-13	7.26E-14	4.72E-14	3.15E-14	7.38E-14	2.76E-13
^{143}Pr		5.15E-09	1.47E-08	1.70E-12	8.23E-12	1.91E-19	8.99E-18	1.13E-18
^{144}Pr		1.78E-11	9.68E-13	7.26E-14	4.72E-14	3.15E-14	7.38E-14	2.76E-13
^{147}Nd		4.63E-09	1.28E-08	1.91E-11	1.88E-11	2.44E-12	1.79E-10	1.90E-11
^{147}Pm		1.05E-09	3.17E-09	8.46E-16	6.97E-11	1.96E-16	6.86E-15	8.80E-16
^{148m}Pm		5.79E-09	1.37E-08	2.83E-10	2.25E-10	4.44E-11	2.18E-09	2.66E-10
^{148}Pm		1.19E-08	3.10E-08	6.99E-11	5.57E-11	1.19E-11	4.72E-10	6.47E-11
^{149}Pm		5.00E-09	1.14E-08	1.23E-12	1.89E-12	1.62E-13	9.19E-12	1.26E-12
^{151}Pm		3.85E-09	7.05E-09	3.07E-11	2.23E-11	4.23E-12	2.11E-10	3.26E-11
^{147}Sm		7.49E-09	2.30E-08	0.00E+00	2.36E-07	0.00E+00	0.00E+00	0.00E+00
^{151}Sm		3.37E-10	1.01E-09	5.16E-16	9.21E-11	6.52E-16	2.12E-14	7.36E-16
^{153}Sm		3.73E-09	8.18E-09	7.19E-12	5.80E-12	7.13E-13	7.17E-11	8.06E-12
^{152}Eu		4.21E-09	1.00E-08	4.65E-10	2.99E-09	2.40E-10	1.33E-09	4.71E-10
^{154}Eu		6.87E-09	1.80E-08	4.49E-10	3.69E-09	2.16E-10	1.37E-09	4.44E-10
^{155}Eu		1.21E-09	3.45E-09	2.37E-11	4.13E-10	9.64E-12	9.83E-11	2.23E-11
^{156}Eu		8.63E-09	2.28E-08	1.86E-10	1.59E-10	3.24E-11	1.22E-09	1.64E-10
^{153}Gd		1.02E-09	2.71E-09	1.69E-11	2.75E-11	2.19E-12	1.97E-10	1.74E-11
^{160}Tb		5.91E-09	1.56E-08	1.63E-10	1.34E-10	2.72E-11	1.17E-09	1.48E-10
^{166m}Ho		4.97E-09	1.12E-08	5.17E-10	2.05E-09	2.16E-10	2.05E-09	3.10E-09
^{181}W		2.81E-10	7.11E-10	8.70E-12	4.97E-12	6.23E-13	7.33E-11	6.60E-12
^{185}W		2.12E-09	6.32E-09	1.32E-11	2.35E-12	9.45E-16	8.74E-14	9.32E-15

Table E.4 Ingestion organ dose equivalent factors for organ set 2 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		ULI wall	LLI wall	Kidneys	Liver	Lungs	Ovaries	Pancreas
^{187}W		3.56E-09	5.99E-09	4.34E-11	3.03E-11	6.39E-12	2.59E-10	4.38E-11
^{187}Re		2.64E-12	7.16E-12	3.94E-13	5.37E-13	3.94E-13	3.94E-13	3.94E-13
^{185}Os		1.44E-09	2.83E-09	2.48E-10	2.48E-10	5.24E-11	8.35E-10	1.60E-10
^{191}Os		2.37E-09	6.61E-09	5.92E-11	5.05E-11	5.06E-12	1.18E-10	1.69E-11
^{192}Ir		4.90E-09	1.29E-08	4.81E-10	4.43E-10	6.54E-11	1.03E-09	1.92E-10
^{198}Au		4.67E-09	1.07E-08	6.25E-11	4.95E-11	2.44E-11	3.43E-10	6.38E-11
^{203}Hg		1.45E-09	1.34E-09	1.88E-08	1.42E-09	1.23E-09	1.37E-09	1.68E-09
^{210}Pb		1.26E-07	1.30E-07	2.81E-06	6.08E-06	1.25E-07	1.25E-07	1.25E-07
^{212}Pb		1.67E-08	1.99E-08	1.09E-08	2.21E-08	1.63E-09	1.96E-09	1.69E-09
^{212}Bi	1.0000	6.61E-10	1.27E-10	1.11E-09	1.36E-11	9.86E-12	2.76E-11	3.18E-11
^{212}Po	0.6407	Note: Contribution included with parent.						
^{208}Tl	0.3593	Note: Contribution included with parent.						
^{210}Bi		5.77E-09	1.54E-08	5.88E-09	1.97E-11	1.97E-11	1.97E-11	1.97E-11
^{212}Bi		6.61E-10	1.27E-10	1.11E-09	1.36E-11	9.86E-12	2.76E-11	3.18E-11
^{212}Po	0.6407	Note: Contribution included with parent.						
^{208}Tl	0.3593	Note: Contribution included with parent.						
^{210}Po		9.82E-08	1.31E-07	2.55E-06	4.39E-07	8.23E-08	8.23E-08	8.23E-08
^{222}Rn		9.82E-08	1.31E-07	2.55E-06	4.39E-07	8.23E-08	8.23E-08	8.23E-08
^{218}Po	1.0000	Note: Contribution included with parent.						
^{214}Pb	1.0000	2.49E-10	4.89E-11	4.17E-11	5.68E-11	2.32E-11	3.19E-11	3.86E-11
^{214}Bi	1.0000	5.86E-11	7.31E-12	6.25E-11	3.25E-12	2.38E-12	5.17E-12	1.58E-11
^{214}Po	0.9998	Note: Contribution included with parent.						
^{223}Ra		1.25E-07	2.77E-07	4.23E-08	4.23E-08	4.23E-08	4.26E-08	4.23E-08
^{219}Rn	1.000	Note: Contribution included with parent.						
^{215}Po	1.000	Note: Contribution included with parent.						
^{211}Pb	1.000	2.27E-10	4.14E-11	2.73E-11	3.68E-11	1.90E-11	1.97E-11	2.06E-11
^{211}Bi	1.000	Note: Contribution included with parent.						
^{211}Po	0.0028	Note: Contribution included with parent.						
^{207}Tl	0.9972	Note: Contribution included with parent.						
^{224}Ra		8.25E-08	1.99E-07	2.06E-08	2.06E-08	2.05E-08	2.12E-08	2.06E-08
^{220}Rn	1.000	Note: Contribution included with parent.						
^{216}Po	1.000	Note: Contribution included with parent.						
^{225}Ra		3.91E-08	6.39E-08	3.37E-08	3.37E-08	3.37E-08	3.37E-08	3.37E-08
^{226}Ra		1.05E-07	1.31E-07	9.16E-08	9.15E-08	9.16E-08	9.16E-08	9.17E-08
^{228}Ra		1.63E-07	1.78E-07	1.57E-07	1.57E-07	1.57E-07	1.58E-07	1.57E-07
^{228}Ac	1.0000	2.42E-09	1.90E-09	3.88E-11	8.20E-10	7.34E-12	1.79E-10	5.05E-11
^{225}Ac		9.77E-08	2.82E-07	2.96E-11	2.70E-08	3.98E-12	1.36E-09	2.60E-11
^{221}Fr	1.000	Note: Contribution included with parent.						
^{217}At	1.000	Note: Contribution included with parent.						
^{213}Bi	1.000	4.27E-10	1.04E-10	6.05E-10	4.92E-12	4.56E-12	6.17E-12	7.69E-12
^{213}Po	0.9784	Note: Contribution included with parent.						
^{209}Tl	0.0216	Note: Contribution included with parent.						

Table E.4 Ingestion organ dose equivalent factors for organ set 2 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		ULI wall	LLI wall	Kidneys	Liver	Lungs	Ovaries	Pancreas
^{209}Pb	1.000	3.50E-10	1.73E-10	1.66E-12	3.02E-12	5.37E-13	5.37E-13	5.37E-13
^{227}Ac		1.52E-09	7.66E-09	2.95E-10	1.54E-05	2.20E-10	8.31E-07	3.24E-10
^{223}Fr	0.0138	2.32E-09	2.32E-09	2.32E-09	2.32E-09	2.32E-09	2.32E-09	2.32E-09
^{228}Ac		2.42E-09	1.90E-09	3.88E-11	8.20E-10	7.34E-12	1.79E-10	5.05E-11
^{227}Th		2.53E-08	9.13E-08	1.41E-10	1.06E-09	1.25E-10	2.95E-10	1.40E-10
^{228}Th		3.11E-08	1.32E-07	2.33E-09	2.01E-08	2.31E-09	2.53E-09	2.32E-09
^{229}Th		2.32E-08	6.32E-08	4.57E-09	3.98E-08	4.56E-09	4.69E-09	4.57E-09
^{230}Th		1.65E-08	4.93E-08	6.80E-10	5.94E-09	6.80E-10	6.82E-10	6.80E-10
^{231}Th		1.90E-09	3.42E-09	1.26E-12	9.78E-13	1.43E-13	2.08E-11	1.72E-12
^{232}Th		1.47E-08	4.27E-08	1.25E-09	1.02E-08	1.25E-09	1.25E-09	1.25E-09
^{234}Th		1.47E-08	4.30E-08	3.71E-12	4.17E-12	7.05E-13	3.12E-11	3.49E-12
^{234m}Pa	0.9980	Note: Contribution included with parent.						
^{234}Pa	0.0020	3.13E-09	2.46E-09	8.29E-11	5.88E-11	1.51E-11	3.30E-10	1.06E-10
^{231}Pa		1.75E-08	5.35E-08	6.79E-09	4.36E-09	6.80E-11	1.21E-10	7.19E-11
^{233}Pa		3.62E-09	1.02E-08	3.40E-11	2.41E-11	3.70E-12	2.58E-10	2.93E-11
^{234}Pa		3.13E-09	2.46E-09	8.29E-11	5.88E-11	1.51E-11	3.30E-10	1.06E-10
^{232}U		2.53E-08	6.09E-08	1.57E-06	8.21E-09	8.29E-09	8.27E-09	8.30E-09
^{233}U		1.80E-08	4.98E-08	4.74E-07	2.62E-09	2.62E-09	2.62E-09	2.62E-09
^{234}U		1.79E-08	4.95E-08	4.68E-07	2.58E-09	2.58E-09	2.59E-09	2.58E-09
^{235}U		1.84E-08	5.31E-08	4.33E-07	2.46E-09	2.46E-09	2.67E-09	2.49E-09
^{236}U		1.69E-08	4.68E-08	4.43E-07	2.45E-09	2.45E-09	2.45E-09	2.45E-09
^{237}U		3.37E-09	8.89E-09	2.96E-11	1.33E-11	2.17E-12	1.81E-10	2.02E-11
^{238}U		1.61E-08	4.57E-08	4.15E-07	2.30E-09	2.30E-09	2.31E-09	2.30E-09
^{240}U		6.99E-09	9.50E-09	2.62E-11	1.62E-11	3.69E-12	1.24E-10	2.35E-11
^{240m}Np	1.0000	Note: Contribution included with parent.						
^{237}Np		1.74E-08	5.32E-08	1.65E-10	9.73E-07	1.53E-10	2.46E-07	1.78E-10
^{238}Np		4.20E-09	8.93E-09	6.00E-11	1.07E-10	1.02E-11	3.89E-10	5.74E-11
^{239}Np		3.85E-09	8.72E-09	2.05E-11	1.54E-11	2.40E-12	1.62E-10	2.16E-11
^{236}Pu		1.94E-08	5.96E-08	4.34E-13	1.13E-08	3.49E-13	7.85E-10	4.93E-13
^{237}Pu		3.96E-10	1.03E-09	7.30E-12	4.93E-12	7.54E-13	7.22E-11	7.56E-12
^{238}Pu		1.85E-08	5.68E-08	9.03E-14	2.92E-08	8.64E-14	2.33E-09	1.21E-13
^{239}Pu		1.73E-08	5.31E-08	8.78E-14	3.14E-08	7.89E-14	2.64E-09	9.95E-14
^{240}Pu		1.74E-08	5.34E-08	8.69E-14	3.14E-08	8.22E-14	2.64E-09	1.17E-13
^{241}Pu		8.96E-11	2.70E-10	5.15E-15	5.44E-10	4.48E-15	5.66E-11	5.56E-15
^{242}Pu		1.65E-08	5.06E-08	1.75E-13	2.98E-08	9.18E-14	2.51E-09	1.98E-13
^{243}Pu		5.99E-10	4.10E-10	9.94E-13	6.19E-13	1.47E-13	4.56E-12	1.57E-12
^{244}Pu		2.39E-08	8.35E-08	4.94E-11	2.96E-08	9.29E-12	2.94E-09	4.38E-11
^{241}Am		1.90E-08	5.82E-08	3.99E-11	3.25E-06	3.36E-11	2.70E-07	4.24E-11
^{242m}Am		2.38E-09	9.72E-09	1.94E-11	3.09E-06	1.65E-11	2.66E-07	2.04E-11
^{242}Am		1.66E-09	2.54E-09	1.17E-12	3.84E-10	1.58E-13	2.74E-11	1.46E-12
^{243}Am		1.91E-08	6.03E-08	2.58E-10	3.22E-06	1.95E-10	2.71E-07	2.76E-10
^{242}Cm		2.05E-08	6.25E-08	8.84E-12	1.13E-07	8.84E-12	5.20E-09	8.88E-12

Table E.4 Ingestion organ dose equivalent factors for organ set 2 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		ULI wall	LLI wall	Kidneys	Liver	Lungs	Ovaries	Pancreas
^{243}Cm		2.20E-08	6.69E-08	1.15E-10	2.39E-06	7.73E-11	1.73E-07	1.21E-10
^{244}Cm		1.95E-08	5.97E-08	8.75E-12	1.99E-06	8.81E-12	1.33E-07	8.77E-12
^{245}Cm		1.93E-08	5.86E-08	1.17E-10	3.31E-06	8.34E-11	2.80E-07	1.24E-10
^{246}Cm		1.83E-08	5.62E-08	5.80E-11	3.30E-06	2.67E-11	2.77E-07	5.30E-11
^{247}Cm		1.98E-08	6.06E-08	3.88E-10	3.03E-06	2.66E-10	2.56E-07	4.32E-10
^{243}Pu	1.0000	5.99E-10	4.10E-10	9.94E-13	6.91E-13	1.47E-13	4.56E-12	1.57E-12
^{248}Cm		1.06E-07	2.88E-07	1.78E-08	1.20E-05	6.52E-09	1.02E-06	1.60E-08
^{252}Cf		5.25E-08	1.53E-07	1.60E-09	5.65E-07	4.67E-10	5.39E-08	1.46E-09

Table E.5 Ingestion organ dose equivalent factors for organ set 3

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		R marrow	Skin	Spleen	Testes	Thymus	Thyroid	Uterus
^{3}H		1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11
^{10}Be		7.23E-10	2.42E-11	2.42E-11	2.42E-11	2.42E-11	2.42E-11	2.42E-11
^{14}C		5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10
^{18}F		5.94E-11	4.25E-12	1.72E-11	2.27E-12	3.33E-12	4.52E-12	3.57E-12
^{22}Na		4.29E-09	1.91E-09	2.73E-09	2.69E-09	2.52E-09	2.50E-09	2.86E-09
^{24}Na		3.74E-10	2.11E-10	3.14E-10	2.82E-10	3.02E-10	2.60E-10	3.26E-10
^{32}P		8.09E-09	6.55E-10	6.55E-10	6.55E-10	6.55E-10	6.55E-10	6.55E-10
^{33}P		4.99E-10	9.37E-11	9.37E-11	9.37E-11	9.37E-11	9.37E-11	9.37E-11
^{35}S		9.53E-12	9.53E-12	9.53E-12	9.53E-12	9.53E-12	9.53E-12	9.53E-12
^{36}Cl		7.99E-10	7.99E-10	7.99E-10	7.99E-10	7.99E-10	7.99E-10	7.99E-10
^{40}K		4.91E-09	4.76E-09	4.91E-09	4.93E-09	5.02E-09	4.85E-09	4.96E-09
^{41}Ca		1.78E-09	3.34E-12	3.64E-12	2.60E-12	3.03E-12	2.84E-12	2.60E-12
^{45}Ca		3.47E-09	5.36E-11	5.36E-11	5.36E-11	5.36E-11	5.36E-11	5.36E-11
^{46}Sc		4.03E-10	9.68E-11	2.43E-10	1.76E-10	2.18E-11	7.69E-12	8.52E-10
^{51}Cr		1.25E-11	3.95E-12	7.46E-12	6.78E-12	5.04E-12	3.71E-12	1.88E-11
^{54}Mn		4.89E-10	1.60E-10	2.65E-10	2.11E-10	1.60E-10	1.33E-10	5.03E-10
^{56}Mn		2.43E-11	7.84E-12	3.54E-11	7.70E-12	4.45E-12	2.40E-12	5.88E-11
^{55}Fe		1.05E-10	9.99E-11	5.64E-10	1.05E-10	1.03E-10	1.10E-10	1.05E-10
^{59}Fe		8.45E-10	5.03E-10	1.82E-09	7.47E-10	6.32E-10	6.03E-10	1.25E-09
^{57}Co		2.67E-10	1.04E-10	1.80E-10	1.38E-10	1.66E-10	1.15E-10	2.48E-10
^{58}Co		5.40E-10	2.75E-10	5.10E-10	4.91E-10	3.54E-10	3.64E-10	7.85E-10
^{60}Co		5.49E-09	3.54E-09	5.58E-09	5.42E-09	5.27E-09	4.68E-09	7.13E-09
^{59}Ni		3.66E-11	3.40E-11	3.74E-11	3.65E-11	3.53E-11	3.90E-11	3.66E-11
^{63}Ni		8.50E-11	8.50E-11	8.50E-11	8.50E-11	8.50E-11	8.50E-11	8.50E-11
^{65}Ni		7.26E-12	2.51E-12	1.17E-11	2.25E-12	1.43E-12	6.79E-13	1.93E-11
^{64}Cu		1.94E-11	1.14E-11	1.88E-11	1.47E-11	1.16E-11	1.13E-11	2.83E-11
^{65}Zn		4.50E-09	2.29E-09	3.63E-09	3.56E-09	3.03E-09	3.21E-09	4.72E-09
^{69m}Zn		9.15E-11	3.31E-11	5.04E-11	4.10E-11	3.51E-11	3.28E-11	7.49E-11
^{69}Zn	0.9997	5.36E-13	4.17E-13	4.17E-13	4.17E-13	4.17E-13	4.17E-13	4.17E-13
^{69}Zn		5.36E-13	4.17E-13	4.17E-13	4.17E-13	4.17E-13	4.17E-13	4.17E-13
^{76}As		1.20E-10	9.52E-11	2.44E-10	1.06E-10	9.54E-11	9.35E-11	1.50E-10
^{75}Se		2.07E-09	8.76E-10	3.65E-09	1.18E-09	1.85E-09	1.13E-09	1.90E-09
^{79}Se		9.06E-10	9.06E-10	4.32E-09	9.06E-10	9.06E-10	9.06E-10	9.06E-10
^{82}Br		4.14E-10	2.65E-10	4.83E-10	4.48E-10	3.87E-10	3.83E-10	5.05E-10
^{83}Br		7.35E-12	7.31E-12	7.45E-12	7.34E-12	7.33E-12	7.33E-12	7.35E-12
^{83m}Kr	1.0000	Note: Contribution included with parent.						
^{84}Br		6.21E-12	5.19E-12	1.62E-11	5.27E-12	5.88E-12	5.20E-12	6.93E-12
^{86}Rb		3.72E-09	2.11E-09	2.16E-09	2.15E-09	2.13E-09	2.14E-09	2.20E-09
^{88}Rb		2.76E-12	2.52E-12	5.24E-12	2.45E-12	2.61E-12	2.43E-12	2.77E-12
^{89}Rb		3.53E-12	2.47E-12	1.09E-11	2.26E-12	2.76E-12	2.21E-12	3.25E-12
^{85}Sr		5.97E-10	1.66E-10	2.39E-10	2.15E-10	1.78E-10	2.05E-10	3.27E-10
^{89}Sr		3.23E-09	2.40E-10	2.40E-10	2.40E-10	2.40E-10	2.40E-10	2.40E-10

Table E.5 Ingestion organ dose equivalent factors for organ set 3 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		R marrow	Skin	Spleen	Testes	Thymus	Thyroid	Uterus
^{90}Sr		1.94E-07	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09	1.51E-09
^{91}Sr		5.53E-11	1.38E-11	4.21E-11	1.98E-11	4.51E-12	1.90E-12	1.26E-10
^{91m}Y	0.5780	2.24E-12	7.09E-13	6.39E-12	3.23E-13	2.67E-13	1.17E-13	5.75E-12
^{90}Y		3.70E-13	1.26E-14	1.26E-14	1.26E-14	1.26E-14	1.26E-14	1.26E-14
^{91m}Y		2.24E-12	7.09E-13	6.39E-12	3.23E-13	2.67E-13	1.17E-13	5.75E-12
^{91}Y		6.59E-12	2.90E-13	5.08E-13	4.14E-13	1.54E-13	1.29E-13	1.63E-12
^{92}Y		4.91E-12	1.40E-12	6.46E-12	1.39E-12	5.90E-13	1.77E-13	1.30E-11
^{93}Y		4.93E-12	1.21E-12	3.87E-12	1.77E-12	3.60E-13	1.26E-13	1.13E-11
^{93}Zr		7.42E-10	2.25E-13	1.83E-13	4.62E-14	1.05E-13	7.31E-14	4.75E-14
^{95}Zr		2.14E-10	4.19E-11	8.83E-11	8.04E-11	1.31E-11	8.27E-12	3.33E-10
^{97}Zr		1.30E-10	3.04E-11	8.02E-11	5.21E-11	7.53E-12	2.66E-12	2.83E-10
^{97m}Nb	0.9470	Note: Contribution included with parent.						
^{97}Nb	0.0530	4.20E-12	1.28E-12	9.72E-12	7.83E-13	5.71E-13	2.11E-13	1.11E-11
^{93m}Nb		2.32E-11	2.43E-12	3.29E-11	3.34E-11	2.51E-12	2.44E-12	2.51E-12
^{94}Nb		7.39E-10	1.85E-10	6.27E-10	5.25E-10	1.34E-10	1.23E-10	8.21E-10
^{95m}Nb		3.33E-11	4.24E-12	1.52E-11	1.45E-11	1.97E-12	1.63E-12	3.44E-11
^{95}Nb		1.99E-10	4.40E-11	1.12E-10	9.66E-11	1.65E-11	1.18E-11	3.35E-10
^{97m}Nb		1.99E-10	4.40E-11	1.12E-10	9.66E-11	1.65E-11	1.18E-11	3.35E-10
^{97}Nb		4.20E-12	1.28E-12	9.72E-12	7.83E-13	5.71E-13	2.11E-13	1.11E-11
^{93}Mo		2.82E-10	7.28E-11	9.64E-11	8.30E-11	1.20E-10	9.42E-11	9.43E-11
^{99}Mo		8.32E-11	1.74E-11	3.10E-11	2.72E-11	1.22E-11	1.03E-11	9.93E-11
^{99m}Tc	0.8760	6.29E-12	1.91E-12	7.03E-12	2.29E-12	3.07E-12	8.46E-11	7.17E-12
^{99m}Tc		6.29E-12	1.91E-12	7.03E-12	2.29E-12	3.07E-12	8.46E-11	7.17E-12
^{99}Tc		6.04E-11	6.04E-11	6.04E-11	6.04E-11	6.04E-11	1.62E-09	6.04E-11
^{101}Tc		4.36E-13	2.01E-13	1.85E-12	1.22E-13	1.55E-13	3.89E-12	6.39E-13
^{103}Ru		1.66E-10	6.85E-11	1.18E-10	1.22E-10	6.73E-11	6.25E-11	2.66E-10
^{105}Ru		2.35E-11	6.51E-12	2.50E-11	7.59E-12	3.02E-12	1.82E-12	5.53E-11
^{106}Ru		1.46E-09	1.40E-09	1.45E-09	1.45E-09	1.42E-09	1.41E-09	1.52E-09
^{106}Rh	1.0000	Note: Contribution included with parent.						
^{103m}Rh		1.01E-14	3.58E-15	1.11E-14	3.23E-15	3.32E-15	3.27E-15	1.60E-14
^{105}Rh		1.47E-11	4.69E-12	8.68E-12	7.22E-12	3.41E-12	2.91E-12	2.61E-11
^{103}Pd		6.58E-12	1.83E-13	2.78E-13	1.55E-13	4.87E-14	4.40E-14	1.88E-12
^{103m}Rh	0.99974	1.01E-14	3.58E-15	1.11E-14	3.23E-15	3.32E-15	3.27E-15	1.60E-14
^{107}Pd		5.36E-14	9.91E-15	9.91E-15	9.91E-15	9.91E-15	9.91E-15	9.91E-15
^{109}Pd		2.04E-12	1.80E-13	4.54E-13	2.19E-13	1.03E-13	9.48E-14	1.71E-12
^{110m}Ag		9.42E-10	3.75E-10	7.13E-10	4.37E-10	4.04E-10	1.81E-10	1.41E-09
^{110}Ag	0.0133	Note: Contribution included with parent.						
^{111}Ag		1.38E-11	8.53E-12	1.03E-11	9.85E-12	8.01E-12	7.48E-12	1.90E-11
^{109}Cd		3.70E-10	2.55E-10	4.27E-10	2.57E-10	2.94E-10	2.75E-10	2.87E-10
^{113m}Cd		3.44E-09	3.44E-09	3.44E-09	3.44E-09	3.44E-09	3.44E-09	3.44E-09
^{115m}Cd		1.68E-10	1.62E-10	1.72E-10	1.63E-10	1.62E-10	1.61E-10	1.72E-10
^{115}Cd		7.40E-11	2.05E-11	4.37E-11	3.58E-11	1.23E-11	9.49E-12	1.28E-10

Table E.5 Ingestion organ dose equivalent factors for organ set 3 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		R marrow	Skin	Spleen	Testes	Thymus	Thyroid	Uterus
^{115m}In	1.0000	6.11E-12	1.08E-12	5.23E-12	1.22E-12	3.69E-13	1.86E-13	1.17E-11
^{111}In		1.08E-10	1.39E-11	4.18E-11	3.07E-11	4.56E-12	2.10E-12	1.65E-10
^{114m}In		3.51E-09	1.20E-10	9.94E-10	1.26E-10	1.20E-10	1.17E-10	1.65E-10
^{114}In	0.9570	Note: Contribution included with parent.						
^{115m}In		6.11E-12	1.08E-12	5.23E-12	1.22E-12	3.69E-13	1.86E-13	1.17E-11
^{117m}Sn		1.03E-10	8.32E-12	1.88E-11	1.67E-11	3.79E-12	3.03E-12	8.51E-11
^{119m}Sn		8.07E-11	8.79E-12	9.40E-12	8.92E-12	9.07E-12	8.89E-12	1.24E-11
^{121m}Sn		2.32E-10	2.85E-11	2.90E-11	2.86E-11	2.87E-11	2.86E-11	3.08E-11
^{121}Sn		2.23E-12	2.00E-13	2.00E-13	2.00E-13	2.00E-13	2.00E-13	2.00E-13
^{123}Sn		2.41E-10	3.16E-11	3.21E-11	3.19E-11	3.14E-11	3.13E-11	3.43E-11
^{125}Sn		2.08E-10	2.21E-11	4.03E-11	3.41E-11	1.19E-11	9.78E-12	1.28E-10
^{126}Sn		2.72E-09	5.48E-10	7.28E-10	6.80E-10	5.32E-10	5.51E-10	1.27E-09
^{126m}Sb	1.0000	2.16E-12	8.23E-13	9.71E-12	2.95E-13	4.60E-13	1.73E-13	4.60E-12
^{124}Sb		3.81E-10	9.54E-11	2.00E-10	1.84E-10	3.04E-11	1.76E-11	7.55E-10
^{125}Sb		2.26E-10	5.46E-11	9.43E-11	9.04E-11	5.25E-11	4.62E-11	2.30E-10
^{126m}Sb		2.16E-12	8.23E-13	9.71E-12	2.95E-13	4.60E-13	1.73E-13	4.60E-12
^{126}Sb		5.93E-10	1.32E-10	3.03E-10	2.79E-10	3.44E-11	1.74E-11	1.18E-09
^{127}Sb		1.33E-10	2.90E-11	6.68E-11	5.89E-11	8.28E-12	4.64E-12	2.54E-10
^{123m}Te		2.33E-09	8.69E-11	1.03E-10	9.40E-11	8.54E-11	9.44E-11	1.59E-10
^{125m}Te		1.21E-09	3.82E-11	4.30E-11	3.82E-11	3.92E-11	3.93E-11	5.27E-11
^{127m}Te		5.43E-09	9.37E-11	9.55E-11	9.31E-11	9.34E-11	9.43E-11	9.86E-11
^{127}Te		6.57E-12	2.90E-12	3.06E-12	2.93E-12	2.87E-12	2.86E-12	3.41E-12
^{129m}Te		3.50E-09	1.56E-10	1.63E-10	1.61E-10	1.56E-10	1.57E-10	1.83E-10
^{129}T9	0.6500	7.64E-13	4.17E-13	1.20E-12	3.77E-13	3.61E-13	3.36E-13	1.27E-12
^{129}Te		7.64E-13	4.17E-13	1.20E-12	3.77E-13	3.61E-13	3.36E-13	1.27E-12
^{131m}Te		2.42E-10	6.83E-11	1.33E-10	9.86E-11	7.00E-11	4.29E-08	3.59E-10
^{131}Te	0.2220	6.60E-12	2.72E-12	9.13E-12	2.11E-12	4.23E-12	4.21E-09	1.18E-11
^{131}Te		6.60E-12	2.72E-12	9.13E-12	2.11E-12	4.23E-12	4.21E-09	1.18E-11
^{132}Te		4.44E-10	2.62E-10	3.65E-10	3.63E-10	3.77E-10	5.95E-08	4.63E-10
^{132}I	1.0000	2.46E-11	1.79E-11	5.30E-11	2.21E-11	2.52E-11	3.87E-09	2.69E-11
^{133m}Te		1.31E-11	5.67E-12	3.15E-11	4.45E-12	6.04E-12	4.17E-09	2.96E-11
^{133}Te	0.1300	1.18E-12	6.97E-13	4.42E-12	4.91E-13	9.76E-13	9.39E-10	1.76E-12
^{133}Te		1.18E-12	6.97E-13	4.42E-12	4.91E-13	9.76E-13	9.39E-10	1.76E-12
^{134}Te		1.49E-11	9.82E-12	2.18E-11	1.26E-11	1.21E-11	8.82E-10	2.15E-11
^{134}I	1.0000	1.09E-11	7.90E-12	3.42E-11	8.86E-12	9.95E-12	6.21E-10	1.24E-11
^{125}I		6.82E-11	6.96E-11	3.05E-11	2.38E-11	1.27E-10	3.44E-07	2.94E-11
^{129}I		2.21E-10	2.11E-10	1.40E-10	1.29E-10	3.51E-10	2.48E-06	1.38E-10
^{130}I		6.74E-11	5.05E-11	9.34E-11	5.52E-11	1.14E-10	3.94E-08	6.19E-11
^{131}I		9.44E-11	8.31E-11	5.53E-11	3.77E-11	3.09E-10	4.76E-07	4.29E-11
^{132}I		2.46E-11	1.79E-11	5.30E-11	2.21E-11	2.52E-11	3.87E-09	2.69E-11
^{133}I		4.30E-11	3.74E-11	4.78E-11	3.63E-11	7.15E-11	9.10E-08	3.75E-11
^{134}I		1.09E-11	7.90E-12	3.42E-11	8.86E-12	9.95E-12	6.21E-10	1.24E-11

Table E.5 Ingestion organ dose equivalent factors for organ set 3 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		R marrow	Skin	Spleen	Testes	Thymus	Thyroid	Uterus
^{135}I		3.65E-11	2.94E-11	5.55E-11	3.20E-11	5.12E-11	1.79E-08	3.85E-11
^{135m}Xe	0.1540	Note: Contribution included with parent.						
^{134m}Cs		6.91E-12	5.32E-12	7.30E-12	6.72E-12	6.24E-12	6.22E-12	7.19E-12
^{134}Cs		1.87E-08	1.24E-08	2.01E-08	2.06E-08	1.70E-08	1.76E-08	2.23E-08
^{135}Cs		1.91E-09	1.91E-09	1.91E-09	1.91E-09	1.91E-09	1.91E-09	1.91E-09
^{136}Cs		2.95E-09	1.87E-09	3.14E-09	3.04E-09	2.66E-09	2.74E-09	3.84E-09
^{137}Cs		1.32E-08	1.04E-08	1.37E-08	1.39E-08	1.24E-08	1.26E-08	1.44E-08
^{137m}Ba	0.9460	Note: Contribution included with parent.						
^{138}Cs		7.37E-12	5.93E-12	2.22E-11	6.01E-12	7.04E-12	5.73E-12	7.98E-12
^{139}Ba		8.59E-13	3.35E-13	1.02E-12	3.07E-13	2.89E-13	2.66E-13	1.23E-12
^{140}Ba		4.39E-10	8.58E-11	1.27E-10	1.43E-10	5.84E-11	5.25E-11	4.15E-10
^{141}Ba		1.47E-12	5.58E-13	5.27E-12	3.10E-13	4.08E-13	2.25E-13	2.56E-12
^{142}Ba		3.00E-12	1.09E-12	7.88E-12	8.11E-13	7.09E-13	2.71E-13	7.41E-12
^{140}La		2.81E-10	7.25E-11	1.75E-10	1.22E-10	1.75E-11	6.40E-12	6.28E-10
^{141}La		1.07E-12	2.96E-13	1.18E-12	3.18E-13	1.29E-13	5.29E-14	2.55E-12
^{142}La		1.93E-11	6.54E-12	3.86E-11	5.30E-12	3.21E-12	1.16E-12	5.17E-11
^{141}Ce		3.39E-11	3.14E-12	1.80E-11	7.58E-12	5.15E-13	1.80E-13	4.51E-11
^{143}Ce		5.07E-11	7.48E-12	2.25E-11	1.53E-11	1.43E-12	4.35E-13	8.53E-11
^{144}Ce		8.92E-11	7.39E-12	5.75E-10	1.02E-11	5.54E-12	5.15E-12	3.07E-11
^{144m}Pr	0.0178	Note: Contribution included with parent.						
^{144}Pr	1.0000	3.22E-14	1.51E-14	1.58E-13	6.73E-15	1.05E-14	3.59E-15	6.84E-14
^{143}Pr		1.03E-12	4.01E-19	9.34E-19	8.32E-19	8.24E-20	2.66E-20	3.67E-18
^{144}Pr		3.22E-14	1.51E-14	1.58E-13	6.73E-15	1.05E-14	3.59E-15	6.84E-14
^{147}Nd		5.05E-11	5.77E-12	1.45E-11	1.37E-11	8.94E-13	2.64E-13	6.85E-11
^{147}Pm		2.09E-11	2.11E-16	5.56E-16	4.52E-16	5.49E-17	3.12E-17	2.83E-15
^{148m}Pm		4.41E-10	9.46E-11	2.17E-10	2.05E-10	1.92E-11	6.47E-12	8.76E-10
^{148}Pm		9.85E-11	2.42E-11	5.50E-11	4.30E-11	5.25E-12	1.85E-12	2.11E-10
^{149}Pm		2.27E-12	3.39E-13	9.05E-13	7.49E-13	6.28E-14	1.78E-14	3.81E-12
^{151}Pm		4.94E-11	8.01E-12	2.31E-11	1.61E-11	1.57E-12	4.55E-13	9.01E-11
^{147}Sm		6.87E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{151}Sm		2.76E-11	2.29E-16	1.97E-16	8.37E-17	4.37E-17	3.27E-17	1.02E-15
^{153}Sm		2.72E-11	1.62E-12	5.56E-12	3.63E-12	1.57E-13	2.36E-14	2.87E-11
^{152}Eu		9.19E-10	1.46E-10	2.40E-10	1.58E-10	1.03E-10	6.66E-11	5.94E-10
^{154}Eu		1.15E-09	1.41E-10	2.40E-10	1.60E-10	9.72E-11	5.71E-11	6.15E-10
^{155}Eu		1.56E-10	4.83E-12	1.06E-11	7.49E-12	2.62E-12	1.78E-12	4.33E-11
^{156}Eu		2.56E-10	6.07E-11	1.35E-10	1.17E-10	1.41E-11	5.23E-12	5.14E-10
^{153}Gd		8.07E-11	4.25E-12	1.23E-11	1.04E-11	4.92E-13	2.18E-13	7.23E-11
^{160}Tb		2.54E-10	5.40E-11	1.25E-10	1.01E-10	1.21E-11	4.29E-12	4.93E-10
^{166m}Ho		8.12E-10	1.55E-10	3.95E-10	2.17E-10	1.03E-10	5.53E-11	8.64E-10
^{181}W		3.26E-11	1.66E-12	7.13E-12	4.52E-12	1.19E-13	5.41E-14	3.08E-11
^{185}W		1.64E-12	2.32E-15	1.14E-11	5.92E-15	2.44E-16	7.64E-17	3.87E-14
^{187}W		5.89E-11	1.14E-11	3.33E-11	2.13E-11	2.45E-12	7.70E-13	1.15E-10

Table E.5 Ingestion organ dose equivalent factors for organ set 3 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		R marrow	Skin	Spleen	Testes	Thymus	Thyroid	Uterus
^{187}Re		3.94E-13	3.94E-13	3.94E-13	3.94E-13	3.94E-13	1.05E-11	3.94E-13
^{185}Os		2.16E-10	5.21E-11	2.05E-10	1.02E-10	3.51E-11	2.65E-11	3.60E-10
^{191}Os		4.82E-11	6.13E-12	4.98E-11	1.09E-11	3.96E-12	3.40E-12	5.37E-11
^{192}Ir		2.54E-10	6.80E-11	4.00E-10	1.28E-10	5.36E-11	3.78E-11	4.40E-10
^{198}Au		8.57E-11	2.87E-11	5.21E-11	4.80E-11	2.17E-11	1.85E-11	1.53E-10
^{203}Hg		1.69E-09	1.03E-09	1.65E-09	1.13E-09	1.48E-09	1.29E-09	1.44E-09
^{210}Pb		1.48E-06	1.25E-07	1.25E-07	1.25E-07	1.25E-07	1.25E-07	1.25E-07
^{212}Pb		1.51E-08	1.64E-09	1.67E-09	1.65E-09	1.63E-09	1.62E-09	1.78E-09
^{212}Bi	1.0000	1.29E-11	8.86E-12	2.16E-11	8.22E-12	7.80E-12	7.11E-12	2.30E-11
^{212}Po	0.6407	Note: Contribution included with parent.						
^{208}Tl	0.3593	Note: Contribution included with parent.						
^{210}Bi		1.97E-11	1.97E-11	1.97E-11	1.97E-11	1.97E-11	1.97E-11	1.97E-11
^{212}Bi		1.29E-11	8.86E-12	2.16E-11	8.22E-12	7.80E-12	7.11E-12	2.30E-11
^{212}Po	0.6407	Note: Contribution included with parent.						
^{208}Tl	0.3593	Note: Contribution included with parent.						
^{210}Po		8.23E-08	8.23E-08	4.38E-06	8.23E-08	8.23E-08	8.23E-08	8.23E-08
^{222}Rn		8.23E-08	8.23E-08	4.38E-06	8.23E-08	8.23E-08	8.23E-08	8.23E-08
^{218}Po	1.0000	Note: Contribution included with parent.						
^{214}Pb	1.0000	1.12E-10	2.24E-11	3.15E-11	2.19E-11	2.19E-11	2.14E-11	3.05E-11
^{214}Bi	1.0000	2.51E-12	1.49E-12	9.35E-12	1.05E-12	1.29E-12	8.55E-13	4.76E-12
^{214}Po	0.9998	Note: Contribution included with parent.						
^{223}Ra		2.80E-07	4.23E-08	4.23E-08	4.23E-08	4.23E-08	4.23E-08	4.24E-08
^{219}Rn	1.000	Note: Contribution included with parent.						
^{215}Po	1.000	Note: Contribution included with parent.						
^{211}Pb	1.000	3.07E-11	1.89E-11	1.98E-11	1.89E-11	1.89E-11	1.88E-11	1.96E-11
^{211}Bi	1.000	Note: Contribution included with parent.						
^{211}Po	0.0028	Note: Contribution included with parent.						
^{207}Tl	0.9972	Note: Contribution included with parent.						
^{224}Ra		1.52E-07	2.06E-08	2.06E-08	2.06E-08	2.05E-08	2.05E-08	2.08E-08
^{220}Rn	1.000	Note: Contribution included with parent.						
^{216}Po	1.000	Note: Contribution included with parent.						
^{225}Ra		1.68E-07	3.37E-08	3.37E-08	3.37E-08	3.37E-08	3.37E-08	3.37E-08
^{226}Ra		5.98E-07	9.16E-08	9.15E-08	9.15E-08	9.15E-08	9.15E-08	9.15E-08
^{228}Ra		6.53E-07	1.57E-07	1.57E-07	1.57E-07	1.57E-07	1.57E-07	1.57E-07
^{228}Ac	1.0000	2.75E-10	8.84E-12	3.37E-11	4.38E-11	3.06E-12	9.39E-13	8.43E-11
^{225}Ac		7.99E-09	9.43E-12	2.09E-11	1.14E-09	1.68E-12	5.49E-13	9.95E-11
^{221}Fr	1.000	Note: Contribution included with parent.						
^{217}At	1.000	Note: Contribution included with parent.						
^{213}Bi	1.000	4.89E-12	4.38E-12	6.19E-12	4.27E-12	4.26E-12	4.20E-12	5.89E-12
^{213}Po	0.9784	Note: Contribution included with parent.						
^{209}Tl	0.0216	Note: Contribution included with parent.						
^{209}Pb	1.000	2.19E-12	5.37E-13	5.37E-13	5.37E-13	5.37E-13	5.37E-13	5.37E-13

Table E.5 Ingestion organ dose equivalent factors for organ set 3 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		R marrow	Skin	Spleen	Testes	Thymus	Thyroid	Uterus
^{227}Ac		5.40E-06	8.62E-11	1.07E-10	8.31E-07	9.10E-11	7.55E-11	7.02E-11
^{223}Fr	0.0138	2.32E-09	2.32E-09	2.32E-09	2.32E-09	2.32E-09	2.32E-09	2.32E-09
^{228}Ac		2.75E-10	8.84E-12	3.37E-11	4.38E-11	3.06E-12	9.39E-13	8.43E-11
^{227}Th		5.69E-09	1.28E-10	1.36E-10	1.37E-10	1.24E-10	1.23E-10	1.90E-10
^{228}Th		1.93E-07	2.31E-09	2.32E-09	2.33E-09	2.31E-09	2.30E-09	2.38E-09
^{229}Th		1.91E-06	4.55E-09	4.56E-09	4.56E-09	4.55E-09	4.55E-09	4.60E-09
^{230}Th		2.89E-07	6.80E-10	6.80E-10	6.80E-10	6.80E-10	6.80E-10	6.80E-10
^{231}Th		5.30E-12	2.88E-13	1.00E-12	5.24E-13	3.39E-14	8.80E-15	4.85E-12
^{232}Th		1.48E-06	1.24E-09	1.23E-09	1.23E-09	1.23E-09	1.21E-09	1.22E-09
^{234}Th		1.84E-11	1.31E-12	2.90E-12	2.53E-12	4.15E-13	2.88E-13	1.26E-11
^{234m}Pa	0.9980	Note: Contribution included with parent.						
^{234}Pa	0.0020	7.86E-11	1.87E-11	7.04E-11	2.34E-11	6.06E-12	1.86E-12	1.83E-10
^{231}Pa		5.78E-06	5.45E-11	5.31E-11	4.53E-11	4.02E-11	6.33E-11	6.08E-11
^{233}Pa		6.89E-11	8.58E-12	2.16E-11	2.10E-11	1.41E-12	4.81E-13	1.03E-10
^{234}Pa		7.86E-11	1.87E-11	7.04E-11	2.34E-11	6.06E-12	1.86E-12	1.83E-10
^{232}U		4.19E-07	8.24E-09	8.20E-09	8.26E-09	8.20E-09	8.11E-09	8.14E-09
^{233}U		7.36E-08	2.62E-09	2.62E-09	2.62E-09	2.62E-09	2.62E-09	2.62E-09
^{234}U		7.21E-08	2.58E-09	2.58E-09	2.58E-09	2.58E-09	2.58E-09	2.58E-09
^{235}U		6.81E-08	2.45E-09	2.46E-09	2.45E-09	2.43E-09	2.45E-09	2.52E-09
^{236}U		6.83E-08	2.45E-09	2.45E-09	2.45E-09	2.45E-09	2.45E-09	2.45E-09
^{237}U		5.69E-11	5.04E-12	1.46E-11	1.21E-11	7.42E-13	2.31E-13	7.38E-11
^{238}U		6.80E-08	2.30E-09	2.30E-09	2.30E-09	2.30E-09	2.30E-09	2.30E-09
^{240}U		2.62E-11	5.95E-12	1.69E-11	9.56E-12	1.52E-12	5.59E-13	5.62E-11
^{240m}Np	1.0000	Note: Contribution included with parent.						
^{237}Np		2.18E-06	9.97E-11	1.00E-10	2.46E-07	8.18E-11	1.10E-10	9.69E-11
^{238}Np		2.17E-10	1.84E-11	4.63E-11	4.63E-11	4.58E-12	1.50E-12	1.64E-10
^{239}Np		4.66E-11	5.04E-12	1.51E-11	1.14E-11	8.13E-13	2.07E-13	6.88E-11
^{236}Pu		4.49E-09	2.32E-13	2.38E-13	7.82E-10	2.34E-13	1.56E-13	2.95E-13
^{237}Pu		2.35E-11	1.82E-12	5.47E-12	4.28E-12	2.10E-13	3.28E-14	2.87E-11
^{238}Pu		1.27E-08	9.14E-12	8.89E-14	2.33E-09	8.02E-14	7.99E-14	1.64E-13
^{239}Pu		1.41E-08	8.17E-14	8.47E-14	2.64E-09	7.54E-14	7.50E-14	1.38E-13
^{240}Pu		1.41E-08	8.68E-14	8.50E-14	2.64E-09	7.56E-14	7.51E-14	1.61E-13
^{241}Pu		2.78E-10	1.40E-15	1.77E-15	5.66E-11	1.04E-15	1.01E-15	1.89E-15
^{242}Pu		1.34E-08	1.16E-13	1.50E-13	2.51E-09	7.86E-14	7.38E-14	4.39E-13
^{243}Pu		1.82E-12	1.50E-13	9.46E-13	1.65E-13	3.12E-14	5.50E-15	2.60E-12
^{244}Pu		1.33E-08	1.97E-11	3.64E-11	2.56E-09	4.65E-12	2.22E-12	1.62E-10
^{241}Am		1.45E-06	1.61E-11	1.94E-11	2.70E-07	1.36E-11	1.32E-11	3.00E-11
^{242m}Am		1.41E-06	6.39E-12	7.44E-12	2.66E-07	5.18E-12	3.77E-12	9.83E-12
^{242}Am		1.24E-10	2.41E-13	9.10E-13	1.80E-11	5.60E-14	2.61E-14	3.57E-12
^{243}Am		1.44E-06	7.97E-11	1.00E-10	2.71E-07	7.30E-11	6.80E-11	1.28E-10
^{242}Cm		3.57E-08	8.84E-12	8.83E-12	5.20E-09	8.82E-12	8.82E-12	8.93E-12
^{243}Cm		9.81E-07	3.93E-11	5.35E-11	1.72E-07	3.37E-11	3.15E-11	1.01E-10

Table E.5 Ingestion organ dose equivalent factors for organ set 3 (Continued)

Radio-nuclide	Implicit progeny fraction	Organ name (Sv/Bq)						
		R marrow	Skin	Spleen	Testes	Thymus	Thyroid	Uterus
^{244}Cm		7.82E-07	8.57E-12	8.54E-12	1.33E-07	8.46E-12	8.44E-12	8.61E-12
^{245}Cm		1.49E-06	3.80E-11	5.04E-11	2.80E-07	3.46E-11	3.02E-11	8.40E-11
^{246}Cm		1.48E-06	2.65E-11	2.73E-11	2.77E-07	2.08E-11	1.87E-11	3.44E-11
^{247}Cm		1.36E-06	1.37E-10	1.79E-10	2.55E-07	1.40E-10	1.20E-10	2.57E-10
^{243}Pu	1.0000	1.82E-12	1.50E-13	9.46E-13	1.65E-13	3.12E-14	5.50E-15	2.60E-12
^{248}Cm		5.42E-06	6.60E-09	6.90E-09	1.01E-06	4.63E-09	3.87E-09	9.42E-09
^{252}Cf		4.69E-07	6.71E-10	9.66E-10	4.83E-08	3.12E-10	2.68E-10	3.11E-09

Table E.6 Inhalation class and gastrointestinal tract uptake fractions for internal dose factors

Radionuclide	Inhalation class	GI tract uptake fraction (f1)
^{3}H	V[a]	1.0
^{10}Be	Y	5 E-3
^{14}C	C[b]	1.0
^{18}F	D	1.0
^{22}Na	D	1.0
^{24}Na	D	1.0
^{32}P	W	8E-1
^{33}P	W	8E-1
^{35}S	W	1E-1
^{36}Cl	W	1.0
^{40}K	D	1.0
^{41}Ca	W	3E-1
^{45}Ca	W	3E-1
^{46}Sc	Y	1E-4
^{51}Cr	Y	1E-1
^{54}Mn	W	1E-1
^{56}Mn	D	1E-1
^{55}Fe	D	1E-1
^{59}Fe	D	1E-1
^{57}Co	Y	3E-1
^{58}Co	Y	3E-1
^{60}Co	Y	3E-1
^{59}Ni	V[a]	5E-2
^{63}Ni	V[a]	5E-2
^{65}Ni	V[a]	5E-2
^{64}Cu	Y	5 E-1
^{65}Zn	Y	5 E-1
^{69m}Zn	Y	5 E-1
^{69}Zn	Y	5 E-1
^{76}As	W	5 E-1
^{75}Se	W	8 E-1
^{79}Se	W	8 E-1
^{82}Br	W	1.0
^{83}Br	W	1.0
^{84}Br	D	1.0
^{86}Rb	D	1.0
^{88}Rb	D	1.0
^{89}Rb	D	1.0
^{85}Sr	Y	3 E-1
^{89}Sr	Y	1 E-2
^{90}Sr	Y	3 E-1
^{91}Sr	Y	1 E-2
^{90}Y	Y	1 E-4
^{91m}Y	Y	1 E-4
^{91}Y	Y	1 E-4
^{92}Y	Y	1 E-4
^{93}Y	Y	1 E-4
^{93}Zr	D	2 E-3
$^{93}Zr+C$[c]	(Values for each chain member are used.)	
^{95}Zr	D	2 E-3
^{97}Zr	Y	2 E-3
^{93m}Nb	Y	1 E-2
^{94}Nb	Y	1 E-2
^{95m}Nb	Y	1 E-2
^{95}Nb	Y	1 E-2
^{97m}Nb (dose not included: short-lived)		
^{97}Nb	Y	1 E-2

Table E.6 Inhalation class and gastrointestinal tract uptake fractions for internal dose factors (Continued)

Radionuclide	Inhalation class	GI tract uptake fraction (f1)
^{93}Mo	Y	8 E-1
^{99}Mo	Y	5 E-2
^{99m}Tc	D	8 E-1
^{99}Tc	D	8 E-1
^{101}Tc	D	8 E-1
^{103}Ru	Y	5 E-2
^{105}Ru	Y	5 E-2
^{106}Ru	Y	5 E-2
^{103m}Rh	D	5 E-2
^{105}Rh	Y	5 E-2
^{103}Pd	Y	5 E-3
^{107}Pd	Y	5 E-3
^{109}Pd	Y	5 E-3
^{110m}Ag	Y	5 E-2
^{111}Ag	Y	5 E-2
^{109}Cd	D	5 E-2
^{113m}Cd	D	5 E-2
^{115m}Cd	D	5 E-2
^{115}Cd	Y	5 E-2
^{111}In	W	2 E-2
^{114m}In	D	2 E-2
^{115m}In	D	2 E-2
^{117m}Sn	W	2 E-2
^{119m}Sn	W	2 E-2
^{121m}Sn	W	2 E-2
^{121}Sn	W	2 E-2
^{123}Sn	W	2 E-2
^{125}Sn	W	2 E-2
^{126}Sn	W	2 E-2
$^{126}Sn+C^{(c)}$	(Values for each chain member are used.)	
^{124}Sb	W	1 E-2
^{125}Sb	W	1 E-1
^{126m}Sb	D	1 E-2
^{126}Sb	W	1 E-2
^{127}Sb	W	1 E-2
^{123m}Te	W	2 E-1
^{125m}Te	W	2 E-1
^{127m}Te	W	2 E-1
^{127}Te	W	2 E-1
^{129m}Te	W	2 E-1
^{129}Te	D	2 E-1
^{131m}Te	W	2 E-1
^{131}Te	D	2 E-1
^{132}Te	W	2 E-1
^{133m}Te	D	2 E-1
^{133}Te	D	2 E-1
^{134}Te	D	2 E-1
^{125}I	D	1.0
^{129}I	D	1.0
^{130}I	D	1.0
^{131}I	D	1.0
^{132}I	D	1.0
^{133}I	D	1.0
^{134}I	D	1.0
^{135}I	D	1.0
^{134m}Cs	D	1.0
^{134}Cs	D	1.0
^{135}Cs	D	1.0
^{136}Cs	D	1.0
^{137}Cs	D	1.0
^{138}Cs	D	1.0
^{139}Ba	D	1 E-1
^{140}Ba	D	1 E-1
^{141}Ba	D	1 E-1
^{142}Ba	D	1 E-1
^{140}La	W	1E-3
^{141}La	D	1E-3
^{142}La	D	1E-3

Table E.6 Inhalation class and gastrointestinal tract uptake fractions for internal dose factors (Continued)

Radionuclide	Inhalation class	GI tract uptake fraction (f1)
^{141}Ce	Y	3E-4
^{143}Ce	Y	3E-4
^{144}Ce	Y	3E-4
^{143}Pr	Y	3E-4
^{144}Pr	Y	3E-4
^{147}Nd	Y	3E-4
^{147}Pm	Y	3E-4
^{148m}Pm	Y	3E-4
^{148}Pm	Y	3E-4
^{149}Pm	Y	3E-4
^{151}Pm	Y	3E-4
^{147}Sm	W	3E-4
^{151}Sm	W	3E-4
^{153}Sm	W	3E-4
^{152}Eu	W	1E-3
^{154}Eu	W	1E-3
^{155}Eu	W	1E-3
^{156}Eu	W	1E-3
^{153}Gd	D	3E-4
^{160}Tb	W	3E-4
^{166m}Ho	W	3E-4
^{181}W	D	1E-2
^{185}W	W	1E-2
^{187}W	D	1E-2
^{187}Re	W	8E-1
^{185}Os	D	1E-2
^{191}Os	Y	1E-2
^{192}Ir	Y	1E-2
^{192}Ir	Y	1E-2
^{198}Au	Y	1E-1
^{203}Hg	D	1.0
^{210}Pb	D	2E-1
^{212}Pb	D	2E-1
^{210}Bi	W	5E-2
^{212}Bi	D	5E-2
^{210}Po	D	1E-1
^{222}Rn[d]	(Values for each chain member are used.)	
^{223}Ra	W	2E-1
^{224}Ra	W	2E-1
^{225}Ra	W	2E-1
^{226}Ra	W	2E-1
$^{226}Ra+C$[c]	(Values for each chain member are used.)	
^{228}Ra	W	2E-1
^{225}Ac	D	1E-3
^{227}Ac	D	1E-3
$^{227}Ac+C$[c]	(Values for each chain member are used.)	
^{228}Ac	D	1E-3
^{227}Th	Y	2E-4
^{228}Th	Y	2E-4
$^{228}Th+C$[c]	(Values for each chain member are used.)	
^{229}Th	W	2E-4
$^{229}Th+C$[c]	(Values for each chain member are used.)	
^{230}Th	W	2E-4
$^{230}Th+C$[c]	(Values for each chain member are used.)	
^{231}Th	Y	2E-4
^{232}Th	W	2E-4
$^{232}Th+C$[c]	(Values for each chain member are used.)	
Th-Nat[e]	(same as for ^{232}Th)	
^{234}Th	Y	2E-4
^{231}Pa	W	1E-3
$^{231}Pa+C$[c]	(Values for each chain member are used.)	
^{233}Pa	Y	1E-3
^{234}Pa	Y	1E-3

Table E.6 Inhalation class and gastrointestinal tract uptake fractions for internal dose factors (Continued)

Radionuclide	Inhalation class	GI tract uptake fraction (f1)
^{232}U	Y	5E-2
$^{232}U+C^{(c)}$ (Values for each chain member are used.)		
^{233}U	Y	5E-2
$^{233}U+C^{(c)}$ (Values for each chain member are used.)		
^{234}U	Y	5E-2
^{235}U	Y	5E-2
$^{235}U+C^{(c)}$ (Values for each chain member are used.)		
^{236}U	Y	5E-2
^{237}U	Y	2E-3
^{238}U	Y	5E-2
U-Nat[f] (same as ^{234}U, ^{235}U, and ^{238}U)		
$^{238}U+C^{(c)}$ (Values for each chain member are used.)		
^{240}U	Y	2E-3
^{237}Np	W	1E-3
$^{237}Np+C^{(c)}$ (Values for each chain member are used.)		
^{238}Np	W	1E-3
^{239}Np	W	1E-3
^{236}Pu	Y	1E-5
^{237}Pu	Y	1E-5
^{238}Pu	Y	1E-5
^{239}Pu	Y	1E-5
^{240}Pu	Y	1E-5
^{241}Pu	Y	1E-5
^{242}Pu	Y	1E-5
^{243}Pu	Y	1E-5
^{244}Pu	Y	1E-5
^{241}Am	W	1E-3
^{242m}Am	W	1E-3
^{242}Am	W	1E-3
^{243}Am	W	1E-3
^{242}Cm	W	1E-3
^{243}Cm	W	1E-3
^{244}Cm	W	1E-3
^{245}Cm	W	1E-3
^{246}Cm	W	1E-3
^{247}Cm	W	1E-3
^{248}Cm	W	1E-3
^{252}Cf	Y	1E-3

(a) V denotes that intake is in the form of vapor.
(b) C denotes ^{14}C is treated as labeled organic compounds.
(c) Radioactive decay chain members with half-lives less than 9 hours and less than 10% of the half-life of the parent are included with the parent. For decay chains having two or more radionuclides that reach secular equilibrium (i.e., a constant activity ratio as a function of time), a "+C" notation is included when all progeny of the chain member have half-lives less than 10% of the half-life of the listed member.
(d) The dose factors for ^{222}Rn represent the dose from short-lived daughters that are in equilibrium with the parent radon. These entries are provided because ^{222}Rn is an explicit daughter of ^{226}Ra and dose values for all explicit daughters are needed to estimate dose for non-equilibrium cases.
(e) Where Th-Nat includes an equilibrium mixture of ^{232}Th plus 10 daughters in the decay chain. Note that the dose entries for Th-Nat are equal to those for $^{232}Th+C$.
(f) Where 1 Ci U-Nat equals 48.9% ^{238}U plus 48.9% ^{234}U plus 2.25% ^{235}U.

Appendix F

Glossary

Appendix F

Glossary

Absorbed dose - The energy imparted by ionizing radiation per unit mass of irradiated material. The units of absorbed dose are the rad and the gray (Gy).

Activity - The rate of disintegration (transformation) or decay of radioactive material. The units of activity are the curie (Ci) and the becquerel (Bq).

Airborne radioactive material - Radioactive material dispersed in the air in the form of dusts, fumes, particulates, mists, vapors, or gases.

Annual total effective dose equivalent (annual TEDE) - The total effective dose equivalent (TEDE) received during a year of exposure. The duration of exposure for each pathway is determined by the scenario considered and need not be 8766 h/y. For example, an individual may reside or work at a contaminated site for only a fraction of the year.

Class (or "lung class" or "inhalation class") - A classification scheme for inhaled material according to its rate of clearance from the pulmonary region of the lung. Materials are classified as D, W, or Y, and apply to a range of clearance half-times for D(Days) of less than 10 days, for W(Weeks) from 10 to 100 days, and for Y(Years) of greater than 100 days.

Collective dose - The sum of the individual doses received in a given period of time by a specified population from exposure to a specified source of radiation.

Committed dose equivalent ($H_{T,50}$) - The dose equivalent to organs or tissues of reference (T) that will be received from an intake of radioactive material by an individual during the 50-year period following the intake.

Committed effective dose equivalent ($H_{E,50}$) - The sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated by internally deposited radionuclides and the committed dose equivalent to these organs or tissues ($H_{E,50} = \Sigma w_T H_{T,50}$).

Conservative - The application of a cautious approach to a dose analysis that is likely to produce an overestimate of the expected result. A conservative analysis involves the deliberate selection of parameter values that maximize the expected result.

Deep dose equivalent (H_d) - Applied to external whole-body exposure, H_d is the dose equivalent at a tissue depth of 1 cm (1000 mg/cm^2). Note: for this generic application, the annual TEDE is calculated using the external effective dose equivalent, using dose factors from the U.S. Environmental Protection Agency (EPA), as described in Section 6.

Dose or "radiation dose" - A generic term that means absorbed dose, dose equivalent, effective dose equivalent, committed dose equivalent, committed effective dose equivalent, or total effective dose equivalent, as defined in other paragraphs of this appendix.

Dose equivalent (H_T) - The product of the absorbed dose in tissue, quality factor, and all other necessary modifying factors at the location of interest. The units of dose equivalent are the rem and sievert (Sv).

Effective dose equivalent (H_E) - The sum of the products of the dose equivalent to the organ or tissue (H_T) and the weight factors (w_T) applicable to each of the body organs or tissues that are irradiated ($H_E = \Sigma w_T H_T$).

Exposure - Being exposed to ionizing radiation or to radioactive material.

External dose - That portion of the dose equivalent received from radiation sources outside of the body.

Gray (Gy) - The SI unit of absorbed dose. One gray is equal to an absorbed dose of 1 joule/kg (100 rad).

Internal dose - That portion of the dose equivalent received from radioactive material taken into the body.

Licensed material - Source material, special nuclear material, or byproduct material received, possessed, used, or transferred under a general or specific license issued by the U.S. Nuclear Regulatory Commission (NRC).

Member of the public - An individual in a uncontrolled or unrestricted area. However, an individual is not a member of the public during any period in which the individual receives an occupational dose.

NRC - The U.S. Nuclear Regulatory Commission or its duly authorized representatives.

Pathway - The potential routes through which people may be exposed to radiation or radioactive materials. Typical radiation exposure pathways include external exposure to penetrating radiation, inhalation of airborne materials, and ingestion of materials contained in surface contamination, food products, or drinking water.

Public dose - The dose received by a member of the public from exposure to radiation and to radioactive material released by a licensee, or to another source of radiation either within a licensee's controlled area or in unrestricted areas. It does not include occupational dose, or dose received from natural background, as a patient from medical practices, or from voluntary participation in medical research programs.

Rad - The special unit of absorbed dose. One rad is equal to an absorbed dose of 100 ergs/g or 0.01 joule/kg (0.01 gray).

Radiation (ionizing radiation) - Alpha particles, beta particles, gamma rays, x-rays, neutrons, high-speed electrons, high-speed protons, and other particles capable of producing ions. Radiation, as used here, does not include nonionizing radiation, such as sound, radio, or microwaves, or visible, infrared, or ultraviolet light.

Reference man - A hypothetical aggregation of human physical and physiological characteristics arrived at by international consensus. These characteristics may be used by researchers and public health workers to standardize results of experiments and to relate biological insult to a common base.

Rem - The special unit of dose equivalent. The dose equivalent in rem is equal to the absorbed dose in rad multiplied by the quality factor (1 rem = 0.01 Sv).

Scenario - A combination of radiation exposure pathways used to model conceptually the potential conditions, events, and processes that result in radiation exposure to individuals or groups of people.

Sievert - The SI unit of dose equivalent. The dose equivalent in sieverts is equal to the absorbed dose in grays multiplied by the quality factor (1 Sv = 100 rem).

Total effective dose equivalent (TEDE) - The sum of the deep dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures).

Uranium fuel cycle - The operations of milling of uranium ore, chemical conversion of uranium, isotopic enrichment of uranium, fabrication of uranium fuel, generation of electricity by a light-water-cooled nuclear power plant using uranium fuel, and reprocessing of spent uranium fuel, to the extent that these activities directly support the production of electrical power for public use. The uranium fuel cycle does not include mining operations, operations at waste disposal sites, transportation of radioactive material in support of these operations, and the reuse of recovered non-uranium special nuclear and byproduct materials from the cycle.

Weighting factor, w_T, for an organ or tissue (T) - The proportion of the risk of stochastic effects resulting from irradiation of that organ or tissue to the total risk of stochastic effects when the whole body is irradiated uniformly. For calculating the effective dose equivalent, the values of w_T are:

Organ or tissue	w_T
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder	0.30*
Whole body	1.0**

* 0.30 results from 0.06 for each of 5 "remainder organs" (excluding the skin and the lens of the eye) which receive the highest doses.

**For the purpose of weighting the external whole-body dose (for adding it to the internal dose), a single weight factor, $w_T = 1.0$, has been specified. The use of other weighting factors for external exposure will be approved on a case-by-case basis until such time as specific guidance is issued.

Whole body - For purposes of external exposure, head, trunk (including male gonads), arms above the elbow, and legs above the knee.

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This document is the first volume of a three-volume report to provide generic and site-specific estimates of radiation dose for exposures to residual radioactive contamination after decommissioning of facilities licensed by the U.S. Nuclear Regulatory Commission (NRC). The detail included in this volume serves as the basis for user-friendly computer software developed under strict quality-assurance procedures. Volume 1 describes the scenarios, models, mathematical formulations, assumptions, and justifications of parameter selections. The generic modeling addresses residual radioactive contamination inside buildings and in soils. For buildings, two scenarios are presented to relate volume and surface contamination levels to estimates of the annual total effective dose equivalent (TEDE), as defined in 10 CFR 20, received during a year of exposure. Because of concerns about potential ground-water contamination, a generic water-use model was developed to permit evaluation of the annual TEDE for drinking water from wells. The generic water-use model was also used in the evaluation of multiple pathways associated with contaminated soil. The information in this volume is intended to serve as the technical basis for the NRC's derivation of screening values supporting its development of policy applied to residual radioactive contamination from decommissioning.

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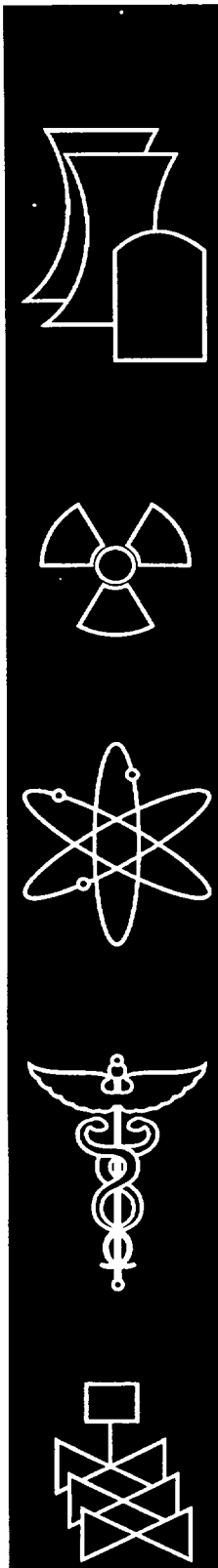

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User's Manual
DandD Version 2.1

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ABSTRACT

The Decommissioning and Decontamination (DandD) software package developed by Sandia National Laboratories for the Nuclear Regulatory Commission (NRC) provides a user-friendly analytical tool to address the technical dose criteria contained in NRC's Radiological Criteria for License Termination rule (10 CFR Part 20 Subpart E). Specifically, DandD embodies the NRC's screening methodology to allow licensees to convert residual radioactivity contamination levels at their site to annual dose, in a way consistent with both 10 CFR Part 20 and the corresponding implementation guidance currently under development by NRC. The screening methodology and DandD are part of a larger decision framework that allows and encourages licensees to optimize decisions regarding alternative actions at their site, including the collection of additional data and information. The screening methodology employs reasonably conservative scenarios, fate and transport models, and default parameter values and parameter distributions to allow the NRC to quantitatively estimate the risk of terminating a license given only information about the level of contamination. A licensee has the option of specifying only the level of contamination and running the code with the default parameters or, if site-specific information is available, modifying scenario pathways or providing site-specific parameter distributions and then calculating dose. The original draft of Volume 2 of the NUREG/CR-5512 series documented a User's Manual for the deterministic Version 1.0 of the DandD software. This final version of Volume 2 provides an entirely new User's Manual for the Version 2.1 release of DandD, thus superceding and replacing DandD Version 1.0 and its draft User's Manual. The latest version of the software allows probabilistic (Monte Carlo) dose assessments and incorporates a new and improved Microsoft® Windows® standard user interface.

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ACRONYMS

ALI	Annual limit on intake
ALARA	As low as reasonably achievable
AMCG	Average member of the critical group
BWR	Boilingwater reactors
CCDF	Complementary cumulative distribution function
CEDE	Committed effective dose equivalent
CFR	Code of Federal Regulations
CI	Confidence Interval
DAC	Derived air concentration
DandD	Decontamination and decommissioning (software)
DCF	Dose conversion factor
DLL	Dynamically-linked library
EPA	Environmental Protection Agency (U.S.)
FGR	Federal guidance report
FRC	Federal Radiation Council
GUI	Graphical user interface
HTML	Hypertext markup language
ICRP	International Commission on Radiological Protection
K-S	Komolgorov-Smirnov (statistical test)
LHS	Latin Hypercube Sampling
MDAC	Microsoft Data Access Components
mrem/y	millirem/year
MS	Microsoft® Corporation
NRC	Nuclear Regulatory Commission (U.S.)
ORNL	Oak Ridge National Laboratory
P.O.	Performance objective
PDF	Probability distribution function
PNL	Pacific Northwest Laboratories
PWR	Pressurized water reactors
R&D	Research and development
SNL	Sandia National Laboratories
SRP	Standard Review Plan
TEDE	Total effective dose equivalent
UOM	Units of measurement
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture

FOREWORD

This technical contractor report, NUREC/CR-5512, Volume 2, was prepared by Sandia National Laboratories under their DOE Interagency Work Order (JCN W6804) 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. The report is a user's manual for version 2 of the DandD software, which implements the modeling methodology described in Volume 1 of NUREG/CR-5512 "Residual Radioactive Contamination From Decommissioning: Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent" issued October 1992.

The purpose of the DandD software is to provide a simple screening approach for demonstrating compliance with 10 CFR 20, Subpart E. Version 2 of the software described in this report supercedes the earlier version described in the draft of this volume. Volume 2 of the software supports both a simple screening using generic scenarios and default parameter values or default probabilistic parameter distributions, as well as allowing input of site-specific parameters and modification of scenarios by changing or eliminating pathways. This software may be used to demonstrate compliance with the dose criterion in 10 CFR 20, Subpart E, as described in NUREG-1727 "NMSS Decommissioning Standard Review Plan" issued in September 2000.

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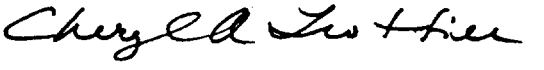

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1 INTRODUCTION

1.1 Background

The Nuclear Regulatory Commission (NRC) is responsible for evaluating requests from facility owner/operators for the partial or total termination of NRC operating licenses for their facilities. This evaluation is based on radiological criteria defined in 10 CFR Part 20 Subpart E (NRC, 1998a). These criteria establish limits on the annual total effective dose equivalent (TEDE) received during the year to the average member of the critical group (AMCG). The critical group is "the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances" (10 CFR 20.1003).

NRC recognized that licensees who must decontaminate lands and structures would require assistance and guidance in determining the extent of decommissioning required to allow unrestricted release of their property. In making such a determination, the NRC must first ensure that public health, safety, and the environment are protected by determining that the total dose to an individual in the public from licensed operations is less than the public dose limit of 100 mrem/y. However, the NRC has set the goal for public doses attributable to residual contamination after decommissioning at a fraction (25 mrem/y) of the public dose limit (for the case of unrestricted release). The estimate of dose reduction is accomplished by first judging the potential future uses of the lands and structures as described by NRC-defined scenarios and exposure pathways, and then evaluating levels of radioactivity through modeling equations to arrive at a reasonable expectation of dose. The modeling and scenarios involved in this determination can become extremely complicated depending upon the level of detail and complexity required. Therefore, a methodology and associated analytical tools were developed in support of license termination.

1.1.1 Origin of Deterministic Methods for Decommissioning

In 1987, Pacific Northwest Laboratories (PNL) began developing the NUREG/CR-5512 methodology to translate residual radioactive contamination levels at sites licensed by the NRC into potential radiation doses to the public. Volume 1 documenting the methodology was issued in 1992 (Kennedy and Strenge, 1992).

During 1993, Sandia National Laboratories (SNL) calculated dose conversion factors (DCFs) using the NUREG/CR-5512 methodology to support the NRC's draft regulatory guidance in NUREG-1500 (Daily et al., 1994) and the draft generic environmental impact study on radiological criteria for decommissioning, NUREG-1496 (NRC, 1994). SNL developed and used four stand-alone Fortran computer codes to perform those calculations for the four exposure scenarios defined in Volume 1. These codes were not designed for external release or use.

In 1994, SNL began developing the Decontamination and Decommissioning (DandD) Version 1.0 code, a user-friendly software product that implements the NUREG/CR-5512 methodology. DandD Version 1.0 integrates the Fortran scenario modeling codes with a graphical user interface designed to run under Microsoft® Windows® with a minimal hardware configuration. DandD Version 1.0 is a deterministic code using default scenarios, exposure pathways, and constant parameter values. Version 1.0 of DandD was released in July 1998 and the user's manual for the program was published in draft as Volume 2 of the NUREG/CR-5512 series (Wernig et al., 1999).

DandD assists NRC licensees who have requested termination of their license and who, in some cases, must decontaminate lands and structures as part of the decommissioning process. The software does this by providing a tool that allows licensees to translate residual radioactive contamination levels at their site to TEDE values by analyzing and modeling the set of NRC-prescribed scenarios of future land use. DandD contains models of the transport and exposure pathways associated with each of the scenarios, and default values for most parameters. The software only requires information on source concentration from the user. Within strictly defined limits, the user may supply site-specific parameter values if available and defensible. The user may also modify or eliminate exposure pathways.

1.1.2 Nuclear Regulatory Commission Decommissioning Guidance

In support of the July 1998 release of the final rule on Radiological Criteria for License Termination (NRC, 1998a) as 10 CFR Part 20 Subpart E, NRC was required to draft and publish implementing guidance to interpret rule provisions and evaluate actions licensees would need to take to comply with license termination

processes. In March 1998, NRC staff completed development of Draft NUREG-1549, "Decision Methods for Dose Assessment to Comply with Radiological Criteria for License Termination" (NRC, 1998b). NUREG-1549 was intended to provide an overall framework for dose assessment and decision-making at sites undergoing decommissioning. In July 1998, the Commission approved publication of draft guidance DG-4006 for the License Termination Rule (NRC, 1998c) for a two-year interim use period and instructed the NRC staff to maintain a dialogue with the public through the use of a web site and public workshops. The Commission also directed the NRC staff to develop a Standard Review Plan (SRP) that incorporates the risk-informed iterative approach in NUREG-1549. (The NMSS Decommissioning Standard Review Plan (NUREG/SR-1727) is accessible through: http://www.nrc.gov/NRC/NUREGS/SR1727/index.html.) The goal of the SRP is to enable NRC staff to evaluate information submitted by licensees in a timely, efficient, consistent manner and in such a way that the public health and safety is protected and the facility can be released in accordance with NRC's requirements.

1.1.3 Evolution of Probabilistic Evaluations

DandD Version 1.0 includes constant default parameter values and thus only allows deterministic analyses. However, all dose assessments are uncertain due to uncertainty about the processes and parameters that control exposure. The range of possible dose values given this uncertainty must be considered in order to support decisions based on dose. A tendency for a screening calculation to produce a dose value in the upper end of the range of possible doses allows that calculation to be used in decision making. The scenarios, models, and parameter values defined in Volume 1 (and embodied in DandD Version 1.0) were intended to have this tendency, but the supporting arguments were qualitative. NRC directed SNL to develop probability distribution functions (PDFs) for parameters, based on the information in Volume 1 and on any newer published studies, and to identify default values for those parameters suitable for screening calculations. Volume 3 of NUREG/CR-5512 provided the parameter analysis (Beyeler et al., 1999).

In March 1999, NRC directed SNL to develop an improved version of DandD based on the parameter analysis that would allow formalized treatment of parameter uncertainty through implementation of probabilistic features and that would provide an improved, updated graphical user interface. Section 1.2 discusses the capabilities embodied in the Monte Carlo Version 2.1 of the DandD code.

1.1.4 Decision Framework for License Termination

NRC guidance in support of the license termination rule provides a useful context for licensees using the DandD code for dose assessments related to decommissioning decisions. NUREG-1549 documents use of a decision framework to implement a phased approach in conducting dose assessments. The decision framework can be used throughout the decommissioning and license termination process for more simple sites to the most complex or contaminated sites. The framework allows iterative (phased) development and treatment of the uncertainties associated with regulatory decisions. As such, a licensee can begin with existing (and often very limited) knowledge about the site, conduct screening assessments, update the state of knowledge with site-specific information (thus reducing uncertainty), and refine the screening assessments, if necessary. By following this approach, the licensee is able to optimize resources and decisions related to site characterization, remediation, and potential land-use restrictions.

The decision framework methodology is based on the premise that screening dose assessments are performed with little site-specific information. An initial analysis using DandD Version 2.1 and default DandD Version 2.1 parameter distributions, along with a simple representation of contamination at the site, will produce generic dose assessments that are unlikely to be exceeded. The scenarios and models in DandD Version 2.1 were defined to be "reasonably conservative" so that they would not be "bounding" or unrealistic, while still generally overestimating (rather than underestimating) potential dose. The physical parameter distributions were defined to represent real conditions and expected variability across the United States. Behavioral and metabolic parameters were defined to represent the average individual within the defined screening group (or generic critical group).

Beginning with the simple screening assessments, the methodology ensures that as more site-specific information is incorporated, the uncertainty is reduced (state of knowledge is increased), and the estimate of the resulting dose generally decreases. DandD Version 2.1 can be used to incorporate new knowledge based on site characterization that may lead to eliminating certain exposure pathways or reducing parameter uncertainty. DandD used in the context of the decision framework provides assurance that obtaining additional site-specific information is worthwhile because it is

probable that a more "realistic" dose assessment will not result in a dose higher than that estimated using a simple screening analysis.

Steps in the Decision Framework

NUREG-1549 provides a summary of the decision framework and methodology for conducting dose assessments in support of license termination decisions. It also provides three separate discussions to illustrate the phased and iterative nature of assessments as increasing complexity occurs. The following provides a summary of the decision framework steps that provide the overall context for use of the DandD software within the NRC license termination decision process. Refer to Figure 1.1 (taken from NUREG-1549) while reviewing the following steps of the framework.

Step 1: The first step in a dose assessment involves gathering and evaluating existing data and information about the site, including the nature and extent of contamination at the site. Often, minimal information is all that is needed for initial screening analyses (e.g., a simple representation of the source of contamination). However, licensees should use all information about the site that is readily available. This step also defines the performance objectives that must be met in order to demonstrate compliance with decommissioning criteria.

Step 2: This step involves defining the scenarios and pathways that are important and relevant for the site dose assessment.

DandD contains two generic exposure scenarios: residential and building occupancy.

Step 3: Once scenarios are defined and exposure pathways identified, a basic conceptual understanding of the system is developed, often based on simplifying assumptions regarding the nature and behavior of the natural systems. System conceptualization includes conceptual and mathematical model development and assessment of parameter uncertainty. DandD includes predefined conceptual models for the scenarios along with default parameter distributions (based on Kennedy and Strenge, 1992 and Beyeler et al., 1999).

Step 4: This step involves the dose assessment or consequence analysis, based on the defined scenario(s), exposure pathways, models, and parameter distributions. For generic screening, the licensee can accept and use the generic models and default parameter PDFs simply by running DandD with the appropriate site-specific source term, leaving all other information in the software unchanged. Site-specific assessments allow the user to change pathways and parameter distributions based on data and information obtained from the site. DandD provides various plots and reports of the dose distribution based on Monte Carlo sampling of the input distributions.

Step 5: This is the first major decision point in the license termination decision process and involves answering the question of whether the dose assessment results from Step 4 demonstrate compliance with the dose criterion in 10 CFR Part 20, Subpart E (for unrestricted release, this is 25 mrem/y). NRC establishes the confidence required when interpreting the results from the probabilistic dose assessment. For instance, licensees may need to demonstrate that the 90th percentile value of dose is less than 25 mrem/y. If the results are below the limit, the licensee proceeds with Steps 6 and 7 to demonstrate As Low As Reasonably Achievable (ALARA) requirements and initiate the license termination process defined by NRC in other guidance documents. Note that DandD does not involve or automate these steps.

If the results exceed the performance objective, the user should proceed to Steps 8 and 9.

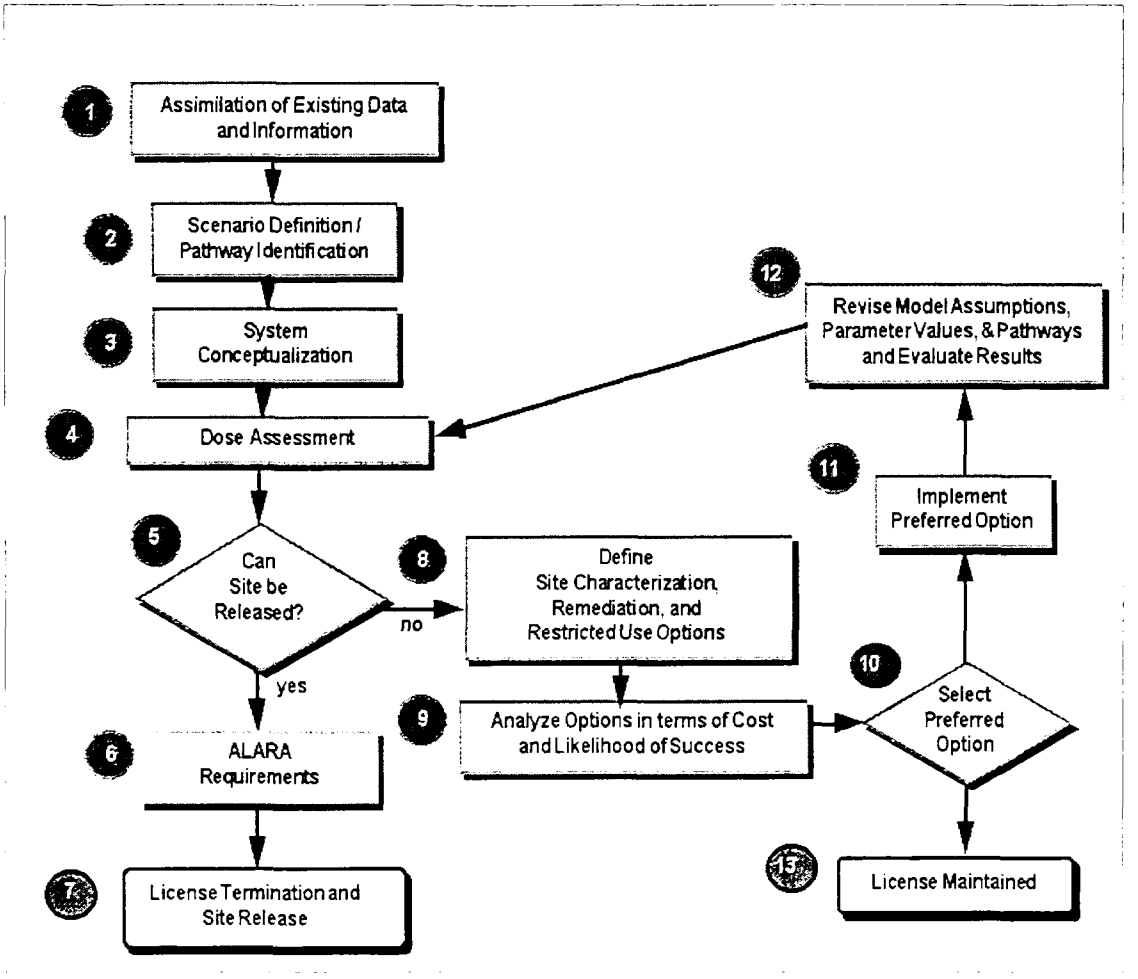


Figure 1.1 Decommissioning and license termination framework

Step 6: If the result in Step 5 is that the calculated dose is less than 25 mrem/y, the Licensee can proceed to satisfy NRC requirements to demonstrate dose is As Low As Reasonably Achievable (ALARA) (see NRC, 1998c).

Step 7: Following ALARA determination, Licensees would proceed with license termination procedures as outlined in applicable NRC guidance documents.

Step 8: Full application of the decision framework involves defining all possible options the licensee might address in order to defend a final set of actions needed to demonstrate compliance with license termination criteria. Options may include acquiring more data and information about the site and source(s) of contamination in order to reduce uncertainty about the pathways, models, and parameters and thus reduce the calculated dose; reducing actual contamination through remediation actions; reducing exposure to radionuclides through implementation of land-use restrictions; or some combination of these options.

DandD provides a sensitivity analysis module to identify sensitive parameters (e.g., those having the greatest impact on dose assessment results) and to explore potential reductions in the uncertainty associated with those parameters. Note that one option may include elimination of exposure pathways due to site-specific considerations.

Step 9: All of the options identified in Step 8 are analyzed and compared in order to optimize election of a preferred set of options. This options analysis may consider cost of implementation, likelihood of success (and the

expected costs associated with success or failure to achieve the desired results when the option is implemented), timing considerations and constraints, and potentially other quantitative and/or qualitative selection criteria. At this time, the DandD software is limited to evaluating the potential impact on the dose results through selective truncation of the uncertainty bounds of the input parameters.

Step 10: The activities in Steps 8 and 9 provide information for the licensee to choose the preferred options based on considerations of cost, likelihood of success, timeliness, and other considerations. Based on the results of the DandD sensitivity analysis, for example, a licensee may identify one or more parameters that may be modified based on acquisition of site-specific information and data. If new data could reduce the uncertainty associated with sensitive parameters, the licensee may be able to defend a new calculated dose that meets the license termination criteria.

Step 11: Under Step 11, the preferred option is implemented. The licensee commits resources to obtain the information necessary to support revisions to the parameters identified in Steps 8 and 9.

Step 12: Once data are successfully obtained, the affected parameters for the predefined models are revised, as appropriate. Also, data may support eliminating one or more of the exposure pathways in the predefined scenarios. DandD provides for very simple and straightforward modification of the pathways and parameters of interest. The software also includes in the Help menu full documentation of the original basis for the parameter distributions, references, and sources of information the licensee might use in order to defend modifications based on their site-specific data and circumstances.

Once the pathways and parameters are revised, the licensee would revisit Steps 4 and 5 to determine the impact of the revisions on demonstrating compliance with the performance objectives. If met, the licensee proceeds to Steps 6 and 7. If the performance objective is still exceeded, the licensee returns to Steps 8 and 9 to analyze remaining options.

Step 13: If no viable options exist at this time, the licensee may decide to defer actions at this site until circumstances allow revisiting license termination actions.

1.2 DandD Version 2.1 Overview

DandD Version 2.1 updates, improves, and significantly enhances the capabilities of Version 1.0. As such, this final Volume 2 of the NUREG/CR-5512 series documents the User's Manual for DandD Version 2.1, superceding and replacing the original draft of Volume 2 (Wernig et al., 1999) that documented DandD 1.0. In particular, Version 2.1 allows full probabilistic treatment of dose assessments, whereas Version 1.0 only allowed deterministic analyses. DandD Version 2.1 implements the methodology and information contained in NUREG/ CR-5512, Volume 1, the methodology modifications described in Wernig et al. (reproduced as Appendix A), as well as the parameter analysis in Volume 3 that established the PDFs for all of the parameters associated with the scenarios, exposure pathways, and models embodied in DandD.

1.2.1 Summary of Requirements for Version 2.1

The most prominent new feature of DandD Version 2.1 is the incorporation of a Monte-Carlo simulation capability, a significant enhancement to the deterministic approach embodied in Version 1.0. This new capability was designed to be simple to use, while allowing more knowledgeable users to take full advantage of the Monte Carlo capability.

The completed system allows the user to perform an initial default screening analysis using the default parameter distributions defined in the parameter analysis. As with the existing deterministic code, only a source-term estimate is required for this calculation. The result of the Monte Carlo calculation is summarized by the dose at a default selected quantile value, which the user may compare against the 25 mrem/year standard to assess compliance. An original requirement was that this default operation should have a similar look and feel to that in Version 1.0.

Requirements for additional capabilities included:

- The user should be able to view the complete dose distribution functions, as well as the distribution functions for the time of peak dose and for the individual pathway doses.

- The user should be able to view the default distribution functions for each of the input parameters and to access the portions of Volume 3 documenting the basis for each default distribution.

- The user should be able to specify new distribution functions (or deterministic values) for each parameter based on site conditions and to record the justification for these distributions or values.

- The user should be able to request a ranking of parameters based on the sensitivity of dose to the parameter value.

- The user should be able to access pertinent information about the decision methodology for guidance on options for achieving compliance.

1.2.2 Features of DandD Version 2.1

Two scenarios are implemented in DandD: building occupancy and residential. The building occupancy scenario relates surface contamination levels in existing buildings to estimates of the TEDE received during a year of exposure with the conditions defined in the scenario for unrestricted commercial or light industrial use. The exposure pathways for this scenario include external exposure, inhalation exposure, and secondary ingestion.

The more complex residential scenario is meant to address sites with contamination in soils. The residential scenario considers more exposure pathways, including external exposure, inhalation, and the following ingestion pathways: drinking water, food grown from irrigation water, land-based food, soil, and fish. The types of land-based food considered are leafy vegetables, other root vegetables, fruit, grain, beef, poultry, milk, and eggs. Three types of animal feeds are considered: forage, stored grain, and stored hay.

A generic water-use model was developed to permit evaluation of the annual TEDE from drinking water from wells and from multiple pathways associated with irrigation water. This simple water-use model accounts for radionuclide decay, progeny ingrowth, and environmental transport. The three boxes (or layers) in the water-use model are the surface soil, unsaturated soil, and the aquifer. Appendix A describes a modification to the three-box water-use model that allows up to 50 boxes in the unsaturated zone. The generic treatment of potentially complex groundwater systems provides a conservative analysis that may only suggest when additional site data and more sophisticated modeling are warranted.

The default input parameter distributions for each scenario and exposure pathway are consistent with conducting screening dose assessments, and represent large uncertainty about site conditions. To accommodate site-specific conditions the DandD software allows a simple, straightforward approach to modify scenario selection, exposure pathways, source, and many of the modeling parameters.

Figure 1.2 shows the overall information flow that takes place in the DandD code and the major processes that are involved. A Microsoft® Access® database is the repository for all of the information used by the system. It contains initial default values for all parameters, current parameter settings, sampled parameter values generated by the Latin Hypercube Sampling (LHS) code (Iman and Shortencarier, 1984), dose model results, and report templates.

- The graphical user interface (GUI) controls the overall information flow, at the user's direction, and invokes the supporting components to generate parameter samples and run the dose model. An important design goal for this interface was to quickly step through a default analysis, while allowing any aspect of the calculation to be adjusted to site-specific conditions, if required.

- The LHS pre/post processor builds the input file for the LHS program based on the current parameter distributions in the database, invokes LHS to generate the samples, and processes the LHS output file. The resulting parameter values are stored in the database and are checked against any limits that have been defined.

Figure 1.2 Information flow in DandD Version 2.1

- The LHS program performs the parameter sampling. The system uses the official version of LHS, which is maintained by SNL for general distribution.

- The dose model pre/post processor retrieves the simulation options and parameter values for a specified simulation (sample vector) from the database and invokes the appropriate scenario model to calculate dose. The resulting dose values are appended to output tables in the database.

- The dose model dynamically-linked libraries (DLLs) perform the dose calculations. For each realization in a simulation, an annual TEDE is calculated for every year in the exposure period.

- The peak TEDE over the exposure period is then identified from the set of annual TEDEs. This will yield a set of peak TEDE values, one for each realization. From this set, statistics such as percentiles may be determined, along with associated confidence intervals.

- Finally, DandD Version 2.1 includes a sensitivity analysis module that assists licensees and NRC users to identify those parameters in the screening analysis that have the greatest impact on the results of the dose assessment. Armed with this information and the guidance available in NUREG-1549, licensees are able to make informed decisions regarding allocation of resources needed to gather site-specific information. When cost and likelihood of success associated with acquisition of this new knowledge are considered, licensees are better able to optimize the decisions to acquire site data that allow more realistic dose assessments that, in turn, may lead to demonstrated and defensible compliance with the dose criteria for license termination.

1.2.3 Comparison to Version 1.0

DandD Version 2.1 provides many useful improvements on Version 1.0 of DandD:

- The GUI was significantly enhanced and upgraded to both incorporate the added features of Version 2.1 as well as to use standard Microsoft® Windows® features and conventions.

- Version 2.1 performs probabilistic dose assessments while maintaining ease of use; Version 1.0 only allowed deterministic analyses.

- Version 2.1 provides direct capability to select or exclude exposure pathways.

- Limits on the area of contamination can be specified in Version 2.1 and are appropriately reflected in the calculated dose values.

- The Help features have been significantly updated to incorporate information pertinent to probabilistic analysis, NRC references and guidance (including NUREG-1549), and the new features presented in the GUI.

- Extensive parameter help has been added based on the NUREG/CR-5512, Volume 3 parameter analysis. This information has been integrated as HTML documents to facilitate maintenance.

- Version 2.1 elicits and tracks user justification for any modifications to pathways, parameters, or parameter correlations.

- Following execution of the models and depending on the results, Version 2.1 provides guidance for increasing sample size to reduce sampling error.

- A parameter sensitivity analysis capability was added.

- The output reports and plots have been improved consistent with the reporting and display requirements of a probabilistic dose assessment.

- Standard file management features have been incorporated.

- Version 2.1 provides window printing capabilities throughout the GUI to allow screen capture documentation of important aspects of an analysis.

- Version 2.1 can save a compressed version of the session for submittal to NRC.

- The application has been redesigned to facilitate separate maintenance of the interface, the initial session file containing default settings, the parameter documentation, and the dose models.

1.3 User Manual Overview

Section 2 summarizes system requirements to install and successfully operate DandD Version 2.1. Installation instructions are provided to install the software from CD-ROM, Web, or FTP location and includes troubleshooting notes. The installation

package includes all necessary installation notes in online documentation.

Section 3 introduces the user to the basic capabilities of DandD Version 2.1 and its documentation. All of the online documentation and selections in the DandD program group found from the Microsoft® Windows® Start menu are summarized. Finally, this section provides a quick tour of DandD and the sensitivity analysis module using example problems.

Section 4 is the heart of the User's Manual. This reference guide provides comprehensive descriptions of all features incorporated in the Version 2.1 user interface. Common interface features and operations are summarized first (Section 4.1), followed by summaries of all the features and controls on the main session window. This latter set of instructions in Section 4.2 provides the procedure users will generally follow to execute DandD. Section 4.3 describes each of the menu options, ranging from file menu operations, to viewing reports and plots, to utilizing the advanced features including the sensitivity analysis module.

Finally, Section 5 provides responses to a set of frequently asked questions based, in part, on past NRC training and workshop experience and on questions users may have with the new features of DandD Version 2.1.

A set of Appendices supplements the discussions provided in the main body of the User's Manual, including the presentation of additional sample problems and technical background information on data tables underlying the DandD software. The design of the DandD database file is explained, and the requirements for specifying and setting up import concentration files are summarized.

2 INSTALLATION OF DandD

2.1 System Requirements

The DandD software requires the following

- a personal computer with Microsoft® Windows® 95/98 or NT 4.0 installed;
- a VGA monitor (recommended desktop set to minimum of 800 × 600 pixels);
- a mouse or other pointing device;
- 40 MB of free disk space;
- a printer to use the print functions included with DandD;
- a floppy drive, network, or Internet connection to submit session files for review;
- a frame-enabled browser such as Internet Explorer or Netscape Navigator to allow access to the DandD reports and an online version of NUREG/CR-5512, Volume 3.

2.2 Installing from CD-ROM

To install DandD, run Setup.exe as follows:

- Click on the Microsoft® Windows® Start button and select the Run command.
- Click on the Browse button, and locate Setup.exe on the installation CD.
- Click Open.
- Click OK in the Run dialog box.

The DandD installation procedure should now execute.

On certain installations, DCOM95 and MDAC (Microsoft® Data Access Components) will automatically install before DandD installs. Some system files will be updated. This is necessary for the correct installation of DandD. This is a Microsoft® update related to the feature that DandD session files are stored as database files. This procedure has been automatically built in the DandD installation process. This update should not affect the Microsoft® Windows® desktop or other applications that are installed.

2.3 Installing by Downloading from the Internet

Users may access the DandD code for installation at the NRC site: http://www.nrc.gov/RES/rescodes.htm. Scroll down to the "Radionuclide Transport and Decommissioning Codes" section. Select "Click here to Download" to access the setup.exe file. Also, select "Click here for Installation and Setup of DandD on your Computer" for additional installation instructions.
Proceed to run the file Setup.exe as described in Section 2.2.

2.4 Troubleshooting Installation Problems

When installation is completed, the user can access the files 'Read Me,' 'Getting Started with DandD,' and 'Introduction to DandD' from the DandD program group off the Microsoft® Windows® Start menu under the Programs group.

If difficulty is experienced installing DCOM95 or MDAC, users should contact their system administrator for assistance. Users may also contact NRC technical support at DandD@nrc.gov with questions regarding installation and use of DandD.

2.5 Uninstalling DandD

Select 'Uninstall DandD' from the DandD program group off the Microsoft® Windows® Start menu under the Programs group. When executed, the DandD files will be removed from the user's system. However, existing session files in the DandD_Docs directory will not be removed. There is no uninstall for DCOM95 or MDAC. Microsoft® considers these to be system upgrades and does not offer an uninstall procedure.

3 WELCOME TO MONTE CARLO DandD

3.1 The DandD Group

The DandD installation will create a program group that can be accessed from the Microsoft® Windows® Start menu.

From the Start button, select Programs, then select DandD. The first menu level includes a subgroup called Documents. This subgroup contains the following:

- Getting Started with DandD - a document that describes the items in the DandD group and the database metaphor used to manage session files.
- Introduction to DandD - a summary of the DandD decision process, with three example problems. New users should step through these problems to become familiar with DandD features and the interface.
- NRC References - on-line browser-based reference materials on the DandD scenarios and general technical concepts. Users will need a browser such as Internet Explorer or Netscape installed to view this file.
- Readme - notes and information regarding the installation of DandD, including precautions.

Following the Documents entry are:

- DandD - An alternative to the desktop shortcut for launching the DandD application.
- DandD Help - This provides direct access to the Help topics in DandD without launching the software.
- Uninstall DandD - This menu option should be used to remove DandD from user's computers.

3.2 Run a Simple Screening Analysis

Note to users: Refer to Section 4.2 for detailed instructions and illustrations for conducting a dose assessment with the DandD code. Sections 4.1 and 4.3 provide additional guidance and illustrations for common and main menu operations, respectively. Finally, Appendix B provides a breadth of example problems for a wide range of user facilities.

To start the application, either double-click the icon on the desktop or select DandD from the DandD group on the Microsoft® Windows® Start menu.

Press F1 at any time if help is needed for a window.

In the following example, a site with shallow-soil contamination seeks license termination. Preliminary survey data, site operational records, and leakage and spill events show localized contamination from Co-60, Sr-90, and Cs-137 in the soil. Measured contamination levels for each radionuclide averaged over the site area of interest are 3 pCi/g, 2 pCi/g, and 1.2 pCi/g, respectively.

None of the default parameter values are modified in this screening analysis.

Creating a Session File:

1. After opening DandD Version 2.1, select *File/New* and type in a unique file name: Simple Case 1, and click it *Open*.
2. In the *Site Name* field of Session Properties, enter: Site X - Analysis of Co-60, Sr-90, and Cs-137.
3. In the *Analysis Description* field, enter: General Contamination of Soils - Analyzed Today! as shown in Figure 3.1. Click *OK*.
4. Note the *Site Name* in the title bar of the main window and the file name at the bottom of the window. This information can also be reviewed by selecting *File/Properties*. This information will be copied to the summary reports.

Defining Site Contamination (Source Term):

5. Select the tab for the Residential scenario, which applies to this case. For this initial screening assessment, leave all pathways operative (checked). Click the *Edit Exposure Pathway* button to view default pathway settings as shown in Figure 3.2. Click on *Cancel* to return to the main screen.

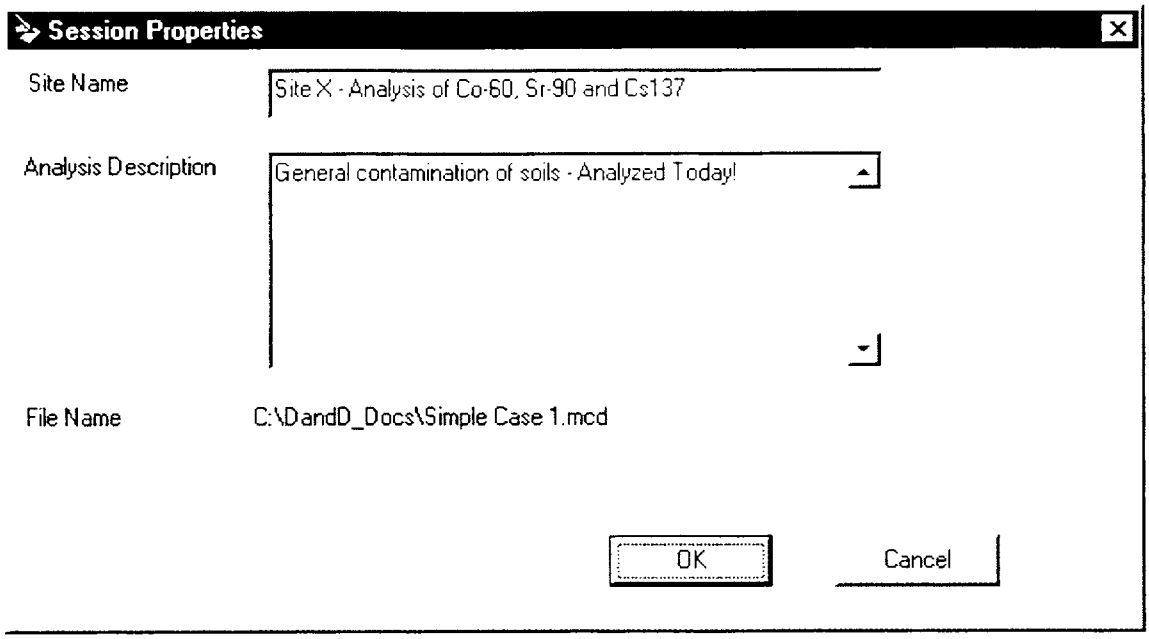


Figure 3.1 Creating a session file

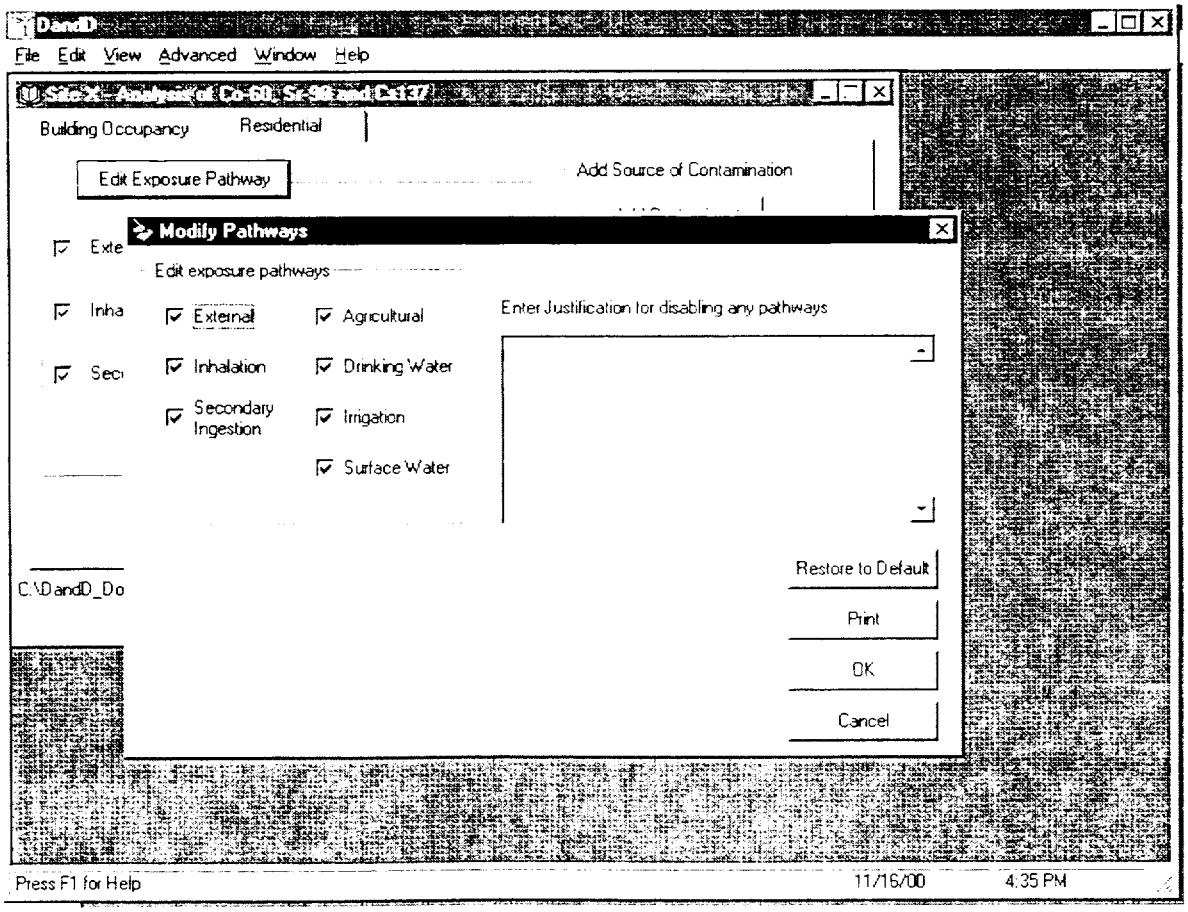


Figure 3.2 Residential default pathway settings

6. In the *Add Source of Contamination* Panel, click on *Add Contaminants*.

7. In the *Potential Contaminants* list (Figure 3.3), scroll down, select 60Co, and click on the right arrow or double-click on the radionuclide to add this nuclide to the *Site Contaminants* list.

8. Repeat #7 to add Sr-90 and Cs-137 to the list of contaminants at the site as shown in Figure 3.3.

9. Do not change the output or calculation options; click *OK*.

10. Click *Add Concentrations* button and note that Co-60 is selected by the dark arrow head to the left of Co-60, but no value has been added.

11. Click *Modify Value*. For Co-60, do not change the *Distribution* or *Units of Measure* (ensure units are pCi/g). In the Value field, enter 3 (Figure 3.4).

12. To justify this value, enter "Site survey data" in the justification field as shown in Figure 3.4. Note that the justification field must be completed. Do not change the *Area of Contamination*. Click *OK*.

13. Select Sr-90.

14. Click on *Modify Value*. Enter 2 in the *Value* field, and enter the justification "Site survey data." Click *OK*.

15. Select Cs-137.

16. Click on *Modify Value*. Enter 1.2 in the *Value* field, and enter the justification "Site survey data." Click *OK*, then *Close*.

17. In this screening analysis, do not change any parameters.

Executing DandD:

18. To run this screening assessment, click on *Execute*.

19. Click on *Run Simulation*; progress can be viewed in the adjoining panel or aborted at any time.

20. When the simulation is completed, the 90th percentile of the peak TEDE distribution 4.89E+01mrem/year with a 95% confidence interval (CI) of 4.53E+01 to 6.25E+01 mrem/year, is displayed as shown in Figure 3.5.

21. If the result had fallen below the 25 mrem/y NRC dose standard, the licensee might have elected to proceed with the NRC license termination process. In this case, the licensee instead decides to explore options for reducing uncertainty regarding the site, potential remediation actions, and/or restricted release provisions.

22. Click on *Close*.

Viewing Results:

23. Before proceeding, more information is desired about the current analysis. Select *View* on the main menu bar, and click on *Reports*. In the View Reports window, select *Detail*, then select *Create Report* to view a brief report of the user input to this analysis (this may take a minute or two to generate in the browser). In the Detail report, take note of the various sections of the report, including the Detailed Results following the Summary Results near the end of the report.

24. Note that 90% of the simulated TEDE values are less than 4.89E+1 mrem/y. Also note in the Detailed Results tables that the agricultural pathway for Sr-90 and the external pathway for Co-60 dominate the results. Close the browser window and click *Close*.

25. Select *View/Graphics/Dose Distribution* from the main menu bar. Clicking an item under both Pathways and Radionuclides will allow additions or deletions from the plot to depict those contributions to dose. Note that the agricultural pathway for Sr-90 and external pathway for Co-60 dominate the results. Click *Done* to close the Dose Distribution plot.

3.3 Run a Site-Specific Analysis

After running a simple screening analysis described in the previous section, the licensee discovers an error in the survey data and is able to justify reductions in the levels of contamination at the site. A re-analysis is performed based on this new information.

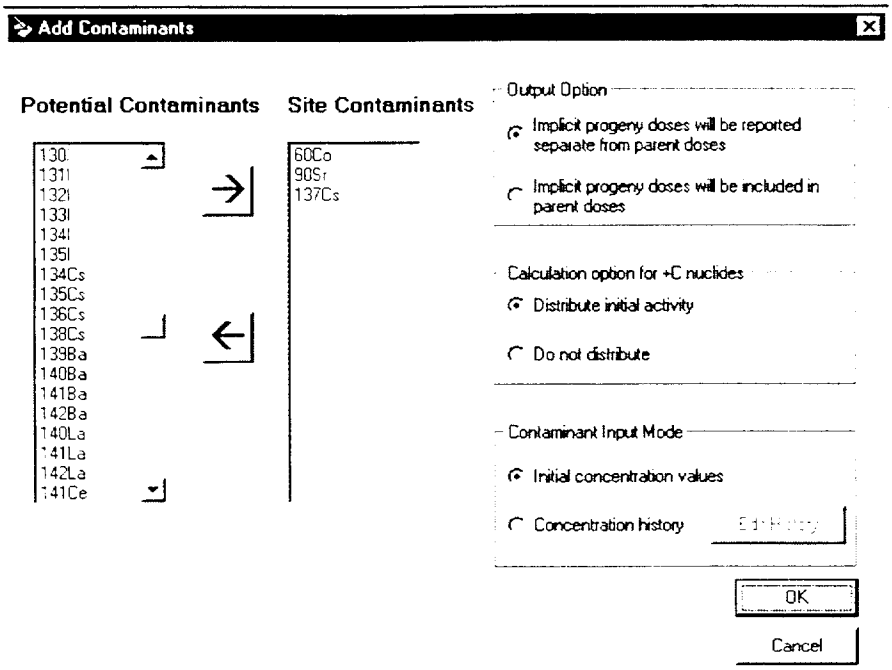


Figure 3.3 Three site contaminants present

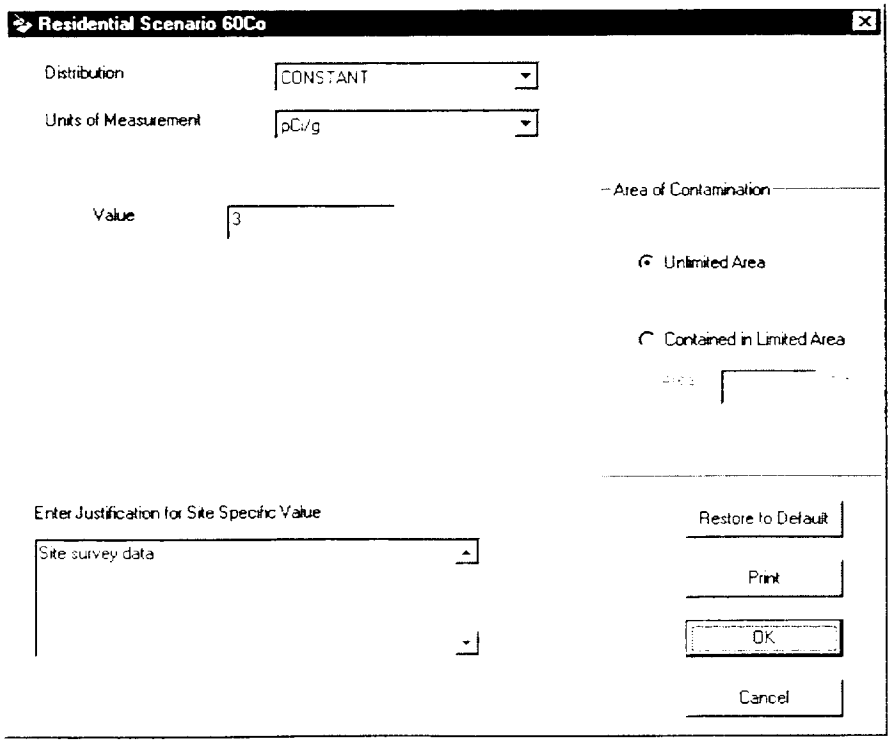


Figure 3.4 Adding concentration of Co60

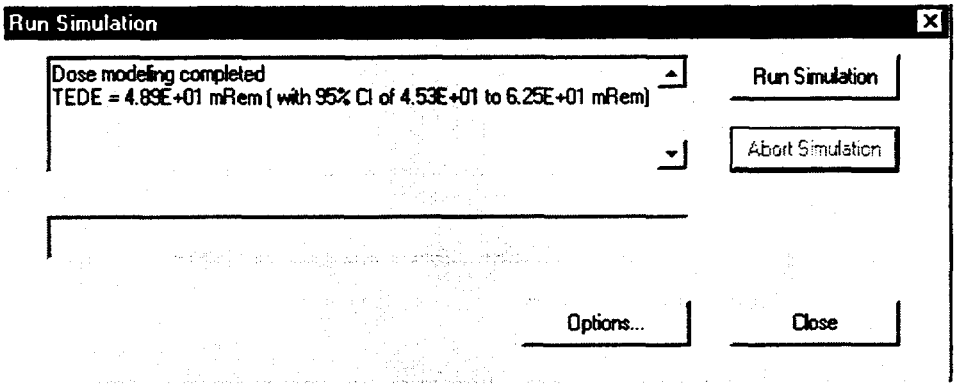


Figure 3.5 Result summary of Case1 analysis

Updating Source Term Information:

1. In the main window, save a new session for the reanalysis by selecting *File/Save As* and naming the new analysis Simple Case 2. Click the *Open* button. If desired, change the *Site Name* and/or *Analysis Description* under *File/Properties* and click the *OK* button.

2. In the main window under the Residential tab, leave all pathways selected for this iteration.

3. In the main window, click on *Add Concentrations*, verify that Co-60 is selected, and click on *Modify Value*. Enter a new constant value of 1. Change the *Area of Contamination* to *Limited Area* and enter 40 m^2. Supplement the justification text that this new information is based on new site survey data as shown in Figure 3.6. Click *OK*, and *OK* regarding deletion of the existing calculations.

4. Select Sr-90 and click *Modify Value*. Enter a new value of 1.5. Supplement the justification text that this new information is based on new site survey data. Change the *Area of Contamination* to *Limited Area* and enter 30 m^2. Click *OK*.

5. Select Cs-137 and click *Modify Value*. Do not change the value for contamination; change the *Area of Contamination* to *Limited Area* and enter 20 m^2. Supplement the justification text that this new information is based on new site survey data. Click *OK*.

6. Click on *Close* to return to the main screen. No other changes to the original settings are needed (contaminants, general, or element parameters).

Executing DandD:

7. Click on *Execute*, and click *Options* to ensure the *Save Dose History* checkbox is selected, then click *OK*. Click *Run Simulation* to reanalyze the dose models with the reduced contaminant data.

8. The displayed results (27.5 mrem/y)* are still above the 25 mrem/y dose standard. When the confidence interval includes the performance objective, the Sample Size Analysis window opens as shown in Figure 3.7. This information allows the user, if desired, to determine the effect of increased sample size on the ability to demonstrate compliance and to rerun the simulation with a larger number of simulations.

Viewing Results:

9. Click *Close* on the Sample Size Analysis and Run Simulation windows.

10. Select *View* on the main menu bar, click on *Reports*, and double-click on *Detail* to create and view the report for this analysis iteration.

*If the displayed results are slightly different, the user did not necessarily make an error. In some cases, the random sample values of the parameters depend on the order the user defined and modified the parameters. This will result in a slightly different value of the TEDE and 95% confidence interval bounds. The program results are still valid. This order dependence is a bug and may be fixed in a future version. When this bug is fixed, users may not get the results reported above.

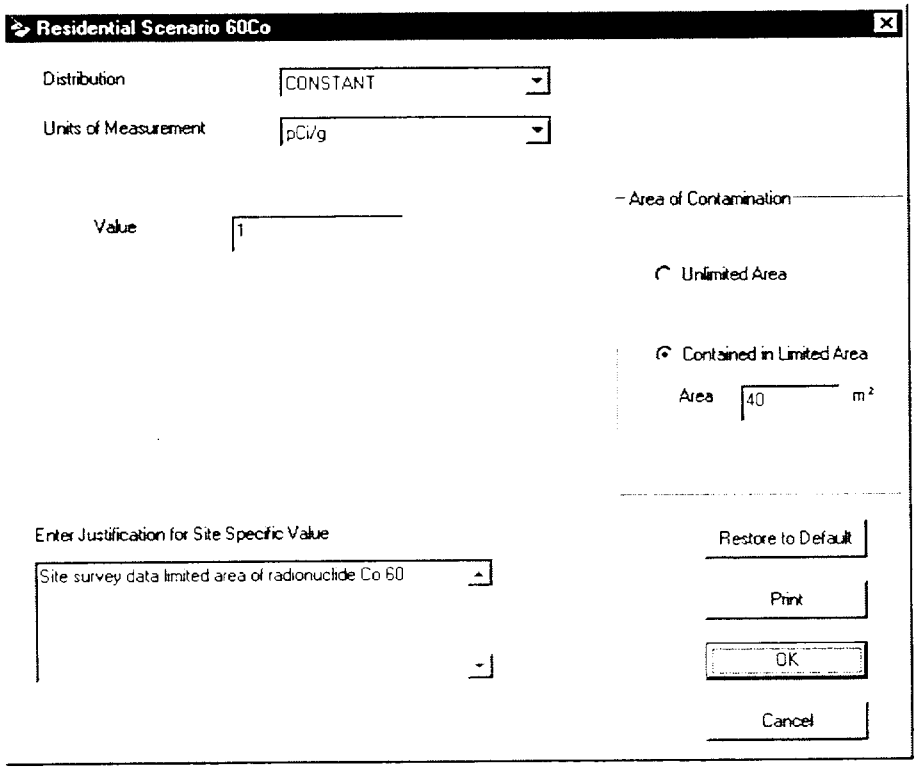


Figure 3.6 Limit area of contamination

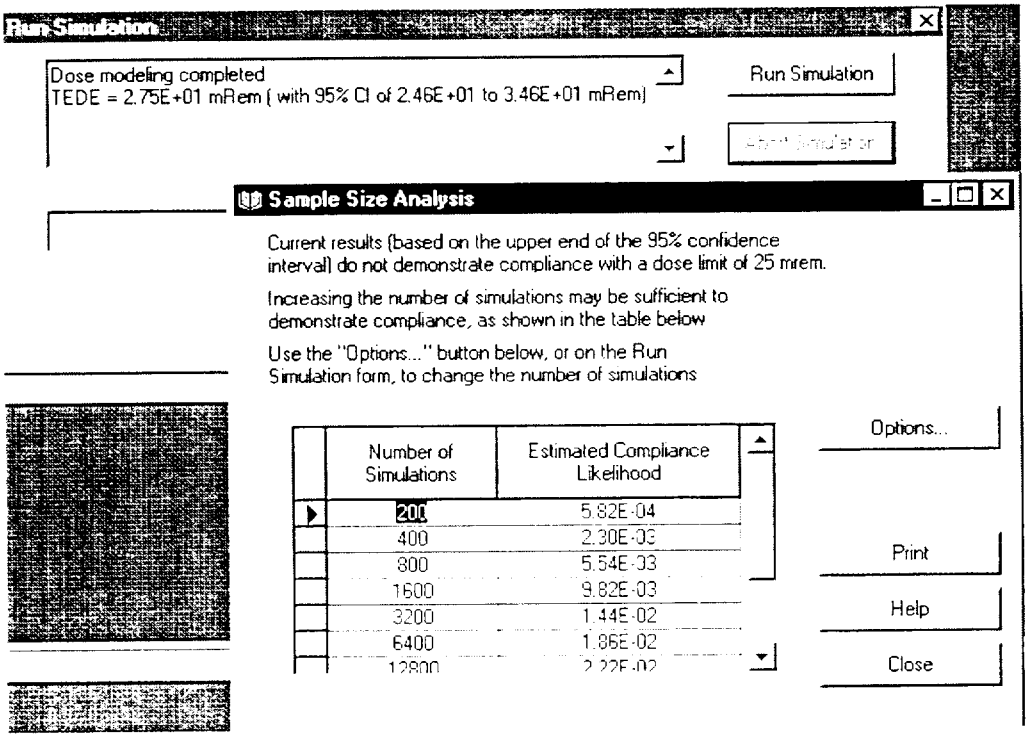


Figure 3.7 Sample Size Analysis window for Case1

11. Scrolling to the end of the report, note that 90% of the simulated TEDE values are less than 2.75 E+01 mrem/y. This result is above the 25 mrem/y standard. As such, the licensee elects to conduct an options identification and analysis process using the DandD sensitivity module. Also note in the detailed report that the external pathway for Co-60 and agricultural pathway for Sr-90 still dominate the results. Close the browser window and select Close to return to the main window.

12. Again, these contributions to dose can be verified: select *View/Graphics/Dose Distribution*. In the *Plot Scale* group of buttons, click *X Axis*, click the *Log* radio button, then click *OK* to change the x-axis to a log scale. Click *External* for *Co-60* and *Agricultural* with *Sr-90* to add those plots to the graph as shown in Figure 3.8. Click *Done* to close all graphs and reports.

Sensitivity Analysis:

DandD provides the capability to conduct sensitivity analysis to identify parameters that have the greatest impact on the dose distribution and those for which new information could impact on the compliance decision.

13. Select *Advanced/Sensitivity Analysis* from the menu bar. The Data Influence Evaluation window lists all uncertain parameters in this analysis and develops a preliminary list of the most sensitive parameters for analysis. The user is able to add or remove parameters from this list for further analysis. Note that the uncertain uptake rates for leafy plants, rooting plants, and fruit for Sr-90 are listed as the most sensitive parameters by the initial analysis.

14. Scroll down the *Available for Analysis* list, highlight CDO (average dust loading outdoors), and click on *Select Parameter for Analysis*. Repeat this process for AP (water application rate) and CDI (average dust loading indoors) to add these additional parameters to the lower list: *Selected for Analysis* as shown in Figure 3.9.

15. Click on the *Analyze* button; this launches a separate module that allows the user to investigate potential effects of parameter values from site-specific data. The overall objective in the greater context of the decision framework is to reduce the uncertainty associated with the parameter(s) via acquisition of supporting site data, update the values for the parameter(s) based on defensible data, and rerun the analysis to determine the impact on the dose distribution. The sensitivity analysis package allows the user to manipulate the preliminary list of parameters by truncating their distributions to reflect either existing site knowledge or informed judgment about the probability of successfully acquiring site data that may support the new truncated distribution. See Section 4.3.11 for detailed instructions on use of the Sensitivity Analysis module.

16. Select either *File/Exit* or click the close window "X" at the upper right portion of the Sensitivity Analysis window. Click *OK* to close the Data Influence Evaluation window.

Reiteration of Dose Assessment:

Based on the sensitivity analysis and other site investigations, the site analyst embarks on the next course of action and analysis. Site land use studies and projections, along with site characterization data, suggest that this site owner can justify eliminating the agricultural pathway. Though drinking water wells and irrigation are still viable future possibilities at this site, the analyst is able to justify modification of the depth to the water table. The following analysis implements those changes.

1. In the main window, save a new session for the reanalysis by selecting *File/Save As* and naming the new analysis "Simple Case 3." Click the *Open* button. If desired, change the *Site Name* and/or *Analysis Description* under File/Properties.

2. In the main window under the *Residential* tab, click the *Edit Exposure Pathway* button to open the Modify Pathways window.

3. Click on the *Agricultural* checkbox to deselect this pathway, and enter a justification that this modification is based on current land-use studies and future land-use projections. Print this window, if desired, by clicking the *Print* button and then click *OK*. Click *OK* to acknowledge that current calculations will be overwritten.

4. Click on *General Parameters* to open the Residential Parameters window. Note the parameter category buttons along the top of this window. Scroll down the list included in the Basic group.

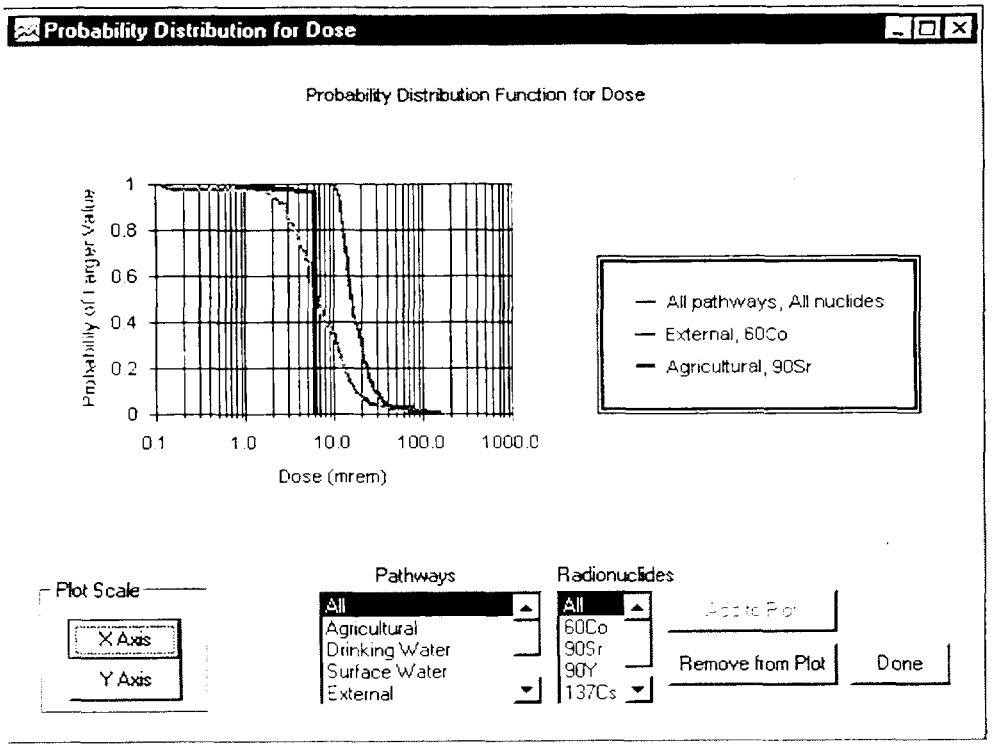


Figure 3.8 Dose distribution for Case 2

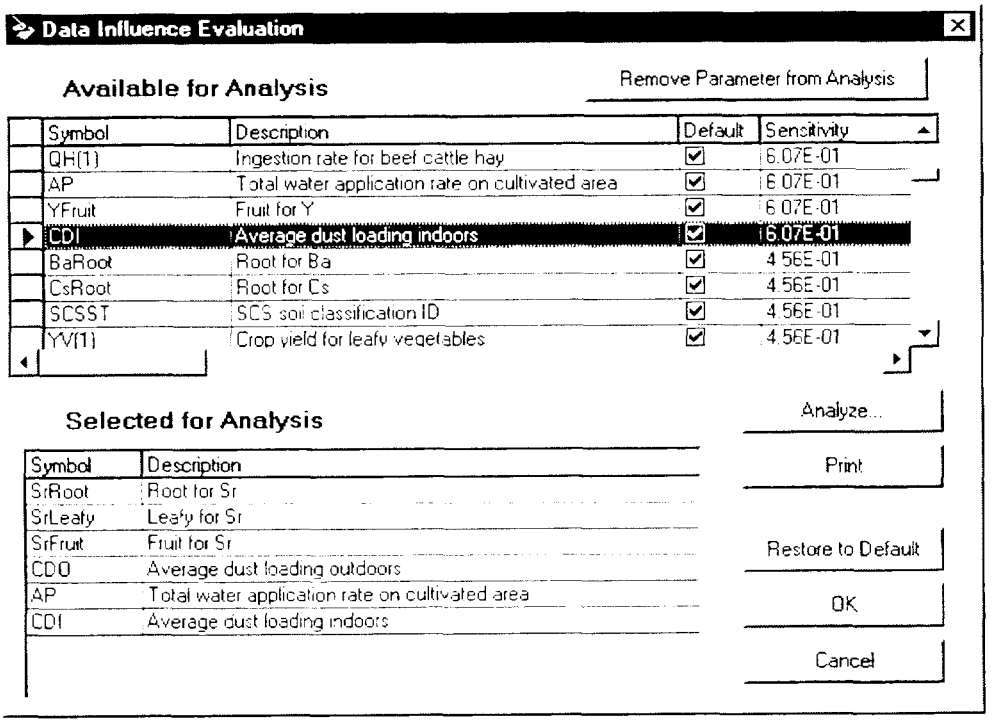


Figure 3.9 Select parameters for analysis

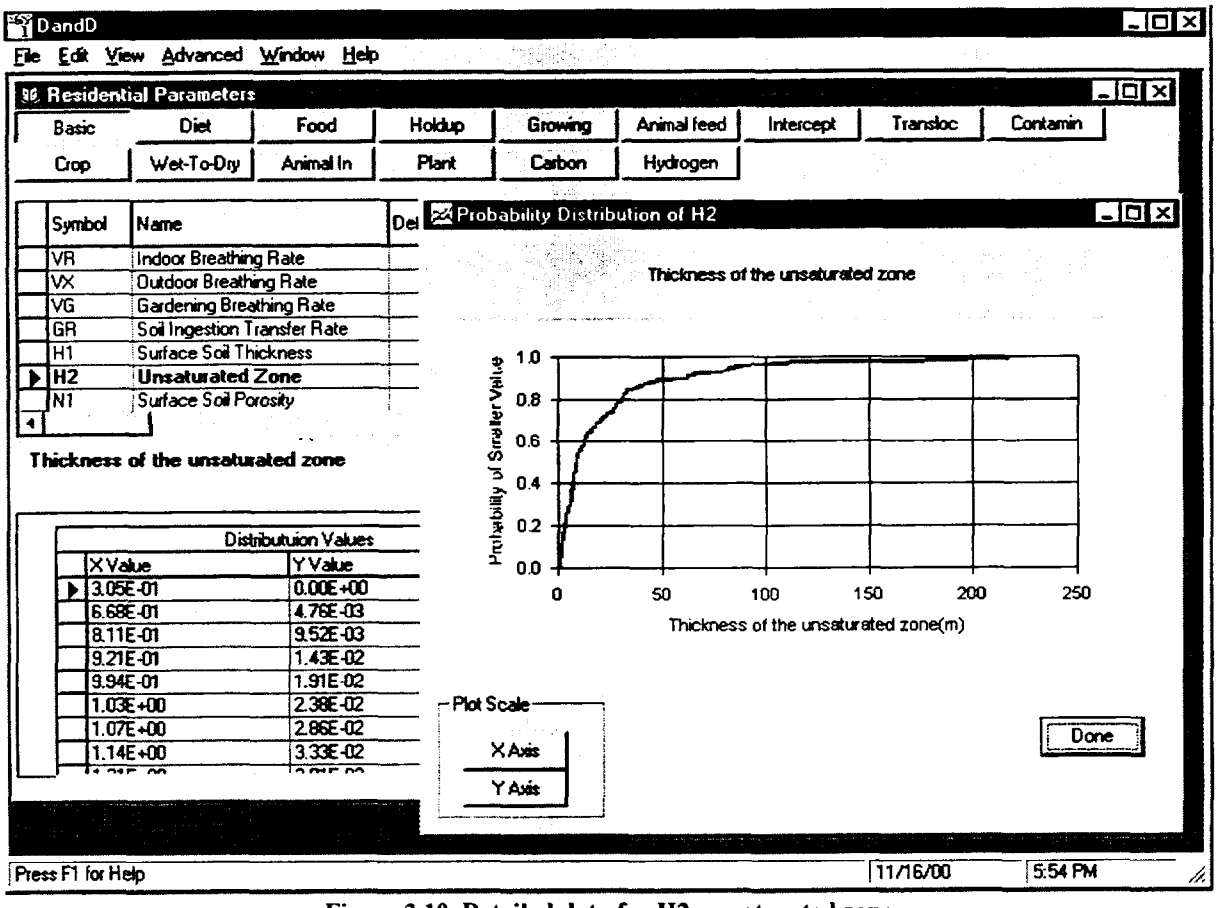


Figure 3.10 Detailed data for H2, unsaturated zone

5. Locate and select H2, Unsaturated Zone Thickness, and click *Plot* to view the current default distribution for this parameter as shown in Figure 3.10. Click *Done* to close the plot. Click *Modify Value*.

6. Change the distribution type to Uniform, leave units unchanged, and enter 100 m and 150 m as the lower and upper limits for the expected thickness of the unsaturated zone at this site. Enter justification text stating that this range of values is based on site characterization studies as shown in Figure 3.11. Click *OK*.

7. Click Plot to review the new distribution, then click on *Done*. Click on *Close* to close the Residential Parameters window.

8. To run this new simulation, select *Execute* followed by *Run Simulation*. When complete, the results of this new analysis—2.84 mrem/y—fall well below the 25 mrem/y performance objectives for this site. As such, the licensee elects to pursue the license termination process with NRC based on well-documented and supported information and analyses using the DandD code.

9. To exit DandD, click the *Close* button in the Run Simulation window. Select File/Exit from the main menu.

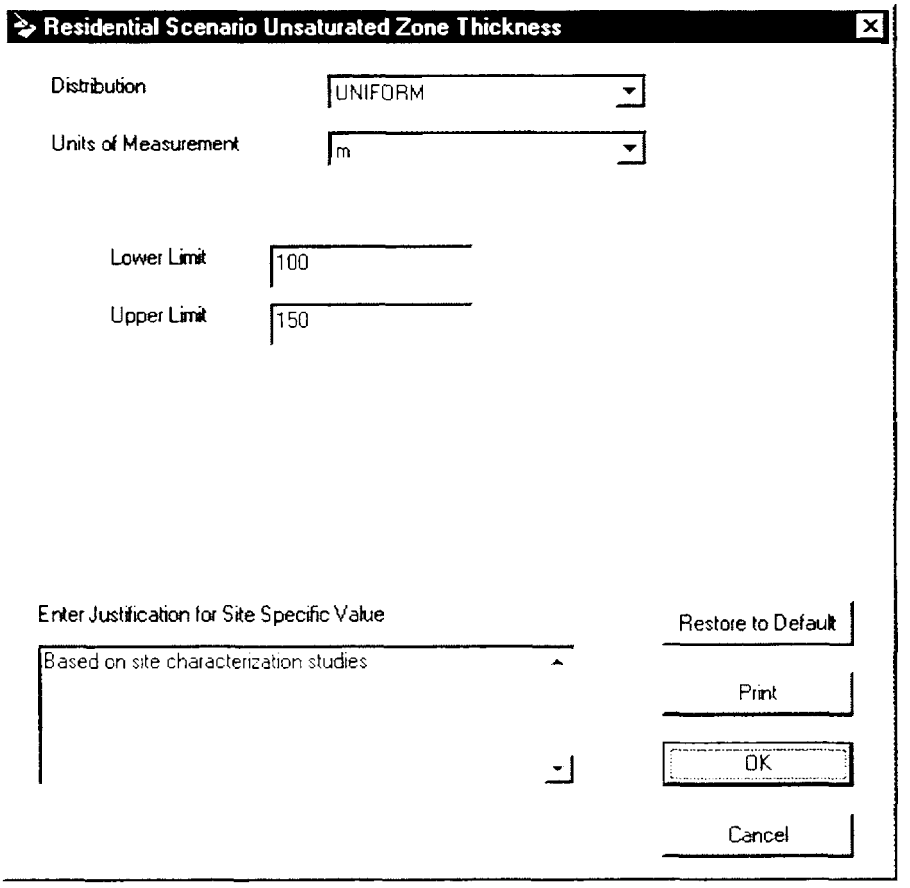


Figure 3.11 Modifying distribution

4 USER INTERFACE REFERENCE GUIDE

4.1 Common Interface Operations

4.1.1 On-Line Help

DandD was designed to provide an on-line user manual that reduces the need to refer to a hard-copy manual. It provides on-line documentation and software guidance using the Microsoft® Windows® Help system and HTML help that is available to view from the user's computer. The HTML help files are local to the user's computer. It is not necessary to have an Internet connection to view the HTML help, but the user will need a browser such as Internet Explorer or Netscape installed.

The Microsoft® Windows® Help facility is a hypertext system that allows the user to easily jump from one topic to another and back again. Hypertext is basically the same as regular text with one exception: hypertext contains connections within the text to other documents. These hypertext links, called hyperlinks, connect to other documents in the help system and appear as colored, underlined text. By clicking on the hyperlink text, the program will display a different help topic document.

The user can get help with the basic program usage by pressing the F1 function key, or by using the *Help/Contents* and *Help/Search For Help On* options from the main menu. Additionally, selecting *Help/NRC References* from the main menu will open a document that describes the models in more detail. The user can get context help on parameters by clicking the *Parameter Help* button. This button is displayed on the parameter viewing window.

The Help system includes Index and Find tabs that help locate particular topics, a Bookmark command that can flag topics of interest, an Annotate feature that lets the user add their own comments to the help text, a Copy command that copies selected information onto the clipboard, and a Print command. More information on Microsoft® Windows® help is available by selecting Help from the Microsoft® Windows® *Start* button, clicking *Help*, and searching for the keyword Help in the Index tab of the Microsoft® Windows® help window.

4.1.2 Parameter Viewing Window

The windows for viewing parameter values all have a similar design. Parameters are divided into three types: source concentrations, general parameters describing the physical properties of the site, and element parameters related to the chemical elements in the decay chains of the source radionuclides.

The source concentration parameter settings can be viewed by clicking the *Add Concentrations* button in the Session window. The general parameter settings can be viewed by clicking the *General Parameters* button in the Session window. If the residential scenario tab is the current scenario, the element parameter settings can be viewed by clicking the *Element Parameters* button in the Session window.

The general parameters and element parameters for the residential scenario are grouped into categories, as shown in Figure 4.1.1. Select the parameter category by clicking on one of the category buttons located at the top of the Parameter Viewing window. These buttons do not appear on the Add Concentrations form nor on the building occupancy parameter viewing forms.

A data grid summarizes information concerning the parameters in the chosen category. The general parameter grid entries have the following meaning:

- **Symbol**: symbol used in Kennedy and Strenge (1992) to identify a parameter.
- **Name**: user-friendly name used to identify the parameter.
- **Default**: check appears if the user has not modified the parameter. No check appears if the user has entered a site-specific value.
- **Read Only**: check appears if DandD does not allow this parameter to be modified.
- **Distribution Name**: name of probability distribution associated with the parameter. If name is CONSTANT, there is no associated distribution.

  If name is DERIVED, the parameter value is calculated from other parameter values.

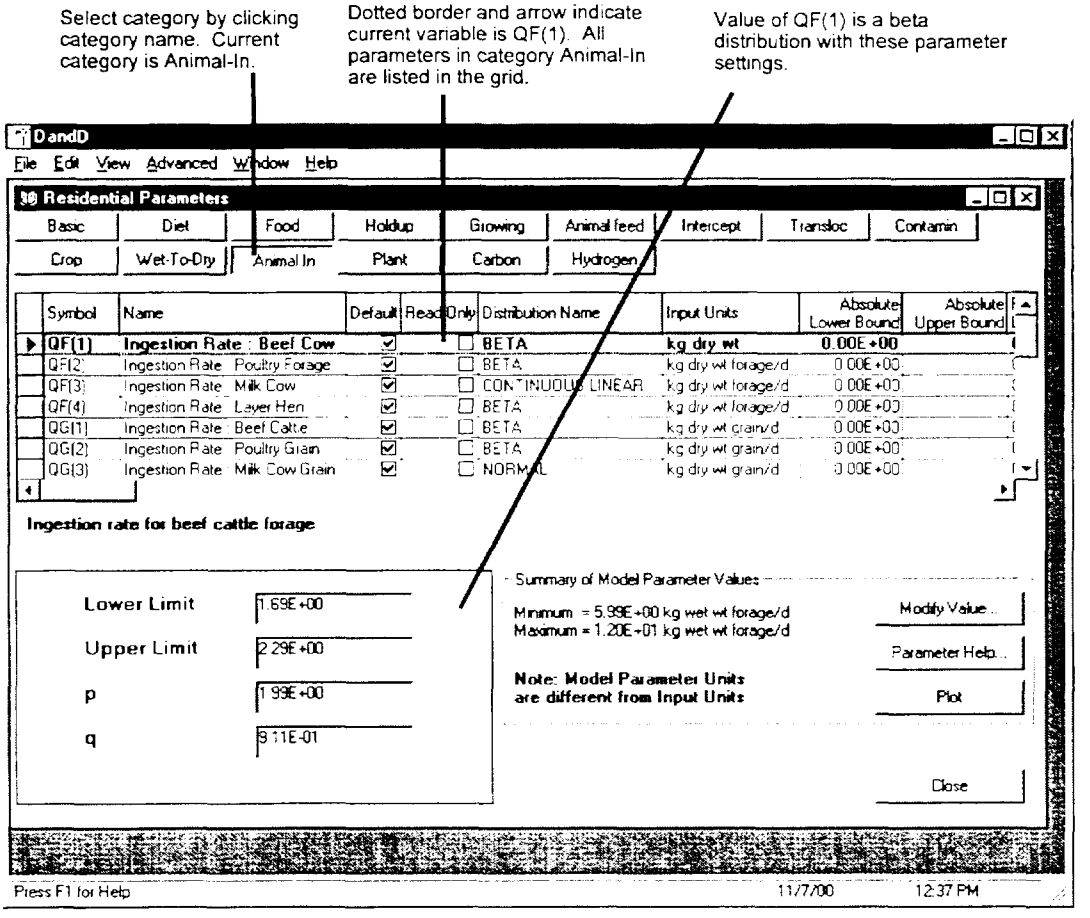


Figure 4.1.1 Viewing a parameter value

- **Input Units**: units of the site-specific or default parameter value. These units can be modified from the Parameter Modification window.

- **Absolute Lower Bound**: smallest value of the parameter that is allowed by the modeling code. DandD will prevent lower values from being used.

- **Absolute Upper Bound**: largest value of the parameter that is allowed by the modeling code. DandD will prevent higher values from being used.

- **Recommended Lower Bound**: DandD will warn about, but not prevent, parameter values smaller than the recommended lower bound.

- **Recommended Upper Bound**: DandD will warn about, but not prevent, parameter values larger than the recommended upper bound.

Select the parameter to view or modify by clicking the appropriate row on the data grid. After the parameter has been selected, the data defining the value or distribution for this parameter is shown on the lower left corner of the screen.

The amount of data needed to define the value depends on the associated distribution. If the parameter is a constant value, only one number is required. If the parameter value is defined by a probability distribution, several numbers may be needed to define the distribution. A normal distribution, for example, requires two numbers: a mean value and a standard deviation. If the parameter is a tabulated (or empirical) distribution, the parameter values will be a list of ordered pairs where the x value is a parameter value and the y value is related to the probability that the parameter has that value. Some parameters may be assigned a distribution called "Derived." This means that the value of the parameter is calculated from the values of other parameters. Unless the derived param-

eter is marked as "Read Only," the user can modify the derived parameter value to a specified value. Beyeler et al. (1999) contains information describing the calculations used to derive parameter values from other parameters.

The actual values for the parameter used in the dose calculation are summarized in the lower right portion of the parameter viewing screen labeled *Summary of Model Parameter Values*. The summary information displayed on the right side of the Parameter Viewing window, and the plots of the parameter values, are presented in the units used by the model, which may be different than the input units.

To modify a parameter value, click on the *Modify Value* button on the right side of the screen or double-click the parameter row in the grid. If the parameter is not a read-only parameter, the Parameter Modification window will open (see Section 4.1.3). If the parameter is a read-only parameter, it cannot be modified and a pop-up box will notify the user of this.

Detailed information about the parameter can be obtained by clicking the *Parameter Help* button. This information includes the parameter definition, how the parameter is used in the dose model, what data was used to develop the default value or probability distribution, and information about assigning a site-specific value.

A probability distribution of the parameter value can be displayed by clicking the *Plot* button, which brings up the Parameter Plot window. This plot will not give any useful information if the parameter value is a constant.

4.1.3 Parameter Modification Window

Modify parameters by clicking on the *Modify Value* button in any Parameter Viewing window. A window similar to Figure 4.1.2 will open.

Select the type of distribution to associate with the parameter from the *Distribution* pull-down list at the top of the screen.

Modify the parameter units by selecting the appropriate entry from the *Units of Measurement* pull-down list. Only units that are appropriate for the parameter and that can be converted into the model input units are displayed. DandD saves the values entered and units used, even if those units are different from the units used by the model.

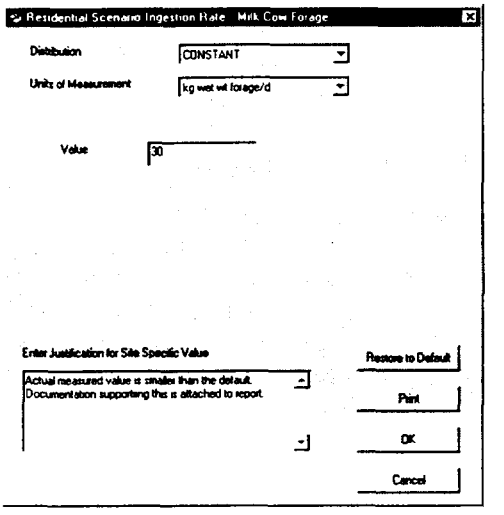


Figure 4.1.2 Parameter modification window

After selecting the units of measurement, enter the values that define the distribution. DandD provides a wide range of distribution types. Each distribution type can accept a wide range of values for its parameters. These values may either consist of a list of (x,y) pairs (known as tabulated data) or a list of specific distribution parameters (such as the mean and standard deviation of the normal distribution). If the parameter has no distribution, but is a single number, set the *Distribution* field to CONSTANT. Type the value in the field labeled *Value*.

It is possible to specify values for the distribution parameters that lead to invalid distributions, causing the LHS sampling to fail. The user will be notified and will need to modify the parameter distribution accordingly.

The distribution DERIVED has no numeric values to enter. This choice means that the parameter value is calculated from the values of other parameters by the model engine. Only some parameters have built-in functions for deriving values. If the parameter cannot be derived by the model engine, the distribution DERIVED will not be available for this parameter. If the user wants the model engine to calculate the parameter value, set the distribution type to DERIVED. The parameter values calculated by the model engine can be viewed from the Parameter Viewing window. A description of the derived parameters can be found in Beyeler et al (1999).

If the user selects an empirical distribution, a grid of tabulated data will be displayed, as shown in Figure 4.1.3. To delete a row of tabulated data, select the row by clicking on the left margin of the row. Press the

Delete key on the keyboard to delete the row. If the cursor has focus on a number in the grid and the pencil icon is present as shown in Figure 4.1.4, press the ESC key on the keyboard to undo typing. As long as the pencil icon is shown on the left margin of a row, click in a cell on that row and press the ESC key to undo changes. Use the arrow keys on the keyboard to go to the next cell.

If a parameter value is modified from the default value, the user will be required to enter text explaining why the value or distribution specified is appropriate (see Figure 4.1.2). This field is labeled *Enter Justification for Site Specific Value*.

To reset the parameter definition to the default value or distribution, click the *Restore to Default* button. It will still be necessary to click the *OK* button to accept the default values for the parameter.

To discard the changes made, click the *Cancel* button.

To save changes, click the *OK* button. This will close the Parameter Modification window and save any changes made to the parameter value. After any parameter values have been changed, DandD regenerates the set of parameter values that will be used in the dose calculation. This may take a few seconds.

If the value or distribution specified is not consistent with the absolute limits defined for the parameter, the user will be notified and required to change the parameter value before executing the dose model. If the parameter value or distribution falls outside of any recommended limits, the user will be notified. The dose model can be executed in this case, however, special justification may be needed for the value or distribution.

4.1.4 Graphics Windows

The Graphics windows can be accessed through the main menu *View/Graphics* after running a simulation. The Graphics windows can also be accessed to view distributions associated with individual parameters through the *Plot* button on the Parameter Viewing windows. A typical graphics window is shown in Figure 4.1.5. For specific information on the meaning of the data, see the appropriate description in Section 4.3 under the associated menu selection (e.g., View/ Graphics).

Not all graphics windows will have all of the functions described below. In particular, windows displaying a parameter distribution and the *Time Distribution* will not have the *Pathways* and *Radionuclides* list boxes. If the parameter or result is a constant value, the graphics window will display a vertical line at the constant value.

PDFs for individual pathways and individual radionuclides can be added to the graph by selecting a specific pathway (or *All*) from the *Pathways* list box, selecting a specific radionuclide (or *All*) from the *Radionuclides* list box, and clicking the *Add to Plot* button.

Curves can be removed from the graph by selecting the curve and pressing the "Delete" key on the keyboard or clicking the *Remove from Plot* button on the form.

Three methods are available for selecting curves. A curve can be selected by clicking it on the graph. A curve can also be selected by clicking on the corresponding line in the legend. This feature can be used to find curves that overlap other curves on the graph or that fall along the y axis. Finally, a curve can be selected for deletion by selecting the appropriate entry in the *Pathways* and *Radionuclides* lists. If a curve is selected by clicking on an entry in the *Pathways* and *Radionuclides* list, and the curve has already been added to the graph, then only the *Remove from Plot* button will be enabled. Otherwise, only the *Add to Plot* button will be accessible to the user.

The plot area can be selected and resized using the resizing controls. The legend can also be selected, resized, and repositioned. If the legend or the plot area are moved or resized, the legend may not be automatically resized to include new curves added to the plot.

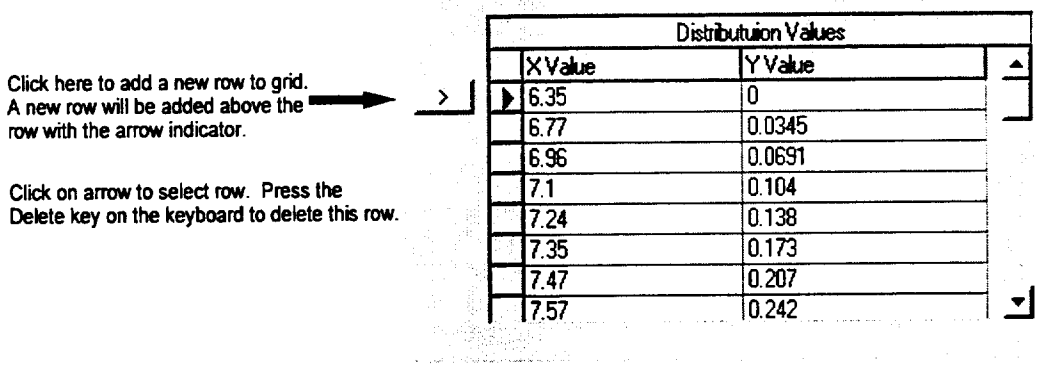


Figure 4.1.3 Empirical distribution grid

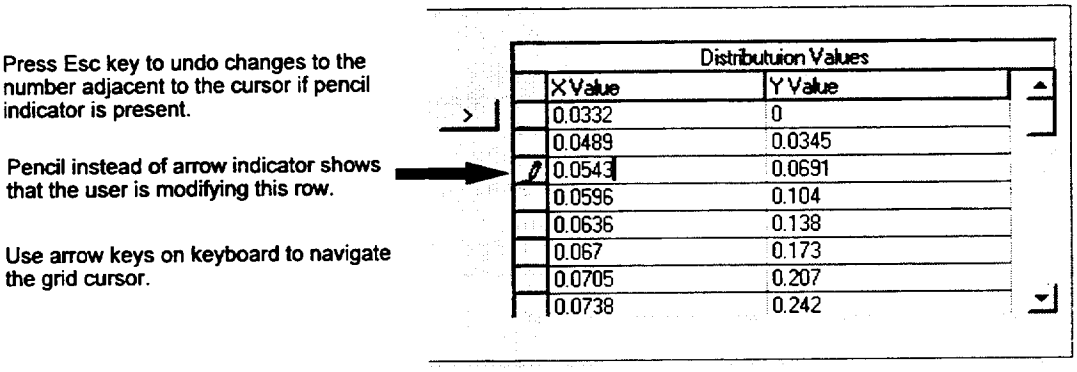


Figure 4.1.4 Modify a grid entry

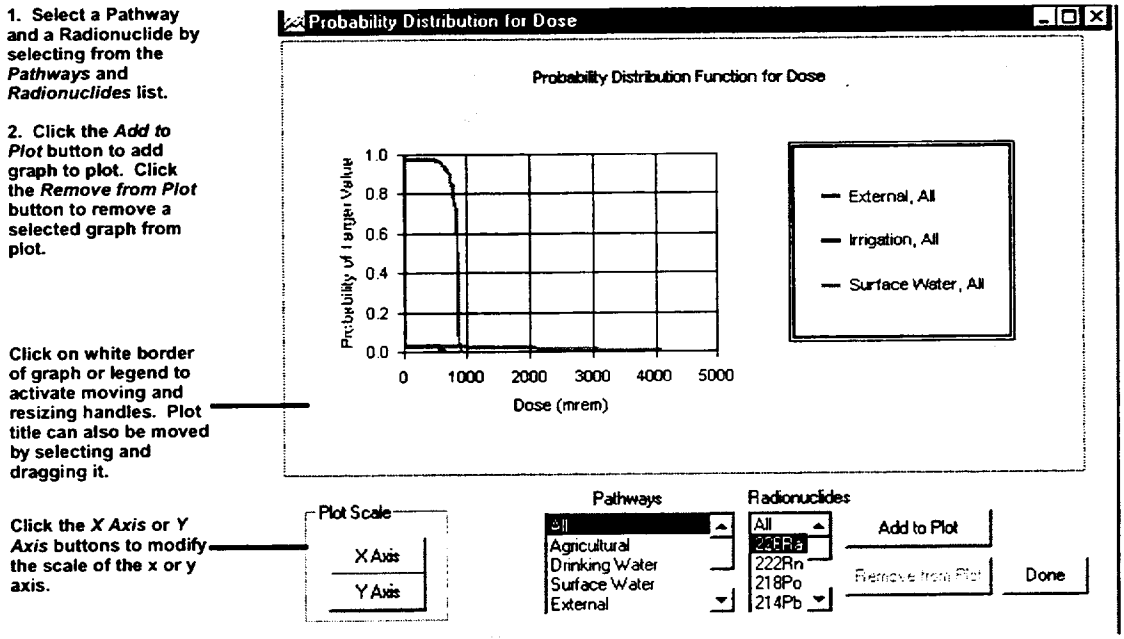


Figure 4.1.5 Typical graphics window

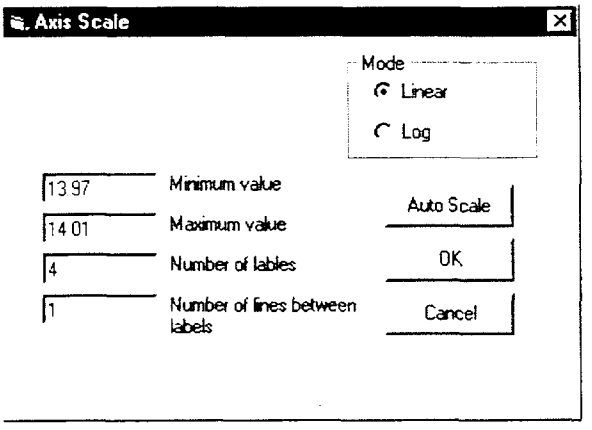


Figure 4.1.6 Modifying the Axis Scale

It may be necessary to manually resize the legend to see descriptions for all of the curves on the plot. The user can also select and move the plot title.

Click the *X Axis* or *Y Axis* buttons to modify the axis on the plot. An Axis Scale window, as shown in Figure 4.1.6, will open.

The scales for the x and y axes can be set using the *Minimum value* and *Maximum value* fields. All scales are initially set automatically based on the range of data in the plot. This automatic scaling can be restored using the *Auto Scale* button.

Minimum value and *Maximum value* determine the range of the plot axis. *Number of labels* determines the number of labeled lines, and *Number of lines between labels* sets the number of axis lines that are shown between labeled lines.

The *Linear/Log* radio buttons set the axis scaling mode. Both the minimum and maximum values must be positive if Log scaling is selected.

Click *OK* in the Axis Scale window when finished.

The plot can be printed using the File/Print command from the main menu.

The plot can be copied to the clipboard using the *Edit/Copy* menu commands. It can be pasted as a graphic image in a word-processing application using the *Paste Special* command in the word processor. By default, the x-y data pairs that define the curves (dose-probability, time of peak-probability, or dose history) will be pasted as text from the clipboard.

Click on the *Done* button to close the window. The graph created will not be saved by DandD.

4.2 Scenario Tabs and Their Controls

When a DandD session is opened (using the File/Open or File/New command), a window with two tabs is opened. This is called the Session window (see Figure 4.2.1). One of the two default scenarios NRC has included in DandD can be selected by clicking the *Residential* or the *Building Occupancy* tabs within the Session window. The underlying engine used for analysis is different between the two scenarios.

Depending on the tab selected, different options are available. The residential scenario includes more exposure pathways and has more site-specific parameters available than the building occupancy scenario. These parameters are accessible by clicking the *General Parameters* or *Element Parameters* button. The residential scenario also allows input of concentration data via a text file. The building occupancy scenario does not have the *Element Parameters* button available.

The building occupancy scenario data is stored independently from the residential scenario data. This allows the saving of data and results from both scenarios in the same session file. The user can also switch between scenarios by clicking the appropriate tab without any loss of data or results.

The following section describes the controls available to the user in the Session window.

4.2.1 Edit Exposure Pathway Button (Site-Specific)

The following exposure pathways are supported for the building occupancy scenario:

1. External: external radiation from inside building surfaces

2. Inhalation: exposure by breathing indoor air contaminated by resuspension of radionuclides from building surfaces

3. Secondary Ingestion: ingestion of contaminated dust inside building surfaces

The residential model supports the following pathways:

1. External: external radiation from inside building surfaces, outside soil, and garden soil

2. Inhalation: exposure by breathing inside air, outside air, and garden air

3. Secondary ingestion: consumption of contamination from dust on inside building surfaces, outside soil, and garden soil

4. Agricultural: consumption of agricultural products that do not use well water

5. Drinking Water: consumption of drinking water from a well

6. Irrigation: consumption of agricultural products that use well water

7. Surface Water: consumption of aquatic products from surface water sources

Detailed information about the meaning of these pathways is available by selecting *Help/NRC References* from the main menu.

By default for screening assessments, all pathways will be selected. Pathways should not be deselected unless users are conducting a site-specific analysis.

The current exposure pathways are shown in the Session window. Select or remove pathways by clicking the check boxes or the *Edit Exposure Pathway* button as shown in Figure 4.2.2. If this is done, the Modify Pathways window will open, as shown in Figure 4.2.3. Turn pathways on or off by clicking the check box adjacent to the pathway.

If a pathway is deselected from the analysis, dose calculations involving that particular pathway are not performed. Selecting or deselecting the various pathways does not change the values or distributions of any parameters, although some parameters may not be used when pathways are deselected.

Changing the values of some parameters can affect doses that occur over more than one pathway. For example, modifying the Time Outdoors parameter changes the calculated dose due to the external, inhalation ad secondary ingestion pathways. Parameter help accessed via the Parameter Viewing window (see section 4.1.2) and the online help accessed by selecting *Help/NRC/References* from the main menu will supply the user with specific parameter and pathway dependency information.

The user is required to justify disabling exposure pathways for a given scenario in the dose assessment. The screen including the user justification text may be saved as hard copy documentation using the *Print* button.

To restore all pathways to original settings, click the *Restore to Default* button. Alternatively, click *Cancel* to ignore all changes to the Modify Pathways window. Otherwise, click *OK* to save pathway settings and return to the main Session window.

4.2.2 Add Contaminants

4.2.2.1 Adding Contaminant Source

The first step in a screening analysis is to indicate the radionuclide contaminants present at the site. Until the source of contamination is specified, all other buttons (with the exception of the *Edit Exposure Pathway* button) in the Session window will not be accessible. Clicking the *Add Contaminants* button in the Session window opens the Add Contaminants window, as shown in Figure 4.2.4.

Add radionuclides to the source term by selecting a symbol from the list labeled *Potential Contaminants*. Click on the right arrow button to add the contaminant. Alternatively, the user can double-click on the symbol to move the radionuclide to the *Site Contaminants* list.

To remove the contaminant from the list labeled *Site Contaminants*, select a contaminant and click on the left arrow button. Double-clicking a symbol in the *Site Contaminants* list will also remove it from the source term.

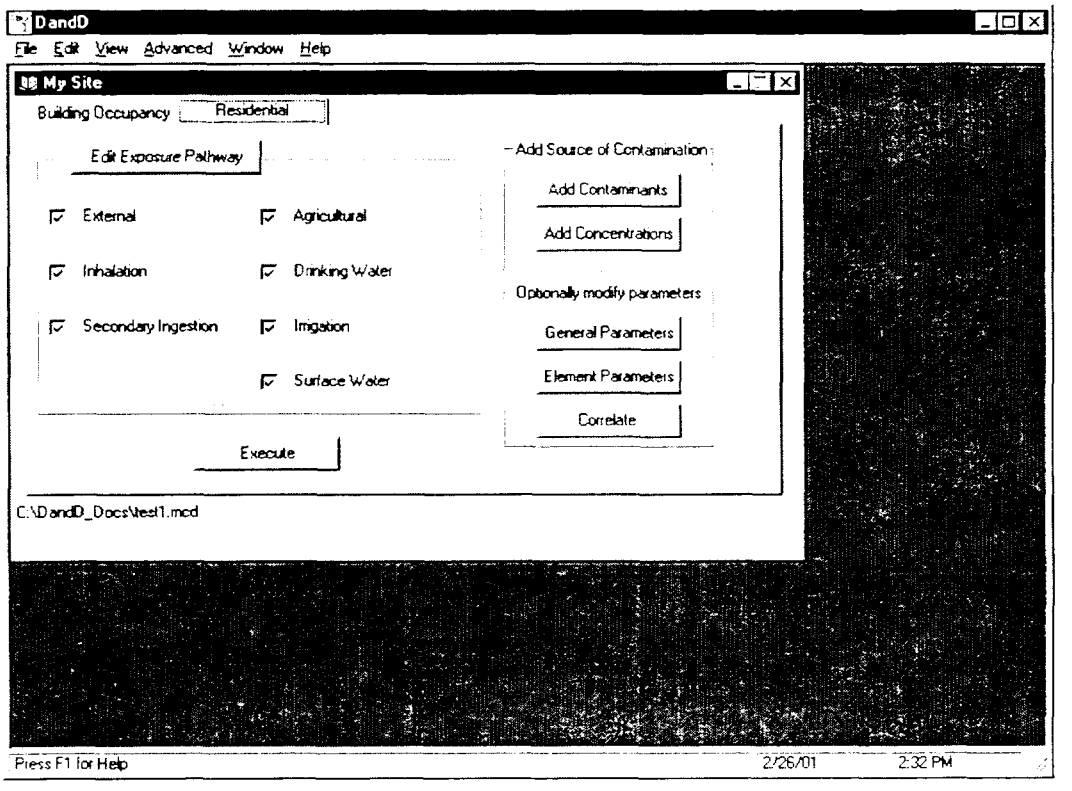


Figure 4.2.1 Session window

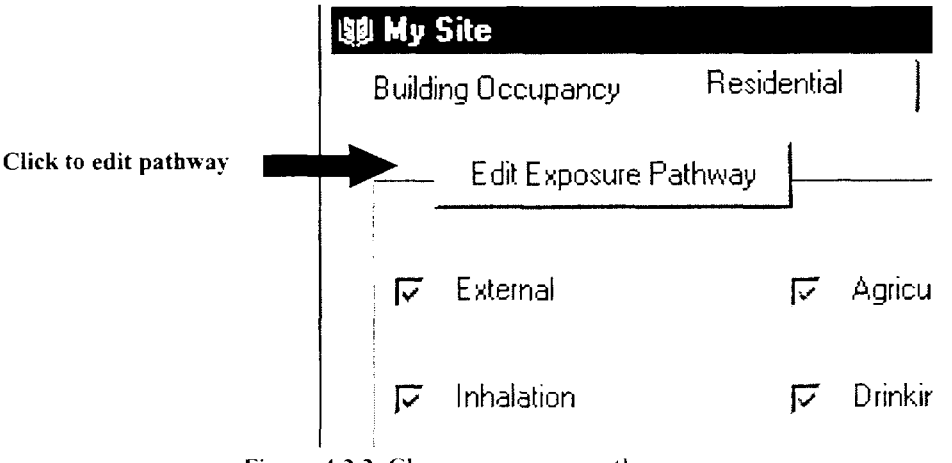


Figure 4.2.2 Change exposure pathways

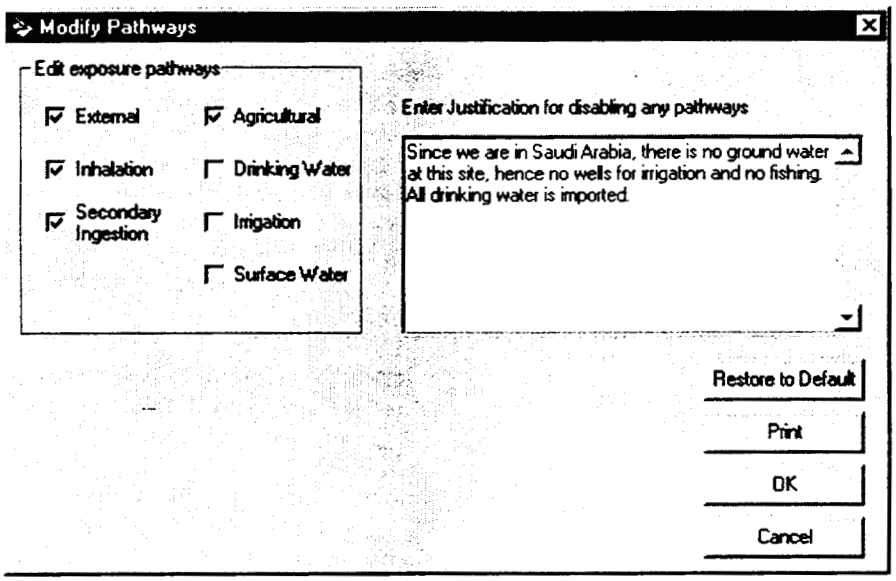


Figure 4.2.3 Modify Pathways window

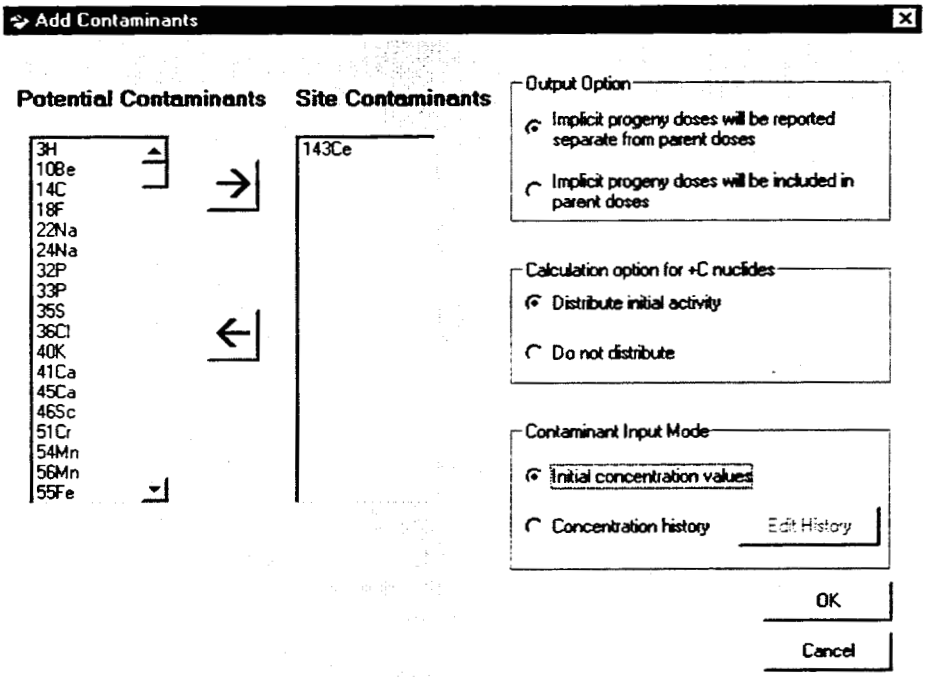


Figure 4.2.4 Add Contaminant window

4.2.2.2 Implicit Progeny Output Option

Some short-lived radionuclides are assumed to be in equilibrium with their parent radionuclides. These particular radionuclides, called *Implicit* progeny, are not in the *Potential Contaminants* list. The user can identify which nuclides are *Implicit* by noting that there are no reported *Half Life* entries in the *Radioactive Decay Data* table. (The *Radioactive Decay Data* table can be viewed by selecting *View/Tables/ Radioactive Decay Data* from the main menu.)

By default, the dose from these radionuclides is not included with the parent dose, but is reported sepa-

rately. If the *Implicit Progeny doses will be reported separate from parent doses* is selected (default), these short-lived radionuclides will be listed in the *Chain Data* portion and the *Detailed Results* portion of the reports (see Section 4.3.7). In the *Chain Data* table from the *Detail* report, as shown in Table 4.2.1, the implicit nuclides have a *Chain Position* value of *Implicit* and no half-life reported.

Table 4.2.1 Excerpt from Chain Data Table, contaminant 225Ac

Nuclide	Chain Position	Half Life	Fractional Yield
225Ac	1	1.0E+01	
221 Fr	Implicit		1
213 Po	Implicit		0.9784
(many more implicit follow)			

Select the radio button *Implicit progeny doses will be included in the parent doses* to have implicit progeny doses included with the parent doses. In this case, the initial concentrations, chain data, and results section of the reports will not reference these radionuclides. No matter which radio button is selected, the dose from implicit radionuclides is always included in the dose calculations.

4.2.2.3 Distribute Option for +C Nuclides

Some radionuclide chains can decay in a state of transient equilibrium. This means that all progeny of a radionuclide chain parent have half-lives somewhat shorter than that of the parent and a long period of time has elapsed since the initial contamination. In essence, all the progeny exponential decay terms are removed from the calculations because they approach zero much faster than the parent exponential decay term. Therefore, after a period of time, all progeny of the chain parent decay at the same rate as the parent. A review of transient equilibrium is given in Kaplan (1962).

In DandD, there are 15 radionuclide chains (including Th_Nat, which is the same as 232Th in equilibrium) that can decay in a state of equilibrium. Except for Th_Nat, these chains are designated with a "+C" after their respective names. For example, the selection 232Th decays in the normal fashion while the selection 232Th+C decays in a state of transient equilibrium.

With respect to DandD, for a radionuclide chain that decays in the normal fashion, only the chain parent is initially at the site; the initial condition is assigned to the parent only. Progeny are generated from the decay of the parent. For a chain in equilibrium, all radionuclides in the chain are initially at the site; the initial conditions for each radionuclide in the chain are assigned based on distributing the assigned initial condition for the chain and the equilibrium relationship among all the radionuclides in the chain.

There are two methods for distributing the initial condition assigned to a chain in equilibrium described, as follows.

Selecting the radio button *Distribute initial activity* means that the specified initial activity is divided among all explicit and implicit radionuclides in the chain based on the decay constants and fractional yields of the radionuclides in the chain (see Table 4.2.1). The initial activity assigned to the parent is always less than that input by the user. The calculated initial activity of all the radionuclides in the chain sum to the initial activity input by the user.

Selecting the radio button *Do not distribute* means that the specified initial activity is used to set the initial activities of all explicit and implicit radionuclides in the chain based on the decay constants and fractional yields of the radionuclides in the chain (see Table 4.2.1). The input initial activity is assigned to the parent and the initial activities of all progeny in the chain are based on the initial activity of the parent. The calculated initial activity of all radionuclides in the chain sum to an activity greater than that input by the user.

The default setting is *Distribute initial activity*. The selected distribution option is applied to all selected equilibrium chains in the Add Contaminants window.

For example, suppose 232Th+C is selected and assigned an initial activity of 10 pCi/g. The 232Th chain has five explicit progeny, including the parent radionuclide and six implicit progeny, for a total of 11 radionuclides. If the *Distribute initial activity* option is selected, each radionuclide is assigned an initial activity of 1 pCi/g except for 212Po and 208Tl, which are assigned initial activities of 0.6407 pCi/g and 0.3593 pCi/g, respectively, because of branching. The initial activities of all radionuclides in the chain sum to 10 pCi/g. If the *Do not distribute* option is selected, each radionuclide is assigned an initial activity of 10 pCi/g, except for 212Po and 208Tl, which are assigned initial activities of 6.407 pCi/g and 3.593 pCi/g, respectively, because of branching. The initial activities of all radionuclides in the chain sum to 100 pCi/g,

which is greater than the initial activity assigned.

4.2.2.4 Import Contaminant and Concentration Data (Residential Scenario Only)

If the current scenario is residential, the option of specifying the radionuclides and their concentrations from a text file is available. The Contaminant Input Mode is a toggle that will switch between manual and import modes.

By default, the *Initial concentration values* radio button will be selected. In this case, the user will be expected to manually specify the source in this form and enter the soil concentrations at the beginning of the scenario via the *Add Concentrations* form. However, site contaminants and time varying values for the concentrations can be specified via a text file by setting the *Concentration history* radio button (Figure 4.2.5).

The concentration history may already be present in the session file if a file has already been imported for this session. If it is present, the nuclides described in the file will be listed in the *Site Contaminants* list box. The user will be required to fill in the *Justification* field. In this case, it is not necessary for the user to enter any initial concentrations.

To replace the current data or specify a new concentration file, click the *Edit History* button, as shown in Figure 4.2.5.

To import a file, click the *Import File* button (Figure 4.2.6). Locate a concentration file (*.con file) and click OK in the *Import Concentration File* dialog box (see Appendix C for file format). The user can replace an imported file with another file by clicking the *Import File* button and specifying the desired replacement file.

At this point, the data in the concentration file should show in the grid, as demonstrated in Figure 4.2.6. A list of the parent nuclides imported will appear in the *Nuclides Imported* list. This data cannot be edited directly through DandD.

If the data are satisfactory, click the *OK* button. The data will be loaded into the session file. Otherwise, click the *Cancel* button to disregard the imported data.

To complete the process of importing the concentrations, enter a justification in the field labeled *Enter Justification for using concentration history* in the *Add Contaminants* form. Click *OK* to save these settings. Notice that the *Add Concentrations* button in the *Session* form is dimmed. This is because the concentrations have already been specified in the concentration file.

4.2.3 Add Concentrations

Specify the initial concentration of the radionuclides at the site by clicking on the *Add Concentrations* button (Figure 4.2.1). This button will be available only if contaminants have been added. This button will not be available if the *Concentration History* toggle has been set from the Add Contaminants window.

The nuclide Parameter Viewing window, shown in Figure 4.2.7, is opened when the user clicks on the *Add Concentration* button. See Section 4.1.2 for a complete description of a Parameter Viewing window. Each nuclide shown in this window has the following grid entries:

- **Nuclide Symbol**: name of radionuclide, atomic weight followed by symbol (e.g., 235U means Uranium 235).
- **Area**: the characters UNLIMITED, meaning the contaminant is spread evenly over the exposure area for the scenario, or an area in square meters defining the contaminated area. The user can modify this value in the Parameter Modification Window.

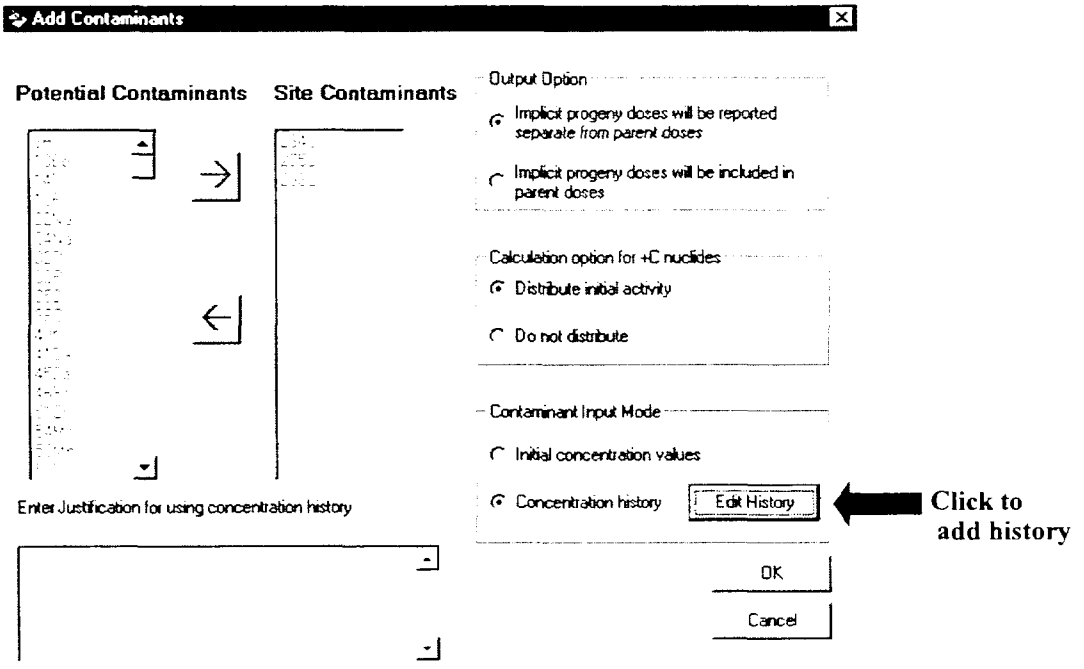


Figure 4.2.5 Contaminant input modes

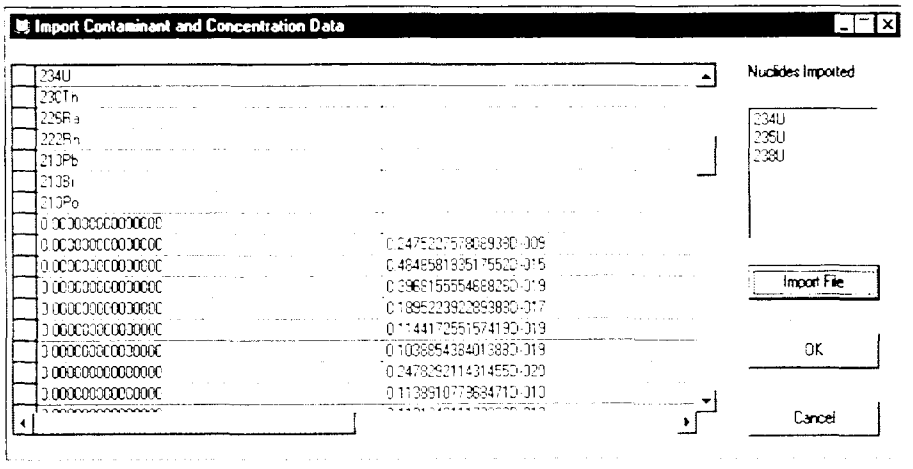


Figure 4.2.6 Import contaminant and concentration data

- **Distribution Name**: same meaning as discussed in Section 4.1.2.

- **Input Units**: Units of concentration. The default units for the building occupancy (dpm/100cm**2) are different than the units for the residential scenario (pCi/g).

To add a concentration of a nuclide, double-click on the nuclide symbol in the data grid. Alternatively, click once on the symbol in the data grid to select the nuclide. The value of the concentration is shown on the lower left portion of the window. Then, click the *Modify Value* button to open the parameter modification window. See Section 4.1.3 for a complete description of a Parameter Modification window.

Once the Parameter Modification window opens, follow the six steps indicated in Figure 4.2.8. The *Restore to Default* button will restore the distribution to *Constant*, the concentration to zero, the units to the default units for the given scenario, the area to *Unlimited*, and the *Justification* to a blank field.

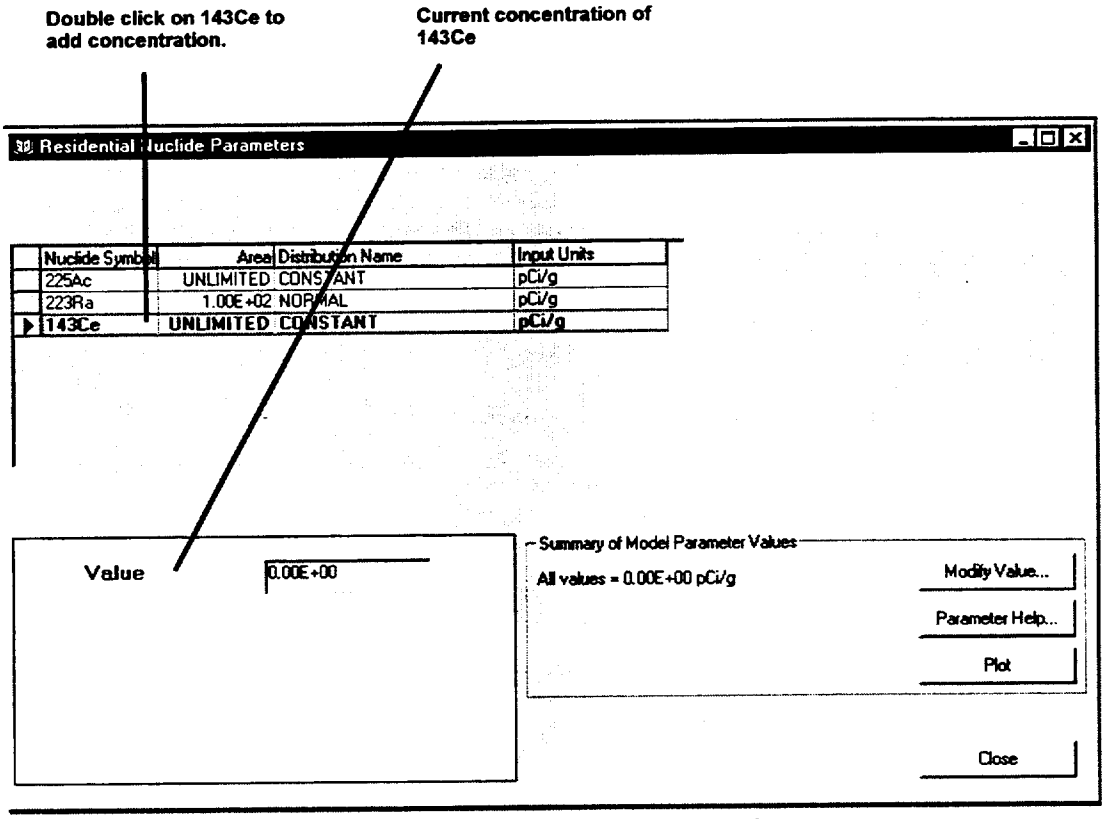


Figure 4.2.7 Nuclide concentration window

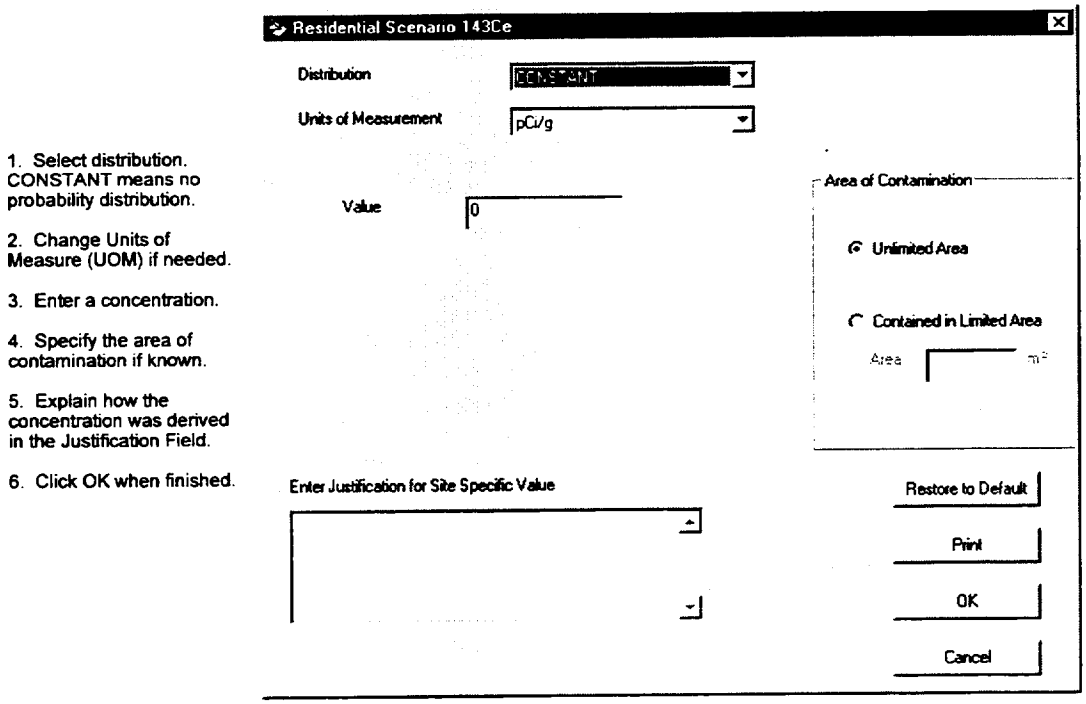


Figure 4.2.8 Parameter modification window for contaminant

The *Print* button will print a copy of the screen, and will print the contents of the grid separately if an empirical distribution (such as Continuous Linear) was specified.

Within the *Area of Contamination* panel, the user has the option of specifying either an unlimited area or a limited area based on site-specific knowledge about the spatial distribution of their site contamination. By default, DandD uses the specified concentration directly in the dose calculation. This usage is equivalent to assuming that all material contacted by the receptor during the duration of the exposure scenario is contaminated at the same concentration (regardless of site location). The specified concentration should be the largest spatially averaged concentration that is consistent with available information about the site. The averaging area should correspond to the smallest exposure area among the active pathways. This approach is selected by the *Unlimited Area* radio button.

Alternatively, if the user can demonstrate that contamination is limited to a particular area, and that no contamination occurs outside that area, then the user may specify the area of contamination by selecting the *Limited Area* radio button and providing the size of the contaminated area. Using this option, the concentration that the user specifies should reflect the average value over the contaminated area. DandD will then use this concentration and the contaminated area, along with the smallest exposure area among the active pathways, to calculate the concentration used in the dose calculations.

For more information on specification of source concentration and exposure area, the user is referred to the online help. Click on *Help/Contents/Reference* and select the items *Source Concentration* and *Exposure Area* for detailed information that can be viewed or printed, as desired.

4.2.4 Modify Parameters (Site-Specific Analysis)

In a site-specific analysis, parameters can be modified based on site information. Click the *General Parameters* button in the main Session window (Figure 4.2.1) to open the general parameters viewing window. See Section 4.1.2 for a complete description of a Parameter Viewing window.

General Parameters

Once the Parameter Viewing window (as shown in Figure 4.2.9) has been opened, select the parameter category (residential scenario only).

If a parameter has been selected in the Parameter Viewing window, clicking the *Parameter Help* button will display detailed information about the selected parameter. This can help the user understand the meaning of the parameter. The parameter distribution can also be viewed graphically by clicking on the *Plot* button in the parameter viewing window.

Double-click on the parameter symbol in the data grid to modify the value of the parameter. Alternatively, click once on the symbol in the data grid to select the parameter. The value of the parameter is shown on the lower left portion of the window. Then, click the *Modify Value* button to open the Parameter Modification window. See Section 4.1.3 for a complete description of a Parameter Modification window.

The Parameter Modification window should now open as shown in Figure 4.2.10. Follow the five steps as indicated in the figure to modify a parameter.

The *Restore to Default* button will restore the value of the parameter to the default probability distribution and value(s) as documented in Beyeler et al. (1999). In this case, the *Enter Justification for Site-Specific Value* field will be blank.

The *Print* button will print a copy of the screen, and will print the contents of the grid separately if an empirical distribution (such as Continuous Linear) was specified.

After a parameter has been modified and the *OK* button is clicked to commit the modification, all of the uncertain parameters are resampled by LHS. This may take a few seconds. This is necessary so dependant variables (such as variables of type Derived) are recalculated correctly and graphical data is current. In addition to resampling the data, if there are any existing data sets in the session corresponding to the results of a simulation, these data sets are deleted. This means that if the user modifies a parameter after running a simulation within the same scenario, the output results are nullified. Even reports will be deleted. This is done to ensure integrity between the results and the current parameter settings.

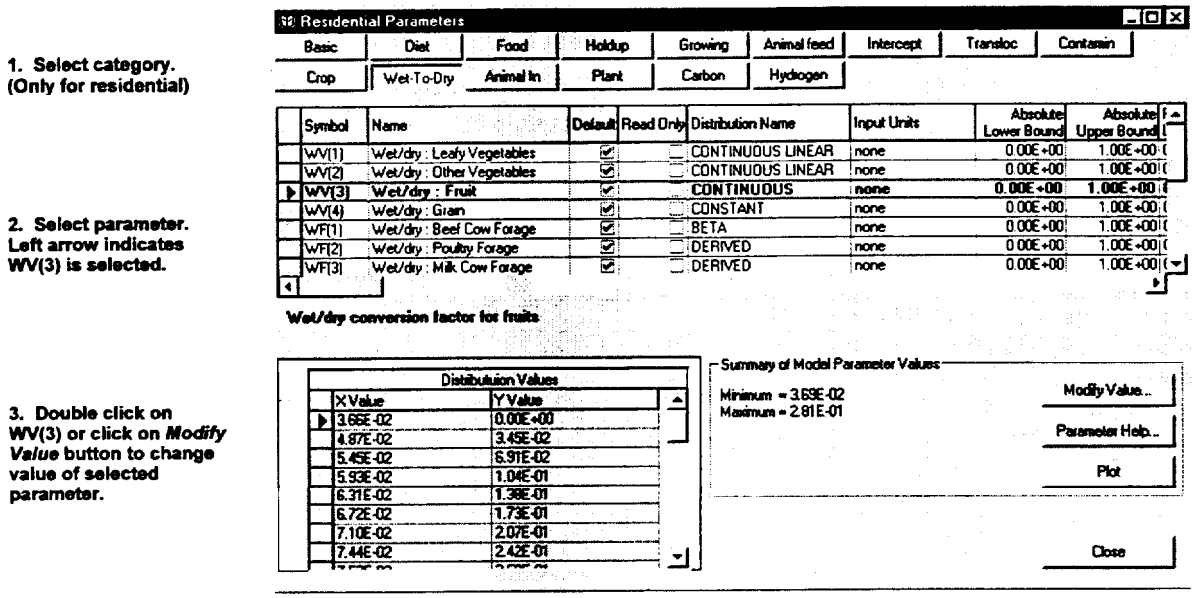


Figure 4.2.9 General parameter viewing window (residential)

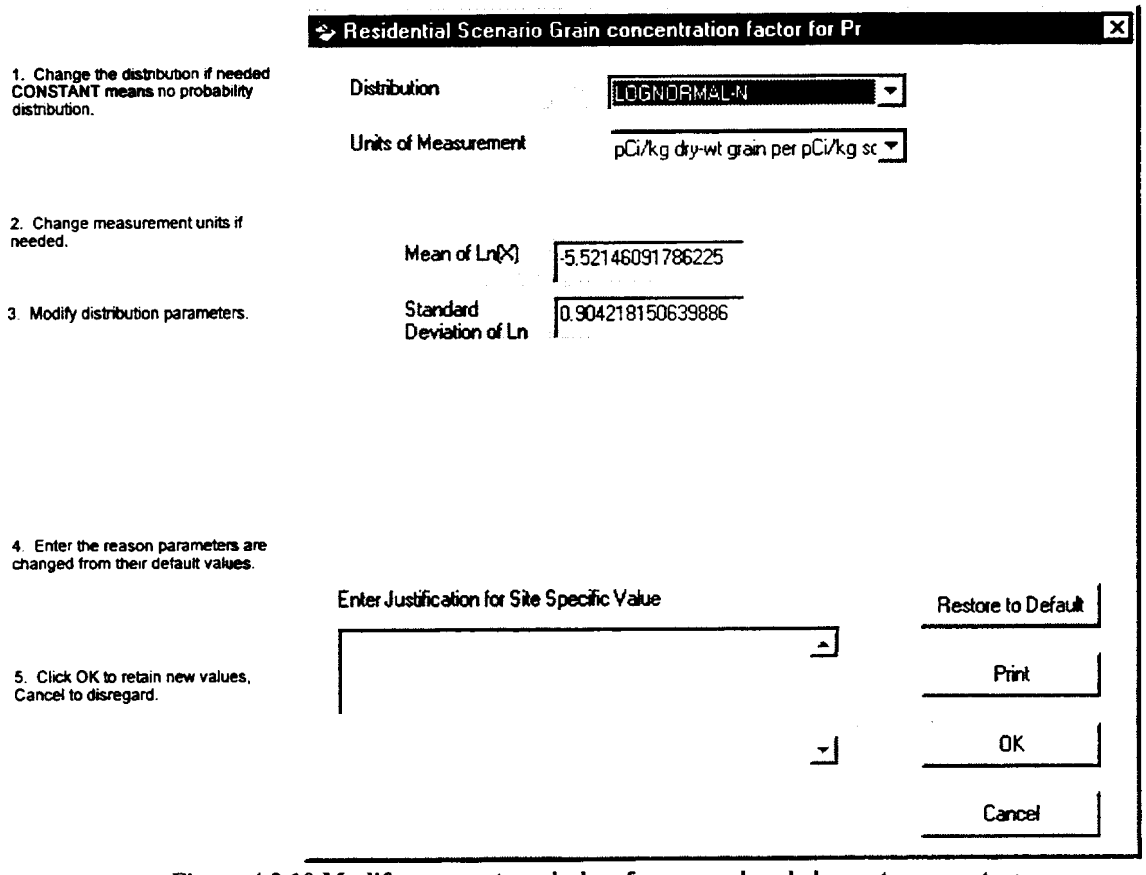


Figure 4.2.10 Modify parameter window for general and element parameters

See the main menu function *File/Restore Parameters to Default Values* to restore all site-specific values to screening, or default, values.

Element Parameters

For the residential scenario only, click the *Element Parameters* button to open the element parameters viewing window (Figure 4.2.11). These parameters are based on elements in the decay chain.

For each category (e.g., Partition Coefficient), the grid depicts an entry for each element present in the decay chains.

- **Element**: Name of element associated with the parameter. This is an element in the decay chain of one of the contaminants. Some elements in the decay chain (such as At) may not be listed because of their short half-lives.

The following grid entries have the same meaning as the entries described in Section 4.1.2:

- **Default**
- **Distribution**
- **Input Units**
- **Absolute Lower Bound**
- **Absolute Upper Bound**
- **Recommended Lower Bound**
- **Recommended Upper Bound**

4.2.5 Correlate Parameters (Site-Specific Analysis)

The user can specify linear rank correlations between any two parameters whose values are defined by probability distributions. Clicking the *Correlate* button in the main session window will open the Correlate Parameters window, as shown in Figure 4.2.12. In the window, there is a main grid that lists each correlation that is currently defined. For the building occupancy scenario, this table is initially empty. For the residential scenario, the default screening analysis includes two correlations.

It is possible to specify combinations of valid correlations that are not mutually consistent. For example, two parameters "A" and "B" can be assigned a correlation of 0.99, parameters "B" and "C" can also be given a correlation of 0.99, but parameters "A" and "C" can be assigned a correlation of −0.99. Each correlation is valid by itself but the three are incompatible. DandD does not check for this type of inconsistency. The parameter sampling may fail if the user defines inconsistent correlations.

Add a correlation in the table's insertion row (indicated by "*") by:

- Clicking in the "Parameter One" cell and selecting one of the uncertain parameters from the list-box;
- Clicking in the "Parameter Two" cell and selecting the second parameter from the list-box;
- Entering the desired rank correlation between the two selected parameters in the "Coeff" cell; and
- Entering an explanation of the correlation in the "Justification" cell.

The correlations specified apply to the ranks of the parameter values rather than to the values themselves. Specified correlations must be greater than -1 and less than 1. These limits are checked by the program. The user is required to enter a justification in the justification cell for every non-default (i.e., user-defined) correlation or modification of the coefficient from the default value.

If any two parameters are not correlated, they have a correlation coefficient of zero. However, this is not listed in the grid, but is an implied correlation.

Default correlations are those that are defined for a screening analysis. For example, in the building scenario, the default correlations are zero for all uncertain parameters. In the Correlate Parameters window, there will be no grid entries. In the residential scenario, there are two default correlations, as shown in Figure 4.2.12.

To remove a *default* correlation, the user must enter a zero for the correlation coefficient in the *Coeff* column in the *Correlation Coefficients* grid, as shown in Figure 4.2.12. The user can also change the correlation coefficient of a default correlation to reflect different correlation values.

User-specified correlations are new grid entries that the user entered for a site-specific analysis. To remove a user-specified correlation, the user should select the grid row by clicking on the row and press the delete key on the keyboard. This method does not work for removing a default correlation.

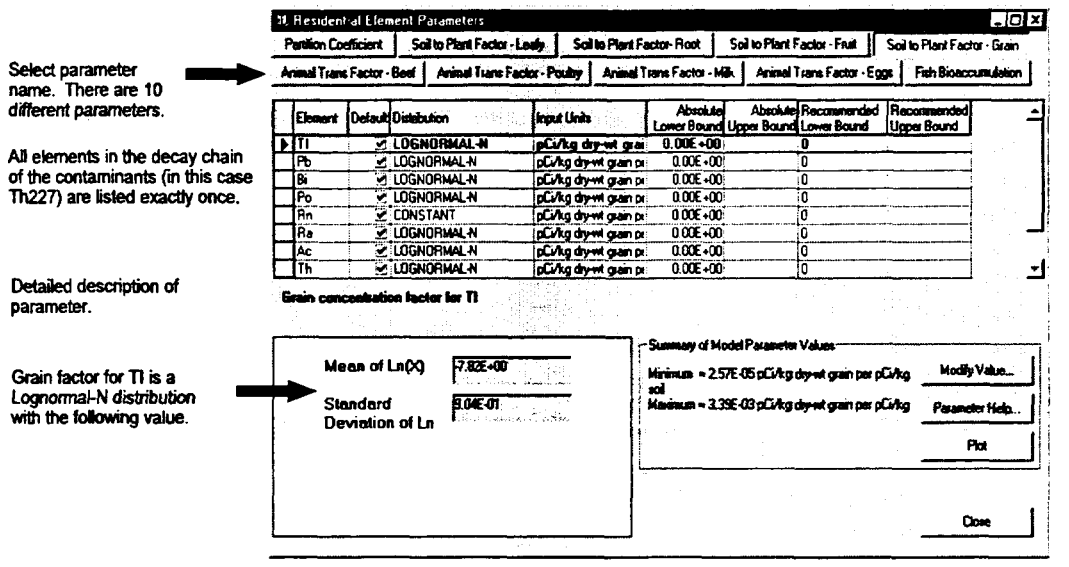


Figure 4.2.11 Residential Element Parameters window

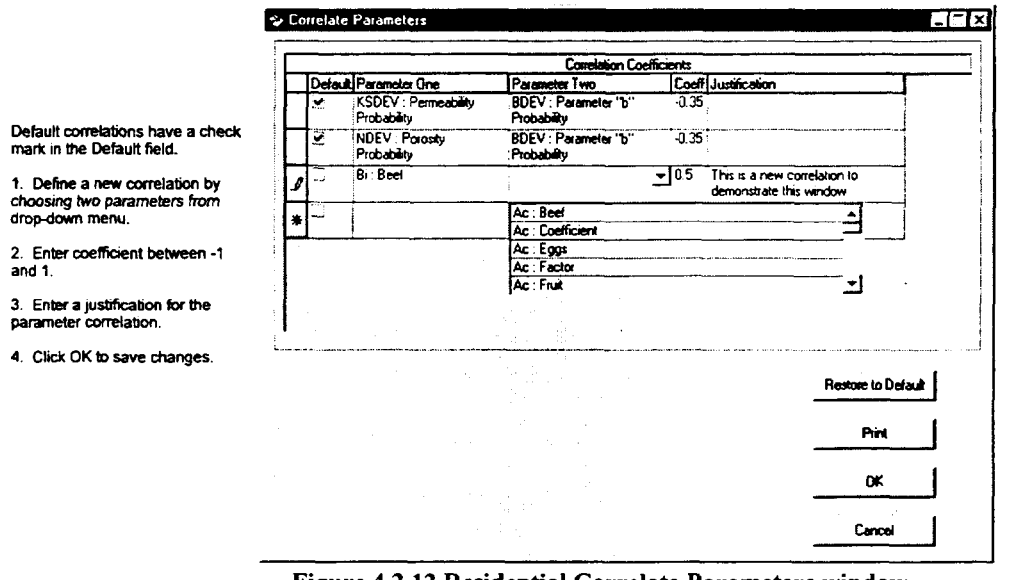


Figure 4.2.12 Residential Correlate Parameters window

The user can move from cell to cell in the grid by using the keyboard arrow keys.

Click the *Restore to Default* button to restore the parameters to their default correlations. Click the *Print* button to print the contents of the grid of correlated parameters. Click OK to preserve changes in the session. Click Cancel to ignore changes made to the correlations.

4.2.6 Execute Simulation

Perform the dose calculations by selecting the *Execute* button from the Session window. The Run Simulation window will open.

Click the *Run Simulation* button to perform all of the calculations required to evaluate compliance with the dose standard. Execution status messages will appear in the text pane of the execution dialog, as shown in Figure 4.2.13. The progress of the dose calculations will be shown in the dialog status meter. Click the *Abort Simulation* button to abort the simulations. DandD will not interrupt the current simulation, but will abort after the current simulation has completed. Therefore, the user may not get an immediate response after clicking this button.

On successful completion, the estimated 90th percentile value of the TEDE distribution used for comparison against the dose standard will be displayed (as shown in Figure 4.2.14). (As noted in Section 1, the NRC dose limit for unrestricted use is 25 mrem/year.) The endpoints of a 95% confidence interval for this quantile value are also reported. The estimated quantile value for TEDE is uncertain because it is estimated using a finite number of parameter samples. The reported confidence interval reflects this uncertainty.

In some cases, the uncertainty due to sampling error can affect the comparison against the dose standard. In these cases, the sampling error can be reduced by increasing the number of simulations (using the advanced simulation *Options*). If comparison against the dose standard is influenced by sampling error, DandD will display the Sample Size Analysis form containing information about increasing the number of simulations (see Section 4.2.7).

Clicking the *Options* button on the *Execute* form will bring up a dialog box that allows the user to set advanced simulation options as follows (see Figure 4.2.15). Most users will not need to change these options from their default settings.

- *Number of Simulations* corresponds to the number of times the model will be executed. Each time the model is executed, the values of each of the uncertain parameters vary depending on the numbers generated from sampling (by LHS). The dose model is always executed using constant values of parameters. The *Number of Simulations* used in the analysis is automatically increased if DandD determines that more samples are needed to adequately control parameter correlations or to estimate the confidence interval for the 90th percentile value of TEDE. DandD will open a window to indicate when it increases the number of simulations. After executing the dose model, DandD performs a sample size analysis and may recommend that the number of simulations be increased.

- *Seed for Random Generation* is the random number seed used to generate the values for the parameters that have probability distributions associated with them. Changing this number will change the sampled values of the uncertain parameters used in the simulations. The seed should be more than five digits long for the best sampling results. Powers of two should be avoided. The value for the seed should be in the range of 1 to 2,147,483,647.

- The *Save Dose History Information* checkbox determines whether or not dose history information is generated and saved in the session file. This information is needed to create history plots. Note that selecting this option can increase the execution time for the dose model and will significantly increase the size of the session file. History plots can be accessed after execution by using the *View/Graphics/Dose History* option on the main menu (see Section 4.3.9).

4.2.7 Sample Size Analysis

The 90th percentile of the TEDE distribution, used for comparison against the regulatory limit of 25 mrem, is estimated in DandD Version 2.1 via Monte-Carlo sampling. The resulting estimate of this statistic is subject to sampling error. The error size can always be reduced by increasing the number of samples used to estimate the TEDE distribution. Sampling error is significant if the 25 mrem limit lies within the range of possible values of the 90th percentile.

The range of possible values is indicated by the 95% confidence interval reported on the Execute form and

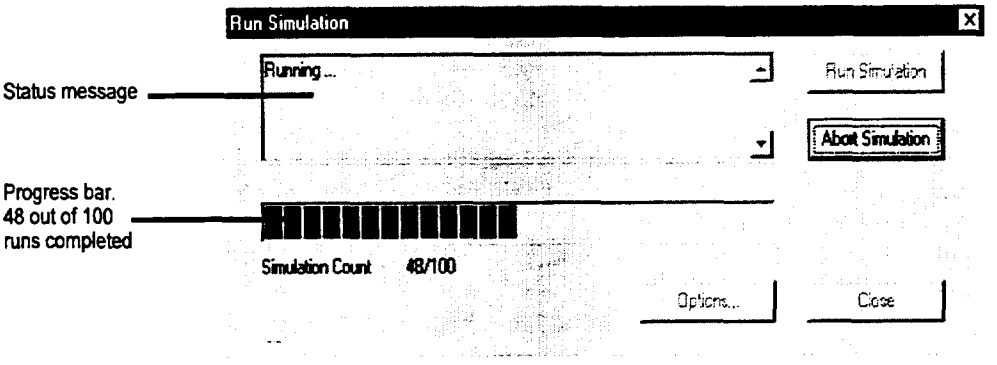


Figure 4.2.13 Run Simulation window - in progress

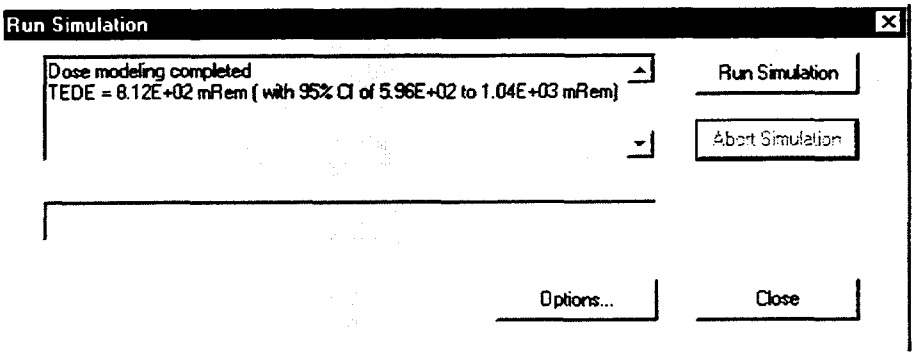


Figure 4.2.14 Run Simulation window - complete

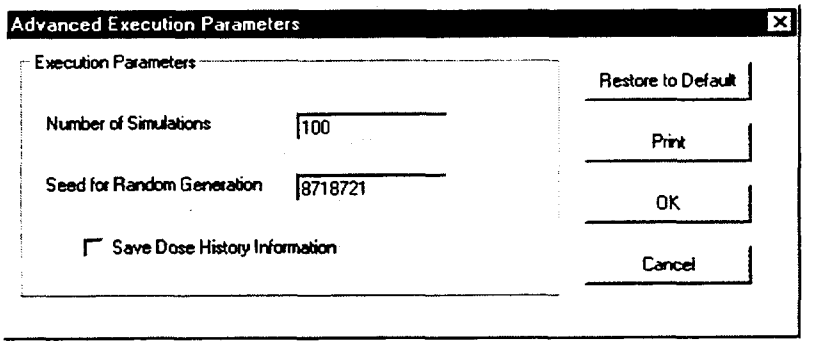


Figure 4.2.15 Advanced Execution Parameters window

in the output reports. To account for sampling error in the compliance determination, the upper endpoint of the confidence interval is the value that is compared to the regulatory limit of 25 mrem. This comparison allows for a defensible regulatory decision given the current estimate of the dose distribution, the number of samples used to estimate that distribution, and the location of the estimate with respect to the 25 mrem limit.

The upper and lower limits of the confidence interval are reported for all calculations. If the upper limit is less than the regulatory limit, or if the lower limit is greater than the regulatory limit, then increasing the

number of samples is unlikely to affect the comparison with the dose limit, and no more information is presented.

When, however, the confidence interval includes the regulatory limit, then reducing the uncertainty due to sampling error may lead to dose estimates below the limit. In this case, the Sample Size Analysis form is automatically displayed (see Figure 4.2.16). Based on the location of the confidence interval compared to the regulatory dose limit, DandD estimates the likelihood that the upper endpoint of a narrower confidence interval, produced by increasing the number of samples, would fall below the regulatory dose limit. This estimate is made for several alternative values for the number of samples, as well as for an infinite number of samples, and is tabulated on the form.

This information can be used to decide whether increasing the number of samples is likely to be useful, and if so, how many samples to use.

For example, the Sample Size Analysis window shown in Figure 4.2.16 will open when a simulation is run resulting in a TEDE value where the 95% confidence interval straddles the performance objective of 25 mrem. In the example, the TEDE was 25.1 mrem with a 95% confidence of the TEDE values falling between 22.4 and 28.5 mrem. Because the upper and lower 95% confidence interval contains the performance objective of 25, increasing the number of samples may by itself be enough to reduce the upper endpoint of the confidence interval below the dose limit. The Sample Size Analysis window (see Figure 4.2.16) shows the effect of increasing the number of samples on the likelihood of this occurring.

The information in the Sample Size Analysis window helps the user decide how many simulations to run. To choose the sample size, the user needs to consider the real time it will take to run the model with the new value for the number of simulations. In the example shown in Figure 4.2.16, setting the number of simulations to 200 has only a 3% likelihood of demonstrating compliance. Setting the number of simulations to 6400 increases the likelihood of demonstrating compliance to approximately 23%. However, it will take 64 times as many model calculations as it takes with the number of simulations set to 100.

The user can change the number of simulations by clicking the *Options* button and entering the number of simulations in the Advanced Execution Parameters window. Alternatively, the user could close the Sample Size Analysis window and click the *Options* button in the Run Simulation window to change the number of simulations in the Advanced Execution Parameters window. The model could then be executed by clicking the *Run Simulation* button in the Run Simulation window.

Clicking the *Print* button in the Sample Size Analysis window will create a hardcopy of this window.

4.3 Main Menu Operations

4.3.1 File Management Menu Options

The file management menu options are the *New*, *Open*, *Save As*, and *Close* commands. To execute any of these commands, click on *File* in the DandD main menu and select an option. The session file consists of a single file with an extension of "mcd" (Monte Carlo DandD).

When DandD is first started, there are no sessions opened. The first step is either:

1. Create a new session by selecting *New* from the File menu, or

2. Open an old session by selecting *Open* from the File menu.

If the user selects *New* from the File menu, a window similar to Figure 4.3.1 will open. The user should then type in a file name for the session and click the *OK* button in the Open Session dialog box.

A directory is created during installation to hold the user's files. This is the default location for all session files and reports. The name of this directory is "DandD_Docs," located on the drive where DandD was installed. However, the user can save or open the session files on any drive or directory desired.

After naming the new session in the Open Session window, a *Session Properties* form will then be displayed, and the user will be asked to enter a site name and description of the analysis. The user must enter the description and no more than 50 characters for the site name. Click the *OK* button on the *Session Properties* form to save this information. The site name and description can be modified at a later date by using the *File/Properties* feature (see Section 4.3.5).

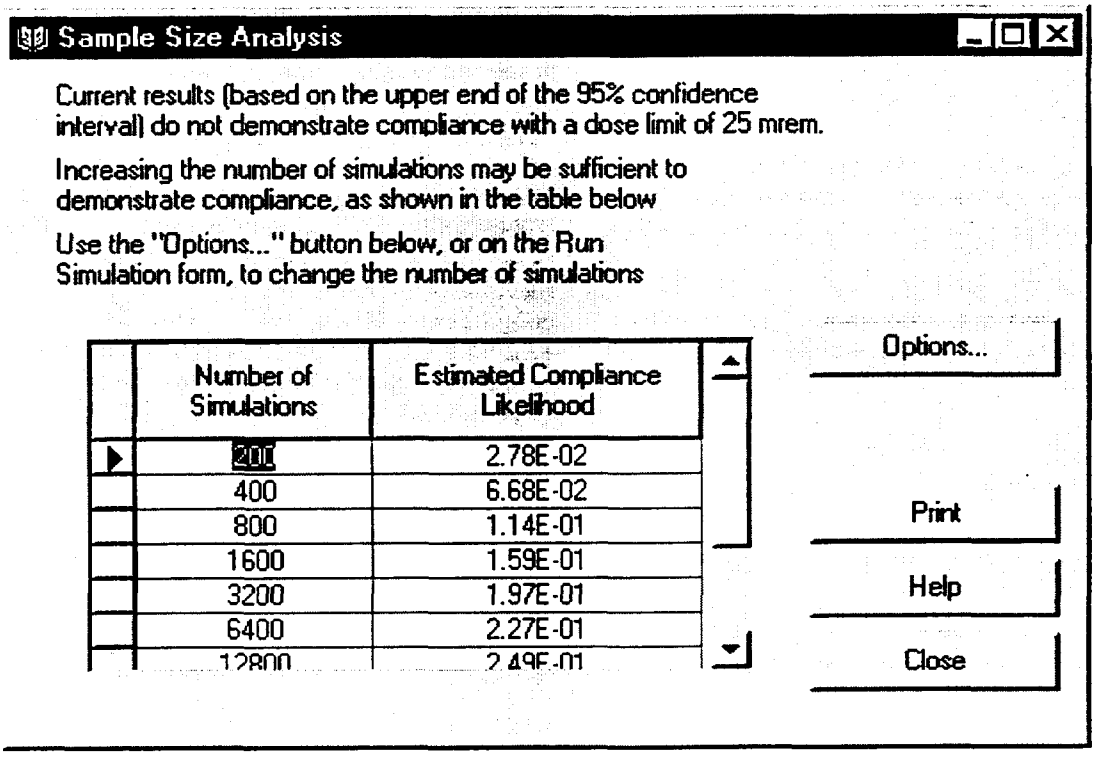


Figure 4.2.16 Sample Size Analysis window

Click on file or enter *File name* and click on *Open* to open an existing session.

Enter *File name* and click *Open* to create a new session.

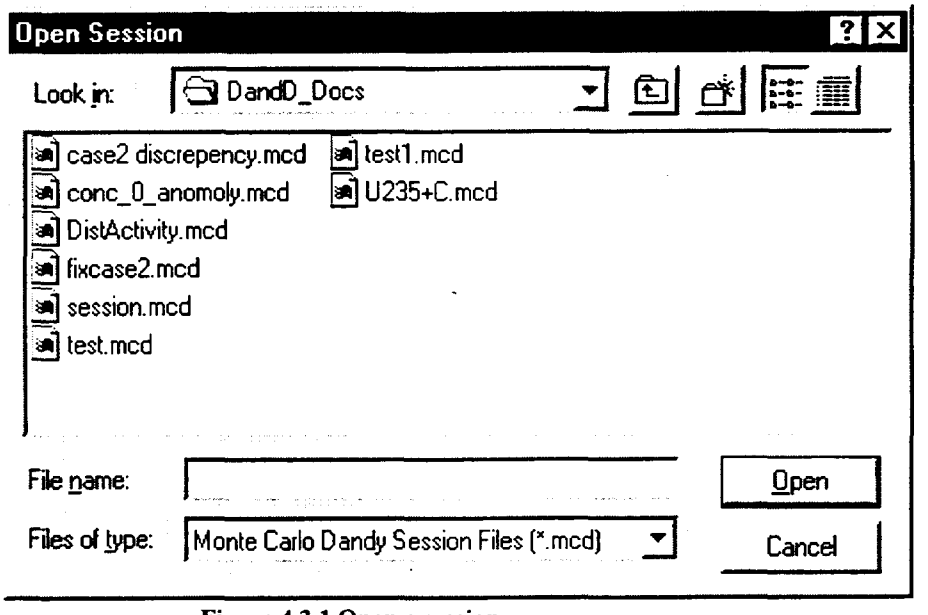


Figure 4.3.1 Open a session

If the user selects *Open* from the File menu, a window similar to Figure 4.3.1 will open. The user should then type in a file name for the session and click the *OK* button or double-click on the session file to open an existing session.

Unlike word processing applications, changes to the session file are automatically saved as they are made. This is why there is not a *File/Save* function available.

Additionally, only one session file may be opened at a time. If the user wants to use an existing session as a starting point for another session, the *File/Save As* command should be used.

See Appendix D for a complete description of the file structure developed for DandD Version 2.1.

If the user clicks *Close*, the session file is closed. All data from the simulation and any user settings will be retained.

4.3.2 File/Restore Parameters to Default Value

All site-specific parameters can be reset to the default (screening) value by using the *File/Restore Parameters to Default Value* option. This will set all parameters other than the contaminants and concentrations, including execution parameters, to their default values. This will also reset the correlations to their default values.

This option only applies to the current scenario. For example, if site-specific parameters have been specified for the residential scenario and the current scenario is building occupancy, then the command *File/Restore Parameters to Default Value* will only apply to the building occupancy scenario. Any modified residential (site-specific) values will be retained.

This option is only available if all parameter viewing windows are closed. Individual parameters can be reset to the default from their Parameter Modification window.

A checked box to the right of the parameter name in the parameter viewing screen (the window that opens when the user clicks the *General Parameters* or *Element Parameters* button; see Figure 4.1.1) indicates if the parameter is set to its default value. However, it is not reasonable to check each parameter for this in the residential scenario because there are too many parameters.

To discover which variables are set to site-specific values (i.e., a value other than the default value), create the report titled *ModelInputSummary* from the *View/Reports* menu selection (see Section 4.3.7).

4.3.3 File/Export as Zip for Submittal

The residential and building occupancy settings and simulation results are contained in a single file with an "mcd" extension (e.g., session.mcd). However, these files usually will not fit on a floppy disk. They are also bulky to email. Session files can be compressed for transmittal to the NRC using the *File/Export as Zip* command. These files can then be unzipped by using commercial packages WinZip or PkUnzip.

If the *File/Export as Zip* option is selected, a window similar to Figure 4.3.2 will open. Once a location has been selected for the new file and the user clicks the *OK* button, a copy of the session file will be compressed and saved with a zip extension. For example, if the session file is called x.mcd and the export function is executed, a new file called x.zip will be created. The file x.mcd will still be available.

It is not necessary to use the function *File/Export as Zip* to submit a session file to the NRC. This was added as a feature to easily transmit on floppy disks or to facilitate sending the session as a compact email attachment.

Using this function is also a convenient way to backup work onto a floppy disk.

4.3.4 File/Print

The *File/Print* option is used to create a hardcopy of the active window. This is only available for screens that allow concurrent interaction with other windows in the interface.

Screens that do not allow concurrent interactions (known as modal screens) will have a *Print* button in the lower right-hand corner of the screen. For example, all of the parameter viewing screens, such as the *General Parameters*, *Add Concentrations*, and *Element Parameters*, allow access to the *File/Print* option. The parameter modification form will have a lower right *Print* button.

For all screens, the print function will create a hardcopy of the window screen. In the example of a parameter viewing screen, this allows the user to identify which category and variable they have selected.

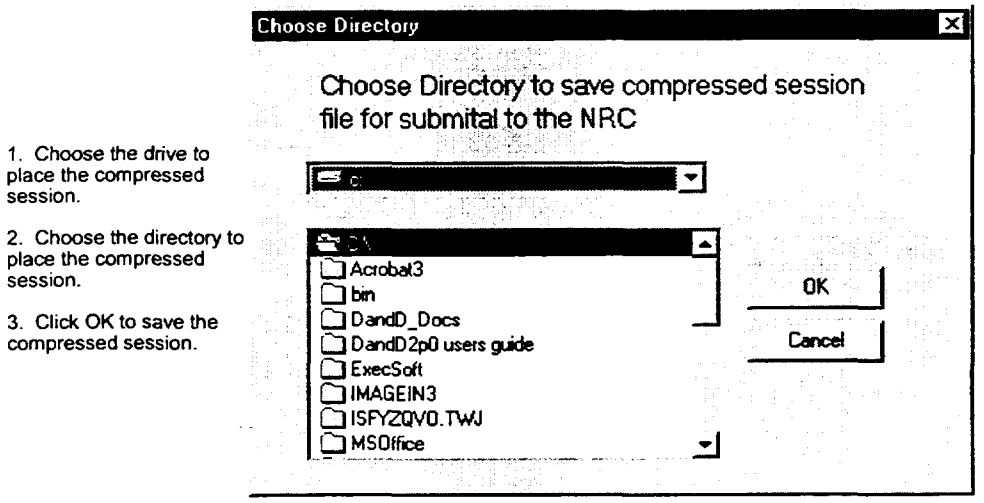


Figure 4.3.2 Save a session as a zip file

Some of the screens contain grid data that require the user to use the scroll bar to view the complete list. For example, the residential scenario *General Parameters* screen may contain two grids if the selected parameter has related empirical data, as shown in Figure 4.3.3. Following the screen shot, a dump of the primary grid will be printed. In the example of a parameter viewing screen, this will be a dump of all parameter information in the selected category. The values defining the probability distribution associated with the parameters will not be printed.

To print the data relevant to a single parameter, double-click the parameter name in the parameter viewing form. The parameter modification form should open. Within the parameter modification form, click the *Print* button. All the data relevant to the selected parameter will be printed.

Create a hardcopy of all site-specific parameter values by creating the report titled *ModelInputSummary* from the *View/Reports* menu selection. Print using the browser window print function.

Create a hardcopy of all values by running a simulation and creating the report titled *Detail* from the *View/Reports* menu selection. Print this information by using the browser window print function.

4.3.5 File/Properties

To modify the properties of a session (i.e., the session name and analysis description), select *Properties* from the File menu. A window will open similar to Figure 4.3.4 that will allow these properties to be modified. Modify the site name and analysis description. Click *OK* to accept the changes and close the window.

When a new session is created, this window will open to allow the user to define the initial session properties. The user will be required to enter the site name and the analysis description (the site name must be no more than 50 characters). This information is used when the final reports are created via the *View/Reports* menu item (see Section 4.3.7).

4.3.6 Edit/Copy

The Edit/Copy function is available when the user has a graph opened. This function will put a copy of the graph and the data associated with the graph on the Microsoft® Windows® clipboard. It can be pasted as a graphic image in Microsoft® Word® or Corel® WordPerfect®, using the *Paste Special* command. If the Paste function in Microsoft® Word®, Corel® WordPerfect®, or Microsoft® Excel® is used instead, the x-y data pairs that define the curves on the plot will be pasted into the document.

The user can use the keyboard shortcuts Ctrl + V (press V while holding down the Control key) to paste, Ctrl + C to copy, and Ctrl + X to cut selected text from the justification and text fields of other windows. However, the *Edit/Copy* menu command is not available for text fields. An example of using the graphics copy feature to paste a copy of a graph into a report

File/Print will output a screen shot of current window.

File/Print will output all data in the selected category. In this example, the category is Wet-To-Dry.

To output all of the data corresponding to a variable, click on *Modify* and use *Print* button in the modify parameter window.

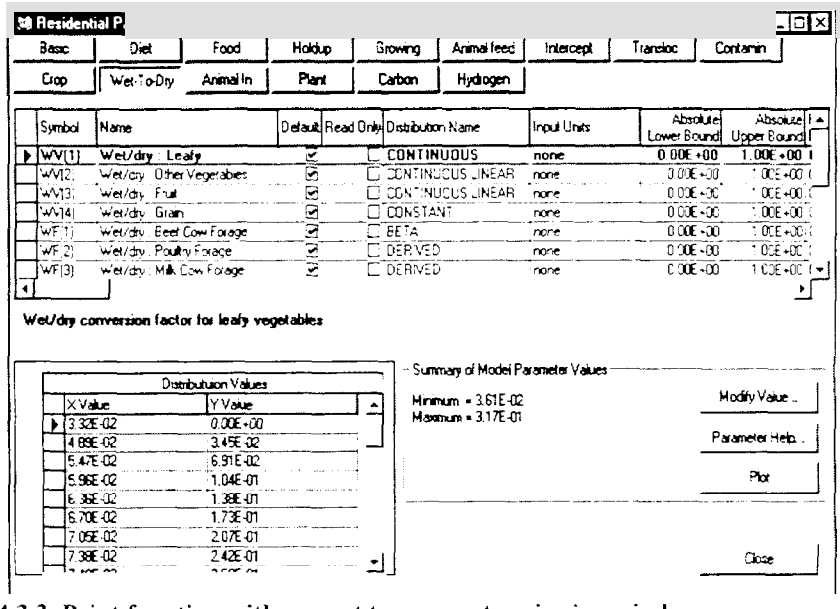


Figure 4.3.3 Print function with respect to parameter viewing window

created by DandD follows

Step 1: Create the report by using the *View/Reports* command. For example, create the report *Summary* under the building occupancy simulation. The default Internet browser will be started and the file containing the report session_bld_Summary.htm will be opened. Make note of the path and filename of this report from the Location field of the browser window, as shown in Figure 4.3.5.

Step 2: Open up a word-processing program such as Microsoft® Word® or Corel® WordPerfect®. Open the report created in Step 1 in this application. Alternatively, the user could select *Communicator/Page Composer* from the Netscape main menu and open the report in this application.

Step 3: Create the desired graph in DandD using the *View/Graphics* choices off the main menu or the *Plot* command from the Parameter viewing screen. Select the desired graphic elements, and then invoke *Edit/Copy* from the main menu to create a copy of the graphic on the clipboard.

Step 4: If using Microsoft® Word® or Corel® WordPerfect®, select the *Edit/Paste Special* function. A window similar to Figure 4.3.6 will open. Choose the *Paste* radio button, *As Picture*, and click *OK*.

If using Composer, first create a file that contains the graphic. The graphics are stored as separate files for web pages. To do this, start Microsoft® Windows® Paintbrush from the Microsoft® Windows® Accessories group. Select *Edit/Copy* from Paintbrush to paste the graphic into Paintbrush. Adjust the size of the paint window to minimize the bits to save by selecting *Image/Attributes* and setting the width and height to the actual width and height of the graphic, as shown in Figure 4.3.7. Save the graphic in the directory where the report is saved (this is, by default, DandD_Docs) as a 24-bit bmp file.

Within Netscape Composer, select *Insert/Image* from the main menu. On the *Image* tab, click the *Choose File* button. Select the file saved in Paintbrush. Click OK when prompted to convert the file to jpg format. The graphic will be inserted.

4.3.7 View/Reports

When the DandD dose calculations are completed (Section 4.2.6), the results can be used to generate reports that describe the input data and resulting dose

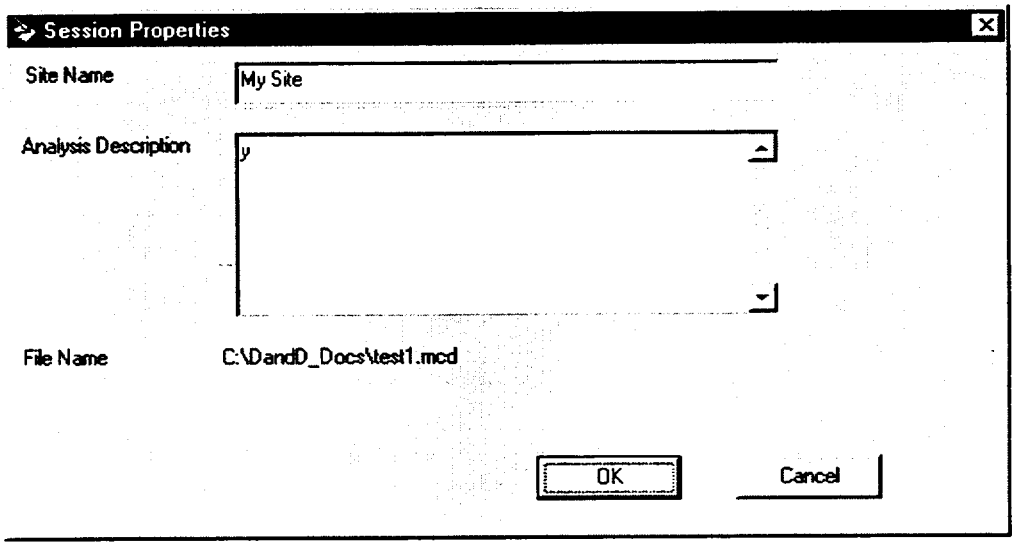


Figure 4.3.4.. Session properties dialog box

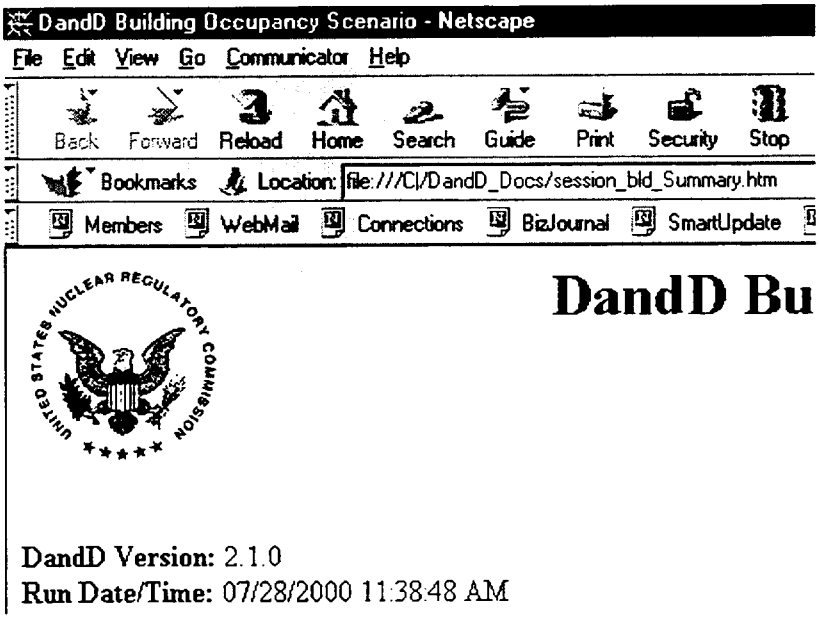


Figure 4.3.5 Path of report shown in location text box in Netscape.

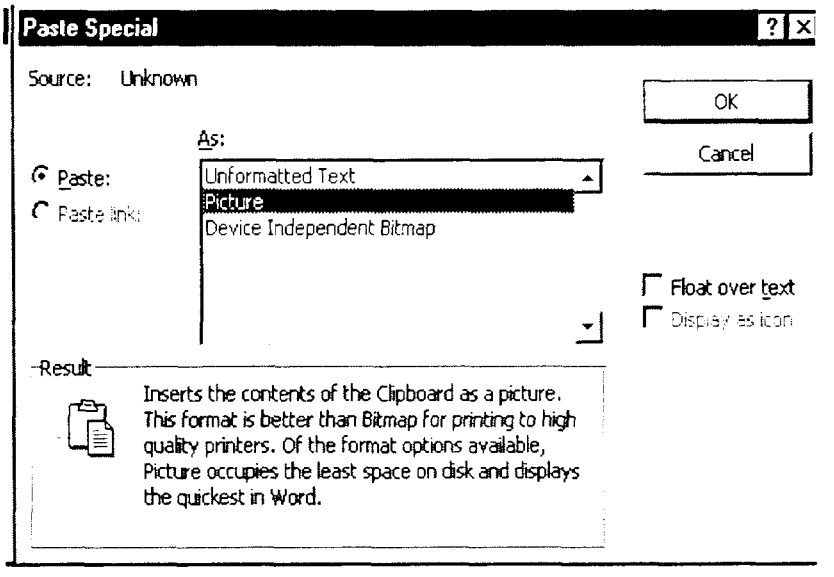


Figure 4.3.6. Paste a graphic into a document using Microsoft® Word® or Corel® WordPerfect®

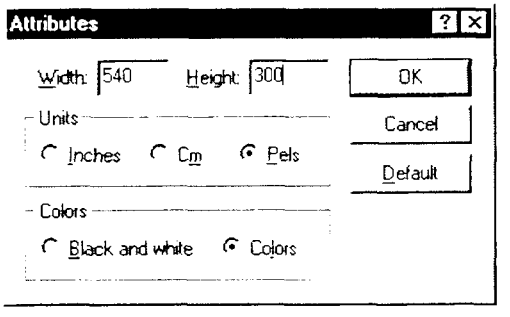


Figure 4.3.7 Adjust size of window in Paintbrush

value by selecting *View/Reports* from the main menu. These reports are generated as HTML files. A browser such as Internet Explorer or Netscape must be installed to view the reports from DandD. Because HTML is a standard format, reports may also be opened in a word-processing package such as Microsoft® Word® or Corel® WordPerfect®. Reports can also be opened in an HTML editor such as Netscape Composer.

The reports are created in the same directory as the session file. The report name is built using the scenario, the session name, and the template name. For example, the report Test_bld_Summary.htm was generated by a session titled Test.med from the building occupancy scenario (bld) using a template called Summary.

After a simulation is completed, reports are not automatically generated. Reports are generated on request by using the *View Reports* form, as shown in Figure 4.3.8. Once the report has been generated, it will be available on the hard drive.

To generate a new report file, click the radio button *Create a report based on current session*. Select the report template by clicking on the desired template. Either double-click on the template name or click on the *Create Report* button to generate a new report.

The first three template entries are default report templates. If any custom templates have been defined by using the *Advanced/Report Template Editor* option from the main menu, those template names will also be listed (see Section 4.3.10).

To view a previously created report, click the radio button *View a saved report*. A *File Open* dialog box will open. Select the desired HTML file to open. The default browser will start and the file will be loaded.

The reports can be opened with a word-processing program such as Microsoft® Word® or Corel® WordPerfect®. They can also be posted to web sites, saved as text files from the browser, or printed from the browser.

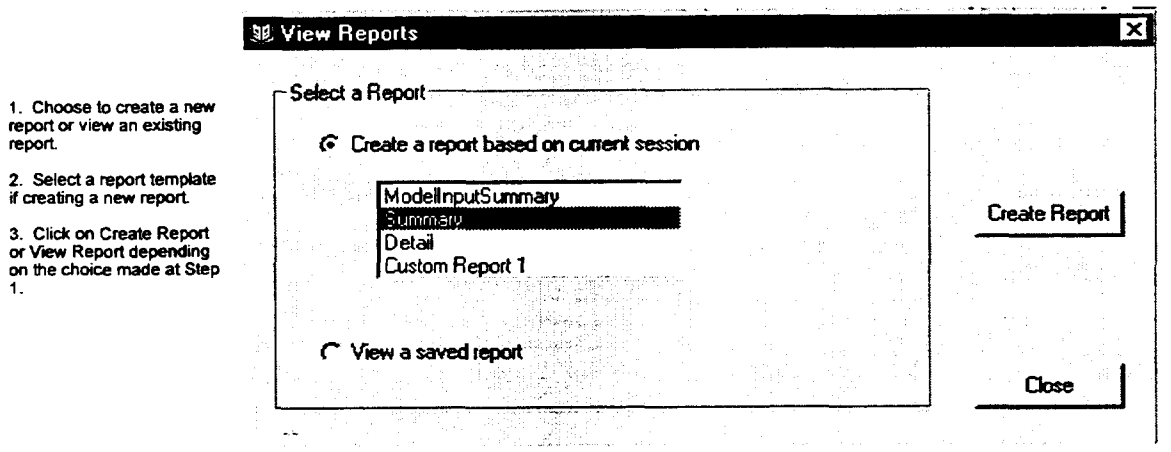


Figure 4.3.8 View Reports window

The following default report templates are always available:

1. *Model Input Summary* summarizes the model input and the site-specific parameter values. This option is available even when there are no output results.

2. The *Summary* report is a terse description of the session. It lists the major program options and describes any changes from the default parameter values or distributions. Parameters left at their default settings are not listed in the report. Output from the simulation is limited to the calculated dose value.

3. The *Detail* report is a comprehensive list of all of the program settings and parameter values, as well as detailed information that breaks down the calculated dose into pathway and nuclide components. The report lists the values or distributions for each parameter, whether or not it has been changed from the default value. Because of the large number of parameters in the residential scenario model, the *Detail* report can be quite lengthy and may take some time to generate.

Additionally, custom report templates can be defined by using the *Advanced/Report Template Editor* option from the main menu (Section 4.3.10).

If the site data are changed in any way, DandD will delete any associated report files that were generated. This allows the software to ensure that the data shown in the report are consistent with the data saved in the session.

4.3.8 View/Tables

There are four tables in DandD that the user is not permitted to edit. However, the user can view the data in these tables by selecting the table name from *View/Tables* in the main menu. A window will open displaying the data, as shown in Figure 4.3.9. When the user has finished viewing the data, the window may be closed by clicking the *Close* button or choosing the *File/Close* option from the main menu.

Appendix E contains an explanation of the data in these tables. The data are not listed in this document, but can be viewed or printed from DandD. The meaning of the columns within these tables is as follows.

Radioactive Decay Data

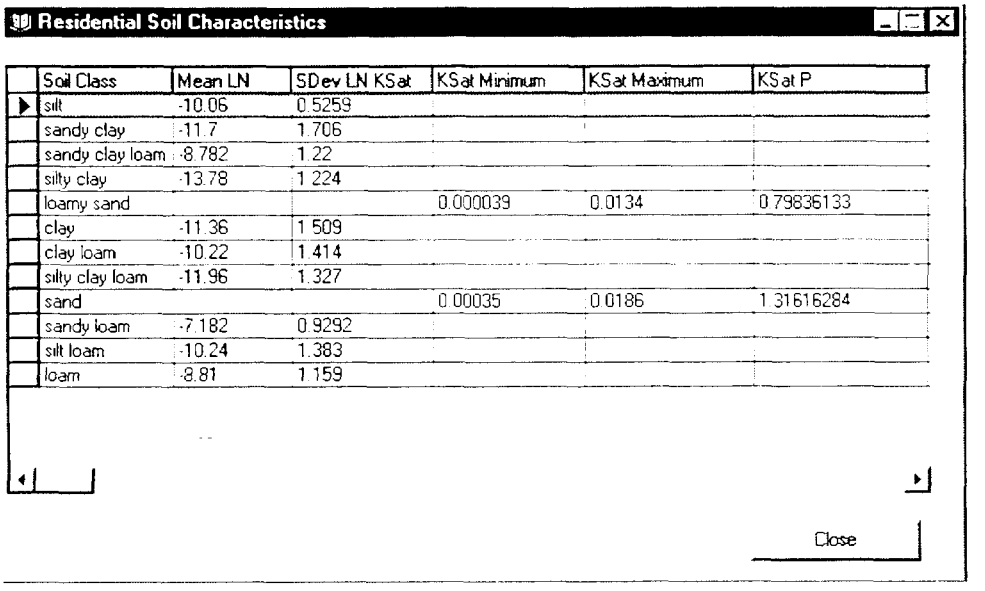
Parent refers to the original contaminant, not the immediate parent in the decay chain.

Progeny is a by-product in the decay chain of *Parent.*

HalfLife is half-life of *Progeny.*

PositionInChain is number of decay generations from *Parent.* A radionuclide directly descended from *Parent* will have a value of 2 for *PositionInChain.* If *Parent* and *Radionuclide* are equal, then *PositionInChain* will be equal to one.

FirstParentIndex indicates which radionuclide in the chain is the immediate parent of this nuclide.



Soil Class	Mean LN	SDev LN KSat	KSat Minimum	KSat Maximum	KSat P
silt	-10.06	0.5259			
sandy clay	-11.7	1.706			
sandy clay loam	-8.782	1.22			
silty clay	-13.78	1.224			
loamy sand			0.000039	0.0134	0.79836133
clay	-11.36	1.509			
clay loam	-10.22	1.414			
silty clay loam	-11.96	1.327			
sand			0.00035	0.0186	1.31616284
sandy loam	-7.182	0.9292			
silt loam	-10.24	1.383			
loam	-8.81	1.159			

Figure 4.3.9 View data table window

FirstParentFraction is fraction of decays of the first parent that produce *Progeny*.

SecondParentIndex indicates alternate radionuclide that can decay to *Progeny*.

SecondParent is fraction of decays of the second parent that produce *Progeny*.

AtomicNumber is number of protons in the *Progeny*.

Dose Equivalent Factors

Parent is name of the parent radionuclide.

Radionuclide is name of the radionuclide.

ImplicitProgenyFraction is fraction of parent transitions that produce this radionuclide.

Ingestion is unit committed effective dose equivalent (CEDE) conversion factor for ingestion.

Inhalation is unit CEDE conversion factor for inhalation.

ExternalSurface is unit CEDE conversion factor for external surface exposure.

External15cm is unit CEDE conversion factor for external exposure at 15 cm.

Residential Soil Characteristics

This table holds the parameters that describe the hydrologic characteristics of 12 soil types defined by the United States Bureau of Reclamation (USBR) (see Appendix E). These characteristics can be used to derive interrelated values for the soil parameters of the residential scenario model. Ksat is the saturated conductivity, and "b" is the "b" parameter of the saturation/permeability model.

SoilClass is the name of the soil classification.
Mean Ln is the mean value of the natural log of Ksat, in cm/sec, for soils with a lognormal distribution.

S Dev LN Ksat is the standard deviation of the natural log of Ksat for soils with a lognormal distribution.

K Sat Minimum is the minimum value of Ksat for soils with a beta distribution.

K Sat Maximum is the maximum value of Ksat for soils with a beta distribution.

K Sat P is the P parameter of the beta distribution of Ksat for soils with a beta distribution.

K Sat Q is the Q parameter of the beta distribution of Ksat for soils with a beta distribution.

Mean Ln B is the mean value of the natural log of parameter "b" for soils with a lognormal distribution.

Sdev LN B is the standard deviation of the natural log of "b" for soils with a lognormal distribution.

B Minimum is the minimum value of "b" for soils with a beta distribution.

B Maximum is the maximum value of "b" for soils with a beta distribution.

B P is the P parameter of the beta distribution of parameter "b" for soils with a beta distribution.

B Q is the Q parameter of the beta distribution of parameter "b" for soils with a beta distribution.

Mean NI is the expected value of porosity.

SDev NI is the standard deviation of porosity.

Residential USBR Percolation Fractions

Ksat is the saturated permeability in cm/sec.

Percolation Fraction is the estimated fraction of applied water that becomes infiltration.

4.3.9 View/Graphics

When the dose calculations are completed, the results can be displayed by selecting View/Graphics from the main menu. Three plot types are available from this menu selection, as described in 4.3.9.1 through 4.3.9.3.

Plots of individual parameter distributions are also available for each parameter if the user clicks the *Plot* button in the parameter viewing window (i.e., the window that opens when the user clicks *Add Concentrations, General Parameters*, or *Element Parameters*; see Section 4.1.2).

See Section 4.1.4 for a description of how to navigate a graphics window.

4.3.9.1 Dose Distribution

The dose distribution graph shown in Figure 4.3.10 shows the complementary cumulative distribution function (CCDF) for peak TEDE. For the possible values of dose, plotted on the x axis, the CCDF shows the fraction of simulations that have larger values. The initial graph depicted following a DandD simulation shows the PDF for dose from all active pathways due to all radionuclides.

4.3.9.2 Time Distribution

The time distribution graph shown in Figure 4.3.11 shows the CCDF for the time of peak TEDE. For the possible values of time, plotted on the x axis, the CCDF shows the fraction of simulations that have peak doses at later times. If the peak dose occurs at the same time in all simulations (as it always will in the building occupancy scenario), the CCDF is a vertical line at the x location of the common time value.

4.3.9.3 Dose History

A statistical summary of dose histories is available if the *Save Dose History Information* option has been selected by using the *Options* button from the Run Simulation window (see Section 4.2.6). Each set of sampled parameters produces a single dose history. At each timestep, DandD calculates the average value of dose, as well as the standard deviation of dose. The graph shown in Figure 4.3.12 shows the time variation of the average dose and the average plus and minus one standard deviation. The initial graph (following DandD execution) shows the history plots for dose from all active pathways due to all radionuclides.

History plots for selected pathways, due to all radionuclides, can be included in the graph by selecting the pathway (or *All*) from the *Pathways* list box and clicking the *Add to Plot* button. Plots for selected radionuclides, via all pathways, can be included by selecting a radionuclide (or *All*) from the radionuclides list box and clicking the *Add to Plot* button. History information for the combinations of individual pathways and individual radionuclides is not saved because of the large amount of storage space that would be required.

For each selected pathway or radionuclide, three curves are added to the graph, showing the average dose and the average dose plus and minus one standard deviation. In some cases, the average dose minus the standard deviation may be negative. This does not mean that the dose can be negative. This result is caused by a standard deviation of dose that is large relative to the average dose.

4.3.10 Advanced/Report Template Editor

The *Report Template Editor* form allows the user to create, modify, or delete a custom report template. Reports are not created in the Report Template Editor

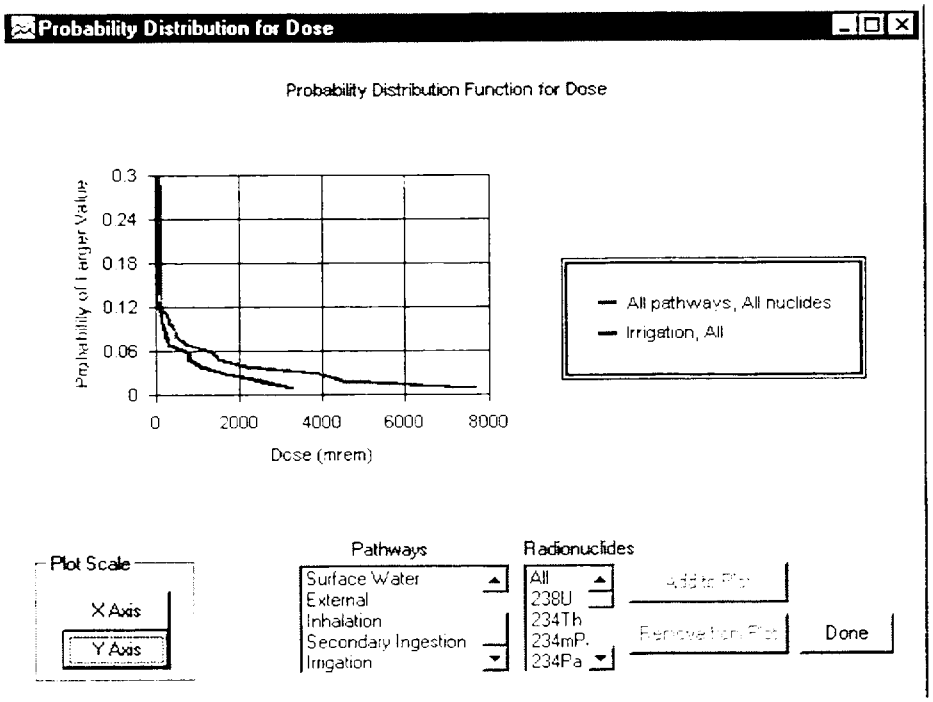


Figure 4.3.10 Dose distribution

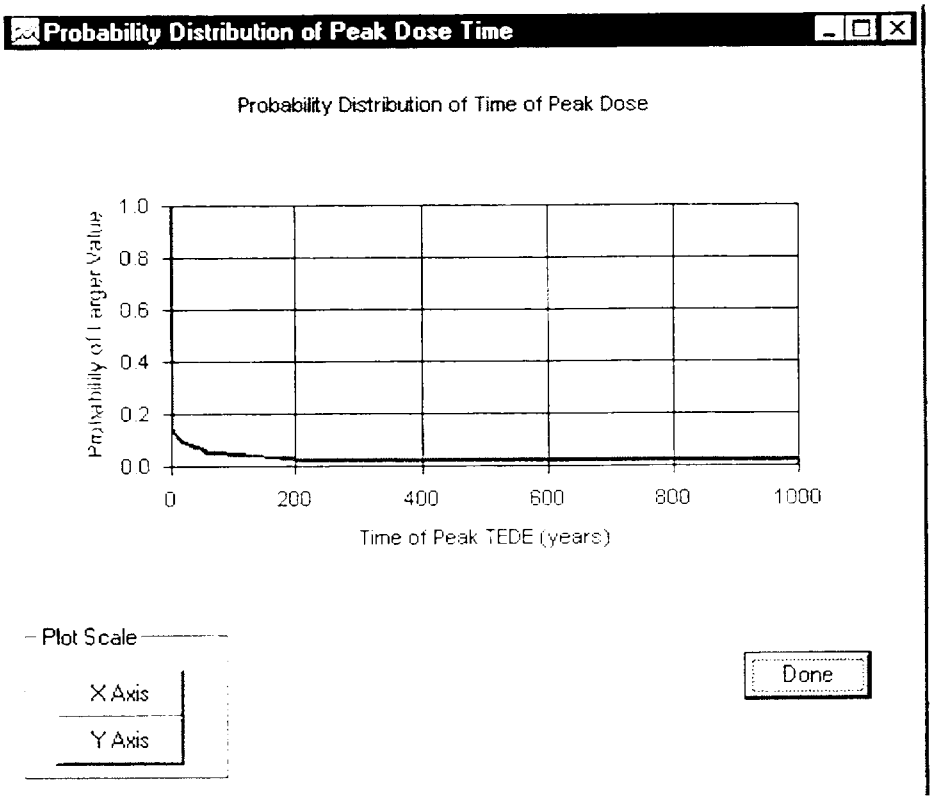


Figure 4.3.11 Time distribution

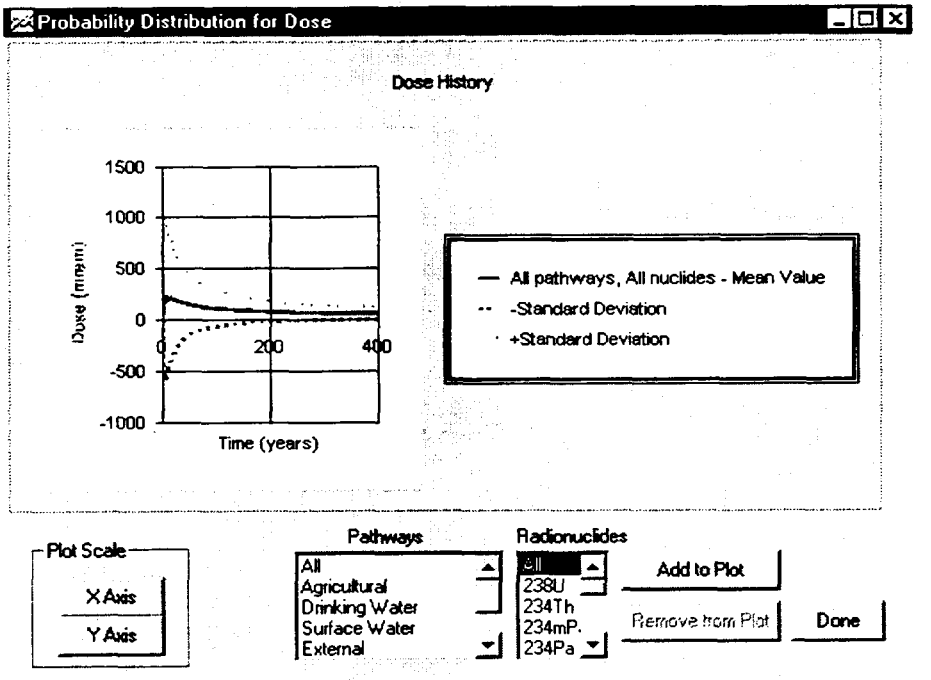


Figure 4.3.12 Dose history

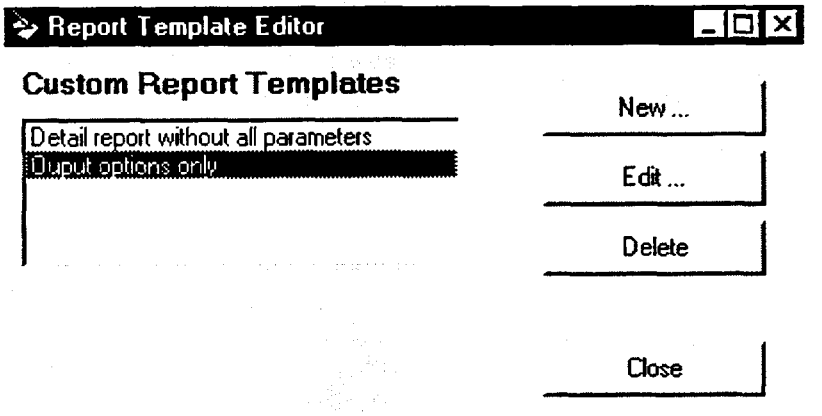


Figure 4.3.13 Selecting a custom report to edit or delete

window. To actually create reports from templates after a DandD simulation, use the *View/Reports* option from the main menu (see Section 4.3.7).

Select *Advanced/Report Template Editor* from the main application menu to open the Report Template Editor window, as shown in Figure 4.3.13. The *Edit Report Template* form will allow the user to change or specify a new custom report template. This form can be accessed by clicking the *New* or *Edit* button on the *Report Template Editor* form.

To create a new report template, click the *New* button. To edit an existing report template, select the template in the *Custom Report Templates* list. Click the *Edit* button. In either case, the *Edit Report Template* form will appear, as shown in Figure 4.3.14.

To delete an existing report template, select the template in the *Custom Report Templates* list. Click the *Delete* button.

To close this window, click the *Close* button.

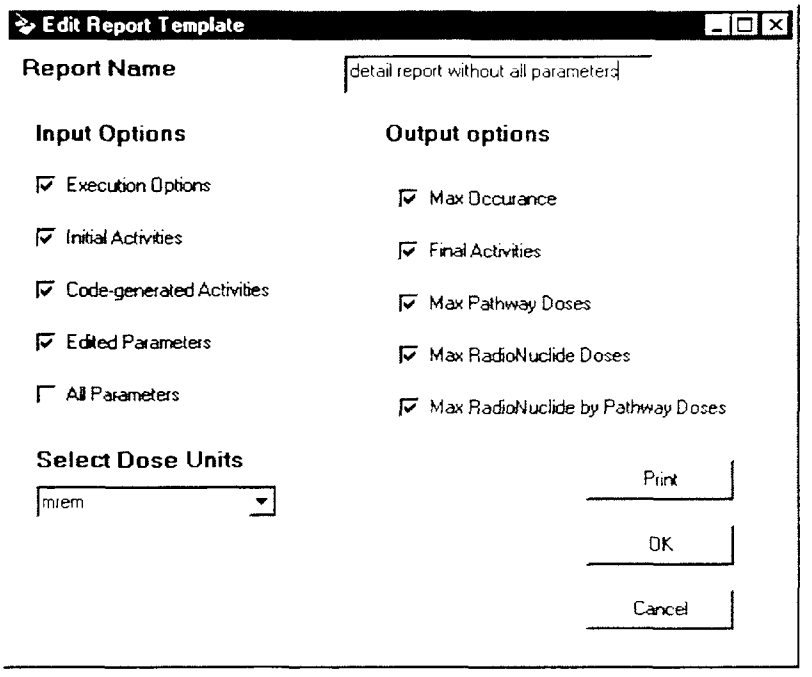


Figure 4.3.14 Report template editor

If creating a new report template (i.e., if the user clicked *New* in the Report Template Editor window), enter a name for the template in the *Report Name* field. Alternatively, if editing an old report template (i.e., the user clicked *Edit* in the Report Template Editor window), the text in the *Report Name* field will already be filled in. This text can be modified.

If an old browser such as Internet Explorer 2.0 is being used to view reports, the template name should have no embedded blanks.

Select (or deselect) the sections wanted on the report by clicking the listed checkboxes. Select the units to report the dose from the *Select Dose Units* pull down menu. Click the *Print* button if a copy of this form is desired.

Click the *OK* button to save the template modifications. Otherwise, click the *Cancel* button.

4.3.11 Advanced/Sensitivity Analysis

Once a simulation is completed by executing the model, the sensitivity analysis portion of DandD can be run to find the relationships between uncertain model parameters and calculated doses. To do this, select *Advanced/Sensitivity Analysis* from the application menu. The Data Influence Evaluation window will open, as shown in Figure 4.3.15.

4.3.11.1 Selecting Parameters for Sensitivity Analysis

The upper grid labeled *Available for Analysis* lists the uncertain model parameters defined by probability distributions. This table includes a symbol of each parameter as used by DandD, a description of each parameter, a checkbox indicating if a default or site-specific value was used, the sensitivity ranking, and whether the parameter is in the *Selected for Analysis* grid. The parameters are sorted by decreasing sensitivity.

Sensitivities are not calculated for model parameters with constant values. Parameters with constant values are not available for selection because the sensitivity analysis module in DandD identifies how uncertainty in the parameter value influences uncertainty in dose.

The program calculates a sensitivity ranking for each of the uncertain parameters. A measure of the sensitivity of the dose to the parameter value, which ranges from 0 to 1, is listed for each parameter, where 1 indi-

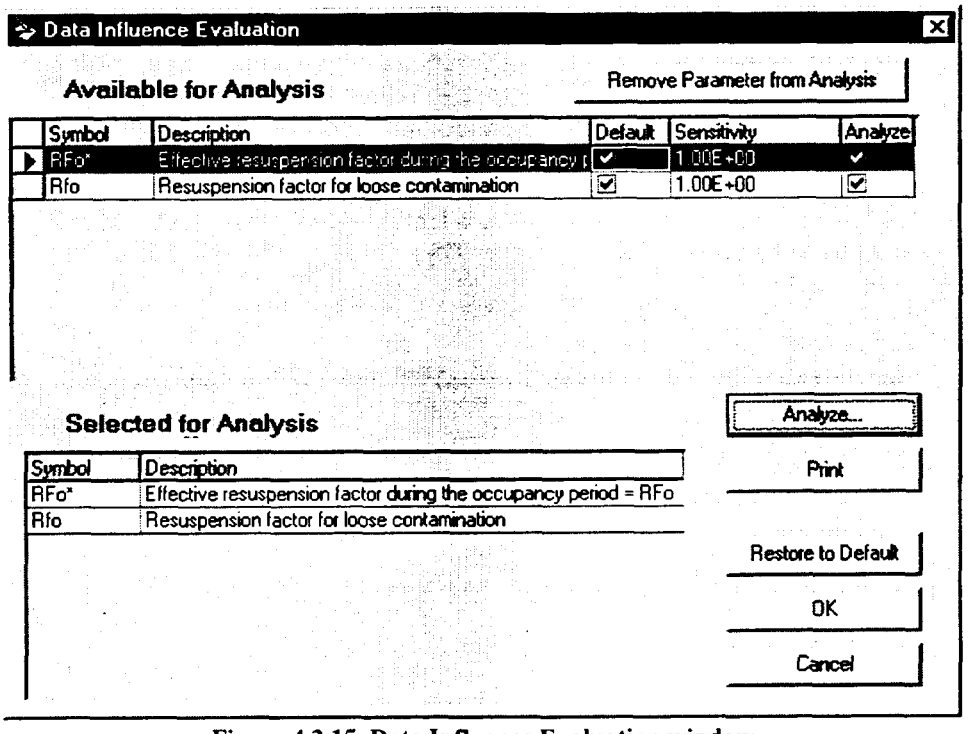


Figure 4.3.15 Data Influence Evaluation window

cates highest sensitivity. This sensitivity measure reflects the dependence of calculated dose on the parameter value. This measure is based on the significance level of the Kolmolgorov-Smirnov (K-S) statistic for the parameter (see Section 4.3.11.4 for a description).

The first time the Data Influence Evaluation window is opened after a simulation, the lower table labeled *Selected for Analysis* contains parameters with a sensitivity of 0.95 or greater. This is the default setting.

The upper table indicates that a parameter is currently selected by displaying a checkmark in the column labeled *Analyze*. The user can select new parameters by selecting the appropriate row in the upper table and clicking the *Select Parameter for Analysis* button. An entry for the parameter will be added to the lower table labeled *Selected for Analysis*.

Parameters that are already selected can be removed by selecting the parameter's row in the upper table and clicking the *Remove Parameter from Analysis* button (note that this button toggles between *Select* or *Remove* depending on the current *Analyze* checkbox setting for the parameter). The user can also remove or add parameters from the *Selected for Analysis* grid by double-clicking on the parameter in the *Available for Analysis* grid.

Click the *Restore to Default* button to restore the *Selected for Analysis* grid to include only parameters with a sensitivity of 0.95 or greater.

After one or more parameters have been selected for analysis, clicking the *Analyze* button will invoke the sensitivity analysis application. A description of this application is provided below. The sensitivity analysis module is an independent application that shares data with DandD.

The *Print* button prints the entire list of parameters, along with their sensitivity indicator values. Click the *OK* button to close this window and save the current state of selected parameters. If this is done, the next time this window is opened the parameters shown in the *Selected for Analysis* grid will reflect this saved state.

Click the *Cancel* button to close this window and disregard the current state of selected parameters as shown in the *Selected for Analysis* grid. If this is done, the next time this window is opened the parameters shown in the *Selected for Analysis* grid will be identical to the initial state the last time the *Data Influence Evaluation* window was opened.

If the simulation is run again, the saved states will be disregarded. The variables selected for analysis in the *Data Influence Evaluation* window will only contain parameters with a sensitivity of .95 or greater.

4.3.11.2 Using the Sensitivity Analysis Application

The objective of the sensitivity analysis is to understand the relationship between the model parameter values and the calculated dose values. This information will help to identify parameter modifications that might lead to significant changes in the calculated dose distribution.

Sensitivity analysis is a separate custom Microsoft® Windows® application. DandD will launch this application when the user clicks the *Analyze* button from the Data Influence Evaluation window. The sensitivity analysis application loads data from the session file. Each parameter in the *Selected for Analysis* list in the Data Influence Evaluation window will be loaded into the sensitivity analysis application.

This application can be closed using its File/Exit command or the "X" button on the Sensitivity Analysis window. Because this is a separate application that shares data with DandD, this window should be closed before returning to DandD.

The Sensitivity Analysis window is divided into top, middle, and bottom sections that are separated visually by thin horizontal black lines, as shown in Figure 4.3.16.

The top section is relatively small and only contains the number of realizations (or simulations) analyzed and a color legend. The middle section is where the user can modify settings specific to a parameter to study the sensitivity of that parameter. This section contains two graphs. The graph on the left, entitled "Total Dose," is the plot of the probability distribution for dose. This plot is identical to the plot displayed when *View/Graphics/Dose Distribution* is selected from the main menu, except that the user may change the displayed performance objective (P.O.) dose value.

The graph on the right, labeled with the name of a selected parameter, is a histogram constructed of the selected parameter values sampled by DandD for each simulation. It consists of the sampled parameter value along the x axis versus the number of occurrences on the y axis.

The bottom section is the largest of the three sections and contains histograms for all of the input parameters specified in the Selected for Analysis list in the Data Influence Evaluation window in DandD. The window may need to be scrolled to see the histograms for all selected parameters. To select an input parameter, the user will need to double-click (or right-click) on the small plot to copy the graph from the bottom to the middle section.

4.3.11.3 Description of Controls

Users can explore the relationship between dose and parameter values by adjusting the P.O. value in the dose graph and observing the tendency of high dose values to cluster near the extreme values of certain parameters.

If a parameter has a strong correlation with dose, then the simulations leading to large dose values, colored red, will tend to cluster near one end of the parameter distribution. If a parameter is only weakly correlated to dose, the red and blue values will tend to be evenly distributed over the range of the parameter values.

If a parameter has a strong correlation with dose, then collecting data about that parameter, which will reduce uncertainty about the parameter value, will tend to change the dose distribution and may therefore change the compliance status.

The potential influence of site-specific parameter information can be approximated by "clipping" or truncating parameter values from the high and low ends of the current parameter distribution. For the currently selected parameter (shown in the upper-right hand graph), the largest or smallest values (or both) can be truncated from the distribution by dragging the vertical limit lines in this graph to the right or left. Parameter samples that fall outside the limit lines are colored green on the parameter graph and are excluded from the main dose distribution graph. In this way, the potential effect of narrowing the distribution for a parameter on the resulting dose distribution can be readily estimated and visualized (see Figure 4.3.17).

The legend in the top section shows the following entries:

- **Passes P.O. Value:** Realizations with dose values less than the P.O. value are shown in blue on the total dose graph and on the parameter graphs.

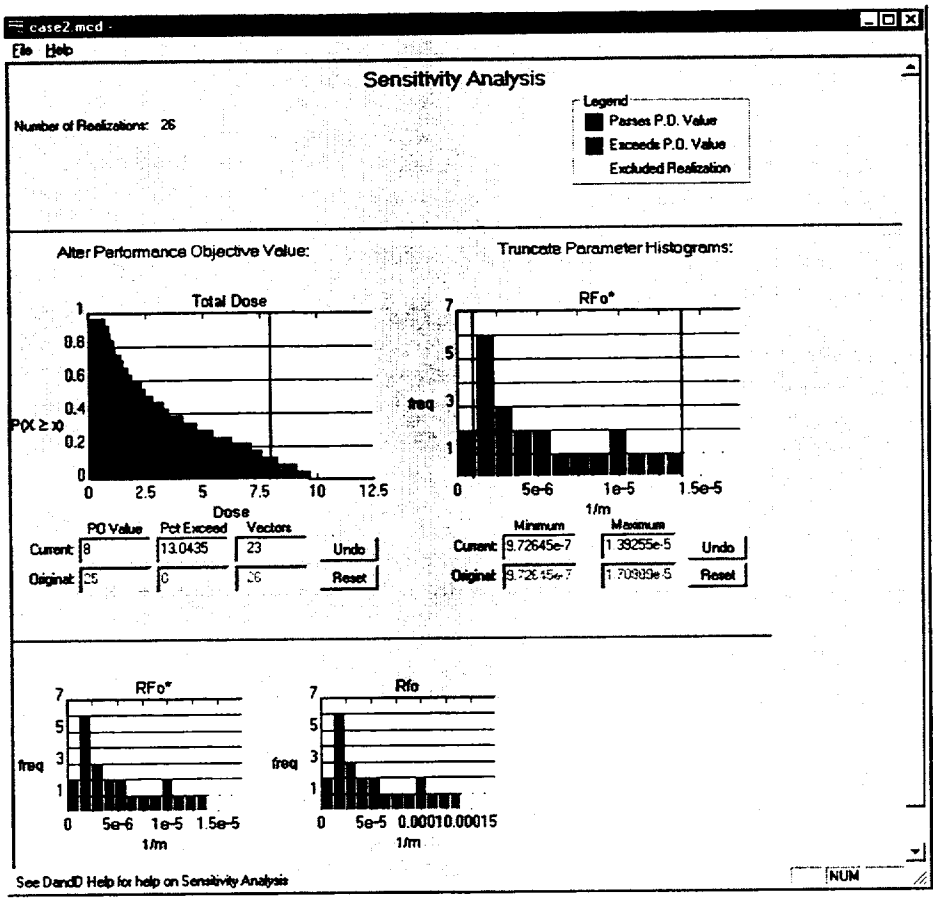


Figure 4.3.16 Three parts of the sensitivity analysis window

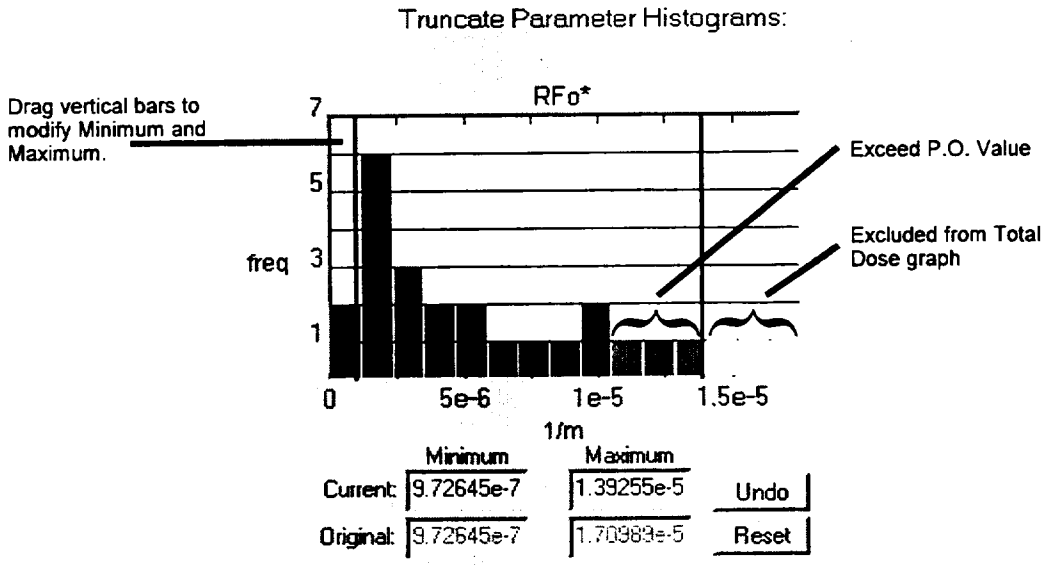


Figure 4.3.17 Histogram of parameter selected for sensitivity analysis

- **Exceeds P.O. Value:** Realizations with dose values larger than the P.O. value are shown in red on the total dose graph and on the parameter graphs.

- **Excluded Realization:** Parameter samples that fall outside the limit lines (maximum and minimum values in the row labeled *Current)* are colored green on the parameter graph and are excluded from the total dose graph.

A given parameter value may have some red and some blue for the same value on the histogram. This indicates that some of the realizations passed and some exceeded for the same value (or close to the same value) of the parameter in question. This happens because other uncertain parameters within that histogram bar may be controlling the total dose.

If all calculated dose values are either above or below the regulatory limit, the entire distribution will be shown as red or blue, respectively. In this case, compliance with the dose standard is either achieved already or is very unlikely given the scenario, pathways, and models.

Both plots in the middle section have two rows of informational text boxes located just below them. The top row, labeled *Current*, shows the current settings of the plot. These may be modified by the user. The next row, labeled *Original*, shows the original settings of the plot.

The total dose plot text boxes have the following meanings:

- **P.O. Value:** The user can modify the P.O. by changing the value of this text box from the default of 25 mrem to a larger or smaller number. The user must tab or select another control for the revised P.O. value to take effect.

If the total dose plot shows values both below and above the P.O. value, the P.O. value is indicated by a vertical line on the chart. This line can be selected and moved to the left and right to change the P.O. value.

- **Pct Exceed:** indicates percentage of realizations that have exceeded the P.O. If the NRC-defined P.O. requires the acceptable percentage of passing results to be 90%, this is equivalent to a 10% exceedance. Lower exceedance rates are better than higher. Excluded vectors are not considered in this calculation. Modifying this number manually will have no effect; it changes automatically when the P.O. value is modified, or when a parameter histogram is truncated.

- **Vectors:** indicates the number of realizations that were used to graph the total dose plot. The user indirectly modifies the number of realizations used by dragging the vertical bars on the parameter plot. Modifying this number manually will have no effect on the plots.

The *Undo* button will cancel the last modification made to the related row labeled *Current*. For example, if some of the simulations were removed from the total dose graph by changing the value of *Minimum*, clicking the *Undo* button will set the value of *Minimum* to the value it had before it was modified.

The *Reset* button located to the right of these rows will reset the row labeled *Current* to the values in the row labeled *Original*. In other words, the current values in the row will be reset to the default values.

The allowed values for the *Minimum* and *Maximum* are restricted to fall within the actual parameter values calculated by LHS. For this reason, the software will restrict the minimum or maximum that is entered for the parameter bounds. These bounds can be modified by:

- moving the vertical lines on the parameter graph by using a click-and-drag motion;

- manually entering a new value in the text boxes labeled *Minimum* and *Maximum*;

- clicking the *Reset* button to reset the *Minimum* and *Maximum* values to the default (original) values; or

- clicking the *Undo* button to reset the last value entered to its previous value.

If there is difficulty in moving the vertical lines on the graph, clicking the *Reset* button under the parameter histogram will reset the *Minimum* and *Maximum* values to their original values. All simulations, other than those removed by modifying other parameter bounds, will be reset in the total dose plot.

Distributions for more than one parameter can be truncated as described. After the upper and lower limit lines are set for the first parameter, any other parameter can be selected by double-clicking on the small distribution graph for that parameter. The distribution for the second parameter will then be moved to the main

parameter graph, where its upper and lower limits can be set. Any limits set for the first parameter are preserved and can be recalled by selecting that parameter from the field of small parameter graphs.
The eliminated simulations are preserved and cumulative when multiple parameter histograms are modified. For example, if ten realizations have been eliminated by restricting the bounds on parameter one, and the user double-clicks on the histogram representing parameter two, then those realizations previously eliminated will still be eliminated. More simulations can be eliminated by restricting the bounds on parameter two. All of the other plots will be updated to show these additional eliminated simulations.

When eliminating bounds or modifying the P.O., some of the parameter graphs may become greyed out. This means that by calculation of the K-S test, these parameters do not significantly determine whether dose is above or below the P.O. (see Section 4.3.11.4). If a parameter has a sensitivity ranking less than 0.95, the histogram will have a grey background.

Some dose and parameter distributions are more easily viewed using a logarithmic scale. The scales for both the total dose graph and main parameter graph can be changed by right-clicking on the x axis title or the y axis title. A pop-up menu allows the axis scaling to be changed between linear and logarithmic.

Referring to Figure 4.3.17, there were a total of 26 simulations. This can be directly read from the graph by counting the number of squares on the histogram. Each square represents one simulation. The total number of squares in the histogram is the same as the *Number of Realizations* indicated on the upper left corner of the *Sensitivity Analysis* window, as shown in Figure 4.3.16.

The user eliminated three of the 26 simulations from consideration in the total dose graph by changing the value of *Maximum* to 1.39255E-5, indicated by the color green, as shown in Figure 4.3.17. Out of the 23 simulations remaining, three had a total dose that exceeded the performance objective, indicated by the color red, as shown in Figure 4.3.17. The vertical bars in Figure 4.3.17 indicate the *Minimum* and *Maximum* values graphically. The value for *Current Vectors* will be 23 in the total dose graph, indicating that 23 of the 26 vectors are plotted in the total dose graph, as shown in Figure 4.3.16.

4.3.11.4 Kolmolgorov-Smirnov Statistical Test for Sensitivity

The sensitivity measure that indicates the dependence of the calculated dose on the value of each uncertain parameter is based on the K-S test for differences between the distributions underlying two sets of sample values.

The calculated dose values are first divided into two groups: one group with "high" doses and the second with "low" doses. Second, the parameter values used in the calculations leading to high doses are grouped together, while the parameter values for the low dose calculations are placed into a separate group. Third, the empirical probability distributions defined by these two groups of samples are compared using the K-S test. Parameters having a strong influence on dose will show large differences between the two distributions, leading to a large value for the K-S test statistic. Parameters with little or no influence on dose will have approximately the same distribution in the high-dose and low-dose groups, leading to a small value for the K-S statistic.

The sensitivity measure reported by DandD is $1 - Q$, where Q is the significance level of the observed value of the K-S statistic. Low values of Q mean that the observed difference between the distributions is unlikely to be the consequence of random error and is therefore likely to reflect a real difference between the high-dose and low-dose parameter sets.

The sensitivity in the Data Influence Evaluation window is based on partitioning the samples by the median dose. In the Sensitivity Analysis window, instead of grouping the simulations based on the median dose, the simulations are grouped based on the *P.O. Value*. This means that it is possible for the Sensitivity Analysis window to indicate that parameters are not sensitive when the same parameter may have had a sensitivity ranking greater than or equal to 0.95 in the Data Influence Evaluation window. This also means that some parameters may be sensitive only for certain *P.O. Values* in the Sensitivity Analysis window.

4.3.12 Window Menu Options

The *Window* menu contains standard windowing operations to help manage the window placement within the application.

The *Window/Cascade* option is very helpful if a window is hidden because one window is directly on top

of another window. Selecting *Window/Cascade* will cause the windows to be stacked. Windows may have to be resized in order to access all of the buttons on each window.

The *Window/Tile Horizontal* and *Window/Tile Vertical* options are useful to compare the contents of two windows. For example, to compare two graphs, minimize the main session window by clicking the *iconize* (or minimize) button on the upper right hand part of the window, as shown in Figure 4.3.18. Open the two graphics windows using the *View/Graphics* selection and select *Window/Tile Horizontal.*

The *Window/Arrange Icons* button may be useful if some of the icons have been moved, and need to be seen. This selection is only relevant if windows have been iconized.

4.3.13 Help Options

The *Help* menu gives access to the online help files (see also Section 4.1.1). Help for using the graphical user interface can be accessed by selecting the *Help/Contents* and *Help/Search On* options.

The*Help/NRC References* addresses the more technical issues of modeling. This will work only if a frame-enabled browser such as Internet Explorer 3.0 or Netscape Navigator 3.0 has been installed.

The *Help/About* option will give information regarding the version of DandD that is currently running.

Additionally, context-sensitive help with the user interface is available by pressing the F1 key.

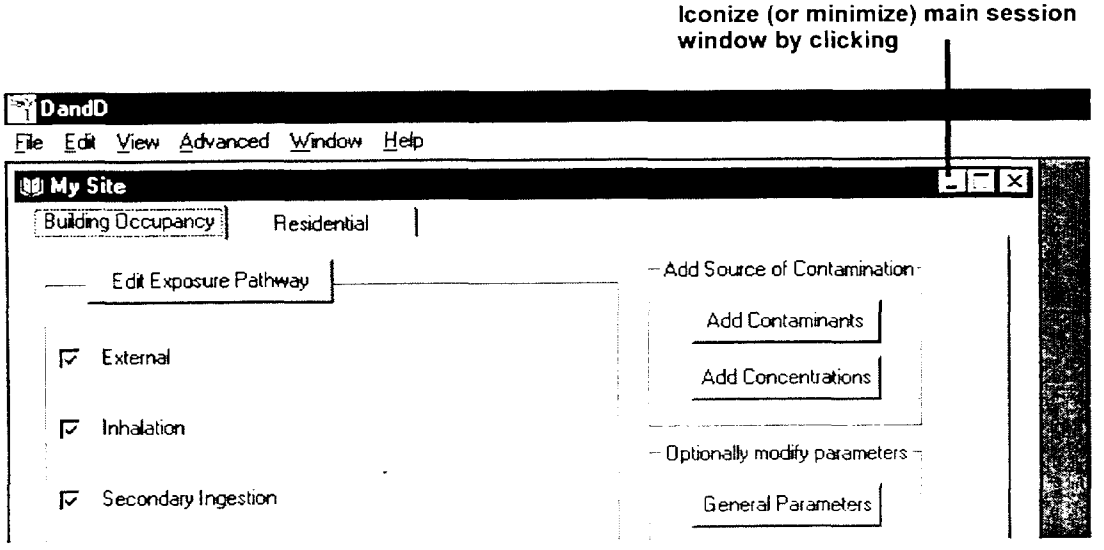


Figure 4.3.18 Iconizing main session window

5 FREQUENTLY ASKED QUESTIONS

Do I need Microsoft® Access® installed in order to run DandD? No.

Do I need Microsoft® Access® installed to look at the raw session file data? Yes.

Can DandD be installed on my new Windows ME or Windows 2000 machines? The DandD Version 2.1 installation procedure was not tested against these platforms. The difficulties that may be encountered are unknown. However, this feature may be supported in future versions.

I am unable to successfully install DandD Version 2.1. Now what do I do? If all of the hints within the "Installation of DandD" section of this document fail, send an e-mail to DandD@nrc.gov including: the version of the Windows® operating system on the computer, the amount of free hard-disk space available, the amount of random access memory (RAM) available, and, if available, the DandD installation log. If the installation has proceeded far enough, an installation log will have been created in a file named "INSTALL.LOG" in the directory where DandD is being installed (usually "C:\Program Files\DandD2").

How do I know what version of DandD I have? Click on "About" or "About DandD" in the "Help" menu. A dialog box will appear giving a multiple digit version number. For example, 2.1.0 is the specific DandD version number available at the time this documentation was published.

How do I know which session file I have open? The bottom left side of the main session window will contain the path name of the file currently opened. Select *File/Properties* for more information.

How do I change the site name and description for a session? Once the session is opened, click on "Properties" in the "File" menu, then edit either the site name or description.

How do I open up a session file using Microsoft® Access®? From the Microsoft® Windows® start menu, start Microsoft® Access®. Select the Open database option. Change the "Files of type:" drop down menu from "Microsoft® Access® Databases" to "All files." Specify the mcd (Monte Carlo DandD session) file in the Open dialog box. Click OK. Enter "2x" for the password.

How do I do a deterministic analysis like I did with DandD Version 1.0? Go through every parameter and change it to a constant along with support justification.

Why do the numbers in the *Summary of Model Parameter Values* disagree with the input values I specified? Because the input units differ from those used by the model. See 4.1.2 for a further discussion.

Why is the *Add Concentration* button dimmed on the scenario tab? This happens if the *Concentration History* toggle from the *Add Contaminants* dialog box is set. To correct this, click on *Add Contaminants*. Set the *Contaminant Input Mode* toggle to *Initial Concentration Values*. Add desired site contaminants. Click OK.

I haven't run a simulation yet, but I need to know what parameter I have modified and their values. How do I do this? The user can see which parameters are modified in the Parameter Viewing windows by looking to see which parameters have their *Default* checkbox unchecked in the main grid. However, it will be easier to create a report called *Model InputSummary* accessed by selecting *View/Reports* from the main menu. All site-specific parameters and contaminations will be reported.

I want to see the Dose History. I ran a simulation, but the dose history is greyed out on the *View/Graphics* menu. What should I do? Click on *Execute*, and click on *Options* in the Run Simulation window. Check the *Save Dose History Information* checkbox in the Advanced Execution Parameters window. Rerun the simulation.

I am getting unclear error messages. My simulation should run but it won't now. What should I do? You may have stumbled onto a bug. Exit DandD, restart DandD, and reopen the session file. Try to run the simulation again. Reproduce the problem and please submit the bug to NRC technical support to repair.

The program was unable to complete the LHS sampling. I received a sequence of error messages from the LHS processor. Why? The system may be low in memory or disk space. The specified parameter distributions or correlations may be invalid. It is also possible that a bug from within LHS may have been found. Try changing the probability distribution and

resampling. If this corrects the problem, the problem is most likely a bug in LHS. If this does not work, exit DandD, restart DandD, and reopen the session file. Try to run the simulation again. If this works, there may be a bug in DandD. Reproduce the problem and please submit the bug to NRC technical support to repair.

I ran the simulation twice. Each time I got different results, even though the random seed and the parameters haven't changed. Is this program broken? In some cases, the random sample values of the parameters depend on the order in which the user defined and modified the parameters. This will result in a slightly different value of the TEDE and 95% confidence interval bounds. The program results are still valid. The user can increase the number of simulations to increase the accuracy of the results. This dependence on the order of input is a bug and may be fixed in a future version.

In the Report, why is the reported all-pathways dose not always equal to the sum of the dose reported for the individual pathways? There are a number of reasons for this apparent inconsistency. First, the numbers reported represent peak values over 1000 simulated years and the pathway peak may occur at different times than the all-pathways peak; thus the all-pathways peak would be less than the sum of the individual pathway peaks. Second, remember that the reported numbers represent a specific quantile of the distributions. There may be an overall relationship between pathway doses such that high values along one pathway coincide with low values on another pathway. The resulting all-pathways quantile would be expected to differ from the sum of the pathway-specific quantile values.

How do I insert a graphic into my Microsoft® Word® or Corel® WordPerfect® Document? Use the Edit/Copy function to copy the graphics to the clipboard from DandD. Use the Paste Special option in the word processing program.

How do I extract the raw data used in the graph? Use the Edit/Copy function to copy the graphics to the clipboard from DandD. Use the Paste option in the word processing or spreadsheet program.

When I try to copy a plot from DandD Version 2.1 and insert it into a word-processor document, all I get are a bunch of numbers. How do I get the plot? When it is desired to "paste" the plot into the document, select "paste special" rather than "paste" to insert the plot.

I used the Edit/Copy function, but when I paste my graphic into the word processing program, the legend is missing. Did I do something wrong? No. This is a missing feature of the Edit/Copy function. Add the legend to the graph within the target word processor application.

How can results be transmitted to the NRC? The session file (the file with the "mcd" filename extension) contains the session data, results, and explanations. Sometimes these files are larger than will fit on a standard floppy diskette. DandD Version 2.1 contains an option to compress these files so they may fit on a diskette or will be smaller to ship electronically. In Section 4, User Interface Reference Guide, read Section 4.3.3 File/Export Session File as Zip.

I entered a probability distribution for some parameters, but a constant value was used instead. Is this a bug in DandD? No. All behavioral parameters use an average of the sampled parameters for every simulation. LHS is used to create a set of values for probabilistic behavioral parameters. However, these values are averaged for use in the model. Parameter help accessed via the Parameter Viewing window (see section 4.1.2) and the online help accessed by selecting *Help/NRC References* from the main menu will tell the user which parameters are behavioral.

6 REFERENCES

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APPENDIX A DIFFERENCES BETWEEN VOLUME 1 AND RELEASE 1.0 OF DandD

A.1 Introduction

NUREG/CR-5512, Volume 1, "Residual Radioactive Contamination From Decommissioning: Technical Basis for Translating Contamination Levels to Annual Effective Dose," (Kennedy and Strenge, 1992), provides the technical basis, associated equations, and data tables for translating residual contamination levels to annual dose for decommissioned sites. The NUREG/CR-5512 modeling is intended to be a screening tool for assessing potential doses from decommissioned sites based on a philosophy of moving from simple, prudently conservative, calculations toward more realistic simulations, as necessary.

In 1993, Sandia National Laboratories (SNL) developed codes to perform calculations using the NUREG/ CR-5512 methodology to support the NRC's draft regulatory guide on release criteria for decommissioning, NUREG-1500 (Daily et al., 1994). Subsequent to performing these calculations, SNL has developed DandD, a user-friendly software application that implements the NUREG/CR-5512 methodology. DandD incorporates the codes developed for the NUREG-1500 calculations within a graphical user interface. In the process of supporting the NUREG-1500 calculations and implementing and testing the DandD software, several problems and issues related to the original methodology in NUREG/CR-5512 have been identified. Consequently, several changes or corrections were made for implementation of the NUREG/ CR-5512 methodology in DandD. Generally, these changes address the following problems or issues:

1. Revisions to the equations published in NUREG/CR-5512, Volume 1;

2. errors found in the data tables published in NUREG/CR-5512, Volume 1; and

3. assumptions and default parameters used in the original NUREG/CR-5512 methodology that have been found to be inconsistent with the iterative screening philosophy of the methodology.

This appendix documents these problems and the corrections/solutions to these problems that have been implemented for Release 1.0 of DandD. Section A.2 describes equation nomenclature. Section A.3 of this report describes (1) the changes made to the equations originally published in NUREG/CR-5512, Volume 1, and (2) changes made as a result of the implementation and testing of DandD to address assumptions that resulted in inconsistencies between the intent of the NUREG/CR-5512 methodology and the originally published equations. Section A.4 identifies the corrections made to the data tables published in NUREG/ CR-5512, Volume 1, to develop the data files for the Release 1.0 of the DandD code. Changes in the default parameter values were documented in Beyeler et al., 1999.

A.2 Nomenclature

The mathematical models originally described in Volume 1 of this report involve many equations with numerous parameters. Because of the complexity of the equations, a system of nomenclature was developed to represent symbols used for the parameters. This system of nomenclature is summarized in Section 2 of Volume 1. For ease of reference to understand the changes to the mathematical formulations that are presented in this appendix, the system of nomenclature is presented here in Table A.1. The system of nomenclature includes a definition of units used to permit a full dimensional analysis.

In general, terms beginning with "D" are dose or dose rate factors; "TEDE" are annual total effective dose equivalents; "AF" are ingestion-pathway committed effective dose equivalent factors; "C" are concentrations (per unit mass, volume, or area), or total activity of a radionuclide, as appropriate; and "λ" are radioactive decay rate constants. General subscripts encountered include "i" or "j" for parent or decay-chain-member radionuclides; "s" for soil; "w" for water; and "v" for food crops (agricultural pathways).

In addition to the parameters listed in tables, a special notation is used for radioactive decay calculations. Decay operators are represented by A{}, S{}, R{}, and G{}, as defined in Appendix B of Volume 1.

A{} = Changes in parent and progeny activities or concentrations over time (i.e. radioactive decay and ingrowth).

Table A.1 Parameter Summary

Parameter	Description
A_{stj}	Concentration factor of radionuclide progeny j in soil for the current year per initial unit concentration of chain parent radionuclide in soil.
A_{wtj}	Average concentration factor of radionuclide progeny j in water for the current year per initial unit concentration of chain parent radionuclide in soil.
Af_{dj}	Committed effective dose equivalent per unit average concentration of chain member j (as a parent) in water from drinking water contaminated by radionuclide chain member.
AF_{fj}	Committed effective dose equivalent per unit average concentration of chain member j (as a parent) in water from aquatic food products contaminated by radionuclide chain member j.
AF_{fj}	Committed effective dose equivalent per unit concentration of chain member j (as a parent) in soil at the start of the growing season from agricultural products contaminated by radionuclide chain member j in soil.
AF_{wj}	Committed effective dose equivalent per unit average concentration of chain member j (as a parent) in water from agricultural products contaminated by irrigation water for radionuclide j.
C_{1j}	Total activity in box 1 of the three box groundwater model for radionuclide chain member j.
C_{2j}	Total activity in box 2 of either the three box or the multiple-layer-unsaturated-zone box groundwater model for radionuclide chain member j.
C_{3j}	Total activity in box 3 of the three box groundwater model for radionuclide chain member j.
$C_{1,n}$	Total activity in box 1 of the three box groundwater model for radionuclide chain member n.
$C_{2,n}$	Total activity in box 2 of either the three box or the multiple-layer-unsaturated-zone box groundwater model for radionuclide chain member n.
$C_{3,n}$	Total activity in box 3 of the three box groundwater model for radionuclide chain member n.
C_{kj}	Total activity in box k of the three box groundwater model for radionuclide chain member j.
C_{lj}	Total activity in box l o fthe multiple-layer-unsaturated-zone groundwater box model for radionuclide chain member j.
$C_{l-1,j}$	Total activity in box l-1 of the multiple-layer-unsaturated-zone groundwater box model for radionuclide chain member j.
$C_{l,n}$	Total activity in box l of the multiple-layer-unsaturated-zone groundwater box model for radionuclide chain member n.
$C_{m+1,j}$	Total activity in box m+1 (box immediately above the aquifer box) of the multiple-layer-unsaturated-zone groundwater box model for radionuclide chain member j.
$C_{m+2,j}$	Total activity in box m+2 (aquifer box) of the multiple-layer-unsaturated-zone groundwater box model for radionuclide chain member j.
$C_{m+2,n}$	Total activity in box m+2 (aquifer box) of the multiple-layer-unsaturated-zone groundwater box model for radionuclide chain member n.
C_{rCc}	Carbon-14 average concentration factor in forage crop at time of forage feeding resulting from resuspension and root uptake from soil for an average unit concentration of carbon-14 in ground water.

Table A.1 Parameter Summary

Parameter	Description
C_{rgCc}	Carbon-14 average concentration factor in stored grain at time of grain feeding resulting from resuspension and root uptake from soil for an average unit concentration of carbon-14 in ground water.
C_{rhCc}	Carbon-14 average concentration factor in stored hay at time of stored hay feeding resulting from resuspension and root uptake from soil for an average unit concentration of carbon-14 in ground water.
C_s	Initial activity in soil for a chain parent radionuclide.
C_{si}	Initial activity in soil for chain i parent radionuclide.
$C_{si}(0)$	Initial activity in soil for chain i parent radionuclide.
C_{swjt}	Activity concentration factor for transfer from soil to water for radionuclide chain member j at time t.
C_{ti}	Total activity in soil for chain i parent radionuclide.
C_{wfCc}	Carbon-14 concentration factor in fresh forage at time of animal consumption for unit initial concentration of carbon-14 in ground water.
C_{wfCd}	Carbon-14 concentration factor in soil at time of animal consumption for unit initial concentration of carbon-14 in ground water.
C_{wgCc}	Carbon-14 concentration factor in stored grain at time of animal consumption for unit initial concentration of carbon-14 in ground water.
C_{whCd}	Carbon-14 concentration factor in stored hay at time of animal consumption for unit initial concentration of carbon-14 in ground water.
C_{wwCc}	Carbon-14 concentration factor in water at time of animal consumption for unit initial concentration of carbon-14 in ground water.
CDG	Dust loading factor for gardening activities.
CDI	Dust loading factor for indoor exposure periods.
CDO	Dust loading factor for outdoor exposure periods.
DAR_i	Committed effective dose equivalent from ingestion of aquatic foods for radionuclide chain i.
$DEXR_i$	External dose for radionuclide chain i.
$DFER_j$	External dose rate factor for radionuclide chain member j from contamination uniformly distributed in the top 15 cm of residential soil.
DFG_j	Committed effective dose equivalent from ingestion of radionuclide chain member j.
DFH_j	Committed effective dose equivalent from inhalation of radionuclide chain member j from contaminated air.
DFO_{jo}	Committed effective dose equivalent to organ o from ingestion of radionuclide chain member j.
DGR	Committed effective dose equivalent from ingestion of home-grown food and animal products for a radionuclide chain.
DGR_i	Committed effective dose equivalent from ingestion of home-grown food and animal products for radionuclide chain i.

Table A.1 Parameter Summary

Parameter	Description
DHR_i	Committed effective dose equivalent from inhalation of airborne soil and house dust for radionuclide chain i.
DIET	Fraction of annual diet derived from home-grown foods.
DIRR	Committed effective dose equivalent from ingestion of home-grown foods and animal products produced with irrigation water for a radionuclide chain.
$DIRR_i$	Committed effective dose equivalent from ingestion of home-grown foods and animal products produced with irrigation water fro radionuclide chain i.
DSR_i	Committed effective dose equivalent from secondary ingestion of soil for radionuclide chain i.
DWR_i	Committed effective dose equivalent from ingestion of drinking water and irrigated food for radionuclide chain i (also used for committed effective dose equivalent from ingestion of drinking water for radionuclide chain member j after modification of Eqn. 5.74).
F_r	Fraction of water removed from the aquifer box that is deposited on the surface layer by irrigation.
GR	Effective transfer rate for ingestion of soil and dust transferred to the mouth during the residential scenario.
$HOCDE_i$	Highest annual organ committed dose equivalent for radionuclide chain i from ingestion of drinking water.
$HOCDE_m$	Highest annual organ committed dose equivalent for a mixture of radionuclides from ingestion of drinking water.
J_i	Number of radionuclides in decay chain for radionuclide chain i.
L_{12j}	Rate constant for movement of radionuclide j between boxes 1 and 2 in the groundwater box model.
L_{23j}	Rate constant for movement of radionuclide j between boxes 2 and 3 in the groundwater three box model.
$\dot{L}_{23j}$	Rate constant for movement of radionuclide j between boxes 2 and 3 in the multiple-layer-unsaturated-zone groundwater box model.
$\dot{L}_{l-1,j}$	Rate constant for movement of radionuclide j between boxes l-1 and 1 in the multiple-layer-unsaturated-zone groundwater box model.
$\dot{L}_{l,l+1,j}$	Rate constant for movement of radionuclide j between boxes l and l+1 in the multiple-layer-unsaturated-zone groundwater box model.
$\dot{L}_{m+1,m+2,j}$	Rate constant for movement of radionuclide j between the box immediately above the aquifer and the aquifer box in the multiple-layer-unsaturated-zone groundwater box model.
M	Number of radionuclide chains.
P_d	Floor dust loading factor for residential scenario.
PF_{sji}	Pathway transfer factor providing uptake by humans per unit concentration in soil for chain member j caused by unit activity of radionuclide chain member i.
PF_{wji}	Pathway transfer factor providing uptake by humans per unit concentration in water for chain member j caused by unit activity of radionuclide chain member i.

Table A.1 Parameter Summary

Parameter	Description
$PPTF_{awC}$	Partial pathway transfer factor of animal product for carbon-14 due to irrigation.
RF_r	Resuspension factor for indoor activity in the residential scenario.
Q_d	Soil dry weight consumption rate as a fraction of the fresh forage consumption rate.
Q_f	Consumption rate of wet weight fresh forage by animal.
Q_g	Consumption rate of wet weight stored grain by animal.
Q_h	Consumption rate of wet weight stored hay by animal.
Q_w	Consumption rate of water by animal.
$S\{A_{stj},t_{tg}\}$	Time integral of total soil activity for radionuclide chain member j over the gardening period from time t to time $t+t_{tg}$.
$S\{A_{stj},t_{tr}\}$	Time integral of soil total activity for radionuclide chain member j over the residential period from time t to time $t+t_{tr}$.
$S_{d3}\{C_{kj},t_y\}$	Time integral of drinking water scenario aquifer total activity for radionuclide chain member j over the time period t_y (one year).
SA_{TaC}	Specific activity equivalence of animal product and the specific activity of the total feed intake.
SFI	Shielding factor by which external dose rate is reduced during periods of indoor residence.
SFO	Optional shielding factor by which external dose rate is reduced during periods of outdoor residence.
$TEDED_i$	Annual total effective dose equivalent for the drinking water scenario for radionuclide chain i.
U_w	Ingestion rate of drinking water by humans.
V_{aq}	Aquifer volume.
V_g	Volumetric breathing rate for gardening activities for residential scenario.
V_{lr}	Volume of water infiltrating through contaminated area in a year for the residential scenario water-use model.
V_{dd}	Volume of water used for domestic purposes during a year of the drinking water scenario.
V_{dr}	Volume of water used for domestic purposes during a year of the residential scenario.
V_{irr}	Volume of water used for irrigation during a year of the residential scenario.
V_{Td}	Total aquifer volume for the drinking water scenario.
V_{Tr}	Total aquifer volume for the residential scenario.
V_r	Volumetric breathing rate for indoor activities for the residential scenario.
V_{sw}	Volume of water in the surface-water pond used in production of aquatic foods.
V_x	Volumetric breathing rate for outdoor activities for the residential scenario.
W_f	Factor to convert mass of fresh forage from a wet-weight to a dry-weight basis.
c_{aq}	Concentration of radionuclides in the aquifer.

Table A.1 Parameter Summary

Parameter	Description
c_{sw}	Concentration of radionuclides in the surface-water pond.
$d_{n,j}$	Fraction of radionuclide n that decays to radionuclide j.
dgr_j	Partial committed effective dose equivalent fro ingestion of home-grown food and animal products for radionuclide chain member j.
$dirr_j$	Partial committed effective dose equivalent from ingestion of home-grown food and animal products produced with irrigated water for radionuclide chain member j.
f_{Ca}	Fraction of animal product that is carbon.
f_{Cf}	Fraction of wet fresh forage that is carbon.
f_{Cd}	Fraction of dry soil that is carbon.
f_{Cg}	Fraction of wet stored grain that is carbon.
f_{Ch}	Fraction of wet stored hay that is carbon.
m	Number of boxes in the unsaturated zone in the multiple-layer-unsaturated-zone groundwater box model.
t	Time.
t_{ca}	Time period over which animal product is consumed by humans.
t_{ff}	Time period over which animal is fed fresh forage.
t_{fg}	Time period over which animal is fed stored grain.
t_{fh}	Time period over which animal is fed stored hay.
t_{fw}	Time period over which animal consumes water.
t_d	Water intake period for drinking water scenario.
t_g	Time (in 24 hour days) spent gardening for residential scenario.
t_i	Time (in 24 hour days) spent indoors for residential scenario.
t_{lg}	Length of gardening period for residential scenario.
t_{lr}	Length of time in an exposure period for the residential scenario.
t_x	Time (in 24 hour days) spent outdoors for residential scenario.
t_y	Time representing one year.
x_f	Fraction of fresh forage consumed by animals that is contaminated.
x_g	Fraction of stored grain consumed by animals that is contaminated.
x_h	Fraction of stored hay consumed by animals that is contaminated.
x_w	Fraction of water consumed by animals that is contaminated.
w_d	Groundwater removal rate constant for the drinking water scenario.
w_r	Groundwater removal rate constant for the residential scenario.

Table A.1 Parameter Summary

Parameter	Description
λ_j	Decay constant for radionuclide chain member j.

S{} = time integrals of activity or concentration.

R{} = accumulation of deposited activity over a time period.

G{} = deposition, accumulation, and time-integration of a constant deposition rate (used for deposition from irrigation water onto plants).

The operations are performed on an initial array of chain member activities or concentrations for a specific time period. For example, the decay calculation is represented as follows:

$$A\{C_\bullet, t_\bullet\}$$

where A{} = the operation of decay calculation (in appropriate units)

$C_\bullet$ = the array of chain members, activities, or concentrations (in appropriate units).

$t_\bullet$ = time period over which the decay occurs (in time units)

For additional information on nomenclature, the reader is referred to Volume 1 of this report.

A.3 Corrections and Changes to Equations

To address several concerns about the equations originally published in NUREG/CR-5512, Volume 1, and to address inconsistent assumptions in the original methodology, several model equations originally published in Volume 1 have been changed for the implementation of the methodology in DandD. The modifications are presented in the following sections. Equation numbers refer to the equation number in Volume 1. The modified version of an equation includes an "m" in the equation number. Equations from Volume 1 modified by more than one equation also have a,b,c, notation.

A.3.1 Ingestion Dose from Food Grown in Contaminated Soil

Equations 5.71 and 5.72 were modified slightly in order to perform the calculations to obtain information requested by the NRC. The NRC requested that dose be specified for each radionuclide in a chain. With the method described in NUREG/CR-5512, Volume 1, calculations are performed for an entire chain. In order to obtain dose by radionuclide, the order for double summation which would occur by combining Equations 5.71 and 5.72 had to be reversed. A matrix can be set up to perform the calculations. The matrix of calculations would look like:

$PF_{s11} * DFG_1 * A_{st1}$	0	0	--	0	$dgr_1/(C_s * DIET)$
$PF_{s21} * DFG_2 * A_{st1}$	$PF_{s22} * DFG_2 * A_{st2}$	0	--	0	$dgr_2/(C_s * DIET)$
$PF_{s31} * DFG_3 * A_{st1}$	$PF_{s32} * DFG_3 * A_{st2}$	$PF_{s33} * DFG_3 * A_{st3}$	--	0	$dgr_3/(C_s * DIET)$
--	--	--	--	0	--
$PF_{sn1} * DFG_n * A_{st1}$	$PF_{sn2} * DFG_n * A_{st2}$	$PF_{sn3} * DFG_n * A_{st3}$	--	$PF_{snn} * DFG_n * A_{stn}$	$dgr_n/(C_s * DIET)$
AF_{s1}	AF_{s2}	AF_{s3}	--	AF_{sn}	$DGR/(C_s * DIET)$

In NUREG/CR-5512, Volume 1, Equation 5.72 sums down each column to obtain the AF_{si}'s. Equation 5.71 then sums the AF_{si} terms across the bottom row to obtain DGR. In order to obtain doses by radionuclide, DandD sums along each row to obtain the dgr_j terms.

The dgr_j terms are stored for use in calculating doses by radionuclide. The column containing the dgr_j terms are then summed to obtain the DGR for the entire chain. This change was made prior to the calculations done in support of NUREG-1500.

A.3.2 Dose Due to Food Grown with Contaminated Irrigation Water

Equations 5.74 and 5.76 model the dose due to food grown with contaminated irrigation water in much the same manner as food grown in contaminated soil. (See Section A.3.8 for separation of Equation 5.74 into drinking water and irrigation components). In Volume 1, the above matrix (with PF_w substituted for PF_s, AF_w substituted for AF_s, A_{wt} substituted for A_{st}, dwr substituted for dgr, and DIRR substituted for DGR) is first summed down each column to obtain the AF_{wt} terms and then summed along the bottom row to obtain the dose due to ingestion of food grown with contaminated irrigation water, DWR, for the chain. Since the NRC wanted doses for each radionuclide in the chain, the sum was first taken along each row to obtain "$dirr_j$" for each radionuclide in the chain. The $dirr_j$ terms are stored for use in calculating doses by radionuclide. The column containing the $dirr_j$ terms is then summed to obtain the DIRR for the entire chain. This change was made prior to the calculations done in support of NUREG-1500.

A.3.3 Secondary Ingestion of Soil

Equation 5.73, which models the secondary ingestion of soil by humans, was modified to account for the time a person was actually on the contaminated site.

The original equation was:

$$DSR_i = GR\, C_{si} \sum_{j=1}^{J_i} DFG_j\, S\{A_{stj}, t_{tr}\} \qquad (5.73)$$

which was based on the assumption of a person being on the contaminated site for the entire year.

The modified equation, as implemented in DandD, is now:

$$DSR_i = GR\, C_{si}(0) \sum_{j=1}^{J_i} \left[DFG_i \left(\frac{T_i + t_s + t_g}{t_{tr}} \right) S\{A_{stj}, t_{tr}\} \right] \qquad (5.73m)$$

The $\left(\frac{t_i + t_s + t_g}{t_{tr}} \right)$ term represents the portion of the year that a person was on the site. This change was made prior to the calculations done in support of NUREG-1500.

A.3.4 Surface Water Pond Decoupling

Following the calculations for NUREG-1500 and during the development and testing of DandD, SNL staff noted that if the surface water pond was not included in a model run, doses due to ground water, most notably the drinking water portion, would increase dramatically. By removing the surface water pond, the aquifer volume decreased causing a concentrating effect on the radionuclide concentrations in the aquifer. Because the dilutive effects of the surface water pond volume were removed, higher groundwater radionuclide concentrations would result than if the surface water pond were present. In addition, removing the surface water pond also removed the aquatic food pathway. However, it was found that if the aquatic pathway was removed as a result of removing the surface water pond, total dose would increase. This did not make intuitive sense because, if pathways are removed, total dose should decrease.

To overcome this problem the surface water pond was decoupled from the aquifer. In Volume 1 the aquifer volume is based on either the amount of water withdrawn from the aquifer plus the surface water pond volume or the amount of recharge to the aquifer, whichever is greater. In addition, Volume 1 essentially sets the surface water radionuclide concentration to the same value as the aquifer radionuclide concentration. To decouple the pond from the aquifer, two modifications to the drinking water methodology were made. First, the aquifer volume depended only on amounts withdrawn from the aquifer and the amount of recharge to the aquifer and not on the surface water pond volume. Thus, Equation 5.88 was modified from:

$$= \max(V_{Ir}, V_{irr} + V_{dr} + \qquad (5.88)$$

to:

$$V_{Tr} = \max(V_{Ir}, V_{irr} + V_{dr}) \qquad (5.88m)$$

In a second modification, a model to estimate radionuclide concentration in the surface water pond was developed. The methodology presented in Volume 1 assumed an equivalent radionuclide concentration between the aquifer and the surface water pond. However, in this type of modification an equivalent concentration between the aquifer and the surface pond, while conservative, would be unreasonable. For a surface water pond larger than the aquifer, equivalent radionuclide concentrations between the aquifer and the sur-

face water pond would create additional radionuclide mass. In essence, mass would not be conserved. Another approach would be to transfer the entire radionuclide mass in the aquifer into the surface water pond. However, if the entire radionuclide mass in the aquifer were transferred to the surface pond, then the radionuclide concentration in the pond would become extremely high for small surface water ponds. It would be unreasonable for the radionuclide concentration in the surface water pond to exceed the concentration in the aquifer. A model that allowed the intermingling of water and radionuclides between the aquifer and surface water pond was developed. In this model, the radionuclide mass in the aquifer was allowed to mix instantaneously with that in the surface water pond so that radionuclide mass is conserved:

$$A_{wtj} V_{Tr} = C_{sw} (V_{Tr} + V_{sw})$$

where A_{wtj} is the concentration in the aquifer, C_{sw} is the concentration in the surface water pond, V_{Tr} is the volume of the aquifer, and V_{sw} is the volume of the surface water pond. Upon rearranging, this equation becomes:

$$C_{sw} = \frac{A_{wtj}}{(1 + V_{sw} / V_{Tr})}$$

which is the equation used by DandD to calculate the surface water pond concentration. This model not only conserves radionuclide mass, but also limits radionuclide concentration in the surface water pond so that it does not exceed the radionuclide concentration in the aquifer.

A.3.5 Water Balance Model - Drinking Water Scenario

Aquifer concentrations for the drinking water scenario (as well as for the residential scenario) are generally calculated with a three-box ground-water model. To a lesser extent the concentrations are calculated with a multiple layer unsaturated zone box ground-water model. The top box represents a soil layer generally consisting of 15 cm of soil. The middle box (or boxes in the multiple layer unsaturated zone box model) represents the unsaturated zone and models radionuclide transport through that zone. The bottom box represents the aquifer and models the radionuclide concentration in the aquifer. Infiltration enters the box model through the top of the soil layer box and transports radionuclides from the soil layer through the unsaturated zone and into the aquifer. Contaminated water is only removed from the aquifer by pumping.

Following the calculations for NUREG-1500 and during the development and testing of DandD, SNL staff observed that in cases where recharge to the aquifer box exceeds pumpage from the box, radionuclides can build up in the aquifer box. This build-up occurs because there is no mechanism for excess radionuclides to leave the box other than through pumpage. Since recharge is greater than pumpage, excess water in the aquifer box must leave the box by natural discharge. This natural discharge would carry radionuclides with it. However, the ground-water contamination models described in Volume 1 do not account for the natural discharge.

An analogy of what happens is in order. There are two cases to consider. First, let a filled bucket of water represent a box aquifer with no contamination. In the bottom of the bucket is a small hole through which water slowly drips out. The hole represents pumpage from the aquifer. At the top of the bucket is a rapidly flowing hose which is used to fill the bucket with salt water. As the salt water flows out the hose and into the bucket, two events happen: (1) the concentration of salt in the bucket increases and (2) the bucket overflows as long as water flows from the hose faster than it leaves through the hole. Logic dictates that the concentration of salt in the water in the bucket never increases above the concentration of salt in water flowing out the hose. However, the aquifer model defined in Volume 1 does not allow the bucket to overflow. The model indicates that the bucket will always remain full (i.e., the hose only flows at the rate water drips out the bottom of the bucket) but that salt is added at a rate consistent with the rapidly flowing hose. (In an extreme case, if the hole in the bottom of the bucket is sealed, the model in Volume 1 indicates that pure salt would be continuously added to the bucket. It is easy to see that the concentration of salt in the water will always increase with time). The model in Volume 1 essentially results in a rapid buildup of salt in the bucket. The concentration of salt in the bucket may then actually exceed that of salt in the rapidly flowing hose.

The second case represents the opposite of the first. The hose slowly drips salt water into the bucket and a large hole in the bottom lets water leave the bucket rapidly. In this case, the concentration of salt in the bucket increases somewhat and the bucket empties. After time there is no water in the bucket, which is analogous to the aquifer drying up. However, the model in Volume 1 keeps the bucket full but without an additional source of water to do so.

To overcome this, a ground-water water balance model has been included in the box equation governing con-

tamination in the aquifer box. The soil layer and unsaturated zone boxes also have an implicit water balance model included in them, i.e. infiltration that enters the top of the box leaves the bottom in a steady-state manner. The ground-water water balance model now includes a natural ground-water underflow recharge and discharge component, which allows radionuclides to leave the aquifer box through natural means other than pumpage and flow downgradient. In the above analogy the ground-water underflow terms account for the overflow of the bucket (first case) or the additional source of water (second case). The result is that radionuclides no longer build up in the aquifer box in an unreasonable manner.

In order to implement the water balance model, Equation 4.16 had to be modified into a simpler form than in the existing model. Equation 4.16 in NUREG/CR-5512, Volume 1, was changed from:

$$Fractional\ Removal = \frac{V_{dd}}{V_{Td}} \qquad (4.16)$$

to:

$$Fractional\ Removal = 1 \qquad (4.16m)$$

This modification, in turn, impacts Equation 4.15 in NUREG/CR-5512, Volume 1, which was changed from:

$$w_d = \left[\frac{Fractional\ Removal}{y}\right]\left[\frac{y}{365.25\,d}\right] \qquad (4.15)$$

to:

$$w_d = \frac{1}{365.25\,d} \qquad (4.15m)$$

A.3.6 Water Balance Model - Residential Scenario

Following the calculations for NUREG-1500 and during the development and testing of DandD, SNL staff observed that, for similar reasons presented under the drinking water scenario, a water balance must also be included in the residential scenario ground-water model. Several equations are impacted by the inclusion of the water balance model. Equation 5.86 in Volume 1 was changed from:

$$Fractional\ Removal = \frac{V_{irr} + V_{dr}}{V_{Tr}} \qquad (5.86)$$

to:

$$Fractional\ Removal = 1 \qquad (5.86m)$$

This modification, in turn, impacts Equation 5.85, which was changed from:

$$w_r = \left[\frac{Fractional\ Removal}{y}\right]\left[\frac{y}{365.25\,d}\right]$$

to:

$$w_r = \frac{1}{365.25\,d} \qquad (5.85m)$$

In addition, Equation 5.89, which describes the fraction of pumped water that is applied to the surface layer, was changed from:

$$F_r = \frac{V_{irr}}{(V_{irr} + V_{dr})} \qquad (5.89)$$

to:

$$F_r = \frac{V_{irr}}{V_{Tr}} \qquad (5.89m)$$

Equation 5.89m now describes the fraction of water in the aquifer that is applied to the surface layer in one year.

A.3.7 Including Initial Soil Concentration Twice in Dose Calculations

Drinking Water Scenario. In the drinking water scenario, the initial concentration of the parent radionuclide in the soil is included twice in the dose calculations. It is used once in the calculation of the ground-water concentration and again in the calculation of dose from the ground-water concentration. For the drinking water scenario, the groundwater concentration is given by Equation 4.13 in Volume 1 as:

$$C_{swtt} = \frac{1}{V_{Td}t_y}\int_0^{t_y} C_{3j}(t)\,dt = \frac{S_{j3}\{C_{kj}t_y\}}{V_{Td}t_y} \qquad (4.13)$$

The definitions of terms for Equation 4.13 in Volume 1 assigns C_{3j} the units of pCi per pCi in the soil in the above equation. However, in the development of the groundwater equations (Equations 4.1 to 4.6 in Volume 1) C_{3j} has the units of pCi. For implementation of the methodology in DandD, Equation 4.13 is used exactly as shown in Volume 1. However, the concentration terms have to be redefined from pCi per pCi in the soil to pCi; from pCi-d per pCi in the soil to pCi-d; and from pCi/L per pCi in the soil to pCi/L. This is a result of having the units of concentration terms changed in the middle of Section 4 of Volume 1.

As a result, the C_{swjt} term is based on the total concentration in the soil layer and not on a unit activity as the definitions would imply. Therefore, the units on C_{swjt} are pCi/L and not pCi/L per pCi in the soil as in NUREG/CR-5512, Volume 1. This has an impact on the drinking water dose equations (Equations 4.18, 4.21, and 4.22). In NUREG/CR-5512, Volume 1, the dose equations are based on the units of C_{swjt} being pCi/L per pCi in the soil. However, as has been shown, C_{swjt} is actually based on the initial concentration of radionuclides in the soil and not on a unit concentration of parent radionuclides. Therefore, because the dose equations contain an initial soil concentration, C_{ti}, and the C_{swjt} based on pCi, the initial concentration is included twice in the dose equations. In order to correct this, Equations 4.18, 4.21, and 4.22 were modified by dropping the C_{ti} term from the respective equations. Thus, Equation 4.18 was changed from:

$$TEDED_i = U_w t_d C_{ti} \sum_{j=1}^{J_i} C_{swjt} DFG_j \qquad (4.18)$$

to:

$$TEDED_i = U_w t_d \sum_{j=1}^{J_i} C_{swjt} DFG_j \qquad (4.18m)$$

Equation 4.21 was changed from:

$$HOCDE_i = U_w t_d C_{ti} \sum_{j-1}^{J_i} C_{swjt} DFO_{jo} \qquad (4.21)$$

to:

$$HOCDE_i = U_w t_d \sum_{j-1}^{J_i} C_{swjt} DFO_{jo} \qquad (4.21)$$

Equation 4.22 was changed from:

$$HOCDE_m = U_w t_d C_{ti} \sum_{i-1}^{M} \sum_{j-1}^{J_i} C_{swjy} DFO_{jo} \qquad (4.22)$$

to:

$$HOCDE_m = U_w t_d \sum_{i-1}^{M} \sum_{j-1}^{J_i} C_{swjt} DFO_{jo} \qquad (4.22m)$$

Residential Scenario. In a manner similar to that for the drinking water scenario described above, the dose equations for the residential scenario in Volume 1 have the initial soil concentrations included twice. The soil concentration equation, Equation 5.90, and the average ground-water concentration equation, Equation 5.92, as presented in Volume 1 both are based on the initial concentration of radionuclides in the soil layer. The definitions of terms associated with the equations indicate that the equations are based on a unit initial value concentration. Again, the units on concentration terms have been redefined in the middle of Section 5.0 of Volume 1. Taking the same approach as that for the drinking water scenario, Equations 5.90 and 5.92 are used exactly as presented in Volume 1 for implementation in DandD. This necessitates modifying the dose terms by removing the C_{si} from the dose equations, Equations 5.69, 5.70, 5.71, 5.73, 5.74, and 5.77. Thus, Equation 5.69 was changed from:

$$DEXR_i = \left[24\left(\frac{t_g}{t_{tg}}\right) SFO\, C_{si} \sum_{j=1}^{J_i} S\{A_{stj}, t_{tg}\}\, DFER_j\right] + \left[24\left(\frac{t_x}{t_{tr}}\right) SFO\, C_{si} \sum_{j=1}^{J_i} S'\{A_{stj}, t_{tr}\}\, DEFR_j\right] + \left[24\left(\frac{t_i}{t_{tr}}\right) SFI\, C_{si} \sum_{j=1}^{J_i} S'\{A_{stj}, t_{tr}\} DEFR_j\right] \qquad (5.69)$$

to:

$$DEXR_i = \left[24\left(\frac{t_g}{t_{tg}}\right) SFO \sum_{j=1}^{J_i} S\{A_{stj}, t_{tg}\}\, DFER_j\right] + \left[24\left(\frac{t_x}{t_{tr}}\right) SFO \sum_{j=1}^{J_i} S'\{A_{stj}, t_{tr}\}\, DEFR_j\right] + \left[24\left(\frac{t_i}{t_{tr}}\right) SFI \sum_{j=1}^{J_i} S'\{A_{stj}, t_{tr}\} DEFR_j\right] \qquad (5.69m)$$

Equation 5.70, which was:

$$DHR_i = \left[24\, V_g\left(\frac{t_g}{t_{tg}}\right) CDG\, C_{si} \sum_{j=1}^{J_i} S\{A_{stj}, t_{tg}\}\, DFH_j\right] + \left[24\, V_x\left(\frac{t_x}{t_{tr}}\right) CDO\, C_{si} \sum_{j=1}^{J_i} S\{A_{stj}, t_{tr}\}\, DFH_j\right] + \left[24\, V_r\left(\frac{t_i}{t_{tr}}\right)(CDI + P_d RF_r)\, C_{si} \sum_{j=1}^{J_i} S\{A_{stj}, t_{tr}\}\, DFH_j\right] \qquad (5.70)$$

becomes:

$$DHR_i = \left[24 V_g\left(\frac{t_g}{t_{tg}}\right) CDG \sum_{j=1}^{J_i} S\{A_{stj}, t_{tg}\} DFH_j\right] + \left[24 V_x\left(\frac{t_x}{t_{tr}}\right) CDO \sum_{j=1}^{J_i} S\{A_{stj}, t_{tr}\} DFH_j\right] + \left[24 V_r\left(\frac{t_r}{t_{tr}}\right)(CDI + P_d RF_r) \sum_{j=1}^{J_i} S\{A_{stj}, t_{tr}\} DFH_j\right] \quad (5.70m)$$

Equation 5.71 was changed from:

$$DGR_i = C_{si} DIET \sum_{j=1}^{J_i} A_{stj} AF_{sj} \quad (5.71)$$

to:

$$DGR_i = DIET \sum_{j=1}^{J} A_{stj} AF_{sj} \quad (5.71m)$$

Equation 5.73, including the modification noted in Section 3.3, becomes:

$$DSR_i = GR \sum_{j=1}^{J_i} DFG_i \frac{t_i + t_x + t_g}{t_{tr}} S\{A_{stj}, t_{tr}\} \quad (5.73m)$$

Equation 5.74, which was:

$$DWR_i = C_{si} \left[\sum_{j=1}^{J_i} A_{wtj} AF_{dj} - DIET \sum_{j=1}^{J_i} A_{wtj} AF_{wj}\right] \quad (5.74)$$

is now:

$$DWR_i = \sum_{j=1}^{J_i} A_{wtj} AF_{dj} + DIET \sum_{j=1}^{J_i} A_{wtj} AF_{wj} \quad (5.74m)$$

(See further modification to this equation in Section A.3.8.)

Equation 5.77 was changed from:

$$DAR_i = C_{si} \sum_{j=1}^{J_i} A_{wtj} AF_{ij} \quad (5.77)$$

to:

$$DAR_i = \sum_{j=1}^{J_i} A_{wtj} AF_{ij} \quad (5.77m)$$

A.3.8 Separation of Irrigation and Drinking Water Dose Equation into Components

At the request of the NRC, the equation for irrigation and drinking water dose for the residential scenario, Equation 5.74, was separated into its two components so that a separate drinking water dose could be calculated. There are now an equation for the drinking water dose and an equation for the irrigation water dose. The drinking water dose equation, including the correction mentioned in Section A.2.7 for Equation 5.74, is:

$$DWR_i = \sum_{j=1}^{J_i} A_{wtj} AF_{dj} \quad (5.74)$$

The equation for the irrigation dose, including the correction mentioned above for Equation 5.74 is:

$$DIRR_i = DIET \sum_{j=1}^{J_i} A_{wtj} AF_{wj} \quad (5.74m)$$

where $DIRR_i$ is the dose due to irrigation for the ith chain.

A.3.9 Multiple Layering in the Unsaturated Zone

The capability to model multiple layers in the unsaturated zone has been added to DandD. This capability can increase the response time for radionuclides deposited at land surface to show in the aquifer over the response time for a single layer unsaturated zone. In Volume 1 the original equation for the soil layer box (box 1), Equation 5.80, for the residential scenario ground-water model (adding commas to separate the subscript, in the discussion that follows) was:

$$\frac{dC_{1,j}}{dt} = \lambda_j \sum_{n=1}^{j-1} d_{n,j} C_{1,n} - \left(L_{12,j} + \lambda_j\right) C_{1,j} + F_r w_r C_{3,j} \quad (5.80)$$

For the multiple layering case, this equation now becomes:

$$\frac{dC_{1,j}}{dt} = \lambda_j \sum_{n=1}^{j-1} [d_{n,j} C_{1,n} - (L_{12,j} + \lambda_j) C_{1,j} + F_r w_r C_{m+2,j}] \quad (5.80m)$$

where m is the number of layers in the unsaturated zone.

The original equation for the unsaturated zone, Equation 5.82, was:

$$\frac{dC_{2,j}}{dt} = \lambda_j \sum_{n=1}^{j-1} [d_{n,j} C_{2,n} + L_{12,j} C_{1,j} - (L_{23,j} + \lambda_j) C_{2,j}] \quad (5.82)$$

It is now replaced with two equations. The first one describes the transport from the soil layer to the top layer in the unsaturated zone. It is given by:

$$\frac{dC_{2,j}}{dt} = \lambda_j \sum_{n=1}^{j-1} [d_{n,j} C_{2,n} + L_{12,j} C_{1,j} - (\acute{L}_{23,j} + \lambda_j) C_{2,j}] \quad (5.82ma)$$

where

$$\acute{L}_{23} = mL_{23j} \quad (5.82mb)$$

The second equation, which describes transport among the remaining boxes in the unsaturated zone, is given by:

$$\frac{dC_{1,j}}{dt} = \lambda_j \sum_{n=1}^{j-1} [d_{n,j} C_{1,n} + \acute{L}_{l-1,1,j} C_{e-1,j} - (\acute{L}_{l,l+1,j} + \lambda_j) C_{l,j}] \quad (5.82mc)$$

where l ranges from 3 to m+1, and

$$\acute{L}_{l-1,1,j} = mL_{23j} \quad (5.82md)$$

The equation describing transport in the aquifer box (box 3), Equation 5.84, has been changed from:

$$\frac{dC_{3,j}}{dt} = \lambda_j \sum_{n=1}^{j-1} [d_{n,j} C_{3,n} + L_{23,j} C_{2,j} - (w_r + \lambda_j) C_{3,j}] \quad (5.84)$$

to:

$$\frac{dC_{m+2,j}}{dt} = \lambda_j \sum_{n=1}^{j-1} [d_{n,j} C_{m+2,n} + \acute{L}_{m+1,m+2,j} C_{m+1,j} - (w_r + \lambda_j) C_{(3j)m+j}] \quad (5.84m)$$

The above equations are valid for the drinking water scenario by setting F_r to zero and replacing w_r with w_d.

A.3.10 Addition of Root Uptake and Resuspension to the C-14 in Water Special Model

Equation C.3 of NUREG/CR-5512, which calculates the partial pathway transfer factor from water to animals ($PPTF_{aw}$), does not include a root uptake/resuspension term. Equation C.3 was modified to include this term. Thus, Equation C.3 was modified from:

$$PPTF_{awC} = [f_{Ca}(Q_f x_f C_{wfCc} t_{ff} + Q_d W_f Q_f x_f C_{wfCd} t_{ff} + Q_g x_g C_{wgCc} t_{fg} + Q_h x_h C_{whCc} t_{fh} + Q_w x_w C_{wwCc} t_{fw}) t_{ca} SA_{tac}] / [(f_{Cf} Q_f t_{ff} + f_{Cd} Q_d W_f Q_f t_{ff} + f_{Cg} Q_g t_{fg} + f_{Ch} Q_h t_{fh}) 365.25] \quad (C.3)$$

to:

$$PPTF_{awC} = [f_{Ca}(Q_f x_f (C_{wfCc} + C_{rfCc}) t_{ff} + Q_d W_f Q_f x_f C_{wfCd} t_{ff} + Q_g x_g (C_{wgCc} + C_{rgCc}) t_{fg} + Q_h x_h (C_{whCc} + C_{rhCc}) t_{fh} + Q_w x_w C_{wwCc} t_{fw}) t_{ca} SA_{tac}] / [(f_{Cf} Q_f t_{ff} + f_{Cd} Q_d W_f Q_f t_{ff} + f_{Cg} Q_g t_{fg} + f_{Ch} Q_h t_{fh}) 365.25] \quad (C.3m)$$

where C_{rfCc}, C_{rhCc}, and C_{rgCc} are the resuspension/root uptake terms defined by Equations 5.47, 5.52, and 5.57 of NUREG/CR-5512.

A.3.11 Modification of the Irrigation Rate Parameter

The parameter IR is defined in Chapter 5 of NUREG/CR-5512 as the annual average irrigation rate and is used that way in the groundwater model. This same parameter is used to calculate the rate of deposition of radionuclides onto plants and soil. Actually, radionuclide deposition occurs only during the growing period of the particular plant. Because irrigation will only realistically occur during the growing period of the plant, the use of an annual average irrigation rate to the plant underestimates the deposition of groundwater and, hence, radionuclides to the plant surfaces and soils. The amount withdrawn for irrigation during a

year is actually withdrawn over the growing period of the plant. Therefore, the rate of irrigation over the plant growing period is much higher than the average rate over the year. Each plant type considered (food crops, forage, hay, and grain) has the same annual average irrigation rate IR. For each plant type, irrigation occurs only during its growing period. In each case, the rate of deposition of radionuclides due to irrigation should be increased from its current value by a factor of $365.25/t_{growth}$, where t_{growth} is the plant growing period. This modification entails changes to the way the R_w terms are calculated in Equations 5.22, 5.27, 5.37, 5.43, 5.48, 5.50, 5.53, 5.55, 5.58, and D.8. Thus, the following modifications were made to those equations:

- Edible plant Equations 5.22 and 5.27 were multiplied by the factor $(365.25/t_{ev})$ for each edible plant type.
- Forage feeding Equations 5.37 and 5.43 were multiplied by the factor $(365.25/t_{ff})$ for each animal type, assuming that the feeding period of forage was the same as the growing period of forage.
- The hay Equations 5.48 and 5.50 were multiplied by the factor $(365.25/t_{gh})$ for each animal type.
- The grain Equations 5.53 and 5.55 were multiplied by the factor $(365.25/t_{gh})$ for each animal type.
- The soil consumption Equation 5.58 was multiplied by the factor $(365.25/t_{ff})$ for each animal type, assuming that the feeding period of forage and, hence, soil was the same as the growing period of forage.
- The special tritium model for soil consumption Equation D.8 was multiplied by the factor $(365.25/t_{ff})$ for each animal type, which is actually a special case of Equation 5.58 for long-lived radionuclides.

The parameters t_{ff}, t_{gg}, t_{gh}, and t_{ev} are the times for feeding on forage, time to grow grain, time to grow hay, and the time to grow edible plants, respectively. These changes are also incorporated into the special C-14 model.

A.3.12 Corrections to Equations

In a number of the pathway equations specified in the Volume 1 report, environmental concentration equations are multiplied by $C_{i1}(0)$, the initial activity of the parent radionuclide. This multiplication was intended to correct a normalization to $C_{i1}(0)$. However, in several equations (e.g., Equations. 4.13, 5.90, and 5.92) the normalization was omitted in the equations published in Volume 1. The effect of this is that the equations in the Volume 1 document contain a spurious factor of $C_{i1}(0)$. For the methodology implemented in DandD, unnormalized versions of the equations were implemented, so the current equations represent a correct implementation of the methodology.

A.4 Corrections and Changes to Data Tables in Volume 1

Several data files are used by the various scenarios in DandD. These files, a description of the data contained in the files, the scenarios for which the data are used, and table numbers from Volume 1 where the data were originally referenced are presented in Table A.2. After the completion of the NUREG-1500 calculations, the following data files referenced in Table A.2 were modified: BIOACCUM.TXT, CEDE.TXT, CHAIN.TXT, ORGAN1.TXT, ORGAN2.TXT, and ORGAN3.TXT. The primary reason for the modifications were errors and incomplete chain descriptions in Table E.1 of Volume 1. This resulted in extensive revisions, modifications, and additions to the CHAIN.TXT file. As a result of additions to CHAIN.TXT, some new radionuclides were introduced into the modeling process. Some or all of these new radionuclides were not included in the versions of these data files used for the

Table A.2 NUREG/CR-5512 Data Descriptions

Data File Name	Data Description	Scenario	NUREG/CR-5512, Volume 1 Table
BIOACCUM.TXT	Fish bioaccumulation data	Residential	Table 6.19
CARBON.TXT	Carbon data for the C-14 model.	Residential	Table 6.24

Table A.2 NUREG/CR-5512 Data Descriptions

Data File Name	Data Description	Scenario	NUREG/CR-5512, Volume 1 Table
CEDE.TXT	Internal committed effective dose equivalent and external effective dose equivalent factors.	Renovation Occupancy Drinking Water Residential	Table E.2
CHAIN.TXT	Radioactive decay data and decay chain specifications.	Renovation Occupancy Drinking Water Residential	Table E.1
CONCEN.TXT	Soil-to-plant concentration factors	Residential	Table 6.16
DW.TXT	Drinking water scenario parameters	Drinking Water	Table 6.22
TRITIUM.TXT	Hydrogen data used for the tritium model	Residential	Table 6.25
KD.TXT	Partition coefficients for water use model	Residential Drinking Water	Table 6.7
OCC.TXT	Building occupancy and scenario parameters	Occupancy	Table 6.21
ORGAN1.TXT	Ingestion organ dose equivalent factors for organ set 1.	Drinking Water	Table E.3
ORGAN2.TXT	Ingestion organ dose equivalent factors for organ set 2.	Drinking Water	Table E.4
ORGAN3.TXT	Ingestion organ dose equivalent factors for organ set 3.	Drinking Water	Table E.5
REN.TXT	Building renovation scenario parameters	Renovation	Table 6.20
RES.TXT	Residential scenario parameters	Residential	Table 6.23
TRANSFER.TXT	Animal product transfer factors	Residential	Table 6.18

NUREG-1500 calculations. The bioaccumulation factors, internal and external committed effective dose equivalents, and organ dose equivalent factors for the new radionuclides had to be added to the respective data files.

A.4.1 Changes to the CHAIN.TXT File

The CHAIN.TXT file for DandD implements Table E.1 from Volume 1, in the DandD code. Reviews of the chain decay data file, CHAIN.TXT, used for the NUREG-1500 calculations indicated that many decay chains were incomplete. Some chains were missing as many as 12 radionuclides. The decay chains as presented in Table E.1 of Volume 1 were compared to the source document from which they were derived (ICRP, 1983). The review of Table E.1 of Volume 1 consisted of the following items:

(1) Confirmation that they were listed correctly, if a parent radionuclide has progeny. Note: progeny are implicit, and are to be listed without half life if they meet the following criteria: they have half life less than 9 hours and their half life is less than one-tenth of the parent's.

(2) Confirmation that the transformation fractions were listed correctly, if a parent radionuclide has progeny.

(3) Confirmation that the position listed in the chain was correct.

(4) Confirmation that no implicit progeny were listed

explicitly, and that no explicit progeny were listed as implicit.

To determine the correctness of the decay chains, the full decay chains were redeveloped using ICRP Publication 38 (1983). All decay chains corrections were checked twice independently.

The review did not examine whether a parent belonged in the list, nor did the review look at all possible parents that might have been included. It was assumed that the no parent nuclides needed to be added to those listed in Table E.1 were agreed to by NRC for the original NUREG/CR-5512 methodology of Volume 1. However, note that some very short-lived radionuclides were included as parents (e.g., 115mIn is implicit in some chains, but it is also a parent).

A.4.2 Changes to BIOACCUM.TXT

The DandD data file BIOACCUM.TXT was modified to include bioaccumulation data for the element Xe. Since Xe is a gas, it is assigned the same bioaccumulation value (0.0) as other gases in the data file.

A.4.3 Changes to CEDE.TXT

The additions to this file show the inclusion of committed effective dose equivalent factors for 103mRh, 115In, 123Te, 131mXe, 133Xe, 133mXe, 135Xe, 152Gd, and 218At. These were new radionuclides that appeared after the CHAIN.TXT file was corrected. After comparison of the CHAIN.TXT file with the decay chains presented in the ICRP document [1983], the decay fraction value for 214Pb was changed from 1.0000 to 0.9998.

A.5 References

Beyeler, W.E., W.A. Hareland, F.A. Duran, T.J. Brown, E. Kalinina, D.P. Gallegos, and P.A. Davis, 1999. "Residual Radioactive Contamination From Decommissioning, Parameter Analysis, Draft Report for Comment," Sandia National Laboratories, NUREG/CR-5512, Volume 3, October 1999.

Daily, M.C., A Huffert, F. Cardile, and J.C. Malaro, 1994. Working Draft Regulatory Guide on Release Criteria for Decommissioning: NRC Staff's Draft for Comment, NUREG-1500, U.S. Nuclear Regulatory Commission, Washington, DC.

ICRP, 1983. Radionuclide Transformations-Energy and Intensity of Emissions, Vol. 11-13, International Commission on Radiological Protection, Publication 38, Pergamon Press, New York, NY.

Kennedy, Jr., W.E., and D.L. Strenge, 1992. Residual Radioactive Contamination From Decommissioning: Technical Basis for Translating Contamination Levels to Annual Effective Dose Equivalent, Vol. 1, NUREG/CR-5512, PNL-7994, U.S. Nuclear Regulatory Commission, Washington, DC.

APPENDIX B SAMPLE PROBLEMS

B.1 Introduction

Running through a sample problem will help the user become familiar with the program and confirm that DandD is producing the same results as the documented sample problems. For instructions on running a sample problem, see Section 3.2.

The facilities described in the sample problems were taken from the *Draft Generic Environmental Impact Statement in Support of Rulemaking on Radiological Criteria for Decommissioning of NRC-Licensed Nuclear Facilities* (NRC, 1994). The baseline sample problems assume the standard methodology presented in Kennedy and Strenge (1992) as modified by Wernig et al. (1999, Appendix A) and default probability distributions and respective parameters listed in Beyeler et al. (1999). Additional sample problems that go beyond the defaults are also included and contain a brief discussion of how the changes affect the results. All of the sample problems only include the residential scenario because it exercises all exposure pathways and is the most complex. The output option in the "Add Contaminants" window was set so that implicit progeny doses were combined with their respective parent doses. The results for some problems do not show a table for the radionuclide component of the total dose because there are no progeny for the parent radionuclide.

The following sample problems are for illustrative purposes only and may not represent good examples for license termination applications. For example, the user should be aware that deselecting a pathway without modifying any other parameters may be nonconservative. This is because the effect of deselecting a pathway only deactivates the associated dose calculation; it does not eliminate radionuclide transport. The user should keep this in mind when applying DandD 2.1 to license termination analyses.

B.2 Reference Facilities

The sample problems use reference facilities considered to be sufficiently representative of facilities licensed by NRC. They are divided into fuel cycle and non-fuel-cycle groups. A brief description of each type of facility is provided along with the parameters needed to set up the sample problems for the DandD software and the results that were calculated.

Fuel cycle facilities include:

- power reactors
- non-power (research and test) reactors
- uranium fuel fabrication plants
- uranium hexafluoride conversion facilities
- uranium mills
- independent spent fuel storage installations (ISFSI)

Non-fuel-cycle facilities include:

- sealed source manufacturers
- research and development laboratories
- rare metal refineries

B.3 Nuclear Fuel Cycle Facilities

Nuclear fuel cycle facilities are those facilities involved in any of the steps leading to or resulting from the generation of electricity by controlled nuclear fission of uranium. The nuclear fuel cycle process consists of several steps in which uranium ore is processed into fuel elements. The facilities involved in these steps include uranium mills, uranium hexafluoride conversion plants, enrichment plants, and uranium fuel fabrication plants. The next step in the fuel cycle is the generation of electricity by nuclear power plants. The end of the fuel cycle consists of steps in which fuel removed from the reactor is stored and then disposed of in some manner. The facility considered in this step is ISFSI.

B.3.1 Nuclear Power Reactors

There are two major types of nuclear power reactors in the United States; pressurized water reactors (PWRs) and boiling water reactors (BWRs). The analysis described in Appendix C of NRC (1994) indicates that, within the common variations of contamination levels in nuclear power plants, the contaminants and contamination of a PWR approximate the levels for a BWR. Therefore, the reference power reactor in this case is a large PWR (1095 Mwe). The reference power reactor comprises five major structures: the reactor containment, the auxiliary building, the fuel handling building, the turbine building, and the control building. For the reference facility, it is assumed that there are areas of contaminated soil resulting from on-site spills.

The sample problem file names for this group are preceded by "NPP" and the contaminants consist of ^{60}Co, ^{90}Sr, and ^{137}Cs with initial activities of 1 pCi/gram. The results shown are for the residential scenario only.

B.3.1.1 NPP Baseline Sample Problem

This sample problem is set up by selecting the three radionuclides shown below and using all default probability distributions and parameters.

Selected Radionuclides	Initial Activity
^{60}Co	1 pCi/gram
^{90}Sr	1 pCi/gram
^{137}Cs	1 pCi/gram

Results (see Tables B.1 and B.2):

There is a 90% chance that a total effective dose equivalent (TEDE) of 2.22E+01 mrem with a 95% confidence interval from 2.02E+01 mrem to 2.88E+01 mrem will not be exceeded within 1000 years after license termination.

Table B.1. Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the NPP Sample Problem

Pathway	TEDE (mrem)
External	7.67E+00
Inhalation	4.29E-04
Agricultural	2.05E+01
Secondary Ingestion	3.20E-03
Drinking Water	2.14E-13
Irrigation	6.84E-13
Surface Water	218E-13
All	2.88+01

Table B.2 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the NPP Sample Problem

Radionuclide	TEDE (mrem)
^{60}Co	6.69E+00
^{90}Sr	1.96E-01
^{90}Y	9.75E-01
^{137}Cs	2.34E+00
All	2.88E-001

B.3.1.2 NPP1 Contamination Under a House

This sample problem assumes that all the contamination lies directly under a 2000 ft^2 house and turns off all pathways except for external exposure inside the house, soil ingestion inside the house, and inhalation inside the house.

This sample problem is set up by deselecting the Agricultural, Drinking Water, Irrigation, and Surface Water pathway doses from the "Edit Exposure Pathway" button under the "Residential" tab.

The selected radionuclides are the same as in the NPP baseline sample problem and are shown below.

Selected Radionuclides	Initial Activity
^{60}Co	1 pCi/gram
^{90}Sr	1 pCi/gram
^{137}Cs	1 pCi/gram

The following parameters were changed to constants:

Time Outdoors	0.0000	days/year
Time Gardening	0.0000	days/year
Cultivated Area	186.000	m^2

These parameters are changed by clicking on the "General Parameters" button under the "Residential" tab.

The bases for the changes in the above default parameters are as follows:

- The Time Outdoors is set to zero on the assumption that when a person is outdoors, they are not exposed to contamination because the contaminated area is under the house.
- The Time Gardening is set to zero because there is no contamination present in the garden.
- The area is based upon a 2000 ft^2 (186 m^2) house.

Results (see Tables B.3 and B.4):

There is a 90% chance that a TEDE of 5.79E+00 mrem with a 95% confidence interval from 5.79E+00 mrem to 5.79E+00 mrem will not be exceeded within 1000 years after license termination.

B.3.1.3 NPP2 Contamination in the Garden

This sample problem assumes that the contamination is only in the garden. Therefore:

- The Time Indoors is set to zero to turn off exposure from inside the house.
- The Time Outdoors assumes that a person has the same behavior as in the default case and spends 104.44 days spread over 3800 m^2 of ground, but

only 4.89% of that time is spent on contaminated ground: 40.2* 186/3800 = 1.97.

Table B.3 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the NPP1 Sample Problem

Pathway	TEDE (mrem)
External	5.78E+00
Inhalation	2.34E-04
Agricultural	0.00E+00
Secondary Ingestion	2.71E-03
Drinking Water	0.00E+00
Irrigation	0.00E+00
Surface Water	0.00E+00
All	5.79E+00

Table B.4 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the NPP1 Sample Problem

Radionuclide	TEDE (mrem)
^{60}Co	4.67E+00
^{90}Sr	2.14E-03
^{90}Y	8.15E-03
^{137}Cs	1.10E+00
All	5.79E+00

- The area is based upon a 2000 ft^2 (186m^2) garden.
- The diet parameters are proportionately scaled against the default site area of 3800 m^2 as follows:

Diet-Leafy	21.4* 186/3800 = 1.05	
Diet-Roots	44.6* 186/3800 = 2.18	
Diet-Fruit	52.8* 186/3800 = 2.58	
Diet-Grain	14.4* 186/3800 = 0.705	
Diet-Beef	39.8* 186/3800 = 1.95	
Diet-Poultry	25.3* 186/3800 = 1.24	
Diet-Leafy	233.* 186/3800 = 11.4	
Diet-Leafy	19.1* 186/3800 = 0.935	

Selected Radionuclides	Initial Activity
^{60}Co	1 pCi/gram
^{90}Sr	1 pCi/gram
^{137}Cs	1 pCi/gram

This sample problem is set up by selecting the three radionuclides specified above and changing the following parameters:

Time Indoors	0.0000	days/year
Time Outdoors	5.1121	days/year
Cultivated Area	186.000	m^2
Diet-Leafy	1.05	kg/y
Diet-Roots	2.18	kg/y
Diet-Fruit	2.58	kg/y
Diet-Grain	0.705	kg/y
Diet-Beef	1.95	kg/y
Diet-Poultry	1.24	kg/y
Diet-Milk	11.4	L/y
Diet-Egg	0.935	kg/y

Results (see Tables B.5 and B.6):

There is a 90% chance that a TEDE of 9.94E-01 mrem with a 95% confidence interval from 8.93E-01 mrem to 1.25E+00 mrem will not be exceeded within 1000 years after license termination.

Table B.5 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the NPP2 Sample Problem

Pathway	TEDE (mrem)
External	2.19E-01
Inhalation	1.24E-04
Agricultural	1.00E+00
Secondary Ingestion	5.52E-05
Drinking Water	1.41E-10
Irrigation	2.70E-11
Surface Water	2.73E-10
All	1.25E+00

Table B.6 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the NPP2 Sample Problem

Radionuclide	TEDE (mrem)
^{60}Co	2.02E-001
^{90}Sr	9.58E-001
^{90}Y	5.34E-002
^{137}Cs	8.52E-02
All	1.25E+00

B.3.2 Non-Power Reactors

Non-power reactors are generally divided into two classes; research reactors and test reactors. The reference research reactor is considered to be a 1 mW nuclear training and research facility. The facility is made up of a reactor tank, a core structure, and a TRIGA-type control system.

The reference research reactor comprises these major structures:

- reactor building–housing the reactor and support area
- annex–housing a hot laboratory and hot cell
- heat exchanger building–housing a water purification system, water pumping systems, and an air compressor system
- pump house–housing a liquid waste retention tank
- cooling tower

Test reactors are larger facilities than research reactors and the reference test reactor considered is a 60-mW test reactor, light-water moderated and cooled, used in testing materials for certain applications. The system is made up principally of the test reactor vessel (containing the nuclear core and experimental beam tubes) and the reactor water recirculation system.

The reference test reactor comprises these major structures:

- reactor building–housing the test reactor
- hot laboratory building
- primary pump house
- office and laboratory building–housing radiochemistry laboratories
- fan house–housing ventilation systems and waste ion exchangers and filters
- hot retention area–holding waste tanks
- waste handling building

B.3.2.1 Research Reactor

The sample problem file names for this group are preceded by "RR" and the contaminants consist of ^{60}Co, ^{90}Sr, and ^{137}Cs with initial activities of 1 pCi/gram. The baseline sample problem for the research reactor is the same as the one used for the power reactor in Section B.3.1.1 and will not be included here. The results shown are for the residential scenario only.

B.3.2.1.1 RR1 Contamination Under a House

This sample problem is comparable to the sample problem in Section B.3.1.2, except the area of contamination is smaller (.25 * 186 m^2 = 46.5 m^2) and the time spent indoors is therefore reduced to 60.0 (240 * .25) days per year. The change in the time indoors assumes that a person spends 240 days spread over the 2000 ft^2 house but that only 25% of the time is on contaminated ground because of the smaller contaminated area.

Selected Radionuclides	Initial Activity
^{60}Co	1 pCi/gram
^{90}Sr	1 pCi/gram
^{137}Cs	1 pCi/gram

This sample problem is set up by selecting the three radionuclides specified above and changing the following parameters:

Time Indoors	60.0	days/year
Time Outdoors	0.0	days/year
Time Gardening	0.0	days/year
Cultivated Area	46.5	m^2

Doses from human consumption of food and water are eliminated by deselecting the Agricultural, Drinking Water, Irrigation, and Surface Water pathway doses.

Results (see Tables B.7 and B.8):

There is a 90% chance that a TEDE of 1.45E+00 mrem with a 95% confidence interval from 1.45E+00 mrem to 1.45E+00 mrem will not be exceeded within 1000 years after license termination.

Table B.7 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the RR1 Sample Problem

Pathway	TEDE (mrem)
External	1.45E+00
Inhalation	5.84E-05
Agricultural	0.00E+00
Secondary Ingestion	6.78E-04
Drinking Water	0.00E+00
Irrigation	0.00E+00
Surface Water	0.00E+00
All	1.45E+00

Table B.8 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the RR1 Sample Problem

Radionuclide	TEDE (mrem)
^{60}Co	1.17E+00
^{90}Sr	5.35E-004
^{90}Y	2.04E-003
^{137}Cs	2.76E-001
Total	1.45E+000

B.3.2.1.2 RR2 Contamination in the Garden

This sample problem assumes that the contamination is only in the garden and is comparable to the sample problem in B.3.1.3 except the area of contamination is smaller (46.5 m^2), which was used to scale the time outdoors and the diet parameters.

This sample problem is set up by selecting the three radionuclides specified below:

Selected Radionuclides	Initial Activity
^{60}Co	1 pCi/gram
^{90}Sr	1 pCi/gram
^{137}Cs	1 pCi/gram

The following parameters were changed:

Time Indoors	0.0000	days/year
Time Outdoors	0.492	days/year
Cultivated Area	46.5	m^2
Diet-Leafy	0.262	kg/y
Diet-Roots	0.546	kg/y
Diet-Fruit	0.646	kg/y
Diet-Grain	0.176	kg/y
Diet-Beef	0.487	kg/y
Diet-Poultry	0.310	kg/y
Diet-Milk	2.85	L/y
Diet-Egg	0.234	kg/y

Results (see Tables B.9 and B.10):

There is a 90% chance that a TEDE of 3.57E-01 mrem with a 95% confidence interval from 3.11E-01 mrem to 4.54E-01 mrem will not be exceeded within 1000 years after license termination.

Table B.9 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the RR2 Sample Problem

Pathway	TEDE (mrem)
External	1.54E-01
Inhalation	1.23E-04
Agricultural	2.13E-01
Secondary Ingestion	3.85E-05
Drinking Water	2.12E-01
Irrigation	6.74E-03
Surface Water	5.84E-01
All	4.54E-01

B.3.2.2 Test Reactor

The sample problem file names for this group are preceded by "TR" and the contaminants consist of ^{60}Co, ^{90}Sr, and ^{137}Cs with initial activities of 1 pCi/gram. The baseline sample problem for the test reactor is the same as the one used for the power reactor in Section B.3.1.1 and will not be included here. The results shown are for the residential scenario only and have the Combine Progeny switch turned on.

Table B.10 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the RR2 Sample Problem

Radionuclide	TEDE (mrem)
^{60}Co	1.33E-01
^{90}Sr	3.37E-01
^{90}Y	2.01E-02
^{137}Cs	3.92E-02
All	4.54E-01

B.3.2.2.1 TR1 Contamination Under a House

This sample problem is comparable to the sample problem in Section B.3.1.2 except that the area of contamination is larger (465 m^2 or 5000 ft^2). This is larger than the default house but smaller than the default area, which assumes that there is contamination under the entire house with 3000 ft^2 (279m^2) left over to contaminate the garden. The default parameters are changed as shown below based on a 279 m^2 contaminated area and a 3800 m^2 default area:

Selected Radionuclides	Initial Activity
^{60}Co	1 pCi/gram
^{90}Sr	1 pCi/gram
^{137}Cs	1 pCi/gram

The following parameters were changed:

Time Outdoors	2.95	days/year
Cultivated Area	465.0	m^2
Diet-Leafy	1.57	kg/y
Diet-Roots	3.27	kg/y
Diet-Fruit	3.88	kg/y
Diet-Grain	1.06	kg/y
Diet-Beef	2.92	kg/y
Diet-Poultry	1.86	kg/y
Diet-Milk	17.1	L/y
Diet-Egg	1.40	kg/y

Results (see Tables B.11 and B.12):

There is a 90% chance that a TEDE of 7.12E+00 mrem with a 95% confidence interval from 6.97E+00 mrem to 7.60E+00 mrem will not be exceeded within 1000 years after license termination.

B.3.2.2.2 TR2 Garden Contamination

This sample problem assumes that the contamination is only in the garden and is comparable to the sample problem in Section B.3.1.3 except that the area of

Table B.11 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the TR1 Sample Problem

Pathway	TEDE (mrem)
External	6.05E+00
Inhalation	3.17E-04
Agricultural	1.50E+00
Secondary Ingestion	2.78E-03
Drinking Water	1.54E-13
Irrigation	3.61E-14
Surface Water	6.62E-14
All	7.60E+00

Table B.12 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the TR1 Sample Problem

Radionuclide	TEDE (mrem)
^{60}Co	4.92E+00
^{90}Sr	1.44E+00
^{90}Y	7.93E-02
^{137}Cs	1.22E+00
All	7.60E+00

contamination is larger (465 m^2). The default parameters are changed based on a default area of 3800 m^2 as shown below:

Selected Radionuclides	Initial Activity
^{60}Co	1 pCi/gram
^{90}Sr	1 pCi/gram
^{137}Cs	1 pCi/gram

The following parameters were changed:

Time Indoors	0.0	days/year
Time Outdoors	4.92	days/year
Cultivated Area	465.0	m^2
Diet-Leafy	2.62	kg/y
Diet-Roots	5.46	kg/y
Diet-Fruit	6.46	kg/y
Diet-Grain	1.76	kg/y
Diet-Beef	4.87	kg/y
Diet-Poultry	3.10	kg/y
Diet-Milk	28.5	L/y
Diet-Egg	2.34	kg/y

Results (see Tables B.13 and B.14):

There is a 90% chance that a TEDE of 2.29E+00 mrem with a 95% confidence interval from 1.95E+00 mrem to 2.93E+00 mrem will not be exceeded within 1000 years after license termination.

Table B.13 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the TR2 Sample Problem

Pathway	TEDE (mrem)
External	3.48E-01
Inhalation	1.26E-04
Agricultural	2.51E+00
Secondary Ingestion	8.86E-05
Drinking Water	2.15E-10
Irrigation	1.03E-10
Surface Water	6.28E-10
All	2.93E+00

Table B.14 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the TR2 Sample Problem

Radionuclide	TEDE (mrem)
^{60}Co	3.42E-01
^{90}Sr	2.39E+00
^{90}Y	1.18E-01
^{137}Cs	1.76E-01
All	9.07E+00

B.3.3 Uranium Fuel Fabrication Plants

A uranium fuel fabrication plant (U-fab plant) is a facility in which enriched uranium, received as uranium hexafluoride (UF_6), is converted to UO_2 and formed into fuel pellets that are inserted into fuel rods. These fuel rods are, in turn, assembled into fuel bundles. The reference fuel manufacturing plant consists of five potentially contaminated buildings, including the fuel manufacturing building, the chemical manufacturing laboratory, the uranium scrap recovery room, the contaminated waste incinerator, and the fluoride and nitrate waste treatment plant. Operation of the reference facility is assumed to result in areas of contaminated soil on the site. The principal contaminant in the buildings and soils is uranium. The files for this sample problem have the prefix UFFP.

B.3.3.1 U_Nat Baseline Sample Problem

This sample problem is set up by selecting the U_Nat (natural uranium) radionuclide and using all default probability distributions and parameters. The results shown are for the residential scenario only.

Selected Radionuclides	Initial Activity
U_Nat	1 pCi/gram

Results (see Tables B.15 and B.16):

There is a 90% chance that a TEDE of 2.17E+00 mrem with a 95% confidence interval from 1.26E+00 mrem to 3.83E+00 mrem will not be exceeded within 1000 years after license termination.

Table B.15 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the UFFP Sample Problem

Pathway	TEDE (mrem)
External	3.74E-02
Inhalation	3.51E-02
Agricultural	1.16E+00
Secondary Ingestion	3.90E-03
Drinking Water	7.62E-01
Irrigation	1.82E+00
Surface Water	8.66E-01
All	3.83E+00

Table B.16 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the UFFP Sample Problem

Radionuclide	TEDE (mrem)
^{234}U	1.89E+00
^{230}Th	4.51E-04
^{226}Ra	5.87E-05
^{222}Rn	7.81E-05
^{210}Pb	1.61E-03
^{210}Bi	1.24E-06
^{210}Po	1.04E-03
^{235}U	8.33E-02
^{231}Th	5.75E-04
^{231}Pa	7.91E-03
^{227}Ac	2.21E-03
^{227}Th	8.87E-06
^{223}Ra	1.20E-04
^{238}U	1.70E+00
^{234}Th	1.08E-01
All	3.83E+00

B.3.4 Uranium Hexafluoride Plants

The function of a uranium hexafluoride (UF_6) conversion plant is to convert uranium concentrates, received from various uranium mills, to the purified uranium hexafluoride that is used as the feed material for the enrichment of ^{235}U. Buildings or site areas associated with the reference UF_6 plant include processing buildings, including warehouse and storage areas of normal industrial construction with heavy concrete floors to support equipment, a series of on-site retention ponds for storage of process raffinates and sanitary wastes, and a burial area for disposal of defunct equipment.

Operation of the reference facility is assumed to result in areas of contaminated soil on the site. The principal contaminant in the buildings and in soils is uranium. The U_Nat baseline sample problem for this facility is the same as the Uranium Fuel Fabrication Plant in Section B.3.3.1. Additional baseline sample problems for the ^{230}Th and ^{226}Ra radionuclides are included below. The files for these sample problems are preceded with UHP.

B.3.4.1 ^{230}Th Baseline Sample Problem

This sample problem is set up by selecting the ^{230}Th radionuclide and using all default probability distributions and parameters.

Selected Radionuclides	Initial Activity
^{230}Th	1 pCi/gram

Results (see Tables B.17 and B.18):

There is a 90% chance that a TEDE of 1.40E+01 mrem with a 95% confidence interval from 1.28E+01 mrem to 1.55E+01 mrem will not be exceeded within 1000 years after license termination.

Table B.17 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the UHP1 Sample Problem

Pathway	TEDE (mrem)
External	1.61E+00
Inhalation	8.21E-02
Agricultural	1.29E+01
Secondary Ingestion	4.86E-02
Drinking Water	5.29E-01
Irrigation	8.23E-01
Surface Water	1.47E+00
All	1.55E+01

Table B.18 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the UHP1 Sample Problem

Radionuclide	TEDE (mrem)
^{230}Th	1.93E+00
^{226}Ra	1.50E+00
^{222}Rn	1.60E+00
^{210}Pb	7.32E+00
^{210}Bi	9.16E-03
^{210}Po	2.90E+00
All	1.55E+01

B.3.4.2 ^{226}Ra Baseline Sample Problem

This sample problem is set up by selecting the ^{226}Ra radionuclide and using all default probability distributions and parameters.

Selected Radionuclides	Initial Activity
^{226}Ra	1 pCi/gram

Results (see Tables B.19 and B.20):

There is a 90% chance that a TEDE of 3.53E+01 mrem with a 95% confidence interval from 3.36E+01 mrem to 3.71E+01 mrem will not be exceeded within 1000 years after license termination.

Table B.19 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the UHP2 Sample Problem

Pathway	TEDE (mrem)
External	4.63E+00
Inhalation	9.61E-03
Agricultural	3.22E+01
Secondary Ingestion	1.13E-01
Drinking Water	1.63E-05
Irrigation	2.25E-05
Surface Water	1.36E-04
All	3.71E+01

B.3.5 Uranium Mill Facilities

The two most common methods of mining and uranium milling operations are conventional removal and processing and in situ leach mining. The reference case is for conventional mining and the scope is limited to the uranium mill buildings and the immediate lands surrounding the mill buildings.

Table B.20 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the UHP2 Sample Problem

Radionuclide	TEDE (mrem)
^{226}Ra	4.45E+00
^{222}Rn	4.35E+00
^{210}Pb	2.03E+01
^{210}Bi	2.55E-02
^{210}Po	8.52E+00
Total	3.71E+01

A *model* (or reference) uranium mill is described in Section 5 of NUREG-0706, *Final GEIS on Uranium Milling* (NRC, 1980c). At that model mill, ore is brought to the mill in trucks and is stored on ore pads, usually occupying an area of about 1.3 acres. Yellowcake produced in the mill is shipped by truck in 55-gallon drums. The product purity is 90% U_3O_8.

The baseline sample problem for this facility is the same as the Uranium Fuel Fabrication Plant in Section B.3.3.1 (U_Nat Baseline Sample problem).

B.3.6 Independent Spent Fuel Storage Installations

An ISFSI is a facility for handling and storing irradiated spent fuel assemblies from nuclear power reactors until they can be permanently disposed of as high-level waste. The two basic design categories of ISFSIs are wet storage and dry storage. The design of the wet storage ISFSI is similar to that of reactor spent fuel storage pools, except that the storage capacity is significantly greater. Dry storage ISFSIs take several different forms; the four basic types considered here are drywell storage, silo storage, vault storage, and cask storage. These dry storage designs depend on air currents, heat dissipation in the soil, and metal heat transfer fins for cooling the fuel.

A dry ISFSI is used as the reference facility because it represents the current designs in use. Although the major structures and areas of a dry ISFSI vary with the type of design, the reference dry ISFSI consists of three reinforced open air concrete pads on which the vertical sealed metal casks are placed. The contaminants, ^{60}Co and ^{137}Cs, are similar to those used for the research reactor in Section B.3.2.1 but they are not combined for this sample problem. The files for these sample problems are preceded by ISFSI.

B.3.6.1 ^{60}Co Baseline Sample problem

This sample problem is set up by selecting the ^{60}Co radionuclide and using all default probability distributions and parameters.

Selected Radionuclides	Initial Activity
^{60}Co	1 pCi/gram

Results (see Table B.21):

There is a 90% chance that a TEDE of 6.60E+00 mrem with a 95% confidence interval from 6.55E+00 mrem to 6.68E+00 mrem will not be exceeded within 1000 years after license termination.

Table B.21 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the ISFSI1 Sample Problem

Pathway	TEDE (mrem)
External	6.20E+00
Inhalation	7.42E-05
Agricultural	4.84E-01
Secondary Ingestion	3.57E-04
Drinking Water	1.60E-18
Irrigation	7.54E-18
Surface Water	1.10E-17
All	6.68E+00

B.3.6.2 ^{137}Cs Baseline Sample Problem

This sample problem is set up by selecting the ^{137}Cs radionuclide and using all default parameters.

Selected Radionuclides	Initial Activity
^{137}Cs	1 pCi/gram

Results (see Table B.22):

There is a 90% chance that a TEDE of 2.20E+00 mrem with a 95% confidence interval from 2.14E+00 mrem to 2.30E+00 mrem will not be exceeded within 1000 years after license termination.

B.4 Non-Fuel-Cycle Nuclear Facilities

Non-fuel-cycle facilities handle byproduct, source, and/or special nuclear materials that are not involved in the production of electric power. These non-fuel-cycle facilities must be licensed by the NRC or the Agreement States.

Table B.22 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the ISFSI2 Sample Problem

Pathway	TEDE (mrem)
External	1.46E+00
Inhalation	9.31E-06
Agricultural	8.24E-01
Secondary Ingestion	6.99E-04
Drinking Water	5.17E-21
Irrigation	2.67E-20
Surface Water	2.25E-19
All	2.30E+00

Non-fuel-cycle facilities comprise a variety of different facilities with widely varying levels of contamination. These materials licensees include universities, medical institutions, radioactive source manufacturers, and companies that use radioisotopes for industrial or analytical purposes. Certain types, such as radioactive source manufacturers, radiopharmaceutical producers, and radioactive ore processors conduct operations that could result in substantial radioactive contamination in portions of the facility. Broad Research and Development (R&D) facilities also use isotopes in a way that could potentially produce contamination requiring decommissioning activities. About 75% of NRC's 7,000 materials licensees use either sealed radioactive sources or small amounts of short-lived radioactive materials in their business operations.

B.4.1 Sealed Sources

B.4.1.1 Sealed Source Users

A sealed source is defined in 10 CFR Part 30 as any byproduct material that is encased in a capsule designed to prevent leakage or escape of the byproduct material. Sealed source users are licensed under 10 CFR Parts 30, 33, and 35 and include medical users of sealed sources (teletherapy, brachytherapy), users of industrial gauges, well loggers, radiographers, and irradiators. Nuclides contained in the capsules and used by sealed source users include ^{60}Co, ^{137}Cs, ^{125}I, ^{192}Ir, ^{90}Sr, and ^{241}Am. The sealed sources are designed and tested according to the requirements of industrial standards and radiation safety criteria set out in the regulations to prevent leakage.

B.4.1.2 Sealed Source Manufacturers

Sealed sources are manufactured for such uses as reference standards, moisture probes, quality control instruments, therapy units, and smoke detectors. The sealed source manufacturing process is carried out in buildings that contain a number of small laboratories, each of which is devoted to a specific process and/or isotope. Each laboratory contains one or more hoods, glove boxes, and/or hot cells. Alpha and beta emitters are plated on platinum, stainless steel, or aluminized mylar film and mounted in aluminum rings to form standard disc sources. Liquid gamma sources are sealed in plastic or glass vials, and solid gamma sources are mounted in rods or plastic discs. Depending on the exposure potential of the isotope being handled, the materials are handled in hoods, glove boxes, or hot cells, which have controlled ventilation systems.

The major radionuclides considered for this facility include ^{60}Co, ^{137}Cs, ^{125}I, ^{192}Ir, ^{90}Sr, and ^{241}Am. The baseline sample problems for ^{60}Co and ^{137}Cs are the same ones used for the ISFSI facility in Section B.3.6 and will not be included here.

B.4.1.3 ^{125}I Baseline Sample problem

This sample problem is set up by selecting the ^{125}I radionuclide and using all default probability distributions and parameters.

Selected Radionuclides	Initial Activity
^{125}I	1 pCi/gram

Results (see Table B.23):

There is a 90% chance that a TEDE of 2.30E-01 mrem with a 95% confidence interval from 1.70E-01 mrem to 3.25E-01 mrem will not be exceeded within 1000 years after license termination.

B.4.1.4 ^{192}Ir Baseline Sample Problem

This sample problem is set up by selecting the ^{192}Ir radionuclide and using all default probability distributions and parameters.

Selected Radionuclides	Initial Activity
^{192}Ir	1 pCi/gram

Table B.23 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the SSU1 Sample Problem

Pathway	TEDE (mrem)
External	1.94E-03
Inhalation	2.36E-06
Agricultural	2.63E-01
Secondary Ingestion	1.27E-04
Drinking Water	4.96E-10
Irrigation	1.48E-09
Surface Water	5.46E-09
Total	3.25E-01

Results (see Table B.24):

There is a 90% chance that a TEDE of 6.05E-01 mrem with a 95% confidence interval from 6.06E-01 mrem to 6.05E-01 mrem will not be exceeded within 1000 years after license termination.

Table B.24 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the SSU2 Sample Problem

Pathway	TEDE (mrem)
External	6.02E-01
Inhalation	3.27E-06
Agricultural.	3.29E-03
Secondary Ingestion	2.30E-05
Drinking Water	1.91E-18
Irrigation	1.01E-18
Surface Water	8.17E-19
All	6.05E-01

B.4.1.5 ^{90}Sr Baseline Sample Problem

This sample problem is set up by selecting the ^{90}Sr radionuclide and using all default probability distributions and parameters.

Selected Radionuclides	Initial Activity
^{90}Sr	1 pCi/gram

Results (see Tables B.25 and B.26):

There is a 90% chance that a TEDE of 1.40E+01 mrem with a 95% confidence interval from 1.19E+01 mrem to 2.08E+01 mrem will not be exceeded within 1000 years after license termination.

Table B.25 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the SSU3 Sample Problem

Pathway	TEDE (mrem)
External	1.10E-02
Inhalation	3.81E-04
Agricultural.	1.67E+01
Secondary Ingestion	2.14E-03
Drinking Water	2.34E-12
Irrigation	4.72E-12
Surface Water	2.71E-12
All	2.08E+01

Table B.26 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the SSU3 Sample Problem

Radionuclide	TEDE (mrem)
^{90}Sr	1.96E+01
^{90}Y	1.21E+00
All	2.08E+01

B.4.1.6 ^{241}Am Baseline Sample Problem

This sample problem is set up by selecting the ^{241}Am radionuclide and using all default probability distributions and parameters.

Selected Radionuclides	Initial Activity
^{241}Am	1 pCi/gram

Results (see Tables B.27 and B.28):

There is a 90% chance that a TEDE of 1.18E+00 mrem with a 95% confidence interval from 1.10E+00 mrem to 1.39E+00 mrem will not be exceeded within 1000 years after license termination.

B.4.2 Short-Lived Radionuclides

Licensees using short-lived byproduct radionuclides are licensed under 10 CFR Parts 30, 33, and 35 and use short-lived nuclides for specific reasons, primarily in the area of medical diagnostics. Short-lived nuclides licensed for such use include ^{99m}Tc, ^{131}I, and ^{123}I.

Table B.27 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the SSU4 Sample Problem

Pathway	TEDE (mrem)
External	2.13E-02
Inhalation	1.35E-01
Agricultural.	1.17E+01
Secondary Ingestion	5.15E-02
Drinking Water	1.64E+00
Irrigation	2.70E+00
Surface Water	8.58E+00
All	1.39E+01

Table B.28 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the SSU4 Sample Problem

Radionuclide	TEDE (mrem)
^{241}Am	1.39E+01
^{237}Np	1.63E-03
^{233}Pa	7.60E-07
^{233}U	5.65E-10
^{229}Th	5.32E-12
^{225}Ra	5.69E-13
^{225}Ac	3.28E-13
Total	1.39E+01

B.4.2.1 Generic R&D Facilities

R&D facilities using radioactive materials cover an extremely broad range of activities, including laboratories or health treatment facilities that use radioisotopes. University or industrial chemistry and physics laboratories use radioisotopes in basic experiments, and biological laboratories use them to investigate absorption and metabolic phenomena. These laboratories, in general, present no decommissioning problems because the isotopes used are short-lived and of low activity. Medical facilities, such as hospitals and clinics, also use radioisotopes for various medical purposes. These uses include both radiation exposure from sealed sources and injections of short-lived isotopes.

Contaminated areas associated with the reference R&D facility include laboratory floor and wall areas and storage areas. It is assumed that operation of the facility results in some soil contamination on the site.

The baseline sample problems include the ^{99m}Tc and ^{131}I radionuclides. File associated with these sample problems are preceded with "SLN."

B.4.2.2 ^{99m}Tc Baseline Sample Problem

This sample problem is set up by selecting the ^{99m}Tc radionuclide and using all default probability distributions and parameters.

Selected Radionuclides	Initial Activity
^{99m}Tc	1 pCi/gram

Results (see Tables B.29 and B.30):

There is a 90% chance that a TEDE of 2.79E-04 mrem with a 95% confidence interval from 2.78E-04 mrem to 2.79E-04 mrem will not be exceeded within 1000 years after license termination.

Table B.29 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the SLN1 Sample Problem

Pathway	TEDE (mrem)
External	2.76E-004
Inhalation	1.52E-11
Agricultural	3.10E-06
Secondary Ingestion	8.72E-10
Drinking Water	1.75E-17
Irrigation	1.81E-16
Surface Water	5.72E-18
All	2.79E-04

Table B.30 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the SLN1 Sample Problem

Radionuclide	TEDE (mrem)
^{99m}Tc	2.79E-04
^{99}Tc	5.22E-09
All	2.79E-04

B.4.2.3 ^{131}I Baseline Sample Problem

This sample problem is set up by selecting the ^{131}I radionuclide and using all default probability distributions and parameters.

Selected Radionuclides	Initial Activity
^{131}I	1 pCi/gram

Results (see Tables B.31 and B.32):

There is a 90% chance that a TEDE of 6.28E-02 mrem with a 95% confidence interval from 5.51E-02 mrem to 7.14E-02 mrem will not be exceeded within 1000 years after license termination.

Table B.31 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the SLN2 Sample Problem

Pathway	TEDE (mrem)
External	3.25E-02
Inhalation	4.92E-07
Agricultural	3.89E-02
Secondary Ingestion	2.40E-05
Drinking Water	2.92E-17
Irrigation	2.87E-17
Surface Water	3.15E-16
All	7.14E-02

Table B.32 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the SLN2 Sample Problem

Radionuclide	TEDE (mrem)
^{131}I	7.14E-02
^{131m}Xe	4.02E-06
All	7.14E-02

B.4.3 Rare-Metal Ore Processors

A rare-metals ore processor is a facility, not part of the fuel cycle, that refines raw ore materials to recover rare metals such as tantalum and niobium. These ores can contain appreciable concentrations of radionuclides, such as uranium and thorium, which are found in the waste tailings of the refining process. The NRC licenses such facilities principally to regulate the handling of these waste tailings. While relatively few such facilities operate in the United States, the volumes of tailings are sufficient to require a significant decommissioning effort.

The raw material can be a slag produced by smelters. The slag can consist of glassy flakes or tin pellets containing 0.1 to 0.5 wt% U_3O_8 and ThO_2. In one building, the slag is ground, roasted, and digested with hydrofluoric acid. The hydrofluoric acid is passed to a facility for the chemical extraction of the rare metals, such as niobium and tantalum.

The reference rare metal ore processor is a plant that refines raw ore materials for the recovery of rare metals such as tantalum and niobium. The raw ores can contain appreciable quantities of uranium and thorium, which are waste tailings of the refining process.

Contaminated facilities and areas associated with the reference rare metal ore processor include:

- buildings in which slag is processed and the rare metals are extracted,
- settling ponds on site that contain the tailings from the metal extraction process, and that contain essentially all of the radioactivity (the pond is assumed to be unlined at the reference rare metal ore processor, although it may be lined at newer facilities),
- a slag pile containing solid wastes from the extraction process.

It is assumed that operation of the facility results in soil contamination on the site. The U_Nat baseline sample problem for this facility is the same as for the Uranium Fuel Fabrication Plant in Section B.3.3.1. An additional baseline sample problem for the ^{232}Th radionuclide in equilibrium is shown here. The files associated with this sample problem is preceded with "RMOP."

B.4.3.1 ^{232}Th+C Baseline Sample Problem

This sample problem is set up by selecting the ^{232}Th+C radionuclide and using all default probability distributions and parameters. The "Calculation option for +C radionuclides" option on the "Add Contaminants" screen is set to "Do not distribute."

Selected Radionuclides	Initial Activity
^{232}Th+C	1 pCi/gram

Results (see Tables B.33 and B.34):

There is a 90% chance that a TEDE of 2.30E+01 mrem with a 95% confidence interval from 2.24E+01 mrem to 2.59E+01 mrem will not be exceeded within 1000 years after license termination.

Table B.33 Upper Limit of the 95% Confidence Interval of the Pathway Component of All Maximum Annual Doses for the RMOP Sample Problem

Pathway	TEDE (mrem)
External	6.53E+00
Inhalation	6.65E-01
Agricultural	1.67E+01
Secondary Ingestion	7.05E-02
Drinking Water	8.63E-09
Irrigation	1.39E-08
Surface Water	1.28E-08
All	2.59E+01

Table B.34 Upper Limit of the 95% Confidence Interval of the Radionuclide Component of All Maximum Annual Doses for the RMOP Sample Problem The "Calculation option for +C radionuclides" option on the "Add Contaminants" screen is set to "Do not distribute."

Radionuclide	TEDE (mrem)
^{232}Th	1.04E+01
^{228}Ra	7.76E+00
^{228}Th	1.53E+00
^{224}Ra	1.44E+00
^{212}Pb	4.15E+00
All	2.59E+01

B.5 References

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APPENDIX C FORMAT OF IMPORT CONCENTRATION FILE

The residential scenario includes the ability to import concentrations calculated by other modeling codes to compute doses. To use this capability, an import concentration data file is required for inputting soil and groundwater radioactivity concentrations. This appendix (Table C.1) describes the format for the concentration input files. Table C.2 provides an example import concentration file.

The first record in the file tells how many chains will be in the input file and is followed by two more groups of records. The second group gives the number and description of the radionuclides for each chain. The third group contains the time step values and the concentration data associated with each time step.

Table C.1 Residential Scenario Import Concentration File Format

Record	Description
Group 1:	Number of Chains
Record:	Number of radionuclide chains that will be imported.
Format:	Free-format integer: Valid values are 1 - 50.
Description:	The number of chains in the scenario. A description of each individual chain must be provided in the Radionuclide Description group of records following this record (one group per chain).
Comment:	The number of chains must be less than or equal to 50. If not, the results may be undefined. For the purpose of importing concentrations, the natural uranium (U-Nat) chain must be broken into its components and, therefore, counts as three chains.
Error Messages:	• Premature end of file reached reading number of chain records in import concentration file: The file has no data in it. • Error reading number of chain records in import concentration file: Input/Output system error. An error number will be shown that allows support personnel to determine the cause of the problem. If an error code of 6101 is encountered, an invalid integer (such as text) was entered. • Number of chains in import concentration file exceeds maximum allowable (50): This number must be less than or equal to 50.
Group 2:	Radionuclide Descriptions
Record 1:	Number of explicit radionuclides in this chain.
Format:	Free-form integer; valid values are 1 - 50.
Description:	The number of explicit radionuclides in this chain including the parent radionuclide. This number determines the number of explicit Radionuclide Name records immediately following this record.
Comment:	The number of explicit radionuclides must be less than or equal to 50. Do not include any implicit radionuclides associated with this chain.
Record 2:	Name of the explicit radionuclide.
Format:	Six characters, alphanumeric, in columns 1 through 6.

Table C.1 Residential Scenario Import Concentration File Format

Record	Description
Description:	Explicit radionuclide name. There must be one record for each explicit radionuclide in the chain. For example, if there are seven explicit radionuclides in the chain, there must be seven records of this type.
Comment:	The order and number of explicit radionuclides in this description must comply exactly with the chain descriptions in the Radioactive Decay Data tables (see Section 4.3.8). The code compares this description with the one presented in the table and, if there are any discrepancies, the code will abort the run and issue an error message.
Error Messages:	• Premature end of file reached reading names of explicit radionuclides in chain: The file is truncated too soon. • Error reading names of explicit radionuclides in chain: Input/Output system error. An error number will be shown that allows support personnel to determine the cause of the problem. • Radionuclide name is not a valid radionuclide name: The code was unsuccessful in comparing the radionuclide name entered with.
Group 2 is repeated until all chain descriptions have been entered.	
Group 3:	Concentration Description.
Record 1:	Time of Interest
Description:	The Time of Interest is the time at which the imported concentrations were calculated and at which time the subsequent dose results will be calculated. The input must be in days.
Record 2:	Residential soil and groundwater concentrations.
Format:	Free-format, floating point, one pair of variables per record, separated by a space.
Description:	The first variable is the soil concentration in pCi/g for the radionuclides described in Group 2, above, at the beginning of the Time of Interest. The second variable is the average groundwater concentration in pCi/L of the same radionuclide over a one-year time frame beginning with the Time of Interest.
Comment:	This record is repeated for each radionuclide described in Group 2, above. In Table C.2, there are three chains with 7, 6, and 9 radionuclides in each chain respectively. Therefore, there must be 22 (7 + 6 + 9) records of this type for each time step. The order of presentation of the concentrations must comply with the order presented in Group 2. The code has no way to check if the concentrations are in the correct order. Therefore, caution must be used in the order and number of these concentration records.
Group 3 is repeated as many times as necessary. The code will read Group 3 records until the scenario end time given in the Residential Basic Parameters is reached or an end-of-file condition is reached. A sample file is shown that includes four time steps for the natural uranium chain. Do not include the description shown in parentheses in an actual input file.	

Table C.2 Example File for Importing Concentrations for the U_Nat Chain (U234, U235, U238)

Value	Value	Comments
3		(Number of Chains)
7		(Number of Radionuclides in chain 1)
234U		(Radionuclide Names for chain 1)
230Th		
226Ra		
222Rn		
210Pb		
210Bi		
210Po		
6		(Number of Radionuclides in chain 2)
235U		(Radionuclide Names for chain 2)
231Th		
231Pa		
227Ac		
227Th		
223Ra		
9		(Number of Radionuclides in chain 3)
238U		(Radionuclide Names for chain 3)
234Th		
234U		
230Th		
226Ra		
222Rn		
210Pb		
210Bi		
210Po		
0.000000000000000		(Time of Interest)
0.000000000000000	0.247522757808938D-009	(Concentrations)
0.000000000000000	0.484858183517552D-015	
0.000000000000000	0.396815555468826D-019	
0.000000000000000	0.189522392289388D-017	
0.000000000000000	0.114417255157419D-019	
0.000000000000000	0.103885438401388D-019	
0.000000000000000	0.247829211431455D-020	
0.000000000000000	0.113891077868471D-010	
0.000000000000000	0.112124311179322D-010	
0.000000000000000	0.528562229862447D-016	
0.000000000000000	0.317236495338320D-018	
0.000000000000000	0.218981181517277D-018	
0.000000000000000	0.177312704861995D-018	
0.000000000000000	0.247523276052333D-009	
0.000000000000000	0.179475815505557D-009	
0.000000000000000	0.366644216333686D-015	
0.000000000000000	0.554102623933457D-021	
0.000000000000000	0.330316344522203D-025	
0.000000000000000	0.118831796675130D-023	
0.000000000000000	0.000000000000000	
0.000000000000000	0.000000000000000	
0.000000000000000	0.387340435476567D-024	
365.250000000000		(Time of Interest)
0.685469165302906D-009	0.134741024908478D-008	(Concentrations)

Table C.2 Example File for Importing Concentrations for the U_Nat Chain (U234, U235, U238)

Value	Value	Comments
0.175871147027935D-014	0.495362899770729D-014	
0.180111318876507D-018	0.776131599674565D-018	
0.630573744828938D-017	0.174234077170609D-016	
0.477334332848322D-019	0.188000175498888D-018	
0.441835648737467D-019	0.178169650961613D-018	
0.123247502921888D-019	0.664865553040717D-019	
0.315400817560165D-010	0.619976830856126D-010	
0.311885356501322D-010	0.614777022667660D-010	
0.192885440984453D-015	0.548391965969810D-015	
0.144706730419307D-017	0.629031681703798D-017	
0.106100397269115D-017	0.507338766497242D-017	
0.894389208483707D-018	0.456388539794910D-017	
0.685471110732884D-009	0.134741631416726D-008	
0.539059448934161D-009	0.112433606659562D-008	
0.148840725562149D-014	0.511011675415349D-014	
0.276333981176464D-020	0.146035126829713D-019	
0.000000000000000	0.177935345835221D-023	
0.464827012918598D-023	0.253708387955905D-022	
0.000000000000000	0.274573361685459D-024	
0.000000000000000	0.421344011293412D-024	
0.000000000000000	0.172359583696953D-024	
730.500000000000		(Time of Interest)
0.206879336191261D-008	0.285187089665718D-008	(Concentrations)
0.903777804491166D-014	0.145081994022596D-013	
0.169366852946708D-017	0.331261541522632D-017	
0.326728487233615D-016	0.575680706015900D-016	
0.407145837169490D-018	0.835776321078462D-018	
0.388745850894128D-018	0.803567262443758D-018	
0.159893738089962D-018	0.367820596468893D-018	
0.951904187751751D-010	0.131222001499207D-009	
0.945051445996075D-010	0.130377562981958D-009	
0.100528461620271D-014	0.162396085407654D-014	
0.137743262380402D-016	0.270814455674890D-016	
0.114419666828799D-016	0.231249634432062D-016	
0.104923428582542D-016	0.215971076532749D-016	
0.206880510481380D-008	0.285189150527488D-008	
0.177048526051827D-008	0.248112032955631D-008	
0.102389493906991D-013	0.185035180403758D-013	
0.344371423650410D-019	0.749019946800425D-019	
0.496419537842190D-023	0.135319565732186D-022	
0.619363558574050D-022	0.150151780226801D-021	
0.625908757379270D-024	0.175685216656883D-023	
0.573455698477810D-024	0.164872343100813D-023	
0.245519978623145D-024	0.682968925414381D-024	
1095.75000000000		(Time of Interest)
0.364671423177404D-008	0.444454267854206D-008	(Concentrations)
0.204720606482233D-013	0.270903875440447D-01	
0.527880440156510D-017	0.787895755091530D-017	
0.879295903899320D-016	0.130412336018944D-015	
0.139407830043134D-017	0.225891066434437D-017	
0.134514657550422D-017	0.218692384046246D-017	

Table C.2 Example File for Importing Concentrations for the U_Nat Chain (U234, U235, U238)

Value	Value	Comments
0.650941479418464D-018	0.111951764593952D-017	
0.167795027852860D-009	0.204505545609364D-009	
0.166794414137780D-009	0.203354588605064D-009	
0.230237188616761D-014	0.306465073296225D-014	
0.433096232478005D-016	0.649656442895449D-016	
0.375113673072341D-016	0.569570227737363D-016	
0.353629674552019D-016	0.541436534350816D-016	
0.364674528108021D-008	0.444458720426173D-008	
0.320488262938123D-008	0.393428619996491D-008	
0.283336250978395D-013	0.411984665622026D-013	
0.127318200099534D-018	0.205208884640300D-018	
0.258386353915024D-022	0.474492466919941D-022	
0.275567255043353D-021	0.501436105729973D-021	
0.356620193728023D-023	0.721972314186154D-023	
0.340581445167568D-023	0.695579766118310D-023	
0.145960036701288D-023	0.319243681886171D-023	

APPENDIX D DandD DATABASE TABLE DESCRIPTIONS

D.1 Introduction

The input and output of DandD are saved in a Microsoft® Access® database. This appendix describes the tables and fields in this database.

When a new session is created, a copy of the database InitVBASession.mdb is created. This database will have an extension of mcd (Monte Carlo DandD); for example, "session.mcd."

The tables in the database are identified by a three-character prefix. These are as follows.

Prefix	Meaning
app	Tables used by application. These tables are only modified by the programming staff. They contain initialization constants and default values.
bld	Tables containing data for the building scenario. These tables can be modified by the user indirectly through the DandD interface.
dat	Tables created as a result of the model runs.
err	Tables generated by Latin Hypercube Sampling (LHS) or scenario models containing error details.
par	Tables output from LHS.
res	Tables containing data for the residential scenario. These tables can be modified by the user indirectly through the DandD interface.
sen	Tables related to sensitivity analysis.
usr	General session settings.

Input to the dose model program takes on many characteristics. In most cases, the user can specify the input as probability distributions or constants.

General parameter data will always be fed to the modeling code. The user will have the option to modify this data from within the graphical interface. Within the residential model, this data is also grouped in categories such as Basic, Growing Period, etc. (15 categories total).

Data associated with contaminants will also be input to the modeling code. The user will be able to add contaminants, modify the area associated with a contaminant, and input the concentration of the contaminant.

Each nuclide additionally has decay or daughter products. Each daughter product has parameters associated with it in the residential model. The user will be able to modify these parameters also.

All of the user-modifiable data has been stored in the database in tables, as discussed in Section D.2.

D.2 Table Descriptions

D.2.1 Application Tables (app tables)

appAuxCHAIN, appCHAIN

This is a list of decay or daughter nuclide data that is used by the dose model program. This data will be accessible to the user for viewing as a table. This table contains constants that cannot be changed by the user.

Most of the information on the nuclides is in the *appChain* table. However, some extra decay data that is used only by the user interface is stored in the *appAuxChain* table. These tables have an identical structure. The user interface unites these tables to define the element parameters for any contaminant. The underlying modeling software only uses table *appChain*.

The table *appAuxChain* was initially designed because of the special case introduced for U_Nat and Th_Nat. These two elements have many associated element parameters, but the interface requires that this information is not present in the *appChain* table. It is required that all entries in table *appAuxChain* not have values equal for [Parent] and [Radionuclide]. Since each [Parent] will have an entry where [Parent] and [Radionuclide] fields are equal, this particular record will be in the *appChain* table.

From this table, all daughter nuclides in the decay chain can be accessed. The decay products, or daughters, are found by looking up records based on the value of the field [Parent]. The source contaminants are found in the *appCandC_Decode* table.

The user will input the contaminants. The DandD software will then find the decay products in the *appChain* table and offer the user the ability to modify data related to these daughter product contaminants.

[RecordID]	is an index used to order the table records.
[Parent]	refers to the original contaminant, not the immediate parent in the decay chain.
[Radionuclide]	is a by-product in the decay chain of [Parent].
[HalfLife]	is the half-life of [Radionuclide].
[PositionInChain]	is the number of decay generations from [Parent]. A radionuclide directly descended from [Parent] will have a value of 2 for [PositionInChain]. If [Parent] and [Radionuclide] are equal, then [PositionInChain] will be equal to one.
[FirstParentIndex]	indicates which radionuclide in the chain is the immediate parent of this nuclide.
[FirstParentFraction]	is the fraction of decays of the first parent that produce [Radionuclide].
[SecondParentIndex]	indicates alternate radionuclide that can decay to [Radionuclide].
[SecondParentFraction]	is the fraction of decays of the second parent that produces [Radionuclide].
[AtomicNumber]	is the number of protons in the [Radionuclide].

Example:

RecordID	**Parent**	**Radionuclide**	**HalfLife**	**PositionInChain**
303	228Ra	228Ra	2.10E+03	1
304	228Ra	228Ac		
305	228Ra	228Th	6.99E+02	2
306	228Ra	224Ra	3.66E+00	3
307	228Ra	220Rn		
308	228Ra	216Po		
309	228Ra	212Pb	4.43E-01	4
310	228Ra	212Bi		
311	228Ra	212Po		

FirstParentIndex	FirstParentFraction	SecondParentIndex	SecondParentFraction
1	1.00		
1	1.00	0	0.00
2	1.00	0	0.00
3	1.00		
3	1.00		
3	1.00	0	0.00
4	1.00		
4	0.64		

AtomicNumber
88
89
90
88
82

appBldCorrelations, appResCorrelations

These tables define the default Spearman (rank) correlation coefficients between pairs of parameters. Table *appResCorrelations* and *appBldCorrelations* contain the default correlation coefficients for the residential and building occupancy scenarios, respectively. If two parameters do not have an entry in the *appResCorrelations* or *appBldCorrelations* tables, then the default correlation coefficient is assumed to be zero for the appropriate scenario. This means that the parameters are statistically independent.

[ParameterID1] identifies one of the pair of correlated parameters.
[ParameterID2] identifies the other correlated parameter.
[Correlation] is the correlation coefficient between the ranks of the parameter values, between -1 and 1 inclusive.

The following integrity rules should be followed for this table:
[ParameterID1] must be strictly less than [ParameterID2].
[ParameterID1, ParameterID2] are also a key for each of these tables. In other words, the ordered pair [ParameterID1, ParameterID2] is unique for the given table.

Example:

ParameterID1	ParameterID2	Correlation
84	85	-0.49
85	86	-0.49
84	86	-0.49

appCandC_Decode

This is a list of possible nuclide contaminants and corresponding keys used to identify them in the dose model program. This table contains constants that cannot be changed by the user.

[SourceNumber] is used to identify contaminants. This number is passed to the dose model program to communicate the presence of a contaminant.

[Source] identifies the contaminant. It is prefixed by the atomic weight.

[ElementID] identifies the chemical element for the nuclide.

[HasElement] indicates that element-dependent parameters are associated with the nuclide.

Example:

SourceNumber	Source	ElementID	HasElement
62	101Tc	Tc	Yes

appCEDE

This is a list of nuclide data that is used by the dose model program. This table contains constants that cannot be changed by the user.

[Parent]	is the name of the parent radionuclide.
[Radionuclide]	is the name of the radionuclide.
[ImplicitProgenyFraction]	is the fraction of parent transitions that produce this radionuclide.
[Ingestion]	is the unit committed effective dose equivalent (CEDE) conversion factor for ingestion.
[Inhalation]	is the unit CEDE conversion factor for inhalation.
[ExternalSurface]	is the unit CEDE conversion factor for external surface exposure.
[External15cm]	is the unit CEDE conversion factor for external exposure at 15 cm.

Example:

Parent	Radionuclide	ImplicitProgenyFraction	Ingestion	Inhalation	ExternalSurface
240U	240U		1.20E-09	6.13E-10	3.65E-13
240U	240mNp	1.00	0.00E+00	0.00E+00	2.82E-11

External15cm
6.58E-16
8.20E-13

appCHAIN: see *appAuxChain*

appDependencies

This is a description of the potential dependencies among parameters. Only parameters in the *appParameter* table that have 'Derived' as a default distribution are present in this table. These should also be the parameters that have the field [Derived] set to Yes in the table *appParameter*. Neither element nor nuclide parameters can be derived.

Only if the user has the distribution type set to 'Derived' for a parameter will its values be calculated from the independent parameters listed in this table.

These dependencies are implemented in the LHS preprocessor, and are used to obtain the values for parameters having the special distribution type 'Derived.' In other words, a parameter identified by the field [ParameterID] is derived functionally in code, using the value of [IndependentParameterID].

The user cannot modify this table.

The graph of dependencies defined by this table must be acyclic.

[ParameterID] identifies the parameter whose value can be provided by the dependency. Only parameters that have a default value of 'Derived' and whose field [Derived] is set to Yes in the *bld/resParameterDetail* table are listed in this table. All such parameters must have one or more entries in the table.

[DependencyNumber] indexes the independent parameters that are used in the dependency, beginning with one.

[IndependentParameterID] identifies a parameter used to derive the value of the dependent parameter. These are only parameters from table *appParameter.*

Example:

If the parameter INFIL has its distribution set to 'Derived,' then its value will be calculated in the code using the parameters Ksat1, IR, and AP

ParameterID	DependencyNumber	IndependentParameterID
INFIL	1	Ksat1
INFIL	2	IR
INFIL	3	AP

appDerivationMethod

This table lists the methods used to derive the values for 'Derived' parameters. The named methods are implemented by the LHS preprocessor. This table contains constants that cannot be changed by the user.

[ParameterID] identifies the parameter whose value can be provided by the dependency. Only parameters that can be "Derived," or whose unit conversion factors are also model parameters, are listed in this table. All such parameters must have one entry in the table.

[MethodName] identifies the procedure used to derive the parameter value from the value(s) of other model parameters. The specific parameters used in the derivation are listed in the *appDependencies* table.

Example:

ParameterID	MethodName
INFIL	InfiltrationModel

appDistributions

Contains data related to distributions. This table contains constants that cannot be changed by the user.

[DistributionID] is an index that identifies the distribution.

[DistributionName] is the name (or description) of the distribution.

[Empirical] indicates whether the distribution requires a set of ordered pairs or a fixed sized set of parameters for definition. For example, the Normal distribution is not empirical because it has exactly two parameters. The Continuous Linear distribution is empirical because it is defined by a set of ordered pairs.

[DistributionDesc] contains a description of integrity rules for the distribution.

Example:

DistributionID	DistributionName	Empirical	DistributionDesc
17	CONTINUOUS FREQUENCY	Yes	Y >= 0
20	EXPONENTIAL	No	
21	MAXIMUM ENTROPY	No	

appDistributionSymbols

This table identifies the number of parameters and their associated parameter names for each non-empirical distribution. This table contains constants that cannot be changed by the user.

[DistributionID] matches with field [DistributionID] in table *appDistributions*.

[ParameterNumber] identifies the parameter number the [ParameterLabel] is associated with (this is a sequence number starting at 1 for the first label, 2 for the second label, etc.).

[ParameterLabel] is the label as it will appear on the graphical user interface (GUI).

For example: assume the following in the *appDistributions* table:

DistributionID	DistributionName	Empirical
2	NORMAL	No

Then, the following entries are in the *appDistributionSymbols* table.

DistributionID	ParameterNumber	ParameterLabel
2	1	Mean
2	2	Standard Deviation

The entry {15, "Continuous Linear," Yes} in the *appDistributions* table has no corresponding entries in the *appDistributionSymbols* table because the distribution is empirical.

appElementParameterNames, appElementParameters

These tables contain information related to parameters whose values depend on the chemical composition of the contamination. Each daughter product within the decay chain for a source contaminant will have additional parameters that the user can modify. These parameters are only used in the residential scenario model. The default values for these additional parameters, referred to as element parameters, are defined in these tables.

The labels associated with the element parameters and the units required by the dose model are stored in the *appElementParameterNames* table. The element parameters have corresponding default values and limits for each of the variables in each of the categories.

The table *appElementParameterNames* contains the following data.

NuclideParameterNameID	Name	ModelUnitsID
0	Coefficient	mL/g
1	Leafy	pCi/kg dry-wt leafy per pCi/kg soil
2	Root	pCi/kg dry-wt roots per pCi/kg soil
3	Fruit	pCi/kg dry-wt fruit per pCi/kg soil
4	Grain	pCi/kg dry-wt grain per pCi/kg soil
5	Beef	d/kg
6	Poultry	d/kg
7	Milk	d/L
8	Eggs	d/kg
9	Factor	pCi/kg wet-wt fish per pCi/L water

Note: the field [ModelUnitsID] is a long integer that joins with table *appUOM* to obtain the string shown describing the units.

Finally, each of the 73 elements will have ten entries in the *appElementParameters* table that describe default values for each parameter listed in the above table. The fields in this table are described as follows.

[ParameterID]: by convention, all element parameters will have ParameterIDs between 2001 and 9999. Parameter IDs for element-dependent parameters will be assigned as follows.

ID = 2000 + NuclideParameterNameID*100 + SourceNumber

In this expression, SourceNumber is the identifying number of the element used in the *appKd_Decode* table.

[Source] corresponds to symbol identifying element in the periodic table of elements. This entry should match on field [Source] with a record in table *appKd_Decode*.

[NuclideParameterNameID] identifies in which of the ten categories this element parameter belongs.

[Description] is used as a label in the user interface.

[DistributionID] is the default distribution used for this parameter.

[NoEdit] is not used at this time.

[Derived] is not used at this time.

[LowerBound] [UpperBound]: if the user has specified parameter values outside of these bounds, the user will be warned that the value may be inappropriate and may require additional justification. However, the user will be permitted to use the value.

[HardLowerBound] [HardUpperBound]: if the user has selected a constant distribution and enters a value outside these bounds, the user will not be permitted to run a simulation. If the user has entered a distribution other than constant, and any of the values from LHS fall outside these bounds, the user will not be permitted to run any Monte Carlo simulations, even if the values for a given simulation are within bounds.

[DefaultUnitsID] are the units that correspond to default values in the tables *appEmpirical*, etc.

[HelpLink] is a hyperlink to documentation related to this parameter from Beyeler et al. (1999) as saved in HTML format. This is expected to be a relative link. However, the software will use the path of the application for the bases of this relative link.

Example from table *appElementParameters*:

ParameterID	Source	NuclideParameterNameID	Description
2073	Cf	Partition Coefficients : Coefficient	Partition coefficient for Cf
2101	H	Soil to Plant Concentration : Leafy	Leafy plant concentration factor for H

DistributionID	NoEdit	Derived	LowerBound	UpperBound	HardLowerBound	HardUpperBound
NORMAL	No	No	0		0	
CONSTANT	No	No	0		0	

DefaultUnitsID	HelpLink
Log10(mL/g)	
pCi/kg dry-wt leafy	nrcvol3\SessionGenBuildSummary.htm

Note: the field [NuclideParameterNameID] is actually a long integer that joins to field [NuclideParameterNameID] in the *appElementParameterNames* table. Similarly, the field [DistributionID] and [DefaultUnitsID] are actually long integers that join to tables *appDistributions* and *appUOM*, respectively.

The data associated with these parameters will be placed in the same tables as the data for the parameter values, namely *appEmpirDefValues*, *resEmpirValues*, *bldEmpirValues*, *appNonEmpirDefValues*, *resNonEmpirValues*, and *bldNonEmpirValues*. However, the data will only be in the res* and bld* tables if the associated elements are present in the source decay chain. All default data for the element-dependent parameters will be in the *appEmpirDefValues* and *appNonEmpirDefValues* tables.

appElementParameters: see *appElementParameterNames*

appEmpirDefValues, resEmpirValues, bldEmpirValues

Each of these tables contains values for parameters with empirical (tabulated) default distributions. These distributions are defined by tables of varying lengths containing numbers representing the parameter value and the probability of that value.

If the default distribution type in the relevant parameter table (*appParameter* or *appElementParameters*) is set to a distribution that is flagged as empirical in the *appDistributions* table, the default data will be found in table *appEmpirDefValues*. This table contains constants that cannot be changed by the user.

When a new session is created, tables *resEmpirValues* and *bldEmpirValues* are initialized to the default parameter values. These tables will not be the same because not all parameter numbers used for the different scenarios are the same. These tables, *resEmpirValues* and *bldEmpirValues*, will be modified when the user changes parameter values in the residential and building scenarios, respectively.

Example:

The default value for parameter one has been set to an empirical distribution in the *bldParameterDetail* table as follows:

ParameterID	Name	DistributionID
1	Time In Building	CONTINUOUS LINEAR

Because the distribution Continuous Linear is an empirical distribution, the data corresponding to this will be stored in the *appEmpirDefValues* table. The meaning of fields [Value1] and [Value2] are dependent on the empirical distribution. The data are stored as follows.

ParameterID	Value1	Value2
1	35	0
1	39	0.1
1	40	0.1001
1	40.01	0.581
1	41	0.5811
1	48	0.739
1	49	0.7391
1	59	0.892
1	60	0.8921
1	65	1

appKd_Decode

This is a list of element names that are passed to the dose model program.

[SourceNumber] contains a key used by the dose model program to identify the chemical element.

[Source] contains the text identifying the nuclide. The atomic weight has been stripped from the chemical name.

Example:

SourceNumber	Source
10	Ca

appNonEmpirDefValues, resNonEmpirValues, bldNonEmpirValues

If the default distribution type in the relevant parameter table (*appParameter* or *appElementParameters*) is set to a distribution that is flagged as nonempirical in the *appDistributions* table, the default data will be found in table *appNonEmpirDefValues*. This table contains constants that cannot be changed by the user.

The default data for the nuclide parameters are not stored in *appNonEmpirDefValues* because the default is the same for all nuclides; namely, the concentration is zero and the distribution is Constant.

Each entry in this table contains nonempirical values for parameters. These tables are handled by the application similar to the empirical tables (*appEmpirDefValues*, *resEmpirValues*, and *bldEmpirValues*).

Example:

The default values for parameter 5 has been set to the non-empirical Lognormal distribution in the *bldParameterDetail* table as follows:

ParameterID	Name	DistributionID
5	Ingestion Rate	LOGNORMAL

The data corresponding to the default values used can be found in the *appNonEmpirDefValues* table as follows:

ParameterID	ParameterNumber	Value
5	1	0.0112
5	2	1.4268

DandD determines the meaning of the [ParameterNumber] and [Value] fields by looking up the Lognormal distribution in the *appDistributionSymbols* table as follows:

DistributionID	ParameterNumber	ParameterLabel
LOGNORMAL	1	Mean
LOGNORMAL	2	Error Factor

In this example, the distribution is LOGNORMAL with a mean of .0112 and an error factor of 1.4268 for the Ingestion Rate.

Note: the actual value stored in these tables for the Distribution ID is a long integer, not the character string "LOGNORMAL." The field [DistributionID] is joined with the field [DistributionID] in table *appDistributions* in order to find the [DistributionName]. In the above example, the [DistributionID] is 6. The entry in the *appDistribution* table is as follows:

DistributionID	DistributionName	Empirical
6	LOGNORMAL	No

appNuclides

The *appNuclides* table contains the list of all possible nuclides.

The default value for the nuclide parameters (namely, the concentrations of the nuclides) is set to zero. The nuclide concentration default values cannot be changed by modifying the database, but are initialized in the software. These values are not stored in the *appNonEmpirDefValues* table, but are inserted by the software into the *resNonEmpirValues* and *bldNonEmpirValues* tables when contaminants are added.

The fields have the following meaning:

[ParameterID] is used to find the associated data in the tables *resNonEmpirValues*, *bldNonEmpirValues*, *resEmpirValues*, and *bldEmpirValues* when contaminants are added. By convention, all values of [ParameterID] will be between 1001 and 2000 for the nuclide parameters.

[NukeID] is the ID to pass to the dose model program.

[NuclideSymbol] is the symbol used by the GUI to identify the nuclide.

[IsSource] flags nuclides that can be explicitly included in the source term. This includes most nuclides except a few that have very short half-lives.

[HelpLink] is a hyperlink to documentation related to this parameter from Beyeler et al. (1999) as saved in HTML format. This is expected to be a relative link. However, the software will use the path of the application for the bases of this relative link.

The data associated with the nuclides will be placed in the same tables as the data for the other parameters, namely *resEmpirValues*, *resNonEmpirValues*, etc.

Example:

ParameterID	NukeID	NuclideSymbol	IsSource	HelpLink
1001	1	3H	Yes	
1002	2	10Be	Yes	nrcvol3\SessionGenBuildSummary.htm
1003	3	14C	Yes	

appParameter

Each parameter listed in this table is used as input to the dose model program. There are no parameters associated with nuclides or elements in this table. By convention, all values for the [ParameterID] will be between 1 and 1000 for the parameters in *appParameter* table.

The fields [DistributionID], [Scenario], [Residential Category], [DefaultUnitsID], [ParameterCategoryID], and [ModelUnitsID] are joined to tables *appDistribution*, *appSenario*, *appResidentialCategories*, *appUOM*, *appParameterCategories*, and *appUOM*, respectively.

The fields have the following meaning:

[ParameterID] identifies associated data in one of the data tables *bldEmpirValues*, *resEmpirValues*, *bldNonEmpirValues*, or *resNonEmpirValues*. The default data associated with this parameter will be in tables *appNonEmpirDefValues* or *appEmpirDefValues*.

[Name] is the concise description of the parameter.

[Description] is the detailed description of the parameter.

[DistributionID] is the default distribution used for this parameter.

[Input] indicates parameters that are directly required by the dose model. Not all parameters are input to the dose model. The parameters that have [Input] set to No are used to calculate other parameters that are input to the model.

[InputSequence]: for input parameters, this gives a sequence number that is unique for each scenario. This sequence number defines the order that the parameters are required by the dose model. If the parameter is not an input parameter, then the input sequence number should be Null. If the [Input] field is set to Yes, then [InputSequence] value must be a number.

[NoEdit]: if set, the user cannot modify this value from the default value.

[Derived]: if set, the user is allowed to set the distribution type to 'Derived.' If this is Yes, the [DistributionID] in this table must also be set to 'Derived.'

[LowerBound] [UpperBound]: if the user has specified a value outside of these bounds, the user will be warned that the value may be inappropriate and will require additional justification. However, the user will be permitted to use the value.

[HardLowerBound] [HardUpperBound]: if the user has selected a constant distribution and enters a value outside these bounds, the user will not be permitted to run a simulation. If the user has entered a distribution other than constant, and any of the values from LHS fall outside these bounds, the user will not be permitted to run any Monte Carlo simulations, even if the values for a given simulation are within bounds.

[DefaultUnitsID] are the units that correspond to default values associated with this parameter.

[Symbol] is used to identify this parameter in the dose model program.

[Scenario] identifies if parameter is used for the building occupancy or residential scenario. Because there are different default values associated with parameters in this table depending on the scenario, this table can be partitioned into parameters used for the residential and parameters used for the building occupancy scenarios.

[ResidentialCategory]: if the scenario is residential, this field identifies the parameter category for grouping within the GUI. Otherwise, this entry is Null.

[ParameterCategoryID] assigns the parameter to one of the categories given in the *appParameterCategories* table.

[ModelUnitsID] indicates the units of measure required by the dose model. This may differ from the values used to specify the default. These fields are joined with table *appUOM* to obtain a full description and label.

[HelpLink] is a hyperlink to documentation related to this parameter from Beyeler et al. (1999) as saved in HTML format. This is expected to be a relative link. However, the software will use the path of the application for the bases of this relative link.

[ExternalCode], [InhalationCode], [SecIngestionCode], [FarmCode], [DrinkingCode], [IrrigationCode], and [PondCode] are not used at this time. The intention was to use these fields as binary flags to indicate to which pathways the parameter is applicable.

Example:

ParameterID	Name	Description	DistributionID
1	Time In Building	The time in the building (converted to effective 24-hr days) during the occupancy period	CONTINUOUS LINEAR
2	Occupancy Period	The duration of the occupancy exposure period	CONSTANT
3	Breathing Rate	The average volumetric breathing rate during building occupancy for an eight-hour work day	CONTINUOUS LINEAR

Input	InputSequence	NoEdit	Derived	LowerBound	UpperBound
Yes	1	No	No	0	250
Yes	2	No	No	1	365.25
Yes	3	No	No	0	3.63

HardLower Bound	HardUpper Bound	DefaultUnitsID	Symbol	Scenario
0	250	days/year	To	Building Occupancy
1	365.25	days	Tto	Building Occupancy
0	3.63	m**3/hr	Vo	Building Occupancy

ResidentialCategory	ParameterCategoryID	ModelUnitsID	HelpLink
	Behavioral	days/year	nrcvol3\SessionGenBuildSummary.htm
	Behavioral	days	
	Metabolic	m**3/hr	

ExternalCode	InhalationCode	SecIngestionCode	FarmCode	DrinkingCode

IrrigationCode	PondCode

appParameterCategories

This table names the four categories of the parameters required by the scenario models. The LHS sampling used depends on the categories for these parameters. If a parameter is in the Metabolic or Program Control category, then only the Constant distribution is allowed. If the parameter is Behavioral, then the average value of the LHS sampling is used when the field [AverageBehavior] is set to True in the *resSettings* or *bldSettings* table.

[ParameterCategoryID] is the category index, referenced in table *appParameter*.

[ParameterCategory] is the name of the category.

ParameterCategoryID	ParameterCategory
0	Metabolic
1	Behavioral
2	Physical
3	ProgramControl

appResCorrelations: see *appBldCorrelations*

appResidentialCategories

This table lists the categories used to classify residential parameters. It contains the following information:

ResidentialCatID	ResidentialCatName
1	Basic
2	Human Diet
3	Food Consumption Period
4	Holdup Period
5	Growing Period
6	Animal Feeding Periods
7	Interception Fraction
8	Translocation Factor
9	Contaminated Fraction
10	Crop Yields
11	Wet-To-Dry Conversion
12	Animal Intake Rates
13	Plant Mass-Loading
14	Carbon Model
15	Hydrogen Model

appResSoilCharacteristics

This table holds the parameters that describe the hydrologic characteristics of 12 soil types defined by the U.S. Bureau of Reclamation (USBR) (see Appendix E). These characteristics can be used to derive interrelated values for the soil parameters of the residential scenario model.

[SoilClass] is the name of the soil classification.
[SoilID] is the index of the soil classification.
[KdistType] is an index for the probability distribution type for Ksat, the saturated conductivity. If zero, the lognormal distribution is used. If one, the beta distribution is used.
[MeanLnKsat] is the mean value of the natural log of saturated conductivity, in cm/sec, for soils with a lognormal distribution for Ksat.
[SlnKsat] is the standard deviation of the natural log of Ksat for soils with a lognormal distribution for Ksat.
[KMinimum] is the minimum value of Ksat for soils with a beta distribution of Ksat.
[KMaximum] is the maximum value of Ksat for soils with a beta distribution of Ksat.
[KP] is the P parameter of the beta distribution of Ksat for beta-distributed soils.
[KQ] is the Q parameter of the beta distribution of Ksat for beta-distributed soils.
[BdistType] is an index for the probability distribution type for the "b" parameter of the saturation/permeability model. If zero, the lognormal distribution is used. If one, the beta distribution is used.
[MeanLnBeta] is the mean value of the natural log of parameter "b" for soils with a lognormal distribution for "b."
[SLnBeta] is the standard deviation of the natural log of "b" for soils with a lognormal distribution for "b."
[BMinimum] is the minimum value of "b" for soils with a beta distribution of "b."
[BMaximum] is the maximum value of "b" for soils with a beta distribution of "b."
[BP] is the P parameter of the beta distribution of parameter "b" for beta-distributed soils.
[BQ] is the Q parameter of the beta distribution of parameter "b" for beta-distributed soils.
[MeanN1] is the expected value of porosity.
[SN1] is the standard deviation of porosity.

Example:

SoilClass	SoilID	KDistType	MeanLnKsat	SLnKsat	KMinimum	KMaximum
silty clay	4	0	-13.78	1.224		
loamy sand	5	1			0.000039	0.0134
clay	6	0	-11.36	1.509		

KP	KQ	BDistType	MeanLnBeta	SLnBeta	BMinimum	BMaximum
		0	2.282	0.2844		
0.79836133	1.90143765	0	0.2978	0.2781		
		1			4.93	75

BP	BQ	MeanN1	SN1
		0.36	0.07
		0.41	0.09
1.74608936	11.5961659	0.38	0.09

appResUSBRPercolationFraction

This table holds the estimated fraction of applied water that becomes infiltration as a tabulated function of saturated permeability.

[ID] is an index used to order the tabulated values.
[Ksat] is the saturated permeability in cm/sec.
[PercFraction] is the estimated fraction of applied water that becomes infiltration.

Example:

ID	KSat	PercFraction
2	0.0000353	0.03
3	0.0000706	0.05
4	0.000141	0.08

appSenario

This table names the available scenarios. It currently contains the following information:

SenarioID	SenarioName
1	Building Occupancy
2	Residential

appSettings

This single record table contains the default application settings for each run. These settings are not modifiable by the user.

The following fields have the same basic meaning as the same fields in the *bld/resSettings* tables: [CombineProgeny], [DistActivity], [NumberSim], [Seed], [Tracking], [AverageBehavior], [SaveHistory], and [DoseQuantile].

[NuRegThree] is a hyperlink to the home page of Beyeler et al. (1999) as saved in HTML format. This is expected to be a relative link. However, the software will use the path of the application for the bases of this relative link.

Example:

CombineProgeny	DistActivity	NumberSim	Seed	Tracking	AverageBehavior
Yes	Yes	100	8718721	1	Yes

SaveHistory	DoseQuantile	NuRegThree
No	0.9	Nrcvol3\vol3Home.html

appStatNames

This table names the various dose statistics reported in the dose statistics tables *datBldDoseStats* and *datResDoseStats*.

[StatID] is a unique integer identifier for the statistic.
[StatName] is a descriptive name for the statistic.
[StatDesc] is an optional extended description of the statistic.

Example:

StatID	StatName	StatDesc
1	Minimum	Smallest value in the set of simulations
2	Maximum	Largest value in the set of simulations
3	Average	Average value in the set of simulations
4	StdDev	Sample standard deviation from the set of simulations
5	Xcrit	Maximum likelihood estimate of the Pcrit quantile value
6	XcritLCL	Lower bound of the symmetric 95% confidence interval for the Pcrit quantile value
7	XcritUCL	Upper bound of the symmetric 95% confidence interval for the Pcrit quantile value

appUOM

This table defines the units of measure used in specifying the values of model parameters.

Example:

UnitsID	Units	Description
1	pCi	Picocuries
2	nCi	Nanocuries

appUOMConversionFactors

The following table indicates how units listed in table *appUOM* can be interchanged.

The fields are as follows:

[UnitFrom] and [UnitTo] are long integers that match with field [UnitsID] in table *appUOM*. [UnitTo] identifies the conversion family.

[Factor] is optional. If the field [Factor] is not Null, then [UnitFrom] can be converted to [UnitTo] by multiplying [UnitFrom] by [Factor].

[Functional] is a boolean field. If it is set to Yes, a conversion between the units exists. However, this conversion is not done using multiplication by [Factor], but via a special function identified in field [FunctionID].

[FunctionID] identifies the function used for functional conversions. This field matches the [FunctionID] field in the *appUOMConversionFunctions* table.

[ConversionParameter] names an optional model parameter that may be required by the conversion function. This field matches with the [Symbol] field in the *appParameter* table.

The following integrity rules should hold for this table:
If [Functional] is No, then [Factor] is not Null.
If [Factor] is Null, then [Functional] should be Yes.
If [Functional] is Yes, then [Factor] is Null and [FunctionID] is not Null.

For each record in this table, there should exist exactly one method to convert from [UnitFrom] to [UnitTo].

By grouping these records into (disjoint) subsets where the [UnitTo] field is equal, the result is a conversion family that allows conversion between any units within this subset. For example, perhaps there is a need to convert between lengths, and a need to support centimeters, meters, inches, and miles. There will be exactly four entries in this table. A family must be selected, say, "meters," for this example. The user sets the [UnitTo] field to meters for each of the four new records. The values for the [UnitFrom] field will be set to centimeters, meters, inches, and

miles for the four records. The DandD software has sufficient information to convert between any of these four units. It will not be allowed to have an entry in this table to convert, for example, from inches to miles. This type of entry would not support the DandD algorithm used for unit conversion. The way the DandD software uses this table, the value of UnitFrom must be unique to this table. To enforce this, the [UnitFrom] field is a key to this table.

Note: there must be an entry for the base unit within the conversion family. In the above example, this means that DandD software requires that there be an entry for the field where [UnitFrom] is set to meters, [UnitTo] is set to meters, and the conversion factor is set to one.

Example:

UnitFrom	UnitTo	Factor	Functional
grams	kg	0.001	No
kg	kg	1	No
mg	kg	0.000001	No
pCi/kg wet-wt leafy per pCi/kg soil	pCi/kg dry-wt leafy per pCi/kg soil		Yes

FunctionID	ConversionParameter
Divide	WV(1)

appUOMConversionFunctions

This table lists the functions used to convert units.

FunctionID	FunctionName
0	Exponentiate
1	Multiply
2	Divide
3	Power10

D.2.2 Scenario Specific Tables (bld/res tables)

bldCorrelations, resCorrelations

Tables *resCorrelations* and *bldCorrelations* contain parameter correlation coefficients specific to the user scenario. If a parameter is constant or from a derived distribution, DandD will not permit the parameter to be correlated to any other parameter. With the exception of two additional fields described below, the fields in these tables are identical to the fields used in tables *appResCorrelations* and *appBldCorrelations*.

[DefaultVal] indicates if this record is a member of the default table *appBldCorrelations* or *appResCorrelations* for the scenario (e.g., this record agrees with a record in *appBld/ResCorrelations* with respect to [ParameterID1], [ParameterID2], and [Correlation]).

[Justification] contains text that the user has entered justifying the correlation coefficient and the dependence of the parameters [ParameterID1] and [ParameterID2]. This description is only relevant if the [DefaultVal] field is set to False.

Example:

ParameterID1	ParameterID2	Correlation	DefaultVal	Justification
109	111	-0.35	Yes	
110	111	-0.35	Yes	
2465	2565	0.2	No	Ac Beef and grain are dependant variables

bldElementParameters table is unused.

bldEmpirValues: see *appEmpirDefValues*.

bldNonEmpirValues: see *appNonEmpirDefValues*.

bldNuclides, resNuclides

The *resNuclides* and *bldNuclides* tables contain the contaminants for the current session, residential and building scenarios, respectively.

The fields have the following meaning:

[ParameterID] identifies associated data in the data tables *resEmpirValues*, etc., and matches with a [ParameterID] in table *appNuclides*.

[NuclideSymbol] is identical to [NuclideSymbol] in table *appNuclides*.

[Area] is a constant representing the area of contamination. This is a variable that cannot be associated with a probability distribution. By default, it is set to zero. A zero value implies that the contaminant is spread over the total area of concern.

[DistributionID] is the probability distribution associated with the concentration of this contaminant. By default, this is initialized to the Constant distribution.

[Justification] is a memo field that is defined by the user when the user enters the concentration for the nuclide. This justification should contain evidence to support the concentration value or probability distribution.

[UnitsID] identifies the units of concentration. The default values used can be found in field [SourceUnits] within tables *bldSettings* and *resSettings*. At this time, the default units are set to 'dpm/100cm**2' for the building scenario and 'pCi/g' for the residential scenario.

Example:

ParameterID	NuclideSymbol	Area	DistributionID
1002	10Be	0	CONSTANT
1003	3H	0.2	TRUNCATED NORMAL

Justification	UnitsID
	dpm/100cm**2
	dpm/100cm**2

bldParameterDetail, resParameterDetail

These tables contain data related to the parameters listed in the *appParameter* table for a session. This table is created from the *appParameter* table fields [ParameterID] and [DistributionID]. When the table is first created, [DefaultVal] is set to Yes. As the user modifies the parameter values, the data tables (*resEmpirValues*, etc.) will be modified. The values of these fields represent user input to the GUI.

The fields have the following meaning:

[ParameterID] identifies the parameter data in tables *resNonEmpirValues*, etc.

[DefaultVal] indicates if the current value of this parameter is set to the default value. Initially, this value is set to True.

[DistributionID] indicates the associated distribution for this parameter. Initially, this value is set to the default distribution, [DistributionID], from table *appParameter*.

[Justification] is user-supplied documentation of any non-default value or distribution.

[UnitsID] indicates the current units corresponding to the data associated with this parameter. Initially, this value is set to the default units, [DefaultUnitsID], from table *appParameter*.

Example:

ParamaterID	DefaultVal	DistributionID	Justification	UnitsID
1	Yes	CONTINUOUS LINEAR		hr/week
2	Yes	CONSTANT		days
3	Yes	CONTINUOUS LINEAR		m**3/hr

bldReports, resReports

These tables are used to store information about custom reporting capabilities.

[ReportID] is an index used to order the table records.
[Name] is the name of report template.
[Units] are the units used in the simulation results portion of the report for the total dose.

The following Yes/No fields determine the contents of the custom report:

[Execution] Set to True if execution settings will be reported.
[InitialAct] Set to True if initial activities will be reported.
[CodeAct] Set to True if calculated activities will be reported.
[ChangedParam] Set to True if all changed parameters will be reported.
[AllParam] Set to True if all parameters will be reported, including those set to default values.
[MaxOcc] Set to True if the total effective dose equivalent (TEDE) value will be reported.
[MaxPath] Set to True if the dose due to each pathway is reported.
[MaxRadioDose] Set to True if the dose due to each nuclide through all active pathways is reported.
[MaxPathRadioDose] Set to True if the dose due to each nuclide and each pathway is reported.
[FinalAct] Set to True if Concentration of time at peak dose for each nuclide is reported.

ReportID	Name	Units	Execution	InitialAct
4	Summary	mrem	Yes	Yes
5	Final Activity	mrem	No	No
6	Detailed results	mrem	No	No

CodeAct	ChangedParam	AllParam	MaxOcc	MaxPath
No	Yes	No	Yes	No
No	No	No	No	No
No	No	No	Yes	Yes

MaxRadioDose	MaxPathRadioDose	FinalAct
No	No	No
No	No	Yes
Yes	Yes	Yes

bldSettings, resSettings

These single record tables contain the actual settings for the building occupancy and the residential scenarios, respectively. The user can modify these values via advanced execute options. These tables should initially agree with the values in table *appSettings*.

The fields are as follows:

[CombineProgeny] is set to Yes or No. This indicates if the daughter product results are included with the parent dose results when the model is run.

[DistActivity] is set to Yes or No. This is a calculation option that applies only to equilibrium (+C) nuclides. If set to Yes, then the initial activity for the +C nuclide is shared with all of its daughter nuclides.

[NumberSim] is set to the number of times the model will be run with different values from LHS.

[Seed] is set to Random Seed used to generate parameter values that have associated distributions for the Monte Carlo simulation.

[Tracking] is the time delay for tracking the peak dose.

The following settings indicate allowable nuclide pathways and initial default settings:

[ExternalPathway] is set to Yes.
[InhalationPathway] is set to Yes.
[SecIngestionPathway] is set to Yes.
[FarmPathway] is set to Yes (always No for the building occupancy scenario).
[DrinkingWaterPathway] is set to Yes (always No for the building occupancy scenario).
[IrrigationPathway] is set to Yes (always No for the building occupancy scenario).
[PondPathway] is set to Yes (always No for the building occupancy scenario).

[SourceUnits] indicates the units of measure used to specify source concentration. Different units are used for the *resSettings* and *bldSettings* tables. The user cannot change this value. These are the units used by the model.

[AverageBehavior] is set to Yes or No to indicate whether the behavioral parameters should be averaged to represent the average member of the critical group, or sampled to represent individual members of the critical group.

[SaveHistory]: if this is True, then the average dose and the standard deviation of the dose at every time step broken down for every pathway, every individual nuclide, and for the combined nuclides will be saved. This information will be saved in tables *datBld/ResHistNucMean, datBld/ResHistNucStdDev, datBld/ResHistPathMean,* and *datBld/ResHistPathStdDev.*

[DoseQuantile] indicates the order of the quantile of the estimated TEDE distribution reported for comparison against the dose standard.

[Justification] is a memo field that is defined by the user when the user changes the pathway behavior.

[FarmCat], [WellCat], and [WaterCat] are not used at this time. However, the intention was that the user could turn on or off categories that allow access to certain pathways. This may become a feature in the future, hence, it was not removed from the code nor the database.

[ImportConcen] is a software mode that is only relevant for the residential scenario, but is in both *bldSettings* and *resSettings* tables for convenience only. By default, the user will enter the source contaminants and their respective concentrations. In this case, [ImportConcen] will be set to False. However, on occasion, the user will want to specify this in a file instead. This file, known as the *Import Concentration File* (*.con file), is of a specialized format that was defined for DandD Version 1.0. This is included for backward compatibility. If [ImportConcen] is set to True, then table *resImportCon* will be populated with the file contents.

[JustImportConc] is the justification for importing the concentration. This is only relevant if [ImportConcen] is set to True.

[Stamp] is the date and time corresponding to the dat tables in the database. This value is Null if there is no current execution data present.

Example:

CombineProgeny	DistActivity	NumberSim	Seed	Tracking	ExternalPathway	InhalationPathway
No	Yes	100	8718721	1	Yes	Yes

SecIngestionPathway	FarmPathway	DrinkingWaterPathway	IrrigationPathway	PondPathway	SourceUnits
Yes	Yes	Yes	Yes	Yes	pCi/g

AverageBehavior	SaveHistory	DoseQuantile	Justification	FarmCat	WellCat	WaterCat	ImportConcen
Yes	No	0.9		Yes	Yes	Yes	No

JustImportConc	Stamp
	10/25/00 1:21:59 AM

resCorrelations: *see bldCorrelations*

resElementParameters

This table contains the parameters associated with the nuclide elements. For the residential scenario, each element will have a total of ten entries in this table. An element will be in this table only if the element was entered as a source of contamination or if the element is in the decay chain of a nuclide that the user added as a source of contamination. These parameters have default settings that the user can edit through the GUI. These default settings are read from the *appElementParameters* table and the associated data tables (*appEmpirDefValues, appNonEmpirDefValues*). The actual values used in the model calculations are stored in tables *resNonEmpirValues* and *resEmpirValues*.

The meaning of the fields is identical to the meanings in tables *bldParameterDetail* and *resParameterDetail.*

Example:

ParamaterID	DefaultVal	DistributionID	Justification	UnitsID
2005 Na:Coefficient	No	NORMAL	Reason this was modified from default	Log10(mL/g)
2105 Na:Leafy	Yes	LOGNORMAL-N		pCi/kg dry-wt leafy per pCi/kg soil

resEmpirValues: see *appEmpirDefValues*.

resImportCon

This table contains the import concentration data if *resSettings*.[ImportConcen] is set to True. This is specially formatted data that is used as an alternative to data in the bld/res data tables with respect to nuclide concentrations. A description of the meaning of this data is not contained in this document (see Appendix C). The data in this table is read from an ASCII file. Fields are separated by blanks. There are at most two fields per record, which corresponds to one line in the ASCII file.

[Index] is an automatically generated key field corresponding to the line number of the file.
[Col1] corresponds to field 1.
[Col2] corresponds to field 2.

Example: The first three lines of an import concentration file are stored as follows

Index	Col1	Col2
1	3	
2	7	
3	234U	

resNonEmpirValues: see *appNonEmpirDefValues*.

resNuclides: see *bldNuclides*.

resParameterDetail: see *bldParameterDetail*.

resReports: see *bldReports*.

resSettings: see *bldSettings*.

D.2.3 Model Result Tables (dat tables)

datBldConcStats, datResConcStats

These tables contain statistics related to the estimated concentration distributions for individual nuclides and locations.

[NuclideID] is the nuclide identifier from *appNuclides*.
[StatID] is the identifier of the statistic from *appStatNames*.
[*medium*] is the value for the given statistic for the initial concentration in the given medium.

Example:

NuclideID	StatID	Soil	Water
196	1	4.16084457563249E-02	0
196	2	14.964099652933	1239.70825282387
196	3	8.66493478048292	31.462158203012
196	4	3.624682408305	140.484521900805
196	5	12.1437	43.0735269616935
196	6	11.6443851913763	6.34659042206096E-11
196	7	12.5712	108.611964210352

datBldDoseStats, datResDoseStats

These tables contain statistics related to the estimated dose distributions for individual nuclides and pathways, and for total dose.

[NuclideID] is the nuclide identifier from *appNuclides*, or zero to denote total dose.
[StatID] is the identifier of the statistic from *appStatNames*.
[Total] is the value for the given statistic for the current values of dose through all pathways.
[*pathway*] is the value for the given statistic for the current values of dose through the given pathway.

Example:

NuclideID	StatID	Total	FarmPathway	DrinkingWaterPathway	PondPathway
22	1	6.31501720090655	0.115859163824551	0	0
22	2	7.8054251335416	1.60627683958954	4.58202776252917E-11	2.85148594600873E-10
22	3	6.45835541172811	0.259211517137271	4.58225232183848E-13	2.85164307648308E-12
22	4	0.181999388536105	0.181998907034963	4.58202549880339E-12	2.8514843624432E-11
22	5	6.60386781823706	0.404729170853565	2.0587002001501E-30	1.40541955425932E-29

ExternalPathway	InhalationPathway	SecIngestionPathway	IrrigationPathway
6.19876318636059	4.77371614627895E-06	3.57355296801155E-04	0
6.19876318636059	1.01873605162395E-04	3.57355296801155E-04	1.80156990512671E-10
6.19876318636058	2.33529283291658E-05	3.57355296801154E-04	1.80162625031057E-12
4.77739405288454E07	1.95202543764743E-05	2.25863862366848E-11	1.80156933666473E-11
6.19876318636059	4.61932408044741E-05	3.57355296801155E-04	8.92814968327486E-30

datBldDoseSummary, datResDoseSummary

These tables contain a single record with the TEDE quantile value report for comparison against the dose limit based on the most recently calculated dose distributions (these distributions are stored in the *datBldTotal* and *datResTotal* tables).

[Tcrit] is the critical dose value reported for comparison.

Example:

Tcrit
4.32114734947361E-03

datBldHistNucMean, datResHistNucMean, datBldHistNucStdDev, datResHistNucStdDev, datBldHistPathMean, datResHistPathMean, datBldHistPathStdDev, datResHistPathStdDev

These tables contain history data. If the option is turned on to collect this data (*bld/resSettings*.[SaveHistory] = True), then the *histNucMean* tables will contain the average total dose broken down by individual nuclides for each time step. The *bld/resHistPathMean* will contain the average dose broken down by pathways. The standard deviations are stored in the *NucStdDev* table.

Example: Table *datResHistNucMean*

Time	AllIsotopes	Nuc6
1	16.772316845586	16.772316845586
2	2.66008144165796E-21	2.66008144165796E-21
3	1.7170072754837E-29	1.7170072754837E-29

Three time steps were run for each of the Monte Carlo simulations. [AllIsotopes] contains the average over all simulations of the total dose for all contaminants combined. In this example, there was only one contaminant. The average over all simulations of the total dose for this contaminant is recorded in [Nuc6]. The field name [Nuc6] identifies that contaminant as having parameter ID 1006. This can then be referenced in the *appNulide* table, where this corresponds to Na 24.

Example: Table *datResHisPathMean*

Time	ExternalPathway	InhalationPathway	FarmPathway
1	16.7610990285165	4.58142219584829E-07	1.11875676527068E-02
2	2.65868079721869E-21	6.5950796285523E-29	1.39585266728979E-24
3	1.71610396991989E-29	4.24355366503163E-37	9.00209152594661E-33

Again, the total dose due to each of the pathways is averaged over all Monte Carlo simulations, and is listed for each time step. The standard deviations are stored in the *HistPathStdDev* table.

datBldHistNucStdDev: see *datBldHistNucMean*.

datBldHistPathMean: see *datBldHistNucMean*.

datBldHistPathStdDev: see *datBldHistNucMean*.

datBldInitSurface

[Vector] is the vector number corresponding to simulation.
[AllIsotopes] is unused.

The remainder of the fields will contain the initial surface concentration of a nuclide or progeny for simulation identified by vector number [Vector]. The field names will correspond to [nukeID] in table *appNuclides*.

Example:

Nuc187 corresponds to nuclide ID 187, or U 232. The initial surface concentration of U232 at the beginning of simulation number two was 1052.

Vector	AllIsotopes	Nuc187	Nuc173
1		1052	1081
2		1160	1191
3		1248	1282

datBldNucIndex, datResNucIndex

These tables contain the field indices for each of the nuclides with reported doses. These tables are used by DandD to locate doses in the pathway dose tables for individual radionuclides.

[NuclideID] is a unique nuclide identifier that matches the [Source] field of the *appCandCDecode* table.
[OutputFieldID] is the index of the field containing the dose value in the dose value tables (e.g., the *datBldExternalPathway* table) where [OutputFieldID] = 1 corresponds to the first field.

Example:

NuclideID	OutputFieldID
23	2

datBldSurface

This table is formatted identical to table *datBldInitSurface*. However, the data in this table is the surface concentration of the nuclide at the time of peak dose.

datBldTmax, datResTmax

These tables contain the time (in years) at which the calculated maximum TEDE occurs for each parameter sample. The building occupancy scenario is only simulated for one year; however, the table is generated for this scenario to accommodate possible extensions.

[Vector] is a unique sample vector index that ranges from 1 to the number of samples.
[Time_of_Maximum] is the time (in years) at which the calculated TEDE reaches its maximum value.

Example:

Vector	Time_of_Maximum
1	1
2	1
3	6
4	1
5	6
6	1

datBldTotal, datResTotal

These tables contain the calculated combined dose values along the various exposure pathways for each parameter sample vector. The total dose for all nuclides, and the dose due to individual nuclides, are stored. The structure is the same as that of the pathway dose tables *datBldXXXPathway* and *datResXXXPathway*.

datBldXXXPathway, datResXXXPathway

These tables contain the calculated dose values along the individual exposure pathways for each parameter sample vector. A separate table, denoted by XXX, is created for each pathway.

For the residential scenario,

XXX = DrinkingWater, External, Farm, Inhalation, Irrigation, Pond, SecIngestion;

while for the building occupancy scenario,

XXX = External, Inhalation, SecIngestion.

Each table contains the total dose along the pathway at the time of peak dose and the contributions of the component nuclides:

[Vector] is a unique sample vector index that ranges from 1 to the number of samples.
[AllIsotopes] is the total dose along the pathway due to all isotopes.
[Nuc*i*] is the pathway dose from nuclide *i*.

Example:

Vector	AllIsotopes	Nuc23
1	3.52192694572157E-08	3.52192694572157E-08
2	2.21202219082726E-08	2.21202219082726E-08
3	5.94394714605343E-03	5.94394714605343E-03
4	3.85410853236806E-10	3.85410853236806E-10
5	3.19504183051653E-03	3.19504183051653E-03

datResConcStats: see *datBldConcStats*.

datResDoseStats: see *datBldDoseStats*.

datResDoseSummary: see *datBldDoseSummary*.

datResHistNucMean: see *datBldHistNucMean*.

datResHistNucStdDev: see *datBldHistNucMean*.

datResHistPathMean: see *datBldHistNucMean*.

datResHistPathStdDev: see *datBldHistNucMean*.

datResInitSoil

This table is formatted identical to table *datBldInitSurface*. However, the data in this table is the initial soil concentration of a nuclide or progeny for simulation identified by vector number [Vector]. The field names will correspond to [nukeID] in table *appNuclides*.

datResNucIndex: see *datBldNucIndex*.

datResSoil

This table is formatted identical to table *datBldInitSurface*. However, the data in this table is the soil concentration of the nuclide at the time of peak dose.

datResTmax: see *datBldTmax*.

datResTotal: see *datBldTotal*.

datResWater

This table is formatted identical to table *datBldInitSurface*. However, the data in this table is the water concentration of the nuclide at the time of peak dose.

datResXXXPathway: see *datBldXXXPathway*.

D.2.4 Error Information Tables (err tables)

errCorrelationErrors

This table describes warnings and errors detected by the LHS preprocessor that prevent the correlations specified in *bldCorrelations* or *resCorrelations* from being implemented. This table is only created and populated if warning or error conditions are detected. If the table exists when the LHS processor is called, it will be deleted.

[ParameterID1]	identifies one of the pair of correlated parameters.
[Code1]	is the error code for this parameter: if 0, there is no problem. if 1, then the parameter is a Constant or Derived parameter, and is not sampled. If 2, the parameter was not found. This implies an internal inconsistency among the parameter tables.
[ParameterID2]	identifies the other correlated parameter.
[Code2]	is the error code for this parameter.

Example:

ParameterID1	Code1	ParameterID2	Code2
3	0	42	2

errSampleBoundaryViolations

This table describes parameter value warnings and errors detected by the LHS postprocessor. This table is only created and populated if one or more of the model parameter values generated by LHS fall outside the "hard" or "soft" limits defined in the appropriate tables (e.g., *appParameter*). If the table exists when the LHS processor is called, it will be deleted. The dose model can be executed, following user notification, if only the soft limits are exceeded. Exceeding either hard limit should preclude execution of the dose model.

[ParameterID]	identifies the parameter whose bounds were exceeded in one or more samples.
[SoftLowerLimit]	is True if the soft lower limit was exceeded, and False otherwise.
[SoftUpperLimit]	is True if the soft upper limit was exceeded, and False otherwise.
[HardLowerLimit]	is True if the hard lower limit was exceeded, and False otherwise.
[HardUpperLimit]	is True if the hard upper limit was exceeded, and False otherwise.

D.2.5 Sampling Result Tables (par tables)

parBldBasicSampleValues, parResBasicSampleValues

These tables hold values for the sampled basic model input parameters for each sample vector generated by LHS. These tables are created and filled by the LHS pre/postprocessor function. Basic model parameters that are known not to vary from sample to sample are stored in the *parBldConstantValues* or *parResConstantValues* table.

[Vector] is a unique sample vector index that ranges from 1 to the number of samples.
[*parameter_i*] is the value of parameter *i*. The specific parameter name depends on the scenario, and on whether the parameter can vary from vector to vector.
The field name matches the [Symbol] field in the *appParameter* table.

Example:

Vector	SFI	PD	RFR	CDO	CDI
1	0.58474815	0.232044	0.00000166272	0.000000256544	1.56421803488E-07
2	0.58474815	0.0206941	0.000000215785	0.00000444799	1.58842615689E-06
3	0.58474815	0.233635	0.00000556082	0.000000166557	1.15857215757E-07

parBldConstantValues, parResConstantValues

These tables hold the values for the basic model input parameters that are known to be invariant from vector to vector. This determination is made at the time parameters are sampled based on the distributions currently assigned to the parameters.

[ParameterID] is the parameter identifier.
[Value] is the constant value.

Example:

ParameterID	Value
10	1
11	0.1
12	0.1

parBldFieldIndex, parResFieldIndex

These tables describe the locations in which the sampled parameter values have been stored by the LHS postprocessor. They are created by the LHS pre/postprocessor function.

[ParameterID] is the parameter identifier.
[Varies] is a logical flag which is -1 if a separate parameter value is stored for each sample vector. If the value is zero, the fixed value for the parameter is stored in *parBldConstantValues* or *parResConstantValues*.
[FieldID] is the zero-based index of the field containing sampled values for this parameter if the parameter is variable (if [Varies] is -1). Values for this parameter are stored in the indexed field of the table containing values for this parameter type (either *parXXXBasicSampleValues*, *parXXXSourceSampleValues*, or *parResElementSampleValues*).
[Minimum] is the minimum sampled value.
[Maximum] is the maximum sampled value.
[HasRange] if -1, the parameter varies from one vector to another. If zero, the parameter values do not change from one vector to another.

Example:

ParameterID	Varies	FieldID	Minimum	Maximum	HasRange
3	0	0	1.4	1.4	0
4	-1	1	0.000000927394	0.0000187132	-1

parBldSourceSampleValues, parResSourceSampleValues

These tables hold the input source specification for the dose models for each sample vector generated by LHS. These tables are created and filled by the LHS pre/postprocessor function.

[Vector] is a unique sample vector index that ranges from 1 to the number of samples.
[*nuclide_i*] is the source concentration of nuclide *i*. The specific nuclide names depend on user specification.

parResBasicSampleValues: see *parBldBasicSampleValues*.

parResConstantValues: see *parBldConstantValues*.

parResElementSampleValues

This table contains the values for the element-dependent parameters for each sample vector generated by LHS and each chemical element appearing in the source term decay chain.

[Vector] is a unique sample vector index that ranges from 1 to the number of samples.
[NuclideParameterNameID] is the identifying number of the parameter category matching the *appElementParameterNames* table.
[*element*] is the parameter value for the element corresponding to the field name.

Vector	NuclideParameterNameID	Ni
1	0	51.4315958409505
1	1	0.0144274
1	2	5.06598505778435E-02

parResFieldIndex: see *parBldFieldIndex*.

D.2.6 Sensitivity Analysis Tables (sen tables)

senBldSelectedPvaues, senResSelectedPvalues

[Vector] is the vector number corresponding to simulation number.

The remainder of the fields will contain the value of variables used for the simulation identified by vector number [Vector]. The field names will correspond to the [Symbol] field in tables *senBld/ResSensitiveParams*.

Example:

This table shows that during simulation number one, Rfo* had a value of 0.0000101235.

Vector	RFo*	Rfo	232U+C
1	0.0000101235	0.0000734183	8624.3004
2	0.000010886	0.000115646	9503.931
3	0.0000106881	0.0000136194	10223.7438

senBldSensitiveParams, senResSensitiveParams

These tables are created by the DandD software for sensitivity analysis. There is one entry in this table for each of the uncertain variables.

[ParameterID]	identifies the parameter ID. It matches with [ParameterID] in *appNuclides*, *appParameter*, etc.
[Symbol]	is the symbol used to identify this parameter from within the modeling codes.
[Description]	is a detailed description of the parameter.
[Default]	is 0 (False) if the parameter value is different than the screening (default) value. is -1 (True) if the parameter value is the same as the default value.
[Units]	are the units associated with the parameter value.
[KSProb]	are the results of the Komolgorov-Smirnov (K-S) test for sensitivity.
[Sensitive]	is 0 (false) if 1 - [KSProb] <.95. In other words, False if varying parameter values do not affect TEDE values significantly. is -1 (True) if varying parameter does affect TEDE value.
[Selected]	is -1 (True) if parameter has been selected for analysis; zero (False) otherwise.
[Committed]	is a boolean indicator (-1 or 0) used by the DandD software to indicate if the selection of a parameter should be retained.

Example:

ParameterID	Symbol	Description
4	RFo*	Effective resuspension factor during the occupancy period = RFo * Fl
287	Rfo	Resuspension factor for loose contamination
1188	232U+C	Concentration of 232U+C

Default	Units	KSProb	Sensitive	Selected	Committed
0	1/m	2.954970987048E-04	-1	-1	-1
-1	1/m	0.711234867572784	0	-1	-1
0	nCi/m**2	4.57946978948964E-11	-1	-1	-1

senResSelectedPvalues: see *senBldSelectedPvalues*.

senResSensitiveParams: see *senBldSensitiveParams*.

D.2.7 User Settings Tables (usr tables)

usrSettings

This table contains a single record consisting of session settings. It is initialized when the session is created. Some fields can be modified by the user during the session.

[Title] is the session title.
[Description] is the description of the session.
[Version] is the database version used for compatibility checking by the interface.
[Scenario] indicates the current scenario selected by the user at the time the session file was closed. The value of this field matches with a value of *appSenario.SenarioID*.

Example:

Title	Description	Version	Scenario
My First Session	details are typed here	2.1.0	Building Occupancy

D.2.8 Other Tables

These tables are used by the software as scratch workspaces, and are not relevant to the site specification or results; *resScratchImportCon*, *usrScratch*.

D.3 References

Beyeler, W.E., W.A. Hareland, F.A. Duran, T.J. Brown, E. Kalinina, D.P. Gallegos, and P.A. Davis, 1999. "Residual Radioactive Contamination From Decommissioning, Parameter Analysis, Draft Report for Comment," Sandia National Laboratories, NUREG/CR-5512, Volume 3, October 1999.

APPENDIX E TABLES OF TECHNICAL DATA

E.1 Introduction

This appendix contains auxiliary information on data tables needed to calculate annual total effective dose equivalents (TEDEs) for the residual radioactive contamination scenarios defined in Kennedy and Strenge (1992) with differences as described in Appendix A (taken from Wernig et al. (1999)). These tables cannot be changed by the user of the DandD software. The data in these tables can be reviewed through the DandD graphical user interface (see Section 4.3.8).

E.2 Radioactive Decay Data

The radioactive decay chain table contains decay data for the master list of radionuclides. The decay chain representations in the table are taken from International Commission on Radiological Protection (ICRP) Publication 38 (ICRP, 1983). The table contains a data set for each radionuclide or chain, except natural thorium and natural uranium, for which dose factors are calculated from entries for the radionuclides in the decay chain. For single-member chains (i.e., no progeny), the table contains the radionuclide name, decay half-life, and atomic number. Decay chains having progeny also contain listings for each chain member, including the radionuclide name, decay half-life (explicit members only), atomic number, and branching information.

The chains in the radioactive decay chain table are organized by atomic number of the decay chain parent. Within each decay chain, members follow according to their decay sequence. The treatment of progeny radionuclides as implicit or explicit is indicated by the presence of a value for the radioactive half-life. Implicit radionuclides have no value for the radioactive half-life, while explicit radionuclides have the half-life listed. The table also includes a chain member position index for each explicit radionuclide, with the parent always having position 1. The position indices are used to indicate the decay sequence, which is necessary when branching occurs. Implicit radionuclides have no chain member position index because they are not included in the decay calculations performed by the decay processor.

The branching information listed in the table defines the sequence and fraction of parent decays that result in the production of each chain member. The branching fractions defined for each member indicate the source of production of the chain member. This convention is the opposite of the usual method of defining the fractions for the parent and an indication of the radionuclides produced by the parent decay. A chain member may be produced by one or two precursor chain members. The decay chain table contains the following information:

- index of the first precursor (if any) for the chain member,
- fraction of first precursor decays that result in production of the chain member,
- index of the second precursor (if any) for the chain member, and
- fraction of second precursor decays that result in production of the chain member.

The decay fractions for implicit progeny represent the total fraction of explicit precursor decays that result in production of the implicit progeny. The atomic number as provided in the radioactive decay database is used as a cross-reference index with other element-specific data.

E.3 Dose Equivalent Factors

External dose conversion factors and internal committed effective dose equivalent (CEDE) factors were obtained from existing Federal Guidance published by the Environmental Protection Agency (EPA), implementing the recommendations of the ICRP. This table provides a complete listing of these factors.

E.3.1 External Dose Rate Conversion Factors

The external dose rate conversions were obtained directly from the EPA Federal Guidance Report No. 12 developed by Oak Ridge National Laboratory (ORNL) (Eckerman and Ryman, 1992). These factors provide the external effective dose equivalent by summing the product of individual organ doses and organ weighting factors over the body organs. These factors are consistent with ICRP 26 (1977) guidance; however, they are inconsistent with the concept of deep dose equivalent, as defined by the NRC (see Appendix F of Kennedy and Strenge, 1992). For purposes of this generic study, the EPA factors are judged to be an adequate representation of the external dose because skin is not considered as one of the organs. For most radionuclides,

the numerical difference between the effective dose equivalent evaluated without skin and the deep dose equivalent will be a few percent. If skin were included, the difference would likely be greater for radionuclides with low photon energies. The external dose rate conversion factors from the EPA are used to determine factors for the source conditions used for this study: 1) infinite surface (thin-layer) contamination (for surface sources in the building occupancy scenario), and 2) volume contamination in a 15-cm-thick slab source (for surface-soil sources used in the residential scenario). The table contains the external dose conversion factors for exposure to surface and volume sources. These factors are in units of

- Sv/d per Bq/m^2 for external exposure to surface sources and
- Sv/d per Bq/m^3 for external exposure to volume sources.

E.3.2 Inhalation and Ingestion Dose Conversion Factors

For inhalation and ingestion of radioactive materials, unit CEDE conversion factors were obtained from EPA Federal Guidance Report No. 11 (Eckerman, Wolbarst, and Richardson, 1988). This Federal Guidance Report supersedes previous Federal Radiation Council (FRC) guidance and, in addition to listing CEDE conversion factors per unit intake, it presents values for derived annual limits on intake (ALIs) and derived air concentrations (DACs). The unit CEDE conversion factors for inhalation and ingestion from the EPA references are included in the table for the radionuclides considered in this application. These factors are in units of Sv/Bq inhaled or ingested.

E.4 Residential Soil Characteristics

Several input parameters represent characteristics of the surface soil or the soil of the unsaturated layer. These parameters include porosity, infiltration rate, and saturation ratio. Rather than sample independently from distributions of these parameters, the dependence of these parameters is represented by first sampling soil texture then selecting an appropriate distribution for the soil characteristics. These soil characteristics include porosity, hydraulic conductivity, and a shape parameter "b" for the soil moisture retention curve. The model input parameters are then calculated from these soil characteristics as described in the on-line references for the hydrologic parameters.

A common method of describing and quantifying soil texture is the U.S. Department of Agriculture (USDA) soil textural classification (Soil Survey Staff, 1997). This classification was used by Meyer et al. (1997) to represent the variability of a number of soil hydrologic properties that are related to porosity and saturation ratio. The USDA soil textural classification is also reported in a variety of available electronic databases for the United States.

Normal distributions of porosities (assumed to be equivalent to saturated water content) are given in Carsel and Parrish (1988). They are reported based on the 12 Soil Conservation Service textural classifications and a compilation of data for each of the textural classes. The soil characteristics table contains the means and standard deviations for these normal distributions.

Distributions of saturated hydraulic conductivity are given in Carsel and Parrish (1988). They are reported based on the 12 Soil Conservation Service textural classifications. Carsel and Parrish (1988) fitted distributions from a class of transformed normal distributions. Meyer et al. (1997) refitted the distributions of Carsell and Parrish (1988) to distributional forms that are more commonly used and more easily constructed— either lognormal or beta. The lognormal distribution is completely specified by the mean and standard deviation while the beta distribution is completely specified by mean, standard deviation, and range (upper and lower limits of the distribution). The soil characteristics table contains the parameters for these distributions for each of the 12 soil types.

Campbell (1974) derived a relationship between unsaturated hydraulic conductivity and saturation ratio that includes a curve fitting parameter "b" related to pore size distribution. Meyer et al. (1997) derived a relationship for "b" using soil water retention parameters considered in Carsel and Parrish (1988). Using this relationship, Meyer et al. (1997) constructed distributions for "b." The soil characteristics table lists the parameters for these distributions for each of the 12 soil types.

See DandD's on-line reference for hydrologic parameters for more information on how this data is used.

E.5 Residential U.S. Bureau of Reclamation Percolation Fractions

The U.S. Bureau of Reclamation (USBR) has developed an empirical relationship between soil permeability and the proportion of water that percolates beneath the root zone (USBR, 1993). The percolation fraction table contains the permeability-percolation fraction pairs that define this relationship. This relationship is used to derive the default distributions for saturation fraction and infiltration rate.

See DandD's on-line reference for hydrologic parameters for more information on how this data is used.

E.6 References

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Wernig, M.A., A.M. Tomasi, F.A. Durán, and C.D. Updegraff, 1999, *Residual Radioactive Contamination From Decommissioning: User's Manual*, Vol. 2, Draft Report, NUREG/CR-5512, U.S. Nuclear Regulatory Commission, Washington, DC.

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10. SUPPLEMENTARY NOTES

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11. ABSTRACT *(200 words or less)*

The Decommissioning and Decontamination (Dand D) software package developed by Sandia National Laboratories for the Nuclear Regulatory Commission (NRC) provides a user-friendly analytical tool to address the dose criteria contained in NRC's Radiological Criteria for License Termination Rule (10 CFR Part 20 subpart E). Specifically, Dand D embodies the NRC's screening methodology and Dand D are part of a larger decision framework that allows and encourages licensees to optimize decisions regarding alternative actions at their site, including the collection of additional data and information. The screening methodology employs reasonably conservative scenarios, fate and transport models, and default parameter values and parameter distributions to allow the NRC to quantitatively estimate the risk of terminating a license given only information about the level of contamination. A licensee has the option of specifying only the level of contamination and running the code with the default parameters or, if site-specific information is available, modifying scenario pathways or providing site-specific parameter distributions and then calculating dose. Version 2.1 of the software allows probabilistic (Monte Carlo) dose assessments and incorporates a new and improved Microsoft Windows standard user interface.

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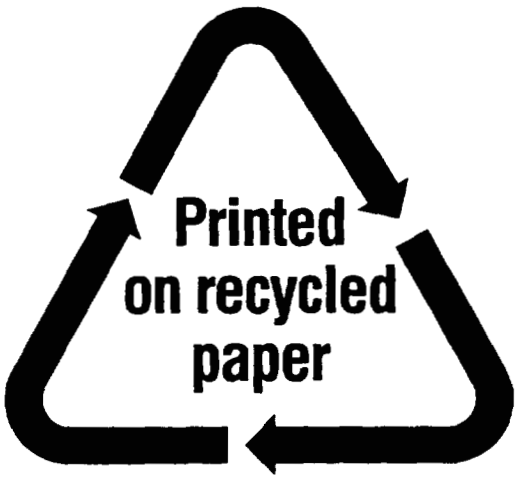

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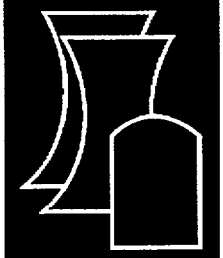

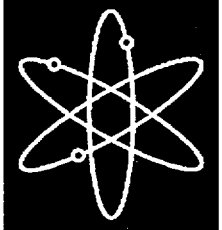

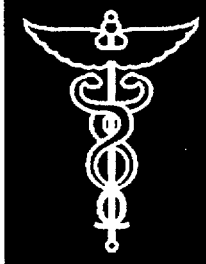

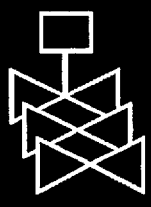

Residual Radioactive Contamination From Decommissioning

Parameter Analysis

Draft Report for Comment

Sandia National Laboratories

U.S. Nuclear Regulatory Commission
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Residual Radioactive Contamination From Decommissioning

Parameter Analysis

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Abstract

NUREG/CR-5512 is a multi-volume report describing a generic modeling analysis of the potential radiation dose from exposures to residual radioactive contamination after the decommissioning of facilities licensed by the U.S. Nuclear Regulatory Commission. Individual volumes describe the generic scenarios, models, and parameter values for screening calculations, and the software that implements these calculations. This third volume describes the analysis used to define default parameter values for the Building Occupancy and Residential scenarios and the results of that analysis. Different procedures are used to define default values for parameters that characterize the behavior of potential receptors (behavioral parameters) and parameters that characterize the physical features of the site (physical parameters). Both procedures start from a literature review which identifies current sources of data about the parameter, considering the way the parameter is defined and used in the screening model. Behavioral parameters represent the average member of the critical group. For screening calculations, a screening group has been defined for each scenario, and a distribution of parameter values was assigned that describes the variations among individuals in the screening group. The default value for behavioral parameters is the average value of this distribution. Values for physical parameters depend on the conditions existing at each site. Screening calculations are designed to support dose-based decisions without requiring information about specific site conditions. To provide this support, the range of conditions that might exist at licensed sites was used to develop distributions describing the variability in site-specific parameter values. These distributions were then used, along with the scenario models defined in Volume 2, to derive distributions of potential dose values for unit concentrations of individual source radionuclides. Parameter values were then identified which produce dose values in the upper quantiles of the distributions for all source radionuclides. The resulting parameter values define a generic screening calculation that has a limited risk of underestimating a site-specific dose calculation based on the generic scenarios, models, and screening group. The distributions that underlie these parameter values provide a basis for developing site-specific parameter values for the generic models.

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FOREWORD

This technical report, NUREG/CR-5512, Volume 3, was prepared by Sandia National Laboratory under their DOE Interagency Work Order (JCN W6227) with the Radiation Protection, Environmental Risk & Waste Management Branch, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission. This report is the third volume to be published in the NUREG/CR-5512 series and provides detailed descriptions of the parameters used in the model, and the methodology and results of the parameter analysis that was performed to select a default parameter set for use in simple screening.

NUREG/CR-5512 technical report series includes Volume 1, which describes the scenarios and calculational approach for translating residual radioactivity to dose. Volume 2 is the User's guide for the DandD software, which automates the dose calculations described in Volume 1. Volume 2 also contains an appendix which describes the changes that have been made to the models and calculations since the publication of Volume 1. This series of reports is a part of the technical basis for the License Termination Rule (10 CFR 20, Subpart E), and was used to develop the implementation guidance for the Rule.

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1.0 Overview

NUREG/CR-5512 is a multivolume report describing a generic modeling analysis of the potential radiation dose from exposures to residual radioactive contamination after the decommissioning of facilities licensed by the U.S. Nuclear Regulatory Commission (NRC). Individual volumes describe the generic models, scenarios, and parameter values for screening calculations of the potential dose, and the software that implements those calculations. Volume 1 of this report (Kennedy and Strenge, 1992 [hereafter referred to as "Volume 1"]) provides the technical basis for translating residual contamination levels to annual dose for decommissioned sites. Volume 1 describes four exposure scenarios, and defines default models for these scenarios. Volume 2 (Wernig et al., 1999) is a user's manual for DandD, the computer software that implements the models defined in Volume 1, which runs under Microsoft® Windows. This document, Volume 3 of the report, presents the procedures and results of the default parameter analysis. Volume 4 documents the comparison of DandD models to models developed for similar purposes.

In this volume, Section 2 summarizes the purpose of the dose modeling to provide a context for the default parameter analysis. Section 3 presents the theory and procedure underlying the parameter analysis. The primary input to this procedure is a set of probability distributions describing uncertainty in model parameter values. Section 4 discusses the interpretation and use of these distributions in the analysis, and some general considerations for defining the distributions.

The procedure described in Section 3 was applied separately to two exposure scenarios and associated dose models defined in Volume 1: the building occupancy scenario and residential scenario. Section 5 describes the parameter analysis of the building occupancy scenario, while Section 6 describes the parameter analysis for the residential scenario. Each section includes an overview of the scenario, the default model, and each parameter used in the model. Probability distributions are defined for most of the model parameters, and the bulk of each section is devoted to the literature reviews and analyses that underlie these distributions. For each uncertain parameter, the current relevant literature is identified, reviewed, and assessed and used to develop a probability distribution for the parameter. The results of the analysis include probability distributions of dose for each individual radionuclide that may be specified in the model source term, and a set of parameter values which, if used to calculate dose, produce a dose value at least as large as a specified quantile of the dose distributions for all source radionuclides. These results are summarized for both scenarios. A summary of the procedure and results is provided in Section 7.

2.0 Introduction

2.1 Overview of the NUREG/CR-5512 Methodology

The NRC is responsible for evaluating requests from facility owner/operators for the partial or total termination of NRC operating licenses for their facilities. This evaluation is based on radiological criteria in defined in 10 CFR 20 Subpart E (NRC, 1997). These criteria establish limits on the annual total effective dose equivalent (TEDE) received during a year to an average member of the critical group (AMCG). The critical group is "the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances" (10 CFR 20.1003).

An overall framework for decision making based on these criteria is defined in draft NUREG-1549 (NRC, 1998). This framework entails iterative dose assessments. Each assessment is designed to provide a defensible basis for terminating the license if the calculations meet the limits defined in the radiological criteria. If the limits are not met, the framework allows the licensee to evaluate a range of alternative strategies. Alternatives may include remedial action at the site, but may also include data collection designed to refine the dose assessment calculation. This framework allows the licensee to coordinate their data collection efforts, and other site management actions, to follow the most efficient path to license termination.

Implementing this framework requires a process for assessing dose that can be used with various amounts of information. To provide the greatest flexibility in tailoring data collection to site conditions, the initial dose assessment should require a minimum amount of site data. The decision framework optimizes the transition to more information-intensive site-specific assessments if such assessments are needed. The scenarios, models, and parameters defined in NUREG/CR-5512 are designed for the purpose of providing a defensible basis for calculating dose with minimal information requirements.

Volume 1 defines a Building Occupancy Scenario for assessing unrestricted release of buildings having residual contamination on building surfaces. For unrestricted release of land having soil contamination, Volume 1 defines a Residential Scenario which considers the residential use of the property, including the use of groundwater for drinking and irrigation of farm products. For each scenario, a set of potential exposure pathways have been identified based on the assumed location of residual contamination and receptor behavior. Mathematical models are also defined for each of these pathways in Volume 1, as well as provisional values for the model parameters.

2.2 Background and Previous Work

In 1987, Pacific Northeast Laboratories (PNL) began developing the NUREG/CR-5512 methodology to translate residual radioactive contamination levels into potential radiation doses to the public. A draft of NUREG/CR-5512, Vol. 1, was issued for comment in January 1990. During 1990 over 250 technical and policy comments were received on this draft. The technical approach was revised, and the final Volume 1 report was issued in 1992.

During 1993 Sandia National Laboratories (SNL) calculated dose conversion factors (DCFs) using the NUREG/CR-5512 methodology to support the NRC's draft regulatory guide NUREG-1500 (Daily et al., 1994) and the draft generic environmental impact study (dGEIS) on radiological criteria for decommissioning, NUREG-1496 (NRC, 1994). Four separate FORTRAN computer codes were developed to perform these calculations. These codes implemented the mathematical models defined in Volume 1 for four exposure scenarios: building occupancy, building renovation, drinking water, and residential. The codes were developed by SNL specifically for these calculations and were not designed for external release or use.

In 1994, SNL began developing DandD, a user-friendly software product that implements the NUREG/CR-5512 methodology. DandD integrates the scenario model codes originally developed by SNL with a graphical user interface. DandD is designed to run under Microsoft® Windows with a minimal hardware configuration. A beta version of DandD was released in August 1995. The code was modified based on comments on the beta version. Version 1.0 of DandD was released on July 1998. The user's manual for this program is Volume 2 of NUREG/CR-5512 (Wernig et al., 1999).

Throughout the process of supporting the NUREG-1500 and GEIS calculations, and implementing and testing the DandD software, SNL and the NRC staff continued to evaluate and improve the NUREG/CR-5512 methodolo-

gy. Several changes and corrections were made to the original methodology described in Volume 1. These changes are documented in Volume 2 (Wernig et al., 1999).

All dose estimates are uncertain due to uncertainty about the processes and parameters that control exposure. The range of possible dose values given this uncertainty must be considered in order to support decisions based on dose. A tendency for a screening calculation to produce a dose value in the upper end of the range of possible doses allows that calculation to be used in decision making (see Section 3 of this document). The scenarios, models, and parameter values defined in Volume 1 were intended to have this tendency, but the supporting arguments were qualitative. NRC directed SNL to develop probability distribution functions (PDFs) for parameters, based on the information in Volume 1 and on any newer published studies, and to identify default values for those parameters suitable for screening calculations. This volume documents the process for defining PDFs and selecting default parameter values.

2.3 Scope and Purpose of the Parameter Analysis

The NRC has designed the scenarios and models described in Volume 1, to be an acceptable basis for evaluating compliance at a wide range of sites while requiring minimal information from the licensee. The parameter analysis described in this document supports this objective by defining values for the parameters of the Volume 1 models that require minimal site specific information and provide a defensible basis for evaluating compliance. In particular, the analysis defines parameter values which can be used in the Volume 1 models given only information about the site source term (in addition to any information required to defend the use of the Volume 1 models themselves).

Four scenarios are defined in Volume 1: building occupancy, building renovation, drinking water, and residential. Only the building occupancy and residential scenarios are used to assess compliance with 10 CFR 20 Subpart E. The models defined in Volume 1 for these two scenarios are considered in this document.

Unlike the provisional default values defined in Volume 1, parameter values defined in this document result from a formal quantitative analysis. This analysis is based on probability distributions for the model parameters which describe the variability in potential site-specific values over the current and future population of licensed sites. The parameter distributions developed in this analysis are based on the use of the parameter in the Volume 1 dose model. Although the information used to develop these distributions may be relevant in other applications, the resulting parameter distributions reflect specific model assumptions (such as the size of the region characterized by the parameter) and are not generally appropriate for other models.

3.0 Theory

3.1 Treatment of Uncertainty in Models and Parameters

Default models and parameter values are designed to allow license termination decisions to be made without requiring site data other than source concentrations. Like all dose assessments used to reach regulatory decisions, screening assessments should be reasonably conservative, meaning that the dose estimate is likely to decrease if more site information was included in the dose calculation. By designing the default models and parameter values so that they tend to overestimate the possible site-specific calculations, the screening dose assessment provides a defensible basis for decision-making without site-specific modeling. The purpose of the parameter analysis is to identify default values for the DandD model parameters that are consistent with this requirement.

A specific procedure for calculating dose can be defended by considering the range of possible calculations that might be made if more information was included in the calculation. Figure 3.1 shows the conceptual design of this procedure. A screening analysis is used to calculate dose using a limited amount of site information. This dose value is then compared to the value that would be calculated if additional site information was used. Because this additional information is not available for the screening calculation, a range of possibilities must be considered, leading to a range of possible site conditions. Each possible condition lends to a possible site-specific dose calculation. The tendency of the screening calculation to overestimate the *possible* calculations can then be assessed. The screening calculations can also be tailored to overestimate an acceptable fraction of the possible calculations.

This process provides a precise and objective characterization of the risk in using the screening calculation to make decisions, but it requires a specific set of alternative calculations to which the screening calculation will be compared. These alternative calculations depend on three factors:

1. The type and amount of additional information that would be available for the alternative calculations,

2. How this information would modify the dose assessment and

3. What range of possible values this information might have.

The conceptual approach illustrated in Figure 3.1 can be applied to manage uncertainty for a broad class of problems. Applying the approach to a specific problem requires definition of the possible site conditions, and corresponding dose calculations, using the three factors described above. The analysis described in this report is designed to control the risk of using the screening calculation to make decisions when the values of the parameters describing the site are unknown. Information added to the screening calculations includes any data that might limit or determine values for the dose model parameters. This information modifies the dose assessment by establishing the appropriate site-specific value for the parameter. The range of possible site conditions is defined by the range of possible parameter values that might be established from this information. The likelihood of obtaining different values for the parameters is described by defining probability distributions for each parameter. These probability distributions allow parameter values to be chosen in a way that quantitatively limits the risk associated with the screening calculation.

3.2 Overview of Procedures used to Define Default Parameter Values

The initial screening calculations are defined by the default parameter values used in place of site-specific values. The method used to establish default values depends on whether the parameter represents the behavior of potential receptors, the metabolic characteristics of potential receptors, or the physical characteristics of the site. The approaches for defining defaults for these distinct classes of parameters are summarized in this section.

Licensees may propose alternative values for physical and behavioral parameters based on site-specific features or conditions, or on site data, as discussed in NUREG/CR-1549 (NRC, 1998). The type of information used to support site specific parameter values depends on whether the parameter describes physical characteristics of the site, or behavioral characteristics of potential receptors.

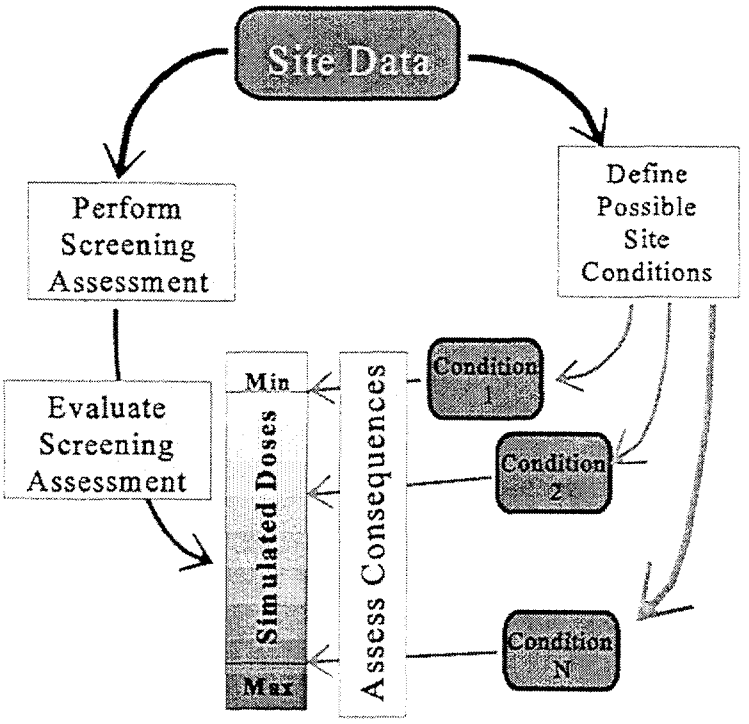

Figure 3.1 Conceptual design for assessing or designing screening calculations

3.2.1 Behavioral Parameters

In a site-specific analysis, behavioral parameters characterize the *AMCG* at the site. The critical group is the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances (10 CFR 20.1003). Default values for behavioral parameters are defined by stipulating a generic *screening group* for the scenario. The screening group is a site-independent population, appropriate for use at all sites, which is reasonably expected to receive the greatest exposure given the scenario definition (generic critical groups are defined in Volume 1). For the building occupancy scenario, the screening group consists of full-time adult male workers in light industry. For the residential scenario, the screening group consists of male resident farmers.

Default values for behavioral parameters were determined by:

1. Identifying the potential variability in the parameter value among individuals in the screening group;
2. Defining a probability distribution describing this variability;
3. Finding the average value from this distribution, which was used to estimate the value for the average member of the screening group (AMSG).

The average parameter value calculated in Step (3) is an estimate of the parameter for the AMSG because the average member is defined as the member receiving the average dose for the screening group, rather than the member with the average behavior. Using average parameter values produce the average dose provided the dose model is a linear function of each of the behavioral parameters. This provision is satisfied by the behavioral parameter values in the default models for the occupancy and residential scenarios.

3.2.2 Metabolic Parameters

Following the recommendation of International Commission on Radiological Protection (ICRP) 43 (ICRP, 1984), parameters representing metabolic characteristics are defined by average values for the general population. These values are not expected to be modified as part of a site-specific analysis. Breathing rates were the only metabolic parameters considered in the analysis.

3.2.3 Physical Parameters

Site-specific values for parameters describing physical characteristics of the site would generally be supported by collecting site-specific data, or by citing relevant literature data. Following the conceptual design shown in Figure 3.1, default values for these parameters were

defined by considering the range of possible site-specific values that might be obtained at a site located anywhere in the United States. The remainder of Section 3 details the procedure used to establish default values for the physical parameters. In overview, this procedure consists of:

1. Identifying the potential variability in the parameter value considering the range of possible site conditions and locations;

2. Defining a probability distribution to describe this variability;

3. For each individual source radionuclide, finding the distribution of doses that might result from a site specific analysis. The dose distribution is based on the distributions of physical parameter values that might be used in such an analysis, defined in Step 2.

4. For each radionuclide, selecting a screening dose value from the dose distribution that is appropriate for decision making (e.g., a value that overestimates some acceptable fraction of the possible values);

5. Identifying parameter values which, when used with any source nuclide, reproduce, as closely as possible, the screening dose value selected from the dose distribution in Step 4.

In the absence of site data, the dose distributions defined in Step 3 describe the potential variability in site-specific dose values, and allow an appropriate dose value to be selected in Step 4 as a basis for making license termination decisions. These screening dose values are defined for unit amounts of individual source nuclides. The parameter values defined in Step 5 provide a way of reproducing these screening dose values for *all sources* using a single DandD calculation, rather than the multiple calculations that would be required to reproduce the complete dose distribution. This procedure produces *one* set of default parameter values that is applicable to all radionuclides.

3.3 Probabilistic Formulation

A screening dose assessment is a defensible basis for making decisions because the dose is likely to be overestimated rather than underestimated. The analysis described below uses a quantitative (probabilistic) definition of "likelihood" to insure that the physical parameter values satisfy this requirement. Demonstrating that a particular dose calculation satisfies this condition requires a probability value for each of the alternative conditions in Figure 3.1. These probabilities are then applied to the possible alternative dose calculations, which the screening calculation should tend to overestimate.

For a particular scenario, the default dose assessment model is denoted by the function m. The model calculates a TEDE value using a vector[1] of input parameters $\mathbf{x}$ and a vector source term specification $\mathbf{s}$:

$$d_T = m(\mathbf{x},\mathbf{s}) \tag{3.1}$$

The goal of the parameter analysis is to find some vector of default parameter values $\mathbf{x_d}$ that are appropriate when site-specific values are unknown. The unknown site-specific parameter values, and site-specific source term, are designated by the random variables $\mathbf{X}$ and $\mathbf{S}$. To be appropriate for decision-making, the set of default parameters is designed to limit the risk of making an incorrect decision.

The default parameter values $\mathbf{x_d}$ can *potentially* lead to an incorrect decision if they underestimate the site-specific dose. This condition is termed an *inversion*, designated by the binary random variable I. Default parameter values are sought which limit the probability of inversion:

$$P(I) = P\left(m(\mathbf{x_d},\mathbf{S}) < m(\mathbf{X},\mathbf{S})\right) \le P_{crit} \tag{3.2}$$

This equation defines a quantitative test following the conceptual design of Figure 3.1. The screening dose calculated with default parameters is required to overestimate all but a fraction P_{crit} of the dose calculations that follow from the possible site conditions. The possible site conditions are defined by the distributions assigned to the random variables $\mathbf{X}$ and $\mathbf{S}$.

There is insufficient information to estimate a distribution for the source term $\mathbf{S}$. Therefore a more restrictive condition is used: the probability of inversion conditional on a unit source is limited for each component of the source vector:

$$P\left(I(\mathbf{s}_i)\right) \equiv P\left(I|\mathbf{S} = \mathbf{s}_i\right) = P\left(m(\mathbf{x_d},\mathbf{s}_i) < m(\mathbf{X}(\mathbf{s}_i),\mathbf{s}_i) \le P_{crit}\right) \qquad i = 1...n_s \tag{3.3}$$

[1]A *vector* is a quantity that is defined by an ordered set of numbers rather than by a single number. A location in a three-dimensional space, for example, is a vector defined by the values for the x, y, and z coordinates of the location.

where:

$$\mathbf{s}_i \equiv \{s_j\} \text{ with } s_j = \begin{cases} 1 & i=j \\ 0 & i \neq j \end{cases} \quad (3.4)$$

The n_s components of the source vector corresponds to the individual radionuclides that can occur in the source term. Table 3.1 lists these radionuclides.

As indicated in Equation 3.3, variability in site-specific parameter values is generally a function of the site source-term. This potential interdependence has been assumed to be insignificant in this analysis, so that:

$$\mathbf{X}(\mathbf{s}_i) = \mathbf{X} \quad (3.5)$$

From Equation 3.1, the (random) site-specific parameters $\mathbf{X}$ produce a (random) TEDE value D_{Ti} for each of the n_s source terms:

$$D_{Ti} = m(\mathbf{X}, \mathbf{s}_i) \quad i = 1 \ldots n_s \quad (3.6)$$

Each of these random dose values has an associated probability distribution F_{Di} that depends on the probability distribution assigned to the parameters. For each F_{Di}, there is an associated quantile d_{Ci} of order $1 - P_{crit}$ such that:

$$F_{Di}(d_{Ci}) \equiv P(D_{Ti} < d_{Ci}) = 1 - P_{crit} \quad (3.7)$$

In order for Equation 3.3 to be satisfied, the TEDE value calculated using the default parameters, denoted d_{Di}, must be larger than the corresponding d_{Ci} for each source:

$$d_{Di} \equiv m(\mathbf{x}_d, s_i) \geq d_{Ci} \quad i = 1 \ldots n_s \quad (3.8)$$

Equation 3.8 defines a set of n_s inequality constraints that must be satisfied by the default parameters. In words, the default values must produce dose values in the upper P_{crit} tail of the dose distribution for each source nuclide.

For both scenario models considered in this analysis, the number of constraints (i.e. source nuclides) is larger than the number of adjustable parameters (i.e. the dimension of $\mathbf{x}_d$)[2]. Solutions for $\mathbf{x}_d$ may not exist for over-constrained problems of this kind. Whether or not solutions can be found depends on the compatibility of the n_s constraints, that is, whether parameter values that tend to produce large doses for one source also tend to produce large doses for other sources.

Appendix B describes the procedure used to solve Equation 3.8. The algorithm generates sets of possible solutions for $\mathbf{x}_d$, which are then evaluated to determine whether they solve Equation 3.8. If no solution is found in the set, the algorithm creates a new set of candidate solutions based on the evaluation.

Multiple solutions to Equation 3.8 were identified for both scenario models. Two figures of merit, the average inversion probability (AIP) and the joint parameter exceedance probability (JPEP), were defined to help select among these solutions. The AIP measures how close a particular solution comes to solving Equation 3.8 as a strict equality, and JPEP measures how plausible the parameter values are.

3.4 Remarks on the Formulation

The screening dose assessment is required to over-estimate a specified fraction of the dose values that are consistent with the available information. This requirement is imposed in order to create a defensible basis for decision making according to the conceptual design described in Section 3.1. The resulting dose estimate is conservative in the sense that it is designed to over-estimate dose with a specified probability.

The formulation of the screening calculation introduces two additional sources of conservatism. First, the probability of an inversion is always larger than the probability of an incorrect dose-based decision, so that limiting the former is a conservative means of controlling the latter. Second, the requirement that the limit on inversion probability be satisfied for all source nuclides using a common set of deterministic parameters practically requires that the limit be surpassed for some source nuclides.

By definition, an inversion occurs whenever the default parameters underestimate the site-specific dose. The default parameters would lead to an inappropriate regulatory decision if the default dose was less than the regulatory limit of 25 mrem, and the site-specific dose was greater than the regulatory limit. Not all inversions lead to potentially inappropriate decisions: limiting the probability of inversion in Equation 3.2 is therefore more restrictive than limiting the probability of an inappropriate decision.

The dose values d_{Di} and d_{Ci} can be interpreted as factors that convert unit amounts each source nuclide i to dose

[2]Note that although the residential scenario model has 652 input parameters, many of these parameters (e.g. partition coefficients and plant uptake factors) are specified by chemical element, and therefore only affect the dose from particular radionuclides.

values which might be used to reach a regulatory decision. The dose conversion factor d_{Ci} is *the minimum dose factor that satisfies the specified risk tolerance* P_{crit}. The probability that a site-specific dose (for a unit source) would exceed d_{Ci} is exactly P_{crit}, given the assumptions underlying the dose model m. The default dose conversion factor d_{Di} must be at least as large as d_{Ci}, as indicated in equation (3.8). In addition to satisfying the specified risk tolerance P_{crit}, the d_{Di} values are further required to arise from a common set of parameter values for all sources.

An explicitly probabilistic screening calculation would use the dose conversion factor d_{Ci} directly as the dose (per unit source) that overestimates site-specific dose with a likelihood of $1 - P_{crit}$. By definition, the "real" dose (represented by the calculation using model m and site-specific parameters) is greater than this value with probability P_{crit}. The calculation using the default parameters is instead apparently deterministic, in that only a single calculation using $\mathbf{x}_d$ is required. The default parameters $\mathbf{x}_d$, however, are selected and justified through the underlying probabilistic analysis: the resulting "default" dose d_{Di} must be greater than (or equal to) the corresponding quantile of order $1 - P_{crit}$, d_{Ci}. The default parameters are simply a mechanism for producing doses that bound the appropriate quantiles for all sources.

The advantage of using default parameters to make screening decisions is that the deterministic defaults subsume the complexities of the underlying (probabilistic) justification. The disadvantage is that the "default" doses d_{Di} are more restrictive than the doses d_{Ci} (which exactly satisfy the specified tolerance for decision error) because the "default" doses are required to come from a common set of parameter values for all sources.

Table 3.1 Source nuclides used in the parameter analysis

Source ID	Source*	Source ID	Source	Source ID	Source
1	3H	87	126Sn+C	180	232Th
2	10Be	89	125Sb	181	232Th+C
3	14C	93	123mTe	183	231Pa
5	22Na	95	127mTe	184	231Pa+C
9	35S	106	129I	187	232U
10	36Cl	114	134Cs	188	232U+C
11	40K	115	135Cs	189	233U
12	41Ca	117	137Cs	190	233U+C
13	45Ca	128	144Ce	191	234U
14	46Sc	132	147Pm	192	235U
16	54Mn	137	147Sm	193	235U+C
18	55Fe	138	151Sm	194	236U
20	57Co	140	152Eu	196	238U
21	58Co	141	154Eu	197	238U+C
22	60Co	142	155Eu	199	237Np
23	59Ni	144	153Gd	200	237Np+C
24	63Ni	145	160Tb	203	236Pu
27	65Zn	146	166mHo	205	238Pu
31	75Se	147	181W	206	239Pu
32	79Se	148	185W	207	240Pu
41	90Sr	150	187Re	208	241Pu
48	93Zr	151	185Os	209	242Pu
49	93Zr+C	153	192Ir	211	244Pu
52	93mNb	156	210Pb	212	241Am
53	94Nb	160	210Po	213	242mAm
58	93Mo	165	226Ra	215	243Am
61	99Tc	166	226Ra+C	216	242Cm

Table 3.1 Source nuclides used in the parameter analysis (continued)

Source ID	Source*	Source ID	Source	Source ID	Source
65	106Ru	167	228Ra	217	243Cm
69	107Pd	169	227Ac	218	244Cm
71	110mAg	170	227Ac+C	219	245Cm
73	109Cd	173	228Th	220	246Cm
74	113mCd	174	228Th+C	221	247Cm
81	119mSn	175	229Th	222	248Cm
82	121mSn	176	229Th+C	223	252Cf
84	123Sn	177	230Th		
86	126Sn	178	230^{Th}+C		

* "+C" denotes equilibrium initial activity assumption for progeny. Initial progeny activity is zero for all other radionuclides.

4.0 Use of Parameter Distributions in Dose Calculations

Although distributions are used to define defaults for both behavioral and physical parameters, distributions for behavioral and physical parameters describe different types of variability, and have different roles in the analysis:

- *Behavioral parameter distributions* describe variability over individuals in the screening group. These distributions serve two purposes: the average values define the default behavioral parameter values, and the range of values allows the range of doses to individual members of the screening group to be calculated. This calculation of the possible variability in dose to individuals provides assurance that the defined screening group is homogeneous.

- ICRP-46 proposes that the "critical group ... should be relatively homogeneous," while ICRP-43 suggests that "to satisfy the homogeneity requirement the ratio of maximum to minimum [dose] values should not exceed an order of magnitude."

- *Physical parameter distributions* describe variability in parameter values over sites. These distributions also represent uncertainty in the value at a particular site if no site-specific information is available about that parameter. Like the behavioral parameters, default values for physical parameters depend on the assigned distributions. Unlike the behavioral parameters (which are selected directly from their respective distributions), default values for the physical parameters must satisfy restrictions based on the dose distribution, as detailed in Section 3.3. The dose distribution is derived from the distributions for all physical parameters.

4.1 Considerations for Defining Parameter Distributions

As used in this analysis, both behavioral and physical parameter distributions describe the variability of values over a population. It is possible, in principle, to establish these distributions exactly using a large number of measurements from the defined population. In practice this is not possible because the number of available measurements is often quite small and the measured quantities often do not directly correspond to the model parameters. There is some uncertainty about the parameter distributions arising from the assumptions needed to develop these distributions from limited information.

In general there is less uncertainty about the distributions of behavioral parameters than about the distributions for physical parameters. This is because relevant human behavior has been extensively studied for risk assessment purposes, and the screening groups for both scenarios closely correspond to population groups used to summarize results from these studies. The main limitation of behavioral data is the difference in time scale between the data collection period (typically a single day) and the one-year model exposure period. This discrepancy can introduce uncertainty about the parameter distribution as a whole, yet the default values, which are defined as the mean values of the behavioral parameter distributions, are arguably unaffected. In contrast, the population of licensed sites has not been extensively characterized to define distributions of physical parameters. Assumptions are therefore required to relate data reported in the literature to this specialized population. As an example, licensed sites are assumed to be uniformly spatially distributed across the contiguous United States.

Uncertainty in parameter distributions themselves can be quantified by assigning probability values to the alternative parameter distributions that are consistent with available information. An embedded probabilistic analysis of this kind would provide a rigorous and formal treatment of uncertainty about the parameter distributions. The additional information, interpretation, and analysis that would be required, however, are beyond the scope of the current analysis. Uncertainty in parameter distributions was treated qualitatively by describing, for each parameter, the limitations of existing information in determining a distribution for the parameter. These qualitative descriptions of uncertainty could be the basis for assigning probabilities to alternative distributions, and therefore serve as the first step in any formal quantitative treatment of uncertainty in distributions.

4.1.1 Behavioral Parameters

Distributions for the behavioral parameters were developed using the definition of the screening group for each scenario. Large national population studies have been conducted to characterize human behavior, often for the specific purpose of providing data for exposure assessments (e.g., the studies cited in the Exposure

Factors Handbook (U.S. Environmental Protection Agency [EPA], 1996), the Nationwide Food Consumption Survey (U.S. Department of Agriculture [USDA] 1993)). Data from these studies provide a good basis for estimating the time that individuals spend in various activities and environments, and their rates of consumption of various goods and substances. Data are typically reported for population cohorts defined by age, race, sex, geography, as well as by other factors. Distributions describing the screening group were generally developed from these studies by identifying a cohort that most closely matched the definition of the screening group. As discussed above, data on activity and consumption are typically collected over a period of days or weeks, and are therefore more variable than the annual average values required by the scenario models. Discrepancies between the measurement time scale and the model time scale are discussed for each of the behavioral parameters (Sections 5.2 and 6.2).

4.1.2 Physical Parameters

Unlike the behavioral parameters, a large number of representative samples is usually not available for defining physical parameter distributions. Physical parameter distributions describe the variability of the physical parameters over the licensed sites. The population of licensed sites, unlike the general population of humans, is not a common subject of study. Distributions must often be assembled from separate studies of specialized situations. Constructing distributions in this way necessarily requires assumptions about the representativeness of the available information, that is, how well the existing studies cover the range of possible site conditions. Variations in experimental conditions among studies create uncertainty about whether and how their separate results can be pooled. As discussed above, these considerations create uncertainty about how accurately the parameter distributions describe variability over licensed sites. In developing the parameter distributions, the key assumptions are identified and discussed, however the resulting uncertainty is not quantified. The assigned distribution generally depends, to some extent, on judgements made in consideration of this uncertainty. The diversity in the amount, type, quality, and relevance of available data for the various physical parameters led to diverse procedures for defining distributions.

Measurements reported in the literature seldom correspond to the conditions defined for the scenario. To develop a parameter distribution, reported data must be interpreted in light of the use of the parameter in the model. Like the behavioral parameters, experimental data are typically collected at a smaller scale than the scale of the corresponding model parameter, which represents an annual average value over an extensive exposure area. Discrepancies in time scale are important for some parameters (such as dust loading), but are not important when the phenomenon characterized by the parameter is expected to be constant over time (e.g., soil density).

Discrepancies between the spatial scales of the model parameters and experimental data are common. Usually the experimental results cover a smaller area than the corresponding model parameter, and are collected over a much shorter period than the one year exposure period used in the scenario models. When this is true, the model parameter values are estimated by averaging some number of the experimental results to produce an effective value over the area and time period used in the model. The potential variability in model parameter values is therefore smaller than the potential variability in experimental values because of this averaging process.

Some parameters are supported by a large body of experimental data. In these cases the potential variability in experimental values is captured in the actual variability in reported results. In other cases very few relevant experimental results were identified. In these cases available data cannot be assumed to reflect the potential variability in experimental results because of the small sample size. In these cases, the assigned parameter distribution can extend beyond the range of reported experimental results.

4.2 Modifying Default Distributions with Site-specific Data

4.2.1 Behavioral Parameters

Behavioral parameter values are a function of the critical group used in the dose assessment. The defaults defined in this analysis reflect the generic screening group. Alternative distributions, leading to alternative mean values, can be supported by defining a site-specific critical group. NUREG/CR-1549 discusses the procedure for defining such a critical group. Once defined, the data sources and procedures used in this analysis (see Sections 5.2 and 6.2) should be reviewed to determine whether the site-specific screening group corresponds to one of the cohorts defined in the cited studies. If so, distributions for the screening group can be developed using data for the corresponding cohort. If not, distributions for the screening group might be developed

using the raw survey data from a large national sample (e.g., the National Human Activity Pattern Survey) by selecting observations for individuals matching the critical group definition.

4.2.2 Physical Parameters

The physical parameter distributions defined in this analysis describe the variability of parameter values over all potential sites. As discussed above, these parameter distributions also describe uncertainty about the value at a particular site provided no additional information about that parameter is available. If additional parameter information is available for a site, this information reduces uncertainty about the parameter value. A site-specific parameter distribution is therefore expected to be narrower than the distribution defined in this analysis. The spread of the parameter distribution decreases as more information, or more accurate information, is included, ultimately converging on a single value if all uncertainty is eliminated.

Site specific information can be incorporated by updating the distributions defined in this analysis. There are two basic strategies for integrating site information with the information used to define the default distributions. Site information can be used to screen the data cited in this report by demonstrating that certain values or value ranges are not appropriate for the site, or new data specific to the site can be added to the data considered in this analysis, either supplementing or replacing the data used here. Whether site information is used to filter the default data set, or to supplement or replace the default data set, will depend on the type of information provided, the type of information in the default data set, and on other site-specific considerations.

The default parameter distributions describe the variability of parameter values over all sites. In the filtering approach, the effect of information about a particular site is to identify which subset of all sites the current site belongs to. For example, the initial distribution for the hydrologic parameters in the residential scenario model is based on the relative frequency of soil classifications across the United States. If the soil classification for a site can be determined, this information can be used to limit the ranges of values for a variety of hydrologic parameters (see Section 6.4.3 for the connection between soil classification and model parameters).

Measurements made at a site, or at a suitable analog location, might also be used to supplement or replace the data used to define default parameter distributions. The specific procedure for integrating new experimental information with the data cited in this analysis will depend on the amount, type, and quality of new data, and on the amount, type, and quality of data used to establish the default distributions. Specific procedures are not proposed because of the wide diversity of circumstances. There are several important factors that will need to be considered, however, when using any set of experimental data to establish parameter values, including:

- Differences between the experimental conditions and the conditions defined for the scenario;
- Differences between the temporal and spatial scales of the experimental results and the scenario model;
- Potential errors or bias in the experimental data.

These factors should be considered both for the data sets used in this analysis, and for any site specific data. The relative strengths of each data set, according to these factors, should be considered when developing a site-specific parameter distribution.

5.0 Building Occupancy Scenario in NUREG/CR-5512

The building occupancy scenario model, as defined in Volume 1 and implemented in Release 1.0 of DandD (Wernig et al., 1999), is based on the following assumptions:

- Radioactive dose results from exposure via three major exposure pathways:
  - (1) external exposure to penetrating radiation from surface sources,
  - (2) inhalation of resuspended surface contamination, and
  - (3) inadvertent ingestion of surface contamination
- Four other potential exposure pathways are not included in the analysis:
  - (1) external exposure during submersion in airborne radioactive dust,
  - (2) internal contamination from puncture wounds infected by contaminated surfaces,
  - (3) dermal absorption of radionuclides, and
  - (4) inhalation of indoor radon aerosol
- The building will be commercially used after decommissioning.
- The occupancy of the building will occur immediately after its release.
- The residual contamination will be represented by a thin surface layer left on the inner building surfaces.
- The exposure type will be a long-term chronic exposure to low level radioactive contamination since major contamination will be cleaned up prior to decommissioning.

The building occupancy scenario model includes eight parameters:

- External dose rate factor for exposure from contamination uniformly distributed on surfaces, $DFES_j$ (mrem/h per dpm/100 cm^2)
- Inhalation committed effective dose equivalent (CEDE) factor, DFH_j (mrem/pCi inhaled)
- Ingestion CEDE factor, DFG_j (mrem/pCi ingested)
- Length of the occupancy period, t_o (d)
- Time that exposure occurs during the occupancy period, t_o (d)
- Resuspension factor for surface contamination, RF_o (m^{-1})
- Volumetric breathing rate, V_o (m^3/h)
- Effective transfer rate for ingestion of removable surface contamination from surfaces to hands, from hands to mouth, GO (m^2/h)

The length of the occupancy period (t_{to}), the time that exposure occurs (t_o), and the effective transfer rate for ingestion (GO) are behavioral parameters. The volumetric breathing rate (V_o) is a metabolic parameter. The committed effective dose equivalent factors and the resuspension factor are physical parameters. As discussed below, the committed effective dose equivalent factors are classified as physical parameters because their values depend on the source geometry and contaminant solubility class.

The annual TEDE for a parent radionuclide in the building occupancy scenario $TEDEO_i$ is calculated as a sum of:

- external dose resulting from external exposure to penetrating radiation from the surface sources represented by the parent and daughter (if any) radionuclides, $DEXO_i$;
- CEDE for inhalation resulting from inhalation of resuspended surface contamination represented by the parent and daughter (if any) radionuclides, DHO_i; and
- CEDE for ingestion resulting from inadvertent ingestion of surface contamination represented by the parent and daughter (if any) radionuclides, DGO_Q.

The mathematical formulation of the above is (NUREG/CR-5512, Vol. 1, p. 3.14):

$$TEDEO_i = DEXO_i + DHO_i + DGO_i \qquad (5.1)$$

$DEXO_i$, DHO_i, and DGO_i are calculated using the average annual surface activity per unit area of the

parent, C_i, and daughter radionuclides, C_j, during the first year of the building occupancy scenario. Although ingrowth of daughter nuclides may, in some cases, cause TEDE to increase with time, in the default scenario model the maximum TEDE is assumed to occur during the first year of the scenario to simplify the analysis.

The average annual activity is determined as an integral of the radionuclide activities during the first year after the building release over the length of the occupancy period, t_{to}, divided by an averaging time, t_{av}, which is equal to one year (365.25 days). The release of the building is conservatively assumed to occur at time zero, and building occupancy is conservatively assumed to be at least one year. The default value for t_{to} is 365.25 days (see Section 5.2.1 below). The mathematical formulation is as follows:

$$C_{avj} = 1/t_{av} \int_o^{t_{to}} C_j(t)dt = \lambda_{rj} * \sum_{(n=1,j)} K_{jn}\left[\left(1-exp\left(\lambda_{rn} * t_f o\right)/\lambda_{rn}\right)\right]$$
$$K_{jn(n=1 \text{ to } j-1)} = \sum_{(p=n,j-1)} \left[d_{pj} * \lambda_{rp} * K_{pn}\right]/$$
$$\left(\lambda_{rj}-\lambda_{rn}\right)K_{jj} = C_j(0)/\lambda_{rj} - \sum_{(n=1,j-1)} K_{jn} \quad (5.2)$$

where λ_{rj} is the radioactive decay constant of radionuclide j, d_{pj} is the decay fraction, and $C_j(0)$ is the initial activity of radionuclide j. The external dose ($DEXO_i$), the inhalation CEDE (DHO_i), and the ingestion dose (DGO_i) are obtained as follows (NUREG/CR-5512, Vol. 1, pp. 3.12–3.14):

$$DEXO_i = 24 * t_o * \sum_{(j=1,Ji)} DFES_j * C_{avj} \quad (5.3)$$

$$DHO_i = 45.05 * 24 * t_o * RF_o * V_o * \sum_{(j=1,Ji)} DFH_j * C_{avj} \quad (5.4)$$

$$DGO_i = 45.05 * 24 * t_o * GO * \sum_{(j=1,Ji)} DFG_j * C_{avj} \quad (5.5)$$

where J_i, RF_o, V_o, GO, $DFES_j$, DFH_j, and DFGj are, respectively: the number of radionuclides in chain i; the resuspension factor; the volumetric breathing rate; the effective transfer factor; the external dose rate factor; the inhalation CEDE factor; and the ingestion dose factor. Substituting Equations (5.3), (5.4), and (5.5) in (5.1), the annual TEDE can be expressed as:

$$TEDEO_i = 24/365.25 * t_o * \sum_{(j=1,Ji)} \left[C_{avj} * \left(DFES_j + 45.05 * RF_o * V_o * DFH_j + 45.05 * GO * DFG_j\right)\right] \quad (5.6)$$

As Equation (5.6) indicates, TEDE is directly proportional to the parameter t_o. The larger the time that exposure occurs during the building occupancy period, the higher the total dose.

The total dose is not in direct proportion to the other parameters. However, increasing these parameter values will result in a linear increase in the total dose. The sensitivity of dose to the parameters that are not radionuclide specific, such as RF_o, V_o, and GO, will be different for different radionuclides and will depend on the dose factors for each radionuclide in the chain. For example, if the external dose rate factor $DFES_j$ is significantly larger than the inhalation CEDE factor DFH_j and the ingestion dose factor DFG_j for all radionuclides in the chain, then $TEDEO_i$ will not be sensitive to RF_o, V_o, or GO.

5.1 Definition of Screening Group

The screening group is a site-independent population, appropriate for use at all sites, which is reasonably expected to receive the greatest exposure given the scenario definition. For the building occupancy scenario, the screening group consists of full-time adult male workers in light industry.

5.2 Behavioral Parameters

5.2.1 Length of the Occupancy Period, t_{to} (d)

5.2.1.1 Description of t_{to}

The time parameter t_{to} is used to determine the time integral of activity over the building occupancy period, which in turn is used to determine the mean activity level of each radionuclide. The value for this parameter defined in NUREG/CR-5512, Vol. 1, is 365.25 d or one year. Using 365.25 days in a year accounts for a leap year. This represents continuous use of a building for 100% of the calendar year so that, as stated in the regulatory criterion, annual TEDE is calculated. The RESRAD value for the same parameter is 365.0 d.

5.2.1.2 Use of t_{to} in Modeling

The longer the building occupancy period, the higher the total annual dose during the first year of the scenario.

This parameter is used to calculate the average annual surface activity of radionuclide j per unit area C_{avj} during the first year of the building occupancy scenario. The relationship between C_{avj} and t_{to} is given in Equation 5.2 above.

5.2.1.3 t_{to} Uncertainty

The value for this parameter is defined by the regulatory criterion to calculate annual TEDE.

5.2.1.4 Alternate t_{to} Values

This parameter would vary if the licensee defined a site-specific critical group which did not have year-round access to the building.

5.2.2 Time That Exposure Occurs During the One-Year Building Occupancy Period (Behavioral), t_o (d)

5.2.2.1 Description of t_o

The exposure time parameter, t_o, describes the actual time spent on the job during the one-year duration of the building occupancy scenario by the average member of the screening group.

5.2.2.2 Use of t_o in Modeling

The total dose is directly proportional to the time of exposure during the building occupancy period.

As a behavioral parameter, t_o represents the amount of time spent in a contaminated building by the average member of the screening group. This parameter is used to calculate the total dose, $TEDEO_i$, from parent radionuclide i and its daughters due to external exposure to surface contamination, inhalation of resuspended surface contamination, and inadvertent ingestion of surface contamination during the first year of the building occupancy scenario. The relationship between $TEDEO_i$ and t_o is described by the following formula:

$$TEDEO_i = 24/365.25 * t_{o(j=1,Ji)} C_{avj} * \left(DFES_j + 45.05 * RF_o * V_0 * DFH_j + 45.05 * GO * DFG_j\right) \quad (5.7)$$

where J_i is the number of radionuclides in chain i, C_{avj} is the average annual activity of the radionuclide j during first year of the building occupancy scenario, RF_o is the resuspension factor, V_o is the volumetric breathing rate, GO is the effective transfer rate factor, $DFES_j$ is the external dose rate factor, DFH_j is the inhalation CEDE factor, and DFGj is the ingestion dose factor. An increase in the t_o value results in a proportional increase in the annual total dose value.

5.2.2.3 Information Reviewed to Define A PDF for t_o

The value for this parameter defined in NUREG/CR-5512, Vol. 1, is 83.33 effective 24-h days. This is calculated assuming that the actual time on the job is 100% of a work year during which a person spends 2000 h/y working in the building (40-h work week for 50 working weeks with two weeks of vacation/sick leave/any other leave).

The default assumption in the RESRAD code is that 50% of a person's time is spent indoors, while 25% is spent outdoors in the presence of contamination.

For this analysis, data on current work patterns was reviewed to establish a PDF for t_o describing variability among members of the screening group. Information reviewed included Bureau of Labor Statistics (BLS) data on hours worked (BLS, 1996a; BLS, 1996b; and BLS, 1997) and relevant references cited in the EPA Exposures Factors Handbook (1996) for human activity patterns. The following sections summarize the data and information available from these sources.

5.2.2.3.1 BLS Data on Hours Worked

In June, 1996, data from the BLS Current Population Survey (CPS) were obtained from the BLS website. The CPS is a monthly survey. During 1995, the CPS was sent out to approximately 50,000 households a month, and was used to obtain information for about 94,000 persons ages 16 years and older (BLS, 1996a). During 1996, approximately 56,000 household units were surveyed, and information was obtained for about 107,000 persons ages 16 and older (BLS, 1997). Annual averages from the CPS are also published in January issues of *Employment and Earnings* (BLS, 1996a; BLS 1997).

The CPS is used to determine "Characteristics of the Employed" statistics, including hours worked. Current data for "Characteristics of the Employed" can be accessed from the BLS home page for "Labor Force Statistics from the Current Population Survey" at the website http://stats.bls.gov/cpshome.htm. The specific page for the data listings on "Characteristics of the Employed" is located at http://stats.bls.gov:80/cpsaatab.h#charemp. and can be accessed from the CPS home page. In June 1996, the data for persons at work in agriculture and non-agricultural industries by hours of work for 1995 were downloaded and are presented in Table 5.1. These data are also published in the January 1996 issue of *Employment and Earnings*. The reported data range is from 1 to 4 h/wk of work to 60 h/wk and over. The 1995 overall annual average reported is 39.3

h/wk. In April 1997, the data from the 1996 Annual Average Tables (BLS, 1997) were also reviewed. The numbers were slightly different, but the percentages in any range did not differ by more than two tenths of a percent.

The other available BLS data are from the National Current Employment Statistics (CES). These statistics are determined from a industry survey of employers that report man hours, number of employees, and payroll information, but do not report anything about part-time or full-time employees. The website location for these statistics is http://stats.bls.gov:80/cgi-bin/surveymost?ee. In June 1996, several series of data related to national employment, hours, and earnings, were downloaded and reviewed, including the following:

- Total Private Average Weekly Hours of Production Workers - Seasonally Adjusted
- Total Private Indexes of Aggregate Weekly Hours - Seasonally Adjusted
- Total Private Average Weekly Hours of Production Workers - Not Seasonally Adjusted
- Goods-producing Average Weekly Hours of Production Workers - Seasonally Adjusted
- Goods-producing Indexes of Aggregate Weekly Hours - Seasonally Adjusted
- Mining Average Weekly Hours of Production Workers - Seasonally Adjusted
- Manufacturing Average Weekly Hours of Production Workers - Seasonally Adjusted
- Manufacturing Average Weekly Overtime of Production Workers - Seasonally Adjusted
- Manufacturing Indexes of Aggregate Weekly Hours - Seasonally Adjusted
- Private Service-producing Average Weekly Hours of Production Workers - Seasonally Adjusted
- Private Service-producing Indexes of Aggregate Weekly Hours - Seasonally Adjusted

Table 5.1 1995 data for "Persons at work in agriculture and nonagricultural industries by hours of work" (BLS, 1996a)

Hours of work	Thousands of persons			Percent distribution		
	All industries	Agriculture	Non-agricultural industries	All industries	Agriculture	Non-agricultural industries
Total Persons at Work, 16 years and over	119,318	3,247	116,071	100.0	100.0	100.0
1 to 34 hours	30,664	1,051	29,613	25.7	32.4	25.5
1 to 4 hours	1,297	83	1,214	1.1	2.6	1.0
5 to 14 hours	4,943	262	4,681	4.1	8.1	4.0
15 to 29 hours	15,120	476	14,644	12.7	14.7	12.6
30 to 34 hours	9,304	229	9,075	7.8	7.1	7.8
35 hours and over	88,654	2,196	86,458	74.3	67.6	74.5
35 to 39 hours	8,783	173	8,610	7.4	5.3	7.4
40 hours	42,228	635	41,592	35.4	19.6	35.8
41 hours and over	37,643	1,388	36,255	31.5	42.7	31.2
41 to 48 hours	13,958	250	13,708	11.7	7.7	11.8
49 to 59 hours	13,591	388	13,203	11.4	11.9	11.4
60 hours and over	10,094	750	9,344	8.5	23.1	8.1
Average hours, total at work	39.3	42.2	39.2	-	-	-
Average hours, persons who usually work full time	43.4	49.7	43.2	-	-	-

5.2.2.3.2 Data from Studies on Human Activity Patterns

The EPA Exposure Factors Handbook (EPA, 1996) includes a summary of several studies on human activity patterns, including some information relevant for estimating occupancy duration. The discussion for each cited study outlines the methodology and type of data collected, and discusses the strengths and limitations of each. The following is a discussion of four studies cited in the Handbook, and the data relevant to occupancy duration adapted from the Handbook summary.

In each of these studies, data on time use was recorded for either the preceding 24 hours, based on recall (telephone surveys) or for the succeeding 24 hours (based on diaries). In some studies (e.g., Hill, (1985)) the same respondents were polled periodically throughout the year. This follow-up aside, the data cited in these studies provides information on the variability over the sample population of time spent during a single day. The occupancy duration parameter instead describes average behavior of individuals over the year. This average is not the same as the average of daily behavior over a population of individuals. To estimate the former, information on the variability in daily activities for single individuals would also be required.

Robinson and Thomas (1991) report population averages for time spent performing various activities (e.g., "Paid Work," "Household Work") and in various micro-environments (e.g., "Restaurant/Bar," "Work/Study-nonresidence"). Data from Californians (1,762 respondents ages 12 and older collected between October 1987 and August 1988) and from a national sample (5,000 respondents across the United States ages 12 and older collected during January through December 1985) are categorized by activity and by gender. Separate statistics are also reported for "Doers" of an activity as distinct from the general population (for example, time spent cooking by people who actually cook). Population statistics are not reported, however, the standard error of the mean is given in some cases. The mean time spent in paid work for ages 18-64 years ranged from 190 min/d (34.31 effective 24-h d/y) for women in the national survey to 346 min/d (62.47 effective 24-h d/y) for men in the California study. These numbers correspond to 15.83 h/wk and 28.83 h/wk, respectively. (Effective 24-h d/y are calculated based on 52 wk/y; weekly hours are based on a five-day work week.) Given the age range for the survey, a significant portion of the survey population must be part-time workers, and therefore not representative of the screening group. The mean time for "doers" spent in the work/study-other micro-environment in the total population (ages 12 years and older) ranged from 383 to 450 min/d (69.15 to 81.25 effective 24-h d/y); during the weekday, from 401 to 415 min/d (72.40 to 74.93 effective 24-h d/y); and for ages 24-64 from 410 to 429 min/d (74.02 to 77.46 effective 24-h d/y), respectively. The range of all these values (383 to 450 min/d) corresponds to 31.92 to 37.50 h/wk.

Tsang and Klepeis (1996) contains information from the largest and most recent human activity pattern survey currently available. The survey was conducted by the EPA. Data from 9,386 respondents in the 48 contiguous states were collected via minute-by-minute 24-h diaries between October 1992 and September 1994. Distributions are reported for the number of minutes spent working for pay, the number of minutes spent in a "main job," the number of minutes spent indoors at work, the number of minutes spent in a plant/factory/warehouse, and the number of minutes spent in an office or factory. Distributions are provided for the entire sample populations, as well as subpopulations defined by gender, race, employment status, region, season, and other factors. The mean 24-h cumulative number of minutes in a main job for full-time employees is 504.350 min/d (standard deviation = 164.818), which corresponds to 91.06 effective 24-h d/y and 42.03 h/wk.

Robinson (1977) compares average time spent in "Work for Pay" in 1965 and 1975. Averages are reported by gender, employment status, age, race, and education. These data are not as current as the two previous sources. For four age categories spanning 25-65 years of age, these averages ranged from 29.2 to 35.9 h/wk in 1965 and 20.4 to 34.4 h/wk in 1975.

Hill (1985) reports average time spent at "Market Work" from data collected during the mid-1970s for subpopulations defined by gender, region, day of the week, and season. Distributions are not provided, however, sample standard deviations are given for some quantities. Mean hours per week, weighted to reflect the number of workdays and weekend days in a week (along with the reported standard deviation) for married men and women working full-time were 47.84 (16.54) and 38.55 (16.87), respectively. Data on seasonal variations were obtained by resampling the same population.

5.2.2.4 Distribution and Default Value for t_o

The data used to develop the PDF for t_o is based on the BLS CPS 1995 data (BLS, 1996a) for hours worked by full-time workers (those working 35 hours per week or more) at work in nonagricultural industries. These data are representative of annual estimates for the entire U.S. worker population and are determined from the largest sample of data that has been collected and processed in

a standardized manner for almost 40 years. Limiting the data to full-time non-agricultural workers provides a more representative estimate for the screening group. Although the BLS reports statistics for a number of worker categories, no category directly corresponds to workers in light industry.

Table 5.2 shows the relative frequency of hours worked for persons working 35 hours or more per week in non-agricultural industries. These relative frequencies were calculated from the data in Table 5.1 by dividing the number of persons in each "Hours of Work" range by the total number of persons working 35 hours or more per week. Persons reported to work 40 hours were assumed to have worked between 39 and 41 hours. A histogram based on this data is presented in Figure 5.1. This histogram defines the PDF for members of the screening group. The cumulative distribution function based on this histogram is presented in Figure 5.2. In developing this distribution, the number of hours worked in each of the intervals reported by the BLS was assumed to be uniformly distributed across the interval.

Table 5.2 Relative frequency of hours worked by persons working 35 hours or more per week

Hours Worked per Week	Relative Frequency
35-39	9.96×10^{-2}
39-41	4.81×10^{-1}
41-48	1.59×10^{-1}
49-59	1.53×10^{-1}
60-65	1.08×10^{-1}

As indicated in Table 5.1, significant portions of the working population in nonagricultural industries work less than or more than 40 h/wk. Only 35.8% of workers in nonagricultural industries work 40 h/wk; 27.8% work 15 to 39 h/wk and 23.2% work 41 to 59 h/wk. From Table 5.1, the 1995 weekly average for persons who usually work full time for nonagricultural industries is 43.2 h/wk. The default value for t_o, determined by the expected value of the distribution shown in Figures 5.1 and 5.2, is 97.5 d/y, or 45 h/wk. The difference between the expected value of the distribution and the average value reported in Table 5.1 is due to the difference between the actual distribution of hours worked within each range, and the uniform distribution over each range assumed in constructing the PDF.

5.2.2.5 t_o Uncertainty

In general, uncertainty about this parameter exists because of a lack of complete knowledge about the hours worked by workers in the screening group. The PDF proposed in Figure 5.2 represents the variability of individual worker hours across different industries and different regions of the country. Although the BLS provides data for a number of worker categories, no category directly corresponds to workers in light industry.

The BLS data used for the PDF are representative of annual estimates for the entire U.S. worker population and are determined from the largest sample of data available that has been collected and processed in a standardized manner for almost 40 years. The BLS CPS covers about 92% of the decennial census population. Also, a sample rotation scheme allows for 50% of the sample to be common from year to year. Thus, the

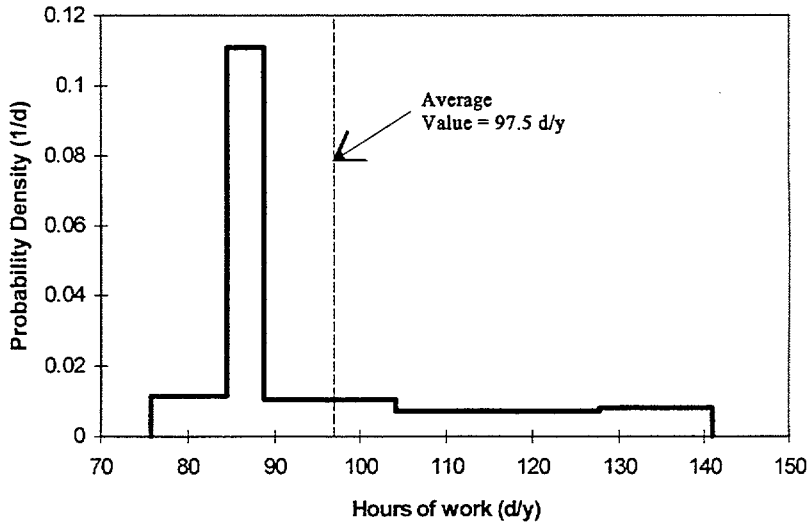

Figure 5.1 Probability Density Function for t_o

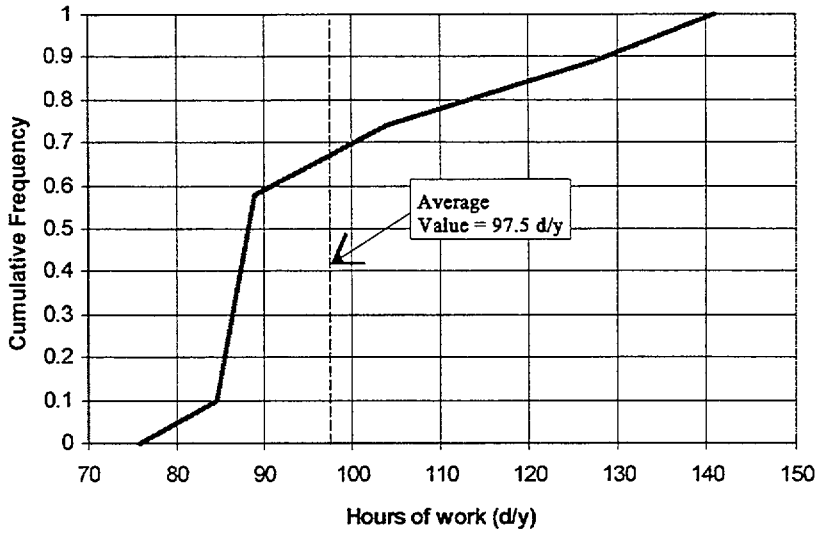

Figure 5.2 Cumulative Distribution Function for t_o

uncertainty due to sampling and non-sampling error and historical comparability is minimal and well-characterized (BLS, 1996a).

5.2.2.6 Alternative t_o Values

For this parameter, other BLS or similar data sets may provide the basis for a licensee to develop a different distribution of hours worked for a site-specific critical group. For example, a licensee may propose that the primary use of the building following license termination will be for manufacturing. Then, the licensee may use the BLS data to define the range of expected hours for the dose assessment. However, the licensee may need to provide the NRC with the assurance that the building will only be used for manufacturing over the regulated time period.

5.2.3 Effective Transfer Rate for Ingestion of Removable Surface Contamination from Surfaces to Hands, from hands to Mouth (Behavioral) GO (m^2/h)

5.2.3.1 Description of GO

Ingestion of removable surface contamination inside buildings that is transferred from contaminated surfaces via hands, food, and other items to the mouth is referred to as secondary ingestion. The parameter GO is defined as the effective transfer rate and provides a mechanism for calculating the quantity of secondary ingestion. The effective transfer rate is described as the surface area contacted per unit time, the contents of which are ultimately transferred to the mouth by inadvertent fingering of the mouth or placing contaminated objects, such as food, cigarettes, pencils, etc., that had been in contact with a contaminated surface, into the mouth.

The occupancy scenario definition does not include contaminated furniture such as desks and table tops. Only walls and floors are assumed to have residual contamination. The value of GO should reflect the rate of ingestion from contaminated surfaces (walls and floors) rather than the rate of ingestion from all surfaces.

5.2.3.2 Use of GO in Modeling

As described below, the dose for the ingestion pathway is directly proportional to GO. GO is therefore an important parameter for situations in which a significant proportion of the total dose is received through ingestion.

The parameter GO is used to calculate CEDE for internal ingestion dose (DGO_i) resulting from inadvertent ingestion of surface contamination. The relationship between GO and internal dose due to ingestion is defined by the following formula (NUREG/CR-5512, Vol. 1, p. 3.14):

$$DGO_i = 45.05 * 24 * t_o * GO * \sum_{(j=1, Ji)} DFG_j * C_{avj} \quad (5.8)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period, C_{avj} is the average annual activity of the radionuclide j during the first year of the building occupancy scenario, and DFG_j is the ingestion dose factor for radionuclide j. The resulting internal ingestion dose is directly proportional to the effective transfer rate.

As discussed above, GO measures the tendency for occupants to ingest surface contamination as a surface area per unit time. Ingestion is caused by touching contaminated walls and floors with the hands or other objects, and placing contaminated objects in the mouth. GO is a summary measure of chronic behavioral patterns for members of the screening group.

In Equation 5.8, all surface contamination is assumed to be available for ingestion by this mechanism, and the concentration of ingested material is assumed to be equal to the source concentration C_{avj}. The overall ingestion rate may be lower if the amount of "loose" contamination (i.e., contamination available for transport by this mechanism) is less than the total amount of contamination or if the ingested dust or soil is only partially composed of contaminated material. Equation 5.8 can be generalized to include the fraction of "loose" contamination and the fraction of contacted surfaces that are contaminated by scaling the available concentration:

$$DGO_i = 45.05 * 24 * t_o * GO * \sum_{(j=1,Ji)} DFG_j * F_S * F_l * C_{avj} \quad (5.9)$$

where F_l is the fraction of "loose" contamination and F_S is the contaminated fraction of the total surface area contacted by the receptor. This scaling is equivalent to defining an effective secondary ingestion transfer factor as:

$$GO^* = F_S * F_l * GO \quad (5.10)$$

and by replacing GO in Equation 5.8 by the effective rate GO*. This decomposition preserves the definition of GO as a measure of behavior (the area accessed per unit time), and allows the ingestion rate to be modified to account for site-specific measurements of removable activity. This is the same approach as is used for resuspension (see Section 5.4.2 below). In Equation 5.10, GO represents an ingestion rate from all surfaces, while GO* represents ingestion of loose material from contaminated walls and floors.

5.2.3.3 Review of Information Related to Secondary Ingestion

The value for GO is defined in NUREG/CR-5512, Vol. 1, as 1×10^{-4} m^2/h. This value was defined based on the literature analysis of surface-contamination ingestion data. Eight references are listed for this data (Dunster, 1962; Gibson and Wrixon, 1979; Healy, 1971; Kennedy et al., 1981; Sayre et al., 1974; Lepow et al., 1975; Walter et al., 1980; and Gallacher et al., 1984). Half of these studies focused on intake by children of surface contamination. These estimates tend to be larger than the corresponding estimates for adults (i.e., greater than 1×10^{-3} m^2/h). The range of ingestion rates for the adult-worker/members of the public is 4×10^{-5} to 1×10^{-3} m^2/h. The value of 1×10^{-4} m^2/h is consistent with the range for adults.

Kennedy and Strenge (1992) (hereafter referred to as "Volume 1") summarize estimates of GO published prior to 1992. In general, these estimates derive from postulates about behavior or from measured rates of ingestion. Information on ingestion by adults is especially sparse, and no direct measurements of adult ingestion rates are cited as a basis for GO. In addition, most theoretical estimates cited for GO or for adult ingestion rates found in the literature (Dunster (1962), Gibson and Wrixon (1979), Hawley (1985)) derive from the supposition by Dunster that 10 cm^2 of surface area would be accessed by a typical adult in a typical day. Hawley (1985), in calculating adult ingestion rates, assumed that adults working outdoors would transfer contamination from the inside surface of the fingers twice during a typical day of outdoor work, implying a secondary ingestion transfer rate of 137 cm^2 in an eight-hour day. This estimate, however, is speculative, and was proposed in the absence of empirical data on adult ingestion or behavior.

Recent publications, including references cited in the EPA *Exposure Factors Handbook* (1996) were reviewed to identify and evaluate data related to secondary ingestion transfer rate. The goal of most studies was to estimate rates of soil ingestion as a mass per unit time, rather than to estimate a transfer factor analogous to GO. In addition, most of the recent literature continues to focus on children. Because they are not representative of the screening group, and because children are presumably exposed to higher densities of dust and soil, and to ingest dust and soil at greater rates for a given density, estimated ingestion rates for children are not considered to be directly relevant for estimating GO.

Several studies on soil ingestion have been published since 1990. Ingestion rates for adults have been measured or estimated by a number of techniques and under a variety of conditions. Sheppard (1995) summarized the literature and described a basic model for soil ingestion that included food consumption and other activities, such as mouthing and ingestion of non-food items, concentration enrichment, and the bio-availability of contaminants in soil. He recommended the use of simple models, rather than explicit use of empirical data, for estimating soil ingestion in humans. Reported values for soil ingestion rates by normal adults,

summarized by Sheppard (1995) from other studies, range from 1 to 65 mg/d.

Soil ingestion rates in adults have been estimated by 1) analysis of selected tracer elements in human diets and comparing the dietary intake of tracer elements with tracer elements in feces and 2) observations of individual behavior patterns under a range of environmental conditions and activities. Recently, numerous studies on soil ingestion rates have been conducted using a tracer method (BTM) developed by Binder et al. (1986) (Stanek and Calabrese, 1995; Sedman and Mahmood, 1994; Stanek et al., 1997 and others). Stanek and Calabrese (1995) and Stanek et al. (1997) estimated soil ingestion rates in adults based on mass-balance studies in which intake rates were estimated from concentrations of several trace elements in foods, medicines, environmental dust and soil, and feces. Both studies collected data over multiple one-week periods, during which each subject ingested a controlled quantity of soil from their environment. This mass, along with soil mass ingested with food, was subtracted from the estimated mass in feces to estimate the daily amount of inadvertent ingestion. These studies are the only published measurements of adult ingestion found in the literature review, and are therefore the only empirical basis for defining a distribution for GO.

Two types of published data related to the secondary ingestion transfer factor were found: direct estimates of the area of skin surface (and therefore area of contaminated surface) contacted by mouth in a given time, and measurements or estimates of the rate of soil ingestion by adults. No studies report actual measurements of contacted area: the two primary sources for direct area estimates are Dunster's (1962) proposal that "in order to arrive at some indication of the magnitude of the problem, it is assumed here that a person may ingest all the contamination from 10 cm^2 of contaminated skin every day," and Hawley's (1985) assumption that adults working outdoors would transfer contamination from the inside surface of the fingers twice during a typical day of outdoor work, implying a secondary ingestion transfer rate of 137 cm^2 in an eight-hour day. Both estimates, while plausible, have no empirical support.

5.2.3.4 Inferring GO from Ingestion Rates

Estimates of inadvertent soil ingestion rates by adults provide indirect information on secondary ingestion transfer rates. The rate of soil ingestion by an individual can be related to the individual's behavior (reflected in the secondary ingestion transfer rate for the individual), and to the environmental conditions (reflected in the average dust or soil loading experienced by the individual) using the following simple model:

$$SI_{C,I} = GO_{C,I} * DL_{C,I} \qquad (5.11)$$

where SI is the inadvertent soil ingestion rate (mg/hr), GO is the transfer factor (m^2/hr), and DL is the average surface density of dust or soil in the environment in which ingestion was measured. The suffix C,I denotes chronic (annual average) values for individual subjects. Equation 5.11 is consistent with the exposure model used in dose assessment (Equation 5.8).

In the absence of direct measurements of transfer factor, this model was used to derive a distribution of individual transfer factor values from estimates of soil ingestion rate and soil densities. In making these estimates, measured soil ingestion rates are assumed to reflect the soil density in the subjects' environment, as well as mannerisms and behavior that are independent of the environment. The chronic behavior of individuals, characterized by $GO_{C,I}$, is assumed to be independent of their environment, characterized by $DL_{C,I}$, so that

$$E\left[\log\left(SI_{C,I}\right)\right] = E\left[\log\left(GO_{C,I}\right)\right] + E\left[\log\left(DL_{C,I}\right)\right] \qquad (5.12)$$

and

$$\mathrm{Var}\left[\log\left(SI_{C,I}\right)\right] = \mathrm{Var}\left[\log\left(GO_{C,I}\right)\right] + \mathrm{Var}\left[\log\left(DL_{C,I}\right)\right] \qquad (5.13)$$

where E(X) and Var(X) denote the expected value and variance over the population of individuals. Equations 5.12 and 5.13 allow distributional properties of $GO_{C,I}$ to be inferred from distributional properties of $SI_{C,L}$ and $DL_{C,L}$. This procedure requires a distribution for $SI_{C,I}$, describing the variability of soil ingestion rate over individuals, and a distribution for $DL_{C,I}$, describing the variability in the soil density on skin corresponding to the conditions under which SI was measured or estimated.

Defining a distribution for GO entails three main steps:

1. Estimating distributional properties for individual chronic soil ingestion rates ($SI_{C,I}$) from available literature. As discussed in Section 5.2.2, there are few published estimates of adult ingestion rates, and these rates were measured in residential settings. The summaries of acute (daily) individual ingestion rates provided by Stanek (1997) provide the most recent experimental basis for estimating adult soil ingestion. This study is therefore considered in some detail.
2. Estimating distributional properties for the individual chronic soil densities ($DL_{C,I}$) corres-ponding to

the experimental situation in which the ingestion rates were measured or estimated. Because the available ingestion rate measurements were made in residential settings, an estimate of dust density in residences is required in order to calculated the transfer rate corresponding to the measured rates of ingestion.

3. Deriving distributional properties for the individual chronic transfer factor ($GO_{C,I}$) from the distributional properties of soil ingestion rate and soil density, assuming that the variations in transfer factor and soil density among individuals are independent. This derivation assumes that the behavior characterized by GO would be the same in occupational and residential environments. Differences in mass ingestion rates in these two environments are therefore assumed to be due to differences in the surface density of dust and soil.

Section 5.2.2.3 below describes the application of this procedure to derive a distribution for GO. A number of intermediate assumptions and inferences are required, which create a large degree of uncertainty in the derived distribution. These assumptions are summarized below.

- By using this model to estimate transfer factors for individuals from measurements or estimates of soil ingestion rate, all inadvertent ingestion (i.e., excluding ingestion through food and medicine) is assumed to occur through transfer from surficial sources: other potential sources, such as swallowed wind-borne soil, are neglected.

- Measured inadvertent ingestion SI includes dust and soil ingestion from any surfaces in the subject's environment. In the occupancy scenario model, surface contamination is assumed to occur only on walls and floors. As a result, secondary ingestion transfer factors inferred from measured ingestion rates will overestimate transfer factors from the contaminated surfaces considered in the scenario. Using the effective transfer factor GO^* defined in Equation 5.9, $F_S = 1$ for all measured ingestion rates, while F_S is expected to be less than 1 based on the source location assumed in the scenario definition.

- The few available estimates of adult ingestion rates are for residential environments, while the parameter GO characterizes occupational environments. In Equation 5.10, ingestion rate is decomposed into a behavioral component $GO_{C,I}$ and an environmental component $DL_{C,I}$. Both components will differ between residential and occupational settings, although the size and direction of this difference is uncertain. *Transfer rates* based on soil ingestion in a residential setting are assumed to be representative of *transfer rates* in an occupational setting even though mass ingestion rates differ. Under this assumption, soil ingestion rates in residences would be higher than ingestion rates in occupational settings solely due to the higher soil density in residences.

- In deriving Equations 5.12 and 5.13, $GO_{C,I}$ and $DL_{C,I}$ are assumed to be independent. Individuals who tend to behave in ways leading to large (small) transfer factors are not preferentially exposed to environments with high (low) dust densities. This assumption is plausible, but cannot be tested with available information.

- The distribution of $GO_{C,I}$ describes the variability of transfer factors among individuals in the screening group. Due to the limited data available, no specific estimates for workers in light industry are available. Transfer factor estimates for adults in general are assumed to be appropriate for the screening group.

- The available information on adult soil ingestion rates is quite limited, and is not sufficient to determine the distribution of $SI_{C,I}$. Similarly, the distribution of $DL_{C,I}$ corresponding to the reported ingestion rates is highly uncertain. For both soil ingestion rate and soil density, the mean, minimum, and maximum values of these distributions were estimated as described in Section 5.2.2.3. Lacking specific information on the form of these distributions, distributions were assigned using the principle of maximum entropy. As stated by Jaynes (1982), this principle requires that "when we make inferences based on incomplete information, we should draw from them that probability distribution that has the maximum entropy permitted by the information we do have." In as much as the form of the secondary ingestion rate and dust loading distributions are unknown, the assumption of any specific distribution is arbitrary, and likely to be wrong. Given this uncertainty, the maximum entropy distribution was judged the most reasonable choice in that "most information theorists have considered it obvious that, in some sense, the possible distributions are concentrated strongly near the one of maximum entropy" (Jaynes, 1982). With a specified mean value, lower limit, and upper limit, the maximum entropy distribution corresponds to a truncated exponential distribution

5.2.3.5 Derivation of a Distribution for GO

The procedure described in Section 5.2.2.2 was used to develop a distribution for GO. Details and intermediate results are presented below.

5.2.3.5.1 Distributional Properties of Chronic Individual Ingestion Rate

Mean Individual Ingestion Rate

Sheppard (1995) provides a summary of current literature on soil ingestion, and cited soil ingestion rates by normal adults ranging from 1 to 65 mg/d. These estimates include the theoretical calculations by Hawley (1985), based on assumed transfer rates and soil densities, as well as the estimates based on tracer measurements reported by Calabrese (1989, 1990). Stanek (1997) describes a more recent application of the "best tracer" method to estimate adult soil ingestion, which drew from a larger number of subjects and a longer measurement period than the earlier work of Calabrese (1989). Individual ingestion rates reported by Stanek appear to be the strongest available experimental basis for estimating adult soil ingestion. This study is therefore considered in some detail.

Soil ingestion rates were estimated by Stanek et al. (1997) for each of 10 adult subjects on each of 28 days. The measurement period was divided into four periods of seven days each. During each period, a known mass of soil was ingested by each participant. This mass, along with the estimated soil mass ingested with food, was subtracted from the total estimated ingested mass, yielding 280 values for daily individual inadvertent ingestion. Total ingested mass on a given day was estimated as the mass of dust and soil in feces on the subsequent day. Soil and dust masses in meals and feces were in turn estimated from measured concentrations of eight trace elements found in soil and dust (Al, Ce, La, Nd, Si, Ti, Y, and Zr).

Resulting estimates of daily soil ingestion, and daily dust ingestion are summarized in Stanek et al. (1997). This summary describes the distribution of daily individual ingestion rate estimates over the entire study period, and over each of the four seven-day intervals. There is considerable variability in these estimates, as illustrated in Figure 5.3. Many negative values are reported, suggesting that a large amount of the variability in reported values is due to experimental error rather than to variability in ingestion rate among individuals, or to variability over time. Daily estimates for a single individual over a one-week period (Stanek et al., 1997 Table 8) suggest that estimates of *chronic* ingestion rate may be considerably more stable than daily values, however chronic rates cannot be derived for all individuals from the summaries presented in the report. Overall ingestion rates, averaged over both time and individuals, are provided, and have been used to estimate the potential variability in chronic dust ingestion over individuals.

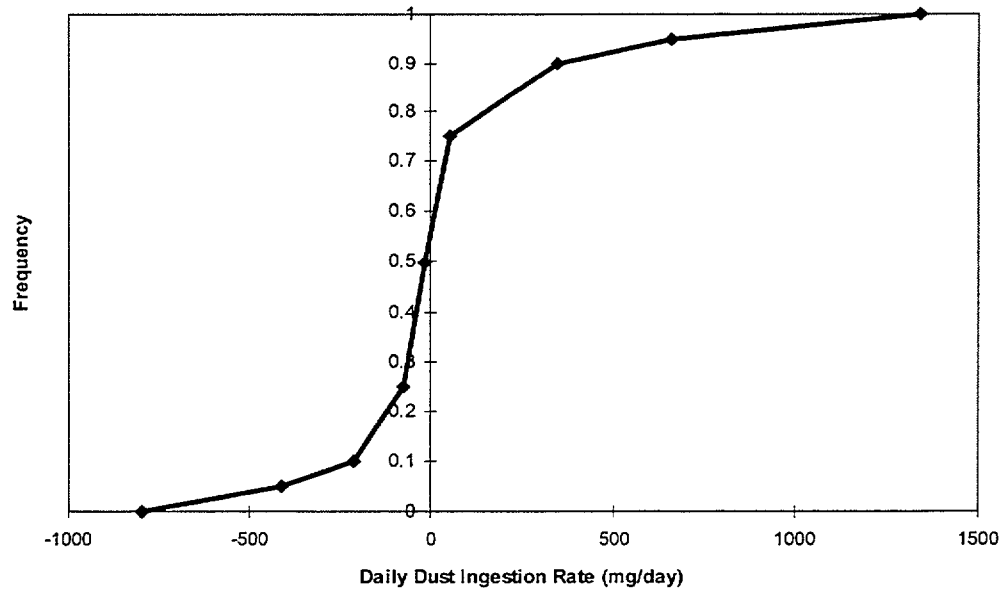

Figure 5.3 Distribution of estimated daily dust ingestion rates for 10 adults and 28 days based on the median value from four tracers (data from Stanek et al., 1997, Table 10)

Table 5.3 shows the average dust ingestion rate over the 10 subjects for the entire study duration, and for each of the four time periods. Standard errors for the average are also reported, calculated from the sample standard deviations provided in Stanek et al. (1997).

Table 5.3 Average estimated daily dust ingestion rates over 10 individuals and four one-week periods using median daily values from the four best tracer elements (from Stanek et al., 1997)

Period	Average dust ingestion rate (mg/d)	Standard error* (mg/d)
Week 1 (0 mg/day capsule ingestion)	139	52
Week 2 (20 mg/day capsule	73	22
Week 3 (100 mg/day capsule ingestion)	129	32
Week 4 (500 mg/day capsule ingestion)	-225	32
All 4 weeks	29	20

* Calculated from reported sample standard deviations.

The overall average ingestion rate of 29 mg/d is an estimate of the mean of the distribution of individual acute (daily) soil ingestion rates over time and over individuals. The mean of this distribution is identical to the mean of *chronic* ingestion rates over individuals, $SI_{C,L}$. Due to the large variation in individual daily values, there is considerable uncertainty in the estimate of the mean, as indicated by the large standard error. Using two standard errors as an indication of this uncertainty, the experimental results are consistent with a mean ingestion rate between 0 and 69 mg/d.

For comparison, Stanek and Calabrese (1995) reanalyzed results of their previous study of adult soil ingestion (Calabrese et al., 1990) using the best tracer method to rank the reliability of estimated rates based on individual tracers. The resulting average ingestion rate over six adults and three weeks was 64 mg/day.

Upper and Lower Limits for Individual Ingestion Rate

Available experimental data appear to be consistent with mean ingestion rates for adults between 0 and 70 mg/day. The large variability in estimates of daily ingestion rate (e.g., Figure 5.3) leads to large uncertainty in the estimate of average chronic ingestion rate. Ingestion rates typically recommended for adults (e.g., 50 mg/day in EPA (1996)) appear to reflect the detection limit associated with current experimental practice.

The minimum chronic individual soil ingestion rate is evidently 0. An upper limit for chronic adult soil ingestion rate is more difficult to establish, however the experimental results summarized in Table 5.3 can be used, along with other information, to assign a plausible upper bound. For a particular subject, the chronic soil ingestion rate (over the 250 day period relevant for the occupancy scenario) would be calculated as the average of 250 daily estimates for that subject. Average values for individual subjects are not available in Stanek et al. (1997), however the data in Table 5.3 indicate that the average ingestion rate over 210 subject-days (that is the average over 10 subjects and 21 days) can be as large as 114 mg/day, taking the average value over the three weekly periods having the largest weekly averages, or can be as small as 0 considering the three weeks having the lowest weekly averages.

Soil ingestion by children has been much more extensively studied than adult soil ingestion. Children's soil ingestion rates tend to be larger than reported adult ingestion rates, presumably due to their more frequent exposure to soil, and to a higher rate of hand-to-mouth transfer. Ingestion rates for children are therefore not appropriate as estimates for adults, but may provide information about reasonable upper limits for adults. A number of recent studies report measurements of soil ingestion rates for children using the tracer mass balance approach described above (Stanek and Calabrese, 1995, Binder et al., 1986, Clausing et al., 1987, van Wijnen et al., 1990, Davis et al., 1990). The EPA *Exposure Factors Handbook* (EPA, 1997) provides summaries and evaluations of these studies, leading to a recommended average ingestion rate for children of 100 mg/day. This rate represents an average over individuals and over the various study periods, however the study periods were typically short (days or weeks), and were typically conducted in the summer when ingestion rates are expected to be higher than during other times of the year. An upper percentile (unquantified) of 400 mg/day is also recommended in the EPA *Exposure Factors Handbook*, however low confidence is assigned to this estimate in view of the limited study period.

An upper limit for the individual chronic adult soil ingestion rate of 200 mg/day was adopted for this analysis based on the above information. This limit is consistent with the averages of daily rates from the limited sample reported by Stanek et al. (1997). The adopted upper limit for adults is larger than the average value recommended for children in the EPA *Exposure Factors Handbook*, however, the latter value represents an average over individuals, while the former represents limiting behavior of a single individual.

5.2.3.5.2 Distributional Properties of Chronic Dust Loading

Mean Dust Loading

Adult ingestion rates from Stanek et al. (1997) and Calabrese et al. (1990) were measured in a residential environment, and other published values for adult ingestion rate (e.g., Sheppard (1995)) typically describe residential conditions. As described in Section 5.2.2.2, estimating GO from measured ingestion rates requires an estimate of dust densities for the environment in which ingestion occurred. Dust densities used to infer secondary ingestion transfer rates from Equation 5.11, using ingestion rates measured or estimated for a residential environment, should therefore represent chronic values that may be encountered in this environment. In an occupational setting, dust densities, and therefore ingestion rates, are expected to be smaller than those observed in residences: the transfer factor GO, however, is assumed to be comparable in the two environments.

Hawley (1985) discusses ranges of dust densities found inside residences. Citing Solomon and Hartford (1976), he reports average dust densities for 239 floor dust samples taken from 12 homes of 320 mg/m² and 290 mg/m² based on concentrations of Pb and Cd, respectively. The larger number was adopted as an estimate of the average chronic dust concentration $DL_{C,I}$.

Upper and Lower Limits for Dust Loading

A lower limit on $DL_{C,I}$ was established based on the range of reported indoor dust-fall rates discussed in Hawley (1985), and assuming daily removal of accumulated dust. In a sample of suburban homes with closed windows, Shaefer et al. (1972, cited in Hawley, 1985) measured a mean dust fall rate of 20 mg/m²/day. This dust-fall rate is the lowest cited by Hawley, and with the assumption of daily cleaning, corresponds to a chronic average density of 10 mg/m² as a lower limit in residential environments.

Ingestion rates in a residential setting may include ingestion while outdoors, where the subject's hands may become heavily soiled. The surface soil density to which the individual is exposed in outdoor settings is assumed to be limited by the density of soil retained on the hands. Sheppard and Evenden (1994) summarizes measured and estimated soil loads on hands for a variety of soil types and conditions, reproduced as Table 5.4. An upper limit of $DL_{C,I}$ of 0.5 mg/c² was assumed on the basis of these estimates. This density is generally consistent with reported densities for soiled hands, with the notable exception of Hawley's theoretical value of 3.5 mg/cm². Sheppard and Evenden (1994) propose that soil loads higher than 1 mg/cm² would prompt cleaning, and that higher densities would therefore not be associated with chronic ingestion.

5.2.3.5.3 Estimated Distribution for Chronic Individual Transfer Rate $GO_{C,I}$ and Default Value for GO

The variation among individuals in chronic values of soil ingestion, and of surface soil densities corresponding to the conditions in which that ingestion occurs, have been characterized by a mean value, an upper limit, and a lower limit. Without additional information to define the distributions for soil ingestion rate and surface soil density, a maximum entropy distribution was assigned for both variables. With a specified mean value, lower limit, and upper limit, the maximum entropy distribution corresponds to a truncated exponential distribution. Figures 5.4 and 5.5 show the assigned distributions for $SI_{C,I}$ and $DL_{C,I}$, respectively.

Table 5.4 Measurements and estimates of soil load on hands for freshly soiled or partially cleaned hands from Sheppard (1994), Table III

Reference	Load (mg/cm²)	Conditions
Driver et al. (1989)	0.2 – 0.9	Dry whole soil, no cleaning
	0.8 – 2	Dry sieved soil, < 150 μm diameter
Hawley (1985)	3.5	Estimate assuming 50-μm-thick covering
Lepow et al. (1975)	0.5	Children, sampled with adhesive film
Que Hee et al. (1985)	0.5	House dust adhering to palm
Sheppard and Evenden (1994)	0.06 – 2	Dry soil, brushed clean, adhesive film sample
	0.3 – 0.5	Moist soil, brushed clean, adhesive film sample
	0.4 – 0.8	Wet soil, brushed clean, adhesive film sample
	<1	Visually clean, adhesive film sample

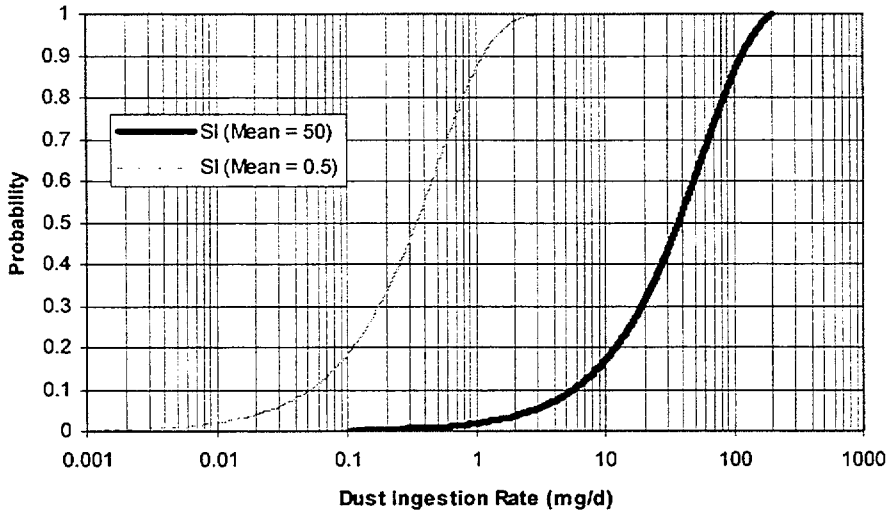

Figure 5.4 Estimated distribution of chronic dust ingestion rates based on two alternative mean ingestion rates

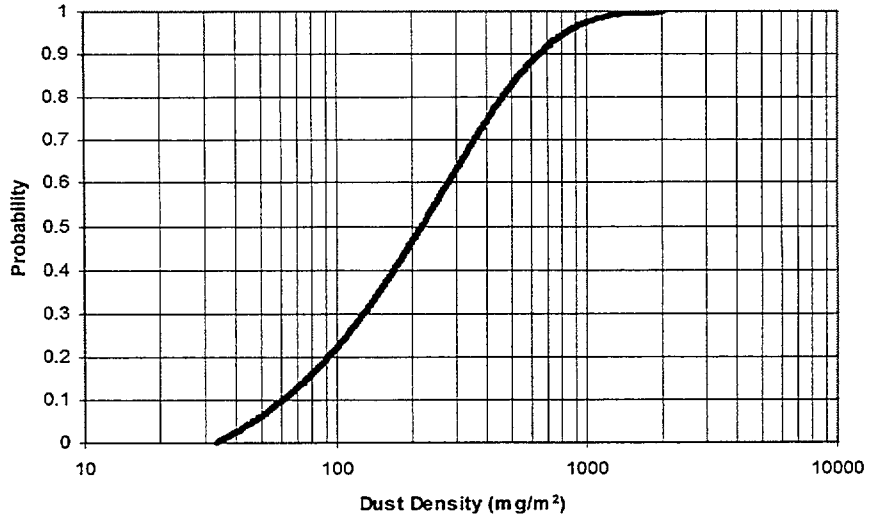

Figure 5.5 Estimated distributional of chronic individual dust densities corresponding to measured ingestion rates

As discussed above, there is considerable uncertainty in the estimate of mean ingestion rate due to the large variability in daily ingestion estimates. Available data are consistent with mean ingestion rates between 0 and 70 mg/day. To illustrate the effect of this uncertainty, two alternative distributions for $SI_{C,I}$, denoted $SI^{L}_{C,I}$ and $SI^{U}_{C,I}$, based on alternative mean ingestion rates of 0.5 mg/day and 50 mg/day, are shown in Figure 5.4.

The mean and variance of the logarithm of chronic individual transfer rate $GO_{C,I}$ was calculated using Equations 5.12 and 5.13 and given the mean and variance of the logarithms of $SI_{C,I}$ and $DL_{C,I}$. The alternative distributions for dust ingestion, $SI^{L}_{C,I}$ and $SI^{U}_{C,I}$, were each used to evaluate the effect of uncertainty in mean ingestion rate on the inferred distribution of transfer rate, producing the corresponding transfer rate distributions $GO^{L}_{C,I}$ and $GO^{U}_{C,I}$. Table 5.5 summarizes the properties of these distributions. Loguniform distributions were then defined for $GO^{L}_{C,I}$ and $GO^{U}_{C,I}$ based on the calculated mean and variance of $\log(GO^{L}_{C,I})$ and $\log(GO^{U}_{C,I})$ from Table 5.5.

Figure 5.6 shows the derived distributions for $GO_{C,I}$. In converting the units of $GO_{C,I}$ from m^2/day to m^2/hr, measured dust ingestion was assumed to occur over a 16-hour period. This period corresponds to the period during which the reported soil ingestion rates, which were measured in a residential setting, would typically be operative.

Table 5.5 Distributional properties for chronic individual dust ingestion rate ($SI_{C,I}$), dust density ($DL_{C,I}$), and transfer factor ($GO_{C,I}$)

Parameter	Mean	Lower limit	Upper limit	Mean of $\log_{10}$	Variance of $\log_{10}$
$SI^{L}_{C,I}$ (mg/d)	0.50	0	200	-0.55	0.30
$SI^{U}_{C,I}$ (mg/d)	50	0	200	1.47	0.29
$DL_{C,I}$ (mg/m^2)	320	10	5000	2.29	0.22
$GO^{L}_{C,I}$ (m^2/d)	1.8E-3	4.4E-4	4.6E-3	-2.85	0.09
$GO^{U}_{C,I}$ (m^2/d)	1.8E-1	5.1E-2	4.3E-1	-0.82	0.07

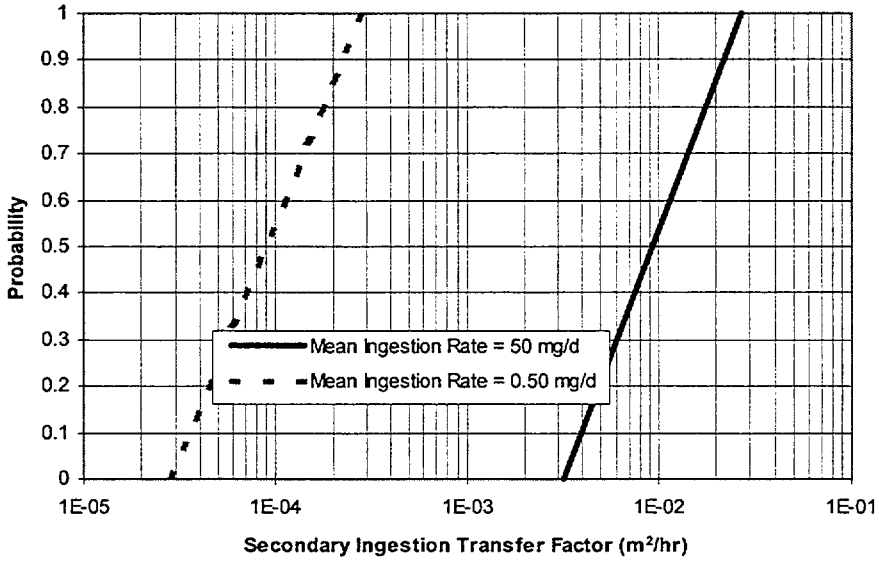

Figure 5.6 Estimated distribution of chronic individual secondary ingestion transfer factor $GO_{C,I}$ corresponding to alternative mean ingestion rates

Both distributions in Figure 5.6 are consistent with available data on adult ingestion, and the larger value is the approximate detection limit of current experimental procedures.

Uncertainty in the mean value of $SI_{C,I}$ creates large uncertainty in GO relative to the estimated variability of GO over individuals, as can be seen in Figure 5.6. Measurements of the frequency of various mouthing behaviors among adults might be used to estimate the surface area potentially accessed through such behavior, as well as the fraction of this surface area consisting of walls and floors. Such information might reduce uncertainty in the distribution of GO. No studies of this kind were identified in the literature review, however some transfer rates consistent with measured ingestion may be judged unrepresentative of adult behavior in an occupational setting.

A transfer rate of 10^{-2} m^2/hr, for example, implies mouthing an area equivalent to the inner surface of the hand once each hour. A rate of 10^{-3} m^2/hr implies transfer from an area roughly equivalent to two postage stamps each hour. The behavior implied by the latter rate is arguably a plausible upper limit for individuals in an occupational setting, and distributions having higher rates may be rejected on the basis of this judgment. The resulting distribution for GO would not be conservative with respect to uncertainty in the average ingestion rate given existing measurements, however the likelihood that additional information would lead to higher transfer rates would still be assumed to be small, in view of the behavior implied by these higher rates.

Among the possible distributions of GO consistent with measured ingestion rates, the lower distribution shown in Figure 5.6 was used in the parameter analysis. The distribution centered around 10^{-2} m^2/hr corresponds to a mean ingestion rate of 50 mg/day, which reflects the apparent detection limit of current experimental practice. The distribution centered around 10^{-4} m^2/hr (corresponding to a mean ingestion rate of 0.5 mg/day) includes

plausible reductions from the higher distribution in consideration of two factors, each of which is assumed to reduce the transfer factor by an order of magnitude: the stipulation that an individual transfer rate of 10^{-2} corresponds to unreasonable behavior in an occupational setting; and the assumption that walls and floors are much less likely to be contacted than other surfaces, such as tables and desks. The average value of 1.1×10^{-4} m^2/hr represents the average member of the screening group, and defines the default value for this parameter.

As discussed in Section 5.2.2, the actual amount of contamination ingested will also depend on other factors, including the fraction F_I of the total source term that is "loose," and therefore available for ingestion. The fraction of loose contamination (F_I) is expected to be estimated or bounded using data collected prior to decommissioning.

5.2.3.6 Uncertainty of $GO_{C,I}$

The proposed distribution describing the variability of the secondary ingestion effective transfer rate rests on a number of assumptions, introducing a large amount of uncertainty in the assigned distribution.

(1) Empirical support for this parameter is very limited. The most recent measurements of soil ingestion in adults are subject to wide variability, and are consistent with average ingestion rates ranging from 0 to 70 mg/day. The upper limit represents the apparent detection limit of current experimental practice. The proposed value of 0.5 mg/day is consistent with available information. This value was established in consideration of judgments about 1) the plausibility of the behavior associated with higher rates, and 2) the fraction of the total contacted surface area consisting of contaminated walls and floors.

(2) Ingestion rates have been measured for adults in residential settings. Transfer factors in occupational settings, representing behavioral characteristics of individuals, are assumed to be similar to those in residential environments. Higher ingestion rates in residences are therefore assumed to be due to exposure to higher soil density, rather than to distinctive behavior.

(3) Surface dust and soil densities associated with available measurements of adult ingestion rates are unknown, and have been estimated from independent studies of dust densities and dust fall rates in residences, and soil densities on soiled hands.

5.2.3.7 Alternative Parameter Values

The value of the parameter used in the model can be modified based on site-specific survey data regarding removable activity, or with additional information on secondary ingestion.

5.3 Volumetric Breathing Rate (Metabolic), V_o (m^3/h)

5.3.1 Description of V_o

The breathing rate parameter (V_o), in conjunction with the resuspension factor and isotope-specific inhalation CEDE factors, is used to calculate the average annual dose due to inhalation. V_o is a metabolic parameter which represents the annual average breathing rate of adult males in the general population engaged in occupational activities.

The default value for this parameter defined in NUREG/CR-5512, Vol. 1, is 1.2 m^3/h. This value corresponds to breathing rates characteristic of light activity as defined in ICRP Publication 23 (1975). The RESRAD value for the same parameter is 0.96 m^3/h.

5.3.2 Use of V_o in Modeling

Inhalation dose is linearly proportional to V_o, as described below. The overall importance of V_o to total dose depends on the relative contribution of inhalation dose to total dose.

V_o is used to calculate the CEDE for the internal dose due to inhalation (DHO_i) resulting from inhalation of resuspended surface contamination. The relationship between V_o and internal dose due to inhalation is described by the following formula (NUREG/CR-5512, p 3.31):

$$DHO_i = 45.05 * 24 * t_o * RF_o * V_o * \Sigma_{(j=1,Ji)} DFH_j * C_{avj} \quad (5.14)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period (d), C_{avj} is the average annual activity of the radionuclide j during first year of the building occupancy scenario(dpm-d/100 cm^2), DFH_j is the inhalation CEDE factor (mrem per pCi inhaled), and RF_o is the resuspension factor (m^{-1}). The resulting internal inhalation dose is directly proportional to the volumetric breathing rate.

5.3.3 Information Reviewed to Define Breathing Rate Distributions

The literature review conducted to support the EPA Exposure Factors Handbook (EPA, 1996) was adopted for this study as the most current compilation of relevant literature. Eleven studies are reviewed and summarized in the Handbook. Five are identified as "key studies," and form the basis for inhalation values recommended there. The six remaining studies are considered "relevant," and contain supporting information relating to inhalation rate. Breathing rate estimates are not specifically reported in any study for general workers, although Linn et al. (1992) studied breathing rates for a small sample of construction workers. In several studies, daily average values are reported, as well as breathing rates for individuals engaged in various levels of activity. These activity levels are descriptively defined, for example as "rest," "sedentary," "light," "moderate," and "heavy."

Reported average daily values include a range and relative weighting of activities typical of an entire day, including sleep: this range and weighting of activities is not representative of activities specifically conducted by workers. For this reason, reported average daily values are not appropriate for V_o. Instead, breathing rates for adult male workers were based on the range of activities that would occur in an occupational setting, and the reported average values for the corresponding activity levels (see Section 5.3.3.1).

The summaries in the Handbook were used to evaluate the five "key" studies for the purpose of defining breathing rates for adult male workers. Each of these studies, and the resulting breathing rates that reflect adult male workers, are summarized below.

Layton (1993) presents a method for estimating breathing rate based on metabolic information:

$$V_E = E \times H \times VQ \qquad (5.15)$$

where:

V_E = the ventilation rate
E = the energy expenditure rate
H = the volume of oxygen consumed in the production of 1 KJ of energy, and
VQ = the ratio of intake volume to oxygen uptake

Three approaches are used to estimate the energy expenditure rate: annual caloric intake (corrected for reporting bias), elevation above basal metabolic rate (BMR) with BMR values estimated from body weight using a fitted regression model, and elevations above BMR using activity-specific elevation factors and time allocation data. These methods are used to estimate average inhalation rates over various population subsets defined by age and gender. This study draws from comparatively large data sets, and provides information on the relative contributions of the diverse factors influencing inhalation rate, including general health, body weight, diet, activity level, age, and gender. The first two methods provide estimates of long-term average breathing rate, which is not specific to occupational settings. The third method provides estimates of breathing rate for different levels of activity. Average inhalation rates for adult males for five activity levels, estimated by the third method, are summarized in Table 5.6. Estimates for two sets of activity classifications are reported. For each set, activity level is characterized by a qualitative description as well as by a BMR value or range. Different sets of BMR values were used for each set.

Linn et al. (1992) estimates inhalation rates for "high-risk" subpopulations, including outdoor workers, elementary school students, high school students, asthmatic adults, young asthmatics, and construction workers. Of these subpopulations, construction workers are most representative of adult male workers. The average breathing rate for construction workers, consisting of seven men between the ages of 26 and 34, is 1.50 m^3/hr. Activity-dependent breathing rates are also reported for three activity levels, as shown in Table 5.7.

Linn et al (1993) reports breathing rates for 19 construction workers who perform heavy outdoor labor both before and during a typical work shift. Spier et al. (1992) reports breathing rates for elementary and high-school students. Although considered "key" studies in the Handbook, these subpopulations do not correspond to adult male workers in light industry. Results of these two studies were not used to establish a default breathing rate value.

The California Air Resources Board (CARB) (1993) reports breathing rates in routine daily activities for children and adults at various activity level classifications. The study included a laboratory protocol, in which ventilation rate, heart rate, breathing frequency, and oxygen consumption were measured during treadmill tests. Heart rate, ventilation rate, and breathing frequency were also measured during a "field" protocol, which included (for adult males) driving and riding in cars, yard work, and mowing. Average breathing rates during the laboratory protocol are reported for five activity classifications. Average values during the field protocol are reported for three activity classifications. Table 5.8 summarizes the reported values for adult males.

Table 5.6 Estimated breathing rates for males from Layton (1993) for two sets of five activity levels (m^3/hr)

Inhalation rates for short-term exposures[1]					
Age (years)	Activity level				
	Rest BMR: 1	Sedentary BMR:1.2	Light BMR: 1.5 -2.5	Moderate BMR: 3 - 5	Heavy BMR: >5 - 20
18 - < 30	0.43	0.52	0.84	1.74	4.32
30 - < 60	0.42	0.50	0.84	1.68	4.20
Activity-dependent inhalation rates used to estimate daily inhalation rate[2]					
Age (years)	Activity level				
	Sleep BMR: 1	Light BMR: 1.5	Moderate BMR: 4	Hard BMR: 6	Very Hard BMR: 10
20 – 34	0.4	0.7	1.7	2.6	4.3
35 – 49	0.4	0.6	1.7	2.5	4.2
50 – 64	0.4	0.6	1.7	2.5	4.2

[1] Source: EPA(1996) Table 5-5
[2] Source: EPA(1996) Table 5-6

Table 5.7 Estimated breathing rates from Linn (1992) for two panels of healthy adult subjects[1] (m^3/hr)

Subject Group	Mean self-estimated breathing bates		
	Slow	Medium	Fast
Construction Workers	1.26	1.50	1.68

[1] Source: EPA(1996) Table 5-7

Table 5.8 Average inhalation rates for adult males from CARB (1993) (m^3/hr)

	Activity level				
	Resting	Sedentary	Light	Moderate	Heavy
Laboratory protocols[1]	0.54	0.60	1.45	1.93	3.63
Field protocols[2]		0.62	1.40	1.78	

[1] Source: EPA(1996) Table 5-13
[2] Source: EPA(1996) Table 5-14

The six studies classified as "Relevant" provide supporting information, such as assessments of the quality of individual's subjective judgments of their breathing rate and activity level. However, they do not provide information directly related to estimating breathing rates.

Three literature surveys are also classified as "Relevant." The EPA (1985) provides a summary of inhalation rates by age, gender, and activity level. This study compiles results of earlier investigations, and does not present information on the accuracy and methods used in these investigations. Reported breathing rates range from 0.7 to 4.8 m^3/hr for adult males depending on activity level. The ICRP (1981) presents ventilation estimates for reference adult males and females at two activity levels ("Resting" and "Light Activity") as well as daily inhalation rates based on an assumed activity pattern during the day. For adult males, the respective rates are given as 0.45 m^3/hr, 1.2 m^3/hr, and 22.8 m^3/day (0.95 m^3/hr). The value for V_0 defined in Volume 1 of NUREG/CR-5512 was based on the "Light Activity" breathing rate for males from this study. It was not considered a sufficient basis for defining the default value for this parameter because of the availability of more extensive empirical data in three of the five "key" studies discussed above. The AIHC (1994) Exposure Factors Sourcebook recommends an average adult inhalation rate of 18 m^3/day based on data presented in

other studies. This report draws from information presented elsewhere, and does not provide primary information on breathing rate.

5.3.4 Breathing Rates for the Average Member of the Screening Group

Breathing rates for adult male workers were estimated from the activity-dependent average breathing rates for adults summarized in Section 5.3.3. Activities of workers in an occupational setting include desk work, operating machinery, sweeping, and carrying items. Such activities correspond to the "Sedentary," "Light," and "Moderate" level classifications used by Layton (1993) and CARB (1993), and to the "Slow" and "Medium" subjective breathing rate classifications used in Linn's studies of construction workers. Although some types of work entail more strenuous activities characterized as "hard" or "very hard," sustained (year long) activity of this type was assumed not to be typical of the screening group.

The reported average breathing rates for the activity levels typical of adult male workers were selected from the values reported in Section 5.3.3. Table 5.9 summarizes the reported breathing rate values for occupational activity levels. (For each of the two sets of values reported by Layton (1993), the median breathing rate over the individual age groups was selected as typical of adult males.) Estimated breathing rates cover a range of values due to differences among the studies, and to differences in activity levels. An estimate of overall average breathing rate would require information on time allocation among these activity levels. Because detailed time allocation information is not available, the median reported value of 1.4 m^3/hr was selected as typical of males in the normal population.

Table 5.9 Reported average breathing rates corresponding to activity levels typical of workers in light industry

Breathing rate	Reference study and activity level
0.5	Layton (1993), Set 1: Median of "Sedentary" values over adult age groups
0.6	Layton (1993), Set 2: Median of "Light" values over adult age groups
0.6	CARB (1993): "Sedentary" value from laboratory protocol
0.6	CARB (1993): "Sedentary" value from field protocol
0.8	Layton (1993), Set 1: Median of "Light" values over adult age groups
1.3	Linn et al. (1992): "Slow" value for construction workers
1.4	CARB (1993): "Light" value from field protocol
1.4	CARB (1993): "Light" value from laboratory protocol
1.5	Linn et al. (1992): "Medium" value for construction workers
1.7	Layton (1993), Set 1: Median of "Moderate" values over adult age groups
1.7	Layton (1993), Set 2: Median of "Moderate" values over adult age groups
1.8	CARB (1993): "Moderate" value from field protocol
1.9	CARB (1993): "Moderate" value from laboratory protocol

5.4 Physical Parameters

5.4.1 External Dose Rate Factor for Exposure From Contamination Uniformly Distributed on Surfaces, $DFES_j$ (mrem/h per dpm/100 cm^2)

5.4.1.1 Parameter Description

The radionuclide-specific external dose rates conversion factors are defined as suggested in EPA Federal Guidance report No. 12 (Eckerman and Ryman, 1992). These factors provide the external effective dose equivalent by summing the product of individual organ doses and organ weighting factors over the body organs. For the building occupancy scenario, these factors are defined for an infinite surface (thin-layer) source condition. This source condition approximates the non-uniform residual contamination on building walls, ceilings, and floors by a uniform concentration over a floor having infinite area. This assumption is based on the earlier sensitivity study by Kennedy and Peloquin (1990). Relative dose rates obtained for rooms of different volumes with uniform and selected non-uniform sources of contamination were compared with the dose rates obtained using an infinite flat uniform source. The infinite flat uniform source provides a conservative estimate for the small rooms (less than 200 m^3) and reasonably conservative estimate (about 15% lower than the rate due to a non-uniform source) for the larger rooms. However, the sensitivity study was performed using one radionuclide only (Co-60). A constant distance between floor and ceiling (3 m) was assumed.

Although a number of assumptions underlie the values defined for the external dose conversion factors, these values have been obtained from a standardized dosimetry data base and have been determined to be appropriate for

use in the NUREG/CR-5512 modeling. Uncertainty in these values was not evaluated in the parameter analysis.

5.4.1.2 Use of $DFES_j$ in Modeling

Radionuclide specific, the sensitivity of this parameter will depend on values of DFH_j, DFG_j, RF_o, V_o, and GO. The higher the value of $DFES_j$ for each of the radionuclides in the chain, the higher the total dose.

This parameter is used to calculate the external dose, $DEXO_i$, resulting from external exposure to penetrating radiation from an infinite surface source. The relationship between $DFES_j$ and external dose is described by the following formula (NUREG/CR-5512, Vol. 1, p. 3.12):

$$DEXO_i = 24 * t_o * \sum_{(j=1,Ji)} DFES_j * C_{avj} \quad (5.16)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period, and C_{avj} is the average annual activity of the radionuclide j during first year of the building occupancy scenario. The higher the value of $DFES_j$ for each of the radionuclides in the chain, the higher the resulting external dose.

5.4.1.3 Uncertainty in $DFES_j$

Dose conversion factors reflect the biological effects induced by exposure to a unit radionuclide activity density. The conversion from activity to a common measure of biological impact requires a number of simplifying assumptions, including assumptions regarding source geometry and spatial variability, the age and physiology of the receptor, and the circumstances of exposure (Eckerman and Ryman, 1992). These assumptions introduce a large amount of uncertainty about the appropriate value for dose conversion factors. Sources of uncertainty are identified in EPA Federal Guidance Report No. 12 (Eckerman and Ryman, 1992), however, this uncertainty is not quantified as distributions for the dose conversion factors recommended in the report. Uncertainty in dose conversion factors has therefore not been explicitly incorporated in this analysis.

5.4.1.4 Alternative Values for $DFES_j$

Variability in dose conversion factors may be related to differences in contaminant distribution on building surfaces. Different types of industrial activities at different buildings/sites could result in different contaminant distributions. In some cases (predominantly gaseous releases of condensible materials), contaminants could be distributed uniformly over all surfaces while liquid contaminants would be on the floor. The licensee may substitute different values from Report 12 based on a site-specific source geometry different from an infinite plane.

5.4.2 Inhalation CEDE Factor, DFH_j (mrem/pCi Inhaled)

5.4.2.1 Description of DFH_j

The radionuclide-specific internal inhalation dose rate conversion factors are defined as suggested in the EPA Federal Guidance report No. 11 (Eckerman et al., 1988). These factors are intended for general use in assessing average individual committed doses for inhalation of radioactive materials in any population that can be characterized by Reference Man.

Although a number of assumptions underlie the values defined for the inhalation dose conversion factors, these values have been obtained from a standardized dosimetry data base and have been determined to be appropriate for use in the NUREG/CR-5512 modeling. Uncertainty in these values was not evaluated in the parameter analysis.

5.4.2.2 Use of DFH_j in Modeling

Radionuclide specific, the sensitivity of this parameter will depend on values of $DFES_j$, DFG_j, RF_o, V_o, and GO. The higher the value of DFH_j for each of the radionuclides in the chain, the higher the total dose.

This parameter is used to calculate CEDE for inhalation (DHO_i) resulting from inhalation of resuspended surface contamination. The relationship between DFH_j and internal dose due to inhalation is described by the following formula (NUREG/CR-5512, Vol. 1, p. 3.13):

$$DHO_i = 45.05 * 24 * t_o * RF_o * V_o * \sum(j=1,Ji)\ DFH_j * C_{avj} \quad (5.17)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period, C_{avj} is the average annual activity of the radionuclide j during the first year of the building occupancy scenario, RF_o is the resuspension factor, and V_o is the volumetric breathing rate. The higher the value of DFH_j for each of the radionuclides in the chain, the higher the resulting inhalation dose.

5.4.2.3 Uncertainty in DFH_j

As with $DFES_j$, DFH_j is uncertain due to the underlying simplifying assumptions, including assumptions about residence time in the body and the spatial distribution of

nuclides among and within various organs. This uncertainty has not been incorporated in this analysis.

5.4.2.4 Alternative DFH_j Values

Inhalation dose conversion factors may vary due to variations in the chemical properties of the contaminant. The licensee may propose a different value from Report 11 based on solubility class.

5.4.3 Ingestion CEDE Factor, DFG_j (mrem/pCi Ingested)

5.4.3.1 Parameter Description

The radionuclide-specific internal ingestion dose rate conversion factors are defined as suggested in the EPA Federal Guidance report No. 11 (Eckerman et al., 1988). These factors are intended for general use in assessing average individual committed doses for inhalation of radioactive materials in any population that can be characterized by Reference Man.

Although a number of assumptions underlie the values defined for the internal ingestion dose conversion factors, these values have been obtained from a standardized dosimetry database and have been determined to be appropriate for use in the NUREG/CR-5512 modeling. Uncertainties in these values were not evaluated in the parameter analysis.

5.4.3.2 Use of DFG_j in Modeling

Radionuclide specific, the sensitivity of this parameter will depend on values of $DFES_j$, DFH_j, RF_o, V_o, and GO. The higher the value of DFG_j for each of the radionuclides in the chain, the higher the total dose.

This parameter is used to calculate CEDE for ingestion (DGO_i) resulting from inadvertent ingestion of surface contamination. The relationship between DFG_j and internal dose due to ingestion is described by the following formula (NUREG/CR-5512, Vol. 1, p. 3.14):

$$DGO_i = 45.05 * 24 * t_o * GO \sum_{(j=1,Ji)} DFG_j * C_{avj} \quad (5.18)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period, C_{avj} is the average annual activity of the radionuclide j during first year of the building occupancy scenario, and GO is the effective transfer factor. The higher the value of DFG_j for each of the radionuclides in the chain, the higher the resulting ingestion dose.

5.4.3.3 Uncertainty in DFG_j

DFG_j, like DFH_j, is uncertain due to the underlying simplifying assumptions (see Section 5.4.2.3). This uncertainty was not incorporated in this analysis.

5.4.3.4 Alternative Values for DFG_j

Ingestion dose conversion factors are radionuclide specific and are not likely to vary from site to site. However, licensees may propose updated dose conversion factors or uptake (f1) factors based on more recent dosimetry information.

5.4.4 Resuspension Factor for Surface Contamination (Physical), RF_o (m^{-1})

5.4.4.1 Parameter Description

The resuspension factor, RF_o, defines the ratio of contaminant concentration in inhaled air to surface contamination concentrations in the default NUREG/CR-5512 dose model. The model uses a single, constant (time-invariant) value. This value should therefore represent the effective value for the average member of the critical group over the one-year duration of the building occupancy scenario.

5.4.4.2 Use of RF_o in Modeling

Resuspension is important to dose because inhalation dose is directly proportional to RF_o, as discussed below.

This parameter is used to calculate CEDE for inhalation (DHO_i) resulting from inhalation of resuspended surface contamination. The relationship between RF_o and internal dose due to inhalation is described by (NUREG/CR-5512, Vol. 1, p. 3.13):

$$DHO_i = 45.05 * 24 * t_o * RF_o * V_o * 3_{(j=1,Ji)} DFH_j * C_{avj} \quad (5.19)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period, C_{avj} is the average annual activity of the radionuclide j during first year of the building occupancy scenario, DFHj is the inhalation CEDE factor, and V_o is the volumetric breathing rate. The resulting internal inhalation dose is directly proportional to the resuspension factor.

5.4.4.3 Information Reviewed to Define A PDF for RF_o

The value for the resuspension factor recommended in NUREG/CR-5512, Vol. 1, is 1×10^{-6} m^{-1}, based on a

literature analysis of studies published from 1964 through 1990. The overall range of values obtained from these literature sources is 2×10^{-11} to 4×10^{-2} m^{-1}. However, most data referenced are not for indoor conditions. Only two of the references cited in Volume 1 provide data for indoor resuspension. The first of these, an IAEA technical report (1970), reports a value of 5×10^{-5} m^{-1} which has been obtained for operating nuclear facilities. The second of these two references, a review by Sehmel (1980), provides different resuspension factors depending on the type of activity conducted within the rooms of the building (walking, vigorous sweeping, and fan). The overall range cited by Sehmel is from 1×10^{-6} to 4×10^{-2} m^{-1}. The lower end of this range is suggested as a default based on the fact that surfaces are assumed to be cleaned of easily removable contamination at the time of license termination.

The parameter analysis requires a distribution describing the variability of site-specific values for this parameter over licensed sites. To define this distribution, a licensee is assumed to have detailed information about (or control over) factors effecting resuspension at their site, such as the activities of occupants. This information would be used to define a critical group for the site by selecting a subset of occupants exposed to a relatively high concentration of resuspended contaminants. RF_o would then be defined as the time-weighted average resuspension factor for this group over the one-year scenario duration.

A literature review was conducted to identify any developments in the understanding of the resuspension process since the review reported in NUREG/CR-5512 in 1992, and to identify data or approaches that could be used to develop a probability distribution function for the indoor resuspension factor. Older publications that were not referenced in NUREG/CR-5512, Vol. 1, were also reviewed for the same purpose.

Resuspension factor values are reported in a number of studies published between 1964 and 1997. Reported values vary over a wide range, from approximately 10^{-11} m^{-1} to approximately 10^{-2} m^{-1}. The review of some older publications indicated that a value of 1×10^{-6} m^{-1} was used in the development of general guidelines. This value has been seen as a general value having a reasonable factor of safety for hazard evaluation and design purposes (Brodsky, 1980). This value was also recommended by the IAEA (1982; 1986) and suggested as an average for Europe in Garland (1982). These sources support (but were not cited to justify) the parameter value adopted for RF_o in NUREG/CR-5512, Vol. 1. Most studies, and all but one study not included in the review reported in NUREG/CR-5512, Vol. 1, provide data on outdoor resuspension factors. These values are not directly relevant for the occupancy scenario model. Additionally, most reported resuspension factor values were measured or inferred under conditions that would not reasonably be sustained during the one-year exposure period. The different time scales of the experimental conditions and the scenario model must be considered in determining site-specific values for RF_o.

Published estimates of resuspension factors and resuspension rates under indoor conditions, identified during the literature review, are summarized in Table 5.10. The reported values from these sources range from 2×10^{-8} to 4×10^{-2} m^{-1}. With one exception (Thatcher and Layton, 1995), no recent information on indoor resuspension was found. This most recent study provides estimates of resuspension *rates* of aerosols measured in a California residence under controlled indoor conditions. However, these rates cannot be directly translated into resuspension factor values.

Various factors affecting resuspension, underlying the range of reported values, have been proposed in the literature. The effects of some factors are quantified in some studies, while other effects are discussed qualitatively. Although many studies consider the factors affecting outdoor resuspension, these factors have analogs in indoor conditions. Such studies are therefore relevant for understanding potential *variations* in RF_o across sites. Sources of variability in reported resuspension factor values are described in more detail below.

The common measurement techniques for determining indoor resuspension factors are:

- direct measurement of contaminant concentrations on surfaces and in the air (Jones and Pond, 1964; Glauberman et al., 1964; Brunskill, 1964; Mitchell, and Eutsler, 1964)
- redispersion of settled particulates (Fish et al., 1964)
- recoil of "hot-atoms" during decay of radionuclides (Leonard, 1995)

In addition to differences in experimental technique, measured values of resuspension factor may vary due to

Table 5.10 Reported information for indoor resuspension

Condition/reference	Range	Comments
Wind stress and mechanical disturbances, (Jones and Pond, 1964)	2×10^{-8} – 5×10^{-5} m^{-1}	Resuspension of loose Pu-nitrate particles deposited on various surfaces
Wind stress and vehicular and mechanical disturbances, (Glauberman et al., 1964)	1×10^{-5} – 1.5×10^{-2} m^{-1}	Resuspension from Pu-contaminated surfaces; 0.2% to 10% removable by smear sampling
Wind stress (Brunskill, 1964)	2.5×10^{-4} – 3.9×10^{-3} m^{-1}	Resuspension of radionuclide contaminants from clothing in change room
Vigorous mechanical disturbance (sweeping) (Mitchell and Eutsler, 1964)	1×10^{-2} – 4×10^{-2} m^{-1}	Resuspension of BeO on contaminated wood floor; ~4% removable by smear sampling
Vigorous mechanical disturbance (sweeping) (Fish et al., 1964)	9.4×10^{-6} – 7.1×10^{-4} m^{-1}	Redistribution of loose thorium oxide and thorium metal aerosol particles, ZnS and CuO particles on stainless steel surfaces
Indoor Residence (Thatcher and Layton, 1995)	1.2×10^{-10} – 1.0×10^{-7} sec^{-1} m^{-1}	Resuspension rate in a California residence (Note: These values cannot be directly translated to resuspension factors).

spatial variability of surface contaminant concentrations, variability of concentrations in air with location and with elevation, and spatial variations in surface texture leading to location-dependent resuspension. These variations can create uncertainty in the effective value of resuspension factor as estimated by the ratio of concentrations measured in air and on the contaminated surface.

A large number of physical factors can affect resuspension. According to IAEA (1992), the major factors are the following:

- time since disposal
- type of disturbance (air flow or mechanical)
- intensity of disturbance (air flow speed, traffic intensity)
- nature of surface (texture, composition, surface area)
- surface moisture
- particle size distribution
- climatic conditions (temperature, humidity, wind)
- type of deposition process (wet or dry)
- chemical properties of the contaminant
- surface chemistry
- topographic features

The potential effects of some of these factors on resuspension have been quantified, while only qualitative characterizations are available for others. As discussed above, some studies discuss the effects of these factors on outdoor resuspension factors. While values of outdoor resuspension factors are not appropriate for the occupancy scenario model, reported effects of variations in physical conditions (e.g., air flow) on relative resuspension factor values do provide useful information about potential variations in indoor resuspension factor values due to variations in the occupant's behavior or environment. Surface moisture and climatic conditions are factors that may influence resuspension in outdoor conditions but are assumed to be irrelevant for indoor resuspension. These factors are therefore not considered in the following discussion. For the other factors listed above, the studies cited in NUREG/CR-5512, Vol. 1, and Fish et al. (1964), Jones and Pond (1964), Brunskill (1964), Glauberman et al. (1964), and Mitchell and Eutsler (1964) were reviewed to better understand the factors controlling resuspension factors. The following discussion considers both outdoor and indoor conditions, but indoor conditions are emphasized.

5.4.4.3.1 Time Since Disposal

The parameter RF_0 is constant with time, however several studies model variations of resuspension factor with time, including Kathren (1968), Langham (1969), NRC (1975), IAEA (1982, 1986), Garland (1982), and Nair et al. (1997). All of these models produce a decrease in resuspension factor with time, reflecting the experimentally observed decrease in contaminant air concentrations with time over contaminated areas. Rather than a decrease in resuspension factor per se, this observed decrease in air concentrations may instead be due to overall depletion of surface contamination (e.g., downward migration of contaminants, downwind transport of resuspended contaminants, and other removal processes). The observed decrease might also be due to preferential depletion of easily-suspended contaminants.

All discussions of reduction of resuspension factor with time found in the literature survey pertain to outdoor resuspension. No information on the potential time-variation of indoor resuspension factors was found.

5.4.4.3.2 Type of Disturbance (air flow or mechanical)

Resuspension factors determined under conditions of mechanical disturbance can be at least one order of magnitude higher than resuspension factors determined under conditions where only wind resuspension occurred (Nair et al., 1997; Stewart, 1964; Thatcher and Layton, 1995; and IAEA, 1992).

Among studies reporting indoor resuspension factors, the higher resuspension factors provided in Brunskill (1964), Glauberman et al. (1964), and Mitchell and Eutsler (1964) were measured when disturbances significantly more severe than in normal operating conditions were applied to obtain measurable contaminant concentrations and when most of the surface contamination was a loose, easily removable, contamination (spills on the floor). Fish et al. (1964) reports a difference in resuspension factor of 1.5 orders of magnitude due to the type of activities in the room.

5.4.4.3.3 Intensity of Disturbance (air flow speed, traffic intensity)

Anspaugh et al. (1975) suggests that contaminant concentra-tions in the air are proportional to the power of the friction velocity which is, in turn, proportional to the horizontal wind velocity. Consequently, the difference of 1 order in magnitude between the wind speed may result in a difference of a few orders of magnitude in resuspension factors. The power law relationship between the wind speed and resuspension factor is also demonstrated by Hollander (1994).

Among studies of indoor resuspension, Fish et al. (1964) observed a power law relationship between the resuspension factor and the air velocity in the room, and Jones and Pond (1964) reports variations in resuspension factor due to different walking speeds.

5.4.4.3.4 Nature of Surface (texture, composition, surface area)

The magnitude of the influence of this factor on resuspension was not quantified in the literature. In a study of indoor resuspension, Glauberman et al. (1964) attributes a difference in resuspension factors of one order of magnitude to differences in room size.

5.4.4.3.5 Particle Size Distribution

Hinton et al. (1995) suggests that resuspension is greatest for particles with diameter smaller than 125 microns and the IAEA (1992) suggests that resuspension factor increases with particle diameter in the range from 1 to 5 microns. In Sehmel (1980), however, it is suggested that further studies are needed. In a study of indoor resuspension, Fish et al. (1964) reports a strong correlation with particle diameter and Thatcher and Layton (1995) report no indoor resuspension of particles less than 5 μm in diameter.

5.4.4.3.6 Chemical Properties of the Contaminant

The difference between resuspension factors determined in the same conditions for different radionuclides is one order of magnitude, but could be significantly smaller as discussed by Hartmann et al. (1989) and the IAEA (1992). Among studies reporting indoor resuspension factors, Jones and Pond (1964) reports variation of the resuspension factor within one order of magnitude depending on the contaminant.

5.4.4.3.7 Surface Chemistry

Although cited by the IAEA (1992) as a factor influencing resuspension, no specific information on the effect of surface chemistry on resuspension factor was found in the literature.

5.4.4.3.8 Topographic Features

No specific information on the effect of topography on resuspension factor was found in the literature. For outdoor resuspension, topographic variations would presumably create variations in near-surface wind speed, leading to variations in the effective resuspension factor. An analogous effect might occur for indoor resuspension due to the placement of ventilation ductwork and furniture.

The main conclusions of this literature review are:

- the new data on resuspension factors falls into the same range that was noted in NUREG/CR-5512, Vol. 1; however, the low end of the range is three orders of magnitude higher (2×10^{-8} vs. 2×10^{-11} m^{-1});
- no significantly new models of resuspension and methods of resuspension measurement were proposed since 1990;

- additional information is available on resuspension factors determined under indoor conditions

- the resuspension factor value of 1×10^{-6} m^{-1} is the most frequently suggested and appears to represent some average of the experimental data;

- data on probability distribution functions that could be used to reflect uncertainty and variability in resuspension factors is very limited; however, it is possible to derive a distribution for RF_0 from experimental data on resuspension; and

- the range of the resuspension factor values measured under indoor conditions is around four orders of magnitude (Jones and Pond, 1964)

5.4.4.4 Estimating RF_0 from Site Information

For a particular site applying the building occupancy scenario model, a licensee might seek to defend a specific value for RF_0 based on the physical features of the site that influence resuspension directly, or based on expectations about, or restrictions on, the behavior of occupants which may affect resuspension. In view of the reported decrease in resuspension factor with time discussed above, a constant value of RF_0 reflecting the *initial* resuspension factor at the time of license termination is assumed to be appropriate for assessing regulatory compliance.

It is useful to express the resuspension factor used for the building occupancy dose calculation as the product of two separate parameters: the resuspension factor for "loose" contamination, and the fraction of the total contaminant that is "loose." "Loose" contamination refers to contamination that is available for transport via resuspension, and excludes any contamination that adheres to, is absorbed into, or is covered by exposed surfaces. This decomposition allows a more direct use of many reported values of resuspension factor given the underlying experimental conditions, and provides a physically plausible mechanism for linking the values of resuspension factor and secondary ingestion rate used in the dose calculation.

Based on the analysis of the literature data, the initial resuspension factor values can differ at least by a few orders of magnitude depending on site specific conditions which depend on the use of the property (i.e., the nature and intensity of mechanical disturbance associated with activities of the critical group), by an order of magnitude depending on radionuclide, and an order of magnitude depending on modeling approach used. Variations due to differences in radionuclides, topography, type of deposition, particle size, surface chemistry, and the nature of the surface are assumed to be uncontrollable by the licensee, but may be evaluated on a site-specific basis to support alternative values for resuspension factor.

Several of the physical factors discussed in Section 5.4.2.3 influencing resuspension may be plausibly bounded by characteristics of the site, or controlled by the licensee in an effort to support a site-specific value for RF_0. Other factors do not appear amenable to characterization or control. Site-to-site variations in these factors create variations among site-specific values of RF_0, but would presumably not be controllable by the licensee. Considerations of these factors follow.

5.4.4.4.1 Time Since Disposal

Because RF_0 is constant with time, the potential for resuspension factor to decrease with time is disregarded, as discussed above.

5.4.4.4.2 Type of Disturbance

Mechanical disturbance significantly increases the observed resuspension factor. Lower values of RF_0 may be appropriate if surface contamination is undisturbed by sweeping or walking. In addition, the effective (time averaged) resuspension factor may be reduced if the contaminated area is subject to brief intermittent disturbance rather than continuous disturbance.

5.4.4.4.3 Intensity of Disturbance

Large air-flow rates and vigorous mechanical disturbance lead to increased resuspension factors. Demonstration of limits on intensity, or of intermittence of periods of intense disturbance, may affect the value of RF_0, which reflects average annual conditions.

5.4.4.4.4 Nature of Surface

Little quantitative information on the effect of this factor was found in the literature. Available information is therefore assumed to be insufficient to support alternative values for RF_0 based on site-specific information about this factor.

5.4.4.4.5 Particle Size Distribution

Particle size is generally regarded as influencing resuspension factor.

5.4.4.4.6 Type of Deposition Process

Reported resuspension factor values are higher for loose, easily removable contamination than for contamination that is bound to, or absorbed into, the surface. Licensees are assumed to have removed most loose contamination prior to decommissioning. This assumption can be reflected in the occupancy scenario calculations in two ways: measured resuspension values for loose contamination may be excluded in defining RF_o, or RF_o may be initially defined for loose contamination, and the licensee may later reduce this value based on the fraction of loose contamination at their site.

Excluding measurements on loose contamination in defining RF_o assumes that *all* loose contamination has been removed, and that no mechanism will loosen contamination during the occupancy period. This assumption does not appear to be justifiable in all cases. The second approach, which decomposes the resuspension factor used in the occupancy scenario model into a resuspension factor for loose contamination, and a fraction of contamination that is loose (i.e., available for resuspension) allows uncertainty in the fraction of loose contamination to be explicitly addressed. This approach also provides a convenient mechanism for connecting the values for resuspension factor and secondary ingestion rate by using a common value for the fraction of loose contamination.

The parameter RF_o is therefore assumed to describe loose (resuspendable) contamination, and the licensee can reduce this value by demonstrating that the fraction of loose contamination at their facility is less than a specified fraction of total contamination (see NUREG-1549).

5.4.4.4.7 Chemical Properties of the Contaminant

The potential effect of chemical properties on resuspension factor is estimated to be one order of magnitude or less. Because it is a source of site-to-site variability in RF_o, licensees may base site-specific values for RF_o on chemical property arguments, however the size of this effect may be small.

5.4.4.4.8 Topography

No quantitative information on the effect of this factor was found in the literature. Available information is therefore assumed to be insufficient to support alternative values for RF_o based on site-specific topographic information.

Of the factors influencing resuspension discussed above, site-specific values for RF_o might be supported by information about the nature and intensity of disturbances likely to occur during the occupancy period. The effect of the remaining factors on resuspension is either relatively small (an order of magnitude or less), or is insufficiently defined in the literature for the licensee to defensibly derive a site-specific value of RF_o from information about these factors. Variations in these factors from site to site introduce variations in RF_o which are not expected be controllable by the licensee by restricting the use of the property (see NUREG-1549 for more information).

In addition to the nature and intensity of disturbance, the fraction of loose contamination will also control resuspension, and may be estimated from site data. As discussed above, any site-specific estimate for this fraction is assumed to be used to scale RF_o, while RF_o is assumed to describe resuspension of loose contamination.

Variations in the site-specific values for RF_o were estimated using published experimental data that were measured under a variety of activities and conditions. The procedure is summarized below, followed by a description of the application and results.

(1) Reported values for resuspension factor were categorized according to similarity in the descriptions of the experimental conditions regarding the nature and intensity of disturbance. As discussed above, variations in resuspension factor due to variations in mechanical disturbance may be plausibly controlled by the behavior of the critical group.

(2) For each category defined in Step 1, a range of acute (short term) resuspension factors was defined based on the reported values in each category. Within each category, variations in reported values are assumed to reflect variations due to factors other than the nature and intensity of surface disturbance, such as surface chemistry, surface topography, and particle size distribution. Variability in these factors among sites will also produce variability in site-specific values for RF_o, however, the effects of these factors on resuspension would not depend on the activities of occupants. Instead, such variations are modeled as random variations among sites, independent of the use of the property.

(3) For each category, a range of chronic (annual average) resuspension factors was defined using the range of reported resuspension factor values for that category. In general, the reported values for resuspension factor correspond to activities that

would be performed at intervals in an occupational setting, and performed only for a limited period of time. RF_o represents a chronic (year-long) effective value, and should therefore reflect the mixture and duration of activities performed by members of the critical group during a typical year. The range of chronic resuspension factor values is based on the observed range in reported resuspension factor values in consideration of uncertainties in time allocation estimates and in the estimated range of acute resuspension factor values.

(4) For a range of possible property uses, the occupation of the critical group at these properties was associated with one of the categories defined by the nature and intensity of disturbance in Step (1). This assignment reflects the occupational conditions to which a member of the critical group is expected to be exposed at such properties. Due to the limited number of measurements, only two categories were used to describe the potential occupational environments for members of the critical group. These categories are distinguished by the presence or absence of high air-flow rates.

(5) A distribution describing the variability of RF_o over sites was constructed based on: the estimated fraction of sites whose critical group is associated with each surface disturbance category defined in Step (4); and the distribution of chronic resuspension factor values associated with each category, defined in Step (3). In estimating the fraction of sites in each category, both the current use of the property, and the potential conversion of the property to other uses were considered.

Grouping of Reported Resuspension Factors based on Experimental Conditions

Table 5.11 summarizes the resuspension factors reported for experimental studies for various conditions (Jones and Pond, 1964; Glauberman et al., 1964; Mitchell and Eutsler, 1964; and Fish et al., 1964). Brunskill (1964) studied resuspension from contaminated clothing in the high air-flow conditions typical of a change room. In the occupancy scenario, contamination is assumed to occur on building surfaces. Resuspension from clothing was assumed to be unrepresentative of resuspension from these surfaces: values reported by Brunskill were therefore not considered in defining a distribution for RF_o.

The experiments by Jones and Pond (1964) provide resuspension factors for a range of activities that are common in occupational settings. The measured resuspension factors reported by Jones and Pond (1964) are for four levels of activities using PuO2-contaminated particles (0.4 - 60 microns diameter) and particulate air samplers positioned at 14-175 cm above the surface.

Glauberman et al. (1964) provides resuspension factors for a range of air-flow rates and mechanical disturbances that may occur in occupational settings. The values for this study reported in Table 5.11 show the relatively narrow range of resuspension factors observed for four experimental conditions. Glauberman measured occupational exposure to airborne particulates in a operating facility by measuring the concentrations of particles in air (high efficiency particulate sampler) and particles on surfaces (smear sampling), and reporting the ratio as a resuspension factor. Airborne particle contaminants in this experiment may have originated from sources other than surfaces (e.g., processing equipment, etc), which would tend to increase estimated resuspension factor values. The reported values from Glauberman et al. (1964) are included in Table 5.11 for comparison with the distribution for RF_o, but were judged to be highly uncertain and to overestimate the resuspension factor associated with the conditions described. These values were not used in developing the distribution. Mitchell and Eutsler (1964) measured resuspension factors during vigorous mechanical disturbance of contamination on a wood floor. The experimental conditions were contrived to deliberately suspend loose contamination in order to produce measurable values of resuspension factor. These conditions are not considered to be representative of conditions that would occur in an occupational setting. The reported values were therefore not included in defining a distribution for RF_o.

Fish et al. (1964) provides resuspension factors for a range of vigorous mechanical disturbances of contamination on a tile floor, and for high air-flow rates. The values in Table 5.11 for this study are reported for four types of disturbance.

In order to separate the effects of occupation-related factors from uncontrollable factors on resuspension, the resuspension factor values reported in Table 5.11 were grouped according to the nature and extent of surface disturbance. The presence or absence of high air-flow rates was first used to define two groups. For measurements made in the absence of high air flow, the descriptions of mechanical disturbance of the surface were used to classify each reported value in to one of two sub-groups based on the presence or absence of mechanical disturbance. For high air-flow conditions, too few values are available to support a distinction based on mechanical disturbance. Table 5.12 shows the values assigned to each of the three resulting categories.

Table 5.11 Resuspension factors measured under various conditions

Experimental condition	RF_0 (m^{-1})
Reported by Jones and Pond (1964)	
Normal room ventilation	3.3×10^{-8}
Walking (14 steps/min)	9.1×10^{-6}
Walking (36 steps/min)	6.9×10^{-5}
Walking (100 steps/min) with wind stress (hair dryer directed toward floor)	1.5×10^{-4}
Reported by Glauberman et al. (1964)*	
Undisturbed	1.5×10^{-5} to 3.6×10^{-4}
Fans on	3.4×10^{-5} to 1.6×10^{-3}
Vibration (dolly)	1.2×10^{-4} to 1.9×10^{-4}
Fans + vibration	1.2×10^{-4} to 1.5×10^{-2}
Reported by Mitchell and Eutsler (1964)**	
Vigorous sweeping by two workmen	1.02×10^{-2} to 4.2×10^{-2}
Reported by Fish et al. (1964)	
Vigorous work activity, including sweeping	1.9×10^{-4}
Vigorous walking	3.9×10^{-5}
Light work activity	9.4×10^{-6}
Rapid air circulation	7.1×10^{-4}

* Values not used due to experimental error (see text)
** Values not used due to unrepresentative conditions (see text)

Table 5.12 Reported resuspension factor values grouped by experimental conditions

Air flow	Mechanical stress	Reference	RF_0 (m^{-1})
Low/none	Absent	**Jones and Pond (1964):** Normal room ventilation	3.3×10^{-8}
Low/none	**Present**	**Jones and Pond (1964):** Walking (14 steps/min)	9.1×10^{-6}
		Fish et al. (1964): Light work activity	9.4×10^{-6}
		Jones and Pond (1964): Walking (36 steps/min)	6.9×10^{-5}
		Fish et al. (1964): Vigorous work activity, including sweeping	1.9×10^{-4}
		Fish et al. (1964): Vigorous walking	3.9×10^{-5}
High		**Fish et al. (1964):** Rapid air circulation	7.1×10^{-4}
		Jones and Pond (1964): Walking (100 steps/min) with wind stress (hair dryer directed toward floor)	1.5×10^{-4}

As discussed above, values reported by Glauberman et al. (1964) are assumed to overestimate resuspension by at least an order of magnitude, and were not included.

Trends among categories in Table 5.12 are generally consistent with expectations about resuspension: values tend to increase when mechanical disturbance or high air flow rates are present. Within each category, however, the range of reported values is generally large. This range is assumed to reflect variability in factors other than the nature and intensity of disturbance, such as surface chemistry, topography, and particle size.

Ranges of Resuspension Factors for Various Stress Conditions

Ranges of resuspension factor values were defined using the information in Table 5.12. Table 5.13 defines the ranges of resuspension factor values corresponding to each category. Estimates of the upper and lower limits, along with the source of these estimates, are provided for each category.

The values in Table 5.13 are based on the range of reported acute resuspension factor values for distinct

conditions of surface disturbance. The particular activities of occupants at a given site will entail characteristic disturbance conditions, and therefore control the effective resuspension factor values appropriate for those occupants. Within each category, the range of reported values is assumed to reflect the effects of factors specific to the site but unrelated to occupation, such as surface topography and chemistry, and particle size.

The value for RF_0 used in the dose calculation should reflect the time-averaged value of condition-specific resuspension factors over the one year duration of the occupancy scenario. This time average (chronic) value will generally differ from the acute values in Table 5.13 due to variations in the occupant's behavior over time. In addition, the larger resuspension factor values given in Table 5.13 for high air-flow conditions imply significant depletion of the source over the one year period of the scenario. The effects of these two factors on the proposed distribution for RF_0 are described in the following sections.

Acute vs. Chronic Resuspension Factor Values

For a given individual, the resuspension factor will vary with time because their activities vary with time. Ideally, an estimate of the chronic (time averaged) resuspension factor value would be based on an estimate of the time spent in activities corresponding to each category. The chronic resuspension factors would then be calculated as the sum of the acute resuspension factors for each category, weighted by the amount of time spent in each category. As a result of this averaging process, the range of chronic values for occupants who tend to spend their time in activities in a given category will be narrower than the range of acute values experienced by the occupant over time.

A formal estimate of chronic resuspension factor values would require estimates of the time spent on each category, and of the acute resuspension factor for each category. For this analysis, the results of such a process would be subject to two important and counteracting sources of uncertainty.

First, estimates of time allocation for particular occupations that might occur at licensed properties would be highly uncertain. Although, as discussed above, the range of chronic values for occupants would be narrower than the range of acute values due to the effect of time averaging, the location of the range of chronic values within the larger range of acute values would be subject to considerable uncertainty due to uncertainty in the estimated time allocation.

Second, the ranges of possible acute resuspension factor values corresponding to distinct stress conditions is uncertain. Although ranges for the categories defined in Table 5.13 were defined by the limits of reported values, very few observations are available for each category. As a result, the potential range of acute resuspension factor values corresponding to distinct stress conditions is expected to be wider than the range in reported values due to limited sampling of these conditions by published experimental results. In order to formally calculate chronic resuspension factor values, estimates of the true range of acute resuspension factors, developed in consideration of the limited number of samples available in each category, would be required. These estimates would also be subject to considerable uncertainty.

Table 5.13 Ranges of potential resuspension factor values for categories of surface stress conditions

Category	Air flow	Mechanical stress	Limit	Value (m^{-1})	Source
A	**Low/ none**	**Absent**	Lower	3.3×10^{-8}	**Jones and Pond (1964):** Normal room ventilation
			Upper	3.3×10^{-8}	**Jones and Pond (1964):** Normal room ventilation
B	**Low/ none**	**Present**	Lower	9.1×10^{-6}	**Jones and Pond (1964):**Walking (14 steps/min)
			Upper	1.9×10^{-4}	**Fish et al. (1964):** Vigorous work activity, including sweeping
C	**High**		Lower	1.5×10^{-4}	**Jones and Pond (1964):** Walking with wind stress
			Upper	7.1×10^{-4}	**Fish et al. (1964):** Rapid air circulation

Rather than attempting a formal calculation of chronic resuspension factor values, the ranges of values in Table 5.13 were directly adopted as estimates of the ranges of potential chronic values for occupants typically exposed to conditions defined by each category. This approach does not require assumptions regarding time allocation for various occupations nor assumptions about the actual range of potential acute values given the range in reported measurements. As discussed above, these assumptions would introduce considerable uncertainty in the calculated chronic values. The ranges in Table 5.13 are also uncertain as estimates of chronic resuspension factors, however the two primary sources of uncertainty discussed above tend to have counteracting effects: time averaging of acute values would result in chronic values that are narrower than the range of acute values, however the actual range of acute values is wider than the range of observed values due to the limited number of samples.

Source Mass Conservation

Based on the above considerations, the ranges of reported acute resuspension factor values in Table 5.13 were assumed to define the ranges in potential annual average resuspension factor values. For high air-flow conditions, however, the annual average resuspension factor value may also be limited by the total source mass. Because the occupancy scenario model does not include source mass loss via resuspension, resuspension factor values which imply substantial depletion of source contaminants will lead to overestimates of dose.

The effect of source depletion by resuspension in the presence of high air flow can be included in one of two ways: the occupancy scenario model can be revised to include source mass conservation, or an effective resuspension factor can be derived which includes the effect of source mass loss during the one-year scenario period. The latter approach was adopted, as described below, to calculate an *effective* chronic resuspension factor value from the *potential* chronic values in Table 5.13. This effective value incorporates the influence of source depletion, which is not modeled in the default occupancy scenario model as defined in NUREG/CR-5512, Vol. 1. *The resulting resuspension factor values are not appropriate for models which explicitly include source mass loss via resuspension.*

Under conditions of high air-flow, any resuspended material is assumed to be removed as a potential source. Under this assumption, the rate of source depletion is equal to the resuspension rate:

$$\frac{dC_s(t)}{dt} = -\lambda_{res} C_s(t) \qquad (5.20)$$

where $C_s(t)$ is the source concentration, and λ_{res} is the resuspension rate. In Equation (5.20), all source mass loss is assumed to occur through resuspension, and mass loss due to other process is assumed to be negligible over the one-year dose assessment period. During this period, the amount of resuspended material is calculated from a constant specified source $C_s(0)$ and the specified resuspension factor value RF_{eff}. Mass depletion implied by Equation 5.20 may be approximately included via RF_{eff} by requiring that the resuspended mass, calculated using RF_{eff} and $C_s(0)$, is equal to the average resuspended mass calculated using the potential chronic resuspension factor RF_c and the depleting source $C_s(t)$:

$$RF_{eff} C_s(0) = \frac{1}{T}\int_0^T RF_c C_s(t)\,dt = \frac{1}{T}\int_0^T RF_c C_s(0) e^{-\lambda_{res} t}\,dt = RF_c C_s(0)\left(\frac{1-e^{-\lambda_{res} T}}{\lambda_{res} T}\right) \qquad (5.21)$$

so that the effective and potential resuspension factors are related by:

$$RF_{eff} = RF_c\left(\frac{1-e^{-\lambda_{res} T}}{\lambda_{res} T}\right) \qquad (5.22)$$

In Equation 5.22, T is the length of time during which source mass loss occurs, which was assumed to correspond to a standard working year of 250 eight-hour days (50 five-day weeks). The resuspension rate can be estimated from the room geometry, the ventilation rate, and the resuspension factor:

$$\lambda_{res} = \left(\frac{V}{A}\right)_{room} RF_c\ \lambda_V \qquad (5\text{-}23)$$

where V is the room volume, A is the room area, and λ_V is the ventilation rate. The ratio $\frac{V}{A}$ typically ranges from approximately 0.5 m for small rooms to approximately 1 m for large rooms. Ventilation rates corresponding to "high" air-flow rates were estimated using the Versar (1990) *Database of PFT Ventilation Measurements*, as summarized in the EPA Exposure Factors Handbook. The database compiles results from a number of separate studies, each study reporting a number of measurements taken at different residences or during different seasons. These measurements were made in residential rather than occupational settings, and cannot be used directly to estimate ventilation rates for high air-flow conditions. Across the summarized

studies, the 90th percentile ventilation rates range from 0.38 to 5.89 h^{-1}. A ventilation rate of 5 h^{-1} was therefore chosen to represent high air-flow conditions in an occupational setting.

5.4.4.5 Proposed Distribution for RF_0

For a given site, a site-specific value for RF_0 should reflect conditions experienced by the average member of the critical group. The critical group at a given site is in turn assumed to be defined by the occupation associated with the upper end of the range of effective resuspension factor values.

A distribution function describing the variability of site-specific values for RF_0 was calculated as the weighted sum of the distributions for the surface stress categories defined in Table 5.13. Weights for each category represent the fraction of sites having critical groups which are chronically exposed to the type of surface disturbance characterizing each category.

Within each category, site-to-site variability in topography, chemistry, particle size, and other factors unrelated to occupation were assumed to produce values between the lower and upper limits for that category. Because no information is available on the potential distribution of values within these limits, the logarithm of RF_0 was assumed to be uniformly distributed between them. For resuspension in the presence of high air-flow, effective resuspension factor values were calculated from the potential resuspension factor values (Category C of Table 5.13) using Equations 5.22 and 5.23.

Assuming that any property might be devoted, at some future time, to light industry, no licensee would be able to exclude the possibility of mechanical disturbance chronically occurring at their site. The fraction of sites having critical groups exposed to Category A is therefore assumed to be 0. Many licensees would, however, be able to exclude the possibility of high air-flow rates, as such rates seem likely to be associated with customized ventilation systems, large openings such as bay doors, or other structural features which the building may lack. The fraction of sites containing such features was estimated as the fraction of non-service enterprises devoted to manufacturing in 1993 (approximately 9.8%), as reported by the U.S. Census Bureau. The remaining sites (90.2%) are assumed to have resuspension factor values from Category B.

In summary, 90.2% of sites are assumed to have resuspension factor values between 9.1×10^{-6} and 1.9×10^{-4} m^{-1}, with a log-uniform distribution assumed between these limits. The remaining 9.8% of sites are assumed to have structural features that might create high air-flow conditions, and therefore have potential resuspension factor values ranging from 1.5×10^{-4} to 7.1×10^{-4} m^{-1}, with a log-uniform distribution assumed between these limits. High resuspension factor values, however, in conjunction with high air-flow conditions, imply substantial depletion of source mass during the one-year performance period. This depletion is included in the resuspension factor value by calculating an effective annual average value from the potential resuspension factor value using Equations 5.22 and 5.23. In this calculation, the ventilation rate was assumed to be 5 h^{-1}, while the volume/area ratio was assumed to be uniformly distributed between 0.5 m and 1.0 m.

Figure 5.7 shows the resulting cumulative distribution functions for RF_0, while Figure 5.8 shows the corresponding probability density function. The proposed distribution for RF_0 ranges from 9.1×10^{-6} m^{-1} to 1.9×10^{-4} m^{-1}, with a median value of 5.0×10^{-5} m^{-1}. Although the resuspension factors for various experimental conditions ranges over several orders of magnitude, values of resuspension factor for the screening group are biased towards the upper end of reported values based on the range of surface stress conditions assumed for the workers in light industry. This distribution reflects resuspension of loose contamination, and should be scaled to reflect the fraction of the total contamination which is available for resuspension.

5.4.4.6 Parameter Uncertainty

The proposed distribution describing the variability in the resuspension factor is based on several assumptions, leading to uncertainty in this distribution as an estimate of the potential variability of RF_0 over sites:

(1) Resuspension of loose particles in a building occurs by a combination of wind stress from normal building ventilation and mechanical disturbances from walking and vehicular traffic. Other than in manufacturing establishments, persistent high air-flow conditions are assumed to be unlikely.

(2) Resuspension factor values are reported to depend to some extent on a number of other factors, including surface texture and topography, particle size distribution, type of deposition, and chemical properties of the contaminant and surface. These factors are assumed to produce site-to-site variations in resuspension factor values which are unrelated to the occupation of the critical group.

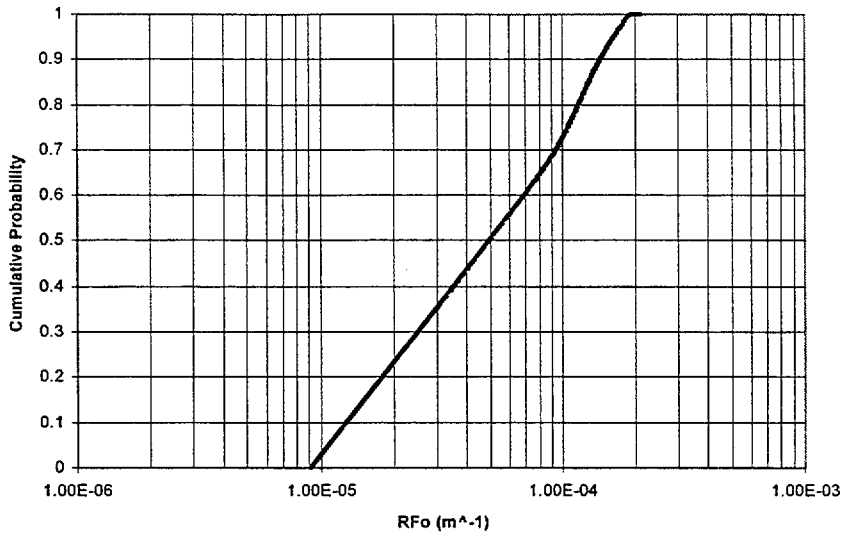

Figure 5.7 Cumulative probability function for RF_o

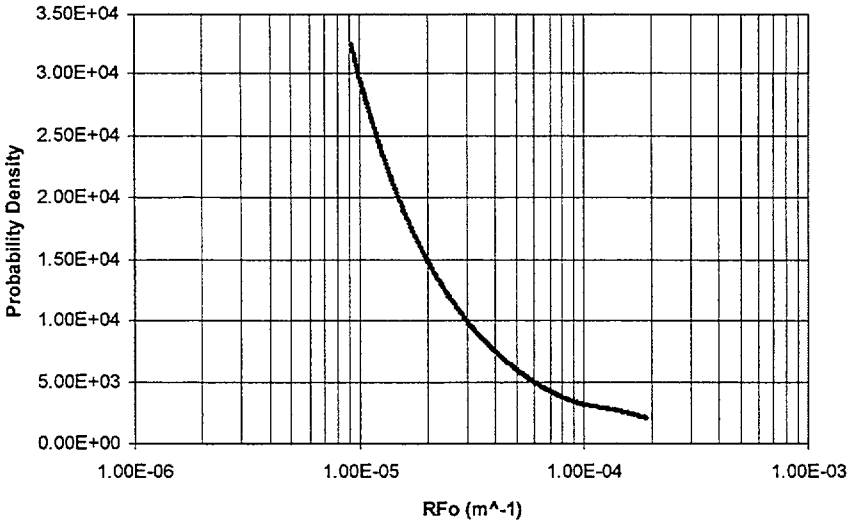

Figure 5.8 Proposed probability density function for RF_o

(3) The reported ranges of resuspension factors, measured under experimental conditions corresponding to episodic occupational activities, were adopted as the range of possible chronic resuspension factor values for occupants typically engaged in these activities. This assumption was made in consideration of the uncertainties associated with estimated time allocations for occupations, the tendency for time-averaged values to have lower variability than the true acute values, and the expectation that the limited number of measurements of resuspension underestimate the true variability in acute resuspension factor values.

(4) The combination of high resuspension factor values with high air flow conditions implies substantial depletion of source mass during the one year dose assessment period. Because the default occupancy scenario model does not include source mass loss through resuspension, effective (annual average) resuspension factor values, which approximate the effect of source depletion, were developed for these conditions. This approximation assumes that resuspension is the primary mechanism of source depletion, and that mass loss through other processes are comparatively small during the performance period. *These effective resuspension factor values are not suitable for use in models that explicitly include source mass loss by resuspension.*

(5) The data on resuspension reported by Glauberman (1964) are regarded as uncertain over-estimates.

(6) U.S. Census data on the numbers and types of industrial divisions in the United States reflect the variability in property uses over the licensed sites.

(7) Alternative future property uses would be considered in establishing a site-specific resuspension factor value. Such uses might increase or decrease mechanical surface disturbance. Increases in air flow are assumed to require extensive modifications to existing structures.

5.4.4.7 Alternative Parameter Values

The resuspension factor will vary across sites due to differences in the use of the properties, and due to factors unrelated to the use of the property such as surface chemistry and topography. A licensee may attempt to support limits on RF_o based on the intended use of the property or provide site-specific data regarding fixed vs. removable contamination. Physical properties of the building, existing zoning requirements, and site survey results may be used to support site-specific values.

5.5 Results

Parameter distributions defined in Section 5.4 were used to derive dose distributions for unit concentrations of each of the 106 potential source radionuclides having half-lives greater than 65 days (see Table 5.14). Screening dose values, corresponding to specified quantiles of the dose distributions, were then identified. Because the resuspension factor RF_o is the only variable physical parameter, the quantile values of the dose distributions correspond to the quantile values of the distribution for RF_o. The default value for RF_o, corresponding to a specified inversion tolerance P_{crit}, is simply the $1 - P_{crit}$ quantile value of the RF_o distribution. The general procedure for establishing these dose values is described in Section 3.0. The application of this procedure to the default Occupancy Scenario, and the resulting screening dose values and default RF_o values, are summarized below.

Table 5.14 Source nuclides used in the parameter analysis

Source ID	Source	Source ID	Source	Source ID	Source
1	3H	87	126Sn+C	180	232Th
2	10Be	89	125Sb	181	232Th+C
3	14C	93	123mTe	183	231Pa
5	22Na	95	127mTe	184	231Pa+C
9	35S	106	129I	187	232U
10	36Cl	114	134Cs	188	232U+C
11	40K	115	135Cs	189	233U
12	41Ca	117	137Cs	190	233U+C
13	45Ca	128	144Ce	191	234U
14	46Sc	132	147Pm	192	235U
16	54Mn	137	147Sm	193	235U+C
18	55Fe	138	151Sm	194	236U
20	57Co	140	152Eu	196	238U
21	58Co	141	154Eu	197	238U+C
22	60Co	142	155Eu	199	237Np
23	59Ni	144	153Gd	200	237Np+C
24	63Ni	145	160Tb	203	236Pu
27	65Zn	146	166mHo	205	238Pu
31	75Se	147	181W	206	239Pu
32	79Se	148	185W	207	240Pu
41	90Sr	150	187Re	208	241Pu
48	93Zr	151	185Os	209	242Pu
49	93Zr+C	153	192Ir	211	244Pu
52	93mNb	156	210Pb	212	241Am
53	94Nb	160	210Po	213	242mAm

Table 5.14 Source nuclides used in the parameter analysis (continued)

Source ID	Source	Source ID	Source	Source ID	Source
58	93Mo	165	226Ra	215	243Am
61	99Tc	166	226Ra+C	216	242Cm
65	106Ru	167	228Ra	217	243Cm
69	107Pd	169	227Ac	218	244Cm
71	110mAg	170	227Ac+C	219	245Cm
73	109Cd	173	228Th	220	246Cm
74	113mCd	174	228Th+C	221	247Cm
81	119mSn	175	229Th	222	248Cm
82	121mSn	176	229Th+C	223	252Cf
84	123Sn	177	230Th		
86	126Sn	178	230Th+C		

5.5.1 Assumed Fraction of Removable Contamination

As discussed in Sections 5.4.2 and 5.2.2, the resuspension factor and secondary ingestion transfer factor parameters describe the uptake of removable contamination. The distributions defined for these parameters describe the resuspension and transfer of loose contamination. In calculating the screening dose values, 10% of the measured source concentration was assumed to be removable.

5.5.2 Definition of the Screening Group for the Occupancy Scenario

The Screening Group is a generic Critical Group suitable for making decisions at any site without site specific information on potential occupant behavior. For the Occupancy Scenario, the Screening Group is defined as workers in light industry. The behavioral parameter values for the AMSG are defined by the mean values of their respective parameter distributions, described in Sections 5.2.1 and 5.2.2. Table 5.15 (see end of this section) lists the values for the behavioral and metabolic parameters of the occupancy scenario model: the time the AMSG spends in the building (T_o), the breathing rate for the AMSG (V_o), and the secondary ingestion rate for the AMSG (GO).

Table 5.15 Behavioral parameters for the average member of the screening group

Parameter	Value
TO (d/y)	97.46
VO (m^3/h)	1.4
GO (m^2/h)	1.11×10^{-5}

5.5.3 Calculation of Screening Dose Values

As described in Section 3.0, screening dose values are calculated by deriving the distribution of possible dose values over all sites (given the behavioral parameter values defining the AMSG), and selecting, for each source nuclide, a dose value near the upper end of the resulting distribution. In general, this calculation entails: sampling the distributions for the scenario parameters characterizing the physical properties of the sites; using the scenario model to calculate the dose to the AMSG for each set of sampled values of the physical parameters; assembling the dose distribution from the resulting individual dose calculations; and identifying the dose value at the selected quantile of this distribution.

The Occupancy Scenario model has one parameter, resuspension factor (RF_o), characterizing the physical properties of the site. The three remaining input parameters describe occupant behavior, and are established by the definition of the AMSG as described in Section 5.5.2. One thousand samples from the distribution for RF_o were generated using stratified Monte-Carlo (LHS) sampling (Iman and Shortencarier, 1984). For each sample, dose to the AMSG was then calculated for unit concentrations of each of the 106 possible source nuclides. For each source, the distribution describing possible doses to the AMSG was then constructed from these calculated doses.

Possible screening dose values were selected from these distributions by stipulating a tolerance for underestimating dose (i.e., P_{crit}). For three alternative values of P_{crit}, and for each source nuclide, a screening dose value was identified such that the fraction of doses larger than the screening dose was equal to P_{crit}. These values correspond to the $(1 - P_{crit})$ quantiles of the calculated dose distributions.

Table 5.16 lists these screening dose values for each of the source nuclides, and for three alternative values for P_{crit}. As a measure of the spread of the dose distributions, Table 5.16 also shows the ratio of dose at

the 95th percentile to the median dose. Figures 5.9 through 5.15 show the calculated dose distributions for seven of the 106 individual sources: Co-60, Sr-90, Cs-137, Ra-226, Th-230, Th-232, and U-238. A P_{crit} value of 0.10 was used to define the screening calculations for DandD interim release 1.0.

Many source nuclides, such as Co-60 and Cs-137, have very narrow dose distributions: the ratio of the 95th percentile dose to the median dose is very close to 1. Dose due to these nuclides is not strongly dependent on resuspension, and presumably is dominated by non-inhalation pathways. Other nuclides, such as Sr-90 and Th-230 have broader (although still compact) distributions. The ratio of the 95th percentile dose to the median dose is greater than three for many nuclides, indicating that dose is strongly controlled by the resuspension factor, and therefore occurs primarily through the inhalation pathway.

5.5.4 Values of Physical Parameters Associated with Screening Doses

Because there is only one physical parameter (RF_o) in the Occupancy Scenario model, and because dose is a monotonically increasing function of resuspension factor, a given quantile of the dose distribution corresponds to the same quantile of the input distribution for RF_o. For example, the 95th percentile of dose for all sources can be directly calculated using the value of RF_o at the 95th percentile of it's distribution, in conjunction with the AMSG behavioral parameters. Table 5.17 lists the resuspension factor values corresponding to the alternative quantiles considered in Table 5.16.

The derived dose distribution functions can also be used to test or formulate more complex decision criteria. As an example, the dose value at the 95th percentile of the dose distribution can be identified by stipulating the dose value at some other quantile of the dose distribution. Table 5.18 lists, for each of the three P_{crit} values, the dose value at the 95th percentile, given that the dose at the $(1 - P_{crit})$ quantile is 25 mrem/year.

Dose values at the selected quantiles can also be used to calculate the source concentration equivalent to a dose of 25 mrem/year. Table 5.19 summarizes these concentration values.

Table 5.16 Quantile values of unit-source dose distributions(mrem/year per dpm/100 cm^2)

Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$	Dose @ $P_{crit} = 0.05$/ Dose @ $P_{crit} = 0.50$
3H	1.68E-07	2.02E-07	2.19E-07	1.87
10Be	5.50E-04	7.43E-04	8.37E-04	3.23
14C	5.66E-06	6.80E-06	7.36E-06	1.86
22Na	2.62E-03	2.62E-03	2.62E-03	1.00
35S	1.53E-06	1.97E-06	2.18E-06	2.53
36Cl	3.81E-05	5.01E-05	5.59E-05	2.78
40K	2.45E-04	2.52E-04	2.55E-04	1.09
41Ca	3.56E-06	4.29E-06	4.65E-06	1.90
45Ca	7.07E-06	8.90E-06	9.80E-06	2.27
46Sc	8.66E-04	8.71E-04	8.73E-04	1.02
54Mn	7.90E-04	7.93E-04	7.94E-04	1.01
55Fe	4.26E-06	5.55E-06	6.18E-06	2.67
57Co	1.15E-04	1.18E-04	1.20E-04	1.09
58Co	3.68E-04	3.69E-04	3.70E-04	1.01
60Co	3.43E-03	3.55E-03	3.60E-03	1.10
59Ni	4.40E-06	5.87E-06	6.59E-06	3.03
63Ni	1.03E-05	1.37E-05	1.54E-05	2.99
65Zn	5.13E-04	5.20E-04	5.23E-04	1.04

Table 5.16 Quantile values of unit-source dose distributions (mrem/year per dpm/100 cm^2) (continued)

Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$	Dose @ $P_{crit} = 0.05$/ Dose @ $P_{crit} = 0.50$
75Se	2.31E-04	2.33E-04	2.34E-04	1.03
79Se	2.53E-05	3.07E-05	3.33E-05	1.93
90Sr	2.17E-03	2.87E-03	3.21E-03	2.90
93Zr	4.95E-04	6.71E-04	7.56E-04	3.27
93Zr+C	5.41E-04	7.32E-04	8.25E-04	3.25
93mNb	4.56E-05	6.12E-05	6.87E-05	3.09
94Nb	2.79E-03	3.01E-03	3.12E-03	1.28
93Mo	5.38E-05	6.97E-05	7.75E-05	2.59
99Tc	1.46E-05	1.91E-05	2.13E-05	2.75
106Ru	7.68E-04	9.56E-04	1.05E-03	2.16
107Pd	1.98E-05	2.67E-05	3.01E-05	3.24
110mAg	2.42E-03	2.45E-03	2.47E-03	1.03
109Cd	1.71E-04	2.19E-04	2.43E-04	2.45
113mCd	2.47E-03	3.28E-03	3.68E-03	2.95
119mSn	1.73E-05	1.96E-05	2.07E-05	1.49
121mSn	2.77E-05	3.41E-05	3.73E-05	2.07
123Sn	3.13E-05	3.91E-05	4.28E-05	2.19
126Sn	2.90E-03	2.96E-03	2.99E-03	1.06
126Sn+C	2.93E-03	2.99E-03	3.01E-03	1.06
125Sb	5.57E-04	5.64E-04	5.67E-04	1.04
123mTe	9.27E-05	9.51E-05	9.63E-05	1.08
127mTe	2.59E-05	3.06E-05	3.28E-05	1.73
129I	6.25E-04	7.20E-04	7.66E-04	1.59
134Cs	1.94E-03	1.96E-03	1.97E-03	1.03
135Cs	1.53E-05	1.78E-05	1.90E-05	1.64
137Cs	8.75E-04	8.92E-04	9.01E-04	1.06
144Ce	4.50E-04	5.85E-04	6.51E-04	2.63
147Pm	5.40E-05	7.28E-05	8.20E-05	3.19
147Sm	1.15E-01	1.56E-01	1.76E-01	3.28
151Sm	4.63E-05	6.26E-05	7.05E-05	3.24
152Eu	1.85E-03	1.96E-03	2.02E-03	1.21
154Eu	2.03E-03	2.18E-03	2.25E-03	1.25
155Eu	1.38E-04	1.59E-04	1.70E-04	1.59
153Gd	1.15E-04	1.23E-04	1.27E-04	1.23
160Tb	4.32E-04	4.36E-04	4.38E-04	1.03
166mHo	3.58E-03	4.00E-03	4.21E-03	1.43
181W	2.33E-05	2.34E-05	2.34E-05	1.00
185W	1.07E-06	1.19E-06	1.25E-06	1.39
187Re	9.46E-08	1.24E-07	1.39E-07	2.78
185Os	3.48E-04	3.50E-04	3.51E-04	1.02
192Ir	3.32E-04	3.37E-04	3.39E-04	1.04
210Pb	3.56E-02	4.57E-02	5.06E-02	2.47
210Po	7.62E-03	9.97E-03	1.11E-02	2.72
226Ra	1.75E-02	2.24E-02	2.47E-02	2.41
226Ra+C	6.18E-02	7.93E-02	8.78E-02	2.48

Table 5.16 Quantile values of unit-source dose distributions (mrem/year per dpm/100 cm^2) (continued)

Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05	Dose @ P_{crit} = 0.05/ Dose @ P_{crit} = 0.50
228Ra	9.24E-02	1.24E-01	1.40E-01	3.12
227Ac	1.02E+01	1.38E+01	1.55E+01	3.28
227Ac+C	1.02E+01	1.38E+01	1.55E+01	3.28
228Th	4.46E-01	6.04E-01	6.81E-01	3.26
228Th+C	4.46E-01	6.04E-01	6.81E-01	3.26
229Th	3.32E+00	4.50E+00	5.08E+00	3.28
229Th+C	3.33E+00	4.51E+00	5.08E+00	3.28
230Th	5.00E-01	6.78E-01	7.64E-01	3.28
230Th+C	5.63E-01	7.58E-01	8.53E-01	3.17
232Th	2.52E+00	3.42E+00	3.85E+00	3.28
232Th+C	3.06E+00	4.15E+00	4.67E+00	3.27
231Pa	2.14E+00	2.90E+00	3.27E+00	3.26
231Pa+C	1.23E+01	1.67E+01	1.88E+01	3.27
232U	1.09E+00	1.48E+00	1.67E+00	3.28
232U+C	1.55E+00	2.10E+00	2.37E+00	3.27
233U	2.08E-01	2.82E-01	3.18E-01	3.28
233U+C	3.70E+00	5.01E+00	5.65E+00	3.28
234U	2.04E-01	2.76E-01	3.11E-01	3.28
235U	1.89E-01	2.56E-01	2.89E-01	3.27
235U+C	1.25E+01	1.69E+01	1.91E+01	3.27
236U	1.93E-01	2.61E-01	2.95E-01	3.28
238U	1.82E-01	2.47E-01	2.78E-01	3.28
238U+C	9.47E-01	1.28E+00	1.44E+00	3.22
237Np	8.34E-01	1.13E+00	1.27E+00	3.25
237Np+C	4.66E+00	6.32E+00	7.12E+00	3.27
236Pu	2.03E-01	2.75E-01	3.10E-01	3.26
238Pu	6.03E-01	8.16E-01	9.20E-01	3.25
239Pu	6.63E-01	8.97E-01	1.01E+00	3.25
240Pu	6.63E-01	8.97E-01	1.01E+00	3.25
241Pu	1.30E-02	1.76E-02	1.98E-02	3.25
242Pu	6.34E-01	8.58E-01	9.67E-01	3.25
244Pu	6.23E-01	8.43E-01	9.50E-01	3.25
241Am	6.85E-01	9.27E-01	1.04E+00	3.25
242mAm	6.67E-01	9.03E-01	1.02E+00	3.25
243Am	6.80E-01	9.20E-01	1.04E+00	3.25
242Cm	1.50E-02	2.04E-02	2.30E-02	3.26
243Cm	4.69E-01	6.34E-01	7.15E-01	3.25
244Cm	3.75E-01	5.08E-01	5.73E-01	3.26
245Cm	7.03E-01	9.52E-01	1.07E+00	3.25
246Cm	6.97E-01	9.43E-01	1.06E+00	3.25
247Cm	6.40E-01	8.66E-01	9.77E-01	3.25
248Cm	2.55E+00	3.46E+00	3.90E+00	3.25
252Cf	2.13E-01	2.88E-01	3.25E-01	3.26

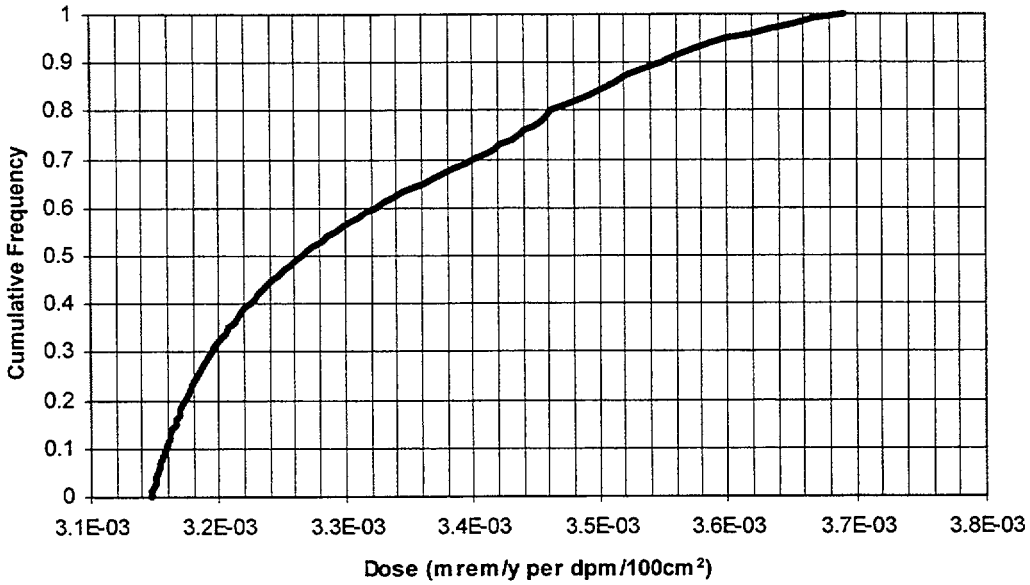

Figure 5.9 Calculated distribution of dose to the average member of the screening group due to a unit source of Co-60

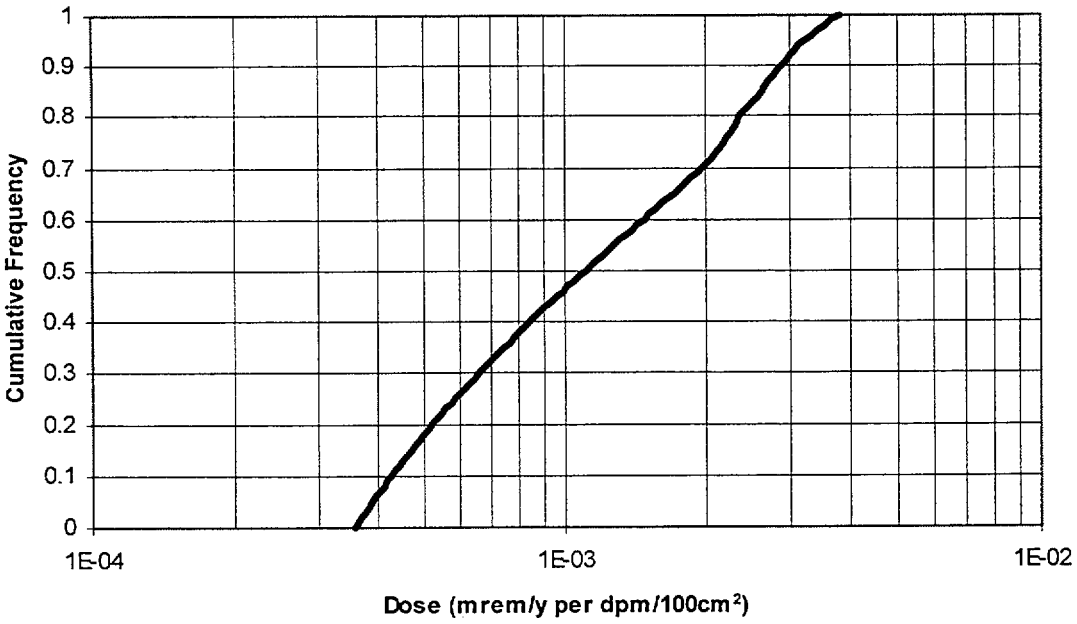

Figure 5.10 Calculated distribution of dose to the average member of the screening group due to a unit source of Sr-90

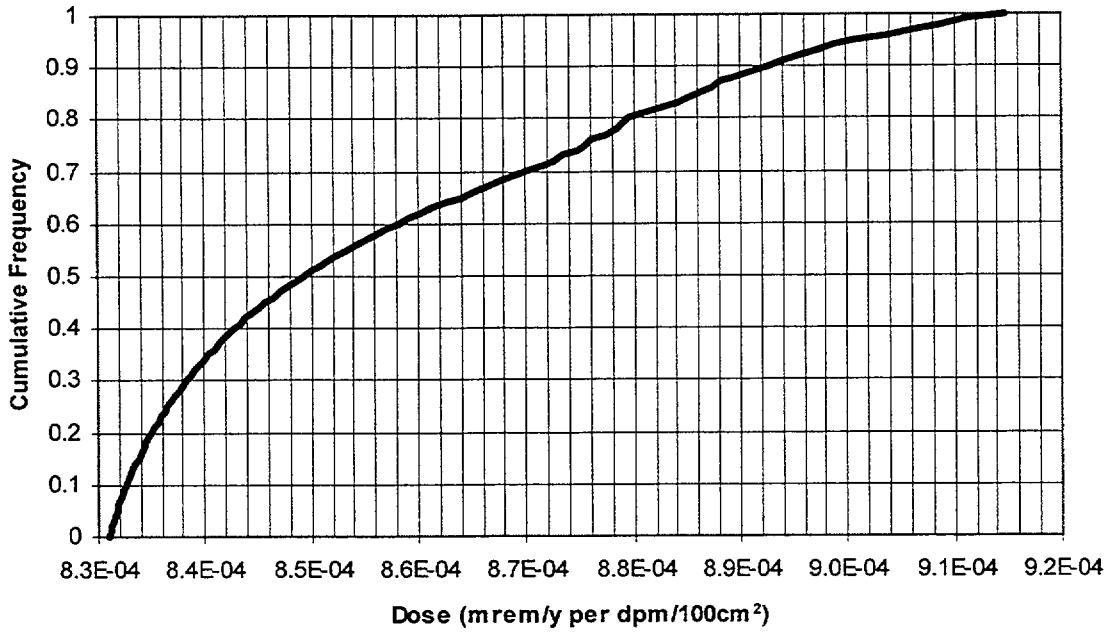

Figure 5.11 Calculated distribution of dose to the average member of the screening group due to a unit source of Cs-137

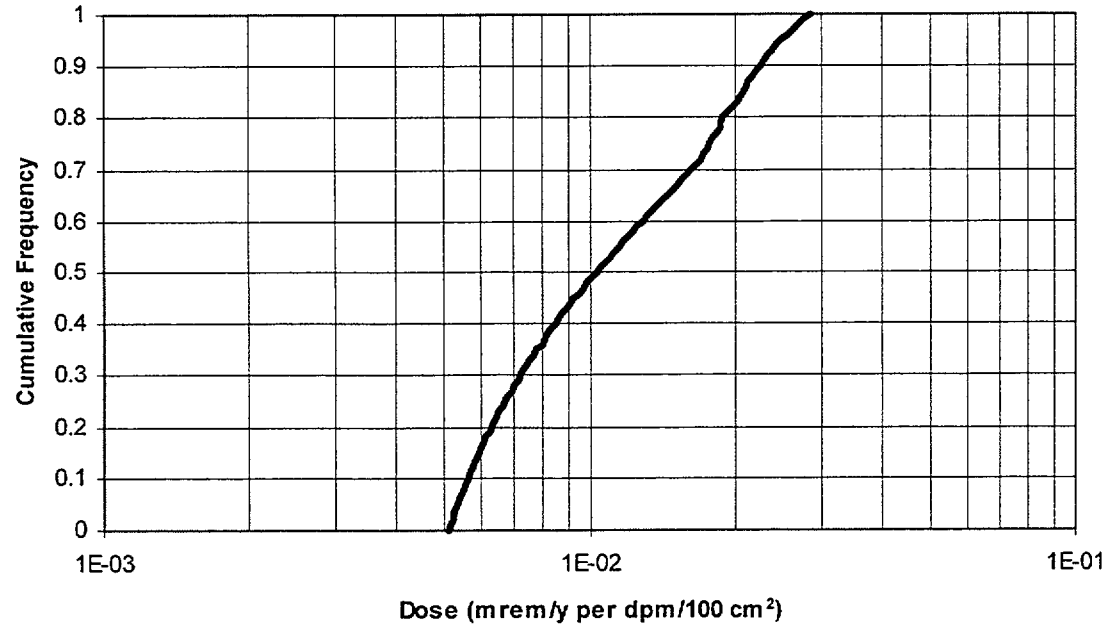

Figure 5.12 Calculated distribution of dose to the average member of the screening group due to a unit source of Ra-226

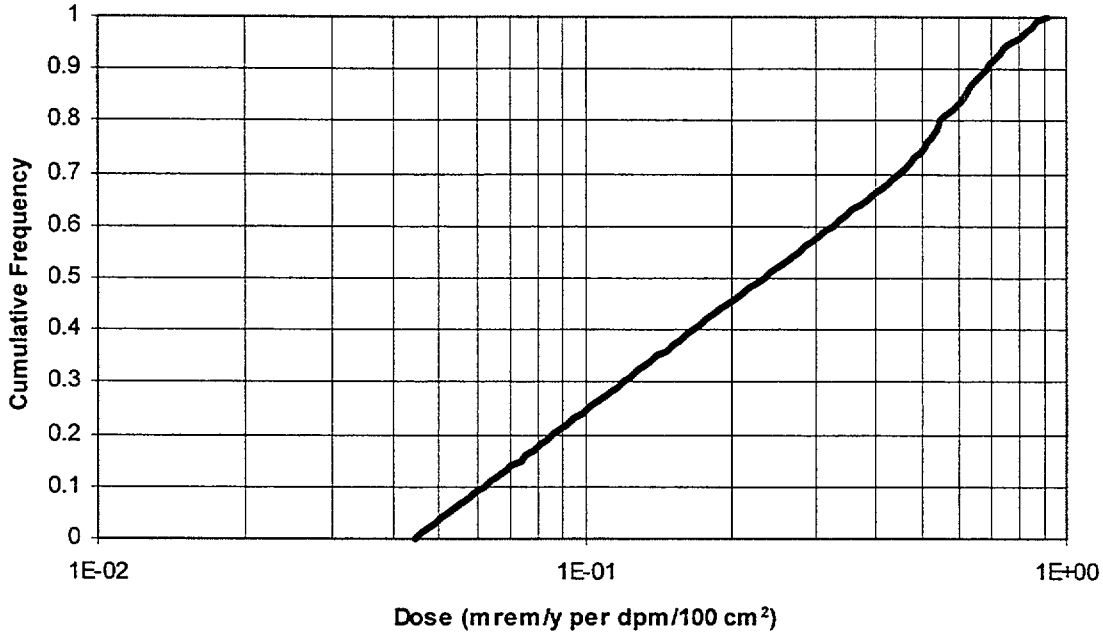

Figure 5.13 Calculated distribution of dose to the average member of the screening group due to a unit source of Th-230

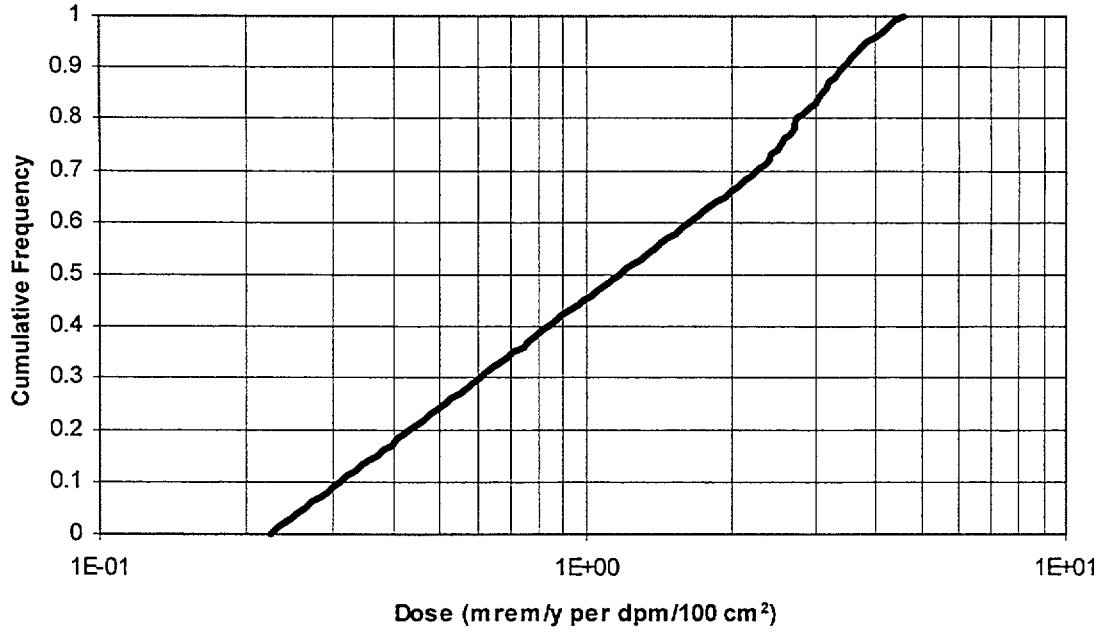

Figure 5.14 Calculated distribution of dose to the average member of the screening group due to a unit source of Th-232

Table 5.17 Resuspension factor values at five quantile levels

	Parameter quantile level				
	0.50	**0.75**	**0.90**	**0.95**	**0.99**
RF_o (m^{-1})	4.97×10^{-5}	1.06×10^{-4}	1.42×10^{-4}	1.62×10^{-4}	1.84×10^{-4}

Table 5.18 95th percentile dose values for 25 mrem/year dose values at P_{crit} (mrem/year)

Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$
3H	32.5	27.0	25
10Be	38.1	28.2	25
14C	32.5	27.0	25
22Na	25.1	25.0	25
35S	35.7	27.7	25
36Cl	36.7	27.9	25
40K	26.0	25.3	25
41Ca	32.7	27.1	25
45Ca	34.6	27.5	25
46Sc	25.2	25.1	25
54Mn	25.1	25.0	25
55Fe	36.3	27.8	25
57Co	26.0	25.3	25
58Co	25.2	25.1	25
60Co	26.2	25.4	25
59Ni	37.5	28.1	25
63Ni	37.4	28.0	25
65Zn	25.5	25.2	25
75Se	25.3	25.1	25
79Se	32.9	27.1	25
90Sr	37.1	28.0	25
93Zr	38.2	28.2	25
93Zr+C	38.1	28.2	25
93mNb	37.7	28.1	25
94Nb	28.0	25.9	25
93Mo	36.0	27.8	25
99Tc	36.6	27.9	25
106Ru	34.1	27.4	25
107Pd	38.1	28.2	25
110mAg	25.4	25.1	25
109Cd	35.4	27.7	25
113mCd	37.2	28.0	25
119mSn	29.9	26.4	25
121mSn	33.7	27.3	25
123Sn	34.2	27.4	25
126Sn	25.7	25.2	25
126Sn+C	25.7	25.2	25
125Sb	25.4	25.1	25
123mTe	26.0	25.3	25
127mTe	31.6	26.8	25

Table 5.18 95th percentile dose values for 25 mrem/year dose values at P_{crit} (mrem/year) (continued)

Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$
129I	30.6	26.6	25
134Cs	25.4	25.1	25
135Cs	31.0	26.7	25
137Cs	25.7	25.2	25
144Ce	36.1	27.8	25
147Pm	37.9	28.1	25
147Sm	38.2	28.2	25
151Sm	38.1	28.2	25
152Eu	27.4	25.7	25
154Eu	27.8	25.8	25
155Eu	30.7	26.6	25
153Gd	27.6	25.8	25
160Tb	25.3	25.1	25
166mHo	29.4	26.3	25
181W	25.1	25.0	25
185W	29.1	26.2	25
187Re	36.7	27.9	25
185Os	25.2	25.1	25
192Ir	25.5	25.2	25
210Pb	35.5	27.7	25
210Po	36.5	27.9	25
226Ra	35.2	27.6	25
226Ra+C	35.5	27.7	25
228Ra	37.8	28.1	25
227Ac	38.2	28.2	25
227Ac+C	38.2	28.2	25
228Th	38.1	28.2	25
228Th+C	38.1	28.2	25
229Th	38.2	28.2	25
229Th+C	38.2	28.2	25
230Th	38.2	28.2	25
230Th+C	37.9	28.1	25
232Th	38.2	28.2	25
232Th+C	38.2	28.2	25
231Pa	38.1	28.2	25
231Pa+C	38.2	28.2	25
232U	38.2	28.2	25
232U+C	38.2	28.2	25
233U	38.2	28.2	25
233U+C	38.2	28.2	25
234U	38.2	28.2	25
235U	38.2	28.2	25

Table 5.18 95th percentile dose values for 25 mrem/year dose values at P_{crit} (mrem/year) (continued)

Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$
235U+C	38.2	28.2	25
236U	38.2	28.2	25
238U	38.2	28.2	25
238U+C	38.0	28.2	25
237Np	38.1	28.2	25
237Np+C	38.2	28.2	25
236Pu	38.1	28.2	25
238Pu	38.1	28.2	25
239Pu	38.1	28.2	25
240Pu	38.1	28.2	25
241Pu	38.1	28.2	25
242Pu	38.1	28.2	25
244Pu	38.1	28.2	25
241Am	38.1	28.2	25
242mAm	38.1	28.2	25
243Am	38.1	28.2	25
242Cm	38.2	28.2	25
243Cm	38.1	28.2	25
244Cm	38.1	28.2	25
245Cm	38.1	28.2	25
246Cm	38.1	28.2	25
247Cm	38.1	28.2	25
248Cm	38.1	28.2	25
252Cf	38.2	28.2	25

Table 5.19 Concentration (dpm/100 cm^2) equivalent to 25 mrem/y for the specified value of P_{crit}

Source	$P_{crit} = 0.75$	P_{crit} 0 .90	P_{crit} 0 .95
3H	1.49E+08	1.24E+08	1.14E+08
10Be	4.55E+04	3.36E+04	2.99E+04
14C	4.41E+06	3.67E+06	3.40E+06
22Na	9.55E+03	9.54E+03	9.53E+03
35S	1.64E+07	1.27E+07	1.15E+07
36Cl	6.55E+05	4.99E+05	4.47E+05
40K	1.02E+05	9.92E+04	9.79E+04
41Ca	7.03E+06	5.83E+06	5.38E+06
45Ca	3.54E+06	2.81E+06	2.55E+06
46Sc	2.89E+04	2.87E+04	2.86E+04
54Mn	3.16E+04	3.15E+04	3.15E+04
55Fe	5.87E+06	4.50E+06	4.04E+06
57Co	2.17E+05	2.11E+05	2.08E+05

Table 5.19 Concentration (dpm/100 cm^2) equivalent to 25 mrem/y for the specified value of P_{crit} (continued)

Source	P_{crit} = 0.75	P_{crit} 0 .90	P_{crit} 0 .95
58Co	6.80E+04	6.77E+04	6.75E+04
60Co	7.28E+03	7.05E+03	6.94E+03
59Ni	5.69E+06	4.26E+06	3.79E+06
63Ni	2.43E+06	1.82E+06	1.63E+06
65Zn	4.87E+04	4.81E+04	4.78E+04
75Se	1.08E+05	1.07E+05	1.07E+05
79Se	9.88E+05	8.15E+05	7.51E+05
90Sr	1.15E+04	8.71E+03	7.78E+03
93Zr	5.05E+04	3.73E+04	3.31E+04
93Zr+C	4.62E+04	3.42E+04	3.03E+04
93mNb	5.48E+05	4.09E+05	3.64E+05
94Nb	8.97E+03	8.29E+03	8.00E+03
93Mo	4.64E+05	3.59E+05	3.23E+05
99Tc	1.71E+06	1.31E+06	1.17E+06
106Ru	3.26E+04	2.62E+04	2.39E+04
107Pd	1.27E+06	9.35E+05	8.30E+05
110mAg	1.03E+04	1.02E+04	1.01E+04
109Cd	1.46E+05	1.14E+05	1.03E+05
113mCd	1.01E+04	7.62E+03	6.80E+03
119mSn	1.44E+06	1.28E+06	1.21E+06
121mSn	9.03E+05	7.32E+05	6.71E+05
123Sn	7.99E+05	6.40E+05	5.83E+05
126Sn	8.61E+03	8.45E+03	8.37E+03
126Sn+C	8.53E+03	8.37E+03	8.30E+03
125Sb	4.49E+04	4.43E+04	4.41E+04
123mTe	2.70E+05	2.63E+05	2.60E+05
127mTe	9.64E+05	8.18E+05	7.62E+05
129I	4.00E+04	3.47E+04	3.26E+04
134Cs	1.29E+04	1.27E+04	1.27E+04
135Cs	1.63E+06	1.41E+06	1.32E+06
137Cs	2.86E+04	2.80E+04	2.78E+04
144Ce	5.56E+04	4.27E+04	3.84E+04
147Pm	4.63E+05	3.43E+05	3.05E+05
147Sm	2.18E+02	1.61E+02	1.42E+02
151Sm	5.40E+05	4.00E+05	3.55E+05
152Eu	1.35E+04	1.27E+04	1.24E+04
154Eu	1.23E+04	1.15E+04	1.11E+04
155Eu	1.81E+05	1.57E+05	1.47E+05
153Gd	2.17E+05	2.02E+05	1.96E+05
160Tb	5.79E+04	5.74E+04	5.71E+04
166mHo	6.98E+03	6.24E+03	5.94E+03
181W	1.07E+06	1.07E+06	1.07E+06

Table 5.19 Concentration (dpm/100 cm^2) equivalent to 25 mrem/y for the specified value of P_{crit} (continued)

Source	P_{crit} = 0.75	P_{crit} 0 .90	P_{crit} 0 .95
185W	2.33E+07	2.10E+07	2.01E+07
187Re	2.64E+08	2.01E+08	1.80E+08
185Os	7.19E+04	7.15E+04	7.13E+04
192Ir	7.52E+04	7.42E+04	7.38E+04
210Pb	7.01E+02	5.47E+02	4.94E+02
210Po	3.28E+03	2.51E+03	2.25E+03
226Ra	1.43E+03	1.12E+03	1.01E+03
226Ra+C	4.05E+02	3.15E+02	2.85E+02
228Ra	2.71E+02	2.01E+02	1.79E+02
227Ac	2.46E+00	1.82E+00	1.61E+00
227Ac+C	2.46E+00	1.81E+00	1.61E+00
228Th	5.60E+01	4.14E+01	3.67E+01
228Th+C	5.60E+01	4.14E+01	3.67E+01
229Th	7.52E+00	5.55E+00	4.92E+00
229Th+C	7.52E+00	5.55E+00	4.92E+00
230Th	5.00E+01	3.69E+01	3.27E+01
230Th+C	4.44E+01	3.30E+01	2.93E+01
232Th	9.91E+00	7.31E+00	6.49E+00
232Th+C	8.17E+00	6.03E+00	5.35E+00
231Pa	1.17E+01	8.61E+00	7.64E+00
231Pa+C	2.03E+00	1.50E+00	1.33E+00
232U	2.29E+01	1.69E+01	1.50E+01
232U+C	1.61E+01	1.19E+01	1.06E+01
233U	1.20E+02	8.86E+01	7.86E+01
233U+C	6.76E+00	4.99E+00	4.43E+00
234U	1.23E+02	9.06E+01	8.04E+01
235U	1.32E+02	9.76E+01	8.66E+01
235U+C	2.00E+00	1.48E+00	1.31E+00
236U	1.30E+02	9.57E+01	8.49E+01
238U	1.37E+02	1.01E+02	8.99E+01
238U+C	2.64E+01	1.95E+01	1.74E+01
237Np	3.00E+01	2.21E+01	1.96E+01
237Np+C	5.36E+00	3.96E+00	3.51E+00
236Pu	1.23E+02	9.10E+01	8.07E+01
238Pu	4.15E+01	3.06E+01	2.72E+01
239Pu	3.77E+01	2.79E+01	2.47E+01
240Pu	3.77E+01	2.79E+01	2.47E+01
241Pu	1.93E+03	1.42E+03	1.26E+03
242Pu	3.94E+01	2.91E+01	2.58E+01
244Pu	4.01E+01	2.96E+01	2.63E+01
241Am	3.65E+01	2.70E+01	2.39E+01
242mAm	3.75E+01	2.77E+01	2.46E+01

Table 5.19 Concentration (dpm/100 cm^2) equivalent to 25 mrem/y for the specified value of P_{crit} (continued)

Source	P_{crit} = 0.75	P_{crit} 0 .90	P_{crit} 0 .95
243Am	3.68E+01	2.72E+01	2.41E+01
242Cm	1.66E+03	1.23E+03	1.09E+03
243Cm	5.34E+01	3.94E+01	3.50E+01
244Cm	6.66E+01	4.92E+01	4.36E+01
245Cm	3.56E+01	2.63E+01	2.33E+01
246Cm	3.59E+01	2.65E+01	2.35E+01
247Cm	3.90E+01	2.89E+01	2.56E+01
248Cm	9.79E+00	7.23E+00	6.42E+00
252Cf	1.17E+02	8.68E+01	7.70E+01

6.0 Residential Scenario in NUREG/CR-5512

The residential scenario model, as defined in Volume 1 and implemented in Release 1.0 of DandD (Wernig et al., 1999), is based on the following assumptions:

- Radioactive contamination occurs in a surface soil layer,
- The property can be used for residential and light farming activities,
- Residency can occur immediately after release of the property.
- Radioactive dose results from exposure via external exposure, inhalation, and ingestion. The model includes twelve exposure pathways created by the activities considered in the scenario:
  - (1) external exposure to penetrating radiation from volume soil sources while outdoors,
  - (2) external exposure to penetrating radiation from volume soil sources while indoors,
  - (3) inhalation exposure to resuspended soil while outdoors,
  - (4) inhalation exposure to resuspended soil while indoors,
  - (5) inhalation exposure to resuspended surface sources of soil tracked indoors,
  - (6) direct ingestion of soil,
  - (7) inadvertent ingestion of soil tracked indoors,
  - (8) ingestion of drinking water from a groundwater source,
  - (9) ingestion of plant products grown in contaminated soil,
  - (10) ingestion of plant products irrigated with contaminated groundwater
  - (11) ingestion of animal products grown onsite, and
  - (12) ingestion of fish from a contaminated surface-water source.
- Eight other potential exposure pathways are not included in the analysis:
  - (1) external exposure to soil tracked indoors,
  - (2) external exposure to penetrating radiation from submersion in airborne radioactive soil,
  - (3) external exposure from swimming and shoreline activities,
  - (4) inhalation of indoor radon aerosol,
  - (5) inhalation of outdoor radon aerosol,
  - (6) ingestion of drinking water from a surface-water source,
  - (7) internal contamination from puncture wounds, and
  - (8) dermal absorption of radionuclides

The residential scenario model includes 652 parameters in addition to external dose rate factors, and inhalation and ingestion CEDE factors. The partition coefficients and plant uptake factors can be independently specified for each chemical element. Other parameters, such as ingestion rates, are defined for each of the major food categories considered in the model.

These parameters are described in detail in Sections 6.2 through 6.4. These descriptions include the way the parameter is used in the model and a summary of the information used to establish default values for the parameters. Table 6.1 summarizes the major parameter groups along with the classification of these parameters as either physical, metabolic, or behavioral. Parameters that were not evaluated in this study, and were given the default values defined in Volume 1, are indicated in the right-hand column of Table 6.1.

The annual TEDE for a parent radionuclide in the residential scenario, $TEDER_i$, is calculated as the sum of:

- external dose resulting from external exposure to penetrating radiation from soil sources, $DEXR_i$;
- CEDE for inhalation resulting from inhalation of dust and resuspended contamination tracked indoors, DHR_i;
- CEDE for ingestion resulting from inadvertent ingestion of soil, DSR_i;

Table 6.1 Summary of residential scenario model input parameters

Parameter	Description	Units	Report section	Type: physical/ behavioral/ metabolic	Vol. 1
TI	Exposure period: indoors	d/y	6.2.3	B	
TX	Exposure period: outdoors	d/y	6.2.3	B	
TG	Exposure period: gardening	d/y	6.2.3	B	
TTR	Total time in the 1-year exposure period	d	6.2.1	B	x
SFI	Indoor shielding factor	-	6.2.4	B	
SFO	Outdoor shielding factor	-	6.4.1	P	x
PD	Floor dust-loading	g/m^2	6.4.4	P	
RFR	Resuspension factor for indoor dust	1/m	6.4.4	P	
CDI	Air dust-loading indoors	g/m^3	6.4.4	P	
CDO	Air dust-loading outdoors	g/m^3	6.4.4	P	
CDG	Air dust-loading gardening	g/m^3	6.4.4	P	
VR	Breathing rate: indoors	m^3/h	6.3	M	
VX	Breathing rate: outdoors	m^3/h	6.3	M	
VG	Breathing rate: gardening	m^3/h	6.3	M	
GR	Soil ingestion transfer rate	g/d	6.2.5	B	
UW	Drinking water ingestion rate	L/d	6.2.6	B	
H1	Thickness of surface-soil layer	m	6.4.1	P	x
H2	Thickness of unsaturated zone	m	6.4.2	P	
N1	Porosity of surface-soil	-	6.4.3	P	
N2	Porosity of unsaturated zone	-	6.4.3	P	
F1	Saturation ratio for the surface-soil layer	-	6.4.3	P	
F2	Saturation ratio for the unsaturated-soil layer	-	6.4.3	P	
VDR	Volume of water for domestic uses	L	6.2.8	B	
VSW	Volume of water in surface-water pond	L	6.4.1	P	x
I	Infiltration rate	m/y	6.4.3	P	
AR	Area of land cultivated	m^2	6.2.2	B	
IR	Irrigation rate	L/m^2-d	6.2.7	B	
PS	Soil areal density of surface plow layer	kg/m^2	6.4.3	P	
DIET	Fraction of annual diet derived from home-grown foods	-	6.2.1	B	
UV	Human diet of plant products	kg-wet/y	6.2.9	B	
UA	Human diet of animal products	kg/y	6.2.9	B	
UF	Human diet of fish	kg/y	6.2.9	B	
TCV(1)	Food consumption periods for plant products	d	6.2.1	B	x
TCA(1)	Food consumption periods for animal products	d	6.2.1	B	x
THV(1)	Holdup periods for plant products	d	6.2.1	B	x
THA(1)	Holdup periods for animal products	d	6.2.1	B	x
TGV(1)	Minimum growing periods for plant products	d	6.4.1	P	x
TGF, TGG, TGH	Minimum growing periods for forage, grain, and hay consumed by farm animals	d	6.4.1	P	x

Table 6.1 Summary of residential scenario model input parameters (continued)

Parameter	Description	Units	Report section	Type: physical/ behavioral/ metabolic	Vol. 1
RV(1)	Interception fractions for food crops	-	6.4.8	P	
RF, RG, RH	Interception fractions for forage, grain, and hay consumed by farm animals	-	6.4.8	P	
TV	Translocation factors for food crops	-	6.4.1	P	x
TF, TG, TH	Translocation factor for forage, grain, and hay consumed by farm animals	-	6.4.1	P	x
XF, XG, XH	Contaminated fractions of forage, grain, and hay consumed by farm animals	-	6.2.1	B	x
XW(1)	Contaminated fractions of water consumed by farm animals	-	6.2.1	B	x
YV(1)	Crop yields for food crops	kg-wet/m^2	6.4.5	P	
YF, YG, YH	Crop yields for forage, grain, and hay consumed by farm animals	kg-wet/m^2	6.4.5	P	
WV(1)	Wet/dry conversion factors for food crops	-	6.4.9	P	
WF, WH	Wet/dry conversion factors for forage and hay consumed by farm animals	-	6.4.9	P	
WG	Wet/dry conversion factors for grain consumed by farm animals	-	6.4.1	P	
QF, QG, QH	Farm animal Ingestion rates of forage, grain, and hay	kg-wet/d	6.4.6	P	
QW	Farm animal Ingestion rates of water	L/d	6.4.1	P	
QD	Soil intake fractions for farm animals	-	6.4.1	P	x
MLV	Mass-loading factors for food crops	g/g	6.4.1	P	x
LAMBDW	Weathering rate for activity removal from plants	1/d	6.4.1	P	x
FA	Animal product transfer factor	d/kg, d/L	6.4.1	P	x
BA	Fish bioaccumulation factor	pCi/kg-wet per pCi/L	6.4.1	P	x
RHO1	Surface Soil Density	g/mL	6.4.3	P	
RHO2	Unsaturated Zone Soil Density	g/mL	6.4.3	P	
TTG	Total time in gardening period	d	6.2.1	B	x
TF	Fish consumption period	d	6.2.1	B	x
TD	Drinking-water consumption period	d	6.2.1	B	x
MLF, MLG, MLH	Mass-loading factors for forage, grain, and hay consumed by farm animals	g/g	6.4.1	P	x
TFF, TFG, TFH, TFW	Feeding periods for forage, grain, hay, and water consumed by farm animals	d	6.4.1	P	x
Kd	Partition coefficients for the Surface Soil and Unsaturated Layers	mL/g	6.4.10	P	
fca	Carbon fractions for farm animals	-	6.4.1	P	
fcf, fch, fcg	Carbon fraction for forage, hay, and grain consumed by farm animals	-	6.4.1	P	
fcd05	Fraction of carbon in soil	-	6.4.1	P	x

Table 6.1 Summary of residential scenario model input parameters (continued)

Parameter	Description	Units	Report section	Type: physical/ behavioral/ metabolic	Vol. 1
satac	Specific activity equivalence for livestock	-	6.4.1	P	x
fha	Hydrogen fractions for farm animals	-	6.4.1	P	x
fhv	Hydrogen fractions for food crops	-	6.4.1	P	x
fhf, fhh, fhg	Hydrogen fractions for forage, hay, and grain consumed by farm animals	-	6.4.1	P	x
fhd016	Fraction of hydrogen in soil	-	6.4.1	P	x
sasvh	Tritium equivalence: plant/soil	-	6.4.1	P	x
sawvh	Tritium equivalence: plant/water	-	6.4.1	P	x
satah	Tritium equivalence: animal product/intake	-	6.4.1	P	x
sh	Moisture content of soil	L/m^3	6.4.1	P	x
B1,B2,B3,B4	Concentration factors for individual chemical elements and plant types leafy	-	6.4.7	P	

- CEDE for a one-year intake of home-grown plant and animal products, DGR_i;
- CEDE for ingestion of drinking water and irrigated food, DWR_i; and
- CEDE for ingestion of aquatic foods, DAR_i.

The mathematical formulation of the above is (NUREG/CR-5512, Vol. 1, p. 5.70):

$$TEDER_i = DEXR_i + DHR_i + DGR_i + DWR_i + DSR_i + DAR_i \quad (6.1)$$

The calculation of the components of TEDER is based on the concentrations of the parent, C_i, and daughter radionuclides, C_j, in the surface soil layer. Each component is a linear, but algebraically complicated, function of the soil concentration.

Initial soil concentrations are specified as input parameters. The model uses a mass balance calculation to update these concentrations due to the effects of radioactive decay, transport from the soil layer to the groundwater, groundwater pumping, and recirculation of some pumped groundwater as irrigation.

Relevant parts of the mathematical model are discussed in Sections 6.2 through 6.4 below to define the connection of the model parameters to dose. The complete mathematical formulation of the model is contained in Chapter 5 of NUREG/CR-5512, Vol. 1.

6.1 Definition of Screening Group

The screening group is a site-independent population, appropriate for use at all sites, which is reasonably expected to receive the greatest exposure given the scenario definition. For the residential scenario, the screening group is adult males who live and work on a farm, producing and consuming a fraction of their diet from the site. They obtain all water required for drinking, domestic and agricultural use from an on-site well.

6.2 Behavioral Parameters

6.2.1 Behavioral Parameters with Constant Values

In this analysis the behavioral parameters that do not have significant variability or uncertainty for the defined screening group are held constant at the average value for the screening group. Other parameters, for example, the exposure period of one year, are held constant by definition of the exposure scenario. Table 6.2 lists the behavioral parameters that were held constant and the values used.

DIET is a behavioral parameter that originally represented the fraction of the diet of an individual at the site that was derived from the intake of home-grown agricultural products. Kennedy and Strenge (1992) (hereafter referred to as "Volume 1") defined the parameter in Table 6.23 (NUREG/CR-5512, Vol. 1) as the Fraction of Diet from Garden; however, the diet

Table 6.2 Behavioral parameters with constant values

Parameter	Description	Units	Value
DIET	Fraction of annual diet derived from home-grown foods	-	1
TTR	Total time in the 1-year exposure period	d	365.25
TCA(1)	Food consumption period for beef	d	365.25
TCA(2)	Food consumption period for poultry	d	365.25
TCA(3)	Food consumption period for milk	d	365.25
TCA(4)	Food consumption period for eggs	d	365.25
TCV(1)	Food consumption period for leafy vegetables	d	365.25
TCV(2)	Food consumption period for other vegetables	d	365.25
TCV(3)	Food consumption period for fruits	d	365.25
TCV(4)	Food consumption period for grain	d	365.25
TD	Drinking-water consumption period	d	365.25
TF	Fish consumption period	d	365.25
THA(1)	Holdup period for beef	d	20
THA(2)	Holdup period for poultry	d	1
THA(3)	Holdup period for milk	d	1
THV(1)	Holdup period for leafy vegetables	d	1
THV(2)	Holdup period for other vegetables	d	14
THV(3)	Holdup period for fruits	d	14
THV(4)	Holdup period for grains	d	14
TTG	Total time in gardening period	d	90
XF(1)	Fraction of contaminated beef cattle forage	-	1
XF(2)	Fraction of contaminated poultry forage	-	1
XF(3)	Fraction of contaminated milk cow forage	-	1
XF(4)	Fraction of contaminated layer hen forage	-	1
XG(1)	Fraction of contaminated beef cattle grain	-	1
XG(2)	Fraction of contaminated poultry grain	-	1
XG(3)	Fraction of contaminated milk cow grain	-	1
XG(4)	Fraction of contaminated layer hen grain	-	1
XH(1)	Fraction of contaminated beef cattle hay	-	1
XH(2)	Fraction of contaminated poultry hay	-	1
XH(3)	Fraction of contaminated milk cow hay	-	1
XH(4)	Fraction of contaminated layer hen hay	-	1
XW(1)	Fraction of contaminated beef cattle water	-	1
XW(2)	Fraction of contaminated poultry water	-	1
XW(3)	Fraction of contaminated milk cow water	-	1
XW(4)	Fraction of contaminated layer hen water	-	1

fraction pertains to all food products produced on-site for human consumption, including vegetables, fruits, grains, beef, poultry, milk, and eggs. The default value for DIET defined in NUREG/CR-5512 is 0.25. As used in the residential scenario model, a single, common value for the DIET parameter is assumed to apply to all food products. This assumption requires, for example, that the fraction of domestically-produced beef in the diet equal the fraction of domestically produced leafy vegetables. This assumption is unlikely to be satisfied in general, and is not representative of the screening group consisting of resident farmers. To better reflect the behavior of the average member of the screening group, who is expected to produce different fractions of each food product domestically, the human consumption rates U_v and U_a (Section 3.9) are defined as the rate of con-

sumption of food *derived from on-site production* rather than the rate of consumption in general. With this definition of consumption rates, the DIET parameter is no longer used as originally defined, and its value is 1 in all cases.

The remainder of the parameters in Table 6.1 are set at the Volume 1 default values. The consumption periods for all foods is set equal to the total time in the exposure period (365.25 days) as determined by the assumptions in the screening scenario. No additional information on the holdup periods was gathered, and these are assumed to represent averages for the screening group. It is assumed for the screening analyses that all the animal feed is grown on-site, in contaminated soil, and that all of the animal's water is from onsite sources (fraction of contaminated feed and water is 1).

6.2.2 Area of Land Cultivated, A_r (m^2) (Behavioral)

6.2.2.1 Description of A_r

A_r is defined in the residential scenario as the area of land that is used for the production of agricultural products for both human and animal consumption. The default value for this parameter defined in NUREG/CR-5512 is 2500 m^2. The cultivated area is the area required to support that portion of the resident farmer's diet that derives from on-site production. Both food crops consumed directly by the resident farmer, and feed for animals raised by the farmer are produced on the cultivated area. As a behavioral parameter, the default value for cultivated area reflects the domestic crop production, and therefore the domestically-produced food consumption rates, for the average member of the screening group.

A distribution for A_r is not defined. Instead, A_r is treated in this analysis as a function of the agricultural pathway parameters describing human consumption, animal consumption, and crop yields. The functional connection between these parameters and the cultivated area is described in this section.

6.2.2.2 Use of A_r in Modeling

A_r is used to calculate the infiltration volume through the cultivated farmland area, V_{Ir}. The relationship between A_r and V_{ir} is described in NUREG/CR-5512, Vol. 1, p. 5.68, by the following equation:

$$V_{ir} = I\, A_r\, 1000 * 1 \qquad (6.2)$$

where I is the infiltration rate (m/y), A_r is the area of land under cultivation (m^2), 1000 is a unit conversion factor (L/m^3), and 1 is the time period for infiltration and irrigation (y). In the parameter analysis, the cultivated area is also used to calculate the volume of water used for irrigation:

$$V_{irr} = IR\, A_r\, 1 \qquad (6.3)$$

based on the specified annual average irrigation rate IR (L/m^2d).

As discussed in NUREG/CR-1549, the definition of the area to which a receptor is exposed is closely related to the definition of the source concentration. Concentrations at a site generally vary in space, however a single value is used in the default dose model and may be used in other dose models. The appropriate source concentration for calculating dose due to exposure along a particular pathway is the average concentration, over the scenario exposure period, to which the receptor is exposed via the pathway under consideration. To properly reflect the actual spatial variability of concentrations over a site, the specified concentration should be the largest average concentration, over the area to which the receptor is exposed, which is also consistent with available site data.

For agricultural pathways, the "exposed" area is the area on which produce and animal feed are grown for domestic consumption, A_r. The minimum cultivated area is that area required to support the specified consumption rates of an individual resident. This minimum required area is functionally related to other parameters of the agricultural pathways model, as described in the following section.

6.2.2.3 Area Required to Support Specified Consumption

The area required to support the specified domestic consumption of the resident, A_r, is given by:

$$A_r = \left[\sum_{v=1}^{N_v} \frac{U_v}{Y_v} + \sum_{a=1}^{N_a} \frac{U_a}{Y_a^*}\right] \qquad (6.4)$$

where:

- N_v is the number of food crops considered in the diet;
- N_a is the number of animal products considered in the diet;
- U_v is the ingestion rate of food crop type v by an individual (kg wet-weight/y);
- U_a is the ingestion rate of animal product type a by an individual (amount/y);

Y_v is the crop yield for food crop type v (kg wet-weight/m^2y);
Y_a* is the animal product yield for animal product type a (amount/m^2y)

The units of the animal product ingestion rates U_a and the animal product yields Y_a* may be different for different animal products, but must be consistent. In NUREG/CR-5512, U_a is specified as kg wet-weight/y for meat, poultry, and eggs, and as L/y for milk.

The animal product yield Y_a* is the amount of consumable animal product produced through cultivation of 1 m^2 of animal feed, and can be defined in terms of the yield and requirements of an individual animal:

$$Y_a^* = \frac{Y_{Ia}}{A_{Ia}} \qquad (6.5)$$

where:

Y_{Ia} is the annual product yield from an individual animal (amount/y);
A_{Ia} is the area required to supply the domestically-produced portion of an individual animal's diet (m^2)

The cultivated area required to support an individual animal is related to the animal's consumption rate and the effective yield for the feed crops in the animal's diet:

$$A_{Ia} = \sum_{k=1}^{N_k} \frac{365.25 * Q_{ka}}{Y_{Eka}} x_{ka} \qquad (6.6)$$

where:

N_k is the number of animal feed crops in the animal's diet;
Q_{ka} is the consumption rate of feed crop type k by animal type a (kg wet-wt/d);
Y_{Eka} is the effective crop yield for feed crop type k (kg wet-wt/m^2/y);
x_{ka} is the fraction of feed crop type k consisting of domestic production in the diet of animal type a;

6.2.2.4 Parameters used to Calculate A_r

Equations 6.4 through 6.6 relate the model parameter A_r to other agricultural parameters used in the residential scenario model. Two additional parameters, which are not required in the default dose model, are required to calculated A_r: the individual animal product yields Y_{Ia}, and the effective crop yields Y_{Eka}.

The individual animal product yields. Y_{Ia}, were assigned using data from the U.S. Department of Agriculture. (USDA) Annual data from the latest complete reported year were used in each case. Per-animal yields for beef were estimated from two data sets. The average dressed weight of federally inspected cattle in 1993 was 315 kg (USDA, 1998a). Total red-meat yield from beef in 1993 was 10.4 billion kg (USDA, 1998b) and the total number of cattle slaughtered under federal inspection in that year was 33.3 million head, giving an average yield per head of 313 kg. The estimated values are consistent, and a median value of 314 kg per animal was assigned. The age at which beef cattle are slaughtered varies with the breed and with short-term economic factors such as current beef and feed price, but is typically between one and two years.[1] A representative age of 18 months gives an annual yield of 209 kg/year per head.

The average per-animal yield for poultry was estimated from the total net ready-to-cook production from young chickens of 11.3 million kg in 1995 (USDA, 1998c), and the total number of young chickens slaughtered in 1995, 7.37 million (USDA, 1998d), giving an average yield of 1.53 kg per chicken. Chickens are assumed to be no older than one year at slaughter.

Average annual milk production per cow, using data described in the USDA source as coming from "22 major states," was 16,333 lbs in 1994 (USDA, 1998e), Assuming a density equal to water, the average volume production was 7415 L per cow. The reported average production of table eggs in 1994 was 260.6 eggs per layer (USDA, 1998f). The individual product yields for beef, poultry, milk, and eggs are summarized in Table 6.3.

The effective crop yield Y_{Eka} is the mass of consumable feed produced per unit cultivated area. For hay and fresh forage, this yield is assumed to be identical to the standing biomass yield. The standing biomass yield, Y_{ka}, is a required parameter for the residential scenario model in NUREG/CR-5512, Vol. 1 (see Sections 3.60 and 3.62). For grain, the effective crop yield was estimated from crop production figures for 1996 reported by the USDA (USDA, 1997c). The effective yield for "grain" was estimated from the reported average yield for three primary components of feed grain: corn, sorghum, and oats.

[1] Robert Pate, Bernalillo County Cooperative Extension Service, Oral Communication, January 15, 1997.

Table 6.3 Annual animal product yields per animal for the four animal product types considered in the residential scenario model

Animal product type	Individual animal product yield	Data source
Beef	209 kg/y	1994 average dressed-weight; assumed age at slaughter of 18 months
Poultry	1.53 kg/y	1995 young chicken ready-to-cook production and number slaughtered
Milk	7414 L/y	1994 average milk production; assumed density of 1 kg/L
Eggs	260.6 eggs/y	1994 average table-egg production per layer hen

$$Y_{Egrain} = f_{corn} Y_{corn} + f_{sorghum} Y_{sorghum} + f_{oats} Y_{oats} \quad (6.7)$$

where f is the fractional area planted with each grain type, and Y is the net feed yield per area for each grain type. Table 6.4 summarizes the fractional area and yield based on the reported national totals for 1996, giving an effective yield for grain of 0.73 kg wet-wt/m^2.

Table 6.4 Area fractions and net yields for feed grains in 1996

Feed grain crop	Fraction of area growing feed grains	Yield (kg wet-wt/m^2)
Corn	0.834	0.798
Sorghum	0.136	0.424
Oats	0.030	0.207

The remaining parameters are required input for the residential scenario dose model. Table 6.5 summarizes the residential scenario model parameters used to calculate cultivated area, and the report sections defining values or distributions for these parameters.

Table 6.5 Parameters of the residential scenario model used to calculate cultivated area

Parameter	Description	Section number
DIET	fraction of the resident's diet derived from domestic produce	6.2.1
U_v	ingestion rate of food crops	6.2.9
U_a	ingestion rate of animal products	6.2.9
Y_v	food crop yields	6.4.5
Q_{ka}	animal feed consumption rates	6.4.6
Y_{ka}	feed crop yields for hay and fresh forage	6.4.5
x_{ka}	fraction of domestically-produced feed in animal diets	6.2.1

6.2.2.5 Alternative Values of A_r

Equation 6.3 provides a cultivated area that is consistent with the consumption patterns of the receptor specified by the parameters of the agricultural pathway model. For the screening calculations, these parameters describe the average member of the screening group, and the default cultivated area is the corresponding area required to support their consumption. Site conditions may set physical limits on the area that can be cultivated: this limit in turn implies limits on one or more of the parameters describing the agricultural pathway. The cultivated area may be modified to conform to site-specific area restrictions by modifying these parameters.

Alternatively, the licensee may define a site-specific critical group. The behavioral parameters for the agricultural pathway model may be different for the average member of this group than for the average member of the screening group (AMSG), leading to a revised value of A_r consistent with the behavior of the critical group.

6.2.3 Exposure Period: Indoors, t_i, Outdoors, t_x, and Gardening, t_g (d/y) (Behavioral)

6.2.3.1 Description of Exposure Periods

The residential scenario model defines three distinct situations or contexts for potential exposure: indoor exposure, gardening exposure, and exposure outdoors other than while gardening. These separate contexts are defined due to the distinctive pathways or transport rates that might apply to these situations. During the one-year scenario period, the AMSG is assumed to divide their on-site time among these three contexts. The three exposure periods ti, tx, and tg are behavioral parameters which specify the number of 24-hour days per year the AMSG spends indoors, outdoors (other than gardening), and gardening. The default values defined in NUREG/CR-5512, Vol. 1, for the times spent indoors, outdoors, and gardening are 200 d/y, 70.83 d/y, and 4.17

d/y, respectively. No reference is provided for these values. Default time allocations in RESRAD are based on the assumption that 50% of a person's time is spent indoors, and 25% is spent outdoors in the contaminated area.

The exposure periods are behavioral parameters. For the screening calculations, the values for these parameters reflect the average member of the screening group, which consists of resident farmers. An estimate of the variability of exposure periods among individuals in this group is also required, to evaluate the homogeneity of the screening group.

Current information on human activity patterns was reviewed to establish screening values for these parameters. Values representative of the screening group, consisting of adult resident farmers, were selected from this literature. For each of the three contexts, the average of these values is proposed as defining the behavior of the AMSG. A distribution was also identified to describe the potential variability in exposure time among individual members of the screening group.

6.2.3.2 Use of Exposure Periods in Modeling

The time allocation factors are used to calculate doses due to direct exposure and inhalation, as discussed in the following section. The rate of exposure differs in each environment due to differences in the physical characteristics of the environment (reflected in the shielding factors, dust loadings, and resuspension factors) and differences in behavior (reflected in environment- specific breathing rates). Within each environment, dose from each pathway varies linearly with the time spent in that environment.

These parameters describe the time that the individual spends in various activities and are used to calculate external dose from exposure to radionuclide i in soils, $DEXR_i$, and inhalation committed effective dose equivalent, DHR_i, from exposure to radionuclide i during residential activity. Dose from external exposure is calculated as (see NUREG/CR-5512, p. 5.53).

$$\begin{aligned} DEXR_i = & \left[24\left(t_g/t_{tg}\right) SFO\ C_{si}\ \Sigma_{(j=1,ji)}\ S\{A_{stj},\ t_{tg}\}\ DFER_j\right] \\ & + \left[24\left(t_x/t_{tr}\right) SFO\ C_{si}\ \Sigma_{(j=1,ji)}\ S\{A_{stj},\ t_{tr}\}\ DFER_j\right] \\ & + \left[24\left(t_i/t_{tr}\right) SFO\ C_{si}\ \Sigma_{(j=1,ji)}\ S\{A_{stj},\ t_{tr}\}\ DFER_j\right] \end{aligned} \quad (6.8)$$

where $DREF_j$ is the external dose rate factor for radionuclide j for exposure to contamination uniformly distributed in the top 15 cm of residential soil (mrem/h per pCi/g), A_{stj} is the concentration factor for radionuclide j in soil at the beginning of the current annual exposure period per initial unit concentration of parent radionuclide i in soil at time of site release (pCi/g per pCi/g), t_{tg} is the gardening period (90 days per year), C_{si} corresponds to the concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil), SFI and SFO are shielding factors by which external dose rate is reduced during periods of 1) indoor residence and 2) outdoor residence and gardening, respectively, J_i is the number of explicit members of the decay chain for parent radionuclide i, $S\{A_{stj},t_{tr}\}$ is the time-integral operator used to develop the concentration time integral of radionuclide j for exposure over a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil), $S\{A_{stj},t_{tg}\}$ is the time-integral operator used to develop the concentration time integral of radionuclide j for exposure over one gardening season during 1-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil), t_g is the time during the gardening period that the individual spends outdoors gardening (d for a year of residential scenario), t_i and t_x are time in the one-year exposure period that the individual spends indoors and outdoors, other than gardening (d for a year of residential scenario), respectively, t_{tr} is the total time in the residential exposure period (d), and 24 is a unit conversion factor (h/d). Inhalation dose is given by (see NUREG/CR-5512, p. 5.55):

$$\begin{aligned} DEXR_i = & \left[24\,V_g\left(t_g/t_{tg}\right) CDG\ C_{si}\ \Sigma_{(j=1,ji)}\ S\{A_{stj},\ t_{tg}\}\ DFH_j\right] \\ & + \left[24\,V_x\left(t_x/t_{tr}\right) CDG\ C_{si}\ \Sigma_{(j=1,ji)}\ S\{A_{stj},\ t_{tr}\}\ DFH_j\right] \\ & + \left[24\,V_r\left(t_i/t_{tr}\right)\left(CDI+P_dRF_r\right)\Sigma_{(j=1,ji)}\ S\{A_{stj},\ t_{tr}\}\ DFH_j\right] \end{aligned} \quad (6.9)$$

where V_g, V_r, and V_x correspond to volumetric breathing rates for time spent gardening, indoors, and outdoors, respectively (m^3/h), t_g is the time during the gardening period that the individual spends outdoors gardening (d for a year of residential scenario), t_i and t_x are time in the one-year exposure period that the individual spends indoors and outdoors, other than gardening (d for a year of residential scenario), respectively, t_{tr} is the total time in the residential exposure period (d), CDI and CDO are dust loading factors for indoor and outdoor exposure periods, respectively, (g/m^3), CDG is the dust loading factor for gardening activities (g/m^3), C_{si} corresponds to the concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil), J_i is the number of explicit members of the decay chain for parent radionuclide i, $S\{A_{stj},t_{tr}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil), $S\{A_{stj},t_{tg}\}$ is a time-integral

operator used to develop the concentration time integral of radionuclide j for exposure over one gardening season during one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil), DFH_j is the inhalation committed effective dose equivalent factor for radionuclide j for exposure to contaminated air (in units of mrem per pCi inhaled), P_d is the indoor dust-loading on floors (g/m^2), and RF_r is the indoor resuspension factor (m^{-1}).

6.2.3.3 Information Reviewed to Define Exposure Periods

The literature review conducted to support the EPA *Exposure Factors Handbook* (EPA 1996) was adopted as the most current compilation of relevant literature. This document contains a review and summary of current time allocation studies, along with detailed results from selected studies. Time allocations are reported for a variety of activities and environments. All reviewed studies minimally provide mean time allocations over the individuals surveyed. Defining ranges or distributions for the time allocation parameters of the residential scenario model, however, requires information on the variability of time allocation among individuals. In addition, time allocation data is required for the three environments considered in the residential scenario. Among the time allocation studies identified in the literature review, three primary sources were considered for the time allocation estimates in the three residential contexts. These sources are summarized below.

Tsang and Klepeis (1996) is "the largest and most current human activity pattern survey available" (EPA, 1996). Over 9000 respondents provided minute-by-minute 24-hour diaries between October 1992 and September 1994, and the responses weighted to produce results representative of the U.S. population. Percentile values are reported for the distributions of time spent in a wide variety of activities for "doers" of those activities. These values describe the variability of day-to-day time allocation, and therefore cannot be used directly as estimates of annual average values. Among the activities and environments considered, reported values for "Minutes Spent Working in a Garden or Other Circumstances Working with Soil" (EPA, 1996, Table 14-60), "Minutes Spent at Home in the Yard or Other Areas Outside the House" (EPA, 1996, Table 14-118), and "Minutes Spent Indoors in a Residence (All Rooms)" (EPA, 1996, Table 14-129) were used to estimate average values for the critical group of resident farmers, as well as distributions for individual members of this group, as described in Section 6.2.3.4.

Hill (1985) also reports on individual variability in time allocation among a variety of activities. Data were collected in four waves, one per season, in 1975 and 1976. Weekly average values, and standard deviations of those weekly averages, are reported for various age and gender cohorts. Unlike other activity pattern studies (exemplified by Tsang and Klepeis) which provide data on daily time allocation, Hill's study provides information on the variability of longer-term averages for individuals. Although the study period was also quite short in Hill (1985), observation periods were distributed throughout the year. The results of this study therefore appear to be the best basis for estimating the variability of annual average activity patterns among individuals. Hill provides time allocation information for a number of specific activities that are typically conducted at residences, including meal preparation and cleanup, indoor cleaning, washing/dressing, and reading. Data on total time spent indoors, however, is not provided. While the mean value for time spent indoors, for example, can be estimated from the mean values reported for activities typically conducted indoors, the variability in total indoor time among individuals cannot be estimated from the reported data without information on (or assumptions about) the correlation of time allocation among these component activities. Similarly, the time spent in a variety of outdoor activities is reported, however the total time spent outdoors at the residence is not. Among the outdoor activities, data on time spent in "gardening/ pet care" (Hill 1985, Table 7.A.1) was considered in defining the distribution for t_g, as discussed in Section 6.2.3.4.

Robinson and Thomas (1991) compare data from the 1987–1998 California Air Resources Board (CARB) time activity study and from a 1985 national study *American's Use of Time*. Reported values from the national study were assumed to be more representative of the screening group because of the broader geographical basis. Time allocation data are reported for a number of activities, locations, and micro-environments. For each of these categories, data are summarized by the average time spent, the standard error of this average, the average value for "doers," and the percentage of "doers" in the total sample. Among activities, locations, and micro-environments considered in this study, data on time spent outdoors at a residence (Robinson and Thomas, 1991, Table 9-1) were considered in defining the distribution for t_x. Data on time spent indoors are provided for two classifications: time spent in the kitchen, and time spent elsewhere indoors. As in the case of the data reported by Hill (1985), the average time spent indoors can be estimated by adding the average values for each classification. Information or assumptions regarding the correlation between time spent in

these two locations is required to estimate the variability in the total time spent indoors.

Both Tsang and Klepeis (1996) and Hill (1985) report separate time allocation data for men and women, as well as aggregate time allocation data. There are significant differences between the gender-specific time allocation values for some environments. For example, Tsang and Klepeis (1996) report an average time spent outdoors at the residence of 158 min/d for men, while women were found to spend and average of 115 min/d in the same environment. This difference presumably reflects a specialization of domestic roles which is relevant for characterizing the screening group for the residential scenario. Because the screening group is defined as resident farmers, data for men, who typically spend more time outdoors and gardening, but less time indoors, were used to estimate the three exposure time parameters.

6.2.3.4 Assumptions and Procedures Used to Derive Time Allocation Distributions

A large amount of information on individual time allocation is available in the literature, however this information cannot be used to directly assign distributions for the exposure periods. In each of the three key studies discussed in Section 6.2.3.2, a number of assumptions and inferences are required to derive parameter distributions from the reported data. These assumptions and inferences are needed to supplement reported information, and to reconcile differences between the data reported and the model parameter values, in three areas:

- Time allocation values are "measured" over a single 24-hour period, while the model parameters reflect annual average values.

- Tsang and Klepeis (1996) provide detailed distributional information; in both Hill (1985) and Robinson and Thomas (1991), however, variability in time allocation among individuals is only characterized by the sample standard deviation. The form of the distribution is not available from the latter two studies, and must be assumed.

- Robinson and Thomas (1991) do not directly report the standard deviation of time spent by "doers." This information must be derived from their reported values for the average times spent by "doers" and by all respondents, the standard deviation of time spent by all respondents, and the fraction of respondents considered "doers."

In each area, the reported variability in time allocation does not directly correspond to the variability in annual average values among individuals in the screening group. The following sections describe the assumptions and procedures used to estimate the parameter distributions from the reported data. The average values over all individuals can be estimated directly from the reported data. These averages do not depend on the assumptions and procedures which are required to estimate the full distribution.

6.2.3.4.1 Estimating Annual Average Values from Daily Values

The time allocation studies found in the literature review use either diaries or retrospective questionnaires to measure individual's time allocation during a single day. Variability in these values represents both variability among individuals, and day-to-day variability of time allocation for a single individual. The time allocation parameters for the residential scenario should describe average behavior of an individual over one year, and the distributions for these parameters should describe variability in this annual average over individuals in the screening group. Because reported distributions generally describe variability of daily time allocation rather than annual average time allocation, they cannot be directly used to assign parameter distributions. Instead, estimating variability of annual average values from the reported distributions of daily values requires information or assumptions on the similarity of an individual's time allocation from one day to the next.

The similarity of an individual's time allocations on successive days can be described by an autocorrelation function. Autocorrelation information is not available in the reviewed literature: three alternative assumptions were therefore considered in order to define the effect of uncertainty in the autocorrelation of daily time allocation on the distribution of annual average time allocation. These alternative assumptions lead to alternative distributions for individual time allocation. The average time allocation over all individuals, as discussed above, does not depend on these assumptions, and can be calculated directly from the reported data. Alternative assumptions will, however, lead to different estimates for variability in dose among members of the screening group.

For a single individual, the correlation between the time spent in a given environment on one day was assumed to be positively correlated with the time spent on any subsequent day: individuals who report spending a large amount of time gardening on a single day, for example, are assumed to be likely to spend a large amount of time gardening on subsequent days. Given this assumption,

the three alternative autocorrelations considered correspond to the two extreme limits on non-negative autocorrelation, and an intermediate degree of autocorrelation.

The first case assumes perfect correlation in a single individual's time allocation from one day to the next. In this case, the time spent in each environment on each day is identical to the time spent on any other day in the year. Under this assumption, the distribution of annual average time allocation values is identical to the distribution of daily values. This case produces the largest variability in the estimated annual average values: all variability in the reported daily values is assumed to be due to variations among individuals. The resulting distributions are probably unrealistically broad: this assumption is used to illustrate the upper limit of variability of annual average time allocation values.

The second case assumes no correlation in time allocation from one day to the next. In this case, an individual's annual average value for time allocation consists of 365 independent samples from the reported distribution of daily time allocation. By the central limit theorem, the distribution of annual average values over individuals will be well approximated by a normal distribution, with a mean value equal to the mean daily value, and a variance equal to 1/365th of the variance of the daily values. This case produces the smallest variability in the estimated annual average values: all variability in the reported daily values is assumed to be due to "random" day-to-day variations which are the same for all individuals, and no variability is attributed to variations in individual habits. The resulting distributions are generally very narrow, and represent a lower limit on the variability of annual average values.

The third case assumes an intermediate degree of autocorrelation. A single individual is assumed to spend a constant amount of time in each environment for 30 successive days. The time spent in each environment is assumed to be independent from one 30-day period to the next. This assumed autocorrelation is not intended to be a realistic description of behavior: a realistic autocorrelation function might be expected to decay gradually with time, rather than to be limited to values of 1 and 0. The simple autocorrelation function used in this case was designed to produce a plausible distribution of annual average values representing an intermediate degree of autocorrelation, and to simplify derivation of the distribution of annual average values. For a single individual, the annual average time allocation for each environment consists of the average of 12 independent samples from the reported distribution of daily values.

6.2.3.4.2 Assumed Distributions for Daily Values Reported by Hill (1985) and Robinson and Thomas (1991)

Hill (1985) reports the mean time spent by individuals, and describes the variability among the sample population by the standard deviation; Robinson and Thomas (1991) report the mean, along with other information from which the sample standard deviation can be derived (see below). No additional information on the form of the distribution is provided in either study. In each environment, and for any individual, the time spent is physically bounded by 0 and 365.25 days/year. Without more specific information on the form of these distributions, distributions were assigned using the principle of maximum entropy. As stated by Jaynes (1982), this principle requires that "when we make inferences based on incomplete information, we should draw from them that probability distribution that has the maximum entropy permitted by the information we do have." In as much as the form of the exposure time distributions are unknown, the assumption of any specific distribution is arbitrary, and likely to be wrong. Given this uncertainty, the maximum entropy distribution was judged the most reasonable choice in that "most information theorists have considered it obvious that, in some sense, the possible distributions are concentrated strongly near the one of maximum entropy" (Jaynes, 1982). Given the mean, standard deviation, and upper and lower limits, the maximum entropy distribution corresponds to a beta distribution. Beta distributions were therefore defined to describe the variability in individual time allocation based on these four pieces of information.

6.2.3.4.3 Calculating Standard Deviation in "Doer" Time from Data Reported in Robinson and Thomas (1991)

Robinson and Thomas (1991) report the average and standard error for the time spent outdoors over all individuals in the national survey *American's Use of Time*. This sample includes both individuals who regularly spend time outdoors ("doers"), as well as those who do not. A separate average value is reported for "doers," as well as the number of individuals in the overall sample, and the fraction of the total sample classified as "doers." Individuals who spend time outdoors are considered to be more representative of the screening group, however the variability in time spent by this sub-group is not reported in Robinson and Thomas (1991).

This variability can, however, be derived from the information presented. The standard error (SE) is related to

the sample standard deviation (S) and the sample size (n) by:

$$SE = \frac{S}{\sqrt{n}} \qquad (6.10)$$

while the sample standard deviation is (for large n):

$$S^2 = \sum_{i=1}^{n} \frac{(t_i - \bar{t})^2}{n} \qquad (6.11)$$

where t_i is the time spent by an individual I. The overall sample of size n can be divided into n_Z "non-doers" of the activity (all of whose time values are zero), and n_D "doers" with non-zero time values. The standard deviation of all time values in Equation 6.10 can then be expressed as the sum of two terms:

$$S^2 = \sum_{i=1}^{n_Z} \frac{\bar{t}^2}{n_Z+n_D} + \sum_{i=n_Z+1}^{n_Z+n_D} \frac{(t_i - \bar{t})^2}{n_Z+n_D} \qquad (6.12)$$

The standard deviation of the sub-population of "doers" is defined as:

$$S_D^2 = \sum_{i=n_Z+1}^{n_Z+n_D} \frac{(t_i - \bar{t}_D)^2}{n_D} \qquad (6.13)$$

which can be expressed in terms of the overall standard deviation, and the other quantities reported in Robinson and Thomas (1991), using Equation 6.14:

$$S_D^2 = \frac{n_Z+n_D}{n_D}\left(S^2 - \bar{t}^2\right) + 2\bar{t}_D\left(\bar{t} - \bar{t}_D\right) \qquad (6.14)$$

6.2.3.5 Time Allocation Distributions

Tsang and Klepeis (1996) provide data on daily time allocation for each of the three environments considered in the residential scenario. These data were used to estimate distributions for each of the three time allocation parameters. As discussed above, three alternative autocorrelation functions were considered to explore the effect of this unknown information on the derived distribution of individual annual average values.

Robinson and Thomas (1991) report data on time spent outdoors at residences. Detailed distributional information is not provided however, and a beta distribution was assumed. Like the data from Tsang and Klepeis (1996), these time allocations are daily values, and three alternative autocorrelation functions were used estimate the distribution of annual average values for t_x from this data.

For the distributions derived from the daily measurements reported by both Tsang and Klepeis (1996) and Robinson and Thomas (1991), the distribution based on the intermediate degree (30 day period) of autocorrelation is recommended, although the bounding distributions (as well as other intermediate distributions) are equally consistent with the data.

Hill (1985) reports the average and standard deviation of time spent gardening. Unlike the two other studies, each single time allocation value is an average of four separate reports from the same individual, taken in four seasonal "waves." As such, these values provide a more direct estimate of the annual average time allocation for each individual. The quality of this estimate is, however, uncertain, as it based on very limited data for each individual. A beta distribution was assumed based on the reported average, reported standard deviation, and the absolute physical upper and lower limits of 0 and 365.25 days/year. Note that although the beta distribution fitted to the data from Hill (1985) has a theoretical upper limit of 365.25 days, this limit is not practically approached: 98% of the distribution values are less than 20 days.

6.2.3.5.1 Time Spent Indoors (t_i)

Data describing the variability in daily values of total time spend indoors at a residence, reported by Tsang and Klepeis (1996), were used to define the distribution for t_i. Table 6.6 reproduces the reported distribution of daily values for men, converted to units of 24-hour days/year. Figure 6.1 shows the distributions for indoor time resulting from the three assumed autocorrelation functions considered. There is considerable uncertainty in the distribution of annual average values due to uncertainty in the autocorrelation of daily values, although the bounding cases of no correlation and 365-day correlation can arguably be dismissed as unreasonable: the former shows very little variability in individual behavior around the common mean value of 266 days, while the latter shows nearly 5% of individuals spending less than 8 hours/day (approximately 120 24-hour days/year) indoors.

6.2.3.5.2 Time Spend Outdoors at the Residence (t_j)

Data describing the variability in daily values of time spent outdoors at a residence, reported by both Tsang

Table 6.6 Distribution of daily values of time spent indoors at a residence (all rooms)*

Sample size = 4269	
Population characteristic	**Value (24-hour days/year)**
Mean	240
Standard deviation	69.4
Minimum	2.03
Maximum	365.25
Percentile values:	
0.05	137
0.25	190
0.5	228
0.75	294
0.9	342
0.95	363
0.98	365
0.99	365

*from Tsang and Klepeis (1996) cited in EPA (1996) Table 14-129, Data for Men

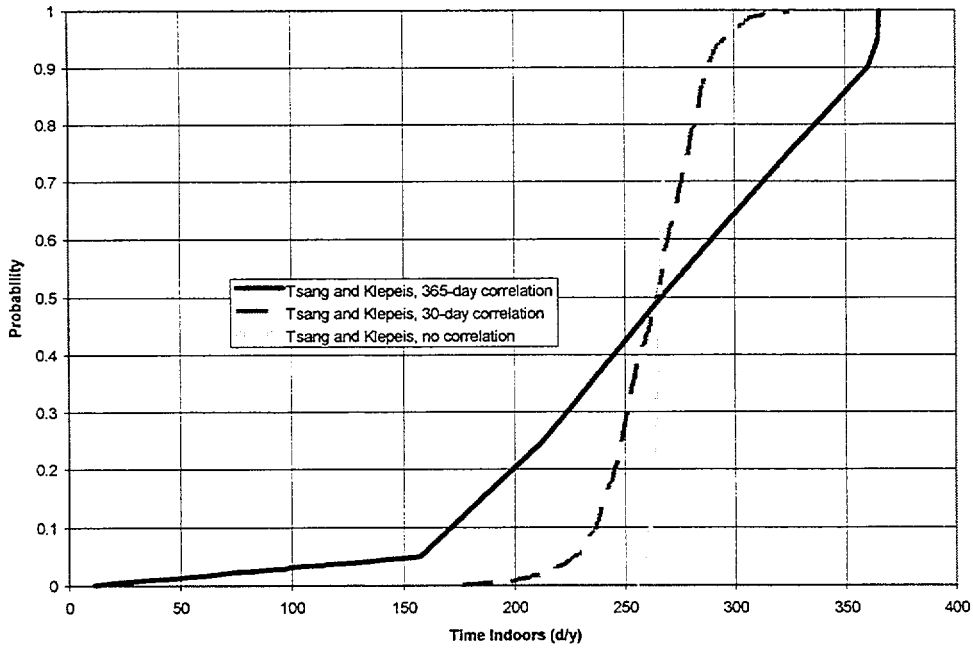

Figure 6.1 CDF of annual average time spent indoors based on daily from Tsang and Klepeis (1996) for three assumed autocorrelations

and Klepeis (1996), and by Robinson and Thomas (1991) were considered in defining the distribution for t_x. Table 6.7 reproduces the distribution reported by Tsang and Klepeis (1996) of daily values for men converted to units of 24-hour days/year. Data for men were selected as more representative of the screening group. Figure 6.2 shows the distributions for outdoor time based on this data, resulting from the three assumed autocorrelation functions considered.

Table 6.7 Distribution of daily values of time spent outdoors at a residence*

Sample size = 1198	
Population characteristic	**Value (24-hour days/year)**
Mean	40.2
Standard deviation	40.6
Minimum	0.3
Maximum	327
Percentile values:	
0.05	2.53
0.25	15.2
0.5	30.4
0.75	50.2
0.9	91.3
0.95	127
0.98	159
0.99	185

* from Tsang and Klepeis (1996) cited in EPA (1996) Table 14-118, Data for Men

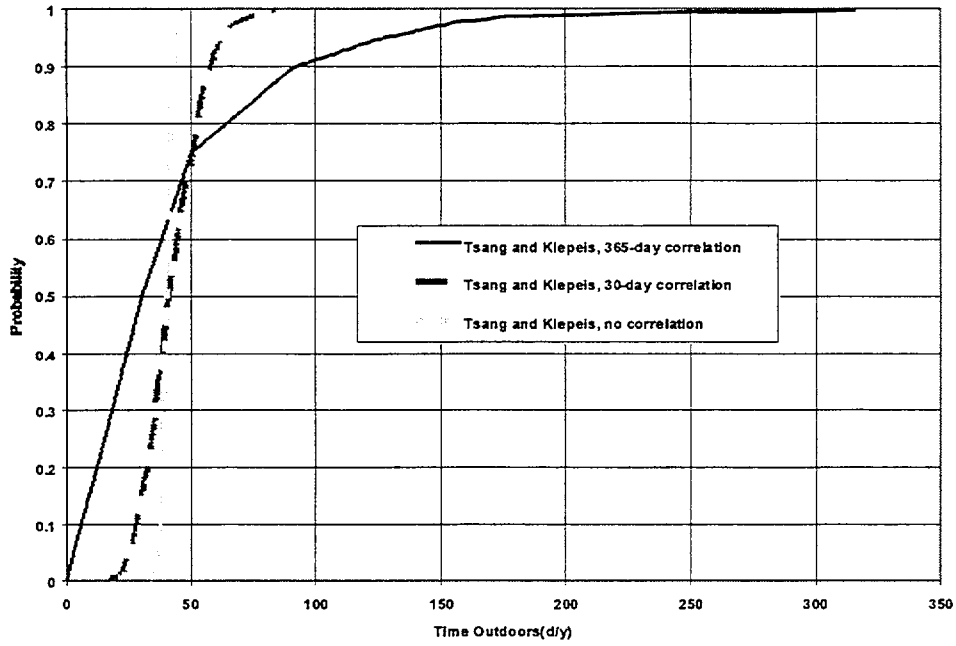

Figure 6.2 CDF of annual average time spent outdoors based on daily data from Tsang and Klepeis (1996) for three assumed autocorrelations

Average daily values reported by Robinson and Thomas (1991), and the sample standard deviation derived from the reported standard error, average for "doers," and sample size (see Section 6.2.3.5), were used to define a beta distribution for daily values of outdoor time. Table 6.8 summarizes the parameters of this distribution. Figure 6.3 shows the distributions for outdoor time resulting from the three assumed autocorrelation functions considered.

Table 6.8 Distribution of daily values of time spent outdoors at a residence*

Sample size = 2762	
Distribution parameter	**Value**
Reported parameters	
Mean (all subjects) (24-hour days/year)	12
Standard error (all subjects) (24-hour days/year)	0.8
Mean (doers) (24-hour days/year)	29.2
% doers	41
Derived parameters for doers	
Standard deviation (doers) (24-hour days/year)	58.3
Minimum (24-hour days/year)	0
Maximum (24-hour days/year)	365.25
Alpha	0.17
Beta	1.9

* from Robinson and Thomas (1991) Table 9-1, National Survey Data

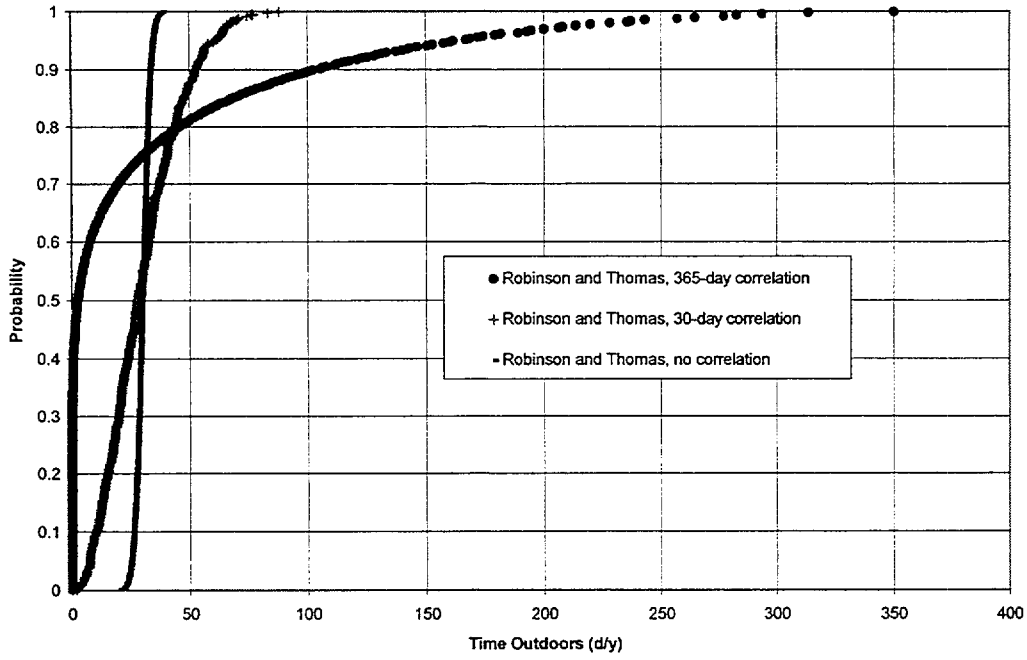

Figure 6.3 PDF of annual average time spent outdoors based on daily data from Robinson and Thomas (1991) for three assumed autocorrelations

Using either set of data, there is considerable uncertainty in the distribution of outdoor time due to uncertainty in autocorrelation of daily values. The distribution based on data from Tsang and Klepeis (1996) has a larger mean value (40 24-hour days/year) than the data from Robinson and Thomas (1991) (29 24-hour days/year). The former is recommended as the distribution for t_x because of this conservative characteristic, and because the underlying distribution of daily time allocation values is more accurately defined.

6.2.3.5.3 Time Spent Gardening (t_g)

Data describing the variability in daily values of time spent gardening, reported by both Tsang and Klepeis (1996), and by Hill (1985) were considered in defining the distribution for t_g. Table 6.9 reproduces the distribution reported by Tsang and Klepeis (1996) of daily values for men of time spent working in a garden or other circumstances working with soil, converted to units of 24-hour days/year. Data for men were selected as more representative of the screening group.

Table 6.9 Distribution of daily values of time spent working in a garden or other circumstances working with soil*

Sample size = 2125	
Population characteristic	**Value (24-hour days/year)**
Mean	2.92
Standard deviation	9.50
Minimum	0
Maximum	365.25
Percentile values:	
0.05	0
0.25	0
0.5	0
0.75	0.761
0.9	5.07
0.95	12.7
0.98	38.0
0.99	58.3

* from Tsang and Klepeis (1996) cited in EPA (1996) Table 14-60, Data for Men

Gardening times reported by Hill (1985) were assumed to approximate annual average values. A beta distribution for t_g was developed directly from the reported mean and standard deviation, and the absolute physical limits of 0 and 365.25 days/year. Unlike the results of Tsang and Klepeis (1996), reported mean values for men and women are quite similar: the overall average and standard deviation using both genders was therefore used to define the distribution. Table 6.10 summarizes the key parameters of this distribution.

Figure 6.4 shows the three distributions for gardening time based on the data of Tsang and Klepeis (1996) (using three alternative autocorrelation functions), along with the beta distribution based on the mean and standard deviation reported by Hill (1985). Although Hill's procedure yields estimates of annual average time

Table 6.10 Distribution of annual values of time spent gardening*

Sample size = 971	
Distribution parameter	**Value**
Reported parameters	
Mean (24-hour days/year)	2.1
Standard deviation (24-hour days/year)	5.4
Derived parameters for doers	
Minimum (24-hour days/year)	0
Maximum (24-hour days/year)	365.25
Alpha	0.17
Beta	29

* from Hill (1985) Table 7.A.1, Data for Men and Women

allocation (based on four daily measurements of the same individual, distributed throughout the year), the fitted distribution is quite similar to the distribution of daily gardening times reported by Tsang and Klepeis (1996). Note that although the beta distribution fitted to the data from Hill (1985) has a theoretical upper limit of 365.25 days, this limit is not practically approached: 98% of the distribution values are less than 20 days.

Three considerations favor the distribution based on Tsang and Klepeis (1996) (assuming a 30-day autocorrelation) over the distribution fitted to Hill (1985): the better definition of the distributional form provided by Tsang and Klepeis (1996); the similarity of the distribution based on Hill (1985) to the distribution of daily values reported by Tsang and Klepeis (1996), suggesting that Hill's data are more representative of daily values than annual average values; and the small number of daily measurements on which Hill's annual average estimates are based. As in the case of annual average values for indoor time and outdoor time, there is considerable uncertainty in the distribution of gardening time due to uncertainty in autocorrelation of daily values.

6.2.3.6 Summary

The National Human Activity Patterns Survey analysis of Tsang and Klepeis (1996) was used to define exposure periods for the average member of the screening group, and to estimate variability in exposure periods among individuals in the screening group. This study was preferred over available alternatives because of the large sample size, the availability of exposure period data for micro-environments considered in the residential scenario, the availability of data for subpopulations approximating the screening group (i.e., "doers" of gardening), and the availability of

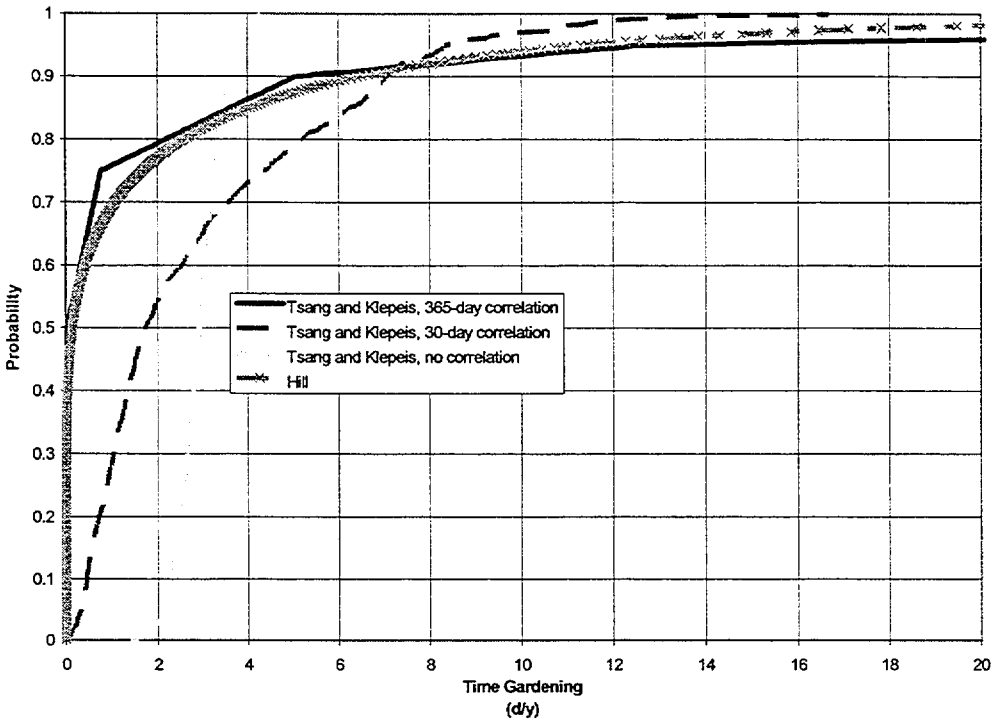

Figure 6.4 CDF of annual average time spent gardening based on data from Hill (1985) and daily data from Tsang and Klepeis (1996) for three assumed autocorrelations

distributions of daily individual exposure time values. Mean values and distributions for time indoors were developed from data in Robinson and Thomas (1991), and Hill (1985) was used to estimate mean values and distributions for gardening time. These estimates are provided for comparison with the recommended values, but are not recommended for use in the residential scenario because of the lack of detailed distribution data from either study, and the difficulty in estimating exposure times for all three contexts from either study alone.

6.2.3.6.1 Average Exposure Time

The exposure time for the average member of the screening group were directly estimated by daily time allocation values for men available in the literature. Tsang and Klepeis (1996) report average values for time spent indoors at a residence and outdoors at a residence. This study also provides quantile values for the distribution of time spent gardening or working with soil. The average value was calculated from this distribution. Robinson and Thomas (1991) report an average for "doers" of time spent outdoors at a residence; Hill (1985) reports an average value for time spent gardening. Table 6.11 summarizes these reported average values. The average values given by Tsang and Klepeis (1996) have been adopted due to the large number of samples in the study, the availability of exposure time values for each of the three scenario contexts in a single study, and the availability of distributions of individual values for each context.

Table 6.11 Summary of average exposure time values (24-hour days/year)

Parameter	Reported average (24-hr days per year)	Source
Indoor time (t_i)	240	Tsang and Klepeis (1996)
Outdoor time (t_o)	40.2	Tsang and Klepeis (1996)
	29.2	Robinson and Thomas (1991)
Gardening time (t_g)	2.92	Tsang and Klepeis (1996)
	2.1	Hill (1985)

6.2.3.6.2 Distribution of Exposure Times

The recommended distributions for annual average time spent in each residential environment are shown in Figures 6.5 and 6.6, and summary properties are listed in Table 6.12. Table 6.13 list quantile values of these distributions, which were generated by Monte-Carlo sampling of the empirical distributions of daily time allocation reported in Tsang and Klepeis (1996) (see Tables 6.6, 6.7, and 6.9 above). Each distribution is based on daily values reported in Tsang and Klepeis (1996). Among the three key studies considered, this survey presents the most complete definition of the distribution of daily values, from which the distributions of annual average values were estimated. The estimated distribution of annual average values is based on an assumed autocorrelation of 30 days. The autocorrelation of daily values is uncertain, and the assumed value is intermediate between the limiting values of no correlation between daily values, and perfect correlation between daily values. The spread of the time allocation distributions is sensitive to the assumed autocorrelation, however the mean value over all individuals does not depend on this assumption.

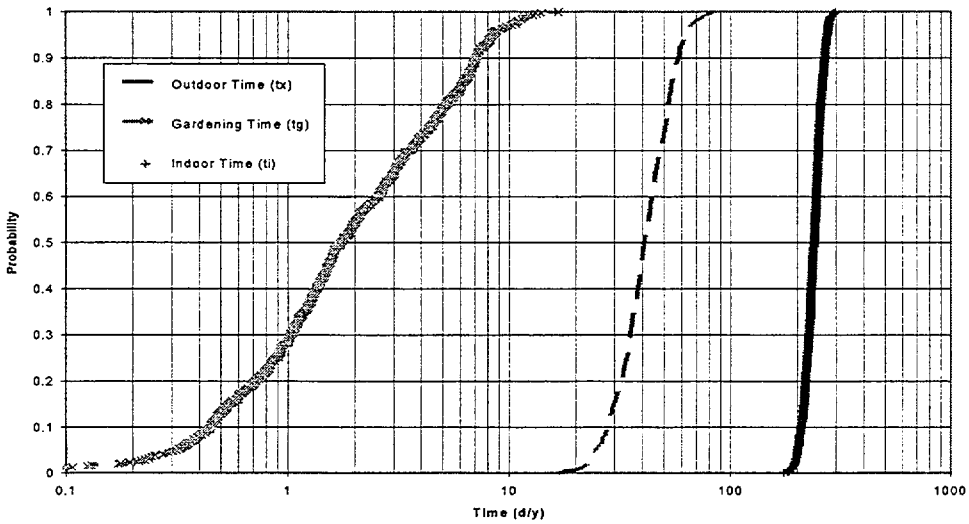

Figure 6.5 Cumulative probability functions for indoor time (ti), outdoor time (tx), and gardening time (tg)

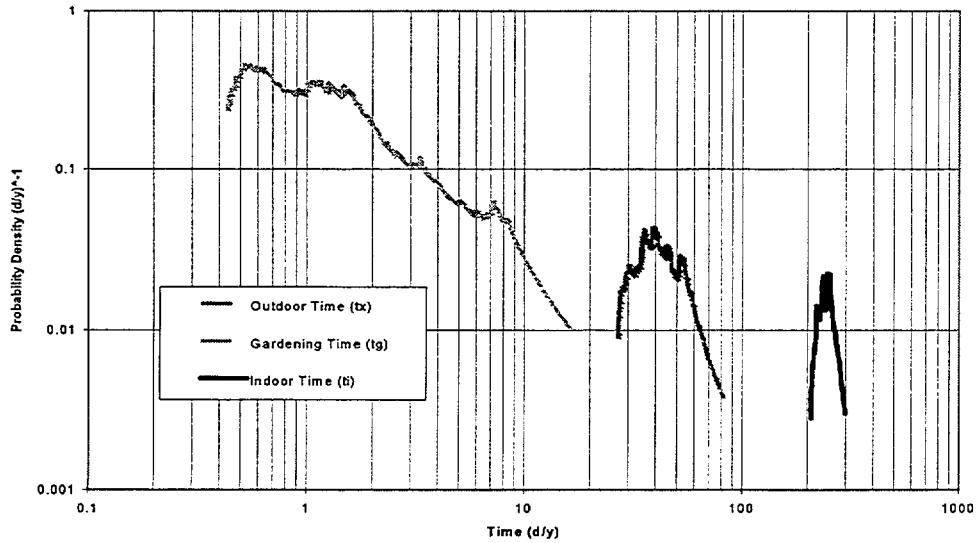

Figure 6.6 Probability density functions for indoor time (ti), outdoor time (tx), and gardening time (tg)

Table 6.12 Summary properties for time allocation parameter distributions

Parameter	Distribution properties (24-hour days/year)			
	Mean	Median	1st percentile	99th percentile
Indoor time (t_i)	240	238	189	285
Outdoor time (t_x)	40.2	40.9	20.1	75.8
Gardening time (t_g)	2.92	1.73	9.10×10^{-2}	12.0

Table 6.13 Quantile values for exposure period distributions

Probability	t_g (d/y)	t_i (d/y)	t_x (d/y)
0.00e+00	2.00e-02	1.74e+02	1.68e+01
1.00e-03	3.50e-02	1.74e+02	1.68e+01
1.10e-02	9.49e-02	1.90e+02	2.11e+01
5.10e-02	3.25e-01	2.02e+02	2.48e+01
1.01e-01	4.50e-01	2.08e+02	2.79e+01
2.01e-01	7.20e-01	2.18e+02	3.25e+01
3.01e-01	1.03e+00	2.26e+02	3.54e+01
4.01e-01	1.35e+00	2.32e+02	3.83e+01
5.01e-01	1.74e+00	2.38e+02	4.09e+01
6.01e-01	2.56e+00	2.44e+02	4.43e+01
7.01e-01	3.58e+00	2.49e+02	4.80e+01
8.01e-01	5.21e+00	2.55e+02	5.23e+01
9.01e-01	7.07e+00	2.66e+02	5.81e+01
9.51e-01	8.44e+00	2.73e+02	6.34e+01
9.81e-01	1.10e+01	2.80e+02	6.99e+01
9.99e-01	1.67e+01	2.98e+02	8.43e+01
1.00e+00	1.70e+01	3.00e+02	9.00e+01

6.2.3.6.3 Correlations Among Exposure Times and Other Parameters

The time that an individual spends in a given context is constrained by the time spent in each of the other two contexts. Some amount of negative correlation should therefore exist between each pair of time allocation distributions, however the size of this correlation is uncertain. The total time an individual spends on site (i.e., the sum of indoor time, outdoor time, and gardening time) was calculated using two limiting assumptions about this correlation: zero correlation, and a rank correlation coefficient of -0.5 between each pair of time categories. The latter correlation is the largest (negative) common correlation coefficient that still produces a positive-definite covariance matrix for the three time allocation parameters. Figure 6.7 shows the distribution of total on-site time under these two assumptions.

The distribution of total time is somewhat narrower when the component distributions are negatively correlated. For example, the 99th percentile value for total time on site is 342 days assuming no correlation, but 325 days when a rank correlation coefficient of -0.5 is assumed. Because the distributions for the two limiting correlation assumptions are similar, uncertainty in the appropriate correlation will not have a large influence on the estimated variability of dose over individuals in the screening group. A correlation coefficient of -0.5 is recommended because it reflects the competition for an individual's time among indoor, outdoor, and gardening activities.

The amount of time spent gardening is also presumably related to the amount of food produced in the garden, although the magnitude of the correlation between these parameters is unknown. A correlation coefficient of 1 between the gardening time and food production rate is

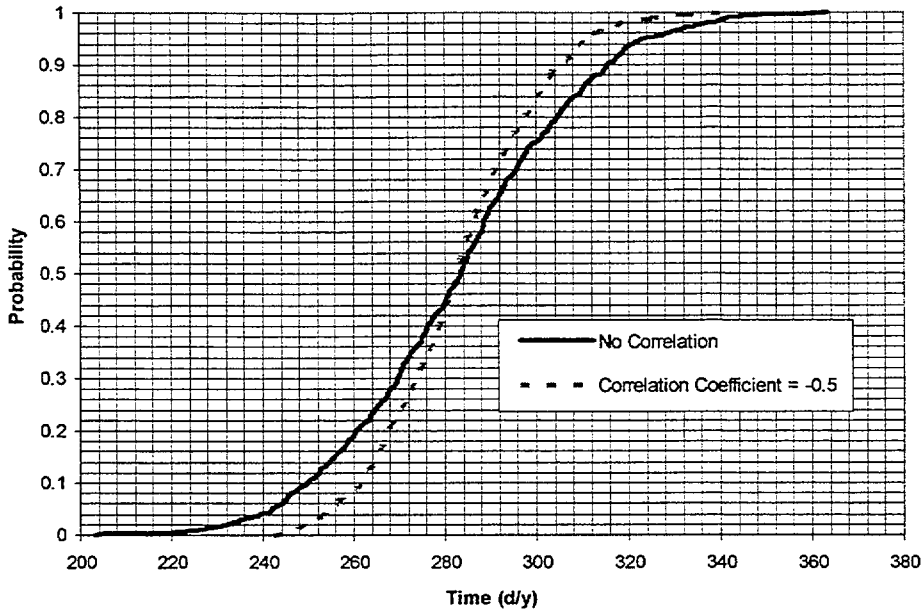

Figure 6.7 CDF of total on-site time (ti + tx + tg) for two assumed rank correlation coefficient values

assumed. Because the calculated dose is an increasing function of both gardening time and ingestion rate for domestic produce, this assumption conservatively bounds the potential variability in dose among members of the screening group. Neither the assumed correlation among exposure times, nor the assumed correlation between gardening time and ingestion rate, affect the estimated mean values for these parameters. Table 6.14 lists the assumed rank correlation coefficients among the exposure times and other model parameters.

Table 6.14 Correlations among exposure times

Parameters	Rank correlation coefficient
t_i, t_x	-0.5
t_x, t_g	-0.5
t_g, t_i	-0.5
t_g,U_V	1.0

6.2.3.7 Uncertainty in Exposure Periods

The proposed distributions describing the variability of time allocation factors for individuals in the screening group rests on several assumptions which introduce uncertainty into the proposed distributions:

(1) The screening group consists of resident farmers. Data from Tsang and Klepeis (1996) on "Time Spent Gardening or Other Activities Working With Soil," for the subset of individuals who engage in these activities, was assumed to be representative of this group. Data for time indoors and outdoors at a residence from this study were not available for this subset of the sample subjects. Exposure periods for the latter two parameters therefore include non-gardeners, and may overestimate the values for the screening group. Because gardening time represents a relatively small proportion of total time, the extent of overestimation would appear to be small.

(2) The majority of reported time allocation values reflect daily values rather than annual average values. The autocorrelation of daily values for individuals is required to estimate annual averages. This function is unknown, however bounding and intermediate approximations can be defined. Uncertainty in this function introduces considerable uncertainty in the variability of annual average time allocation over individual members of the screening group. The average value for this group does not depend on the assumed correlation.

(3) In two key studies, variability in time allocation is only characterized by a standard deviation. The underlying distributions were assumed to follow a beta distribution defined by the reported mean and standard deviation, and by absolute limiting values of 0 and 365.25 days/year. These limits represent theoretical bounds, and the effective range of the fitted distributions are smaller than the theoretical ranges in all cases.

6.2.3.8 Alternative Exposure Period Values

The exposure period parameters are behavioral parameters. Alternative values could be proposed by defining a site-specific critical group, as discussed in NUREG/CR-1549. If this screening group does not grow produce, gardening time (along with ingestion rates of domestic produce, cultivated area, and irrigation rate) for this group would be 0.

6.2.4 Indoor Shielding Factor, SFI (Behavioral)

6.2.4.1 Description of SFI

The indoor shielding factor, SFI, as defined for NUREG/CR-5512, Vol. 1, is a measure of the attenuation of gamma radiation by structural materials such as walls, floors, foundations, and support structures in buildings, and is defined as the ratio of equivalent dose behind the shield to that in front of the shield. The model uses a single, constant value for all radionuclides, and for all structural materials. SFI is classified as a behavioral parameter because its value depends on the type of construction of the residence.

6.2.4.2 Use of SFI in Modeling

SFI is directly related to dose. For a given concentration of a given radionuclide in soil, external dose is proportional to SFI (i.e., the higher the value for SFI, the higher the total annual dose).

This parameter is used for calculating external dose from exposure to radionuclides in soils, DEXRi, (mrem for a year of residential scenario) as described by the following (Equation 5.69, p. 5.53 in NUREG/CR-5512, Vol. 1):

$$\begin{aligned} DEXR_i = & \left[24\left(t_g/t_{tg}\right) SFO\ C_{si}\ \Sigma_{(j=1,Ji)}\ S\left\{A_{stj},\ t_{tg}\right\}\ DFER_j\right] \\ & + \left[24\left(t_x/t_{tr}\right) SFO\ C_{si}\ \Sigma_{(j=1,Ji)}\ S\left\{A_{stj},\ t_{tr}\right\}\ DFER_j\right] \\ & + \left[24\left(t_i/t_{tr}\right) SFO\ C_{si}\ \Sigma_{(j=1,Ji)}\ S\left\{A_{stj},\ t_{tr}\right\}\ DFER_j\right] \end{aligned} \quad (6.15)$$

where $DFER_j$ is the external dose rate factor for radionuclide j for exposure to contamination uniformly distributed in the top 15 cm of residential soil (mrem/h per pCi/g); A_{stj} is the concentration factor for radionuclide j in soil at the beginning of the current annual exposure period per initial unit concentration of parent radionuclide i in soil at time of site release (pCi/g per pCi/g); C_{si} is the concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil); SFI and SFO are shielding factors by which external dose rate is reduced during periods of indoor residence and outdoor residence, including gardening; J_i is the number of explicit members of the decay chain for parent radionuclide i; $S\{A_{stj},t_{tr}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); $S\{A_{stj},t_{tg}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over one gardening season during a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); t_g, t_i, and t_x are times in the one-year exposure period that the individual spends gardening, indoors, and outdoors (excluding gardening); t_{tr} is the total time in the residential exposure period (d); and 24 is a unit conversion factor (h/d). The same shielding factor is used for all radionuclides and is not dependent on the energy of the gamma radiation.

6.2.4.3 Information Reviewed to Define SFI

The value of 0.33 for SFI was adopted as the default value in NUREG/CR-5512, Vol. 1, and is based on information derived from studies on deposition of radioactive material from atmospheric plumes (Alrich 1978; Kocher 1978; Jensen 1985). The radiation sources considered in these models are fallout radioactivity deposited on roofs, outer walls, and ground surfaces, and may have different energy profiles than decommissioned sites. Although these models can be used to approximate shielding factors for contaminants deposited around and on buildings, they do not account for contaminants under structures, as required in DandD dose modeling. The RESRAD value for this parameter is 0.7.

References cited in NUREG/CR-5512, Vol. 1, and more recent publications on radiation shielding were reviewed to determine if information was available to estimate shielding factors for structures or buildings that were constructed or placed on contaminated land. (Jensen 1985) estimated shielding factors for a number of single-family and multistory houses using the computer model, DEPSHIELD. Leung (1992) calculated shielding factors for concrete and glass based on equivalent dose build-up factors in materials, and the shielding factors were used for estimating the protection against radioactive plumes. Graf and Bayer (1991) performed shielding calculations for 12 building types and compared the calculated factors with shielding factors derived from fallout measurements.

Shielding factors can be estimated for structures built or placed on contaminated soil using MicroShield 4.20®. The model simulates radiation levels inside a structure

from external contamination beneath or adjacent to the structure for a wide range of structural materials and, therefore, would approximate the scenario conditions. The shielding factor is determined from the following:

$$SFI = e^{-\mu x}$$

where μ is the attenuation coefficient for the structural material (e.g., wood, concrete, gypsum) and x is the thickness of the material. μ varies with energy of the incident gamma radiation and the type and density of the material. Other factors, such as source geometry and buildup (i.e., scattering of radiation to the detector), are included in MicroShield 4.20®. Attenuation coefficients, buildup factors, and buildup factor coefficients are available from a library of reference data. The spatial distribution of contaminants in soils, energy range of gamma radiation, and physical characteristics and compositions of shielding materials are input parameters for MicroShield 4.20®.

6.2.4.4 Determination of PDF for SFI

Estimates of shielding factors were based on the attenuation of external gamma radiation in a wood frame building with wood siding and either a wood or concrete floor. A wood frame structure assembled from common building materials was selected for these calculations because this type of structure would not overestimate the shielding provided by the residence. Other wall types (brick, cinder block) would be expected to provide somewhat greater shielding.

6.2.4.4.1 Description of Structure

The structure used in this model is a single-story wood frame building (1000 ft^2) with a wood or concrete floor. The construction and materials are based on current standard practice (Marks' Standard Handbook for Mechanical Engineers) The walls consist of parallel 2" × 6" studs spaced 16" apart with gypsum wallboard (1/2" thick) on the internal surface of the wall and external sheathing covered with cedar siding on the outside surface. Fiberglass insulation fills the void volume between the gypsum wallboard and external sheathing. The wood floor is constructed of 1" thick plywood sheathing over parallel 2" × 8" floor joists spaced 16" apart, with fiberglass insulation placed beneath the plywood sheathing and between the parallel floor joists. The thickness of the concrete floor was varied at increments to estimate the effects of varying thicknesses of concrete on shielding. Gamma activity was calculated for a position at the center of the building at a height of 1 m above the contaminated soil surface as shown in Figure 6.8. The model simulates the level of radiation through the floor and walls of the building from an infinite source uniformly distributed over the top 15 cm of soil and neglects shielding by floor joists and studs. The input parameters for the model are identified in Table 6.15.

6.2.4.4.2 Calculation of Shielding Factors

MicroShield 4.20® calculates the effective dose equivalent, EDE (mSv/h) with, and without, shielding. The shielding factor, SFI, is calculated as the ratio of the EDE rate for gamma radiation at the center of the structure, EDE_S, to the EDE rate for gamma radiation expected if no shielding were present, EDE_U:

$$SFI = EDE_S/EDE_U$$

EDE_S is the sum of the attenuated EDE rates attributed to gamma radiation shielding by the floor, EDE_F, and by the walls, EDE_W:

$$EDE_S = EDE_F + EDE_W$$

The energy range used in MicroShield 4.20® represents the range of energies for radionuclides identified in NUREG/CR-5512, Vol. 1. Shielding factors were calculated for discrete gamma energies for wood and concrete floors, and the results are tabulated in Table 6.16 and presented in Figure 6.9. The range of gamma energies used in the model represents variations across radionuclides and not uncertainty in the energies for single isotopes. The information in Table 6.16 can be used for estimating shielding factors for specific radionuclides based on their gamma energy spectrum.

6.2.4.4.3 Distribution for SFI

The distribution for SFI describes the variability in shielding factors over individual members of the screening group, which consists of resident farmers, and depends on the structural and material properties of the residence. Alternative assumptions about the residence corresponding to a range of current residential construction practices were used to define the variability of SFI over members of the screening group. The cumulative probability distribution in Figure 6.10 was derived by conservatively selecting the maximum shielding factor for each of the four floor types in Table 6.16 and assigning equal probabilities to each floor type.

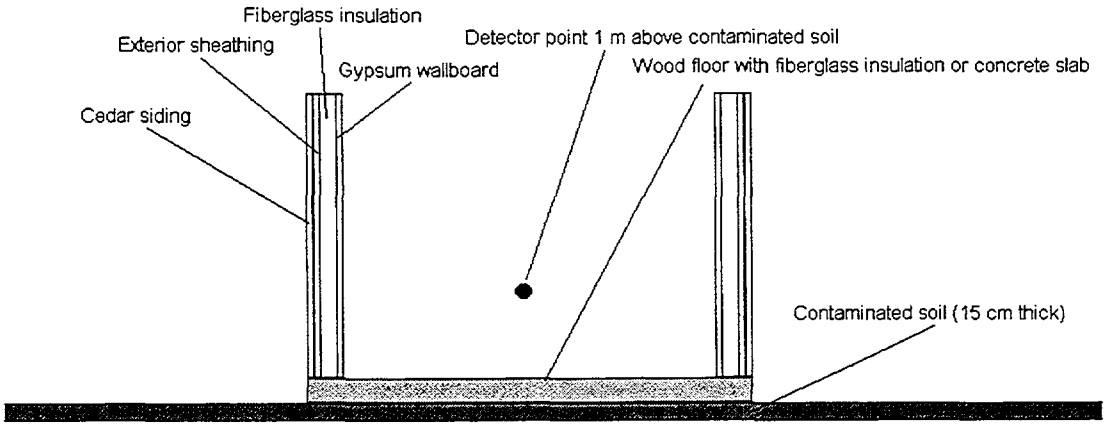

Figure 6.8 Cross section of building for calculating gamma activity from contaminants in soil

Table 6.15 Input parameters for MicroShield 4.20®

Factor	Type or value	Remarks
Wood floor	1" plywood (0.6 g/cm^3)	mobile homes, or manufactured houses, have no concrete slab foundation
Concrete floor	3.5", 5.25", & 7" thick	3.5" is the minimum thickness for concrete slab allowed by the uniform building code
Surface area of floor	1000 square feet	
Density of concrete	2.309 g/cm^3	Marks' Standard Handbook for Mechanical Engineers
Windows, %	20% of total wall area	" "
Window thickness	3 mm, density 2.58 g/cm^3	" "
Wall, gypsum	½" sheet rock, 2.025 g/cm^3	" "
Wall, glass fiber	density 2 g/cm^3	" "
Wall, sheathing	1 cm thick, density 0.35 g/cm^3	" "
Wall, external	½" cedar, density 0.35 g/cm^3	" "
Contaminated soil	Infinite slab, 15 cm thick	Assumed thickness of contaminated soil
Gamma activity	0.037 d/sec/cm^3	d/sec/cm^3 = pCi/g
Energy range	0.03 to 2.25 MeV	Energy range established from: ^{140}Ba (0.0299 MeV); ^{156}Eu (2.27 MeV)

Table 6.16 Shielding factor as a function of gamma energy

Energy (MeV)	Wood (pier & beam)	Shielding factor		
		3.5" concrete	5.25" concrete	7" concrete
0.03	0.0967	0.00810	0.00810	0.00810
0.06	0.608	0.241	0.241	0.241
0.08	0.722	0.380	0.377	0.377
0.10	0.767	0.438	0.432	0.431
0.20	0.807	0.507	0.486	0.479
0.40	0.814	0.517	0.478	0.462
0.80	0.824	0.489	0.425	0.394

Table 6.16 Shielding factor as a function of gamma energy (continued)

Energy (MeV)	Wood (pier & beam)	Shielding factor		
		3.5" concrete	5.25" concrete	7" concrete
1.5	0.845	0.491	0.405	0.359
2.25	0.857	0.514	0.422	0.369

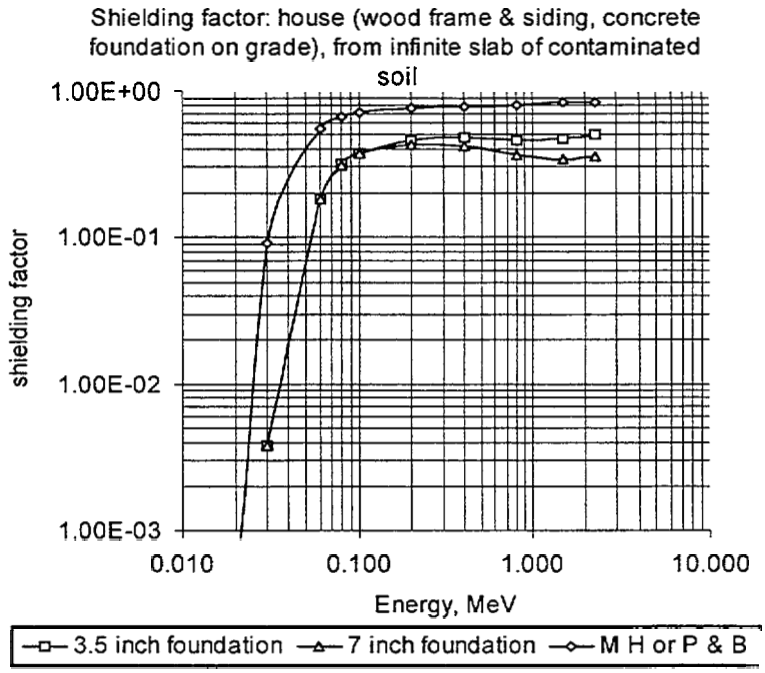

Figure 6.9 Shielding factor as a function of energy for three different floors in building

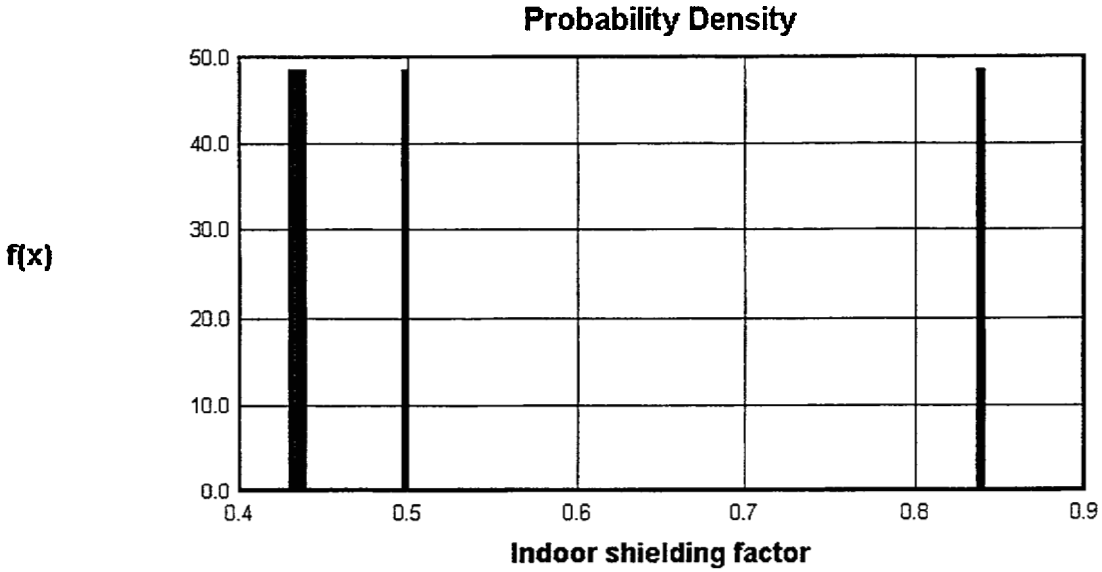

Figure 6.10 Cumulative probability distribution for indoor shielding factor, SFI

6.2.4.5 Uncertainty in SFI

The proposed distribution describing the variability in the shielding factor over members of the screening group of resident farmers rests on several assumptions:

- A wood frame house was used in the model. This type of construction is typical of current practices, although other assumptions (e.g., brick) are also consistent with screening group assumptions.

- Other structural materials that may contribute to shielding, such as steel reinforcement, wall studs, and floor joists, were not included in the model calculations.

6.2.4.6 Variability Across Sites

This parameter is expected to vary from site to site depending on the type and construction of buildings or structures. Alternative distributions for this parameter could be proposed based on site-specific information about the source energy profile.

6.2.5 Soil Ingestion Transfer Rate for the Residential Scenario, GR (g/d) (Behavioral)

6.2.5.1 Parameter Description

The soil ingestion transfer rate, GR, is a behavioral parameter that represents the average daily intake of soil by the AMSG for the residential scenario. GR is the quantity of soil ingested per day, averaged over the one year duration of the scenario, by inadvertent transfer from hands or other objects that have been in contact with a contaminated surface, such as food, cigarettes, etc., into the mouth.

The default value for this parameter defined in Volume 1, is 5×10^{-2} g/d. This value was defined based on published reports on soil ingestion studies. Nine references are listed for this data (National Academy of Sciences, 1980; Lepow, 1975; Hawley, 1985; Binder et al., 1986; Calabrese, 1989; Davis et al., 1990; Calabrese, 1990; Van Wijnen et al., 1990; EPA, 1991). Six of these studies focused on soil ingestion by children. The screening group consists of adult resident farmers, and soil ingestion rates for children are not representative of this group. The range of reported ingestion rates for the adult-workers/ members of the public is 5×10^{-5} to 1×10^{-1} g/d.

6.2.5.2 Use of Parameter in Modeling

As detailed below, the dose from the ingestion pathway is directly proportional to GR. Overall dose will be sensitive to GR for those sources with significant contributions of ingestion dose to total dose. The parameter GR is used to calculate CEDE for internal ingestion dose, DSR_i, resulting from inadvertent ingestion of soil and contaminants on surfaces. The relationship between GR and internal dose due to ingestion is defined in NUREG/CR-5512, Vol. 1, p. 5.73 as:

$$DSR_i = GR\ C_{si} \sum_{(j=1,Ji)} DFG_j\ S\{A_{stj},\ t_{tr}\} \qquad (6.16)$$

where GR is effective transfer rate for ingestion of soil and dust transferred to the mouth (g/d), $S\{A_{sij},t_{tr}\}$ is time-integral operator used to develop the radionuclide j concentration in soil, over the residential exposure period for a unit initial concentration of parent radionuclide i in soil at the time of site release (pCi*d/g per pCi/g for 1 year of residential scenario), J_i = number of explicit members of the decay chain for parent radionuclide i, C_{si} is concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil), and DFG_j is the ingestion CEDE factor for radionuclide j (mrem per pCi ingested). The resulting internal dose is directly proportional to the soil ingestion rate.

6.2.5.3 Review of Additional Information to Define PDF for GR

A literature review was conducted to define a distribution for GR describing the variability in ingestion rate among members of the screening group. The average value of this distribution defines the ingestion rate for the AMSG.

In general, soil ingestion is the inadvertent oral intake of soil through a process whereby soil-contaminated objects (hands, cigarettes, food, etc.) are placed in the mouth. The average value for the parameter GR represents the annual average quantity of soil ingested per day by the AMSG, and the distribution of this parameter describes the variability in annual ingestion rate among individuals in the screening group. Most of the published measurements of soil ingestion found in the literature review pertain to children. The screening group is defined as adult resident farmers, and the soil ingestion rates of children are not representative of this group.

Volume 1 summarizes reported soil ingestion rates published prior to 1992. These estimates were derived from limited studies on soil ingestion in adults, and

postulates about mouthing behavior. Additional information was reviewed to determine if other data or approaches, preferably more recent than those cited in Volume 1, were available to provide a defensible basis for constructing a PDF for GR for use in the analysis. Additional information reviewed included the EPA *Exposures Factors Handbook* (1996), and the references cited therein, LaCoy (1987), Calabrese et al. (1990), Gephart et al. (1994), and Stanek et al. (1997).

Soil ingestion rates in adults have been estimated by: 1) analysis of selected tracer elements in human diets and comparing the dietary intake of these elements with tracer elements found in feces and urine of adult volunteers; and 2) observation of individual behavior pattern in adults under a range of environmental conditions and activities. Numerous studies on soil ingestion have been conducted using a tracer method (BTM) developed by Binder et al. (1986) (Stanek and Calabrese, 1995; Sedman and Mahmood, 1994; Calabrese and Stanek, 1995; Stanek et al., 1997; and others).

Table 6.17, and the following discussion, summarizes published studies of soil ingestion by adults.

Hawley (1985) reported soil ingestion rates of 4.8×10^{-1} g/d for outdoor activities and 5.6×10^{-4} to 1.1×10^{-1} g/d for indoor activities. The highest ingestion rates occurred for outdoor physical activities (e.g., yard work, gardening, etc). The ingestion rates for indoor activities ranged over two orders of magnitude and included typical activities such as occupying a typical living space and working in uncleaned areas (e.g., attic, utility room, garage). Based on an estimated duration for each activity, Hawley calculated an annual average soil ingestion rate of 6.1×10^{-2} g/d for an adult in a typical residential setting. Krablin (1989) estimated the soil ingestion rate in adults from urine arsenic epidemiological studies, mouthing behavior, and time activity patterns. He concluded from these studies that adults ingest 1×10^{-2} g of soil per day. Sheppard (1995) estimated the intake of soil from non-food sources in adults based on indoor and outdoor activities and exposure durations. Based on estimates of exposure duration of 300 h/y and a soil ingestion rate of 2×10^{-2} g/h for gardening activities, and an exposure duration of 5000 h/y and a soil ingestion rate of 3×10^{-5} g/h for indoor activities, he calculated an average daily soil ingestion rate of 2×10^{-2} g/d. Stanek (1995) reviewed previous work and presented revised estimates on soil ingestion in adults. Using data on four tracer elements, they calculated an average soil ingestion rate of 6.4×10^{-2} g/d.

Calabrese et al. (1990), Stanek and Calabrese (1995), and Stanek et al. (1997) estimated soil ingestion rates in adults based on mass-balance studies in which intake rates were estimated from concentrations of several trace elements in ingested foods and medicines, environmental dust and soil, and body excretions (feces and urine). These studies collected data over multiple one-week periods, during which each subject ingested a controlled quantity of soil from their environment. This mass, along with soil mass ingested with food, was subtracted from the estimated mass that was derived from measured tracer elements in feces and urine. Although these studies draw on very limited data, the results are very consistent with previous studies reported in the literature. Calabrese et al. (1990) concluded from his evaluation, however, that the tracers used in his study failed to demonstrate adequate detection limits for assessing soil ingestion in adults.

Using quantitative data on zirconium tracers from Calabrese et al. (1990), Gephart et al. (1994) estimated soil ingestion rates in adults. Their analysis indicated that a soil ingestion rate of $1 \times 10^{-3} - 1 \times 10^{-2}$ g/d is a very conservative estimate and recommended this range for purposes of risk assessments. Gephart et al. (1994) derived a distribution of adult soil ingestion by Monte-Carlo simulation, however this distribution represents the variability in estimated daily ingestion values. These daily estimates were obtained from daily measurements of tracer concentrations in food and waste products. As discussed below, this procedure requires assumptions which create significant experimental error in the estimated daily rates. Because of the large measurement error, and because the distribution for GR should describe variations in average annual ingestion rate among individuals in the screening group, rather than day-to-day variations in ingestion rate, the distribution presented in Gephart et al. (1994) is not appropriate for this analysis.

The study by Stanek et al. (1997) included a larger number of subjects than the 1995 study (10 adults as opposed to six) and incorporated methodological and interpretative improvements based on earlier studies. However, the experimental approach used by Stanek et al. (1997) relies on a number of idealizing assumptions of questionable validity. The resulting estimates of daily ingestion rate are highly uncertain, and are frequently less than 0. For example, they neglected any absorption or metabolism of tracer substances in their studies, and they assumed that the transit time of the tracers in the intestinal tract was constant and consistent for all subjects in the study. The calculated soil ingestion rates were predicated on the assumption that the ratio of tracer element-to-soil in the fecal sample

Table 6.17 Soil ingestion rates in adults

Reference	Soil ingestion rate (g/d)	Comments
Hawley, 1985	6.1×10^{-2}	Ingestion rates and time activity patterns
Calabrese, 1987	$1 \times 10^{-3} - 1 \times 10^{-1}$	Based on CDC estimates
Krablin, 1989	1×10^{-2}	Arsenic studies, mouthing behavior, time activity patterns
Gephart et al., 1994	$1 \times 10^{-3} - 1 \times 10^{-2}$	Estimate based on mass balance studies of soil ingestion in adults
Sheppard, 1995	2×10^{-2}	Intake of soil from non-food sources
Stanek and Calabrese, 1995	6.4×10^{-2}	Revised estimate based on the measurement of four tracer elements in adults
Stanek et al., 1997	1×10^{-2}	Mass balance studies on 10 adults over a period of 28 days

is identical to the ratio of tracer element-to-soil in the local environment of the subject. As a result, their attempts to distinguish contributions from soil and house dust yielded conflicting results.

6.2.5.4 Proposed Distribution for GR

Although there is very little empirical data representative of the screening group, the above studies provide a rough estimate of soil ingestion rates in adults. According to studies on soil ingestion published between 1975 and 1997, soil ingestion rates vary over a range of about 4 orders of magnitude. The variations observed in these studies have been attributed to a number of factors, including the level of loose contaminants in the local environment, the behavior of individuals in the studies, controls that are imposed, and the exposure time. Based on the data in Table 6.17, soil ingestion rates range from a minimum of 0 g/d to a maximum of 1×10^{-1} g/d with a likely ingestion rate of 5×10^{-2} g/d. In the absence of a reliable quantitative estimate of variability in long-term average rates among adult individuals, a triangular distribution for the parameter GR is recommended. Figure 6.11 shows the assigned cumulative distribution function, and Figure 6.12 shows the corresponding probability density function, using the minimum, maximum, and mode values cited above. The mean value of this distribution, representing the AMSG, is 5×10^{-2} g/d.

6.2.5.5 Parameter Uncertainty

The proposed distribution describing the variability in the soil ingestion rate among members of the screening group is based on several assumptions that contribute to uncertainty in the distribution:

- Empirical support for this parameter is very limited. The most recent measurements of soil ingestion in adults are subject to wide variability.

- Soil ingestion has been studied in adults in residential settings using selected trace elements. Several assumptions were made in these experimental measurements:

  (1) The specific elements selected as tracers for soil ingestion studies are not absorbed or retained in the digestive tract of the adult subjects or undergo any metabolic changes that would prevent excretion of the tracer elements.

  (2) Tracer elements in the body excretions originate exclusively from foods, medicines, and ingested soils. The amount ingested in foods and medicines is the same amount found in duplicate samples.

  (3) The quantity of soil ingested is obtained from the ratio of the quantity of tracer excreted to the concentration of tracer in soil, with the assumption that the tracer element concentration is constant and distributed uniformly in soil and dust.

6.2.5.6 Alternative Parameter Values

The default parameter value is representative of the average member of the screening group of adult resident farmers. Alternative, site-specific critical groups may lead to a revised value for this parameter.

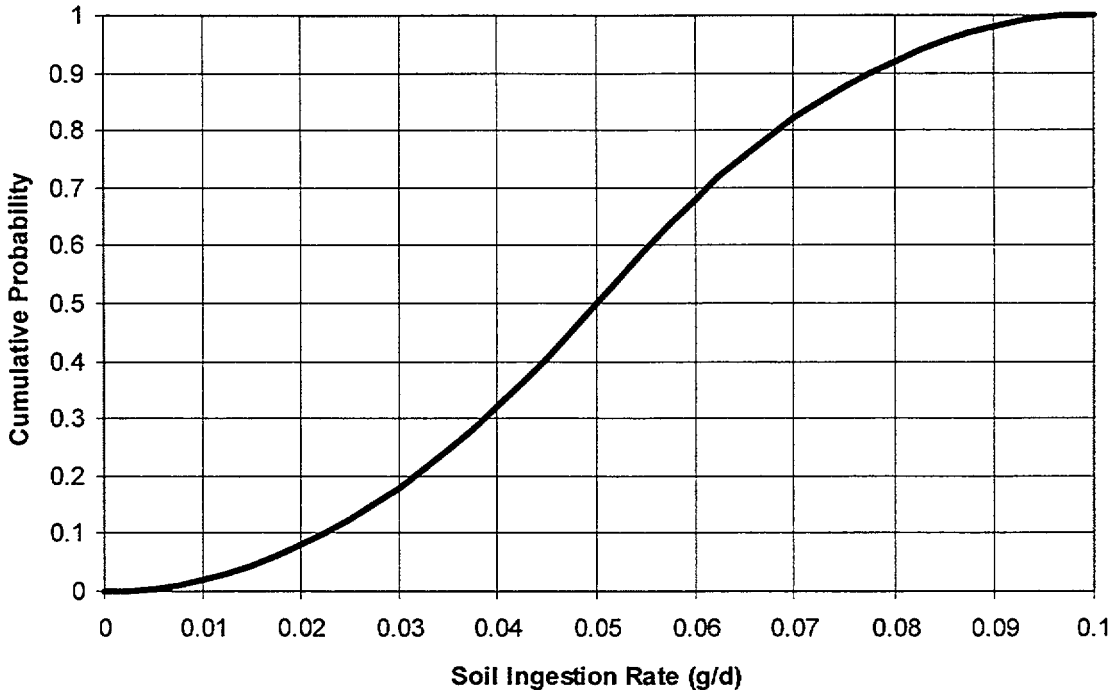

Figure 6.11 Cumulative probability function for GR

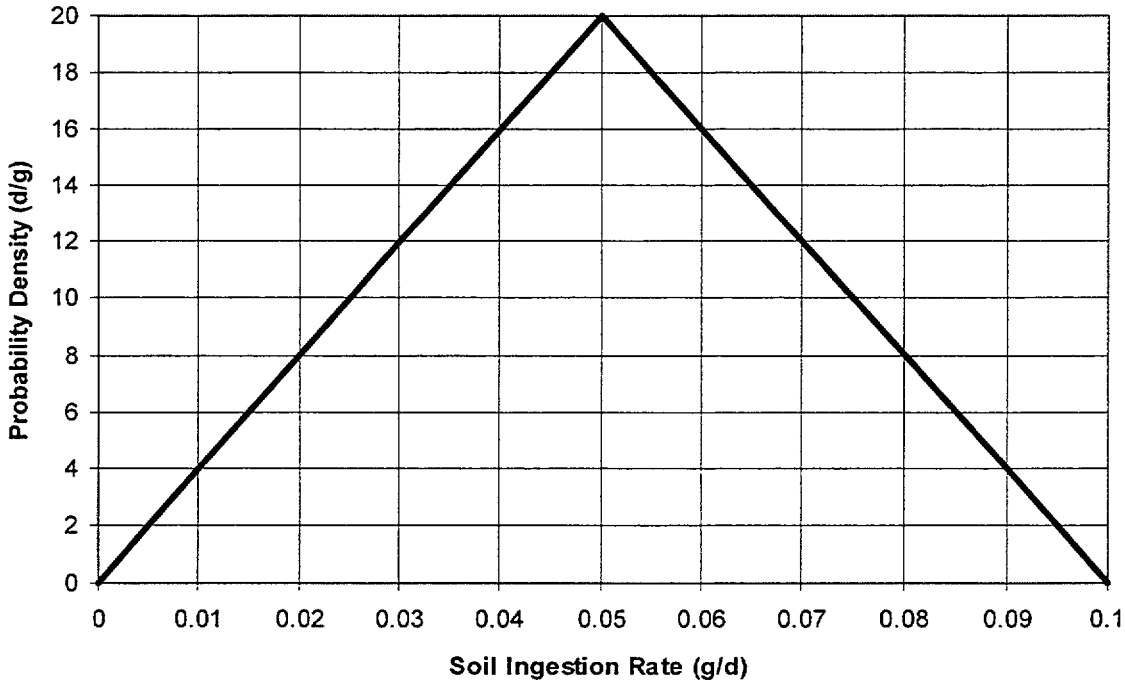

Figure 6.12 Probability density function for GR

6.2.6 Drinking Water Ingestion Rate, U_w (l/d) (Behavioral)

6.2.6.1 Description of U_w

Drinking water ingestion rate, U_w, is the daily average human consumption rate of groundwater from a well. The dose model uses a single, constant value.

6.2.6.2 Use of U_w in Modeling

Use of contaminated groundwater for human consumption increases the dose from radionuclides present in groundwater. The drinking water ingestion rate is used in calculating the dose due to consumption of contaminated groundwater and will depend to a large extent on the ages and dietary needs of individuals at the site. Therefore, U_w is considered a behavioral parameter.

This parameter is used in the irrigation and drinking water dose model for calculating the ingestion dose from contaminated water and may be used to calculate the volume in the aquifer. The drinking water ingestion factor, AF_{dj}, is determined from the drinking water ingestion rate from the following (Equation 5.75, p. 5.59 of NUREG/CR/5512, Vol. 1):

$$Af_{dj} = U_w \, DFG_j \, t_d\left(C_{wj}/C_{wj}\right) \qquad (6.17)$$

where U_w is the daily intake of drinking water (l/d), DFG_j is the ingestion CEDE factor for radionuclide j (mrem per pCi ingested), t_d is the duration of water intake period (d for 1 year of residential scenario), and C_{wj} is the average annual concentration of radionuclide j in groundwater.

6.2.6.3 Information Reviewed to Define a Distribution for U_w

The default value for this parameter, as defined in NUREG/CR-5512, Vol. 1, is 2 l/d. There was no justification or explanation provided for this value. The RESRAD value for the parameter is 1.4 l/d.

The 1977-1978 Nationwide Food Consumption Survey (NFCS) of the USDA collected information about food and beverage consumption from a random sample of the U.S. population (USDA, 1983). Survey results from 26,081 individuals were analyzed, and a statistical analysis of the water intake rates were reported (Ershow and Canter, 1989). Roseberry and Burmaster (1992) fit lognormal distributions to NFCS data and developed distributions for use in public health risk assessments. The justification for applying these data to the screening group (i.e., adult males who garden and obtain drinking water from groundwater sources) is based on the assumption that the screening group would be represented by individuals in the group from 20 to 65 years of age. Although we do not have data specific to adult males or limited just to groups who garden, it is assumed that drinking water intake rates from these large populations is representative of the screening group.

6.2.6.4 Proposed Distribution for Uw

The distribution for drinking water ingestion was determined for adults (20 to 65 years) from data reported by Roseberry and Burmaster (1992). The intake rates for adults are lognormally distributed. The mean and standard deviation of the natural log (drinking water intake rate (l/d)) are 0.1152 and 0.489, respectively, for individuals in the age group from 20 to 65 years. The cumulative distribution for U_w is shown in Figure 6.13 along with the NUREG/CR-5512, Vol. 1, default and RESRAD values. The distribution applies to the screening group by assuming that water intake rates in adults 20 to 65 years old are representative of adult male consumption.

6.2.6.5 Uncertainty in U_w

The distribution for the drinking water ingestion rate was based on a survey of 11,731 adults that were selected randomly from the U.S. population. The individual survey data represents the average daily consumption of water over a three-day period. Results from individual participants in the survey could be influenced by activities of individuals during the three-day survey period and the season of the year. These factors, however, would be expected to balance since the three-day survey periods were spread over the entire year. Drinking water ingestion rates could be less in females than in males.

6.2.6.6 Alternative Values for U_w

This parameter would be expected to vary from site to site due to uncertainty in the activities, dietary habits, and ages of individuals at the site. If a site-specific critical group is defined, an alternative value may be appropriate. Other factors such as the quality of the groundwater could have an influence on the ingestion rate (e.g., use of bottled water for drinking).

The licensee may collect information on water quality at the site and evaluate alternatives for groundwater use based on economic factors. For example, the cost for digging an on-site well may be greater than the cost for

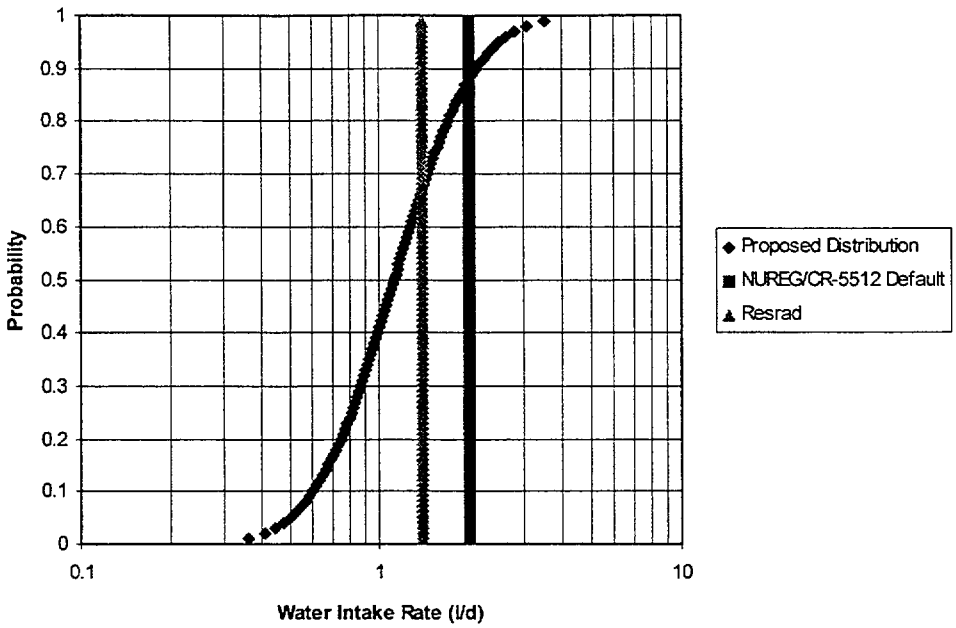

Figure 6.13 Cumulative distribution for drinking water ingestion rate (L/d)

connection to a municipal or a rural water system. Water quality may be very poor, requiring pretreatment of water suitable for drinking.

6.2.7 Irrigation Water Application Rate, IR (L/m^2·d) and Volume of Water Removed From the Aquifer for Irrigation Use, V_{irr} (L/d) - (Behavioral)

6.2.7.1 Description of IR and V_{irr}

The irrigation water application rate is the amount of water, from groundwater, applied on a daily basis per unit area of irrigated land. Parameter IR represents a long-term average rate of water application. The irrigation water application rate is used in the residential scenario to estimate the transfer of radionuclides from irrigation water to food crops. Use of contaminated water via irrigation systems deposits radionuclides on plant surfaces or directly on the soil, resulting in resuspension and plant uptake and transfer to edible parts of the plant. The value for this parameter is 2.08 L/m^2-d in NUREG/CR-5512, Vol. 1, based on an annual average irrigation rate of 76 cm/y, which was considered a representative value sufficient to produce most crops.

V_{irr} is the volume of groundwater removed from the aquifer used for irrigation. NUREG/CR-5512, Vol. 1, does not define a default value for V_{irr}. Instead, V_{irr} is determined from the irrigation rate, IR, and the area of land cultivated, A_r, by assuming that the area defined by A_r is irrigated from groundwater at the site. Since the volume of water for irrigation use is a function of other parameters, an independent probability distribution function is not defined for V_{irr}.

6.2.7.2 Use of IR and V_{irr} in Modeling

The irrigation water application rate, IR, is used in calculating the dose due to consumption of edible plants that are grown in land that is irrigated with contaminated groundwater and the consumption of beef, milk, eggs, and poultry products from animals that consume forage, hay, and grain crops that are grown on the irrigated land.

V_{irr} is important in estimating the transport of radionuclides from contaminated irrigation water to soil and to edible plant and animal products. V_{irr} is used to calculate the total water volume in the aquifer, along with the withdrawn water volume for domestic purposes. It is also used for deriving the fraction of pumped water that is applied to the surface layer.

The higher the irrigation water application rate, the higher will be the deposition rate of radionuclides to edible plants and soil, and consequently the higher the dose due to ingestion of contaminated plants by humans and domesticated livestock. The concentration of contaminants in animals will increase due to ingestion of plant material and soil, and therefore dose to humans will also increase with consumption of animal products (i.e., meat, milk, eggs).

6.2.7.2.1 Irrigation Water Application Rate, IR

The irrigation water application rate, IR, is used in nine different pathways in the residential scenario model for estimating the transfer of radionuclides from contaminated groundwater to edible foods. The equations for each of the nine pathways can be found in Section 5.4.1, Food Crops Contaminated by Irrigation Water, and Section 5.4.2, Animal Products Contaminated by Irrigation Water, in NUREG/CR-5512, Vol. 1, and are summarized in the following:

a) irrigation water-plant-human pathway (Equation 5.22, p. 5.27 of NUREG/CR-5512, Vol. 1)

$$R_{wvjg} = IR\ r_r\ T_v/Y_v\ [C_{wj}/C_{wi}] \qquad (6.18)$$

where R_{wvjg} is the average deposition rate of radionuclide to edible parts of plant v from application of irrigation water per unit average concentration of parent radionuclide i in water, IR is the average annual application rate of irrigation water, r_v is the fraction of initial deposition (in water) retained on the plant, T_v, is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant, Y_v is the yield of plant v, and C_{wj}, and C_{wi} are the average annual concentration of radionuclides j and i, respectively, in irrigation water over the current annual period.

b) irrigation water-soil-plant-human pathway (Equation 5.27, p. 5.30 of NUREG/CR-5512, Vol. 1)

$$R_{wsjg} = IR/P_s\ [C_{wj}/C_{wi}] \qquad (6.19)$$

where R_{wsjg} is the average deposition rate of radionuclide j to soil from irrigation water applied onto the soil during the growing period for an average unit concentration of parent radionuclide i in water, and P_s is the areal soil density (kg/m^2).

c) irrigation water-forage-animal-human pathway. (Equation 5.37, p. 5.36 of NUREG/CR-5512, Vol. 1)

$$R_{wfjf} = IR\ r_f\ T_f/Y_f\ [C_{wj}/C_{wi}] \qquad (6.20)$$

where R_{wfjf} is the average deposition rate of parent radionuclide j to forage crop f from the application of irrigation water during the feeding period for an average unit concentration of parent radionuclide i in water, r_f is the fraction of initial deposition of radionuclides in water retained on the plant, T_f, is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant, and Y_f is the yield of forage crop f.

d) irrigation water-soil-forage-animal-human pathway (Equation 5.43, p. 5.40 of NUREG/CR-5512, Vol. 1)

$$R_{wsjf} = IR/P_s\ [C_{wj}/C_{wi}] \qquad (6.21)$$

where R_{wsjf} is the average deposition rate of radionuclide j to soil from irrigation water applied onto the soil during the feeding period for an average unit concentration of parent radionuclide i in water.

e) irrigation water-stored hay-animal-human pathway. (Equation 5.48, p. 5.41 of NUREG/CR-5512, Vol. 1)

$$R_{whjg} = IR\ r_h\ T_h/Y_h\ [C_{wj}/C_{wi}] \qquad (6.22)$$

where R_{whjg} is the average deposition rate of radionuclide j to stored hay crop h from irrigation water application for an average unit concentration of parent radionuclide i in water, r_h is the fraction of initial deposition of radionuclides in water retained on plant h, T_h is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant, and Y_h is the yield of stored hay crop h.

f) irrigation water-soil-stored hay-animal-human pathway. (Equation 5.50, p. 5.43 of NUREG/CR-5512, Vol. 1)

$$R_{wsjg} = IR/P_s\ [C_{wj}/C_{wi}] \qquad (6.23)$$

where R_{wsjg} is the average deposition rate of radionuclide j to soil from irrigation water applied onto the soil during the growing period for an average unit concentration of parent radionuclide i in water, and P_s is the areal soil density (kg/m^2).

g) irrigation water-stored grain-animal-human pathway. (Equation 5.53, p. 5.46 of NUREG/CR-5512, Vol. 1)

$$R_{wgjg} = IR\ r_g\ T_g/Y_g\ [C_{wj}/C_{wi}] \qquad (6.24)$$

where R_{wgjg} is the average deposition rate of radionuclide j to stored grain crop g from irrigation water application for an average unit concentration of parent radionuclide i in water, r_g is the fraction of initial deposition of radionuclides in water retained on grain plant g, T_g is the translocation factor for transfer of radionuclides from

plant surfaces to edible parts of grain plant g, and Y_g is the yield of stored grain crop g.

h) irrigation water-soil-stored grain-animal-human pathway (Equation 5.55, p. 5.47 of NUREG/CR-5512, Vol. 1)

$$R_{wsjg} = IR/P_s \left[C_{wj}/C_{wi}\right] \quad (6.25)$$

where R_{wsjg} is the average deposition rate of radionuclide j to soil from irrigation water applied onto the soil during the growing period for an average unit concentration of parent radionuclide i in water, and P_s is the areal soil density (kg/m^2).

I) irrigation water-soil-animal-human pathway (Equation 5.58, p. 5.48 of NUREG/CR-5512, Vol. 1)

$$R_{wsjf} = IR/P_s \left[C_{wj}/C_{wi}\right] \quad (6.26)$$

where R_{wsjf} is the average deposition rate of radionuclide j to soil from irrigation water applied onto the soil during the feeding period for an average unit concentration of parent radionuclide i in water.

IR is also used to calculate V_{irr}, along with the land area under cultivation, A_r (m^2), as shown in the following equation:

$$V_{irr} = IR * A_r \quad (6.27)$$

6.2.7.2.2 Volume of Water for Irrigation, V_{irr}

The total water volume in the aquifer remains constant during the simulation and is used as the dilution volume in determining the average annual contaminant concentration in groundwater. The total water volume is taken as the greater of the infiltration water volume or the sum of the water volumes used for irrigation, and domestic purposes.

Thus, the total volume of water is evaluated as (modified from Equation 5.88, p. 5.68 of NUREG/CR-5512, Vol. 1):

$$V_{Tr} = \text{greater of: } V_{lr} \text{ or } V_{irr} + V_{dr} \quad (6.28)$$

where V_{Tr} is the total volume of water in the aquifer for dilution of activity over a one-year period, and V_{dr} is the annual volume of water for domestic water use.

The infiltration volume, V_{lr}, is the sum of the annual net infiltration due to precipitation and irrigation added to the surface layer of soil over the cultivated area. It is calculated (from Equation 5.87, p. 5.68, NUREG/CR-5512, Vol. 1) as follows:

$$V_{lr} = I A_r \, 1000 \cdot 1 \quad (6.29)$$

where I is the infiltration rate, A_r is the area of land under cultivation, 1000 is the area unit conversion factor, and 1 is the annual one-year time period.

Irrigation volume represents recycling of contaminant activity from the aquifer (box 3 of the water use model) to the surface soil layer (box 1). Note that the irrigation rate is an annual average including non-growing periods.

The fraction of irrigation water applied to the surface layer, F_r, is calculated as follows:

$$F_r = \frac{V_{irr}}{V_{Tr}} \quad (6.30)$$

During analysis and testing of the original methodology proposed in NUREG/CR-5512, it was found that the groundwater contamination models described in Volume 1 do not adequately account for possible natural discharge from the aquifer. The result was radionuclide build up in the aquifer box. A water balance model was added to the methodology to correct this problem. These changes are documented in Appendix A of NUREG/CR-5512, Vol. 2. Equations 6.28 and 6.30 reflect these changes.

V_{irr} (and F_r) represent the quantity of groundwater removed for irrigation in the water-use model. F_r is used to calculate the rate of change of the total activity of radionuclide j in box 1, (dC_{1j}/dt) as shown in the following (Equation 5.80, p. 5.65 of NUREG/CR-5512, Vol. 1):

$$dC_{1j}/dt = F_r w_r C_{3j} + \lambda_{rj} \, E_{(n=1,j-1)} \, d_{nj} \, C_{1n} - \left(\lambda_{rj} + L_{12j}\right) C_{1j} \quad (6.31)$$

where w_r is the removal rate constant for pumping of water from box 3 (d^{-1}), C_{3j} is the total activity of radionuclide j in box 3 at time t, j is the index of the current chain-member position in the decay chain, n is the index of precursor chain members in the decay chain ($n<j$), C_{1n} is the total activity of the precursor radio-

nuclide n in box 1 at time t, λ_{nj} is the decay rate constant for decay of radionuclide j (d^{-1}), L_{12j} is the rate constant for movement of radionuclide j from box 1 to box 2 (d^{-1}), and d_{nj} is the fraction of transitions of radionuclide n that result in production of radionuclide j.

It would appear from Equations 6.30 and 6.31 that as V_{irr} increases, F_r increases and will tend to increase the concentration in Layer 1. However, if the modeled infiltration rate (and thus V_{Tr}) is high, contaminants will be removed (flushed) quickly from Layer 1 into the aquifer. Therefore, if total aquifer volume is determined by infiltration water volume (and thus is large compared to removal flows), a high rate of contaminant flushing to the aquifer will occur.

At the same time, if outflows from the aquifer (for irrigation, for instance) are larger than net infiltration, the groundwater water balance model (in Volume 2 of NUREG/CR-5512) allows for natural recharge to make up the deficit, maintaining reasonable aquifer contaminant concentration levels.

6.2.7.3 Information Reviewed to Define the Distribution for IR

The Farm and Ranch Irrigation Survey (1994) (USDC, 1994) provides the most recent and complete compilation of irrigation practices for farms and ranches in the United States. The document contains detailed information on irrigation, including farm size, total irrigated acres, and estimated quantities of water applied by irrigation for individual states and water resource areas over the continental United States. Table 6.18 shows the irrigated land area and the quantities of water used for irrigation in 27 states. These states accounted for 98.22% of total irrigated land area for farms and ranches from which $1,000 or more of agricultural products were produced or sold. These data provide an estimate of long-term (annual) average irrigation rates across a variety of soils, crops, water quality and availability. The data may include surface water as well as groundwater sources. As such, this data set provides an estimate of the irrigation rate for the screening group.

6.2.7.4 Proposed Distribution for IR

The data from Table 6.18 were binned and fit to several distributions and the fitness to each distribution was evaluated with a Kolmogorov-Smirnov test. The data from regional land areas (states) were evenly weighted in developing the distribution. The best fit was obtained with a log normal distribution. Distribution parameters were $\mu = 0.67$, $\sigma = 0.87$, and $\epsilon = 0.32$.

Figure 6.14 depicts the probability density for the irrigation water application rate. This plot includes the corresponding data from Table 6.18 used to generate the fitted distribution. Figure 6.15 is the corresponding cumulative distribution function.

Table 6.18 Irrigation of farm and ranch land in the conterminous U.S. (USDC, 1994)

State	Irrigated area (acres)	Water applied (acre-feet/y)	Ave irrigation rate (acre-feet per acre)	Ave irrigation rate (L/m^2/day)
Arizona	752,019	3,310,159	4.40	3.67
Arkansas	2,853,929	3,196,019	1.12	0.93
California	7,245,487	22,474,499	3.10	2.59
Colorado	2,998,888	5,241,741	1.75	1.46
Florida	1,416,019	1,922,166	1.36	1.13
Georgia	619,536	325,009	0.52	0.44
Idaho	3,183,733	6,023,644	1.89	1.58
Illinois	271,725	168,518	0.62	0.52
Kansas	2,501,925	3,336,027	1.33	1.11
Louisiana	820,816	885,335	1.08	0.90
Michigan	305,481	165,843	0.54	0.45
Minnesota	326,781	185,034	0.57	0.47
Mississippi	646,761	684,643	1.06	0.88
Missouri	702,183	513,940	0.73	0.61
Montana	1,936,292	3,057,884	1.58	1.32
Nebraska	5,979,661	5,025,201	0.84	0.70

Table 6.18 Irrigation of farm and ranch land in the conterminous U.S. (USDC, 1994) (continued)

State	Irrigated area (acres)	Water applied (acre-feet/y)	Ave irrigation rate (acre-feet per acre)	Ave irrigation rate (L/m^2/day)
Nevada	519,507	1,138,138	2.19	1.83
New Mexico	685,695	1,630,390	2.38	1.98
North Dakota	157,426	138,954	0.88	0.74
Oklahoma	474,201	589,076	1.24	1.04
Oregon	1,587,152	2,946,868	1.86	1.55
South Dakota	304,454	302,997	1.00	0.83
Texas	5,100,979	7,605,827	1.49	1.24
Utah	1,085,083	2,412,250	2.22	1.86
Washington	1,434,800	3,125,619	2.18	1.82
Wisconsin	306,096	205,210	0.67	0.56
Wyoming	1,374,447	2,481,740	1.81	1.51

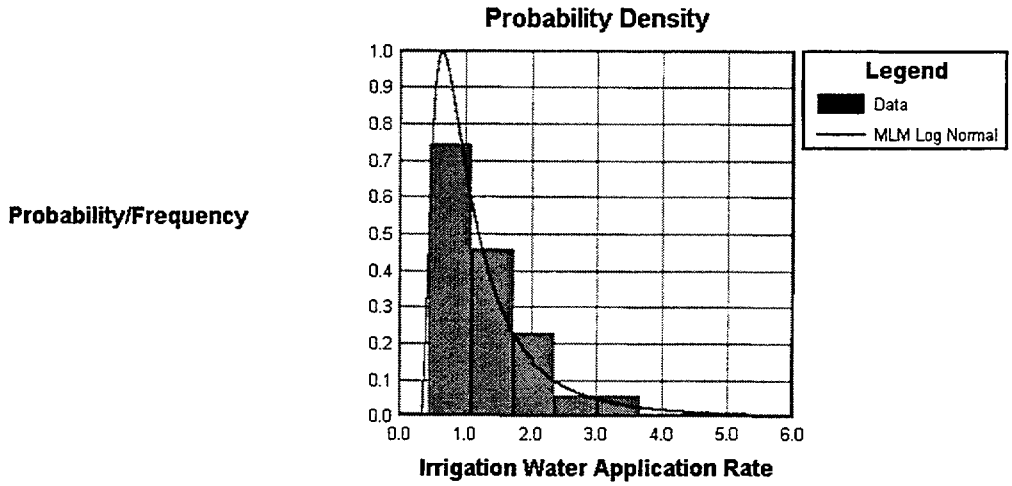

Figure 6.14 Calculated probability distribution for irrigation water application rate

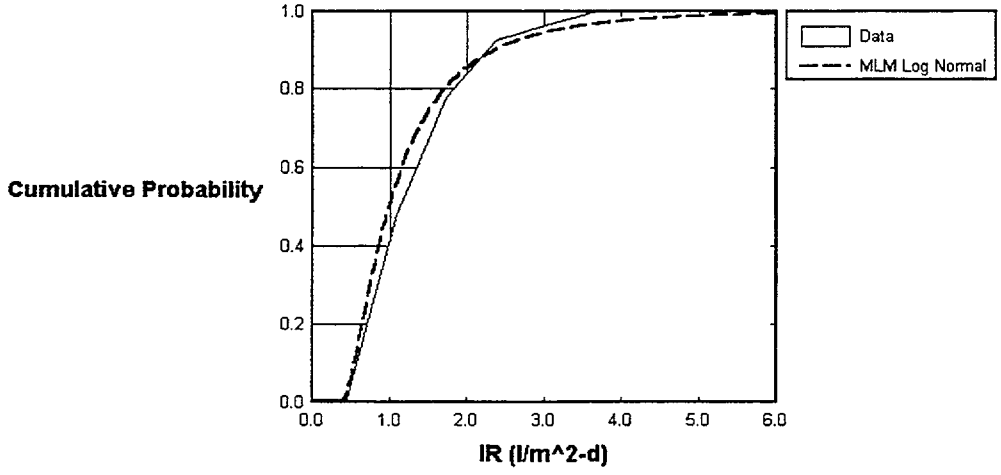

Figure 6.15 Cumulative distribution for irrigation water application rate, IR

6.2.7.5 Uncertainty in IR

The distribution for the irrigation water application rate, IR, was based on annual average irrigation rates throughout the United States. Since most farm and ranch land is irrigated only during the growing season, the data may underestimate the actual daily water irrigation rate for some areas of the country. The amount of water used for irrigation would be expected to vary from year to year, depending on the quantity of added moisture from rainfall. Abnormal levels of rainfall could bias the survey data and skew the proposed distribution.

V_{irr} is a dependent parameter derived from parameters IR and Ar.

6.2.7.6 Alternative Parameter Values

The irrigation rate parameter, IR, would be expected to vary from site to site depending on local climatic conditions, seasonal changes at the site, crops grown, soil hydraulic properties, groundwater quality and quantity, and location and availability of surface water that may also be used for irrigation. In the arid west, high values of irrigation would be expected, whereas, in portions of the northwest, eastern and southeastern states, and humid coastal areas, no irrigation may be needed. This can be seen in the data for arid states like Arizona (3.67 L/m^2-d) versus more humid states like Wisconsin (0.56 L/m^2-d) in Table 6.18.

Applicants may elect to collect data at the site in an attempt to support limits on IR. Limiting values may be supported due to regional precipitation and soil moisture levels (as well as evapotranspiration rates, infiltration rates, etc.), regional soil properties, and data that support alternative irrigation rates for forage crops or edible foods that may be cultivated due to local dietary patterns or land use patterns. IR may also be modified by defining a site-specific critical group different from resident farmers.

6.2.8 Volume of Water Removed from the Aquifer Per Year for Domestic Uses, V_{dr} (L) (Behavioral)

6.2.8.1 Description of V_{dr}

V_{dr} is the annual volume of groundwater removed from the aquifer for domestic uses. This parameter, along with the annual volume of water used for irrigation, V_{irr}, is used for determining aquifer volume. Of the total volume for all domestic uses (showers, washing, etc.), a portion of this domestic use is directly ingested as drinking water or in consumable products made from the drinking water source. Other pathways of contaminated water, such as direct immersion while showering, are not included in the exposure calculations.

In NUREG/CR-5512, Vol. 1, the default value for this parameter was set to 91,250 liters. No basis is provided for this value and the variability of this parameter is not discussed in Volume 1. V_{dr} is used in estimating the transport of radionuclides from contaminated groundwater to humans in the residential scenario. This parameter, along with the volume used for irrigation, establishes the total volume of the aquifer.

6.2.8.2 Use of V_{dr} Modeling

The total water volume in the aquifer (V_{Tr}) remains constant during the simulation and is used as the dilution volume in determining the annual average water concentration. The total water volume is the greater of the infiltration water volume or the sum of the water volumes used for irrigation, and domestic purposes.

The contribution to the ingestion dose from the use of contaminated groundwater, DWR_i, is evaluated for drinking water and ingestion of irrigated foods as follows (Equation 5.74, p. 5.58, NUREG/CR-5512, Vol. 1):

$$DWR_i = C_{si}\left[\sum_{j=1}^{j_I} A_{wtf}\, AF_{dj} + DIET \sum_{j=1}^{j_I} A_{wtj}\, AF_{wj}\right] \qquad (6.32)$$

where C_{si} is the initial concentration of radionuclide i in soil at the time of site release, A_{wtj} is the average concentration factor for radionuclide j in water over the current one-year exposure period per initial unit concentration of parent radionuclide i in soil at the time of site release, AF_{dj} is the CEDE factor for the ingestion of drinking water per unit average concentration of radionuclide j in water, and AF_{wj} is the CEDE factor for radionuclide j per unit average concentration of radionuclide j in groundwater used for irrigation for the current one-year period.

The drinking water ingestion factor, AF_{dj}, is calculated (Equation 5.75, p. 5.59, NUREG/CR-5512, Vol. 1) as follows:

$$AF_{dj} = U_w\, DFG_j\, t_d\, (C_{wj}/C_{wj}) \qquad (6.33)$$

where U_w is the daily intake of drinking water, DFG_j is the ingestion CEDE factor for radionuclide j, and t_d is

the duration of water intake period (one year). The concentration ratio C_{wj}/C_{wj} equal to 1 indicates normalization to unit average concentration in water over the year of the residential scenario.

The fraction of irrigation water applied to the surface layer, F_r, is calculated as follows:

$$F_r = \frac{V_{irr}}{V_{Tr}} \tag{6.34}$$

where V_{irr} is the volume of water used for irrigation during a one-year period (L/d), V_{ir} is the total volume of water in the aquifer, and V_{dr} is the volume of water used for domestic purposes during a one-year period (L/d).

6.2.8.3 Information Reviewed to Define the Distribution for V_{dr}

USGS water use data (USGS, 1990a and USGS, 1995b) provide estimates of domestic water use in the United States by state. Per capita water use estimates were provided for both self-supplied as well as public-supplied delivery systems. Table 6.19 provides the original per capita use of water, by state, from self-supplied water systems in gallons per day. These quantities are converted to total liters/year by assuming a single resident in the household (for consistency with all other parameters in the residential scenario) and 365.25 days per year.

The 50 values for annual per capita domestic water use by state define the distribution for V_{dr}. Each value was assumed to be equally likely. The cumulative distribution for V_{dr}, based on the data in Table 6.19, is shown in Figure 6.16.

6.2.8.4 Uncertainty in V_{dr}

The values in Table 6.19 are based on estimates that depend on population estimates, reported meter readings or other self-supplied means to measure water use, and on the definition of domestic use. Population estimates can be a significant source of uncertainty when considering transient and non-resident users and may also depend on whether the approach used for estimation is consistent with the approach used for determining water use. Reported domestic water use may represent different uses and sources depending on the distribution and metering system and on non-domestic use. It is assumed that uncertainty in the reporting of total annual domestic water use is small relative to regional variability in actual use.

The domestic water use figures given in Table 6.19 include water used for household purposes such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, car washing, and watering lawns and gardens. Depending on the local climate, generally the largest indoor uses are for toilet flushing and bathing. Outdoor uses can range from near zero in humid areas to 60% of total domestic use in arid areas. The data reported in Table 6.19 captures the variability of total domestic water use for the continental United States as well as Alaska and Hawaii.

Table 6.19 Estimated annual domestic water use for U.S. (L)

State	Per capita (gal/d)	Total use (L)	State	Per capita (gal/d)	Total use (L)
AL	75.1	103,824	MT	77.9	107,694
AK	39.7	54,884	NE	124.8	172,532
AZ	117.9	162,993	NV	119.8	165,620
AR	88.3	122,072	NH	65.0	89,861
CA	74.2	102,579	NJ	74.9	103,547
CO	75.9	104,930	NM	77.6	107,280
CT	75.0	103,685	NY	58.2	80,460
DE	79.2	109,492	NC	55.0	76,036
FL	175.1	242,071	ND	78.1	107,971
GA	75.2	103,962	OH	75.0	103,685
HI	188.8	261,011	OK	86.1	119,031
ID	199.8	276,218	OR	103.5	143,086
IL	84.1	116,266	PA	51.6	71,335
IN	76.0	105,068	RI	70.1	96,911
IA	66.6	92,073	SC	75.0	103,685

Table 6.19 Estimated annual domestic water use for U.S. (L) (continued)

State	Per capita (gal/d)	Total use (L)	State	Per capita (gal/d)	Total use (L)
KS	99.5	137,556	SD	62.5	86,404
KY	49.8	68,847	TN	65.0	89,861
LA	82.7	114,330	TX	108.2	149,583
ME	90.0	124,422	UT	85.9	118,754
MD	82.9	114,607	VT	71.9	99,400
MA	72.0	99,538	VA	75.0	103,685
MI	72.8	100,644	WA	115.5	159,675
MN	116.6	161,196	WV	80.0	110,598
MS	49.9	68,985	WI	60.7	83,916
MO	60.0	82,948	WY	75.0	103,685

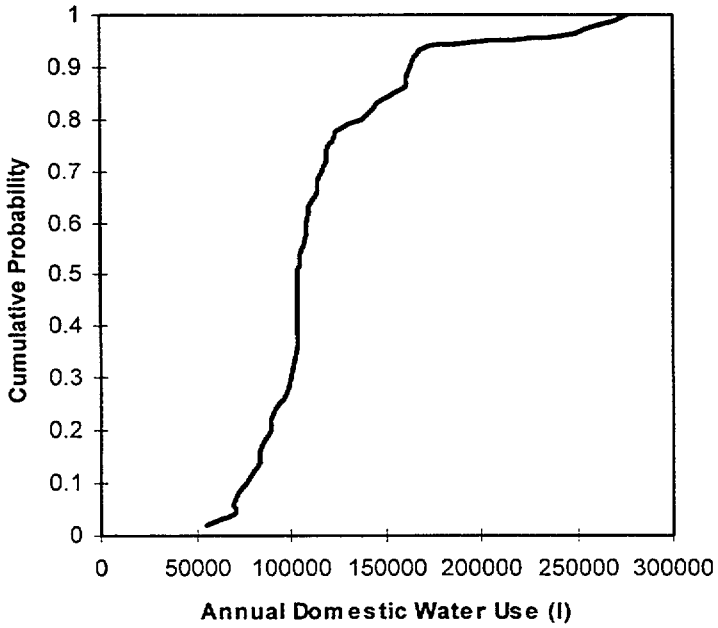

Figure 6.16 Cumulative distribution for annual domestic water use, V_{dr}

6.2.8.5 Alternative Values for V_{dr}

Licensees may attempt to define site specific values for the annual domestic water use for their site under the constraints of the residential farmer scenario. Those alternative values will need to be consistent with typical domestic water use in that region of the country, unless site characteristics, requirements, or use restrictions can be used to defend significant deviation from the representative state-specific values given in Table 6.19 and captured in the parameter distribution derived for V_{dr}.

Licensees may wish to defend new values for the total annual domestic water volume due to site specific considerations impacting water use. Some of those considerations may include regional climate (temperature and humidity), rainfall and its impact on water use for outdoor requirements, local water rates and water use restrictions and other conservation efforts that may not be reflected in typical reported values of water use, and such. The simplest approach for site specific analysis is to select, as an alternative to the default value, the value from Table 6.19 that corresponds to the location of the site. If a licensee defines a critical group different from resident farmers, the distribution for V_{dr} may be affected.

For the purpose of defining the distribution of total annual domestic water use, supporting data similar to that provided in this document could be used to develop such a distribution. More detailed USGS data for all U.S. counties are available.

6.2.9 Ingestion Rates of Home Produced Food, U_v (kg/y), U_a(kg/y) and U_f (kg/y)

6.2.9.1 Description of Ingestion Rates

The ingestion rates of homegrown produce, U_v (kg/y), and other home produced food, U_a (kg/y), and U_f (kg/y), as defined for Volume 1, represent the consumption rate of specific contaminated food. The dose model uses different constant values of U_v for "leafy" vegetables, "other" vegetables, fruits and grains, different constant values of U_a for beef, poultry, milk and eggs and a constant value of U_f for fish. U_v, U_a and U_f are behavioral parameters. Distributions therefore represent the diet of the average member of the screening group (i.e., residential and light farmers), and the default values are the average values of these distributions.

6.2.9.2 Use of Ingestion Rates in Modeling

Ingestion dose is linearly proportional to U_v, U_a and U_f. Therefore, the higher the values for U_v, U_a and U_f the higher the calculated dose. More specifically, the ingestion rates, U_v and U_a are used in the dose model to calculate the agricultural pathway transfer factors (PF). These factors are then used to calculate the annual dose from ingestion of home produced food. The mathematical expression to evaluate the PFs for unit average concentration of a parent radionuclide in soil is given in NUREG/CR-5512 (p. 5.51) as:

$$PF_{sij} = \Sigma_{(v=1,Nv)}\ U_v\ PPTF_{vsij} + \Sigma_{(a=1,Na)}\ U_a PPTF_{asij} \qquad (6.35)$$

where:

PF_{sij} = the agricultural pathway transfer factors for radionuclide j as a progeny of radionuclide i per unit initial concentration of parent radionuclide in soil (pCi ingested per pCi/g dry-weight soil for a year of residential scenario),

U_v = the ingestion rate for food crop type v by an individual (kg wet-weight/y),

$PPTF_{vsij}$ = the partial pathway transfer factor for food crop type v, radionuclide j as a progeny of radionuclide i, for unit average concentration of parent radionuclide i in soil (pCi y/kg dry-weight food per pCi/g dry-weight soil for a year of residential scenario),

U_a = the ingestion rate of animal product type a by an individual (kg wet-weight/y),

$PPTF_{asij}$ = the partial pathway transfer factor for animal product type a, radionuclide j as a progeny of radionuclide i, for unit average concentration of parent radionuclide i in soil (pCi y/kg wet-weight food per pCi/g dry-weight soil for a year of residential scenario),

N_a = the number of animal products considered in the diet, and

N_v = the number of food crops considered in the diet.

The mathematical expression to evaluate the PFs for unit average concentration of a parent radionuclide in irrigation water is given in NUREG/CR-5512 (p. 5.52) as:

$$PF_{wij} = \Sigma_{(v=1,Nv)}\ U_v\ PPTF_{vwij} + \Sigma_{(a=1,Na)}\ U_a PPTF_{awij} \qquad (6.36)$$

where:

PF_{wij} = the agricultural pathway transfer factor for radionuclide j as a progeny of radionuclide i per unit initial concentration of parent radionuclide in irrigation water (pCi ingested per pCi/L water for a year of residential scenario),

U_v = the ingestion rate for food crop type v by an individual (kg wet-weight/y),

$PPTF_{vwij}$ = the partial pathway transfer factor for food crop type v, radionuclide j as a progeny of radionuclide i, for unit average concentration of parent radionuclide i in water (pCi y/kg wet-weight food per pCi/L water for a year of residential scenario),

U_a = the ingestion rate of animal product type a by an individual (kg wet-weight/y),

$PPTF_{awij}$ = the partial pathway transfer factor for animal product type a, radionuclide j as a progeny of radionuclide i, for unit average concentration of parent radionuclide i in irrigation water (pCi y/kg wet-weight food per pCi/L water for a year of residential scenario),

N_a = the number of animal products considered in the diet, and

N_v = the number of food crops considered in the diet.

The ingestion rate of fish, U_f, is used in calculating the aquatic food ingestion factor (AF). AF is then used to calculate the annual dose from ingestion of aquatic foods. The mathematical expression for AF is given in NUREG/CR-5512, Vol. 1 (p. 5.60), as:

$$AF_{fj} = U_f\, t_f\, DFG_j\, BA_{jf}\, (C_{wj}/C_{wj})/365.25 \qquad (6.37)$$

where:

AF_{fj} = the aquatic pathway transfer factor for radionuclide j as a progeny of radionuclide i, per unit average concentration of radionuclide j in surface water (mrem per pCi/L for a year of the residential scenario),

U_f = the ingestion rate of aquatic foods produced in contaminated surface water,

t_f = the duration of fish consumption in days,

DFG_j = the ingestion CEDE factor for radionuclide j (mrem pr pCi ingested),

Ba_{jf} = the bioaccumulation factor for radionuclide j in aquatic foods, and

C_{wj} = the average annual concentration of radionuclide j in water (pCi/L).

U_v and U_a are also used to determine the area of land cultivated, A_r. Section 5.4.1.2 provides a detailed description of the relationships among ingestion rates, crop yields, and the cultivated area.

6.2.9.3 Information Reviewed to Define Distributions for U_v, U_a, and U_f

The values used for U_v and U_a in NUREG/CR-5512, Vol. 1, are based on food ingestion rates found in the 1977–78 Nationwide Food Consumption Survey (USDA, 1983). The specific values are derived from mean values compiled by Higley and Strenge (1988) and Pao et al. (1985). These values are based on consumption data that represent all food sources and not just home grown food. The dose calculation described in Volume 1 uses a single parameter (DIET) to describe the fraction of homegrown food in each food category. This assumption requires, for example, that the fraction of domestically-produced beef in the diet equals the fraction of domestically produced leafy vegetables. This assumption is unlikely to be satisfied in general, and is not representative of the screening group. In this analysis, ingestion rates of homegrown food are estimated separately for each of the food product categories. The DIET parameter is therefore unneeded (see Section 6.2.1). This approach allows consumption patterns to be more accurately represented. In addition, redefining these parameters in this manner makes them consistent with the definition of U_f.

The default value used in NUREG/CR-5512, Vol. 1, for U_f was based on summary data presented by Rupp et al. (1980). The regional percentiles reported in Rupp et al. are based on the entire population, including those individuals who eat no fish, which is not representative of the screening group. To try to compensate for this inaccuracy, (i.e., Rupp et al. reported that over 85% of the population eat no freshwater fish), the value for the highest regional rate reported by Rupp et al. was used as the default value in NUREG/CR-5512, Vol. 1. In the dose calculations, U_f is not scaled by the DIET parameter, which implies that it represents the consumption of domestically-produced fish.

Table 6.20 displays the default values of ingestion rates for the eight food groups defined in NUREG/CR-5512, Vol. 1.

Table 6.20 NUREG/CR-5512 U_v, U_a and U_f default values

Food type	Consumption rate
Leafy vegetables (U_v)	11(kg/y)
Other vegetables (U_v)	51 (kg/y)
Fruit (U_v)	46 (kg/y)
Grain (U_v)	69 (kg/y)
Beef (U_a)	59 (kg/y)
Poultry (U_a)	9 (kg/y)
Milk (U_a)	100(kg/y)
Eggs (U_a)	10 (kg/y)
Fish (U_f)	10 (kg/y)

The most recent Nationwide Food Consumption Survey (USDA, 1993) was conducted in 1987–88 and is more reflective of long-term nationwide consumption trends compared to the 1977–78 survey data. Like the earlier survey, the individual survey data could not be used directly to measure consumption of home produced food because the source of the food item is not identified. However, EPA reports intake rates for various home produced food items (EPA, 1996) based on an analytical method that combined data from both the household and individual 1987-88 USDA survey components. The data is reported in the form of cumulative probability distributions. This data set provides estimates of U_v and U_a defined as rates of consumption of food from *on-site production.*

The data provided by EPA (1996) represent consumption of home-produced food, however the reported values do not directly correspond to the dose model parameters in some respects. Some additional assumptions are required to estimate parameter distributions from the reported data. First, the eight food categories have to be related to the EPA data. EPA reports intake rates that directly match the "other" vegetables, fruits, beef, poultry, eggs and fish categories. For the "leafy"

vegetables category, it is assumed that this category is equivalent to EPA's "exposed" vegetables category. EPA defines the "exposed" vegetables category as those vegetables that are grown above ground. Therefore, assuming that the category of "leafy" vegetables is equivalent to EPA's "exposed" vegetable category is reasonable given the fact that all leafy vegetables are grown above ground, although it may overestimate this category since not all vegetables that are grown above ground are leafy. For the food grain group it is assumed that the EPA data for corn is appropriate, given that corn is the only grain for which data was reported. This assumption is consistent with the study by McKone (1994), where he also used corn to represent the grain category. The milk category is assumed to be equivalent to the EPA's dairy category. Again, this assumption is reasonable but conservative because the reported rates include dairy products other than milk.

EPA notes that the survey data were taken during a week long period, and therefore may not be representative of annual behavior (i.e., more home grown foods are typically eaten in the summer). EPA generated seasonally adjusted intake distributions for all meats, vegetables and fruits by averaging the corresponding percentiles of each of the four seasonal intake distributions reported. This same approach was used to generate seasonally adjusted distributions for the eight food group categories required for the dose model.

EPA reports ingestion rates indexed to the actual body weights of the survey respondents in units of mass ingested per time per respondent body weight. Although EPA does not recommend converting the intake rates into average ingestion rates of mass/time by multiplying by a single average body weight, they do indicate that if this is done, a weight of 60 kg should be used because the total survey population included children.

6.2.9.4 Proposed Distributions for U_v, U_a, and U_f

In order to use the EPA data to represent the average member of the screening group, the seasonally adjusted data were scaled by the percentile average of the ratio of the 20–39 age data to the total population data and then converted by multiplying by the body weight, 70 kg, of the average member of the screening group. This data adjustment assumes that the data scales linearly. EPA does not provide any information about whether or not this assumption is valid, but it is a reasonable approximation.

The homegrown food ingestion rate distributions reported by EPA are based on the amount of food "consumed" in an economic sense (i.e., food that has been brought into the house). EPA recommends converting these intake rates to reflect actual ingestion by decreasing the amounts by percent weight losses from preparing the foods. EPA provides percent weight losses for various meats, fruits and vegetables. Therefore, these losses were accounted for in deriving the distributions for U_v, U_a and U_f. However, losses were not reported for eggs and milk, so these losses were not accounted for in these two food categories.

Table 6.21 lists percentiles of the distributions for U_v, U_a and U_f for the members of the screening group, estimated from the values reported by the EPA as described above. Summary statistics are also listed, along with the equivalent values defined in Volume 1 (i.e., rates multiplied by the DIET parameter), and the 1995 total consumption rates, including both homegrown and purchased food (USDA, 1997a). Figures 6.17, 6.18, and 6.19 present the cumulative distribution functions for U_v, U_a and U_f, respectively. These cumulative distribution functions define the probability distribution functions for U_v, U_a and U_f.

Comparing the equivalent NUREG/CR-5512 default parameters (i.e., consumption rate default parameters multiplied by the default DIET parameter of 0.25) with the mean of the new distributions indicates that the mean of the new distributions are consistently higher than their 5512 equivalent, except for the grain category. However, given the differences in their derivations, the means and the Volume 1 default values are reasonably consistent. The Volume 1 default values typically fall between the upper and lower quantiles of the individual distributions. Poultry and egg consumption rates are notable exceptions: both Volume 1 default values are below their 0.01 quantile values. For both categories the ratio of the average homegrown consumption rate to the average total consumption rate is near 1, suggesting that domestic producers in these categories tend to derive most of their total consumption from domestic production. In this case the default Volume 1 DIET parameter value of 0.25 would be inappropriate for these categories.

6.2.9.5 Uncertainty in Ingestion Rates

The information collected in the Nationwide Food Consumption Survey as interpreted in EPA (1996) describes consumption rates for home-produced food items over a broad range of individuals. Rates were measured over a small time span, but these measurements were seasonally distributed. Estimating annual average ingestion rates for members of the screening

Table 6.21 Statistical characteristics of the distributions for U_v, U_a and U_f

Ingestion rates of homegrown foods									
Cumulative %	Leafy vegetables (kg/y)	Other vegetables (kg/y)	Fruits (kg/y)	Grain (kg/y)	Beef (kg/y)	Poultry (kg/y)	Milk (L/y)	Eggs (kg/y)	Fish (kg/y)
0.01	1.71(1)	2.23	1.93	1.41	2.42	3.85	6.59	2.80	1.85
0.05	1.04	4.15	3.64	2.22	7.03	4.18	6.86	4.50	1.92
0.10	2.40	5.95	5.08	3.22	8.20	5.94	7.67	5.30	2.84
0.25	5.90	11.27	9.48	4.83	13.26	9.57	58.63	8.23	3.68
0.50	11.68	26.64	20.48	8.20	28.79	19.85	148.56	12.36	7.77
0.75	24.58	55.57	45.36	15.80	48.41	38.22	294.81	21.35	16.14
0.90	46.27	77.07	125.96	31.78	76.75	50.83	554.94	35.90	39.08
0.95	66.03	145.57	190.05	44.01	105.71	58.52	721.00	47.35	79.05
0.99	135.52	301.49	460.84	84.78	220.06	72.81	1210.78	120.71	112.82
1.00	222.95	384.03	673.57	99.47	222.75	72.81	1210.78	120.71	852.06
Summary statistics									
Mean[1]	21	45	53	14	40	25	233	19	21
Equivalent 5512 value	2.8	13	12	17	15	2.3	25	2.5	10
1995 U.S. total ingestion rates	185(total)	185(total)	128	87	29	28.5	358	12	7
Ratio of homegrown mean to 1995 totals	(leafy + other)/total = 0.36	(leafy + other)/total = 0.36	0.41	0.17	1.4	0.89	0.65	1.6	2.9

[1] Estimated as average of 580 sample values

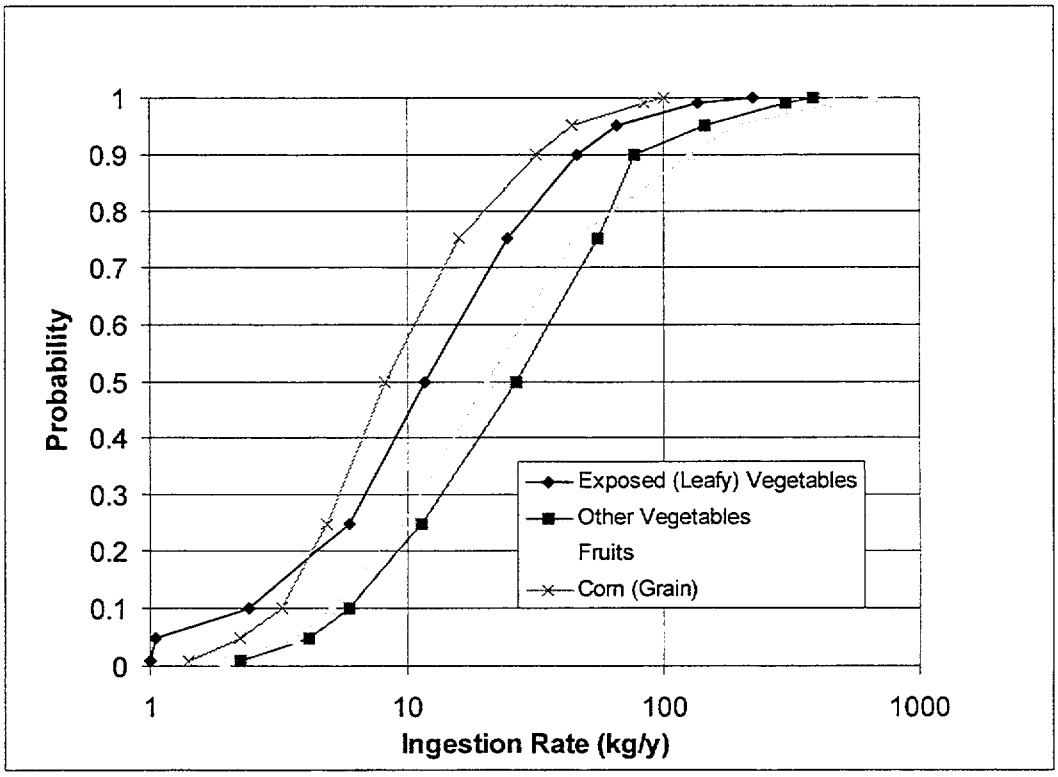

Figure 6.17 Cumulative distribution of U_v for exposed (leafy) vegetables, other vegetables, fruits, and corn (grain)

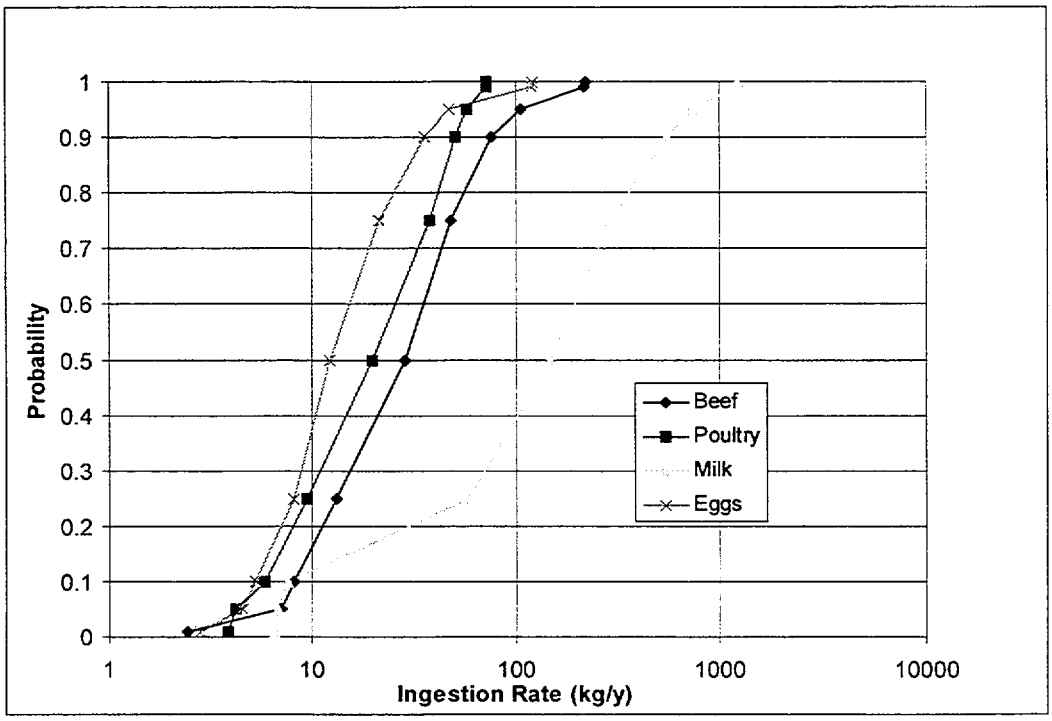

Figure 6.18 Cumulative distribution of U_a for beef, poultry, dairy (milk) and eggs

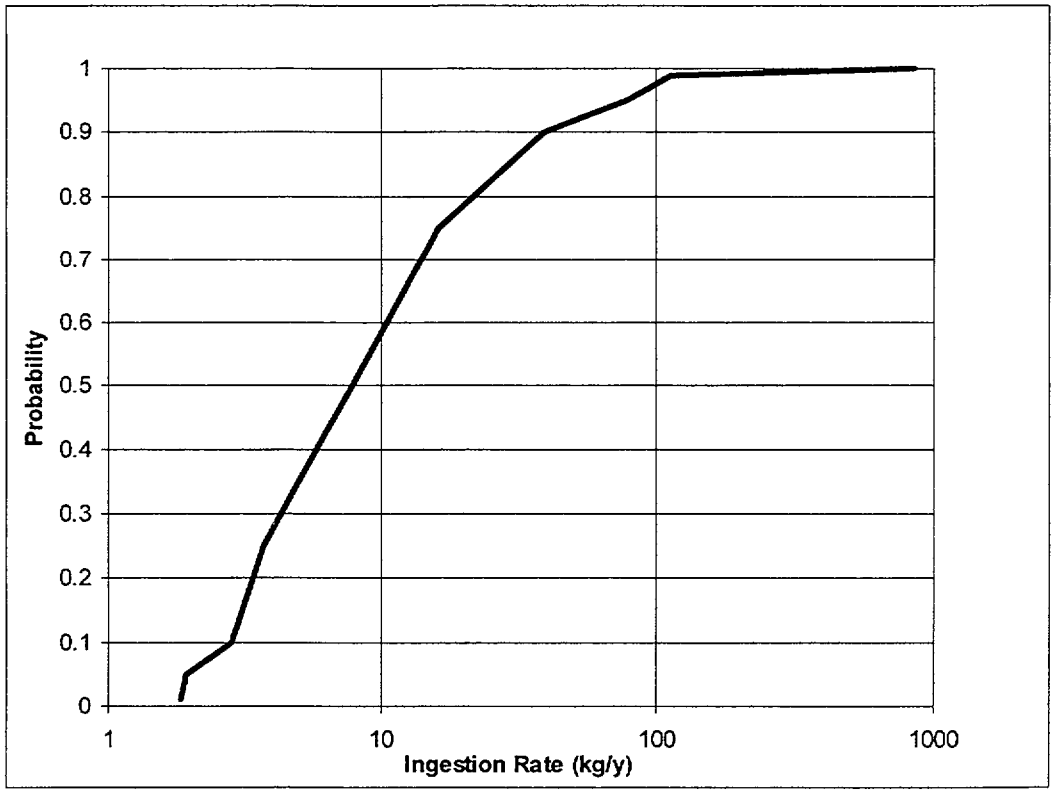

Figure 6.19 Cumulative distribution for U_f for fish

group requires assumptions about the variability of short term versus chronic consumption, the composition of the sample population versus the screening group, and the relative rates of ingestion versus economic consumption. These assumptions introduce some uncertainty about the distributions. We do not expect this uncertainty to be large relative to the mean parameter values, however, and these mean values are comparable to other estimates of ingestion rate.

6.2.9.6 Alternative Ingestion Rate Values

The proposed distribution functions presented above represent the behavioral variability of the members of the screening group and are not related to the physical characteristics of the specific site being considered. Site-specific values for these parameters, like other behavioral parameters, are established by defining a site-specific critical group. Some critical groups may have substantially different consumption rates, for example, groups that do not grow food in one or more categories.

6.3 Volumetric Breathing Rates (Metabolic), V_r, V_x, and V_g (m^3/h)

6.3.1 Description of Breathing Rates

The residential scenario defines three exposure situations or contexts for resident farmers: indoors, outdoors, and gardening. These exposure contexts are distinguished because the transport rates may differ significantly among them. The breathing rate parameters, in conjunction with the indoor resuspension factor, dust loadings, and isotope-specific inhalation CEDE factors, are used to calculate the average annual dose due to inhalation. The breathing rate parameters represent the annual average breathing rate of the average member of the screening group while indoors (V_r), outdoors (V_x) and gardening (V_g). As described in Section 3.2.2 above, default values for metabolic parameters are established by the average value for adult males in the general population.

The default value defined for each of the three breathing rates in NUREG/CR-5512, Vol. 1, is 1.2 m^3/h. This value corresponds to an average for the eight-hour work day assuming light activity for a person, as suggested in International Commission on Radiological Protection (ICRP) Publication 23 (1975). Revised default values for these parameters were defined based on a review of current literature on breathing rate.

6.3.2 Use of Breathing Rates in Modeling

Within each of the three contexts defined for the residential scenario (indoors, outdoors, and gardening), inhalation dose is directly proportional to breathing rate. The overall importance of breathing rate in determining dose depends on the relative contribution of inhalation dose to total dose, which in turn depends on exposure rates via alternative pathways, and on nuclide-specific dose factors.

The breathing rate parameters are used to calculate the committed effective dose equivalent, CEDE, resulting from inhalation of resuspended surface contamination. The relationship between the volumetric breathing rates and internal dose due to inhalation (DHRi) is described by the following (see NUREG/CR-5512, p. 5.55):

$$\begin{aligned} DEXR_i = &\left[24\ V_g\left(t_g/t_{tg}\right) CDG\ C_{si}\ \Sigma_{(j=1,ji)}\ S\left\{A_{stj},\ t_{tg}\right\} DFH_j\right] \\ &+ \left[24\ V_x\left(t_x/t_{tr}\right) CDO\ C_{si}\ \Sigma_{(j=1,ji)}\ S\left\{A_{stj},\ t_{tr}\right\} DFH_j\right] \\ &+ \left[24\ V_r\left(t_i/t_{tr}\right)\left(CDI + P_d RF_r\right) C_{si}\ \Sigma_{(j=1,ji)}\ S\left\{A_{stj},\ t_{tr}\right\} DFH\right. \end{aligned} \quad (6.38)$$

where V_g is the volumetric breathing rate for time spent gardening (m^3/h); V_r is the volumetric breathing rate for time spent indoors (m^3/h); V_x is the volumetric breathing rate for time spent outdoors (m^3/h), t_g is the time during the one-year exposure period that the individual spends outdoors gardening (d); t_i is the time in the one-year exposure period that the individual spends indoors (d); t_x is the time in the one-year exposure period that the individual spends outdoors, other than gardening (d); t_{tr} is the total time in the residential exposure period (d); CDI, CDO, and CDG are the dust loading factors for indoor, outdoor, and gardening activities (g/m^3); respectively, C_{si} corresponds to the concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil); J_i is the number of explicit members of the decay chain for parent radionuclide i; $S\{A_{stj}, t_{tr}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); $S\{A_{stj},t_{tg}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over one gardening season during one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); DFH_j is the inhalation committed effective dose equivalent factor for radionuclide j for exposure to contaminated air (in units of mrem per pCi inhaled); P_d corresponds to the indoor dust-loading on floors (g/m^2); and RF_r is the indoor resuspension factor (m^{-1}). The resulting internal inhalation dose is directly proportional to the volumetric breathing rates for indoor, outdoor, and gardening activities.

6.3.3 Information Reviewed to Define Breathing Rate Distributions

The review conducted to support the EPA *Exposure Factors Handbook* (EPA, 1996) was adopted for this study as the most current compilation of relevant literature. Eleven studies are reviewed and summarized in the Handbook. Five are identified as "key studies," and form the basis for inhalation values recommended there. The six remaining studies are considered "relevant," and contain supporting information relating to inhalation rate. Separate breathing rate estimates are not reported in any study for the specific contexts defined for the residential scenario. Instead, daily average values are reported, as well as breathing rates for individuals engaged in various levels of activity. These activity levels are descriptively defined, for example as "rest," "sedentary," "light," "moderate," and "heavy."

Reported average daily values include a range and relative weighting of activities typical of an entire day: this range and weighting of activities is not representative of activities specifically conducted indoors, outdoors, or while gardening. For this reason, average daily values reported in the handbook are not appropriate for these parameters. The three exposure contexts in the residential scenario can be distinguished by the types of activities that would typically take place in each: indoor activities would typically include sleeping and resting, for example, while outdoor activities would not. For this reason, breathing rates for each context have been assigned based on the range of activities that would occur in each context, and the reported average values for the corresponding activity levels.

The summaries in the Handbook were used to evaluate the five "key" studies for the purpose of defining breathing rates for the average member of the screening group. Each of these five studies, and the resulting breathing rates that reflect the screening group, are summarized below.

Layton (1993) presents a method for estimating breathing rate based on metabolic information:

$$V_E = E \times H \times VQ \qquad (6.39)$$

where:

V_E = the ventilation rate
E = the energy expenditure rate
H = the volume of oxygen consumed in the production of 1 KJ of energy, and
VQ = the ratio of intake volume to oxygen uptake

Three approaches are used to estimate the energy expenditure rate: annual caloric intake (corrected for reporting bias), elevation above basal metabolic rate (BMR) with BMR values estimated from body weight using a fitted regression model, and elevations above BMR using activity-specific elevation factors and time allocation data. These methods are used to estimate average inhalation rates over various population subsets defined by age and gender. This study draws from comparatively large data sets, and provides information on the relative contributions of the diverse factors influencing inhalation rate, including general health, body weight, diet, activity level, age, and gender. The first two methods provide estimates of long-term average breathing rate, which is not specific to the residential exposure contexts. The third method provide estimates of breathing rate for different levels of activity. Average inhalation rates for adult males for five activity levels, estimated by the third method, are summarized in Table 6.22. Estimates for two sets of activity classifications are reported. For each set, activity level is characterized by a qualitative description as well as by a BMR value or range. Different sets of BMR values were used for each activity classification.

Linn et al. (1992) estimates inhalation rates for "high-risk" sub-populations, including outdoor workers, elementary school students, high school students, asthmatic adults, young asthmatics, and construction workers. Of these sub-populations, outdoor workers and construction workers approximate the screening group. The average breathing rate for healthy adult outdoor workers, consisting of 15 women and five men between the ages of 19 and 50, is reported as 0.78; construction workers, consisting of seven men between the ages of 26 and 34 have an average breathing rate of 1.50 m^3/hr. Activity-dependent breathing rates are also reported for both subject groups at three activity levels, as shown in Table 6.23.

Linn et al. (1993) reports breathing rates for 19 construction workers who perform heavy outdoor labor both before and during a typical work shift. The subjects of this study approximate the screening group, although the number of subjects is small. A regression model relating breathing rate to heart rate was developed from data collected in a controlled laboratory protocol. Occupational breathing rates were estimated from measured heart rates using this regression model. Average breathing rates are reported for three self-estimated activity levels, as shown in Table 6.24.

Table 6.22 Estimated breathing rates for males from Layton (1993) for two sets of five activity levels (m^3/hr)

Inhalation rates for short-term exposures[1]					
Age (years)	Activity level				
	Rest BMR: 1	Sedentary BMR:1.2	Light BMR: 1.5 -2.5	Moderate BMR: 3 - 5	Heavy BMR: >5 - 20
18 - < 30	0.43	0.52	0.84	1.74	4.32
30 - < 60	0.42	0.50	0.84	1.68	4.20
Activity-Dependent Inhalation Rates used to Estimate Daily Inhalation Rate[2]					
Age (years)	Activity level				
	Sleep BMR: 1	Light BMR: 1.5	Moderate BMR: 4	Hard BMR: 6	Very Hard BMR: 10
20-34	0.4	0.7	1.7	2.6	4.3
35-49	0.4	0.6	1.7	2.5	4.2
50-64	0.4	0.6	1.7	2.5	4.2

[1] Source: EPA (1996) Table 5-5
[2] Source: EPA (1996) Table 5-6

Table 6.23 Estimated breathing rates from Linn et al. (1992) for two panels of healthy adult subjects[1] (m^3/hr)

Subject group	Mean self-estimated breathing rates		
	Slow	Medium	Fast
Outdoor workers	0.72	1.02	3.06
Construction workers	1.26	1.50	1.68

[1] Source: EPA (1996) Table 5-7

Table 6.24 Estimated breathing rates from Linn et al. (1993) for outdoor workers[1] (m^3/hr)

Mean self-estimated breathing rates		
Slow	Medium	Fast
1.44	1.86	2.04

[1] Source: EPA (1996) Table 5-9

Spier et al. (1992) reports breathing rates for elementary and high-school students. Although considered a key study in the Handbook, this sub-population does not correspond to the screening group for the residential scenario. Results of this study were not used to establish values for the screening group.

The California Air Resources Board (CARB) (1993) reports breathing rates in routine daily activities for children and adults at various activity level classifications. The study included a laboratory protocol, in which ventilation rate, heart rate, breathing frequency, and oxygen consumption were measured during treadmill tests. Heart rate, ventilation rate, and breathing frequency were also measured during a "field" protocol, which included (for adult males) driving and riding in cars, yard work, and mowing. Average breathing rates during the laboratory protocol are reported for five activity classifications. Average values during the field protocol are reported for three activity classifications. Table 6.25 summarizes the reported values for adult males.

The six studies classified as "Relevant" provide supporting information, such as assessments of the quality of individual's subjective judgments of their breathing rate and activity level. These studies were not judged to provide information directly related to estimating breathing rates for the screening group. Three literature surveys are also classified as "Relevant." The U.S. EPA (1985) provides a summary of inhalation rates by age, gender, and activity level. This study compiles results of earlier investigations, and does not present information on the accuracy and methods used in these investigations. Reported breathing rates range from 0.7 to 4.8 m^3/hr for adult males depending on activity level. The ICRP (1981) presents ventilation estimates for reference adult males and females at two activity levels ("Resting" and "Light Activity") as well as daily inhalation rates based on an assumed activity pattern during the day. For adult males, the respective rates are given as 0.45 m^3/hr, 1.2 m^3/hr, and 22.8 m^3/day. (The default values for V_r, V_x, and V_g defined in Volume 1 of NUREG/CR-5512 were based on the "Light Activity" breathing

Table 6.25 Average inhalation rates for adult males from CARB (1993) (m^3/hr)

	Activity level				
	Resting	**Sedentary**	**Light**	**Moderate**	**Heavy**
Laboratory protocols[1]	0.54	0.60	1.45	1.93	3.63
Field protocols[2]		0.62	1.40	1.78	

[1] Source: EPA (1996) Table 5-13
[2] Source: EPA (1996) Table 5-14

rate for males from this study.) This study was not considered a sufficient basis for defining default values for these parameters because of the availability of more recent empirical data in four of the five key studies discussed above. The AIHC (1994) Exposure Factors Sourcebook recommends an average adult inhalation rate of 18 m^3/day based on data presented in other studies. This report draws from information presented elsewhere, does not present new data on breathing rate, and may not be representative of the screening group.

6.3.4 Average Breathing Rates for the Residential Scenario Contexts

For the indoor, outdoor, and gardening contexts defined for the residential scenario, breathing rates of the average member of the screening group were estimated from the average breathing rates for adults discussed in Section 6.3.3. Where separate estimates are provided for males and females, estimates for males were adopted as being more representative of the screening group.

Each context was first characterized by the range of activity levels for the activities that would typically occur in each. Indoor activities include sleeping, reading, watching television, kitchen work and housework, and repair and maintenance. Such activities correspond to the "Resting," "Sedentary," "Light," and "Moderate" level classifications used by Layton (1993) and CARB (1993). Outdoor activities include yard work, recreation, and car and equipment repair and maintenance. Typical outdoor activities were therefore assumed to correspond to the "Sedentary," "Light," and "Moderate" categories of Layton (1993) and CARB (1993), and to the "Slow" and "Medium" subjective breathing rate classifications used in Linn's studies of outdoor workers.

Gardening activities include soil preparation, planting, weeding, hoeing, and harvesting. These activities are assumed to correspond to the "Light," "Moderate," "Heavy," "Hard," and "Very Hard" levels adopted by Layton (1993) and by CARB (1993), and to lead to breathing rates subjectively classified as "Medium" or "Fast" by Linn's subjects.

For the outdoor and gardening contexts, the reported average breathing rates for the activity levels typical of each context were identified. (For each of the two sets of values reported by Layton (1993), the median breathing rate over the individual age groups was selected as typical of adult males.) Table 6.26 lists the reported breathing rate values for activity levels expected to occur outdoors, while Table 6.27 lists breathing rate values for activity levels expected to occur while gardening. For both the outdoor and gardening contexts, estimated breathing rates cover a range of values due to differences among the studies, and to differences in activity levels conducted in these contexts. An estimate of overall average breathing rate would require information on time allocation among these activity levels. Because detailed time allocation information is not available, the median reported value was selected to characterize each context: 1.4 m^3/hr for outdoor activities, and 1.7 m^3/hr for gardening activities.

As in the outdoor and gardening contexts, detailed time allocation information is not available for the variety of activities that might be conducted indoors. Time spent sleeping, however, is estimated in a number of activity surveys. Because a significant portion of indoor time is spent sleeping, and because of the low breathing rates characteristic of sleep, the average indoor breathing rate estimate distinguishes between the time spent sleeping and the time spent conducting other activities indoors:

$$V_r = \frac{T_S V_S + T_A V_A}{T_S + T_A} \qquad (6.40)$$

where T_S and T_A are the average time spent sleeping and awake indoors, and V_S and V_A are the average breathing rates while asleep and awake indoors.

Estimates for T_S and T_A are available from the National Human Activity Pattern Survey (NHAPS) (Tsang and Klepeis, 1996) (see Section 6.2.3 for a discussion of time allocation studies). The EPA Exposure Factors Handbook describes Tsang and Klepeis (1996) as "the largest and most current human activity pattern survey available" (EPA, 1996). Over 9000 respondents provided minute-by-minute 24-hour diaries between

Table 6.26 Reported average breathing rates corresponding to activity levels typical of outdoor activities (excluding gardening)

Breathing rate (m^3/h)	Reference study and activity level
0.5	Layton (1993), Set 1: Median of "Sedentary" values over adult age groups
0.6	Layton (1993), Set 2: Median of "Light" values over adult age groups
0.6	CARB (1993): "Sedentary" value from laboratory protocol
0.6	CARB (1993): "Sedentary" value from field protocol
0.7	Linn et al. (1992): "Slow" value for outdoor workers
0.8	Layton (1993), Set 1: Median of "Light" values over adult age groups
1.0	Linn et al. (1992): "Medium" value for outdoor workers
1.3	Linn et al. (1992): "Slow" value for construction workers
1.4	CARB (1993): "Light" value from field protocol
1.4	Linn et al. (1993): "Slow" value for outdoor workers
1.4	CARB (1993): "Light" value from laboratory protocol
1.5	Linn et al. (1992): "Medium" value for construction workers
1.7	Layton (1993), Set 1: Median of "Moderate" values over adult age groups
1.7	Layton (1993), Set 2: Median of "Moderate" values over adult age groups
1.8	CARB (1993): "Moderate" value from field protocol
1.9	Linn et al. (1993): "Medium" value for outdoor workers
1.9	CARB (1993): "Moderate" value from laboratory protocol

Table 6.27 Reported average breathing rates corresponding to activity levels typical of gardening activities

Breathing rate (m^3/h)	Reference study and activity level
0.6	Layton (1993), Set 2: Median of "Light" values over adult age groups
0.8	Layton (1993), Set 1: Median of "Light" values over adult age groups
1.0	Linn et al. (1992): "Medium" value for outdoor workers
1.4	CARB (1993): "Light" value from field protocol
1.4	CARB (1993): "Light" value from laboratory protocol
1.5	Linn et al. (1992): "Medium" value for construction workers
1.7	Linn et al. (1992): "Fast" value for construction workers
1.7	Layton (1993), Set 1: Median of "Moderate" values over adult age groups
1.7	Layton (1993), Set 2: Median of "Moderate" values over adult age groups
1.8	CARB (1993): "Moderate" value from field protocol
1.9	Linn et al. (1993): "Medium" value for outdoor workers
1.9	CARB (1993): "Moderate" value from laboratory protocol
2.0	Linn et al. (1993): "Fast" value for outdoor workers
2.5	Layton (1993), Set 2: Median of "Hard" values over adult age groups
3.1	Linn et al. (1992): "Fast" value for outdoor workers
3.6	CARB (1993): "Heavy" value from laboratory protocol
4.3	Layton (1993), Set 2: Median of "Very Hard" values over adult age groups
4.3	Layton (1993), Set 1: Median of "Heavy" values over adult age groups

October 1992 and September 1994, and the responses weighted to produce results representative of the U.S. population. Average time allocation values, as well as detailed distributional information, is provided for a number of cohorts defined by age, race, gender, and other factors, however average values for adult males are not reported. The average time spent sleeping and napping by males of all ages is 523 minutes/day, while females spend an average of 529 minutes/day sleeping and napping. Adults of either gender between the ages of 18 and 64 spend an average of 497 minutes/day sleeping and napping. Because time spent sleeping depends on age more strongly than gender, a T_S value of 497 minutes/day was assumed for the screening group. The total time spent indoors ($T_S + T_A$) by the average member of the screening group is 240 24-hour days/year, or 946 minutes/day (see Section 6.2.3).

The breathing rate while sleeping, V_S, was estimated as the median of the values reported in Layton (1993) and from the CARB (1993) laboratory protocols, 0.4 m^3/hr. Table 6.28 lists the reported breathing rate values for activity levels expected to occur while awake indoors. V_A was estimated as the median of these values, 1.4 m^3/hr. The average indoor breathing rate was then calculated from Equation 6.40:

$$V_r = \frac{497 \text{ min/day } 0.4 \text{ m}^3\text{/hr} + 449 \text{ min/day } 1.4 \text{ m}^3\text{/hr}}{946 \text{ min/day}} = 0.9 \text{ m}^3\text{/hr} \quad (6.41)$$

Table 6.29 summarizes the default breathing rate values for the three residential scenario exposure contexts. For comparison with breathing rate values recommended for other applications, the average long-term on-site breathing rate was also calculated using the average time spent in each context (see Section 6.2.3). The resulting long-term breathing rate of 23 m^3/day is the same as that recommended for adult males in ICRP (1981), but larger than the adult male breathing rate of 21.4 m^3/day based on EPA (1985) (see EPA (1996) Table 5-20), and the more recent estimate from Layton (1993) of 17 m^3/day.

6.4 Physical Parameters

6.4.1 Physical Parameters with Constant Values

Physical parameters that do not have significant variability were held constant at a represented value. Table 6.30 lists the physical parameters that were held constant and the value used in the parameter analysis. The constant values were the values defined in Volume 1, in most cases. Additional information was reviewed to determine the variability in the fraction of carbon in plants and animals. Although the data indicate little variability in these parameters, the average values are slightly different than the initial default values. These data are presented in Sections 6.4.1.1 and 6.4.1.2. The plant concentration factors for the noble gases (BjAr, BjKr, BjRn & BjXe) and tritium (BjH) are set to zero because the gases are assumed not to accumulate in plant tissue and tritium is modeled separately. The outdoor shielding factor (SFO) is set to 1 because this scenario is evaluating surface soil contamination.

The potential variability in the animal product transfer factors FA, the fish bioaccumulation factors BA, and mass loading factors MLV, MLF, MLG, and MLH was not assessed. The values defined for these factors in Volume 1 were used in this analysis. The constant values assigned to the mass loading factors appear to represent the upper end of a broad range of potential values.

6.4.1.1 Fraction of Carbon in Forage (f_{Cf}), Stored Grain (f_{Cg}), and Stored Hay (f_{Ch})

These parameters define the mass fraction of elemental carbon in forage, stored grain and stored hay for livestock and is used in the agricultural pathway model in the residential scenario for calculating the dose from ^{14}C. The dose model assumes that the specific activity of ^{14}C in the animal product that is consumed by a human is equal to the specific activity of ^{14}C in the food the animal consumes.

This section begins with brief discussions of the importance of f_{Cf}, f_{Cg} and f_{Ch} with regard to the calculated dose and how f_{Cf}, f_{Cg} and f_{Ch} are specifically used in the dose model. Next the default values used for f_{Cf}, f_{Cg} and f_{Ch} in NUREG/CR-5512, Vol. 1, are discussed. Lastly, distributions for f_{Cf}, f_{Cg} and f_{Ch} are presented and values are proposed based on these distributions.

The fraction of carbon in animal feed is important in estimating the dose from ^{14}C. The higher the value f_{Cf}, f_{Cg} and f_{Ch} the higher the total annual dose in the residential scenario.

The default values for f_{Cf}, f_{Cg} and f_{Ch} defined in NUREG/CR-5512, Vol. 1, are all 0.09.

Table 6.28 Reported average breathing rates corresponding to activity levels typical of waking indoor activities

Breathing rate (m^3/h)	Reference study and activity level
0.5	Layton (1993), Set 1: Median of "Sedentary" values over adult age groups
0.6	Layton (1993), Set 2: Median of "Light" values over adult age groups
0.6	CARB (1993): "Sedentary" value from laboratory protocol
0.6	CARB (1993): "Sedentary" value from field protocol
0.8	Layton (1993), Set 1: Median of "Light" values over adult age groups
1.4	CARB (1993): "Light" value from field protocol
1.4	CARB (1993): "Light" value from laboratory protocol
1.7	Layton (1993), Set 1: Median of "Moderate" values over adult age groups
1.7	Layton (1993), Set 2: Median of "Moderate" values over adult age groups
1.8	CARB (1993): "Moderate" value from field protocol
1.9	CARB (1993): "Moderate" value from laboratory protocol

Table 6.29 Default breathing rates for the residential scenario

Exposure context /parameter	Breathing rate (m^3/hr)	Time spent in context[1] (days/year)
Indoors - V_r	0.9	240
Outdoors - V_x	1.4	40.2
Gardening - V_g	1.7	2.92
Average on-site rate[2]	23 m^3/day	

[1] See Section 6.2.7
[2] Weighted by time spent in each context

Table 6.30 Constant physical parameters

Part 1

Parameters	Description	Units	Value
BjAr,H,Kr,Rn, Xe	Concentration factors for leafy, root, fruit, grain	-	0
fca(1)	Carbon fraction for beef cattle	-	0.36
fca(2)	Carbon fraction for poultry	-	0.18
fca(3)	Carbon fraction for milk cows	-	0.06
fca(4)	Carbon fraction for layer hens	-	0.16
fcd05	Fraction of carbon in soil	-	0.03
fcf(a)	Carbon fraction for all forage	-	0.11
fcg(a)	Carbon fraction for all grain consumed by animals	-	0.4
fch(a)	Carbon fraction for all hay	-	0.07
fha(1)	Hydrogen fraction for beef cattle	-	0.1
fha(2)	Hydrogen fraction for poultry	-	0.1
fha(3)	Hydrogen fraction for milk cows	-	0.11
fha(4)	Hydrogen fraction for layer hens	-	0.11
fhd016	Fraction of hydrogen in soil	-	0.011

Table 6.30 Constant physical parameters (continued)

Part 1			
Parameters	**Description**	**Units**	**Value**
fhf	Hydrogen fraction for forage	-	0.1
fhg, fhv(4)	Hydrogen fraction for all grain	-	0.068
fhh	Hydrogen fraction for hay	-	0.1
fhv (1-3)	Hydrogen fraction for fruits and vegetables	-	0.1
KdH,Xe, Ke, Ar, Rn	Partition coefficients for H, Xe, Ke, Ar, Rn	mL/g	0
Hl	Thickness of surface-soil layer	m	0.15
LAMBDW	Weathering rate for activity removal from plants	1/d	4.95E-02
MLF,MLG, MLH, MLV	Mass-loading factors for forage, grain, hay, fruit, and vegetables	g/g	0.1
QD(1)	Soil intake fraction for beef cattle	-	0.02
QD(2)	Soil intake fraction for poultry	-	0.1
QD(3)	Soil intake fraction for milk cows	-	0.02
QD(4)	Soil intake fraction for layer hens	-	0.1
QH(2)	Ingestion rate for poultry hay	kg/d	0
QH(4)	Ingestion rate for layer hen hay	kg/d	0
QW(1)	Water ingestion rate for beef cattle	L/d	50
QW(2)	Water ingestion rate for poultry	L/d	0.3
QW(3)	Water ingestion rate for milk cows	L/d	60
QW(4)	Water ingestion rate for layer hens	L/d	0.3
sasvh	Tritium equivalence: plant/soil	-	1
satac	Specific activity equivalence for livestock	-	1
satah	Tritium equivalence: animal product/intake	-	1
sawvh	Tritium equivalence: plant/water	-	1
SFO	Outdoor Shielding Factor	-	1
sh	Absolute humidity, H*	L/m^3	0.008
TF	Translocation factor for forage	-	1
TFF, TFG, TFH	Feeding period for all animals, forage, grain & hay	d	365.25
TFW	Water ingestion period for all animals	d	365.25
TG	Translocation factor for all animals grain	-	0.1
TGF	Minimum growing period for forage	d	30
TGG	Minimum growing period for stored grain	d	90
TGH	Minimum growing period for stored hay	d	45
TGV(1)	Minimum growing period for leafy vegetables	d	45
TGV(2)	Minimum growing period for other vegetables	d	90
TGV(3)	Minimum growing period for fruits	d	90
TGV(4)	Minimum growing period for grains	d	90
TH	Translocation factor for hay	-	1
THA(4)	Holdup period for eggs	d	1
TV(1)	Translocation factor for leafy vegetables	-	1
TV(2)	Translocation factor for other vegetables	-	0.1
TV(3)	Translocation factor for fruits	-	0.1
TV(4)	Translocation factor for grains	-	0.1
VSW	Volume of water in surface-water pond	L	1.30E+06
WG(1), WV(4)	Wet/dry conversion factor for grain	-	0.88

Table 6.30 Constant physical parameters (continued)

Part 2 - Animal product transfer factors (Faj) , wet-eight basis (from Volume 1, Table 6.18)				
Element	**Beef (d/kg)**	**Poultry (d/kg)**	**Milk (d/L)**	**Eggs (d/kg)**
H	(-)	(-)	(-)	(-)
Be	1.00E-03	4.00E-01	9.00E-07	2.00E-02
C	(-)	(-)	(-)	(-)
N	7.50E-02	1.00E-01	2.50E-02	8.00E-01
F	1.50E-01	1.00E-02	1.00E-03	2.00E+00
Na	5.50E-02	1.00E-02	3.50E-02	2.00E-01
Mg	5.00E-03	3.00E-02	4.00E-03	1.60E+00
Si	4.00E-05	2.00E-01	2.00E-05	8.00E-01
P	5.50E-02	1.90E-01	1.50E-02	1.00E+01
S	1.00E-01	9.00E-01	1.50E-02	7.00E+00
Cl	8.00E-02	3.00E-02	1.50E-02	2.00E+00
Ar	(-)	(-)	(-)	(-)
K	2.00E-02	4.00E-01	7.00E-03	7.00E-01
Ca	7.00E-04	4.40E-02	1.00E-02	4.40E-01
Sc	1.50E-02	4.00E-03	5.00E-06	3.00E-03
Cr	5.50E-03	2.00E-01	1.50E-03	8.00E-01
Mn	4.00E-04	5.00E-02	3.50E-04	6.50E-02
Fe	2.00E-02	1.50E+00	2.50E-04	1.30E+00
Co	2.00E-02	5.00E-01	2.00E-03	1.00E-01
Ni	6.00E-03	1.00E-03	1.00E-03	1.00E-01
Cu	1.00E-02	5.10E-01	1.50E-03	4.90E-01
Zn	1.00E-01	6.50E+00	1.00E-02	2.60E+00
Ga	5.00E-04	3.00E-01	5.00E-05	8.00E-01
As	2.00E-03	8.30E-01	6.00E-05	8.00E-01
Se	1.50E-02	8.50E+00	4.00E-03	9.30E+00
Br	2.50E-02	4.00E-03	2.00E-02	1.60E+00
Kr	(-)	(-)	(-)	(-)
Rb	1.50E-02	2.00E+00	1.00E-02	3.00E+00
Sr	3.00E-04	3.50E-02	1.50E-03	3.00E-01
Y	3.00E-04	1.00E-02	2.00E-05	2.00E-03
Zr	5.50E-03	6.40E-05	3.00E-05	1.90E-04
Nb	2.50E-01	3.10E-04	2.00E-02	1.30E-03
Mo	6.00E-03	1.90E-01	1.50E-03	7.80E-01
Tc	8.50E-03	3.00E-02	1.00E-02	3.00E+00
Ru	2.00E-03	7.00E-03	6.00E-07	6.00E-03
Rh	2.00E-03	5.00E-01	1.00E-02	1.00E-01
Pd	4.00E-03	3.00E-04	1.00E-02	4.00E-03
Ag	3.00E-03	5.00E-01	2.00E-02	5.00E-01
Cd	5.50E-04	8.40E-01	1.00E-03	1.00E-01
In	8.00E-03	3.00E-01	1.00E-04	8.00E-01
Sn	8.00E-02	2.00E-01	1.00E-03	8.00E-01
Sb	1.00E-03	6.00E-03	1.00E-04	7.00E-02
Te	1.50E-02	8.50E-02	2.00E-04	5.20E+00

Table 6.30 Constant physical parameters (continued)

Part 2 - Animal product transfer factors (Faj) , wet-eight basis (from Volume 1, Table 6.18)				
Element	**Beef (d/kg)**	**Poultry (d/kg)**	**Milk (d/L)**	**Eggs (d/kg)**
I	7.00E-03	1.80E-02	1.00E-02	2.80E+00
Xe	(-)	(-)	(-)	(-)
Cs	2.00E-02	4.40E+00	7.00E-03	4.90E-01
Ba	1.50E-04	8.10E-04	3.50E-04	1.50E+00
La	3.00E-04	1.00E-01	2.00E-05	9.00E-03
Ce	7.50E-04	1.00E-02	2.00E-05	5.00E-03
Pr	3.00E-04	3.00E-02	2.00E-05	5.00E-03
Nd	3.00E-04	4.00E-03	2.00E-05	2.00E-04
Pm	5.00E-03	2.00E-03	2.00E-05	2.00E-02
Sm	5.00E-03	4.00E-03	2.00E-05	7.00E-03
Eu	5.00E-03	4.00E-03	2.00E-05	7.00E-03
Gd	3.50E-03	4.00E-03	2.00E-05	7.00E-03
Tb	4.50E-03	4.00E-03	2.00E-05	7.00E-03
Dy	5.50E-03	4.00E-03	2.00E-05	7.00E-03
Ho	4.50E-03	4.00E-03	2.00E-05	7.00E-03
Er	4.00E-03	4.00E-03	2.00E-05	7.00E-03
Hf	1.00E-03	6.00E-05	5.00E-06	2.00E-04
Ta	6.00E-04	3.00E-04	3.00E-06	1.00E-03
W	4.50E-02	2.00E-01	3.00E-04	8.00E-01
Re	8.00E-03	4.00E-02	1.50E-03	4.00E-01
Os	4.00E-01	1.00E-01	5.00E-03	9.00E-02
Ir	1.50E-03	5.00E-01	2.00E-06	1.00E-01
Au	8.00E-03	5.00E-01	5.50E-06	5.00E-01
Hg	2.50E-01	1.10E-02	4.50E-04	2.00E-01
Tl	4.00E-02	3.00E-01	2.00E-03	8.00E-01
Pb	3.00E-04	2.00E-01	2.50E-04	8.00E-01
Bi	4.00E-04	1.00E-01	5.00E-04	8.00E-01
Po	3.00E-04	9.00E-01	3.50E-04	7.00E+00
Rn	(-)	(-)	(-)	(-)
Ra	2.50E-04	3.00E-02	4.50E-04	2.00E-05
Ac	2.50E-05	4.00E-03	2.00E-05	2.00E-03
Th	6.00E-06	4.00E-03	5.00E-06	2.00E-03
Pa	1.00E-05	4.00E-03	5.00E-06	2.00E-03
U	2.00E-04	1.20E+00	6.00E-04	9.90E-01
Np	5.50E-05	4.00E-03	5.00E-06	2.00E-03
Pu	5.00E-07	1.50E-04	1.00E-07	8.00E-03
Am	3.50E-06	2.00E-04	4.00E-07	9.00E-03
Cm	3.50E-06	4.00E-03	2.00E-05	2.00E-03
Cf	5.00E-03	4.00E-03	7.50E-07	2.00E-03

Table 6.30 Constant physical parameters (continued)

Part 3 - Fish bioaccumulation factors (Ba_{jf}) (from Volume 1, Table 6.19)			
Element	**Bioaccumulation factor (pCi/kg wet-weight per pCi/L)**	**Element**	**Bioaccumulation factor (pCi/kg wet-weight per pCi/L)**
H	1.00E+00	Sb	2.00E+02
Be	2.00E+00	Te	4.00E+02
C	4.60E+03	I	5.00E+02
N	1.50E+05	Xe	0.00E+00
F	1.00E+01	Cs	2.00E+03
Na	1.00E+02	Ba	2.00E+02
P	7.00E+04	La	2.50E+01
S	7.50E+02	Ce	5.00E+02
Cl	5.00E+01	Pr	2.50E+01
K	1.00E+03	Nd	2.50E+01
Ca	4.00E+01	Pm	2.50E+01
Sc	1.00E+02	Sm	2.50E+01
Cr	2.00E+02	Eu	2.50E+01
Mn	4.00E+02	Gd	2.50E+01
Fe	2.00E+03	Tb	2.50E+01
Co	3.30E+02	Ho	2.50E+01
Ni	1.00E+02	W	1.20E+03
Cu	5.00E+01	Re	1.20E+02
Zn	2.50E+03	Os	1.00E+01
As	1.00E+02	Ir	1.00E+01
Se	1.70E+02	Au	3.30E+01
Br	4.20E+02	Hg	1.00E+03
Rb	2.00E+03	Pb	1.00E+02
Sr	5.00E+01	Bi	1.50E+01
Y	2.50E+01	Po	5.00E+02
Zr	2.00E+02	Rn	0.00E+00
Nb	2.00E+02	Ra	7.00E+01
Mo	1.00E+01	Ac	2.50E+01
Tc	1.50E+01	Th	1.00E+02
Ru	1.00E+02	Pa	1.10E+01
Rh	1.00E+01	U	5.00E+01
Pd	1.00E+01	Np	2.50E+02
Ag	2.30E+00	Pu	2.50E+02
Cd	2.00E+02	Am	2.50E+02
In	1.00E+05	Cm	2.50E+02
Sn	3.00E+03	Cf	2.50E+01

Additional information was reviewed to define the variability in f_{Cf}, f_{Cg} and f_{Ch}. The major sources of carbon in foods are proteins, lipids, and carbohydrates (Lehninger, 1970). Therefore, the fraction of carbon in forage, stored grain or stored hay can be determined based on the protein, lipid, and carbohydrate contents of the forage, stored grain or stored hay and the fraction of carbon in proteins, lipids, and carbohydrates. The mathematical expression is given by:

$$f_{Cx} = f_{Px}(f_{Cp}) + f_{Lx}(f_{Cl}) + f_{Cx}(f_{Cc}) \quad (6.42)$$

where:

f_{Px}, f_{Lx}, and f_{Cx} are the fraction of proteins, lipids and carbohydrates in the forage (x=f), stored grain (x=g) or stored hay (x=h), and f_{Cp}, f_{Cl} and f_{Cc} are the fraction of carbon in proteins, lipids and carbohydrates.

Equation 6.42 is based only on the major sources of carbon in livestock feed and neglects minor carbon-containing components such as vitamins and nucleic acids.

6.4.1.1.1 Fraction of Carbon in Proteins, Lipids and Carbohydrates

Protein is a polyamino acid with a molecular weight range of 6,000 to 40,000,000 and consists of 50 to 340,000 amino acid monomer units. Proteins contain approximately 50% carbon, 7% hydrogen, 23% oxygen, 16% nitrogen, and from 0 to 3% sulfur (Lehninger, 1970).

Lipids are esters of aliphatic acids and are composed of a hydrocarbon chain with a terminal carboxyl group linked to a acylglycerol moiety. The carbon composition of lipids varies slightly with the hydrocarbon chain length (14 to 24 carbon atoms in the fatty acid moiety) and the degree of saturation. Lipids contain approximately 76% carbon (Lehninger, 1970).

With the exception of milk, carbohydrates make up a very small portion of the total components in animal products. Carbohydrates consist of carbon, hydrogen, and oxygen in the approximate CHO ratio of 1:2:1 and vary slightly in carbon content from 40% (simple sugars) to about 45% (storage and structural polysaccharides) (Lehninger, 1970).

6.4.1.1.2 Nutrient Composition of Forage, Stored Grain, and Stored Hay

Tables 6.31, 6.32, and 6.33 list common forage crops, stored grain crops, and stored hay crops for livestock and the quantities of protein, lipids, and fibers in each. Fibers include structural polysaccharides and other carbohydrates. These three major components in the crops are readily digestible by livestock. There are, however, minor components of non-digestible proteins and fibers present in plant material (NRC, 1985).

The largest variability in the carbon fraction parameters is due to the variety in the types of forage, stored grain, and stored hay crops that livestock may eat. To account for this variability it is assumed that each type of potential feed is equally likely to be fed to livestock. Therefore, a uniform distribution representing each type was sampled to obtain the specific crop being consumed by the livestock. Given the specific feed type, the amount of nutrients can be determined from Tables 6.31, 6.32, and 6.33, combined with the specific fraction of carbon in the nutrients reported by Lehninger (1970) to calculate the mass fraction of carbon, using Equation 6.42.

Table 6.31 Composition of fresh forage crops (NAP, 1996)

Forage crop	Protein (%)	Lipids (%)	Fiber (%)
Alfalfa	18.9	3.2	77.9
Bermuda grass	12.6	3.7	83.7
Bluegrass	17.4	3.5	79.1
Broome grass	21.3	4.0	74.7
Canary grass	17.0	4.1	78.9
Clover, ladino	25.8	4.6	69.6
Clover, red	14.6	2.9	82.5
Fescue	15.0	5.5	79.5
Orchard grass	12.8	3.7	83.5
Rye grass	17.9	4.1	78.0
Trefoil	20.6	4.0	75.4
Timothy	12.2	3.8	84.0

Table 6.32 Composition of grain (NAP, 1996)

Grain	Protein (%)	Lipids (%)	Fiber (%)
Barley	13.2	2.2	84.6
Canola	30.7	7.4	61.9
Corn	9.8	4.1	86.1
Oats	13.6	5.2	81.2
Sorghum	12.6	3.0	84.4
Wheat	14.2	2.3	83.5

Table 6.33 Composition of stored hay (NAP, 1996)

Hay crop	Protein (%)	Lipids (%)	Fiber (%)
Alfalfa	18.6	2.4	79.0
Bermuda grass	7.8	2.7	89.5
Broome grass	6.0	2.0	92.0
Canary grass	10.2	3.0	86.8
Clover, ladino	22.4	2.7	74.9
Clover, red	15.0	2.8	82.2
Corn w/cob	2.8	0.6	96.6
Corn silage	8.7	3.1	88.2
Fescue	10.8	4.7	84.5
Orchard grass	12.8	2.9	84.3
Sorghum silage	9.4	2.6	88.0
Wheat grass	8.7	2.2	89.1
Wheat silage	12.5	6.1	81.4
Trefoil	15.9	2.1	82.0
Timothy	10.8	2.8	86.4

The variability in f_{Cf}, f_{Cg} and f_{Ch} is relatively small, as the results in Table 6.34 show. In addition, Table 6.34 presents the default values used in NUREG/CR-5512, Vol. 1, which are consistent with the distributions derived in this section. Given the small variability, the mean values were used for all calculations.

These parameters would not be expected to vary from site to site and it is very unlikely that a licensee would conduct any type of data collection activity to modify them. The one exception may be f_{Cf} because of the different forage crops that grow in different regions throughout the United States. A licensee may attempt to support alternative values for the fraction of carbon in forage based on regional data that supports specific forage crop growth.

6.4.1.2 Fraction of Carbon in Animal Products, f_{Ca}

This parameter defines the mass fraction of elemental carbon in meat (beef and poultry), milk, and eggs and is used in the agricultural pathway model in the residential scenario for calculating the dose from ^{14}C. The fraction of carbon in these animal products is a physical parameter because it is a function of the amount of ^{14}C in the specific animal product being considered.

The fraction of carbon in animal products is important in estimating the dose from ^{14}C. The higher the value for f_{Ca}, the higher the total annual dose in the residential scenario.

The default values for this parameter defined in NUREG/CR-5512, Vol. 1, are: beef cattle, 0.24; poultry, 0.20; milk, 0.07; and eggs, 0.15.

The major sources of carbon in foods are proteins, lipids, and carbohydrates (Lehninger, 1970). Therefore, the fraction of carbon in foods can be determined based on the protein, lipid, and carbohydrate contents of the food and the fraction of carbon in proteins, lipids, and carbohydrates. The mathematical expression is given by:

$$f_{Ca} = f_{Pa}(f_{Cp}) + f_{La}(f_{Cl}) + f_{Ca}(f_{Cc}) \qquad (6.43)$$

where f_{Pa}, f_{La}, and f_{Ca} are the fraction of proteins, lipids and carbohydrates in food type "a," respectively, and f_{Cp}, f_{Cl} and f_{Cc} are the fraction of carbon in proteins, lipids and carbohydrates, respectively.

Equation 6.43 is based only on the major sources of carbon in foods and neglects minor carbon-containing components such as vitamins and nucleic acids.

Table 6.35 lists the nutrient composition of products from beef cattle, poultry, milk cows, and layer hens.

The only uncertainty in the data is in the carbon content of lipids (73–79%) and the carbon content of carbohydrates (40–45%). Because there is no basis for any type of distribution of this uncertainty indicated by Lehninger (1970) these fractions are assumed to be uniformly distributed with the minimum and maximum values equal to the reported range. Using these distributions and Equation 6.43, Table 6.36 presents the data for f_{Ca} for milk, eggs, beef and poultry, along with the default values used in NUREG/CR-5512, Volume 1.

As can be seen in Table 6.36, there is little variability in f_{Ca}. The average value was used in all calculations.

Table 6.34 Data variability for f_{Cf}, f_{Cg} and f_{Ch}

Parameter	Minimum	Maximum	Mean	Standard deviation	NUREG/CR-5512 default
f_{Cf}	0.088	0.14	0.11	0.018	0.09
f_{Cg}	0.39	0.44	0.40	0.016	0.40
f_{Ch}	0.020	0.12	0.07	0.031	0.09

Table 6.35 Composition of animal products (Gebhardt and Matthews, 1985)

Product	Protein	Lipids	Carbohydrates (g)
Milk	3.3%	3.3%	4.5%
Eggs	12%	12%	2.0%
Beef	26%	31%	0
Poultry	31%	3.5%	0

Table 6.36 Data on variability of f_{Ca}

Product	Minimum	Maximum	Mean of the range	Default value from 5512
Milk	0.0606	0.0626	0.06	0.07
Eggs	0.157	0.164	0.16	0.15
Beef	0.353	0.371	0.36	0.24
Poultry	0.182	0.185	0.18	0.20

6.4.2 Thickness of the Unsaturated Zone, H_2 (m)

6.4.2.1 Description of H_2

As defined in Volume 1, H_2 is the thickness of the unsaturated zone for the three-box groundwater model used in the residential scenario. The top box in the three box model represents a 15-cm-thick soil layer. The middle box represents the unsaturated zone, and H_2 is the thickness of this middle box. H_2 is a physical parameter that is a characteristic of the specific site being assessed and is independent of the source term and group of exposed individuals.

6.4.2.2 Use of H_2 in Modeling

The thickness of the unsaturated zone is important to dose because it is the distance radionuclides must travel to get into the saturated zone. Once in the saturated zone, the radionuclides contaminate drinking and irrigation water which results in a dose to man via several different possible pathways. A thick unsaturated zone compared to a thin unsaturated zone would provide a longer distance for radionuclides to be transported. This longer distance translates into a longer travel time and, with radioactive decay occurring, may result in a decrease in the amount of radionuclides reaching the saturated zone. Besides travel distance, the unsaturated zone is characterized by adsorption coefficients, water content, and infiltration rate. These parameters, combined with H_2, provide the basis for estimating the total amount of radioactivity that reaches the saturated zone in a given time.

For NUREG/CR-5512, Vol. 1, dose modeling, the thickness of the unsaturated zone is used in determining radionuclide leach rates from the unsaturated zone to the saturated zone in the three box groundwater model. These leach rates are proportional to the amount of water that infiltrates into the unsaturated zone (infiltration rate) and inversely proportional to the thickness of the unsaturated zone, the volumetric water content of the unsaturated zone, and the radionuclide specific retardation factor (which is derived from adsorption coefficients). The mathematical relation between leach rate and unsaturated zone thickness is given in NUREG/CR-5512, Vol. 1 (p. 4.9), as:

$$L_{2j} = \frac{I}{H_2 \Theta_2 Rt_{2j} 365.25} \qquad (6.44)$$

where:

L_{2j} = Leach rate from the unsaturated zone to the saturated zone for radionuclide j (y^{-1})
I = Infiltration rate (my^{-1})
H_2 = Unsaturated zone thickness (m)
Θ_2 = Volumetric water content of the unsaturated zone (dimension less)
Rt_{2j} = Retardation factor for movement of radionuclide j from the unsaturated zone to the saturated zone (dimension less)

The retardation factor is given in NUREG/CR-5512, Vol. 1 (p. 4.9), as:

$$Rt_{2j} = 1 + \frac{Kd_{2j}\ \rho_2}{n_2} \qquad (6.45)$$

where:

Kd_{2j} = Partition coefficient for the jth radionuclide in the unsaturated zone
ρ_2 = Bulk density of the unsaturated zone
n_2 = Total porosity of the unsaturated zone

6.4.2.3 Information Reviewed to Define a Distribution for H_2

The default value for H_2 defined in NUREG/CR-5512, Vol. 1, is 1 m, which represents a thin unsaturated zone. A thin unsaturated zone was assumed to be conservative because it would result in relatively fast travel times through the unsaturated zone which would allow for more radionuclides to reach the groundwater. However, when contaminant transport is coupled with radioactive decay, it is difficult to define a priori whether or not a thin unsaturated zone is conservative. For example, a short travel time through the unsaturated zone would not allow for ingrowth of a particularly toxic daughter product.

Information concerning depth to the water table is a commonly reported quantity given the large number of observation wells located throughout the United States. For example, in New Mexico, there are 33,000 observation wells where data are regularly collected (USGS, 1990b). However, there is no readily available summary digital database for the continental U.S. A report by the USGS (USGS, 1990b), available on CD-ROM, does present State Water Data Reports from USGS observation wells throughout the continental U.S. This information was extracted from USGS open file reports. Therefore, there are inconsistencies in what data are reported and how they are reported from state to state. In addition, information from the western United States is particularly sparse, especially compared to the dense coverage of the eastern United States. For those areas where data is especially sparse, additional references were used (Idaho Department of Water Resources, 1998; USGS Colorado, 1998, Wyoming Water Resources Center, 1997). The only groundwater region where specific well data could not be found was the Columbia Plateau. However, Guzowski et al. (1981) provide summary water table depth information from this region, which was used to confirm that the resulting distribution included that range. Despite these problems with data availability, the combined data set is believed to be appropriate for representing the variability of unsaturated zone thickness throughout the United States for the screening calculation.

6.4.2.4 Proposed Distribution for H_2

To use the water table depths to generate a probability distribution function of H_2 from the referenced material, a 1.5 degree grid was overlayed onto a map of the continental U.S., which delineates the USGS groundwater regions (Fetter, 1988). The coarseness of the grid is chosen based on approximating the density of grid points per groundwater region to the areal density of the groundwater regions. The areal densities and grid point densities for the groundwater regions are presented in Tables 6.37 and 6.38, respectively.

Table 6.37 USGS groundwater regions areal density

Groundwater region	Area in square kilometers	Percent of total area
Alluvial Basins	1016791.19	13.06
Atlantic and Gulf Coastal Plain	889928.98	11.43
Colorado Plateau and Wyoming Basin	464019.23	5.96
Columbia Lava Plateau	369217.96	4.74
Glaciated Central Region	1253496.30	16.10
High Plains	382559.85	4.92
Nonglaciated Central Region	1859575.84	23.89
Northeast and Superior Uplands	379291.25	4.87
Piedmont and Blue Ridge	230726.81	2.96
Southeast Coastal Plain	194674.84	2.50
Western Mountain Ranges	743214.91	9.55

Table 6.38 USGS groundwater regions gridded sampling point density

Groundwater region	Number of grid points	Percent of total number of points
Alluvial Basins	46	12.81
Atlantic and Gulf Coastal Plain	38	10.58
Colorado Plateau and Wyoming Basin	20	5.57
Columbia Lava Plateau	21	5.85
Glaciated Central Region	61	16.99
High Plains	16	4.46
Nonglaciated Central Region	89	24.79
Northeast and Superior Uplands	17	4.74
Piedmont and Blue Ridge	10	2.79
Southeast Coastal Plain	8	2.23
Western Mountain Ranges	33	9.01

To associate a water table depth with a grid point location, the closest well to the grid point is used to assign a value of the water table depth to the grid point. For the eastern states, wells are typically found within a 20 mile radius of the grid point. West of the Mississippi River, wells are typically found within a 50 mile radius of the grid point. This process is chosen, as opposed to interpolation, in order to be consistent within a groundwater region (i.e., to avoid interpolating across groundwater regions) and because the resulting probability distribution is meant to represent the variability across the United States and not specific values at specific locations. The depth to water assigned to the specific grid point is an average of the highest and lowest water levels reported at the associated well, and therefore, represents the average of long term extremes. Values were not found for every grid point. Instead the search for values continued until a representative number of values was found for each groundwater region, based on the sampling point densities presented in Table 6.38. Figure 6.20 illustrates the 1.5 degree grid, along with the wells that were used to assign value to the nearest grid points. The exception to the data analysis process defined above is for Wyoming, where the data that was obtained was a depth to water two-dimensional surface. Therefore, the values at the surface that corresponded directly to the grid point locations were used.

The resulting data set of H_2 ranged from a minimum of 0.3 m in the High Plains groundwater region (a well in north central Nebraska) to a maximum of 316 m in the Alluvial Basins groundwater region (a well on the south rim of the Grand Canyon), with an average depth to groundwater of 22 m for the continental U.S. Table 6.39 lists the water-level depths at the grid locations. The proposed empirical probability distribution and cumulative probability distribution of unsaturated zone thickness, H_2, are shown in Figures 6.21 and 6.22, respectively. An empirical distribution was chosen due to lack of a basis for choosing a specific distributional form.

6.4.2.5 Parameter Uncertainty

The distribution is based on the assumption that licensed sites are uniformly distributed in space throughout the United States. Instead, sites are expected to be concentrated near population centers; however, the effect of this concentration on the distribution is unclear. Water table depth is also a function of time, responding to seasonally variable recharge rates and pumping rates.

6.4.2.6 Alternative Parameter Values

Information on water table depth is often available from state and city government agencies because this data is important for public water resource management and planning. It is expected that a licensee would easily be able to define a site-specific range or distribution from this information, considering uncertainties created by the 1000 year time-frame considered in the dose assessment.

6.4.3 Hydrologic Parameters: Soil Texture, Porosities (n_1, n_2), Relative Saturation (f_1,f_2), Infiltration (I), Bulk Densities (ρ_1, ρ_2) and Soil Areal Density (Ps)

6.4.3.1 Hydrologic Parameter Descriptions

Several input parameters represent characteristics of the surface soil or the soil of the unsaturated layer. These parameters include porosity and saturation ratio. Rather than sample independently from distributions of these parameters, the dependence of these parameters is represented by first sampling soil texture then selecting an appropriate distribution for porosity and saturation ratio for the sampled texture. Soil densities are tied to the soil texture by a functional relationship to porosity.

A common method of describing and quantifying soil texture is the USDA soil textural classification (Soil Survey Staff, 1997). This classification was used by Meyer and others (1997) to represent the variability of a number of soil hydrologic properties that are related to porosity and saturation ratio. The USDA soil textural classification is also reported in a variety of available electronic data bases for the United States.

Porosity (n) is a measure of the relative pore volume in the soil. It is the ratio of the volume of the voids to the total volume:

$$n = \frac{V_{voids}}{V_{total}} = \frac{V_{air} + V_{water}}{V_{air} + V_{water} + V_{soil}} \qquad (6.46)$$

Soil bulk density (ρ)represents the ratio of the mass of dried soil to its total volume (solids and pores together):

$$\rho = \frac{M_{soil}}{V_{total}} = \frac{M_{soil}}{V_{air} + V_{water} + V_{soil}} \qquad (6.47)$$

It is assumed that for each realization the porosities in the surface soil layer and in the unsaturated layer will be equivalent. The same holds true for the bulk densities. That is:

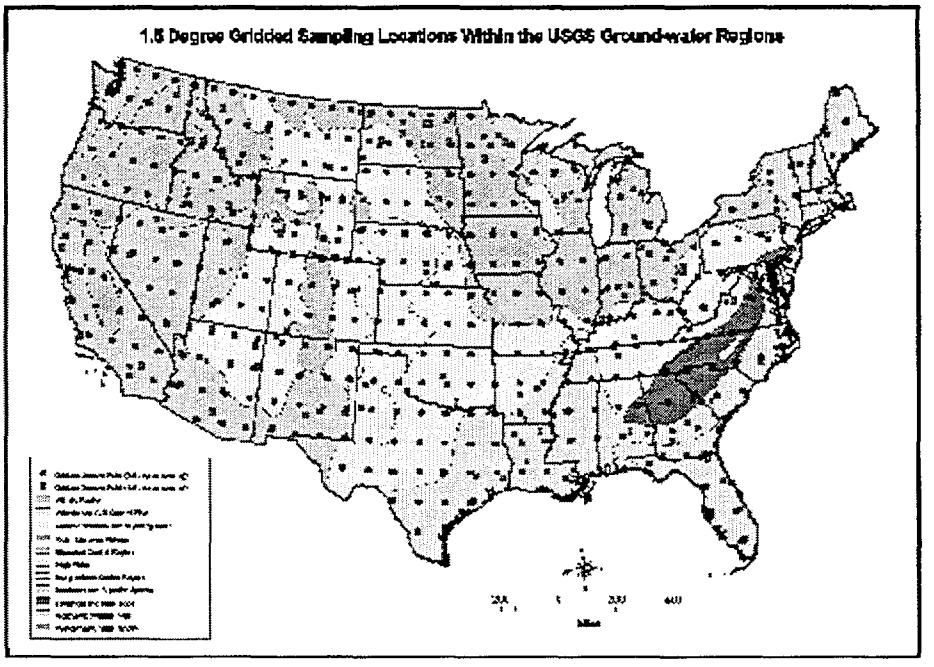

Figure 6.20 Gridded sampling and well locations within the USGS groundwater regions

Table 6.39 Estimated depth-to-water at gridded sampling locations

Observation	Thickness (meters)	Observation	Thickness (meters)	Observation	Thickness (meters)	Observation	Thickness (meters)
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

Table 6.39 Estimated depth-to-water at gridded sampling locations (continued)

Observation	Thickness (meters)	Observation	Thickness (meters)	Observation	Thickness (meters)	Observation	Thickness (meters)
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		

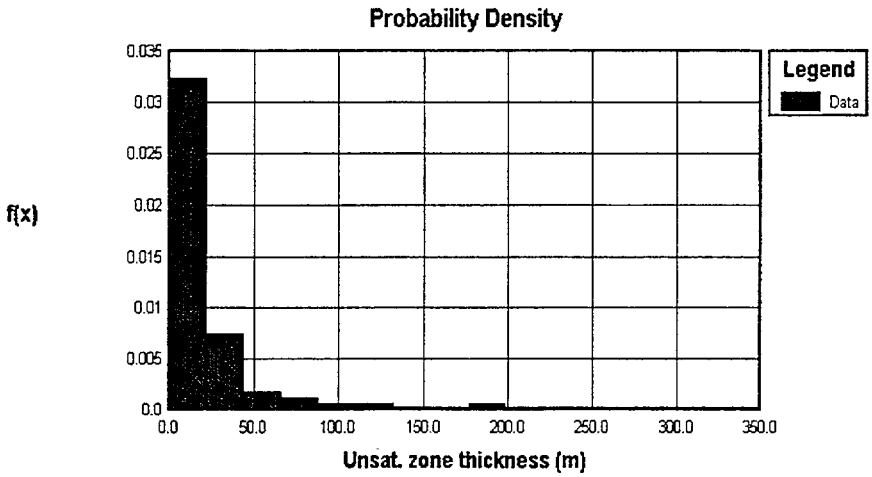

Figure 6.21 Empirical probability distribution for H_2

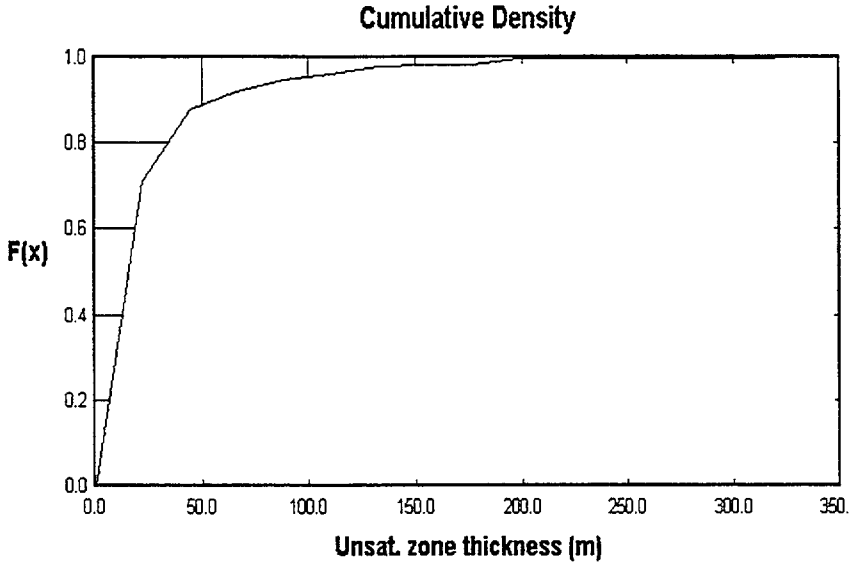

Figure 6.22 Empirical cumulative distribution function for H_2

$$n_1 = n_2 \tag{6.48}$$

$$\rho_1 = \rho_2 \tag{6.49}$$

Soil areal density of the surface plow layer is a measure of the mass of soil per square meter in the surface layer. The depth of this layer is assumed to be 0.15 m in the DandD model.

The infiltration rate is measured as the volume of water per unit area per unit time that percolates deeply beneath the root zone and becomes infiltration. It is the effective rate at which water moves through the surface soil layer and through the unsaturated layer, as well as the rate at which the aquifer receives recharge water. Its units are given as length/time.

The saturation ratio (f) expresses the volume of water relative to the volume of the pore space.

$$f = \frac{V_{water}}{V_{air} + V_{water}} \tag{6.50}$$

It is also a ratio of the moisture content (θ) to the porosity.

$$f = \theta / n \tag{6.51}$$

It is assumed that for each realization the saturation ratios in the surface soil layer and in the unsaturated layer will be equivalent. That is:

$$f_1 = f_2 \tag{6.52}$$

6.4.3.2 Use of the Hydrologic Parameters in Modeling

The hydrologic parameters control the rate at which the contaminant is leached out of each layer and is transported into the next layer. Soil texture is not used directly in the modeling; it is used to determine the active distribution for the directly related parameters; porosity and saturation ratio. The following equation is a generic representation of the leaching model (NUREG/CR 5512, Vol. 1, Equations 4.7–4.12, pp. 4.8–4.9).

$$L_{kj} = \frac{I}{H_k \theta_k Rt_k 365.25} \tag{6.53}$$

Where L is the leach rate for layer k and contaminant j, H is the layer thickness, θ_k is volumetric moisture content, Rt_k is the retardation factor, 365.25 is a time unit conversion factor and I is the infiltration rate (m/y). The retardation coefficient is a function of the partition coefficient (Kd), porosity (n) and bulk density (ρ) and the volumetric moisture content (θ_k) is a function of the sampled relative saturation and the porosity:

$$Rt_k = 1 + \frac{K_{d\rho}}{n} \tag{6.54}$$

$$\theta_R = fn \tag{6.55}$$

The effect of the hydrologic parameters on the dose is uncertain due to uncertainty in the dominant exposure pathway.

6.4.3.3 Information Reviewed to Define the Distribution of Soil Texture

The CONUS-SOIL database created and electronically accessible through Pennsylvania State University (from http://www.essc.psu.edu) is a composite summary of detailed soil databases (STATSGO databases) for states in the continental United States. This CONUS-SOIL database generalizes a variety of soils data, including the USDA soil texture, on a 1 km grid with constant layering. The layering consists of two 5 cm. thick layers near the land surface followed by three 10 cm. layers, three 20 cm. layers and finally three 50 cm. layers.

In general, the total area of each texture class is fairly consistent from layer to layer with the clay content tending to increase slightly with depth. Since the uppermost soil layer in the DandD conceptualization is 15 cm. thick, the three uppermost CONUS-SOIL layers were examined for uniformity and consistency. Approximately 85% of the area covered by materials with USDA classified soil textures is a consistent texture for the three uppermost layers. Table 6.40 summarizes the areal distributions of textures for the three upper layers individually and the volume weighted distribution of textures for the three layers combined.

6.4.3.4 Parameter Distributions

6.4.3.4.1 Soil Texture

The proposed probability distribution for soil texture is related to the volume weighted distribution of soil texture for the first three layers of the CONUS-SOIL database. The probability of encountering a specific soil texture is equal to the percentage of the volume occupied by a this soil texture. For example, the probability of the site having a silt loam soil texture is 24.881%.

Normal distributions of porosities (assumed to be equivalent to saturated water content) are given in Carsel and Parrish (1988). They are reported based on the 12 Soil Conservation Service textural classifications and a compilation of data for each of the textural classes. These distributions are used in the parameter analysis. The means and standard deviations for these normal distributions are given in Table 6.41.

6.4.3.4.2 Soil Bulk Density and Areal Density

Bulk density is functionally related to porosity:

$$\rho = (1-n)\rho_p \tag{6.56}$$

where ρ is the soil bulk density (g/cm^3), n is the porosity, and ρ_p is the particle density (g/cm^3). In most soils the mean particle density is very close to the density of quartz (2.65 g/cm^3), typically the main component of sandy soils. Clay minerals have a similar density. While the presence of heavy minerals such as iron oxides can increase the mean particle density or the presence of organic matter can lower it, as a practical matter mean particle density generally varies between 2.6 and 2.7 g/cm^3 (Hillel, 1980) and can be represented as a constant of 2.65 g/cm^3. With that, the bulk density becomes:

$$\rho = (1-n)\cdot 2.65 \tag{6.57}$$

Table 6.40 CONUS-SOIL texture summary

USDA soil texture	Layer 1 (0–5cm) (% of area)	Layer 2 (5–10cm) (% of area)	Layer 3 (10–20cm) (% of area)	Volume weighted % 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

Table 6.41 Distributions for porosity based on soil texture (after Carsel and Parrish, 1988)

Soil type	Mean	Standard deviation	Number of samples
sand	0.43	0.06	246
loamy sand	0.41	0.09	315
sandy loam	0.41	0.09	1183
sandy clay loam	0.39	0.07	214
loam	0.43	0.10	735
silt loam	0.45	0.08	1093
silt	0.46	0.11	82
clay loam	0.41	0.09	364
silty clay loam	0.43	0.07	641
sandy clay	0.38	0.05	46
silty clay	0.36	0.07	374
clay	0.38	0.09	400

The soil areal density of the surface plow layer, P_s (kg/m^2), is a function of the bulk density (and hence the porosity). Actually, it amounts to nothing more than a conversion of units from the bulk density along with an assumption of a 0.15 m plowing depth. Mass is converted from grams to kilograms. Volume is converted from cubic centimeters to an area (in square meters) times an (implicit) depth of 0.15 meters:

$$P_s = 150 \cdot \rho \tag{6.58}$$

$$P_s = 397.5(1 - n) \tag{6.59}$$

6.4.3.4.3 Infiltration Rate

Infiltration rate is a function of the amount of water applied to the land surface (either by precipitation or irrigation) and the soil hydraulic conductivity which controls the rate at which the soil is able to drain. To determine infiltration rate (I) we assume a model in which the infiltration rate is the product of the application rate (AR) and the fraction of the applied water that will percolate deeply beneath the root zone and become infiltration. (The infiltration fraction is designated as IF.) The infiltration fraction is a function of the saturated hydraulic conductivity (K_{sat}).

$$I = AR \cdot IF(K_{sat}) \tag{6.60}$$

Distributions of saturated hydraulic conductivity are given in Carsel and Parrish (1988). They are reported based on the 12 Soil Conservation Service textural classifications. Carsel and Parrish (1988) fitted distributions from a class of transformed normal distributions. Meyer et al. (1997) refitted the distributions of Carsell and Parrish (1988) to distributional forms that are more commonly used and more easily constructed— either lognormal or beta. The lognormal distribution is completely specified by the mean and standard deviation while the beta distribution is completely specified by mean, standard deviation, and range (upper and lower limits of the distribution). The distribution type and parameters for these distributions for each of the 12 soil types are given in Table 6.42.

The U.S. Bureau of Reclamation (USBR) has developed an empirical relationship between soil permeability and the proportion of water that percolates beneath the root zone (USBR, 1993) (shown in Figure 6.23 and in Table 6.43).

Having now developed a relationship for the propensity of soil to drain based on its ability to transmit water, we now consider water application rates.

Total water application at a particular site must equal or exceed the annual precipitation (assuming negligible runoff). The distribution for precipitation is given in Figure 6.24. This distribution was derived by interpolating a precipitation surface using average precipitation data obtained from weather stations across the conterminous United States (France, 1992; Owenby and Ezell, 1992). In humid regions of the country, precipitation supplies sufficient moisture to grow garden crops. In semi-arid or arid regions however, precipitation alone does not supply sufficient moisture to meet the requirements of garden crops. This water deficit must be met through the application of irrigation water. In determining minimum water requirements, we considered crops grown in arid regions because data are available for irrigation rates and obtaining data for total application of water (irrigation plus precipitation) is more problematic. Under arid conditions, irrigation water alone is sufficient to meet or nearly meet the crop

Table 6.42 Saturated hydraulic conductivity distributions

Soil type	Distribution type	Mean (cm/s)	Standard deviation	Lower limit	Upper limit	Number of samples
sand	beta	8.22E-03	4.49E-03	3.50E-04	1.86E-02	246
loamy sand	beta	3.99E-03	3.17E-03	3.90E-05	1.34E-02	315
sandy loam	lognormal	1.17E-03	1.37E-03			1183
sandy clay loam	lognormal	3.23E-04	5.98E-04			214
loam	lognormal	2.92E-04	4.91E-04			735
silt loam	lognormal	9.33E-05	2.24E-04			1093
silt	lognormal	4.89E-05	2.76E-05			88
clay loam	lognormal	9.93E-05	2.51E-04			345
silty clay loam	lognormal	1.54E-05	3.38E-05			592
sandy clay	lognormal	3.55E-05	1.48E-04			46
silty clay	lognormal	2.19E-06	4.08E-06			126
clay	lognormal	3.65E-05	1.08E-04			114

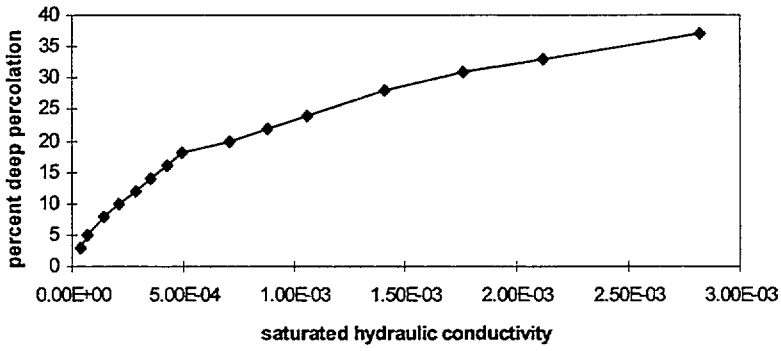

Figure 6.23 Percent percolation as a function of K_{sat}

Table 6.43 USBR relationship between soil permeability and infiltration fraction

Saturated hydraulic conductivity (inches/hr)	(cm/sec)	Deep percolation (%)
0.05	**3.53E-05**	3
0.10	**7.06E-05**	5
0.20	**1.41E-04**	8
0.30	**2.12E-04**	10
0.40	**2.82E-04**	12
0.50	**3.53E-04**	14
0.60	**4.23E-04**	16
0.70	**4.94E-04**	18
1.00	**7.06E-04**	20
1.25	**8.82E-04**	22
1.50	**1.06E-03**	24
2.00	**1.41E-03**	28
2.50	**1.76E-03**	31
3.00	**2.12E-03**	33
4.00	**2.82E-03**	37

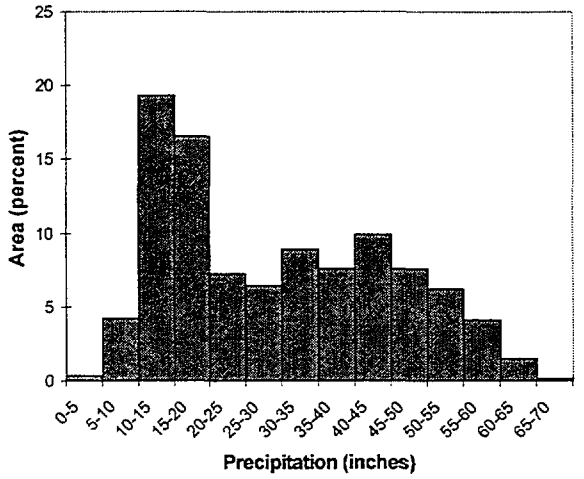

Figure 6.24 PDF for precipitation

water requirements since the contribution of precipitation in meeting the crop water requirements will be small to negligible. For this exercise, we considered irrigation rates for Idaho (USDC, 1994). Idaho data was used for several reasons. Its main commercial crop, potatoes, has similar water requirements to small vegetables typically grown in a home garden. (In fact, potatoes are commonly grown in home gardens.) Its climate is arid such that the vast majority of water for crops is supplied by irrigation. And its position along the Northern border of the country give it a single-crop growing season. Idaho applies just under 2 acre-feet of irrigation water per acre per year. As a comparison, water requirements for small vegetables, melons, and corn in New Mexico were also considered (USBR, 1997). These requirements range from 17 to 30 in. of water depending on the crop and the soil type, with an average requirement of about 24 in. of water, equivalent to the Idaho data.

Based on this data, a cumulative distribution for application rate is presented in Figure 6.25 and Table 6.44. For all precipitation rates at or above the minimum crop requirement of 2 ft of water, the application rate is considered to be equal to the precipitation rate. For all arid and semi-arid regions having precipitation rates of less than 24 in., water application rates are assumed to be equal to 24 in.

An additional logical condition is that the sampled water application rate at a particular site should never be less than the irrigation rate. If the sampled application is less than the irrigation rate, then the application rate is set equal to the irrigation rate.

$$\text{if } AP < IR, \text{ then } AP = IR \qquad (6.61)$$

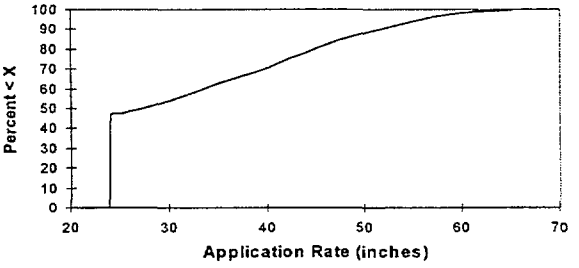

Figure 6.25 CDF for application rates

Table 6.44 CDF for application rates

Annual precipitation (inches)	% < X
<24	0.00
24	46.24
25	47.63
30	54.04
35	62.94
40	70.51
45	80.39
50	87.94
55	94.14
60	98.24
65	99.76
>65	100.00

Based on the preceding discussion, the steps to determining infiltration rate are as follows:

2. Sample soil type, using the volume-weighted percentages in Table 6.40.

2. Sample a saturated hydraulic conductivity for that soil type (Table 6.42).

3. Given the sampled hydraulic conductivity, use the USBR relationship relating soil conductivity to the infiltration fraction to determine the infiltration fraction. (Some interpolation or extrapolation may be required.) (Table 6.43)

4. Sample an application rate from the distribution in Table 6.44. (If AR < IR, then AR = IR.)

5. Calculate infiltration rate from the relationship, I = AR * IF. In some cases, the presence of low permeability soils will prevent infiltration at the calculated infiltration rate. The rate of water infiltration can be limited by the soil's ability to transmit water. The most favorable conditions for transmitting water through soils occur under

saturated conditions and a unit gradient. In this case, the rate at which water can be transmitted is equal to the soil's saturated hydraulic conductivity.

6. Compare (in consistent units) the infiltration rate to the saturated hydraulic conductivity. Use the lesser of the two as the infiltration rate.

7. Report infiltration rate in units of meters/year.

6.4.3.4.4 Saturation Ratios

Campbell (1974) derived a relationship between unsaturated hydraulic conductivity, K(θ) and saturation ratio, f:

$$K(\theta) = K_{sat} f^{2b+3} \qquad (6.62)$$

where b is a curve fitting parameter related to pore size distribution.

Under unit gradient, steady state conditions such as are assumed in the DandD model, the unsaturated hydraulic conductivity is equivalent to the infiltration rate determined above. Substituting infiltration rate for unsaturated hydraulic conductivity and rearranging to solve for the saturation ratio, results in:

$$f = \left[\frac{I}{K_{sat}}\right]^{\frac{1}{2b+3}} \qquad (6.63)$$

Since infiltration rate and saturated hydraulic conductivity are known from Steps 2 and 6 above, all that remains is to determine a value for b. Meyer et al. (1997) derived a relationship for b using soil water retention parameters considered in Carsel and Parrish (1988). Using this relationship, Meyer et al. (1997) constructed distributions for b. They are reported based on the 12 Soil Conservation Service textural classifications. The distribution type and parameters for these distributions for each of the 12 soil types are given in Table 6.45.

Meyer et al. (1997) also developed correlation matrices for parameters for each of the 12 soil types. There exists a moderate negative correlation between b and porosity as well as between b and saturated hydraulic conductivity. These correlations persist across all soil types. Summarizing the correlation matrices given for all soils, a correlation of −0.35 for both relationships is a reasonable approximation.

Once a b value is sampled, the saturation ratio can be calculated using the above equation.

The steps to calculate saturation ratio are:

1. Sample a value for the parameter b using the sampled soil type from Step 1 of the above procedure, then

2. Calculate "f" from Equation 6.63 using the sampled values for b, I, and Ksat.

6.4.3.5 Uncertainty in Hydrologic Parameters

The distribution for the soil texture was based on generalized soil textures throughout the continental U.S. These textures omit bedrock, highly organic soils (peat, muck, etc.), water, and "other" textures and should be representative of soil textures in most regions of the country. The distribution was selected to be most

Table 6.45 Distributions for the parameter *b*

Soil type	Distribution type	Mean	Standard deviation	Lower limit	Upper limit
sand	lognormal	0.998	0.226		
loamy sand	lognormal	1.40	0.397		
sandy loam	lognormal	1.96	0.579		
sandy clay loam	lognormal	4.27	1.39		
loam	lognormal	3.07	0.900		
silt loam	lognormal	3.80	1.42		
silt	lognormal	3.21	0.465		
clay loam	lognormal	5.97	2.37		
silty clay loam	lognormal	7.13	2.34		
sandy clay	lognormal	6.90	2.27		
silty clay	lognormal	10.2	2.96		
clay	beta	14.1	6.24	4.93	75.0

representative of surface soils (the upper 15 cm.). While deeper soils might tend to be slightly more clayey, this uncertainty is not expected to significantly affect the results of this analysis.

The distribution of soil types across sites is uncertain. Sites were assumed to be uniformly distributed over the area described in the CONUS-SOIL database.

6.4.3.6 Alternative Values for Hydrologic Parameters

Soil texture will vary from site to site and may vary over a site. While soil texture is not an explicit parameter in the DandD analysis, knowing it for a site may enable the licensee to refine the distributions of related parameters such as porosity and saturation ratio. For many sites, soil texture can be evaluated by reviewing existing soil surveys available from state agencies or the USDA. For sites located in regions with highly variable soils, site data on soil texture are easily collected by routine sampling and particle-size analysis.

6.4.4 Dust-Loading: Air Dust-Loading Outdoors, CDO and Indoors CDI (g/m^3); Floor Dust-Loading Pd (g/m^2) and Resuspension Rfr (m^{-1})

6.4.4.1 Parameter Descriptions

The dust-loading factors are used to calculate the average annual dose resulting from inhalation of airborne contaminants. The dust-loading factors, CDO and CDG, are used to calculate the inhalation dose due to activities occurring outdoors. CDO (g/m^3) represents the mass concentration of contaminated airborne particles in air outdoors, as defined in the exposure model, and corresponds to the long-term average quantity of respirable particulate material in outdoor air. CDG (g/m^3) represents the higher average mass loading of contaminated airborne particles in air while the individual is gardening. The default values for these parameters defined in Volume 1, are 1×10^{-4} g/m^3 for CDO and 5×10^{-4} g/m^3 for CDG. These values were defined based on the review of literature from outdoor air pollution studies from the National Air Sampling Network and studies on suspended particles in the atmosphere in communities across the United States.

The indoor dust-loading factor, CDI, represents the process of infiltration of contaminated airborne particles into the house (mass-loading) as the mass of infiltrating particles per unit volume of air. These particulates are distinguished from contaminated soil that is tracked indoors and subsequently released into the air by resuspension. Since the source of contamination is the surface soil layer, CDI becomes a function of the outdoor dust loading factor (CDO). CDI is used to calculate the average annual dose resulting from inhalation of airborne contaminants that are represented by parent and daughter radionuclides. The default value for this parameter as defined in Volume 1 (p. 6.10–6.11), is 5×10^{-5} g/m^3. This value was selected based on a fraction (1/100th) of the regulatory limit for total dust loading of respirable particulates in industrial settings (29 CFR 1910.1000, 1990), considered representative of the long-term average concentration of contaminated respirable dust, and is equivalent to 0.5 times the default CDO value.

P_d is a physical parameter that represents the long-term average mass of contaminated soil per unit area of floor inside the residence. Since it is a single parameter value for the entire time spent indoors, it is an average value for the entire house. The dust-loading on floors is used to estimate the airborne particulate concentration due to resuspension of soil tracked into the house. The default value for this parameter defined in NUREG/CR-5512, Vol. 1, is 0.4 g/m^2.

The resuspension factor, RF_r, defined for the NUREG/CR-5512 dose modeling, defines the ratio of the long-term average respirable contaminant concentration in air to the long-term average floor surface contaminant concentration due to contaminated soil tracked indoors. The default value for the resuspension factor recommended in NUREG/CR-5512, Vol. 1, is 5×10^{-5} m^{-1}, based on recommendations from IAEA (IAEA, 1970). The overall range of values obtained from literature published from 1964 to 1990 is 2×10^{-11} to 4×10^{-2} m^{-1}. However, most data referenced are for outdoor conditions (wind stress and vegetation). Only two of the references cited in Volume 1 provide data for indoor resuspension. The first of these, an IAEA technical report (1970), reports a value of 5×10^{-5} m^{-1}, which has been obtained for operating nuclear facilities and may not provide a representative value for resuspension in a residential setting. The second of these two references, a review by Sehmel (1980), provides different resuspension factors depending on the type of activity conducted within the rooms of the building (walking, vigorous sweeping, and fan) but does not differentiate between the resuspension of respirable and non-respirable particle sizes. The overall range cited by Sehmel is from 1×10^{-6} to 4×10^{-2} m^{-1} which may over estimate the resuspension factor used in this model because the data include non-respirable particles.

6.4.4.2 Use of Dust Loading Parameters in Modeling

CDO, CDG, CDI, P_d and Rf_r are important to dose because, the higher the mass loading in air, the higher the total annual dose during the first year of the residential scenario. CDO also influences the dust mass loading indoors (CDI). As described below, the dose for the inhalation pathway is directly proportional to each of these parameters.

These parameters are used for calculating the inhalation committed effective dose equivalent, DHR_i, from contaminated indoor and outdoor air as described in the following formula (NUREG/CR 5512, Vol. 1, p. 5.55, Equation 5.70):

$$\begin{aligned} DHR_i = & \left[24\, V_g (t_g/t_{tg})\, CDG\; C_{si} \sum_{(j=1,Ji)} S\{A_{stj}, t_{tg}\}\, DFH_j\right] \\ & + \left[24\, V_x (t_x/t_{tr})\, CDO\; C_{si} \sum_{(j=1,Ji)} S\{A_{stj}, t_{tr}\}\, DFH_j\right] \\ & + \left[24\, V_i (t_i/t_{tr})\, (CDI + P_d RF_r)\, C_{si} \sum_{(j=1,Ji)} S\{A_{stj}, t_{tr}\}\, DFH_j\right] \end{aligned} \quad (6.64)$$

where V_g, V_r, and V_x correspond to the volumetric breathing rates for time spent gardening, indoors, and outdoors (m^3/h), respectively; t_g is the time during the one-year exposure period that the individual spends outdoors gardening (d); t_{tg} is the total time in one gardening period (d); t_i and t_x are the times in the one-year exposure period that the individual spends indoors and outdoors (excluding gardening), respectively; t_{tr} is the total time in the residential exposure period (d); CDI, CDO, and CDG are dust loading factors for indoor, outdoor, and gardening activities (g/m^3), respectively; C_{si} is the concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil); J_i corresponds to the number of explicit members of the decay chain for parent radionuclide i; $S\{A_{stj}, t_{tr}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); $S\{A_{stj}, t_{tg}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over one gardening season during one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); DFH_j is the inhalation committed effective dose equivalent factor for radionuclide j for exposure to contaminated air (in units of mrem per pCi inhaled); P_d is the indoor dust-loading on floors (g/m^2); and RF_r is the indoor resuspension factor (m^{-1}). The higher the value for each of the dust-loading and resupension factors, the higher the dose.

The concentration of contaminated particles in air indoors due to infiltration was assumed to be a fraction (PF) of the outdoor air concentration. The long-term average outdoor air concentration (C_{Oai}) is estimated as the product of CDO and the contaminant concentration in soil (C_{si}).

$$C_{Oai} = CDO\; C_{si} \quad (6.65)$$

Resulting in the following model of the concentration of contaminant i in indoor air due to infiltration:

$$C_{Iai} = CDI * C_{si} = PF * CDO * C_{si} \quad (6.66)$$

The factor PF represents the fraction of airborne particulates that infiltrate the house and remain airborne. This factor will be a function of the ability of the particulate matter to enter the house (generally reported as a penetration factor) and remain suspended. There will be less suspension of particles indoors (due to cleaning, static electricity and lower wind speed (air disturbance)) which will lead to a net deposition or loss.

6.4.4.3 Information Reviewed to Define Distributions for CDO and CDG

Air concentrations are determined using mass-loading factors and are converted to units of activity from the concentration of the source material. Thirteen references are listed in NUREG/CR 5512, Vol. 1, for this data (Hinton et al., 1986; Stern, 1968; HEW, 1969; MaGill et al., 1956; Shinn et al., 1989; Sehmel, 1975; Sehmel, 1977a; Sehmel, 1984; Sehmel, 1977b; Stewart, 1964; Sinclair, 1976; Soldat et al., 1973; Anspaugh et al., 1975). The outdoor air dust-loading factors range from 1×10^{-5} to 2.3×10^{-1} g/m^3 for all airborne particles. Under extreme conditions, air dust-loading can be as high as 5 g/m^3; however, these conditions persist for only very short periods of time. For particles less than 10 μm diameter (the respirable fraction), air dust-loading factors range from 1×10^{-5} to 7×10^{-4} g/m^3. Table 6.46 summarizes the experimental results on dust loading studies.

Additional information was reviewed to determine if other data or approaches, preferably more recent than those cited in NUREG/CR-5512, Vol. 1, were available to provide a defensible basis for constructing PDFs for CDO and CDG for use in this analysis. The outdoor dust-loading factor, CDO (g/m^3), represents the long-term average quantity of respirable outdoor dust, as defined in the exposure model. In order to define the parameter distribution, a detailed analysis of the factors that contribute to outdoor air-dust loading along with supporting experimental data on outdoor dust-loading measurements is needed.

Table 6.46 Total dust loading

Reference	Dust Loading
Anspaugh et al. (1975)	$9 \times 10^{-6} - 7 \times 10^{-5}$ g/m^3
Soldat et al. (1973)	1×10^{-4} g/m^3
Shinn et al. (1989)	2.1×10^{-5} g/m^3 (background)
	3.4×10^{-5} g/m^3 (sea spray)
MaGill et al. (1956)	$1 \times 10^{-4} - 2 \times 10^{-3}$ g/m^3
HEW (1969)	1×10^{-5} g/m^3 (rural areas)
	$6 \times 10^{-5} - 2.2 \times 10^{-4}$ g/m^3 (urban)
Stern (1968)	9.8×10^{-5} g/m^3 (geometric mean) with maximum of 1.7×10^{-3} g/m^3
Sehmel (1975; 1977a;1984)	upper limit of 7×10^{-4} g/m^3 (<10 μm diameter)
	upper limit of 2.3×10^{-1} g/m^3 (>10μm diameter)

In the absence of human activities that create or suspend airborne particulates, the major factor controlling the suspension and resulting particle concentration in air is wind speed. Higher dust loading due to human activity is represented by gardening. As shown by a number of authors, the particle concentration is an exponential function of the wind speed (e.g., Sehmel, 1977b). Unfortunately, there is no reliable analytical relationship between the wind speed and dust loading factor that could be used in defining dust loading from the average wind speed. Moreover, it is not clear how to specify the function and determine the proportionality coefficient between the wind speed and dust loading under different conditions.

Another important factor influencing dust loading is soil moisture. As discussed in (Tegen and Fung, 1994), suspension of soil particles in air is only possible when the soil matric potential[2] is greater than 10^4 J/kg. In other cases, no suspension will occur even under strong wind conditions. Moreover, suspension is also influenced to a great extent by vegetation cover. High resuspension is common for areas without vegetation or with sparse vegetation, and low resuspension is common for areas of dense vegetative cover. Finally, dust loading is affected by soil type (composition). Some soils are easily eroded, while other soil types are resistant to erosion. Other less significant factors are: topography (surface roughness) and snow cover/surface soil freezing.

Since the wind speed, soil moisture (or amount of precipitation), and vegetation cover are factors related to the climate, different categories could be defined based on different climatic conditions. More generally (including the other factors, such as soil types, topography, and etc.), categories could be defined based on different environmental conditions. The usefulness of one or another category definition depends on the availability of information on dust loading factors measured under different climatic or environmental settings. A second, and equally important factor, is estimating the probability that a particular site is in a specific category.

An extensive literature review was conducted to identify different categories of environmental conditions that could be reasonably defined based on published data. A summary of this review is presented in Table 6.47. The information allows us to evaluate single dust loading measurements and average values from a number of measurements, to distinguish between extreme conditions (dust loading during a dust storm) and normal conditions (dust loading under average wind conditions), and to compare environmental conditions specific to different sites.

Most of the dust loading values available from the literature (Table 6.47) represent the total amount of dust resuspended in air. The dust loading factor, as defined in NUREG/CR-5512, corresponds to the quantity of contaminated, respirable airborne particulates. According to the EPA, the respirable particles are particles smaller than 10 μm. Various studies have been conducted to determine the relationship between the mass loading and particle sizes. Data from Hinton et al. (1986) indicate the mass of respirable particles is 0.5 to 2.5 orders of magnitude less than the total mass of airborne particles. These data are supported by other observations (Sehmel, 1975; 1977a; 1984).

Another factor that influences the way experimental data should be interpreted in defining CDO is the difference in the particle mass suspended in air at different heights above the land surface. The dust loading factor defined in NUREG/CR-5512 should represent the air concentration at the respirable height. As discussed in (Sehmel, 1977a), the air concentration depends on the height. In some cases, the concentrations near the land surface can be lower than at some distance from the surface (usually, below the respirable height) where it reaches a maximum value. In other cases, the functional relationship is monotonic with higher concentrations near the land surface. However, the concentrations of suspended particles in the air vary by about 20% for a height between 0.5 and 2.0 m. Since particles are measured near the land surface or at the reference height of 1 m, these small variations can be neglected when defining the dust loading factor ranges.

[2]A measure of the surface tension of moisture in the soil.

Table 6.47 Outdoor dust loading

Reference	Dust loading (g/m^3)	Site description
Sehmel (1977b)	$7.7 \times 10^{-6} - 7.1 \times 10^{-4}$	Hanford Site, arid climate, sparse vegetation, average annual wind 3.4 m/s, 0.16 - 10 μm particles (numerous long-term average values over a 4 year period)
Sehmel (1977b)*	$2 \times 10^{-5} - 2.3 \times 10^{-1}$	Hanford Site, 10 - 230 μm particles (non-respirable, not included in data to support pdfs)
Prospero (1981)	2×10^{-5}	Near large body of water (Spring)
Pye (1992)	$1 \times 10^{-7} - 6 \times 10^{-5}$	Near large body of water
Hartmann et al. (1989)	$4.5 \times 10^{-5} - 1.3 \times 10^{-4}$	Humid climate, forest
Gao (1992)	4×10^{-6}	Near large body of water (Spring)
Rognon (1991)	$1.6 \times 10^{-6} - 1.3 \times 10^{-5}$	Desert region
Zier (1991)	$2.3 \times 10^{-5} - 1.2 \times 10^{-4}$	Near-surface air
Friedrichs (1993)	8×10^{-5} - 1.6×10^{-4}	Small industrial city
Tegen and Fung (1994)	1×10^{-4}	Areas of high dust loading (deserts, eroding cultivated areas)
Tegen and Fung (1994)	$5 \times 10^{-6} - 2.5 \times 10^{-5}$	Tropical climate, dense vegetation cover
Tegen and Fung (1994)	6×10^{-5}	Pacific Northwest
Clausnitzer and Singer (1996)*	$3 \times 10^{-4} - 1 \times 10^{-2}$	Dust collector mounted 94 cm above disturbed soil on agricultural implement (<4 μm diameter particles). (Respirable fraction, but not representative of average conditions for exposure due to measurement conditions)
Moulin et al. (1997)	1×10^{-5}	Tropical climate, dense vegetation cover (average over 30 year period)
NYS DEC (1981)	6.6×10^{-5}	Annual average over 4-year period

* Shaded rows are not included in the distribution; see text.

The outdoor air-dust loading, CDO, varies with the particle size of the contaminant, quantity of loose particulate contaminants at the surface, and magnitude and types of external stresses. The concentration of dust in the atmosphere has been measured and modeled under a wide range of conditions. Rognon (1991) conducted field measurements near the ground and correlated the dust content with surrounding soils based on the composition of the soil, state of the plant surface and ground cover, surface roughness, drag velocity, turbulence, wind velocity, and the atmospheric dust load and composition. The particle concentration varied from 1.6×10^{-6} to 1.25×10^{-5} g/m^3. Tegen and Fung (1994) applied a model that takes into account the size distribution of the dust particles to estimate the distribution of atmospheric mineral dust. Tegen extended the model to calculate the atmospheric mineral aerosol load under conditions in which the soil surface is disrupted by agricultural activities or the soil surface is exposed to wind erosion through deforestation and shifting desert boundaries. Suspended particulate matter was monitored by the New York State Department of Environmental Conservation in residential and industrial sections of a small city. The concentration of particulate matter averaged 6.6×10^{-5} g/m^3 over a four-year period (NYS DEC, 1982).

These data are not specific to human activities. The residential farmer is likely to work under more extreme dust-loading conditions for short periods of time; however, dust loadings greater than 4×10^{-3} g/m^3 for an extended period of time has resulted in a significant increase in death rates (MaGill et al., 1956). This information can be used to provide an upper bound on CDG if the time spent gardening is representative of the "extended periods of time" in the MaGill study.

6.4.4.4 Distribution for CDO

The potential variability in site-specific conditions and the large variability in the measured mass loading (orders of magnitude) indicate a wide range for the potential values of this parameter. The distribution of the dust loading is best represented by a log-uniform distribution with a lower limit of 1×10^{-7} g/m^3 and an upper limit of 1×10^{-4} g/m^3. The range of values is defined by the range of average values for dust loading of respirable particles (<10 μm in size) in arid and humid climates. The use of a log-uniform distribution ensures that the selection of a particular magnitude of CDO will be equally likely.

In the absence of information on the fraction of sites in each of the two climatic categories, due to unknown location of future sites and the indistinct categories of arid and humid, an equal probability has been assumed.

6.4.4.5 Distribution for CDG

Short-term gardening activities are expected to produce localized, elevated levels of dust loadings. Based on the data presented in Tables 6.46 and 6.47, the upper limit on dust loading for respirable particles is approximately 7×10^{-4} g/m^3 (Sehmel, 1975; 1977a; 1984). Higher dust loading of respirable particles has been measured (Clausnitzer and Singer, 1996) but not under conditions reasonable for human exposure and at levels that would cause physical harm. For this analysis the gardening dust-loading factor is assigned a uniform distribution with a lower limit of 1×10^{-4} g/m^3 and an upper limit of 7×10^{-4} g/m^3, based on the range of values from the literature for particulates less than 10 µm in diameter for higher dust loading activities (as cited in NUREG/CR-5512, Vol. 1). The lower limit for CDG corresponding to the upper limit of CDO, based on the intent of the gardening scenario to represent a higher level of activity while outdoors. This distribution for CDG will result in higher dust-loading during the time spent gardening.

6.4.4.6 Review of Information to Define CDI

Additional information was reviewed to determine data in addition to that presented in NUREG/CR-5512, Vol. 1, were available to provide a defensible basis for constructing a PDF to represent the variability of CDI for residential settings over all current and future sites.

The ratio of indoor to outdoor suspended particle matter has been reported from a number of studies. Whitby et al. (1957) studied the properties of airborne dust indoors and outdoors at various locations and reported values ranging from 65 µg/m^3 indoors to 93µg/m^3 outdoors (a ratio of 0.70). Total suspended particulate concentrations were monitored outdoors over a period of about four years near an industrial site. Sterling and Kobayoshi (1977) compared indoor and outdoor suspended particulate concentrations and observed that the concentration of suspended particles indoors is 77 to 85% of the corresponding concentration outdoors. However these studies did not distinguish between infiltration of airborne particles and resuspension of contaminated soil tracked indoors. As a result, these studies can only provide an upper bound on the potential CDI for the specific conditions evaluated (i.e., by assuming the floor dust loading or resuspension factor indoors are negligible).

A more recent study by Thatcher and Layton (1995) uses experimental data, modeling and evaluation of other published studies, to discriminate between resuspension and infiltration of particles. In their analysis, Thatcher and Layton's measurements and modeling support their conclusion that the difference in the indoor and outdoor air concentration due solely to infiltration (i.e., excluding resuspension) is a function of deposition indoors rather than the ability of the house to limit infiltration of particles. CDI represents the mass loading indoors of infiltrated particles and combines the effects of penetration and net deposition. As a result, studies that neglect deposition can be used to estimate the variability in PF (which is the ratio of CDI to CDO). The studies cited by Thatcher and Layton and the results of Thatcher and Layton's studies are summarized in Table 6.48.

6.4.4.7 Values for Parameter Analysis

Based the studies summarized in Table 6.48 it can be concluded that PF ranges from 0.2 to 0.7. This variability is due to a number of factors including the measurement technique, location within the house, and variability in the airborne particle size distribution. Given the limited number of studies and measurements to support a generic parameter value and the uncertainty in the particle size distribution of the contaminated soil, the variability in PF is best represented by a uniform distribution between the values of 0.2 and 0.7.

A separate PDF was not defined for CDI. Instead, CDI was calculated from values sampled for CDO and PF (see Equation 6.66).

6.4.4.8 Review of Additional Information to Define PDF for P_d

Solomon (1976) measured floor dust in a number of residential settings. The floor dust loading ranged from 0.11 to 0.59 g/m^2 based on 239 samples from 12

Table 6.48 Reported values for the ratio of indoor to outdoor dust loading

PF	Reference	Notes
0.2 – 0.6	Thatcher and Layton, 1995	3-10 μm particle size range, assuming deposition negligible
0.4 – 0.6	Thatcher and Layton, 1995	1-3 μm particle size range, assuming deposition negligible
0.7	Dockery and Spengler, 1981	respirable particles and sulfates
0.4	Freed et al., 1983	sub-micron particles
0.2	Freed et al., 1983	super-micron particles
0.3	Alzona et al., 1979	reported typical for Fe, Zn, Pb,Br and Ca
0.45	Cohen and Cohen, 1980	sub-micron particles, reported average for Fe, Zn, Pb,Br and Ca in residential and industrial settings
0.2	Cohen and Cohen, 1980	super-micron particles, reported average for Fe, Zn, Pb,Br and Ca in residential and industrial settings
0.7	Colome et al., 1992	<10 μm particle size, average for 35 California homes (range 0.4 to 1.5, may neglect resuspension)
0.77–0.85	Sterling and Kobayoshi, 1977	unknown size distribution, includes resuspension therefore not used to establish the pdf.

different dwellings. Similar results were reported from studies conducted by the New York State Department of Environmental Conservation (NYS DEC, 1982). In the absence of additional information, a uniform distribution is proposed. However, the results of these two studies are for total dust loading which may include non-soil components and soil from remote locations. As a result, these studies can be used to estimate an upper bound on P_d.

Thatcher and Layton (1995) performed a detailed modeling and experimental study to quantify the sources of indoor air contamination. They report that the major component of floor dust is soil, but they do not present the results. Total dust loading in the two houses in the Thatcher and Layton study ranged from 0.06 g/m^2 on linoleum to 43.4 g/m^2 on a rug by the door. Dust loading on carpeted floors was significantly higher than on linoleum (0.58 to 2.2 g/m^2) with the higher values in high-traffic areas. Information on the area of floor carpeted and the area covered with linoleum is not provided. If it is assumed that the floors are covered in equal parts linoleum and carpet and the area covered by the rug near the front door is negligible, then the average total dust load is on the order of 0.6 g/m^2.

A recent study by Rutz et al. (1997) evaluated the average total dust loading on floors in two separate homes and estimated the fraction of dust that is from contaminated soil. The results of this analysis provide information necessary to estimate P_d for those two homes if it is assumed that the floors are covered in equal parts linoleum and carpet and that the dust loading in the rug by the door is negligible when the dust density is averaged over the entire house. One house had an average total dust density of 0.4 g/m^2 and an average of 30% of that dust is contaminated soil resulting in a P_d of 0.12 g/m^2. The other home had a lower average total dust density (0.1 g/m^2) and an average of 20% of that dust is contaminated soil resulting in a P_d of 0.02 g/m^2.

Other studies on floor dust loading with contaminated soil cited by Rutz et al. (1997) indicate the dust is comprised of 31 to 50% contaminated soil (Calebrese and Stanek (1992) and Fergusson et al. (1986)).

6.4.4.8.1 PDF for P_d

Given this limited amount of information, the range of P_d values is 0.02 to 0.3 g/m^2 and all values in that range are equally likely. A uniform distribution between 0.02 and 0.3 g/m^2 was used to represent the uncertainty in this parameter.

6.4.4.9 Review of Additional Information to Define PDF for RF_r

An extensive literature review was conducted to identify any developments in the understanding of the resuspension process since the review reported in NUREG/CR-5512 in 1992, and to identify data or approaches that could be used to develop a probability distribution function for the indoor resuspension factor in the residential and occupancy scenarios. The general findings from the literature review are discussed in Section 5.4.4.3.

The published data indicate that resuspension factor values vary over orders of magnitude depending on site specific conditions which include the nature and

intensity of mechanical disturbance associated with activities in the home.

The Thatcher and Layton (1995) study indicates that resuspension indoors is a function of the time individuals spend inside the home and that the two parameters are linearly correlated for the particular set of conditions analyzed. Variability from site to site in surface conditions, humidity, human activities and particle size distributions produces order-of-magnitude variations in RF_r. As a result, the uncertainty in the appropriate effective parameter value overwhelms the linear relationship between time spent indoors and RF_r.

6.4.4.9.1 Grouping of Reported Resuspension Factors based on Experimental Conditions

Table 6.49 summarizes the resuspension factors reported for experimental studies for various conditions (Jones and Pond, 1964; and Fish et al., 1964). The experiments by Jones and Pond (1964) provide average resuspension factors for a range of activities that are common in occupational settings. The measured resuspension factors reported by Jones and Pond (1964) are for four levels of activities conducted for 60 minute periods in a laboratory setting with different floor surfaces, using $Pu(NO_3)_4$ and PuO_2-contaminated particles (0.4–60 μm diameter) and particulate air samplers positioned at 14–175 cm above the surface. The particle size distribution includes non-respirable components and the height above the floor surface is not necessarily representative of the exposure scenario. Fish et al. (1964) provides average resuspension factors for a range of vigorous mechanical disturbances of contamination on a tile floor based on 10 minutes of the reported activity. The values in Table 6.49 for this study are reported for four levels of disturbances.

In order to develop a distribution that represents the average conditions in the residence, the average or effective activity level must be determined. Robinson and Thomas (1991) summarize the results of a national survey on time spent in activities. This survey, conducted in 1985, is based on averages from diaries kept by 1,980 adults (921 men) over a two month period. In this survey, adult men spent an average of 886 minutes per day at home, 6 minutes per day cleaning the house (vigorous activity) and 486 minutes sleeping. Some of this time at home was spent in the yard or garage, using the data presented for California, the time spent at home outside is approximately 37 minutes per day, leaving approximately 849 minutes per day indoors. Of the time at home spent indoors approximately 0.7% is vigorous activity, 57.2% sleeping (no activity), and the remaining 42.1% is spent in moderate to low activity. Given this estimate of how all adult males time is spent indoors, the effective parameter value should be a time weighted average of the Rf_r for each activity category. As can be seen in Table 6.50 the contribution from low to moderate activities while awake will dominate the time-weighted average.

PDF for Rf_r

The variability and uncertainty in the resuspension factor is best represented by a log-uniform distribution with a lower limit of 1×10^{-7}/m and an upper limit of 8×10^{-5} 1/m. These limits are based on the moderate waking activity range from Table 6.50, which dominates the time-weighted sum. The range of values is defined by the time weighted minimum and maximums of measured values for resuspension under low to moderate activities. The use of a log-uniform distribution ensures that the selection of a particular magnitude of RF_r within this range will be equally likely. This distribution reflects the uncertainty in the effective model parameter value given limited data on the relative amount of time spent at different activity levels by adult males indoors at home.

6.4.4.10 Uncertainty in RF_r

The proposed distributions describing the variability in the parameters representing indoor and outdoor dust-loading are determined by the following assumptions that introduce uncertainty in the distributions:

- Respirable particles are less than 10 μm in diameter, as defined in the NUREG/CR-5512 exposure model;
- there are an equal number of sites in each of the two climate categories (arid and humid).
- airborne contaminated particles will have a distribution of sizes such that there is net deposition indoors, and
- the long-term average PF is in the range 0.2 to 0.7 for all sites, indoor activities, outdoor activities and future houses,
- resuspension of loose particles indoors occurs by a combination of wind stress from normal building ventilation and mechanical disturbances from walking and other activities (e.g., cooking, sweeping, running, playing, exercising, working, reading, watching television; and

Table 6.49 Resuspension factors measured under various conditions

Experimental condition	RF_r (m^{-1})
Reported by Jones and Pond (1964)	
Air circulation (no mechanical disturbance)	7.7×10^{-10} to 1.5×10^{-7}
Walking (14 steps/min)	3×10^{-7} to 2×10^{-5}
Walking (36 steps/min)	9.7×10^{-7} to 1.8×10^{-4}
Walking (200 steps/min) with wind stress (hair dryer directed toward floor)	8×10^{-6} to 1.5×10^{-4}
Reported by Fish et al. (1964)	
Vigorous work activity, including sweeping	1.9×10^{-4}
Vigorous walking	3.9×10^{-5}
Light work activity	9.4×10^{-6}

Table 6.50 Time weighted resuspension factors

Activity	Range of Rf_r (m^{-1})	Reference	Fraction of time	Time weighted range RF_r
Sleeping	7.7×10^{-10} to 1.5×10^{-7}	Jones and Pond (1964); Air circulation	0.572	4.4×10^{-10} to 8.6×10^{-8}
Awake (not sweeping)	3×10^{-7} to 1.8×10^{-4}	Jones and Pond (1964); Walking (14 steps/min)	0.421	1.3×10^{-7} to 7.6×10^{-5}
Awake (vigorous, sweeping)	9.4×10^{-6} to 1.9×10^{-4}	Fish et al. (1964); Light to vigorous work activity	0.007	6.6×10^{-8} to 1.3×10^{-6}

- resuspension factor values are reported to depend to some extent on a number of other factors, including surface texture and roughness (in this case the type of floor covering), particle size distribution, type of deposition, and chemical properties of the contaminant and surface. These factors are assumed to produce site-to-site variations in resuspension factor values.

6.4.4.11 Alternative Values for RF_r

Several of the physical factors influencing dust loading and resuspension may be plausibly bounded by characteristics of the site, or controlled by the licensee in an effort to support a site-specific values for these parameters. These parameters may also change if the licensee defines a site-specific critical group.

The outdoor dust-loading factor would be expected to vary from site to site due to local climatic conditions, differences in the activities at the site, use of the property and activities that are likely to occur. The indoor dust-loading factor would be expected to vary from site to site due to differences in the activities at the site resulting in an uncertain distribution of the airborne particle sizes and, to a lesser degree, to the ability of the house to filter and prevent infiltration. The average floor dust loading for an entire house will depend on the relative amount of smooth (wood, tile or linoleum) verses rough (carpet) floor covering, the construction style (number of stories) and to a lesser degree the cleaning habits of the occupant. There may be regional differences in the indoor dust-loading factors due to construction styles and climatic differences. The resuspension factor will vary across sites due to differences in the use of the properties, and due to factors unrelated to the use of the property such as surface chemistry and topography.

6.4.5 Crop Yields for Vegetables, Fruits, and Grains Consumed by Humans, Y_v, and Forage, Y_f, Stored Grain, Y_g, and Stored Hay, Y_h, Consumed by Beef Cattle, Poultry, Milk Cows, and Layer Hens (kg/m^2)

6.4.5.1 Description of Crop Yields

The crop yields represent the average annual yields of garden produce (vegetables, fruit, grain) and livestock

feed (hay, forage, and grain) that are grown on contaminated land and consumed by individuals and livestock at the site.

The crop yields are needed for determining the uptake and transport of radionuclides in: 1) irrigation water-plant-human pathway; 2) irrigation water-forage-animal-human pathway; 3) irrigation water-stored grain-animal-human pathway; and 4) irrigation water-stored hay-animal-human pathway, and the parameters are used to calculate the cultivated area, A_r (see Section 6.2.2).

6.4.5.2 Crop Yields for Vegetables, Fruits, and Grains, Y_v (kg/m^2)

Crop yields for vegetables, fruits, and grains, Y_v, describe the amounts of garden produce grown per unit area of cultivated land at the site. The model allows different values of Y_v for vegetables (leafy), vegetables (other than leafy), fruits, and grains. The default values of 2.0 kg/m^2 (leafy vegetables), 4.0 kg/m^2 (other vegetables), 2.0 kg/m^2 (fruits), and 1.0 kg/m^2 (grains) were adopted as the default values in NUREG/CR-5512, Vol. 1, and are based on information published by Shor et al. (1982), Strenge (1987), and Napier et al. (1988).

6.4.5.2.1 Use of Y_v in Modeling

Y_v is used in determining the average deposition rate of radionuclide j to edible parts of plant v from application of irrigation water per unit average concentration of parent radionuclide i in water (pCi/d·kg wet-weight plant per pCi/L water), R_{wvjg}, as shown by the following (Equation 5.22, p. 5.27 of NUREG/CR-5512, Vol. 1):

$$R_{wvjg} = IR\ r_v\ T_v/Y_v\ [C_{wj}/C_{wi}] \qquad (6.67)$$

where IR is the average annual application rate of irrigation water (L/m^2·d); r_v is the fraction of initial deposition (in water) retained on the plant (pCi retained per pCi deposited); T_v is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant (pCi in edible plant part per pCi retained); Y_v is the yield of plant v (kg wet-weight plant/m^2); C_{wj} is the average annual concentration of radionuclide j in irrigation water over the current annual period (pCi/L water); and C_{wi} is the average annual concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water).

6.4.5.2.2 Additional Information Reviewed to Define Revised Values for Y_v

Estimates of the yields for vegetables, fruits, and grains were obtained from USDA crop reports collected during the period from 1994 to 1996. Distributions for the individual crops for the residential scenario were determined from the annual average yields and the fraction of total crop area that is devoted to each crop. Tables 6.51 through 6.54 list the individual crops in each of the four categories (vegetables (leafy), vegetables (other), fruits, and grains), the total land area (averaged over three years) for production of each crop, and the average annual yield (kg/m^2).

6.4.5.2.3 Distribution for Crop Yields for Vegetables, Fruit, and Grain

The resident farmer is assumed to cultivate a mix of crops based on the reported fraction of cultivated area for each crop type. The yield for each crop type was assumed to be independent of the yield for other crops, and was assumed to follow a normal distribution with the reported average and standard deviation.

Distributions for crop yields were determined from the annual average yields for individual crops and the fraction of land for production of these crops using the following equation:

$$Y_c = \sum_{(j=1,n)} F_j * Y_j \qquad (6.68)$$

where Y_c is the total crop yield for a classification of produce (i.e., leafy vegetables, other vegetables, fruits, or grains), j corresponds to a particular crop, F_j is the fraction of the total land area for production of crop j, and Y_j is the reported yield of crop j. Figures 6.26 through 6.33 show the PDFs and CDFs for each of the edible crops identified in NUREG/CR-5512. The mean and range of crop yields for vegetable, fruit, and grain crops are summarized in Table 6.55.

6.4.5.3 Crop Yield for Forage, Y_f (kg/m^2)

Crop yield for forage, Y_f, represents the quantity of forage produced per unit area of cultivated land. The model accepts different values of Y_f for forage crops grown for consumption by beef cattle, poultry, milk cows, and layer hens. The crop yields are defined by standing biomass. Volume 1 proposes the following values: beef cattle, 1.5 kg/m^2; poultry, 1.0 kg/m^2; milk cows, 1.5 kg/m^2; layer hens, 1.0 kg/m^2. These value were based on information published by Shor (1982), Strenge (1987), and Napier et al. (1988).

Table 6.51 Production of vegetable crops (leafy) in 1994–1996*

Crop	Area (acres)	Fraction	Std Dev	Yield (kg/m^2)	Std dev
Artichokes	8633	0.0143	0.0005	1.182	0.240
Broccoli	119333	0.1978	0.0045	1.355	0.039
Brussel sprouts	3400	0.0056	0.0001	1.926	0.086
Cabbage	81273	0.1348	0.0022	3.811	0.211
Cauliflower	50317	0.0834	0.0057	1.500	0.085
Celery	27833	0.0461	0.0010	7.401	0.527
Head lettuce	204237	0.3385	0.0095	3.582	0.056
Leaf lettuce	39300	0.0652	0.0038	2.546	0.014
Romaine lettuce	30813	0.0511	0.0080	3.116	0.015
Spinach	38030	0.0630	0.0011	1.543	0.048

*Source: "Crop Production Annual Survey," National Agricultural Statistics Service (NASS), Agricultural Statistics Board, U.S. Department of Agriculture, January 1997.

Table 6.52 Production of vegetable crops (other than leafy vegetables) in 1994–1996*

Crop	Area (acres)	Fraction	Std dev	Yield (kg/m^2)	Std dev
Asparagus	74217	0.02675	0.00087	0.31278	0.00895
Beans, Lima	53767	0.01937	0.00093	0.31310	0.00687
Beans, snap	294280	0.10599	0.00266	0.73221	0.04381
Beets	10217	0.00368	0.00015	3.11675	0.32048
Cantaloups	103447	0.03729	0.00113	2.15530	0.20594
Carrots	108323	0.03909	0.00437	3.71015	0.12441
Corn	713270	0.25701	0.00669	1.43156	0.02909
Cucumbers	171103	0.06163	0.00146	1.44046	0.03415
Eggplant	3067	0.00110	0.00015	2.46063	0.27061
Escarole	3613	0.00130	0.00007	1.72619	0.01439
Garlic	28667	0.01035	0.00101	1.90709	0.05609
Honeydews	26000	0.00938	0.00068	1.98313	0.18518
Onions	161653	0.05826	0.00130	4.37844	0.07288
Peas	280203	0.10084	0.00844	0.37263	0.00802
Bell peppers	66700	0.02405	0.00133	2.60024	0.17790
Tomatoes	470387	0.16949	0.00043	6.26320	0.12603
Watermelon	206423	0.07441	0.00224	2.25624	0.11714

*Source: "Crop Production Annual Survey," National Agricultural Statistics Service (NASS), Agricultural Statistics Board, U.S. Department of Agriculture, January 1997.

Table 6.53 Production of fruit crops in 1994–1996*

Crop	Area (acres)	Fraction	Std dev	Yield (kg/m^2)	Std dev
Apples	459703	0.1540	0.00312	2.6400	0.1442
Apricots	21423	0.0072	0.00009	1.0261	0.5190
Avocados	67670	0.0227	0.00221	0.6163	0.0718

Table 6.53 Production of fruit crops in 1994–1996* (continued)

Crop	Area (acres)	Fraction	Std dev	Yield (kg/m^2)	Std dev
Cherries, sweet	47347	0.0159	0.00011	0.8339	0.1438
Cherries, tart	44950	0.0151	0.00132	0.8062	0.1452
Cranberries	32467	0.0109	0.00020	1.5563	0.1282
Dates	5127	0.0017	0.00017	1.0553	0.1678
Figs	14767	0.0049	0.00004	0.7606	0.1160
grapes	759833	0.2545	0.00521	1.7269	0.0965
guaves	733	0.0002	0.00001	2.5727	0.1236
Kiwifruit	6700	0.0022	0.00010	1.2146	0.1251
Nectarines	31633	0.0106	0.00065	1.5735	0.3354
Olives	33133	0.0111	0.00016	0.7374	0.3214
Papayas	2157	0.0007	0.00011	2.6849	0.4294
Peaches	173072	0.0580	0.00132	1.4875	0.1403
Pears	70510	0.0236	0.00047	2.9766	0.3599
Plums	41633	0.0139	0.00034	1.0672	0.3566
Prunes	79300	0.0266	0.00037	1.7867	0.1588
Strawberries	48610	0.0163	0.00044	3.7544	0.0259
Oranges	763757	0.2556	0.01114	3.2780	0.0408
Grapefruit	165297	0.0553	0.00218	3.7573	0.2316
Lemons	61133	0.0205	0.00054	3.5158	0.2279
Limes	1933	0.0006	0.00001	1.2714	0.2656
Tangelos	12133	0.0041	0.00017	2.4964	0.5210
Tangerines	34300	0.0115	0.00124	2.0941	0.2632
Temples	6700	0.0022	0.00007	3.4799	0.2464

*Source: http://mannlib.cornell.edu

Table 6.54 Production of grain crops in 1994–1996*

Grain	Area (acres)	Fraction	Std dev	Yield (kg/m^2)	Std dev
Corn	66,434,000	0.3092	0.0136	0.7282	0.0976
Sorghum	9,960,000	0.0464	0.0056	0.4021	0.0401
Oats	4,802,000	0.0225	0.0073	0.1967	0.0243
Barley	7,562,000	0.0354	0.0059	0.2927	0.0370
Rye	443,000	0.0021	0.0006	0.1697	0.0103
Wheat	60,927,000	0.2838	0.0140	0.2460	0.0155
Rice	2,870,000	0.0134	0.0012	0.6398	0.0230
Flax	221,000	0.0011	0.0005	0.0952	0.0276
Sunflowers	2,385,000	0.0111	0.0028	0.1379	0.0216
Soybeans	59,008,000	0.2752	0.0111	0.2329	0.0258

*Source: "Crop Production Annual Survey," National Agricultural Statistics Service (NASS), Agricultural Statistics Board, U.S. Department of Agriculture, January 1997.

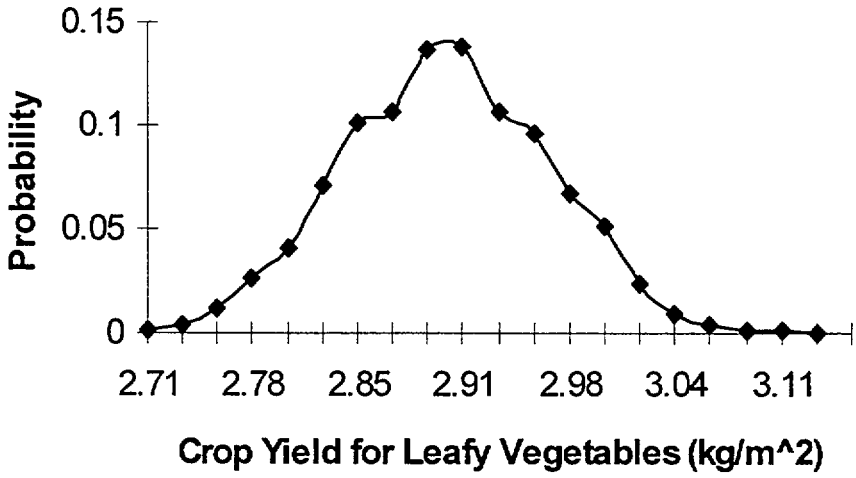

Figure 6.26 PDF for crop yields for vegetables (leafy)

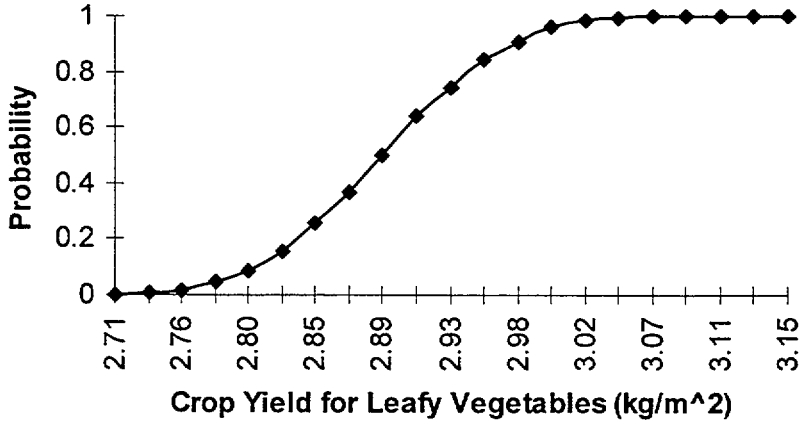

Figure 6.27 Cumulative distribution for Y_v (leafy vegetables)

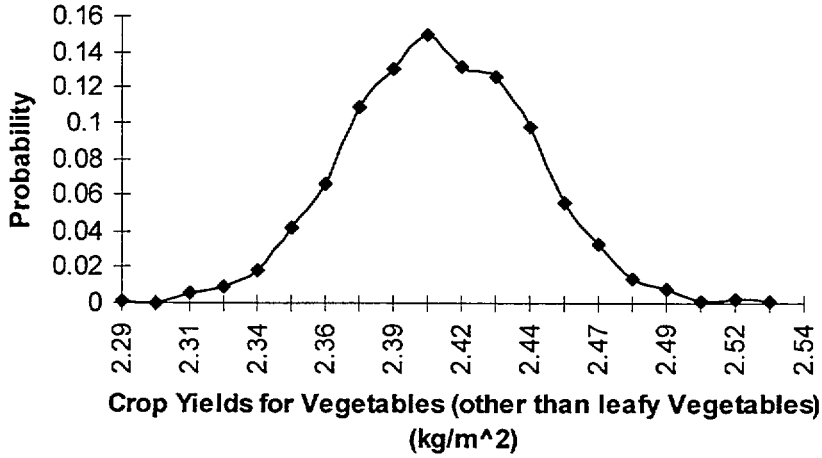

Figure 6.28 PDF for crop yields for vegetables (other)

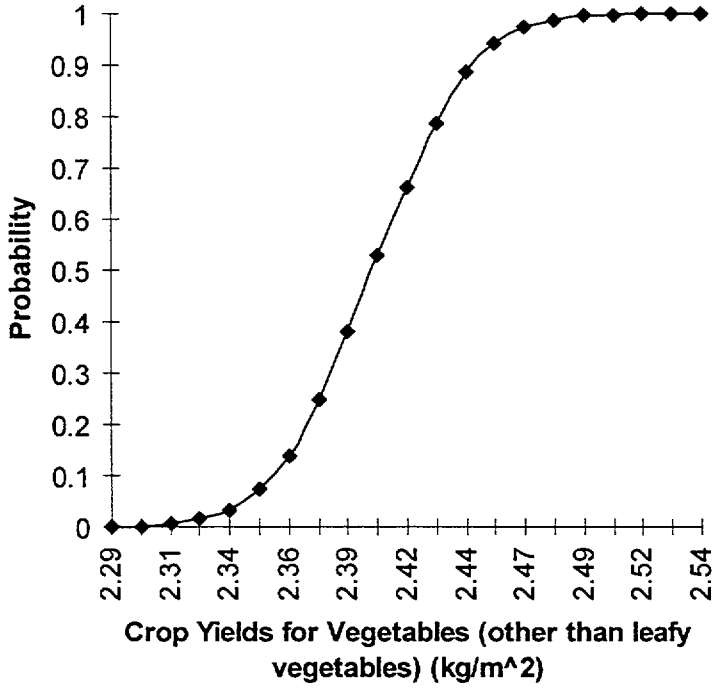

Figure 6.29 Cumulative distribution for Y_v (other vegetables)

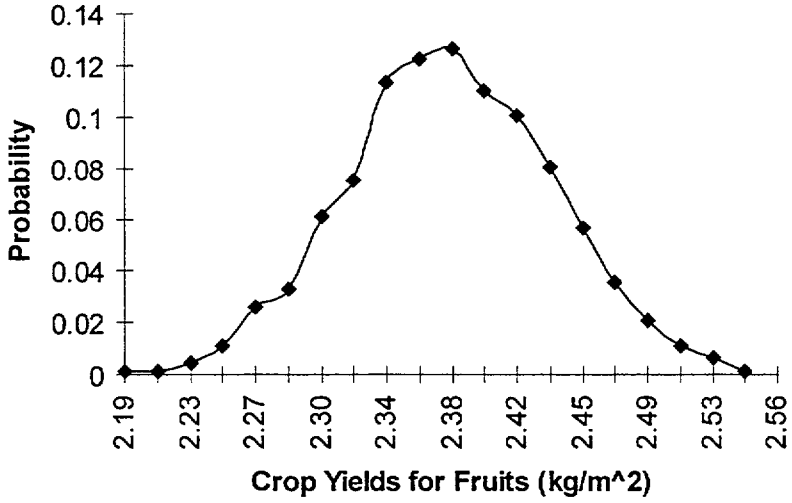

Figure 6.30 PDF for crop yields for fruit

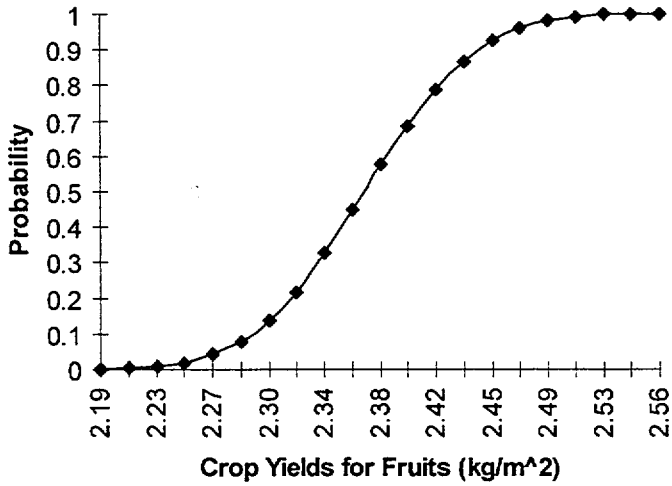

Figure 6.31 Cumulative distribution for Y_v (fruit)

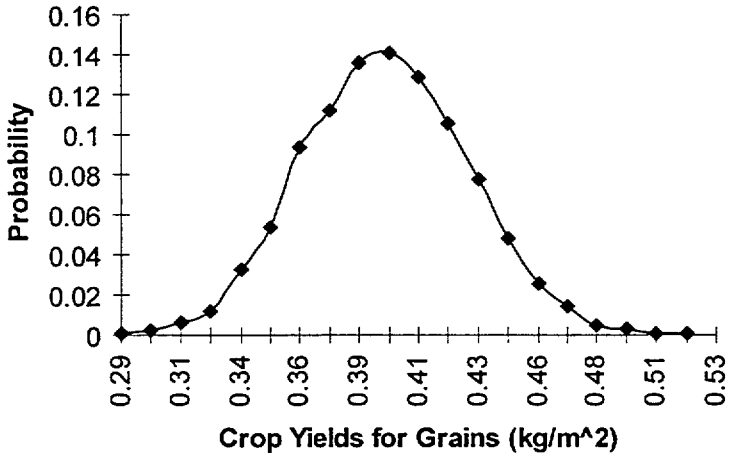

Figure 6.32 PDF for crop yields for grain

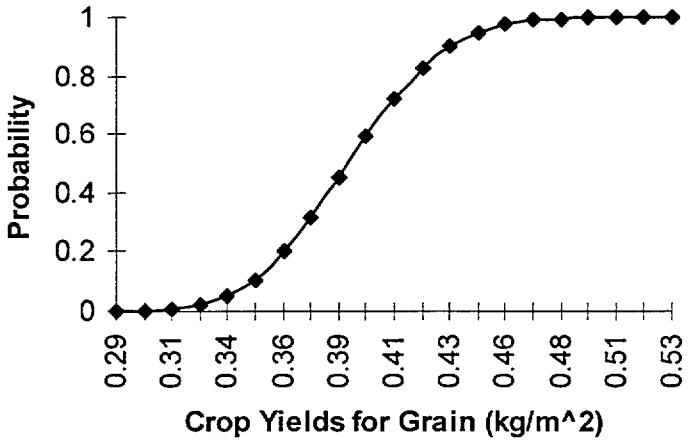

Figure 6.33 Cumulative distribution for Y_v (grain)

Table 6.55 Average yields and distribution for edible crops

Crop	Average yield (kg/m^2)	Range (kg/m^2)
Vegetables (leafy)	2.9	2.7 – 3.2
Vegetables (other)	2.4	2.3 – 2.5
Fruits	2.4	2.2 – 2.6
Grains	0.40	0.28 – 0.52

6.4.5.3.1 Use of Y_f in Modeling

Y_f is used to calculate the average deposition rate of radionuclide j to forage crop f from application of irrigation water during the feeding period for an average unit concentration of parent radionuclide i in water (pCi/d kg wet-weight plant per pCi/L water), R_{wfjf}. The relationship between Y_f and R_{wfjf} is described by the following:

$$R_{wfjf} = IR r_f \, T_f / Y_f [C_{wjj} / C_{wi}] \qquad (6.69)$$

where IR is the annual average application rate of irrigation water (L/m^2 d); r_f is the fraction of initial deposition of radionuclides in water retained on plant h (pCi retained per pCi deposited); T_f is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant (pCi in edible plant parts per pCi retained); Y_f is the yield of the forage crop f (kg wet-weight plant/m^2); C_{wj} is the average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water); and C_{wi} is the average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water).

6.4.5.3.2 Additional Information Reviewed to Define Revised Values for Y_f

Estimates of the crop yields for forage were obtained from information compiled by the USDA (USDA, 1997b,c). These data are summarized in Table 6.56.

The frequency distribution and fitted data PDF for average annual yield of forage crops in Table 6.56 are shown in Figure 6.34. The corresponding calculated and observed cumulative distributions are shown in Figure 6.35.

6.4.5.3.3 Proposed Distribution for Crop Yields for Forage

The distribution for Y_f was based on the average annual yield of forage crops. The binned data from Table 6.56 were fit to several functions and evaluated. The best fit was obtained with a beta function. The distribution parameters are shown in Table 6.57.

Table 6.56 Crop yields for forage crops (USDA, 1997c)

Year	Yield (kg dry-weight/m^2)
1987	0.484
1988	0.383
1989	0.456
1990	0.473
1991	0.486
1992	0.492
1993	0.486
1994	0.503
1995	0.511
1996	0.484

Table 6.57 Distribution parameters for crop yields for forage

Parameter	Value
a_1	2.36
a_2	1.26
δ_1	0.370
δ_2	0.524

6.4.5.4 Crop Yield for Stored Grain, Y_g (kg/m^2)

Crop yield for stored grain, Y_g, is the quantity of grain produced per unit area of cultivated land. The model uses a single, constant value for the yield of grain crops grown for consumption by beef cattle, poultry, milk cows, and layer hens. NUREG/CR-5512, Vol. 1, proposed the following values: beef cattle, 1.0 kg/m^2; poultry, 1.0 kg/m^2; milk cows, 1.0 kg/m^2; layer hens, 1.0 kg/m^2. These values were based on information published by (Shor, 1982), (Strenge et al., 1987), and (Napier et al., 1988).

6.4.5.4.1 Use of Parameter in Modeling

Y_g is used to calculate the average deposition rate of radionuclide j to stored grain from applying irrigation water with a unit concentration of parent radionuclide i (pCi/d kg wet-weight plant per pCi/L water), R_{wgig}. The relationship between Y_g and R_{wgig} is described by the following (Equation 5.53, p. 5,46 if NUREG/CR-5512, Vol. 1):

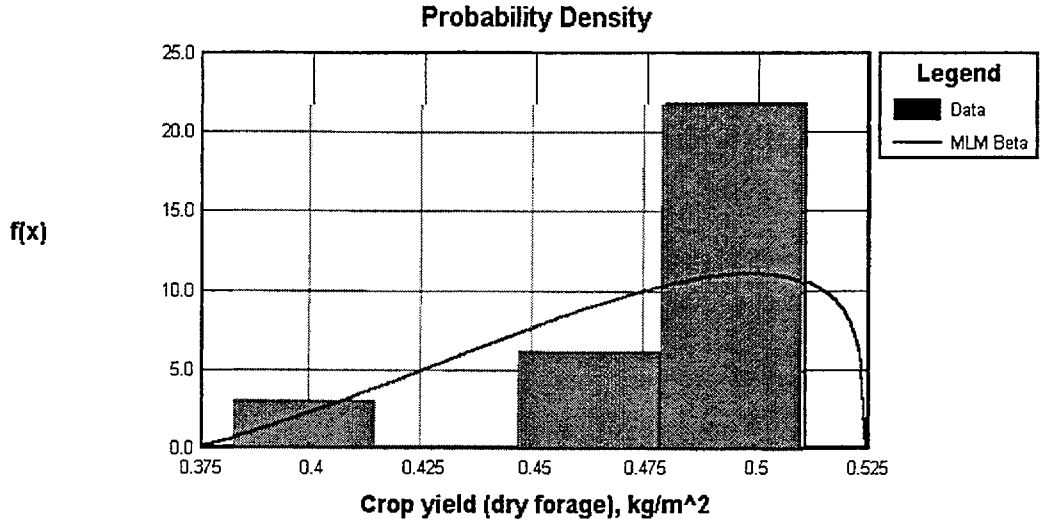

Figure 6.34 Frequency distribution and proposed PDF for Y_f

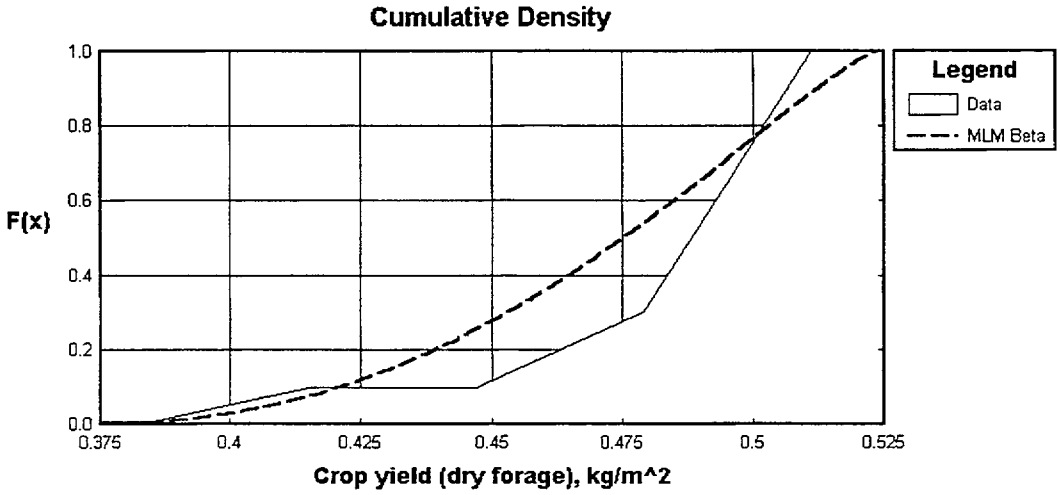

Figure 6.35 Cumulative distribution for Y_f

$$R_{wgjg} = IR\ r_g T_g / Y_g [C_{wj}/C_{wi}] \qquad (6.70)$$

where IR is the annual average application rate of irrigation water (L/m^2 d); r_g is the fraction of initial deposition of radionuclides in water retained on grain (pCi retained per pCi deposited); T_g is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant (pCi in edible plant parts per pCi retained); Y_g is the yield of stored grain g (kg wet-weight plant/m^2 of land); C_{wj} is the average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water); and C_{wi} is the average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water).

6.4.5.4.2 Additional Information Reviewed to Define Revised Values for Y_g

An estimate of the crop yield for grain was obtained from USDA crop reports collected across the United States. Tables 6.58 through 6.60 show the total acres harvested and the quantities and yields of corn, sorghum, and oats during the ten-year period beginning in 1987 (USDA, 1997b,c).

6.4.5.4.3 Proposed Distribution for Crop Yields for Grain

The distribution for Y_g was the value determined from the average annual yields of grain crops in Table 6.61. The resident farmer is assumed to cultivate a mix of

grains that matches the fraction of the total cultivated area devoted to the three major grains. Table 6.61 shows the effective yield for this mixture calculated from the annual data in Tables 6.58 through 6.60. Annual variations in this yield were assumed to approximate the potential variations among sites. The binned data from Table 6.61 were fit to several functions and evaluated. The best fit was obtained with a normal function. The distribution parameters are shown in Table 6.62.

The frequency distribution and fitted PDF for average annual yield of grain crops in Table 6.61 are shown in Figure 6.36. The corresponding calculated and observed cumulative distributions are shown in Figure 6.37.

Table 6.58 Annual production of corn in the United States

Year	Acres	Fraction	Bushels	Yield (kg/m^2)
1987	59,505,000	0.773556	7,131,300,000	0.753
1988	58,250,000	0.799896	4,928,681,000	0.532
1989	64,783,000	0.782706	7,531,953,000	0.730
1990	66,952,000	0.816607	7,934,028,000	0.744
1991	68,822,000	0.824137	7,474,765,000	0.682
1992	72,077,000	0.813299	9,476,698,000	0.826
1993	62,921,000	0.831848	6,336,470,000	0.633
1994	72,917,000	0.84936	10,102,735,000	0.871
1995	64,995,000	0.853681	7,373,876,000	0.713
1996	73,147,000	0.833727	9,293,435,000	0.798
Mean		0.817882		0.728
Std. Dev.		0.02647		0.098

Table 6.59 Annual production of sorghum in the United States

Year	Acres	Fraction	Bushels/1000	Yield (kg/m^2)
1987	10,531,000	0.136901	730,809,000	0.436
1988	9,042,000	0.124166	576,686,000	0.401
1989	11,103,000	0.134146	615,420,000	0.348
1990	9,089,000	0.110858	573,303,000	0.396
1991	9,870,000	0.118192	584,860,000	0.372
1992	12,050,000	0.135969	875,022,000	0.456
1993	8,916,000	0.117874	534,172,000	0.376
1994	8,917,000	0.103911	649,206,000	0.457
1995	8,178,000	0.107414	460,373,000	0.354
1996	11,901,000	0.135647	802,974,000	0.424
Mean		0.122508		0.402
Std. Dev.		0.012687		0.0401

Table 6.60 Annual production of oats in the United States

Year	Acres	Fraction	Bushels	Yield (kg/m^2)
1987	6,888,000	0.089543	373,713,000	0.195
1988	5,530,000	0.075939	217,375,000	0.141
1989	6,882,000	0.083148	373,587,000	0.195
1990	5,947,000	0.072535	357,654,000	0.216
1991	4,816,000	0.057671	243,851,000	0.182
1992	4,496,000	0.050732	294,229,000	0.235

Table 6.60 Annual production of oats in the United States (continued)

Year	Acres	Fraction	Bushels	Yield (kg/m^2)
1993	3,803,000	0.050278	206,770,000	0.195
1994	4,010,000	0.046729	229,008,000	0.205
1995	2,962,000	0.038905	162,027,000	0.196
1996	2,687,000	0.030626	155,225,000	0.207
Mean		0.05961		0.197
Std. Dev.		0.019687		0.0243

Table 6.61 Weighted average annual yield of grain crops

Year	Yield (kg dry-weight/m^2)
1987	0.581
1988	0.428
1989	0.559
1990	0.588
1991	0.543
1992	0.657
1993	0.510
1994	0.701
1995	0.576
1996	0.642

Table 6.62 Distribution parameters for crop yields for grain

Parameter	Value
μ	0.5781
σ	0.0777

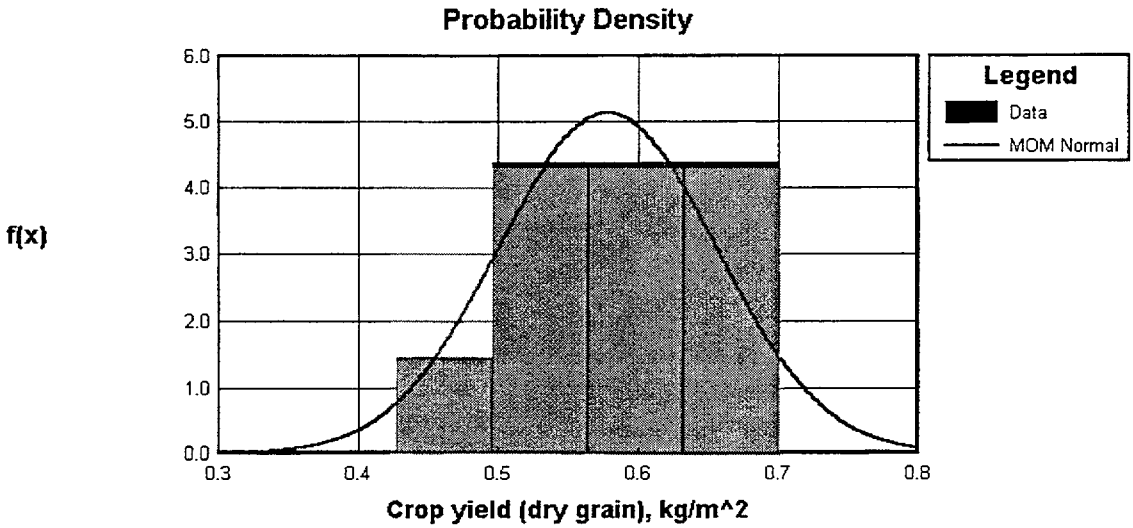

Figure 6.36 Frequency distribution and proposed PDF for Y_g

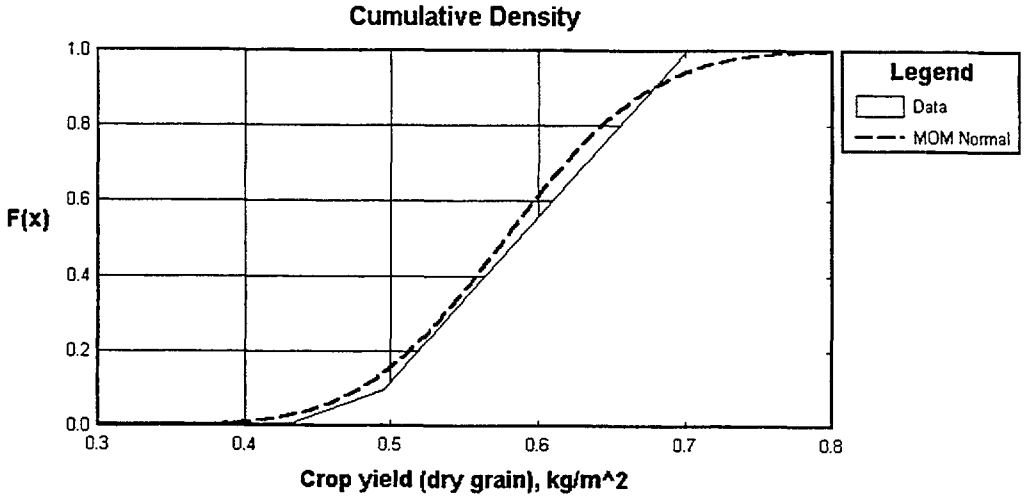

Figure 6.37 Cumulative distribution for Y_g

6.4.5.5 Crop Yield for Stored Hay, Y_h (kg/m^2)

Crop yield for stored hay, Y_h, represents the quantity of hay produced per unit area of cultivated land. The model accepts different values of Y_h for hay crops grown for consumption by beef cattle, poultry, milk cows, and layer hens. The crop yields are defined by standing biomass. Volume 1 proposes the following default values: beef cattle, 1.5 kg/m^2; poultry, 1.0 kg/m^2; milk cows, 1.5 kg/m^2; layer hens, 1.0 kg/m^2. These values were based on information published by Shor (1982), Strenge (1987), and Napier et al. (1988).

6.4.5.5.1 Use of Y_h in Modeling

The average deposition rate of radionuclide j to the stored hay crop from irrigation water, R_{whjg}, is calculated as follows (Equation 5.48, p. 5.41 of NUREG/CR-5512, Vol. 1):

$$R_{whjg} = IR\ r_h T_h / Y_h \left[C_{wj} / C_{wi} \right] \qquad (6.71)$$

where IR is the annual average application rate of irrigation water (L/m^2-d); r_h is the fraction of initial deposition of radionuclides in water retained on plant h (pCi retained per pCi deposited); T_h is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant (pCi in edible plant parts per pCi retained); Y_h is the yield of the stored hay crop h (kg wet-weight plant/m^2); C_{wj} is the average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water); and C_{wi} is the average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water).

6.4.5.5.2 Additional Information Reviewed to Define Revised Values for Y_h

Estimates of the crop yields for hay were obtained from data compiled by the USDA (USDA, 1997b,c). These values are listed in Table 6.63.

6.4.5.5.3 Proposed Distribution for Crop Yields for Stored Hay

The distribution for Y_h was determined from the average annual yields of hay crops. The binned data from Table 6.63 were fit to several functions and evaluated. The best fit was obtained with a beta function. The distribution parameters are shown in Table 6.64.

The frequency distribution and fitted PDF for average annual yield of hay crops in Table 6.63 are shown in Figure 6.38. The corresponding calculated and observed cumulative distributions are shown in Figure 6.39.

Table 6.63 Crop yields for hay crops (USDA, 1997b)

Year	Yield (kg dry-weight/m^2)
1987	0.484
1988	0.383
1989	0.456
1990	0.473
1991	0.486
1992	0.492
1993	0.486
1994	0.503
1995	0.511
1996	0.484

Table 6.64 Distribution parameters for crop yields for hay

Parameter	Value
a_1	2.36
a_2	1.26
δ_1	0.370
δ_2	0.524

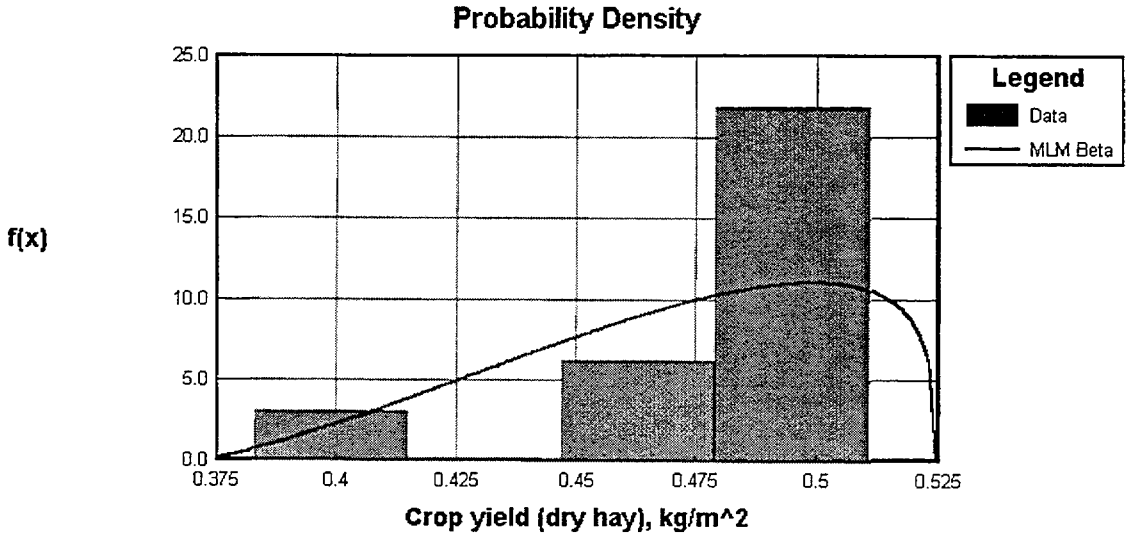

Figure 6.38 Frequency distribution and proposed PDF for Y_h

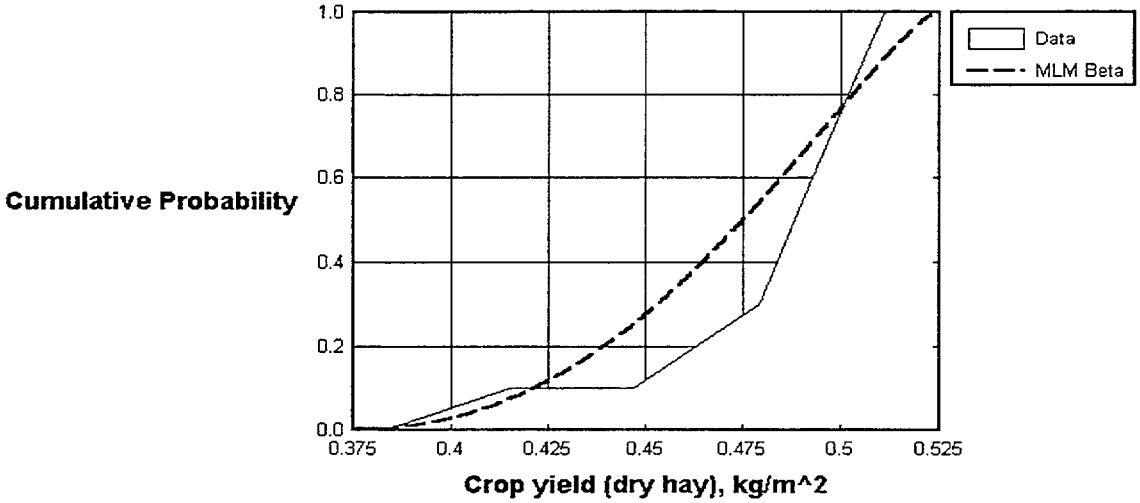

Figure 6.39 Cumulative distribution for Y_h

6.4.5.6 Uncertainty in Y_h

The distributions for each of the individual crops are based on the assumption that the resident farmer produces crops in direct proportion to the production across the United States. This assumption is not intended to describe any individual farmer, but corresponds to the conception of the receptor as the average member of the screening group of resident farmers. The average member of this group grows the average amount of each crop type.

The effective yield for this mixture is expected to vary from site to site because of variations in climate, soil conditions, and farming practice. Data on variations on the effective yield was not found. Instead, the distributions that describe this variability were estimated from other information on crop yields, including:

- Summary statistics for annual yields of individual vegetables, fruits, and grains from 1994 to 1996;
- Annual national average yields for forage, grain, and hay from 1987 to 1996.

Estimating the parameter distributions from this data requires assumptions about the independence of yield variations for different crop types, and about the similarity of site-to-site variations in yield to year-to-year variations in yield for hay, forage, and grain. These assumptions introduce uncertainty in the resulting distributions.

6.4.5.7 Alternative Y_h Values

Crop yields can vary from site to site depending on the location, climatic conditions, and soil type.

6.4.6 Animal Feed Intake Rates for Forage (Q_f), Stored Grain (Q_g), and Stored Hay (Q_h) Consumed by Beef Cattle, Poultry, Milk Cows, and Layer Hens (kg/d)

6.4.6.1 Description of Animal Feed Intake Rates

The animal feed intake rates represent the average daily quantities of on-site produced foods consumed by livestock in the residential scenario. The feed intake rates for beef cattle, poultry, milk cows, and layer hens are used in the agricultural pathway to determine the total dose due to consumption of animal products. The animal feed consumption rates are combined with the fraction of food consumed that is contaminated and plant concentration factors to determine animal product concentration factors of radionuclides in a given quantity of product consumed by humans over the time period of interest.

6.4.6.2 Use of Animal Feed Intake Rates in Modeling

The animal feed intakes rates are used in the calculation of partial pathway transfer factors, PPTFs, for plant and animal products contaminated by soil. For a given concentration of contaminants in foods consumed by animals, the greater the animal feed intake rate, the higher the dose to humans via consumption of animal products.

The animal feed intake rates, Q_f, Q_g, and Q_h, are used to calculate the concentrations of radionuclides in beef, milk-producing cows, egg-laying hens, and meat-producing poultry that consume fresh forage, grain, or hay raised in contaminated soil irrigated with contaminated water. Those contaminated animal products are assumed to be raised and consumed on site by humans. While grazing fresh forage, the transfer of contaminants from soil to animal products occurs by two different processes: 1) ingestion of contaminated plant matter (through resuspension and root uptake from soil to plants) by animals, and 2) ingestion of contaminated soil by animals during grazing. For ingestion of stored grain or stored hay, the transfer of contaminants from soil to stored grain occurs by resuspension and root uptake from soil to the grain crop. Animals consume the contaminated plant matter which is then converted to animal products consumed by humans.

The following equations taken from NUREG/CR-5512, Vol. 1, are those for fresh forage and therefore include the subscript 'f'. Unless noted, identical equations are used for stored grain (subscript 'g') and stored hay (subscript 'h'). Note that some of the parameters in the equations have somewhat different definitions, primarily with respect to the timing of events. The references to the equations for stored hay and stored grain are also given in the following discussion.

The concentration of radionuclides in fresh forage consumed by the animal (at any time) is evaluated as follows (Equation 5.13, p. 5.19, NUREG/CR-5512, Vol. 1):

$$C_{sfjt} = 1000\left(ML_f + B_{jf}\right) W_f \, A\left\{C_{sj}, t\right\} / C_{si}(0) \qquad (6.72)$$

where C_{sfjt} is the concentration factor for radionuclide j in fresh forage crop f at time t, from an initial unit concentration of parent radionuclide i in soil; ML_f is the plant soil mass-loading factor for resuspension of soil

onto the forage plant f; B_{jf} is the concentration factor for uptake of radionuclide j from the soil in fresh forage crop f; W_f is the dry-weight-to-wet-weight conversion factor for fresh forage crop f; $A\{C_{sj}, t\}$ denotes concentration of radionuclide j in soil at time t during the feeding period for fresh forage crop f; t is any point in time during the fresh forage feeding period; and $C_{si}(0)$ is the initial concentration of parent radionuclide i in soil at the start of the growing period. For stored grain and stored hay, the NUREG/CR-5512, Vol. 1, references are Equations 5.12 and 5.11, respectively.

For fresh forage only, the average concentration of radionuclides in forage over the feeding period, t_{ff}, is evaluated as (from Equation 5.15, p. 5.21, NUREG/ CR-5512, Vol. 1):

$$C_{sfjc} = 1000\left(ML_f + B_{jf}\right) W_f \, A\left\{C_{sj}, t_{ff}\right\} / \left[t_{ff} C_{si}(0)\right] \quad (6.73)$$

where C_{sfjc} is the average concentration factor for radionuclide j in fresh forage crop f over the feeding period at time of animal consumption of forage from an initial unit concentration of parent radionuclide i in soil, $S\{C_{sj}, t_{ff}\}$ is the concentration time integral factor for radionuclide j in soil over the feeding period, and t_{ff} is the feeding period for forage crop f.

The concentration factor for animal product *a*, over the time period of feeding on fresh forage for radionuclide j for an initial unit concentration of parent radionuclide in soil, C_{sajf}, is given by (Equation 5.18, p. 5.22 of NUREG/CR-5512, Vol. 1):

$$C_{sajf} = F_{aj} \, Q_f \, x_f \, C_{sfjc} \quad (6.74)$$

where F_{aj} is the transfer coefficient that relates daily intake in animal feed and ingested soil to the concentration of radionuclide j in an animal product *a*, Q_f is the consumption rate of fresh forage by the animal, x_f is the fraction of animal forage intake that is contaminated, and C_{sfjc} is the average concentration factor for radionuclide j in fresh forage crop f, over the feeding period, at the time of animal consumption of forage from an initial unit concentration of parent radionuclide i in soil. For stored grain and stored hay, the NUREG/CR-5512, Vol. 1, references are Equations 5.17 and 5.16, respectively.

While ingesting fresh forage only, the amount of soil ingested while grazing is a function of the fresh forage intake rate. The average concentration factor for animal product *a*, over the fresh forage feeding period for radionuclide j for initial unit concentration of parent radionuclide i in soil, C_{sajd}, is given by the following (Equation 5.19, p. 5.22 of NUREG/CR-5512, Vol. 1):

$$C_{sajd} = 1000 \, F_{aj} \, Q_d \, W_f \, Q_f \, x_f \, S\left\{C_{sj}, t_{ff}\right\} / \left[t_{ff} C_{si}(0)\right] \quad (6.75)$$

where Q_d is the soil intake as a fraction of forage intake for the animal; W_f is the dry to wet-weight conversion factor for fresh forage; $S\{C_{sj}, t_{ff}\}$ is the concentration time-integral factor for radionuclide j in fresh forage crop f over the feeding period, t_{ff}; t_{ff} is the feeding period for the forage crop; and $C_{si}(0)$ is the initial concentration of parent radionuclide in soil at the start of the growing period.

Finally, the ingestion dose from agricultural products grown in contaminated soil, secondary ingestion of soil, and ingestion of animal products is given by the following (Equation 5.71, p. 5.56, NUREG/CR-5512, Vol. 1):

$$DGR_i = C_{si} \, DIET \sum_{j=1}^{J_i} A_{stj} \, AF_{sj} \quad (6.76)$$

where DGR_i is the annual dose from intake of home-grown food and animal products, C_{si} is the initial concentration of parent radionuclide in soil at the time of release of the site (i.e., the start of the growing season for the first year), DIET is no longer used (see Section 6.2.1), A_{stj} is the concentration factor for radionuclide j in soil at the beginning of the current annual exposure period per initial unit concentration of parent radionuclide i is soil at time of site release, and AF_{sj} is the dose factor for ingestion of agricultural product per unit concentration of radionuclide j in soil at the beginning of the growing season.

6.4.6.3 Information Reviewed to Define Animal Feed Intake Rate Distributions

The values proposed in NUREG/CR-5512, Vol. 1 (Table 6.8, p. 6.19), for foods consumed by beef cattle, poultry, milk cows, and layer hens are shown in Table 6.65. Rates are specified for each of the animal product consumed by humans: dairy cattle produce contaminated milk; laying hens produce contaminated eggs.

The transfer of radionuclides to humans from animal products also includes the direct ingestion of soil by animals while consuming fresh forage. The default value for intake rate of soil for cattle (beef and milk cows) was set to 2% of dry-matter forage intake. For poultry and egg-laying hens, the default intake value of soil was set to 10% of dry-matter forage intake. As discussed in Section 6.4.1 on the soil intake fraction, Q_d, these default values will continue to be used in the models.

Table 6.65 Animal feed intake rates from NUREG/CR-5512, Vol. 1

Intake medium	Beef	Intake rate (kg wet-weight/d)		
		Poultry	Milk	Eggs
Fresh forage (Q_f)	27 (14)	0.13	36	0.13
Stored hay (Q_h)	14 (27)	0	29	0
Stored grain (Q_g)	3	0.09	2	0.09

* Corrected values in parenthesis - see text.

Determination of the wet-weight intake rates reported in Table 6.65 was performed using the dry-weight intake rate, the percent intake by feed type, and the percent water content in the feed of interest for the animal type (from NUREG/CR-5512, Vol. 1, Equation 6.12, p. 6.19) as follows:

$$\text{(Wet Weight Intake Rate)} = \frac{\text{(Dry Weight Intake Rate)}\ \text{(Percent Intake)}}{\text{(100-Percent Water Content)}} \quad (6.77)$$

Derivation of the default values in Table 6.65 assumed that the intake rate for beef cattle is based on a total daily intake of 12 kg (dry-weight), with 25% in the form of fresh forage, 50% as stored hay, and 25% as stored grain. A water content of 78% was used in converting stored hay and forage (dry weight) to a corresponding wet-weight basis. The stored grain has a water content of 9%. When the default values were calculated for fresh forage and stored hay for beef using Equation 6.72, we found the corresponding values were transposed in Table 6.8 of NUREG/CR-5512, Vol. 1. The corrected values are shown in parenthesis in Table 6.65.

The intake rate for milk cows was based on a total daily intake of 16 kg (dry-weight), with 50% in the form of fresh forage, 40% as stored hay, and 10% as stored grain. For poultry, the intake rates were based on a total daily intake of 0.11 kg, with 25% as fresh forage and 75% as stored grain. It is assumed that poultry do not consume stored hay or any products made from stored hay in the residential scenario.

Information on the consumption of forage, grain and hay crops by beef and dairy cattle, poultry, and layer hens was obtained from National Research Council publications on the nutrient requirements of livestock (National Research Council, 1996a, and references cited therein). This new information includes and supercedes the original references (such as IAEA, 1982 and Till and Meyer, 1983) provided in NUREG/CR-5512, Vol. 1, for determining the default values for animal food intake.

6.4.6.4 Animal Feed Intake Rate Distributions

In the following four subsections summarizing food consumption by livestock, a consistent approach was followed for developing distributions of dry- and wet-weight matter intake for animals. The NRC publications provide average values from a number of studies for "dry matter intake" (DMI). Those reported averages include a 12% moisture content.

In the following subsections, the DMI values are provided in tables and reduced to actual dry matter by backing out the 12% moisture content as reported. The actual dry matter data, Q_{dry}, are then used to develop distributions for the respective animal feed intake rates as dry matter. The distributions are corrected (shifted) to account for the percentage intake of food products by each animal as originally reported in NUREG/CR-5512 and as summarized above in the discussion of the default values.

In Section 6.4.9, the distributions for W_f, W_g, and W_h, the wet-to-dry-weight conversion factors for forage, stored grain, and stored hay, are determined based on the following equation (using fresh forage as an example):

$$W_f = (100 - \%\ \text{Moisture, Forage})/100 \quad (6.78)$$

The dry intake rate distributions, Q_{dry}, are sampled along with samples of the wet-to-dry conversion factor, to derive the distributions for Q_f, Q_g, and Q_h on a wet-weight basis. These calculations are based on the following (again, using the example for fresh forage):

$$Q_f = \frac{Q_{dry} \times \text{Fraction of Intake}}{W_f} \quad (6.78)$$

where Fraction of Intake is the Percent Intake divided by 100. Therefore,

$$Q_f = \frac{Q_{dry} \times \text{Percent Intake}}{100 - \text{Percent Moisture of Forage}} \quad (6.79)$$

6.4.6.4.1 Fresh Forage, Stored Grain, and Stored Hay Consumed by Beef Cattle

The dominant factors that determine DMI of beef cattle are physiological demand (based on body weight and age), differences among breeds of beef cattle, and gastrointestinal capacity limits. In this analysis, we assume that the nutrient value of fresh forage (as well as stored grain and stored hay) is the same as the dry matter documented here. We also assume, consistent with NUREG/CR-5512, Vol. 1, that fresh forage provides

25% of the total nutrient requirements for beef cattle, and stored grain and stored hay provide 25% and 50%, respectively, of total intake requirements. Researchers referenced by the National Research Council (National Research Council, 1996) developed equations and relationships to predict and estimate DMI requirements for beef cattle.

One of these, Thornton et al. (1985) reported results on 119,482 yearling British breed cattle over a 12-month period. The data in Table 6.66 show 14-day averages for actual daily intake of dry matter as fed to cattle (includes 12% moisture assumed by Thornton). The daily intake for cattle is a function of size and weight. The distribution for dry forage, stored grain, or stored hay, Q_{dry}, consumed by beef cattle was developed from data in Table 6.66 by backing out the moisture content and equally weighting the average daily dry intake rate for each age category. This distribution represents the variability of the daily intake of food.

Table 6.66 DMI for beef cattle (Wernig et al., 1999)

Age (days)	Weight (kg)	Actual average intake (kg/d) - DMI	Dry matter (no moisture)
0 – 14	321	7.91	6.96
15 – 28	329	9.91	8.72
29 – 42	352	9.96	8.76
43 – 56	374	10.04	8.84
57 – 70	394	10.13	8.91
71 – 84	415	10.18	8.96
85 – 98	433	10.13	8.91
99 – 112	451	9.95	8.76
113 – 126	468	9.50	8.36
127 – 140	485	8.95	7.88

The binned data were fit to several distributions and the fitness to each distribution was evaluated with a Kolmogorov-Smirnov test. The best fit was obtained with a beta distribution. Table 6.67 provides the beta distribution parameters for fresh forage, stored grain, and stored hay consumed by beef cattle. The frequency distribution and the corresponding PDF for the intake rate for forage by beef cattle, Q_{dry}, is shown in Figure 6.40. Similar PDFs for stored grain and stored hay are represented in Figures 6.41 and 6.42. The corresponding cumulative distributions for Q_{dry} for fresh forage, stored grain, and stored hay are shown in Figures 6.43, 6.44, and 6.45.

Table 6.67 Beta distribution parameters for fresh forage, stored grain, and stored hay

Parameter	Fresh forage	Stored grain	Stored hay
a_1	1.99	1.99	1.99
a_2	0.911	0.911	0.911
δ_1	1.69	1.69	3.38
δ_2	2.29	2.29	4.58

6.4.6.4.2 Forage, Stored Grain, and Stored Hay Consumed by Dairy Cattle

Table 6.68 shows DMI for dairy cattle by body weight and milk production (NRC, 1996). Estimates of DMI for dairy cattle are complicated by milk production rates, lactation periods, environmental factors, feed quality, body weight, and other physiological factors. Many researchers quoted in the NRC reports have proposed equations and approaches for predicting and estimating feeding rates. Odwongo and Conrad (1983) developed equations for predicting daily DMI for dairy cattle as shown in Table 6.68.

As noted above, these DMI values were corrected to actual DMI, Q_{dry}, by backing out the 12% moisture content that was reported and correcting for the percentage of forage, stored grain, or stored hay intake for dairy cattle. Dairy cattle are assumed to derive 50% of total nutrient requirements from fresh forage, 40% from stored hay, and 10% from stored grain. This allocation is consistent with the allocation assumed in NUREG/CR-5512, Vol. 1.

The binned data from Table 6.68 were then fit to several distributions and the fitness to each distribution was evaluated with a Kolmogorov-Smirnov test. The best fit for fresh forage and stored hay was obtained with a gamma distribution. For stored grain, the best fit was represented by a normal distribution. Table 6.69 provides the gamma and normal distribution parameters for fresh forage, stored grain, and stored hay consumed by dairy cattle. The frequency distribution and the fitted PDF for the intake rate for forage for dairy cattle, Q_{dry}, is shown in Figure 6.46. Similar PDFs for stored grain and stored hay are represented in Figures 6.47 and 6.48. The corresponding cumulative distributions for Q_{dry} for fresh forage, stored grain, and stored hay for dairy cattle are shown in Figures 6.49, 6.50, and 6.51.

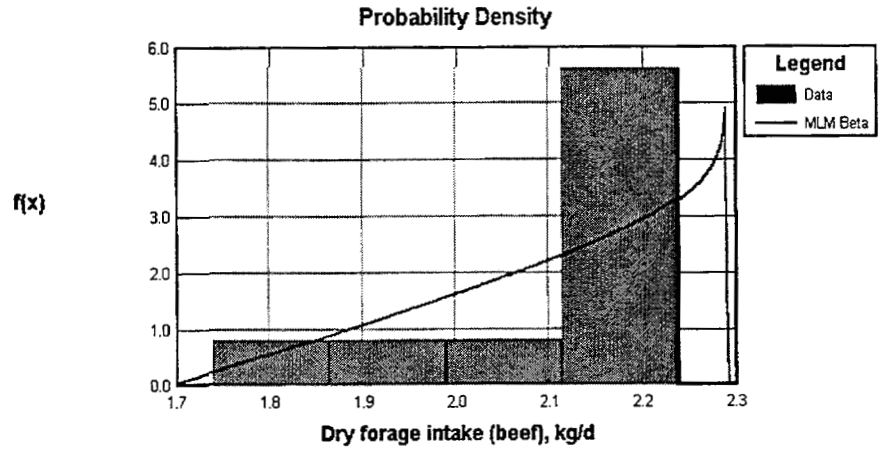

Figure 6.40 Calculated probability distribution for forage consumed by beef cattle

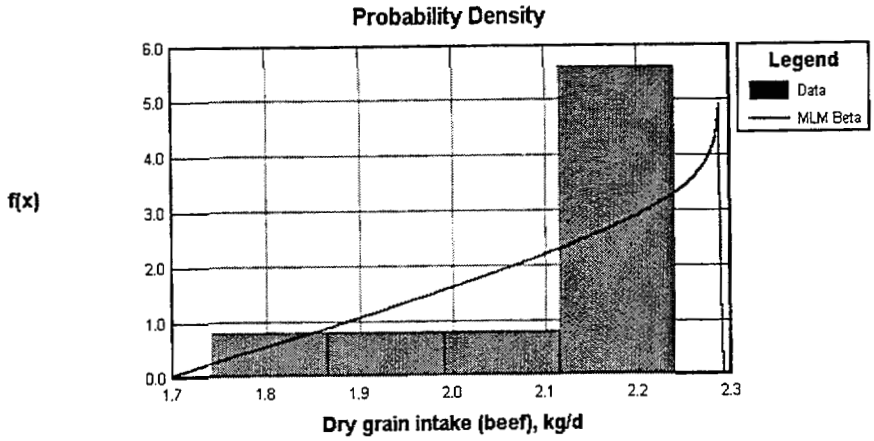

Figure 6.41 Calculated probability distribution for stored grain consumed by beef cattle

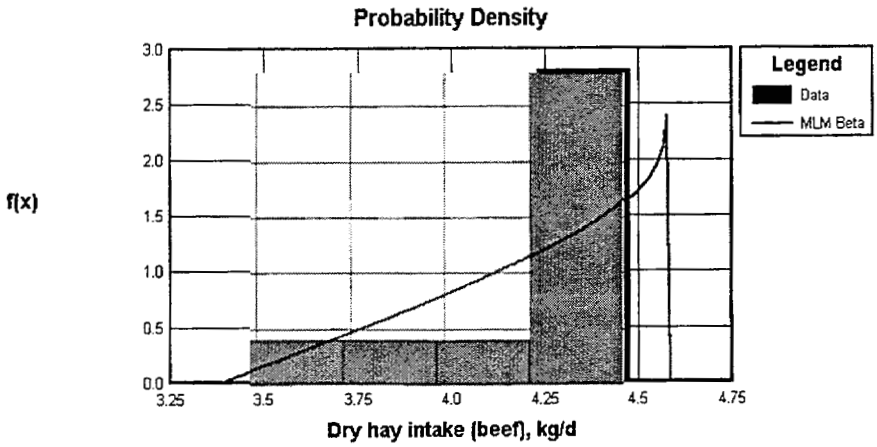

Figure 6.42 Calculated probability distribution for stored hay consumed by beef cattle

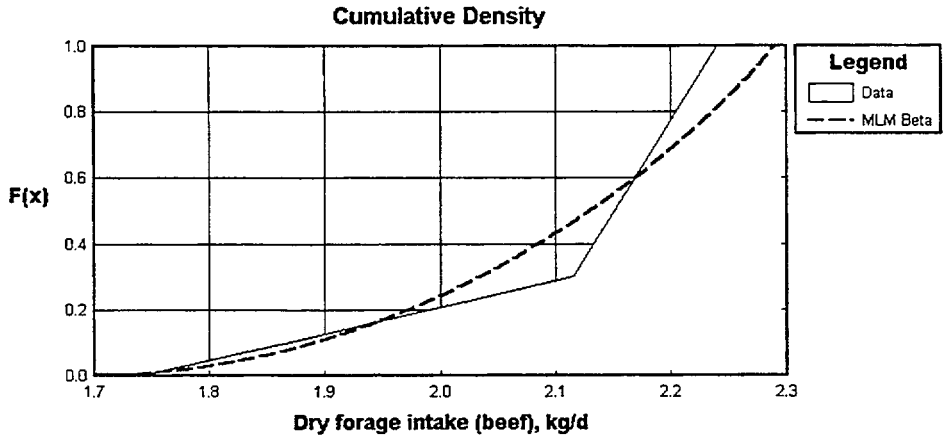

Figure 6.43 Cumulative distribution for forage consumed by beef cattle

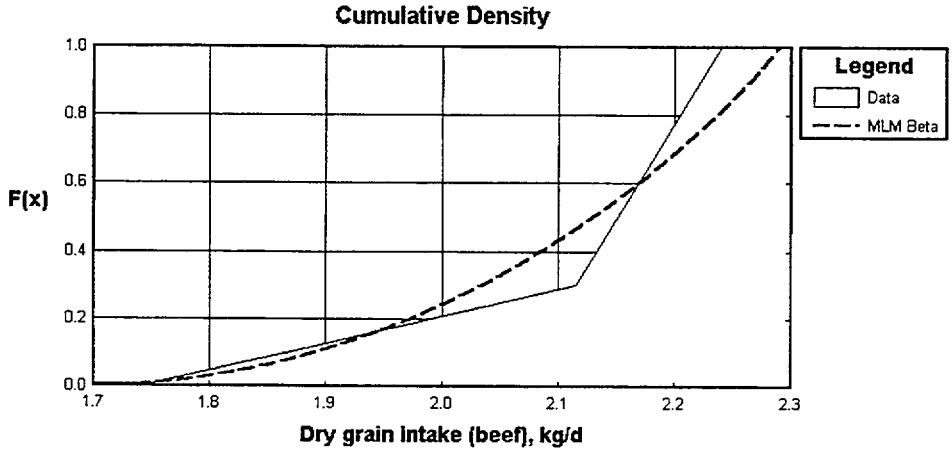

Figure 6.44 Cumulative distribution for stored grain consumed by beef cattle

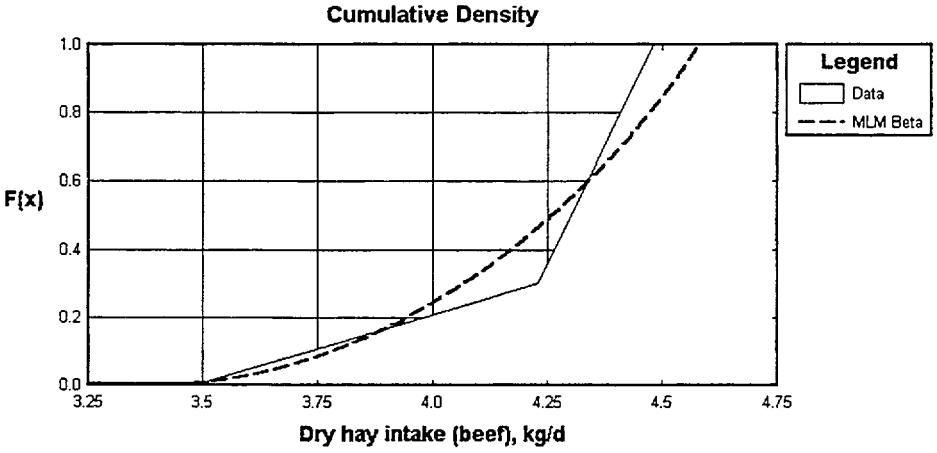

Figure 6.45 Cumulative distribution for stored hay consumed by beef cattle

Table 6.68 Predicted DMI in dairy cattle (kg/d) (NRC, 1996)

Milk production (Kg/d)	Body weight (kg)							
	400	450	500	550	600	650	700	800
	DMI (kg/d)							
15	14.7	15.7	16.8	17.7	18.7	19.6	20.5	22.1
20	14.9	16.0	17.1	18.0	19.0	20.0	20.9	20.5
25	14.7	15.8	16.8	17.8	18.8	19.7	20.5	22.7
30	14.5	15.6	16.6	17.6	18.5	19.4	20.3	22.2
35	*	16.4	17.5	18.5	19.5	20.4	21.3	22.0
40	*	*	18.3	19.4	20.4	21.4	22.4	28.6
45	*	*	*	20.2	21.2	22.2	23.2	29.0
55	*	*	*	19.9	21.0	22.0	23.0	29.7

* amount of feed computed was in excess of the amount that cows would be expected to eat

Table 6.69 Distribution parameters for forage, stored grain, and stored hay

Parameter	Fresh forage	Stored grain	Stored hay
Gamma			
κ	2.74		2.743
λ	1.15		1.43
ϵ	6.26		5.00
Normal			
μ		1.71	
σ		0.262	

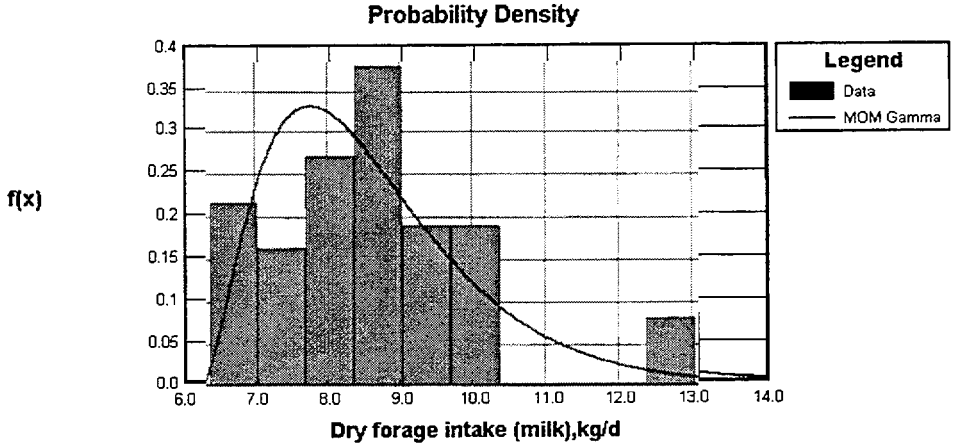

Figure 6.46 Calculated probability distribution for forage consumed by dairy cattle

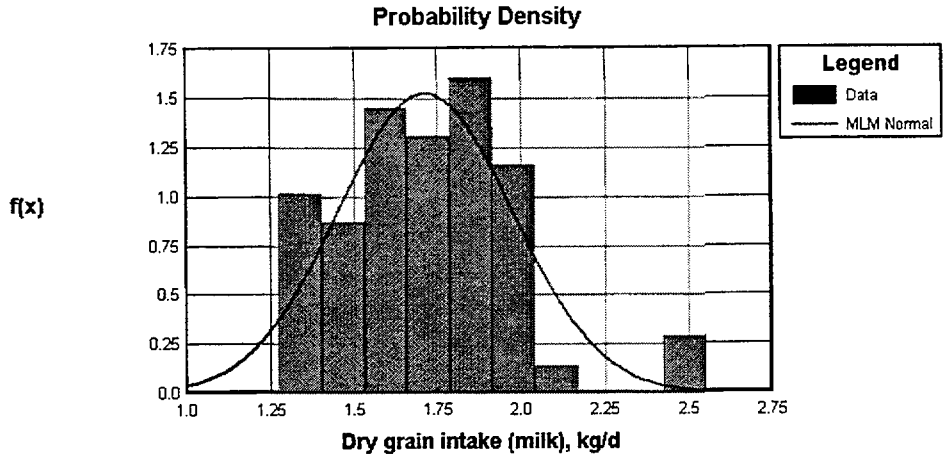

Figure 6.47 Calculated probability distribution for stored grain consumed by dairy cattle

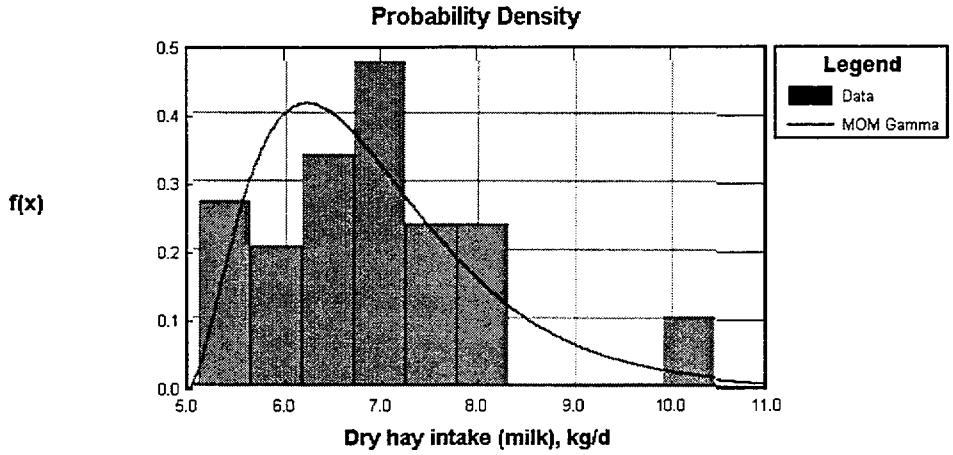

Figure 6.48 Calculated probability distribution for stored hay consumed by dairy cattle

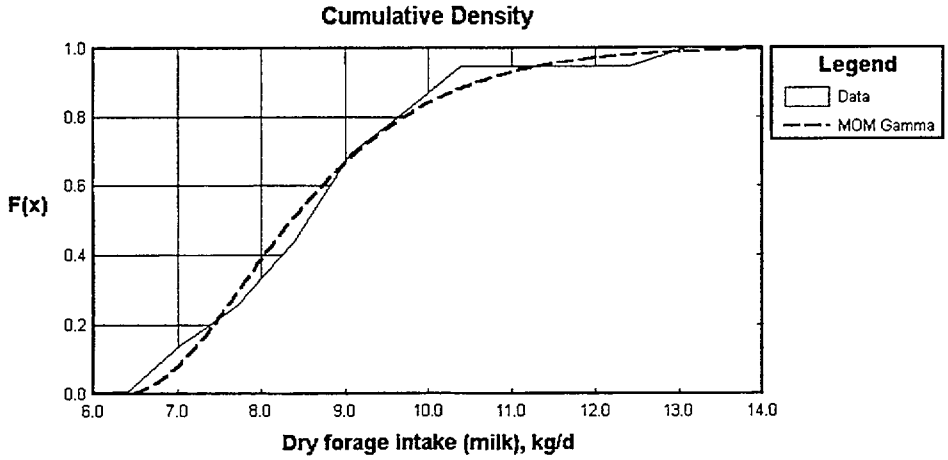

Figure 6.49 Cumulative distribution for forage consumed by dairy cattle

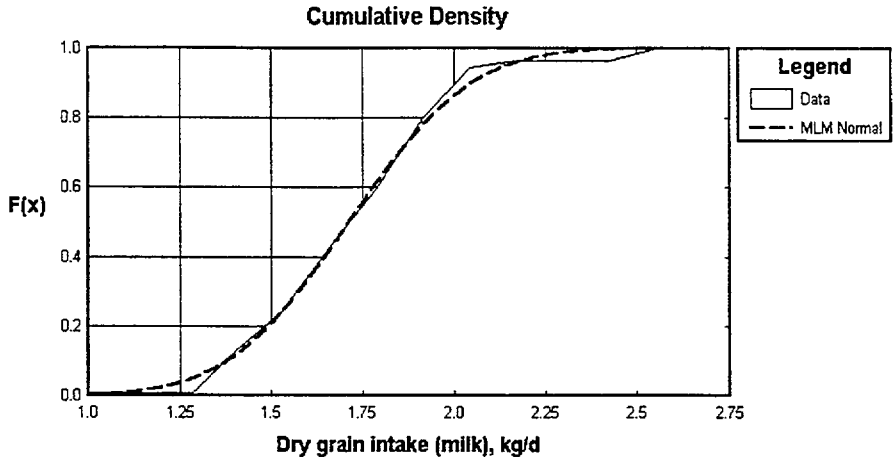

Figure 6.50 Cumulative distribution for stored grain consumed by dairy cattle

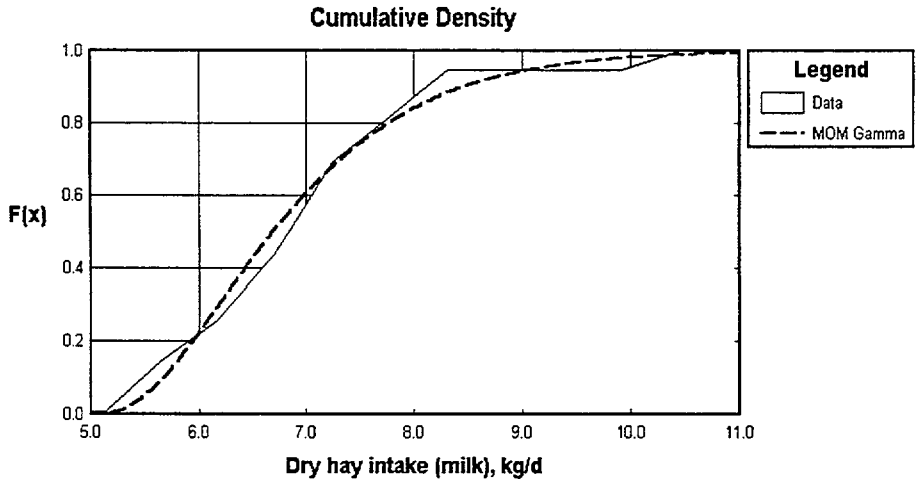

Figure 6.51 Cumulative distribution for stored hay consumed by dairy cattle

6.4.6.4.3 Fresh Forage and Stored Grain Consumed by Poultry

Waldroup et al. (1976), Hurwitz et al. (1978), and the NRC (1981) derived equations and estimates of DMI based on energy needs of a growing broiler chick. Table 6.70 summarizes these estimates in terms of the estimated average daily DMI rate for poultry derived from their estimated energy needs based on age. In poultry (broilers), feeding rate generally increases with age and body weight. The published values included a 12% moisture content which was factored into the DMI values given in the table. As above, this moisture content was then backed out to derive the intake of actual dry matter in broilers. Consistent with NUREG/CR-5512, Vol. 1, poultry are assumed to derive 25% of their total nutrient requirements from fresh forage and 75% from stored grain.

The binned data from the table were converted to consistent units (kg/d), multiplied by the assumed fractions for forage and grain intake for poultry, and were then fit to several distributions. The fitness to each distribution was evaluated with a Kolmogorov-Smirnov test. The best fit was obtained with a beta distribution. Table 6.71 provides the beta distribution parameters for fresh forage and stored grain consumed by poultry. The frequency distribution and the fitted PDF for the intake rates for forage and store grain for poultry, Q_{dry}, are shown in Figures 6.52 and 6.53. The corresponding cumulative distributions for poultry are shown in Figures 6.54 and 6.55.

Table 6.70 Predicted DMI for broilers at different ages (NRC, 1996)

Age (days)	BW (g)	Daily gain (g)	Est. energy needs (kcal/d)	DMI (g/d)	Dry matter (no moisture)
7	130	27	102.7	28.3	24.9
14	320	34	155.6	42.8	37.7
21	560	43	212.5	58.4	51.4
28	860	56	279.9	77.0	67.8
35	1250	63	340.5	93.6	82.4
42	1690	59	378.8	104.2	91.7
49	2100	60	420.6	115.6	101.7

Table 6.71 Beta distribution parameters for fresh forage and stored grain - poultry

Parameter	Fresh forage	Stored grain
a_1	1.51	1.52
a_2	1.41	1.41
δ_1	0.00348	0.0104
δ_2	0.0282	0.0845

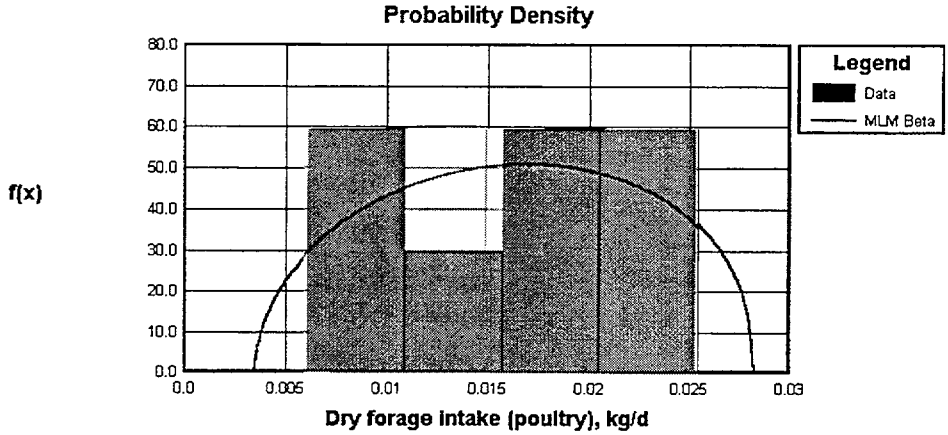

Figure 6.52 Calculated probability distribution for forage consumed by poultry

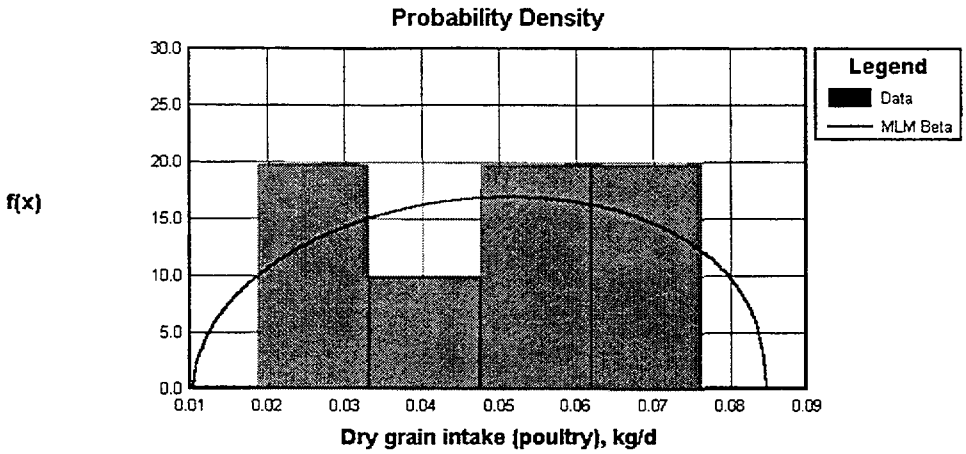

Figure 6.53 Calculated probability distribution for stored grain consumed by poultry

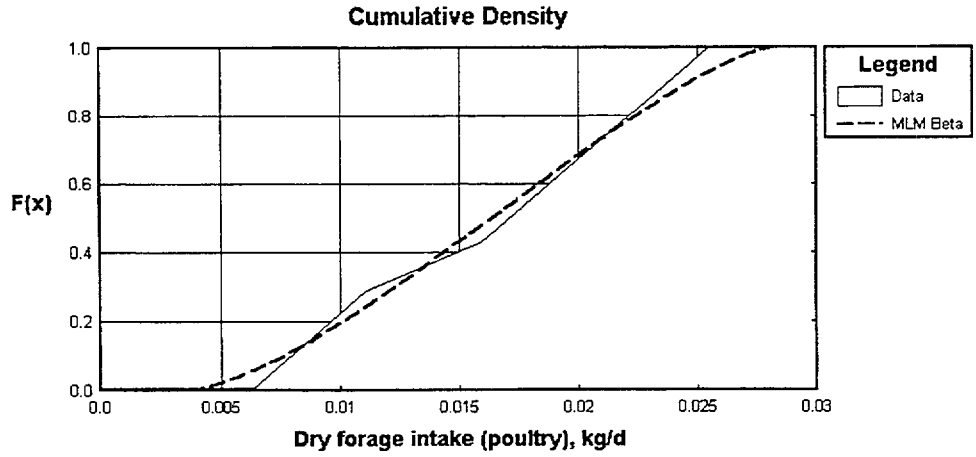

Figure 6.54 Cumulative distribution for forage consumed by poultry

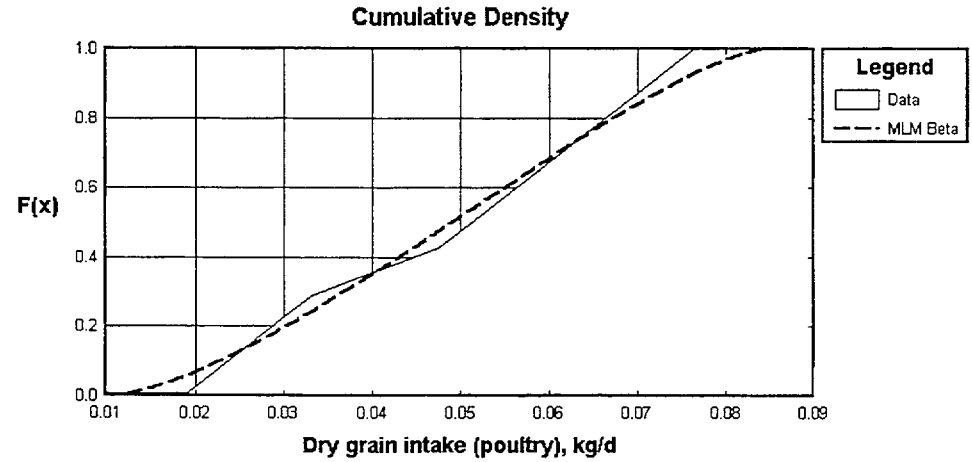

Figure 6.55 Cumulative distribution for stored grain consumed by poultry

6.4.6.4.4 Fresh Forage and Stored Grain Consumed by Layer Hens

Table 6.72 provides estimates of the average daily DMI rate for egg laying hens at different times in the egg production process. Laying hens generally attain a steady state of feed consumption once peak egg production has occurred. Byerly et al. (1980) and Hurwitz et al. (1978) developed equations that characterized observed feeding behavior of laying hens. Those equations were used to derive the DMI rates given in Table 6.72 which confirm the steady state feeding rate when egg production stabilizes in mature hens. The published values included a 12% moisture content which was included in the DMI values given in the table. Once again, this moisture content was used to calculate the intake of actual dry matter by laying hens. As with poultry, layer hens were assumed to derive 25% of their total nutrient requirements from fresh forage and 75% from stored grain.

Based on the average steady state DMI rate for mature hens, the data were converted to consistent units (kg/d) and multiplied by the assumed fractions for forage and grain intake for laying hens. The data were then binned and fit to several distributions and the fitness to each distribution was evaluated with a Kolmogorov-Smirnov test. The best fit was obtained with a beta distribution. Table 6.73 provides the beta distribution parameters for fresh forage and stored grain consumed by laying hens. The frequency distribution and the fitted PDF for the intake rates for forage and store grain for laying hens, Q_{dry}, are shown in Figures 6.56 and 6.57. The corresponding cumulative distributions for laying hens are shown in Figures 6.58 and 6.59.

Table 6.72 Predicted DMI for laying hens at different stages of egg production (NRC, 1996)

Age (weeks)	Egg production (%)	BW (g)	DMI (g/d)	Dry matter (no moisture)
20	5	1317	60.2	53.0
			56.0	49.3
			59.7	52.5
			61.9	54.5
24	62	1513	82.2	72.3
			78.2	68.8
			81.5	71.7
			83.9	73.8
28	91	1663	98.0	86.2
			94.1	82.8
			96.7	85.1
			99.3	87.4
32	89	1737	93.2	82.0
			89.4	78.7
			94.6	83.2
			97.2	85.5
36	87	1821	92.6	81.5
			88.8	78.1
			95.1	83.7
			97.9	86.2
40	85	1877	88.5	77.9
			84.9	74.7
			98.0	86.2
			95.8	84.3

Table 6.73 Beta distribution parameters for fresh forage and stored grain - laying hens

Parameter	Fresh forage	Stored grain
a_1	1.43	1.43
a_2	0.792	0.792
δ_1	0.0119	0.0358
δ_2	0.0222	0.0667

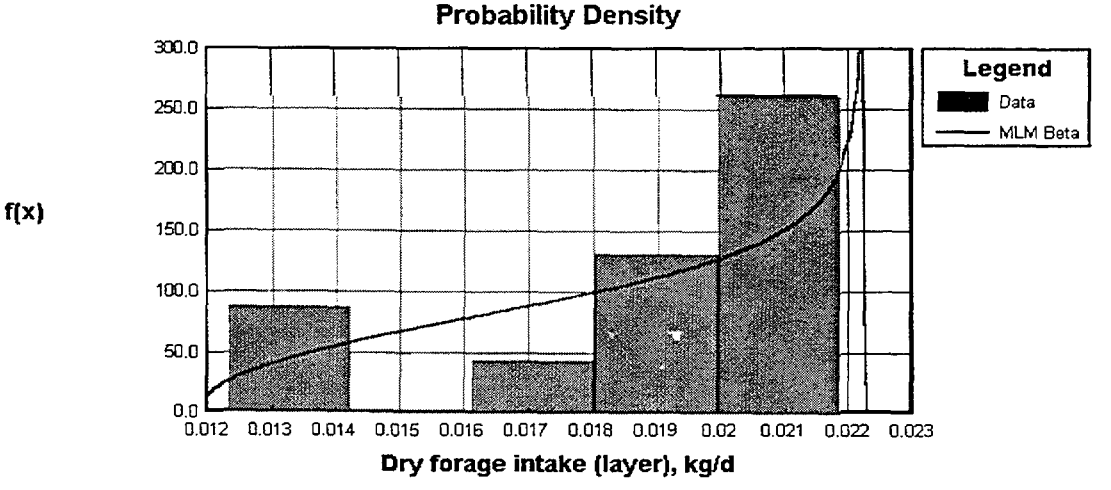

Figure 6.56 Calculated probability distribution for forage consumed by layer hens

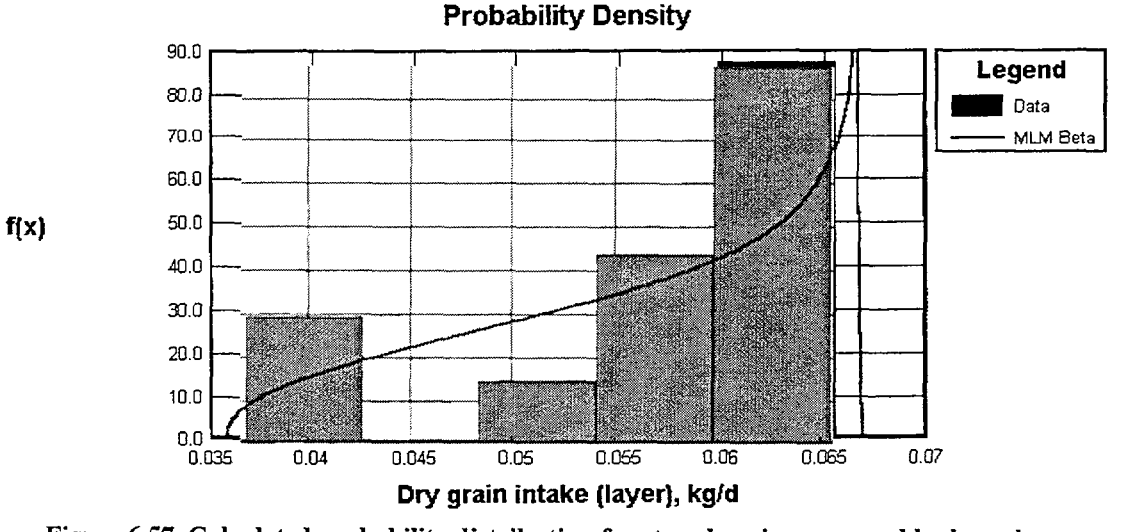

Figure 6.57 Calculated probability distribution for stored grain consumed by layer hens

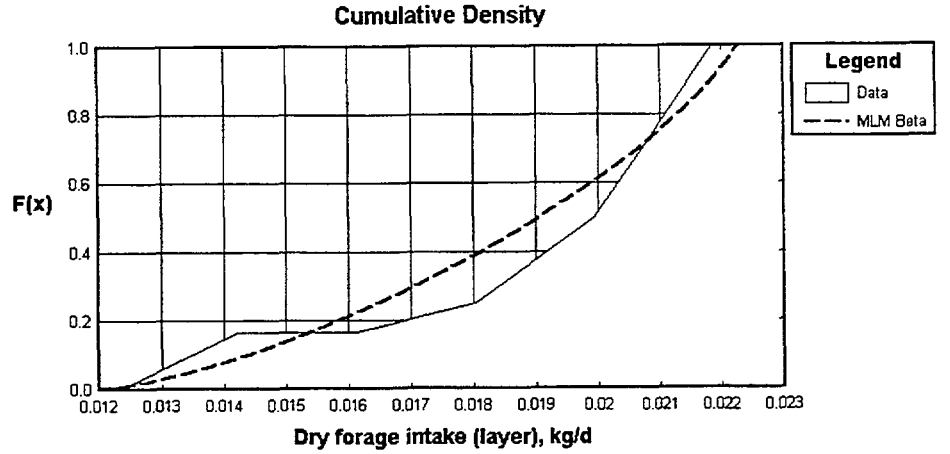

Figure 6.58 Cumulative distribution for forage consumed by layer hens

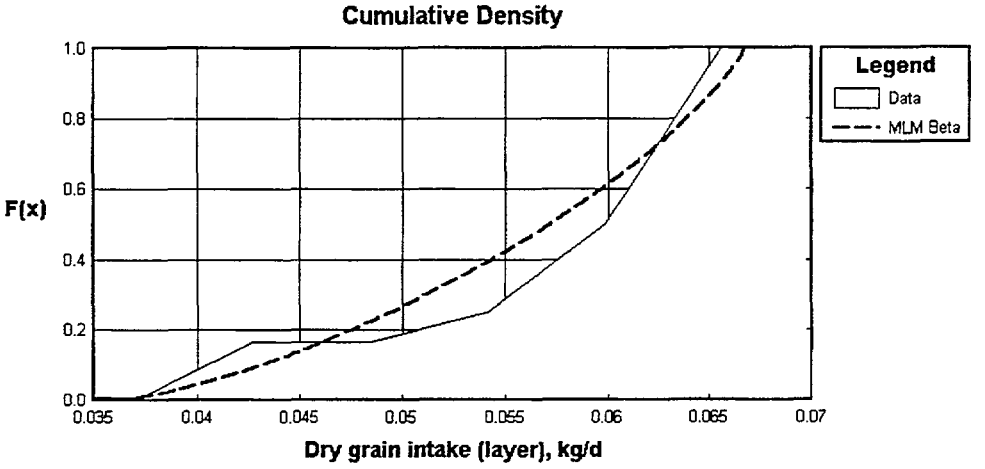

Figure 6.59 Cumulative distribution for stored grain consumed by layer hens

6.4.6.5 Uncertainty in Animal Feed Intake Rates

Distributions describing site-to-site variability in animal feed rates were derived from models developed by the NRC which predict total intake requirements as a function of the animal's age and, for cattle, weight. Variations among sites were assumed to be primarily due to variations in these physiological parameters, and each reporting category was assumed to be equally likely. These assumptions create uncertainty in the parameter distributions. The relative contributions of fresh forage, grain, and hay to each animal's diet were also uncertain. The proportions proposed in NUREG/ CR-5512, Vol. 1, were retained for this analysis.

6.4.6.6 Alternative Values for Animal Feed Intake Rates

These parameters are expected to vary to a small degree from site to site. The distributions for animal feed intake rates are established based on average daily intake rates that depend on factors such as the breed of animal, the age and size of the animal, physiological response, environmental factors (particularly temperature and humidity), diet water content, quantity and quality of food stocks fed to the animals, feed processing methods, use of anabolic stimulants and other feed additives, timing of feeding, and production rates. These factors introduce variability that is captured in the data and proposed parameter distributions.

Applicants may attempt to support alternative values for animal feed intake rates based on regional/seasonal variations in food availability, animal breeds, different varieties of forage and feeds available and intended for animal consumption, and intended production and use of the animal products for human consumption.

6.4.7 Vegetation Concentration Factors For Uptake, B_{jv} (unitless)

6.4.7.1 Description of B_{jv}

The concentration factors for uptake by vegetation, B_{jv}, as defined for NUREG/CR-5512, Vol. 1, dose modeling, estimate the amount of radionuclide uptake by plants grown in contaminated soil for both human consumption and as forage and feed for animals. The model uses a single, constant value for each chemical element for each of the following plant types: vegetables ("leafy" and "root"), fruits, and grains. Each value represents the average uptake for each of these cultivar groups.

6.4.7.2 Use of B_{jv} in Modeling

The concentration factor for uptake is important to modeling dose since the higher the value for B_{jv}, the higher the CEDE value for ingestion via the agricultural pathway (i.e., soil-plant-human and soil-plant-animal-human).

The concentration factor for uptake (B_{jv}) is used to calculate the concentration factor (C_{svjh}) for a radionuclide in a plant at harvest from an initial soil concentration of parent radionuclide. The mathematical relation between B_{jv} and C_{svjh} is given in NUREG/CR-5512, Vol. 1 (Equation 5.5, p. 5.12):

$$C_{svjh} = 1000\left(ML_v + B_{jv}\right) W_v \, A\left\{C_{sj}, t_{gv}\right\} / C_{si}(0), \qquad (6.80)$$

where:

C_{svjh} = concentration factor for radionuclide j in plant v at harvest from an initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight plant per pCi/kg dry-weight soil),

B_{jv} = concentration factor for uptake of radionuclide j from the soil in plant v (pCi/kg dry-weight plant per pCi/kg dry-weight soil),

ML_v = plant soil mass-loading factor for resuspension of soil to plant type v (pCi/kg dry-weight plant per pCi/kg dry-weight soil),

W_v = dry-weight-to-wet-weight conversion factor for plant v (kg dry-weight plant per kg wet-weight plant),

$A\{C_{sj}, t_{gv}\}$ = decay operator notation used to develop the concentration of radionuclide j in soil at the end of the crop-growing period, t_{gv} (pCi/g dry-weight soil),

C_{sj} = concentration of radionuclide j in soil during the growing period (pCi/g dry-weight soil),

$C_{si}(0)$ = initial concentration of parent radionuclide i in soil (pCi/g dry-weight soil),

t_{gv} = growing period for food crop v (d), and

1000 = unit conversion factor (g/kg).

The units of radionuclide activity are not always in pCi. However, as long as the units of activity for the plant and the soil are the same, the ratio of plant to soil concentration is preserved and can be used to compare data from different sources.

6.4.7.3 Information Reviewed to Define B_{jv} Distributions

Soil-to-plant concentration factors are given for leafy vegetables, root vegetables, fruits, and grains in NUREG/CR-5512, Table 6.16, repeated here as Table 6.74. Leafy vegetables are part of the "vegetative" portion of plants, while all the other categories are considered "reproductive" portions of plants. Therefore, there are values for B_{jv} for four vegetation categories and 82 elements, for a total of 328 values. However, for nearly all the elements, there is one value given for leafy vegetables and one value that is given for all the reproductive crop types, reducing the number of distinct values for B_{jv} from 328 to approximately 164.

All but a few of the values given in Volume 1 were obtained from Baes et al. (1984). The remainder come from a compilation of the International Union of Radioecologists (IUR 1989), except for the element californium, for which default values were taken from Strenge et al. (1987). Most of the values taken from Baes et al. (1984) are the geometric means of data distributions. For many elements Baes et al. (1984) also provide the geometric standard deviation. The range between two standard deviations from the mean for a single element often exceeds two orders of magnitude.

Soil-to-plant concentration factor distributions with ranges of several orders of magnitude are not uncommon (Arkhipov et al., 1975, Dahlman et al., 1976, Whicker 1978, and Sheppard and Evenden, 1988). The variability in concentration factors is the result of numerous and complex underlying processes such as climate, growing conditions, plant metabolism, plant rooting traits, soil type, soil moisture, soil texture, and soil pH.

A lognormal distribution is consistently proposed as the most appropriate distribution for concentration factors (Gilbert and Simpson, 1985, Sheppard and Evenden, 1988, Sheppard and Evenden, 1990, and Murphy and

Table 6.74 Soil-to-plant concentration factors from NUREG/CR-5512 (Table 6.16, pages 6.25-6.27), pCi/kg dry weight per pCi/kg soil

Element	Leafy vegetables	Root vegetables	Fruit	Grain
H	*	*	*	*
Be	1.0E-2	1.5E-3	1.5E-3	1.5E-3
C	7.0E-1	7.0E-1	7.0E-1	7.0E-1
N	3.0E+1	3.0E+1	3.0E+1	3.0E+1
F	6.0E-2	6.0E-3	6.0E-3	6.0E-3
Na	7.5E-2	5.5E-2	5.5E-2	5.5E-2
Mg	1.0E+0	5.5E-1	5.5E-1	5.5E-1
Si	3.5E-1	7.0E-2	7.0E-2	7.0E-2
P	3.5E+0	3.5E+0	3.5E+0	3.5E+0
S	1.5E+0	1.5E+0	1.5E+0	1.5E+0
Cl	7.0E+1	7.0E+1	7.0E+1	7.0E+1
Ar	**	**	**	**
K	1.0E+0	5.5E-1	5.5E-1	5.5E-1
Ca	3.5E+0	3.5E-1	3.5E-1	3.5E-1
Sc	6.0E-3	1.0E-3	1.0E-3	1.0E-3
Cr	7.5E-3	4.5E-3	4.5E-3	4.5E-3
Mn	5.6E-1	1.5E-1	5.0E-2	2.9E-1
Fe	4.0E-3	1.0E-3	1.0E-3	1.0E-3
Co	8.1E-2	4.0E-2	7.0E-3	3.7E-3
Ni	2.8E-1	6.0E-2	6.0E-2	3.0E-2
Cu	4.0E-1	2.5E-1	2.5E-1	2.5E-1
Zn	1.4E+0	5.9E-1	9.0E-1	1.3E+0
Ga	4.0E-3	4.0E-4	4.0E-4	4.0E-4
As	4.0E-2	6.0E-3	6.0E-3	6.0E-3
Se	2.5E-2	2.5E-2	2.5E-2	2.5E-2
Br	1.5E+0	1.5E+0	1.5E+0	1.5E+0
Kr	**	**	**	**
Rb	1.5E-1	7.0E-2	7.0E-2	7.0E-2
Sr	1.6E+0	8.1E-1	1.7E-1	1.3E-1
Y	1.5E-2	6.0E-3	6.0E-3	6.0E-3
Zr	2.0E-3	5.0E-4	5.0E-4	5.0E-4
Nb	2.0E-2	5.0E-3	5.0E-3	5.0E-3
Mo	2.5E-1	6.0E-2	6.0E-2	6.0E-2
Tc	4.4E+1	1.1E+0	1.5E+0	7.3E-1
Ru	5.2E-1	2.0E-2	2.0E-2	5.0E-3
Rh	1.5E-1	4.0E-2	4.0E-2	4.0E-2
Pd	1.5E-1	4.0E-2	4.0E-2	4.0E-2
Ag	2.7E-4	1.3E-3	8.0E-4	1.0E-1
Cd	5.5E-1	1.5E-1	1.5E-1	1.5E-1
In	4.0E-3	4.0E-4	4.0E-4	4.0E-4
Sn	3.0E-2	6.0E-3	6.0E-3	6.0E-3
Sb	1.3E-4	5.6E-4	8.0E-5	3.0E-2
Te	2.5E-2	4.0E-3	4.0E-3	4.0E-3

Table 6.74 Soil-to-plant concentration factors from NUREG/CR-5512 (Table 6.16, pages 6.25–6.27), pCi/kg dry weight per pCi/kg soil (continued)

Element	Leafy vegetables	Root vegetables	Fruit	Grain
I	3.4E-3	5.0E-2	5.0E-2	5.0E-2
Xe	**	**	**	**
Cs	1.3E-1	4.9E-2	2.2E-1	2.6E-2
Ba	1.5E-1	1.5E-2	1.5E-2	1.5E-2
La	5.7E-4	6.4E-4	4.0E-3	4.0E-3
Ce	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Pr	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Nd	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Pm	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Sm	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Eu	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Gd	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Tb	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Dy	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Ho	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Er	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Hf	3.5E-3	8.5E-4	8.5E-4	8.5E-4
Ta	1.0E-2	2.5E-3	2.5E-3	2.5E-3
W	4.5E-2	1.0E-2	1.0E-2	1.0E-2
Re	1.5E+0	3.5E-1	3.5E-1	3.5E-1
Os	1.5E-2	3.5E-3	3.5E-3	3.5E-3
Ir	5.5E-2	1.5E-2	1.5E-2	1.5E-2
Au	4.0E-1	1.0E-1	1.0E-1	1.0E-1
Hg	9.0E-1	2.0E-1	2.0E-1	2.0E-1
Tl	4.0E-3	4.0E-4	4.0E-4	4.0E-4
Pb	5.8E-3	3.2E-3	9.0E-3	4.7E-3
Bi	3.5E-2	5.0E-3	5.0E-3	5.0E-3
Po	2.5E-3	9.0E-3	4.0E-4	4.0E-4
Rn	**	**	**	**
Ra	7.5E-2	3.2E-3	6.1E-3	1.2E-3
Ac	3.5E-3	3.5E-4	3.5E-4	3.5E-4
Th	6.6E-3	1.2E-4	8.5E-5	3.4E-5
Pa	2.5E-3	2.5E-4	2.5E-4	2.5E-4
U	1.7E-2	1.4E-2	4.0E-3	1.3E-3
Np	1.3E-2	9.4E-3	1.0E-2	2.7E-3
Pu	3.9E-4	2.0E-4	4.5E-5	2.6E-5
Am	5.8E-4	4.1E-4	2.5E-4	5.9E-5
Cm	3.0E-4	2.4E-4	1.5E-5	2.1E-5
Cf	1.0E-2	1.0E-2	1.0E-2	1.0E-2

* Concentration factors for tritium are not needed because a special model is used to determine tritium uptake in plants.
**Noble gases are not assumed to be taken up by plants.

Tuckfield, 1992). Because B_{jv} is the product of several variables, a lognormal distribution for B_{jv} is expected from the central limit theorem (Sheppard and Evenden, 1988).

The lognormal distribution bounds B_{jv} by zero and allows B_{jv} to go to infinity at probabilities approaching zero. At some level of contaminant concentration for each plant and each element, B_{jv} is bound by a toxicity limit. Rarely are these limits observed experimentally.

6.4.7.4 B_{jv} Probability Distributions

Distribution parameters were taken from Ng et al. (1982) and Baes et al. (1984) (Table 6.75). For the elements reported in Ng et al. (1982), the geometric means and geometric standard deviations (GSD) were taken directly from the text. For data given in Baes et al. (1984) geometric means are provided in the text, but the GSDs are provided only graphically and only for some elements. In lieu of visual estimation of the GSD for an element, a "generic" GSD proposed by Sheppard and Evenden (1990) was used. This GSD (2.47) was determined from a pool of 23 elements and more than 1,250 values for B_{jv}. Sheppard and Evenden (1990) demonstrate that the variance of B_{jv} is unrelated to site or element characteristics, suggesting that a generic GSD is appropriate for stochastic modeling of plant uptake. Because Ng et al. (1982) includes more detailed information on distribution parameters of B_{jv} than Baes et al. (1984), Ng et al. (1982) was used as the primary source for B_{jv} values. No revisions were required to the distributions of B_{jv} as they encompassed concentration factors found in other reports.

All the data from Baes et al. (1984) are given in units of pCi plant dry-weight per pCi soil dry-weight. Ng et al. (1982) give the data for leafy vegetation in units of pCi plant dry-weight per pCi soil dry-weight and for reproductive vegetation in units of pCi plant wet-weight per pCi soil dry-weight. To calculate the input value for the DandD code, the sampled values of dry-to-wet weight conversion factors were used to convert the B_{jv} values where required.

Table 6.75 Distribution properties for soil-to-plant concentration factors

Element	Leafy (non-reproductive) vegetation (pCi dry plant mass/pCi dry soil mass)			Reproductive vegetation[a]		
	Geometric mean	Geometric standard deviation	Data source[b]	Geometric mean	Geometric standard deviation	Data source[b]
H	*	*	*	*	*	*
Be	1.0E-2	2.47E+0	2	1.5E-3	2.47E+0	2
C	7.0E-1	2.47E+0	3	7.0E-1	2.47E+0	3
N	3.0E+1	2.47E+0	2	3.0E+1	2.47E+0	2
F	6.0E-2	2.47E+0	2	6.0E-3	2.47E+0	2
Na	7.4E-2	2.47E+0	1	4.6E-3	4.10E+0	1
Mg	1.0E+0	2.47E+0	2	5.5E-1	2.47E+0	2
Si	3.5E-1	2.47E+0	2	7.0E-2	2.47E+0	2
P	3.5E+0	2.47E+0	2	3.5E+0	2.47E+0	2
S	1.5E+0	2.47E+0	2	1.5E+0	2.47E+0	2
Cl	7.0E+1	2.47E+0	2	7.0E+1	2.47E+0	2
Ar	**	**	**	**	**	**
K	1.0E+0	2.47E+0	2	5.5E-1	2.47E+0	2
Ca	3.5E+0	2.47E+0	2	3.5E-1	2.47E+0	2
Sc	6.0E-3	2.47E+0	2	1.0E-3	2.47E+0	2
Cr	2.2E-2	2.20E+0	1	1.3E-2	2.00E+0	1
Mn	3.3E-1	7.60E+0	1	1.2E-1	4.90E+0	1
Fe	5.6E-3	3.80E+0	1	4.2E-4	3.50E+0	1
Co	8.8E-2	4.70E+0	1	1.5E-2	3.30E+0	1
Ni	3.4E-2	3.20E+0	1	2.1E-2	2.50E+0	1
Cu	4.9E-1	2.60E+0	1	4.3E-2	1.00E+1	1
Zn	5.8E-1	2.60E+0	1	1.1E-1	3.90E+0	1
Ga	4.0E-3	2.47E+0	2	4.0E-4	2.47E+0	2

Table 6.75 Distribution properties for soil-to-plant concentration factors (continued)

Element	Leafy (non-reproductive) vegetation (pCi dry plant mass/pCi dry soil mass)			Reproductive vegetation[a]		
	Geometric mean	Geometric standard deviation	Data source[b]	Geometric mean	Geometric standard deviation	Data source[b]
As	4.0E-2	2.47E+0	2	6.0E-3	2.47E+0	2
Se	2.5E-2	2.47E+0	2	2.5E-2	2.47E+0	2
Br	1.5E+0	2.47E+0	2	1.5E+0	2.47E+0	2
Kr	**	**	**	**	**	**
Rb	8.1E-1	3.60E+0	1	7.0E-2	2.47E+0	2
Sr	1.8E+0	3.80E+0	1	7.5E-2	3.80E+0	1
Y	1.5E-2	2.47E+0	2	6.0E-3	2.47E+0	2
Zr	7.2E-2	2.00E+0	1	7.7E-4	9.50E+0	1
Nb	2.0E-2	2.47E+0	2	5.0E-3	2.47E+0	2
Mo	2.2E+0	3.30E+0	1	6.0E-2	2.47E+0	2
Tc	9.5E+0	2.47E+0	2	1.5E+0	2.47E+0	2
Ru	6.2E-2	4.80E+0	1	1.4E-3	4.90E+0	1
Rh	1.5E-1	2.47E+0	2	4.0E-2	2.47E+0	2
Pd	1.5E-1	2.47E+0	2	4.0E-2	2.47E+0	2
Ag	4.0E-1	2.47E+0	2	1.0E-1	2.47E+0	2
Cd	5.5E-1	2.47E+0	2	1.5E-1	2.47E+0	2
In	4.0E-3	2.47E+0	2	4.0E-4	2.47E+0	2
Sn	3.0E-2	2.47E+0	2	6.0E-3	2.47E+0	2
Sb	2.0E-1	2.47E+0	2	3.0E-2	2.47E+0	2
Te	2.5E-2	2.47E+0	2	4.0E-3	2.47E+0	2
I	1.6E-1	3.50E+0	1	4.5E-3	4.90E+0	1
Xe	**	**	**	**	**	**
Cs	4.1E-2	3.50E+0	1	5.0E-3	4.10E+0	1
Ba	3.9E-2	2.90E+0	1	1.3E-3	3.10E+0	1
La	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Ce	2.1E-2	4.30E+0	1	7.3E-4	6.20E+0	1
Pr	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Nd	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Pm	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Sm	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Eu	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Gd	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Tb	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Dy	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Ho	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Er	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Hf	3.5E-3	2.47E+0	2	8.5E-4	2.47E+0	2
Ta	1.0E-2	2.47E+0	2	2.5E-3	2.47E+0	2
W	4.5E-2	2.47E+0	2	1.0E-2	2.47E+0	2
Re	1.5E+0	2.47E+0	2	3.5E-1	2.47E+0	2
Os	1.5E-2	2.47E+0	2	3.5E-3	2.47E+0	2
Ir	5.5E-2	2.47E+0	2	1.5E-2	2.47E+0	2
Au	4.0E-1	2.47E+0	2	1.0E-1	2.47E+0	2
Hg	9.0E-1	2.47E+0	2	2.0E-1	2.47E+0	2

Table 6.75 Distribution properties for soil-to-plant concentration factors (continued)

Element	Leafy (non-reproductive) vegetation (pCi dry plant mass/pCi dry soil mass)			Reproductive vegetation[a]		
	Geometric mean	Geometric standard deviation	Data source[b]	Geometric mean	Geometric standard deviation	Data source[b]
Tl	4.0E-3	2.47E+0	2	4.0E-4	2.47E+0	2
Pb	4.5E-2	2.47E+0	2	9.0E-3	2.47E+0	2
Bi	3.5E-2	2.47E+0	2	5.0E-3	2.47E+0	2
Po	2.5E-3	2.47E+0	2	4.0E-4	2.47E+0	2
Rn	**	**	**	**	**	**
Ra	1.5E-2	2.47E+0	2	1.5E-3	2.47E+0	2
Ac	3.5E-3	2.47E+0	2	3.5E-4	2.47E+0	2
Th	8.5E-4	2.47E+0	2	8.5E-5	2.47E+0	2
Pa	2.5E-3	2.47E+0	2	2.5E-4	2.47E+0	2
U	8.5E-3	2.47E+0	2	4.0E-3	2.47E+0	2
Np	1.1E+0	4.90E+0	1	6.0E-2	3.00E+0	**1**
Pu	4.5E-4	2.47E+0	2	4.5E-5	2.47E+0	2
Am	5.5E-3	2.47E+0	2	2.5E-4	2.47E+0	2
Cm	8.5E-4	2.47E+0	2	1.5E-5	2.47E+0	2
Cf	1.0E-2	2.47E+0	3	1.0E-2	2.47E+0	3

*Concentration factors for tritium are not needed because a special model is used to determine tritium uptake in plants.
**Noble gases are not assumed to be taken up by plants.
[a]Data Source 1 (pCi wet plant mass/pCi dry soil mass), indicated with bold font; Data Sources 2 and 3 (pCi dry plant mass/pCi dry soil mass).
[b] 1 = Ng et al. (1982); 2 = Baes et al. (1984); 3 = NUREG/CR -5512.

6.4.7.5 Alternative B_{jv} Values

It is not likely that site-specific information can reduce the uncertainty in concentration factors. There are simply too many factors affecting B_{jv}, factors that vary non-linearly in time and across locations, even to determine which ones might be the most important to predicting B_{jv} (and thus, reducing uncertainty) at a particular site. It is known that the inclusion of environmental variables, such as soil texture and pH, reduces the variability in concentration factors only marginally (Sheppard and Evenden, 1990). Thus, there is no benefit in correlating B_{jv} to site-specific parameters such as precipitation or soil properties.

6.4.8 Interception Fraction for Vegetation, r_v (unitless)

6.4.8.1 Parameter Description

The interception fraction for vegetation, r_v, as defined for NUREG/CR-5512, Vol. 1, dose modeling, estimates the fraction of deposited contamination retained on various cultivars grown for food and animal feed after above-ground irrigation with contaminated water. The model accepts different values of r_v for plants grown both for direct human consumption: "leafy" vegetables, "other" vegetables, fruits, and grains and for indirect human consumption as animal feed: forage plants (e.g., grass and alfalfa), grain, and hay. Thus, this value should represent the average fraction of all contaminants retained on edible plant surfaces after irrigation.

6.4.8.2 Use of Parameter in Modeling

The interception fraction is important to modeling dose since the higher the value for r_v, the higher the CEDE value for ingestion via the agricultural pathway (i.e., irrigation water-plant-human and irrigation water-plant-animal-human).

The interception fraction is used to calculate the constant, average rate of accommodation of a contaminant on plants by retention from irrigation. The mathematical relation between deposition and retention is given in NUREG/CR-5512, Vol. 1 (Equation 5.22, p. 5.27), by:

$$R_{wvjg} = IR\ r_v\ T_v/Y_v\left[C_{wj}/C_{wi}\right], \qquad (6.81)$$

where:

R_{wvjg} = average accommodation rate of radionuclide j on edible parts of plant v from application of

irrigation water per unit average concentration of parent radionuclide i in water (pCi/d kg^{-1} wet weight plant per pCi/L water),

IR = average annual application rate of irrigation water ($L/m^2 d^{-1}$),

r_v = fraction of initial application (in water) retained on plant v (pCi retained per pCi applied),

T_v = translocation factor for transfer of radionuclides from plant surfaces to edible parts of plant v (pCi in edible plant part per pCi retained),

Y_v = yield of plant v (kg wet weight/m^2),

C_{wj} = average annual concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water), and

C_{wi} = average annual concentration of radionuclide j in irrigation water over the current annual period (pCi/L water).

Because r_v represents the fraction of a contaminant in irrigation water that is retained on the surface of a plant, r_v must be between zero and one.

Hoffman et al. (1992) demonstrate that contaminants that have dried on plant surfaces after an irrigation event are not lost with subsequent washing. The model of continuous irrigation-rate-dependent accommodation, represented by Equation 6.81, is evidently appropriate. r_v was measured over a broad range of irrigation conditions, assumed here to be broad enough to encompass the expected range of variability in irrigation intensity and amount from one site to another.

Dose calculations require an estimate of the average, annual amount of a contaminant retained on a plant. In the irrigation water-plant-human pathway dose calculations, this is expressed as the amount of concentration received throughout the growing period and retained on the plant at the time of harvest (Equation 5.23, Vol. 1, p. 5.28):

$$C_{wvjh} = R_e\left[R_{wvjg}, t_{gv}\right], \qquad (6.82)$$

where:

C_{wvjh} = concentration factor for radionuclide j in plant v at harvest from retention on surfaces for an average unit concentration of parent radionuclide i in water (pCi/kg wet weight plant per pCi/L water),

t_{gv} = growing period for plant v (d), and

R_e = retention, accumulation operator used to develop the concentration factor of radionuclide j in plant v at harvest from application onto plant surfaces of an average unit concentration of parent radionuclide in water (pCi/kg wet weight plant per pCi/L water).

6.4.8.3 Information Reviewed to Define Distributions for r_v

The common value of 0.25 is proposed in Volume 1 for all plant types. This value, based on recommendations by Baker et al. (1976); is also adopted as a default value in Regulatory Guide 1.109. Baker et al. (1976) provide no explanation or justification of this value. As such, the only way to evaluate the appropriateness of this value is by comparison to existing experimental data.

Experimental results from an interception study using contaminated, simulated rain (Hoffman et al., 1992) indicate that biomass density is more important than vegetation type in affecting retention; when the data are normalized for biomass, differences in vegetation type, while statistically significant, are never major controlling variables for retention. Hoffman et al. (1992) also report similar results for a variety of herbaceous and woody plant types. Dose calculations using r_v include on inverse dependence on biomass yield (Y_v). A separate retention factor for different plant types is not included and the retention factors are assumed to apply equally to all plant types in the Volume 1 model.

The same experiment by Hoffman et al. (1992) provides information about the effects of ionic charge and solubility on retention. The study found that anions are essentially removed with the water once the vegetation surface becomes saturated, that cations are readily adsorbed to the plant surface, and that insoluble particles readily settle out on the plant surface. For cations, insoluble particles, and anions at irrigation rates comparable to those being considered (Section 6.2.7), the adsorption and settling rates are comparable, resulting in similar values of retention. Therefore, it is unnecessary to separate r_v into categories based on solubility or ionic charge. This approach is also impractical because the default scenario model does not represent detailed groundwater geochemistry. Because it is unknown what chemical forms contaminants might take, the effect of chemical form on the r_v parameter cannot be included in the generic model.

The adsorption (retention) of cations and insoluble particles on vegetation is similar, though the underlying processes differ. For cations, retention appears to be controlled by chemical adsorption to cation exchange sites in the leaf cuticle, while for insoluble materials, retention is controlled by the rapid settling out of particles from rain droplets and their consequent

adsorption on the plant surface.

6.4.8.4 r_v Probability Distribution

Interception fractions for cations and insoluble particles as reported by Hoffman et al. (1992) generally range from 0.1 to 0.6 with geometric means ranging from 0.15 to 0.37. The mean of the geometric means is 0.28. Given this, the default value of 0.25 recommended in NUREG/CR-5512 seems appropriate as an average value for the retention of contaminants on plants for this particular group of contaminants. The data provide practical limits for r_v, suggesting that the mean value of r_v can be increased or decreased by a factor of two and still remain within experimentally-derived limits of r_v.

The interception fraction for anions, as measured with ^{131}I by Hoffman et al. (1992) is dependent on the amount of irrigation applied. "Low" irrigation amounts from Hoffman et al. (1992) are approximately 1-15 mm d^{-1} and are the only rates applicable here, as the average irrigation rate being proposed is approximately 0.7 mm d^{-1} (Section 6.2.7).

At low irrigation levels the average r_v for anions is approximately 0.3; as with cations and insoluble particles, the value of 0.25 recommended in NUREG/CR-5512 is slightly lower than that average. The data provide practical limits for r_v, with a range of 0.15 to 0.6, suggesting that the mean value of r_v can be increased or decreased by a factor of two and still remain within experimentally-derived limits. Thus, the range given for cations and insoluble particles (0.1 to 0.6) also applies to anions.

Values for r_v from NUREG/CR-5512, Vol. 1, and the updated range of values for r_v are provided in Table 6.76. The probability distribution function of r_v given three values (minimum, maximum, and mean) is modeled with a uniform distribution (Figure 6.60).

6.4.8.5 Uncertainty in r_v

For all contaminant categories, retention is positively correlated with the total amount of biomass. This is explicitly accounted for in the model, since the modeling of dose using r_v (i.e., Equation 5.22) increases with increasing amounts of biomass (Y_v).

6.4.8.6 Alternative r_v Values

The limits of r_v are not likely to change with site-specific data because r_v is not strongly dependent on vegetation type. The stronger effect of the amount of vegetation at a site is included via yield (as discussed above).

Table 6.76 NUREG/CR-5512, Vol. 1, values and PDFs for r_v

Vegetation type	NUREG/CR-5512 value	PDF of r_v (uniform distribution)		
		Minimum	Maximum	Mean
leafy vegetable	0.25	0.10	0.60	0.35
other vegetable	0.25	0.10	0.60	0.35
fruit	0.25	0.10	0.60	0.35
grain consumed by humans	0.25	0.10	0.60	0.35
forage consumed by beef cattle	0.25	0.10	0.60	0.35
forage consumed by poultry	0.25	0.10	0.60	0.35
forage consumed by milk cows	0.25	0.10	0.60	0.35
forage consumed by layer hens	0.25	0.10	0.60	0.35
stored grain consumed by beef cattle	0.25	0.10	0.60	0.35
stored grain consumed by poultry	0.25	0.10	0.60	0.35
stored grain consumed by milk cows	0.25	0.10	0.60	0.35
stored grain consumed by layer hens	0.25	0.10	0.60	0.35
stored hay consumed by beef cattle	0.25	0.10	0.60	0.35
stored hay consumed by poultry	0.25	0.10	0.60	0.35
stored hay consumed by milk cows	0.25	0.10	0.60	0.35
stored hay consumed by layer hens	0.25	0.10	0.60	0.35

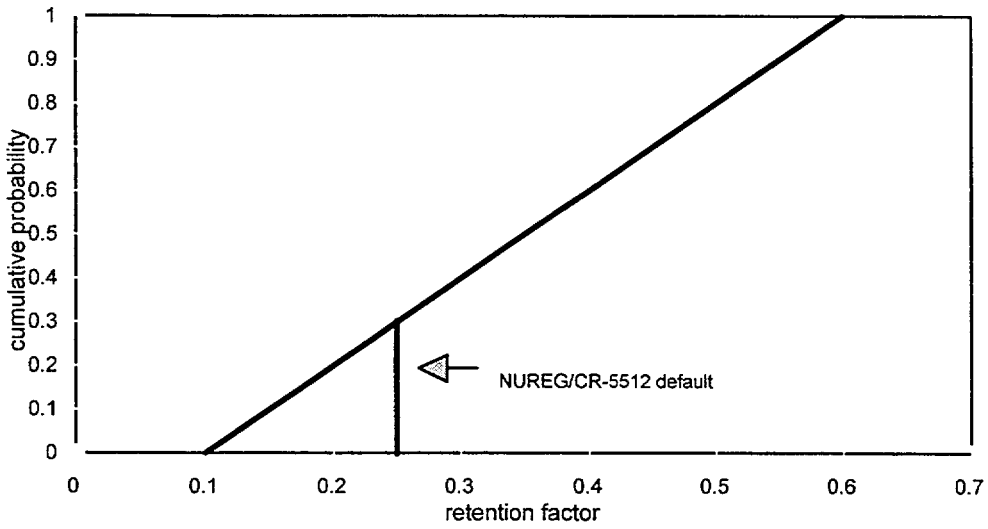

Figure 6.60 Retention factor cumulative probability distribution function

6.4.9 Wet-to-Dry-Weight Conversion Factors for Vegetables, Fruits, and Grains Consumed by Humans, W_v, and Forage, W_f, Stored Grain, W_g, and Stored Hay, W_h, Consumed by Beef Cattle, Poultry, Milk Cows, and Layer Hens (kg dry-weight/kg wet-weight)

6.4.9.1 Parameter Description

The wet-to-dry-weight conversion factors for garden produce and animal feed, as defined for the NUREG /CR-5512, Vol. 1, dose model, describe the dry weight of edible plants grown for human and animal consumption and represent the average concentration of dry matter in plants.

The conversion factors are needed to correct for the moisture content in edible parts of plants since both dry-weight and wet-weight factors are used in the default dose model. For example, the soil-to-plant concentration factors for individual radionuclides are defined in terms of the dry weight of plants, while the crop yields are expressed as the wet weight of plants per area.

6.4.9.2 Wet-to-Dry-Weight Conversion Factors for Vegetables, Fruits, and Grains, W_v

The four wet-to-dry-weight conversion factors for leafy vegetables, non-leafy vegetables, fruit, and grain represent the fractions of dry matter in garden produce.

6.4.9.2.1 Use of Parameter in Modeling

The wet-to-dry-weight conversion factors convert the weight of the garden produce at harvest to the corresponding or equivalent dry weight. These factors are required in two pathways: 1) soil-plant-human pathway to calculate the concentration factor for radionuclide j in plant v at harvest from an initial unit concentration of parent radionuclide i in soil, C_{svjh}, and 2) irrigation water-soil-plant-human pathway to calculate the concentration factor for radionuclide j in plant v at time of harvest resulting from resuspension and root uptake for an average unit concentration of parent radionuclide i in water, C_{rvjh}. C_{svjh} is calculated from the following equation (Equation 5.5, p. 5.12 of NUREG/ CR-5512, Vol. 1):

$$C_{svjh} = 1000\left(ML_v + B_{jv}\right) W_v \; A\{C_{sj}, t_{gv}\} / C_{si}(0) \qquad (6.83)$$

where ML_v is the plant soil mass-loading factor for resuspension of soil to plant type v; B_{jv} is the concentration factor for uptake of radionuclide j from the soil in plant v; W_v is the wet-to-dry-weight conversion factor for plant v; $A\{C_{sj},t_{gv}\}$ is the decay operator notation used to develop the concentration of radionuclide j in soil at the end of the crop-growing period; t_{gv} is the growing period for food crop v; and $C_{si}(0)$ is the initial concentration of parent radionuclide i in soil.

C_{rvjh}, is calculated from the following equation (Equation 5.31, p. 5.31 of NUREG/CR-5512, Vol. 1):

$$C_{rvjh} = \left(ML_v + B_{jv}\right) W_v \; C_{wvjh(soil)} \qquad (6.84)$$

where $C_{wvjh(soil)}$ is the concentration factor for radionuclide j in soil at harvest time for plant v for an average unit concentration of parent radionuclide i in water.

6.4.9.2.2 Information Used to Define the Distributions for W_v

Table 6.77 lists the plant types and the corresponding conversion factors used in NUREG/CR-5512, Vol.1. The conversion factors were taken from Till and Meyer (1983).

Table 6.77 Values for wet-to-dry-weight conversion factors for vegetables, fruits, and grains from NUREG/CR-5512, Vol. 1

Plant type	Conversion factor (kg dry-weight/kg wet-weight)
Vegetables, leafy	0.2
Vegetables, other	0.25
Fruit	0.18
Grain	0.91

The Human Nutrition and Information Service of the USDA compiled information on the nutritive value of over 900 foods, food products, and beverages (Gebhardt and Matthews, 1985). The data included water contents of vegetables, fruits, and grains, which are summarized in Table 6.78. The wet-to-dry-weight conversion factor is calculated from the following equation:

$$W_v = (100 - \%\ \text{water})/100 \qquad (6.85)$$

6.4.9.2.3 Distributions for Wet-to-Dry-Weight Conversion Factors for Vegetables, Fruit, and Grain

The moisture content varies from 77 to 96% in vegetables and fruits and from 11 to 12% in grains. Because of the similarity in the moisture content in vegetables and fruits, W_v for vegetables and fruits were assumed to have the same distribution. The frequency distribution and fitted PDF (Figure 6.61) for W_v (vegetables & fruits) were determined from data in Table 6.78. The PDF is defined by a gamma function with a mean of 0.1088 and lower and upper limits of 0.04 and 0.23. The calculated parameters for the gamma distribution are shown in Table 6.79. Figure 6.62 shows the cumulative distribution function for W_v for fruit and vegetables. Since W_v (grains) varies only slightly, a fixed value of 0.88 was used.

Table 6.78 Moisture content of farm and garden produce (Gebhardt and Matthews, 1985)

Garden produce	Water (% by wt.)
Vegetables, leafy	
Lettuce	96
Broccoli	91
Cauliflower	92
Celery	95
Parsley	88
Spinach	92
Cabbage	92
Vegetables, other	
Carrots	88
Radishes	95
Potatoes	77
Tomatoes	94
Peppers	93
Fruit	
Apples	84
Apricots	86
Blueberries	85
Cherries	90
Grapefruit	91
Grapes	81
Cantaloupe	90
Oranges	87
Peaches	88
Pears	84
Plums	85
Strawberries	92
Watermelon	92
Grain	
Wheat	12
Corn	12
Barley	11
Rice	12

Table 6.79 Distribution parameters for wet-to-dry-weight conversion factor for vegetables and fruits

Parameter	Value
κ	2.68
λ	35.1
ϵ	0.0324

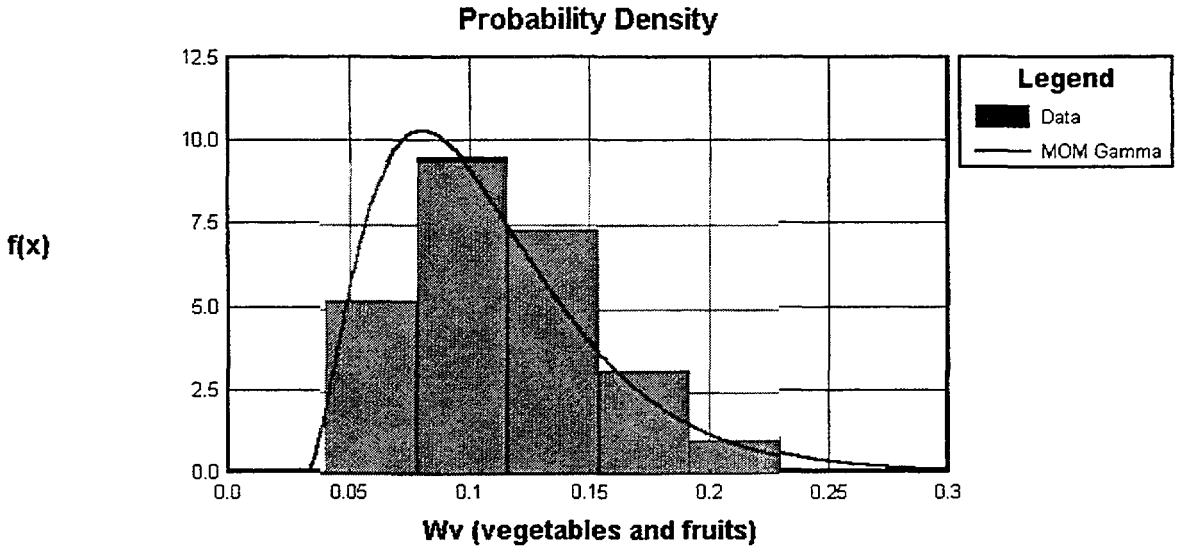

Figure 6.61 Frequency distribution and PDF for the wet-to-dry weight conversion factor for fruits and vegetables

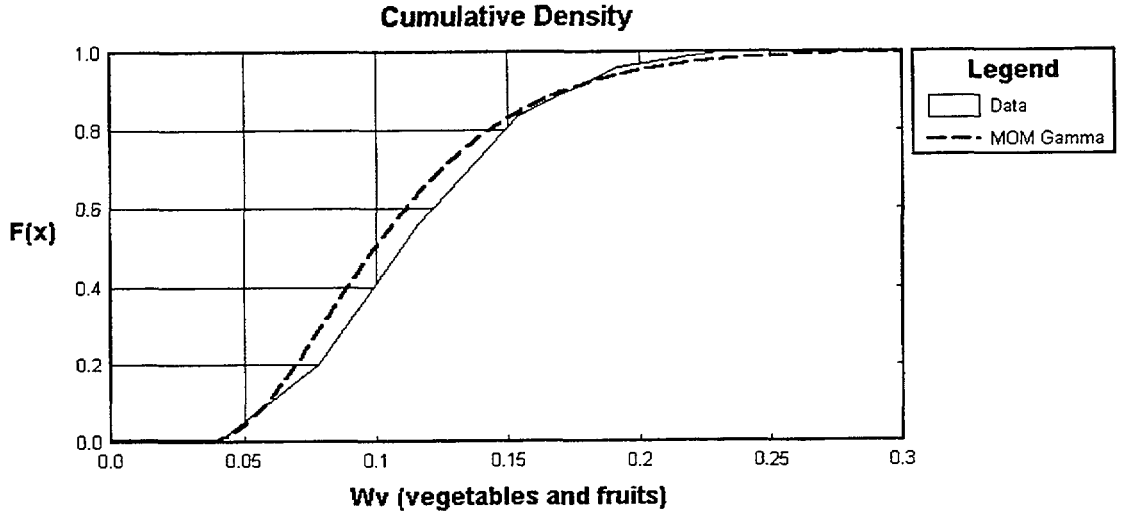

Figure 6.62 Cumulative distribution for the wet-to-dry-weight conversion factor for fruits and vegetables

6.4.9.3 Wet-to-Dry-Weight Conversion Factors for Forage Consumed by Beef Cattle, Poultry, Milk Cows, and Layer Hens, W_f

The wet-to-dry-weight conversion factors for forage, W_f, as defined for the NUREG/CR-5512, Vol. 1, dose model, describe the fraction of dry matter in forage consumed by beef cattle, poultry, milk cows, and layer hens. The model uses a single, constant value for W_f for all contaminants. Thus, this value represents the average concentration of dry matter in all forage crops consumed by livestock in the residential scenario.

6.4.9.3.1 Use of W_f in Modeling

The wet to dry-weight conversion factor converts the weight of forage to the corresponding weight of dry matter. This factor is required in the soil-forage feed-animal-human pathway for calculating 1) the concentration factor for radionuclide j in fresh forage crop f at the time, t, from in initial unit concentration of parent radionuclide i in soil, C_{sfjt} (Equation 5.13, p. 5.19 of NUREG/CR-5512, Vol. 1), 2) the average concentration factor for radionuclide j in fresh forage crop f over the feeding period at the time of animal consumption of

forage from an initial unit concentration of parent radionuclide i in soil, C_{sfc} (Equation 5.15, p. 5.21 of NUREG/CR-5512, Vol. 1) and 3) the average concentration factor for animal product a over the fresh forage feeding period for soil ingestion by animals for radionuclide j for initial unit concentration of parent radionuclide in soil, C_{sajd} (Equation 5.19, p. 5.22 of NUREG/CR-5512, Vol. 1) according to the following equations:

$$C_{sfjt} = 1000\ (ML_f + B_{jf}) W_f\ A\{C_{sj}, t\}/C_{si}(0) \qquad (6.86)$$

where ML_f is the plant soil mass-loading factor for resuspension of soil onto forage plant f, B_{jf} is the concentration factor for uptake of radionuclide j from the soil in fresh forage crop f, W_f is the dry to wet-weight conversion factor for fresh forage, $A\{C_{sj},t\}$ is the decay operator notation used to develop the concentration of radionuclide j in soil at time t during the feeding period for fresh forage crop f, and $C_{si}(0)$ is the initial concentration of parent radionuclide i in soil at the start of the growing period;

$$C_{sfjc} = 1000\ (ML_f + B_{jf})\ W_f\ S\{C_{sj}, t_{ff}\}/[t_{ff} C_{si}(0)] \qquad (6.87)$$

where $S\{C_{sj},t_{ff}\}$ is a concentration time-integral factor for radionuclide j in soil over the feeding period for crop forage, t_{ff}; and

$$C_{sajd} = 1000\ F_{aj}\ Q_d\ W_f\ Q_f\ x_f\ S\{C_{sj}, t_{ff}\}/[t_{ff} C_{si}(0)] \qquad (6.88)$$

where Q_d is the soil intake as a fraction of forage intake for the animal.

6.4.9.3.2 Information Used to Define the Distribution for W_f

A value of 0.22 for W_f was adopted in NUREG/CR-5512, Vol. 1, based on recommendations by Till and Meyer (1983).

The National Research Council published detailed information on nutrients in forage, hay and grain crops for livestock. Since livestock feed intake is based on dry-matter intake, and the corresponding nutrient content in dry matter, the National Research Council data included moisture content. Table 6.80 lists common types of grasses and the fraction of dry matter (National Research Council, 1996).

6.4.9.3.3 Distributions for Wet-to-Dry-Weight Conversion Factors for Forage

A distribution for W_f was defined from the average dry matter content over the twelve hay crops in Table 6.80.

Table 6.80 Moisture content in forage crops (National Research Council, 1996)

Hay crop	Dry matter (kg dry-weight/kg wet-weight
Alfalfa	0.234
Bermuda grass	0.303
Bluegrass	0.308
Broome grass	0.261
Canary grass	0.228
Clover, ladino	0.193
Clover, red	0.262
Fescue	0.313
Orchard grass	0.235
Rye grass	0.226
Trefoil	0.193
Timothy	0.267

Since the type of forage crop consumed by livestock is uncertain, each of the crops was considered equally likely. The distribution for the wet-to-dry weight conversion factor was determined by fitting a beta function to the reported conversion factors in Table 6.80. The parameters for the beta distribution are shown in Table 6.81. The frequency distribution and fitted PDF are shown in Figure 6.63. The PDF has a mean of 0.2519 and lower and upper limits of 0.183 and 0.323. The cumulative distribution for W_f is shown in Figure 6.64.

Table 6.81 Distribution parameters for wet-to-dry-weight conversion factor for forage

Parameter	Value
a_1	1.15
a_2	1.18
δ_1	0.183
δ_2	0.323

6.4.9.4 Wet-to-Dry-Weight Conversion Factors for Stored Grain Consumed by Beef Cattle, poultry, Milk Cows, and Layer Hens, W_g

The wet-to-dry-weight conversion factor, W_g, is the fraction of dry matter in stored grains. The quantity of moisture in grain varies with the type of grain and physical conditions under which the grain is stored (e.g., dew point).

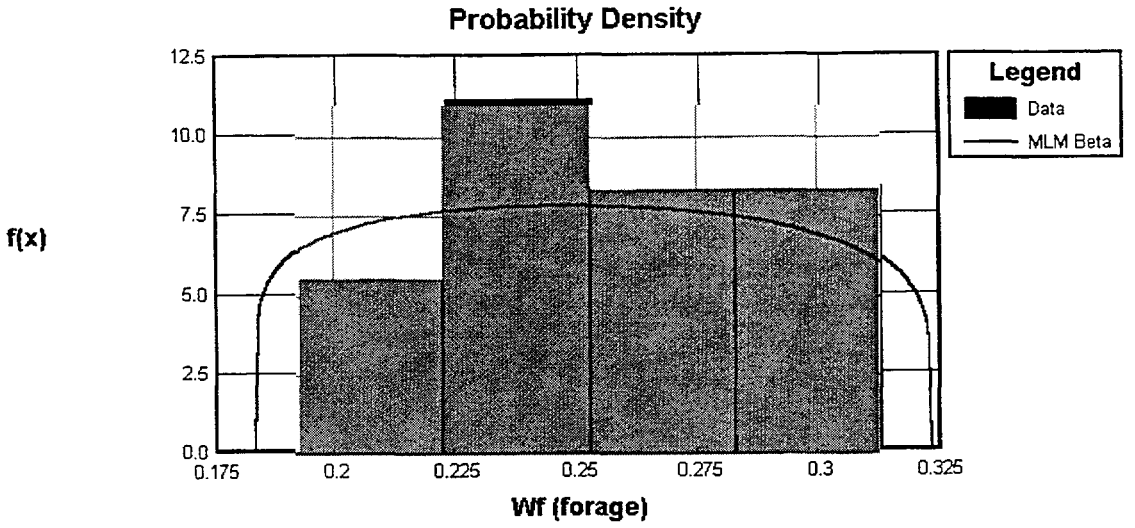

Figure 6.63 Frequency distribution and PDF for wet-to-dry-weight conversion factor for forage consumed by livestock

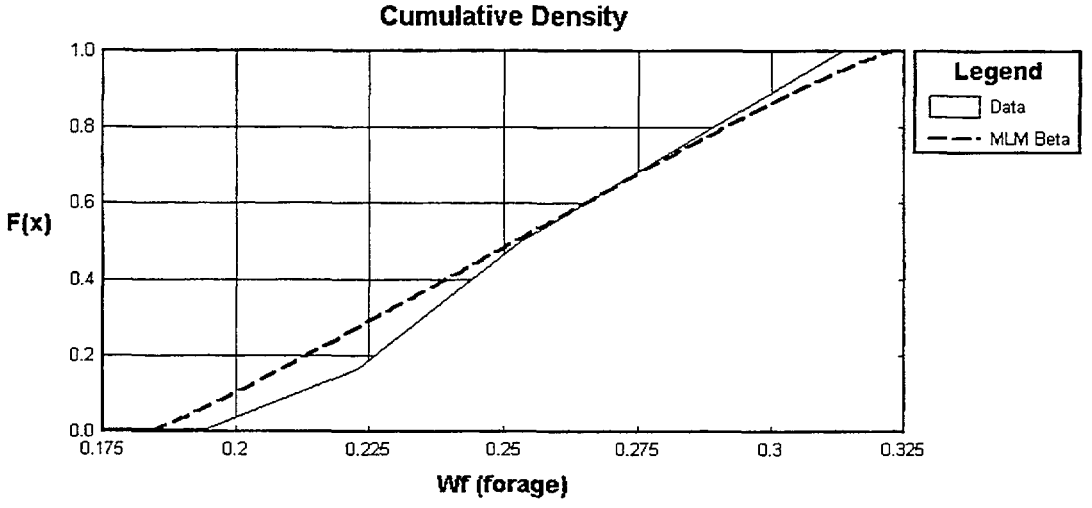

Figure 6.64 Cumulative distribution for wet-to-dry-weight conversion factor for forage consumed by livestock

6.4.9.4.1 Use of W_g in Modeling

The wet to dry-weight conversion factor converts the weight of the as-stored grain to a corresponding weight of dry matter. This factor is required in the soil-stored grain-animal-human pathway to determine the quantity of contaminated grain consumed by livestock and is used in the calculation of the concentration factor for radionuclide j in stored grain crop g at the time of initial feeding to animals from an initial unit concentration of parent radionuclide i in soil, C_{sgjc}, as shown in the following equation (Equation 5.12, p. 5.18 of NUREG/CR-5512, Vol. 1):

$$C_{sgjc} = 1000\left(ML_g + B_{jg}\right) W_g A\left\{C_{sj}, t_{»}\right\} / C_{si}(0) \qquad (6.89)$$

where ML_g is the plant soil mass-loading factor for resuspension of soil onto grain plant g; B_{jg} is the concentration factor for uptake of radionuclide j from the soil into stored grain crop g; W_g is the wet to dry-weight conversion factor for stored grain crop g; $A\{C_{sj},t_{tt}\}$ is the decay operator notation used to develop the concentration of radionuclide j in soil at the end of the crop-growing season; t_{gg} is the growing period for stored grain crop g; and $C_{si}(0)$ is the initial concentration of parent radionuclide i in soil at the start of the growing period.

6.4.9.4.2 Information Used to Define the Distribution for W_g

The value for this parameter defined in NUREG/CR-5512, Vol. 1, is 0.91 (Till and Myer, 1983).

Grain crops provide the major dietary needs for poultry and layer hens and supplement of diets of ruminant animals in agricultural operations. The dry matter content of common grain crops for livestock consumption were taken from data compiled by the NRC (NRC, 1996) and are shown in Table 6.82.

6.4.9.4.3 Distribution for Wet-to-Dry-Weight Conversion Factors for Stored Grain

The distribution for the wet-to-dry weight conversion factor was determined by fitting a log normal function to the values reported in Table 6.82. The distribution parameters for the log normal distribution are shown in Table 6.83. The frequency distribution and fitted PDF are shown in Figure 6.65. The PDF has a mean of 0.8995 and lower and upper limits of 0.881 and 0.922. The cumulative distribution for W_g is shown in Figure 6.66.

Table 6.82 Moisture content in stored grain (National Research Council, 1996)

Grain crop	Dry matter (kg dry-weight/kg wet-weight)
Barley	0.881
Canola	0.922
Corn	0.900
Oats	0.892
Sorghum	0.900
Wheat	0.902

Table 6.83 Distribution parameters for wet-to-dry-weight conversion factor for stored grain

Parameter	Value
μ	0.0224
σ	0.500
ϵ	0.874

6.4.9.5 Wet-to-Dry-Weight Conversion Factors for Stored Hay Consumed by Beef Cattle, Poultry, Milk Cows, and Layer Hens, W_h

The wet-to-dry-weight conversion factor for stored hay consumed by beef cattle, poultry, milk cows, and layer hens converts the weight of the as-cut plant to a corresponding dry weight. The factor is a measure of the dry matter content in hay crops. The model uses a single, constant value for all stored hay crops.

6.4.9.5.1 Use of W_h in Modeling

The wet to dry-weight conversion factor converts the weight of the as-cut hay to a corresponding weight of dry matter. This factor is required in the soil-stored hay-animal-human pathway to determine the quantity of contaminated hay consumed by livestock. W_h is applied in the calculation of the concentration factor for radionuclide j in stored hay h at the time of initial feeding to animals from an initial unit concentration of parent radionuclide i in soil, C_{shjc}, according to the following equation (Equation 5.11, p. 5.18 of NUREG/CR-5512, Vol. 1):

$$C_{shjc} = 1000\left(ML_h + B_{jh}\right) W_h \, A\left\{C_{sj}, t_{gh}\right\} / C_{si}(0) \qquad (6.90)$$

where ML_h is the plant soil mass-loading factor for resuspension of soil onto hay plant h; B_{jh} is the concentration factor for uptake of radionuclide j from the soil into stored hay crop h; W_h is the wet to dry-weight conversion factor for stored hay crop h; $A\{C_{sj},t_{gh}\}$ is the decay operator notation used to develop the concentration of radionuclide j in soil at the end of the crop-growing season; t_{gh} is the growing period for stored hay crop h; and $C_{si}(0)$ is the initial concentration of parent radionuclide i in soil at the start of the growing period.

6.4.9.5.2 Review of Additional Information to Define the Distribution for W_h

The value of 0.22 for W_h was proposed in NUREG/CR-5512, Vol. 1, based on studies by Till and Meyer (1983).

Hay crops provide the major dietary needs for ruminant animals in agricultural operations. These hay crops are identical to the forage crops listed in Table 6.80 except in the manner in which the crops are harvested, stored, and subsequently fed to livestock. Since the wet-to-dry-weight conversion factor is equal to the dry matter content of the hay crop, W_h and W_f are equal.

6.4.9.6 Uncertainty in W_h

The distributions for wet-to-dry-weight conversion factors are established based on the average moisture content in a wide range of garden produce and forage, grain, and grain crops. Among the factors that affect the moisture content are the type of crop and environmental conditions under which the crops are grown (e.g., temperature, humidity, length of growing season).

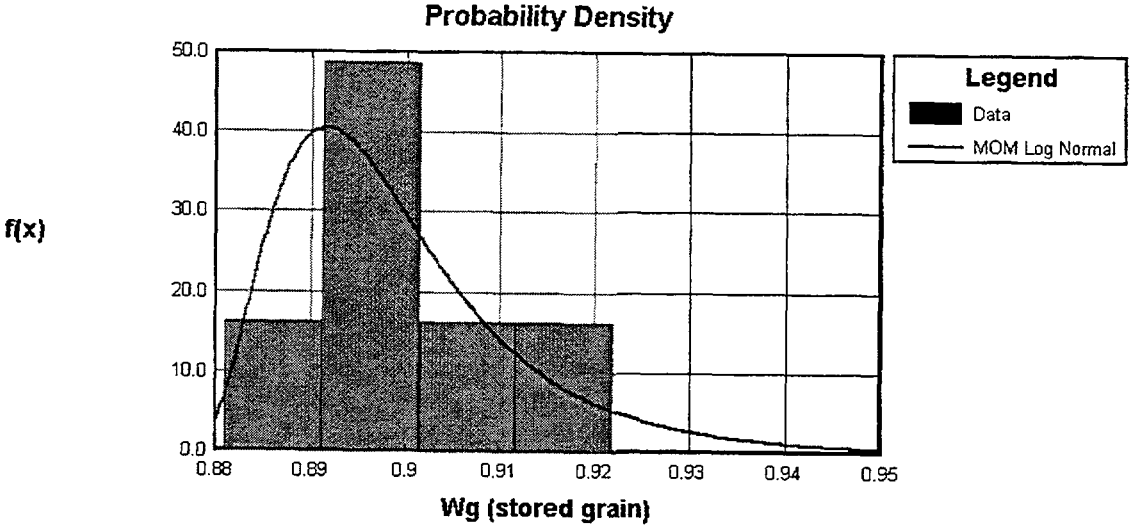

Figure 6.65 Frequency distribution and PDF for wet-to-dry-weight conversion factor for stored grain

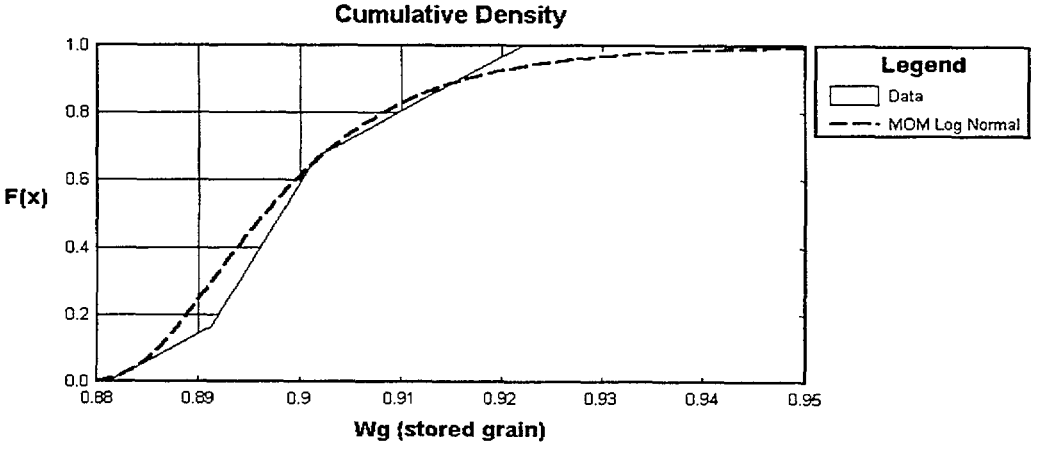

Figure 6.66 Cumulative distribution for wet-to-dry-weight conversion factor for stored grain

6.4.9.7 Alternative Values for W_h

This parameter will likely vary from site to site depending on the local growing conditions (i.e., some crops may not be suitable for growing because of soil and weather). Prevailing agricultural practice might be used to develop alternative values or distributions for these parameters.

6.4.10 Radionuclide Partition Coefficients, $Kd_{1,2i}$

6.4.10.1 Description of K_d

The radionuclide partition coefficients define the ratio between radionuclide solid concentrations (radionuclide quantity adsorbed on the soil/rock particles) and radionuclide liquid concentrations (radionuclide quantity dissolved in the soil/rock pore water) under equilibrium conditions and are expressed in volume per mass units (DandD units are mL/g).

6.4.10.2 Use of K_d in Modeling

Partition coefficients for the ith radionuclide are used to calculate radionuclide retardation in the soil layer (Rt_{1i}) and unsaturated zone (Rt_{2i}) as follows (Vol. 1, p. 49, Equations 4.9 and 4.12):

$$Rt_{1i} = 1 + Kd_{1i}\ \rho_1 / n_1 \qquad (6.91)$$

$$Rt_{2i} = 1 + Kd_{2i}\ \rho_2 / n_2 \qquad (6.92)$$

In Volume 1 it is assumed that partition coefficients for the i^{th} radionuclide in the unsaturated layer (Kd_{2i}) are the same as partition coefficients of the soil layer (Kd_{1i}); bulk density of the soil layer (ρ_1) is the same as the bulk density of the unsaturated layer (ρ_2) ; and total porosity of the soil layer (n_1) is the same as total porosity of the unsaturated layer (n_2). These assumptions lead to an assumption that radionuclide retardation in the soil layer is the same as in the unsaturated layer ($Rt_{1i} = Rt_{2i}$).

The retardation coefficients define the radionuclide transport velocities within the soil layer (v_{1i}) and within the unsaturated layer (v_{2i}) as follows:

$$v_{1i} = I/\left(R_{1i}^{*}\,\theta_1\right) \qquad (6.93)$$

$$v_{2i} = I/\left(R_{2i}^{*}\,\theta_2\right) \qquad (6.94)$$

where I is infiltration rate and θ_1 and θ_2 are volumetric water contents of the soil layer and unsaturated zone respectively.

The differences in the transport velocities of the different elements is due solely to the differences in partition coefficients. The transport velocities determine the radionuclide leaching rates from the soil layer (L_{12i}) and from the unsaturated layer (L_{23i}) which, in turn, are the parameters of the system of ordinary differential equations that describes the time-dependent distribution of mass among the soil layer, unsaturated layer, and aquifer layer.

Partition coefficients can noticeably affect doses because they may significantly influence the mass transfer rates between the soil, unsaturated zone, and the aquifer and, consequently, the radionuclide concentrations in soil, drinking water consumed by the humans, water consumed by animals, water used for irrigation, and water in the surface pond. This affects the time-dependent distribution of the contaminant mass among all the contaminant pathways included in the residential scenario (partial pathway transfer factors, PPTFs, in Volume 1 terminology) and, as a result, the pathway doses and the TEDE. The influence of the partition coefficient on the total dose should be greater in the case when the leaching rates L_{12i} and L_{23i} are comparable to or greater than the radioactive decay constant.

6.4.10.3 Data Reviewed to Develop PDFs for Partition Coefficients

The partition coefficient values defined in Volume 1 are listed in Table 6.84. Of the total (73 elements) four elements in this table (H, Kr, Xe, and Rn) have partition coefficients equal to zero, since they only are transported in gaseous phase. The partition coefficient values for the remaining 69 elements represent either the minimum values (the most mobile conditions) of the experimentally derived values provided in Sheppard and Thibault (1990) and Sheppard, Sheppard, and Amiro (1991) (25 partition coefficients), or values estimated from soil-to-plant concentration ratios (43 partition coefficients) using the following formula:

$$\ln\left(Kd_{ki}\right) = 2.11 - 0.56\ln\left(B_{iv}/4\right) \qquad (6.95)$$

where B_{iv} is concentration ratio for vegetative parts of the plant v (dry-weight basis) for the ith radionuclide, 4 is a dry-weight to wet-weight conversion factor, and 2.11 and 0.56 are empirical coefficients proposed by Thibault, Sheppard, and Smith (1990) for sandy soil. These coefficients were used to calculate lower values for the estimated partition coefficients. The B_{iv} values were based on concentration ratios for leafy vegetables from the IUR (IUR, 1989); Baes et al. (1984); and Strenge, Bander, and Soldat (1987). The concentration ratio based estimates of the partition coefficient were used in the absence of experimental data.

Additional data to support the development of PDFs describing the variability in partition coefficient values were selected for this analysis based on the following:

- Individual measurements of partition coefficients obtained from experiments are preferable to mean or best-estimate values.
- Variability based on experimental measurements (Thibault et al., 1990; Sheppard and Thibault, 1990) represents small-scale spatial variability and may not sufficiently describe the variability in effective Kd values over a large soil volume. Given the potential scale-dependant variability, best estimates of small-scale Kd values derived from Thibault et al. (1990) should be compared to the best estimates of the large-scale Kd values. Estimates of large-scale Kd values are available from McKinkley and Scholtis (1991). McKinkley and Scholtis (1991) presented a summary of Kd databases used in repository performance assessment. These data do not provide information on ranges, number of samples, or other statistics, and cannot be used for developing empirical distributions. However, they provide best estimate values that can be evaluated against smaller-scale best estimates to gauge the scale effects.

Table 6.84 Default values of the radionuclide partition coefficients in mL/g from NUREG/CR-5512, Vol. 1, (Table 6.7 in Volume 1, p. 6.18)

Element	Partition coefficient	Basis*	Element	Partition coefficient	Basis*
H	0.0E+0	M	Sb	4.5E+1	E
Be	2.4E+2	R	Te	1.4E+2	R
C	6.7E+0	C	I	1.0E+0	E
F	8.7E+1	R	Xe	0.0E+0	M
Na	7.6E+1	R	Cs	2.7E+2	E
P	8.9E+0	R	Ba	5.2E+1	R
S	1.4E+1	R	La	1.2E+3	R
Cl	1.7E+0	R	Ce	5.0E+2	E
K	1.8E+1	R	Pr	2.4E+2	R
Ca	8.9E+0	R	Nd	2.4E+2	R
Sc	3.1E+2	R	Pm	2.4E+2	R
Cr	3.0E+1	E	Sm	2.4E+2	R
Mn	5.0E+1	E	Eu	2.4E+2	R
Fe	1.6E+2	E	Gd	2.4E+2	R
Co	6.0E+1	E	Tb	2.4E+2	R
Ni	4.0E+2	E	Ho	2.4E+2	R
Cu	3.0E+1	R	W	1.0E+2	R
Zn	2.0E+2	E	Re	1.4E+1	R
As	1.1E+2	R	Os	1.9E+2	R
Se	1.4E+2	R	Ir	9.1E+1	R
Br	1.4E+1	R	Au	3.0E+1	R
Kr	0.0E+0	M	Hg	1.9E+1	R
Rb	5.2E+1	R	Tl	3.9E+2	R
Sr	1.5E+1	E	Pb	2.7E+2	E
Y	1.9E+2	R	Bi	1.2E+2	R
Zr	5.8E+2	R	Po	1.5E+2	E
Nb	1.6E+2	R	Rn	0.0E+0	M
Mo	1.0E+1	E	Ra	5.0E+2	E
Tc	1.0E-1	E	Ac	4.2E+2	R
Ru	5.5E+1	E	Th	3.2E+3	E
Rh	5.2E+1	R	Pa	5.1E+2	R
Pd	5.2E+1	R	U	1.5E+1	E
Ag	9.0E+1	E	Np	5.0E+0	E
Cd	4.0E+1	E	Pu	5.5E+2	E
In	3.9E+2	R	Am	1.9E+3	E
Sn	1.3E+2	R	Cm	4.0E+3	E
Cf	5.1E+2	R			

* Values for partition coefficients are based on: M - Assumed to be mobile; R - Calculated from concentration ratios; C - Experimental data from Sheppard, Sheppard, and Amiro (1991); or E - Experimental data from Sheppard and Thibault (1990).

- The Nuclear Energy Agency (NEA) data base (NEA, 1989) is a significant source of information on partition coefficient values.

A large number of experimental data on partition coefficients is available from the NEA sorption database (SDB) (NEA, 1989). The SDB incorporates the information previously contained in the International Sorption Information Retrieval System (ISIRS) and additional data compiled by the NEA. The data base contains approximately 11,000 values of partition coefficients for different elements. Most of the data are from static batch sorption experiments, some are from column (dynamic) experiments, and a few data are from retardation (dynamic) studies. When available, the data base provides information on the reference source, method used, solution phase, initial contaminant concentration, type of solid material used, reducing/ oxidizing conditions, experiment duration, and other details.

The SDB was searched to extract data for the 69 elements of interest from experiments using unconsolidated and consolidated deposits. The unconsolidated deposits are described in the SDB in general terms such as: clay, fine sand, sand, soil, and loam. This differs from the classification used in Sheppard and Thibault (1990), where four different types of soils are specified based on the particle size distribution and organic material quantity. Additional data are provided for consolidated deposits, including dolomite, gypsum, sandstone, shale, limestone, rock of unspecified mineral composition and sediment.

Data from the SDB for unconsolidated and consolidated deposits were obtained for the following 19 radionuclides: C, Mn, Co, Ni, Zn, Sr, Y, Tc, Pd, Ag, I, Cs, Ce, Eu, Ra, U, Np, Pu, and Am. Experimental data for Pd and Y are not available from Thibault et al. (1990) or Sheppard and Thibault (1990). Data in the SDB were combined with data from Thibault et al. (1990) for this analysis.

The primary goals of the K_d data analysis were:

- to determine if there is a strong correlation between the composition of the unconsolidated deposits and their ability to sorb different radionuclides;
- to develop radionuclide partition coefficient probability distributions that provide the best fitting to all experimental data available for unconsolidated deposits; and,
- to develop radionuclide partition coefficient probability distributions for elements that do not have individual measurement data.

6.4.10.3.1 Correlation between Partition Coefficient Values and Composition of the Unconsolidated Deposits

Thibault et al. (1990) provide data on partition coefficient values along with information on the composition of the unconsolidated sediments used in each experiment. The data on sediment composition are expressed as percentage of clay particles, silt particles, sand particles, and organic material of the sample. These data were used to generate scatter plots of Kd versus composition (expressed in percent composition), and the degree of correlation was analyzed, quantitatively and qualitatively. When available, the partition coefficients were plotted against the percent of clay, silt, sand, and organic material. Table 6.85 describes the qualitative correlation observed between partition coefficient and composition for 21 elements.

As can be seen from Table 6.85, most of the elements analyzed show an absence of correlation with the percentage of the particles of different sizes: 16 of 19 elements show no correlation to percentage of clay; 14 of 16 elements show no correlation to percentage of silt; 11 of 16 elements show no correlation to percentage of sand; and 15 of 19 elements show no correlation to percentage of organic material. Some of the partition coefficient values show weak correlation; however, it is not sufficient to justify any functional relationship.

The data from NEA (1989) combined with the data from Thibault et al. (1990) were used to analyze correlation between the elements partition coefficient values and composition of deposits. The partition coefficient values for a few elements were plotted for the different unconsolidated deposit types (clay, sand, and loam) and for the different consolidated deposit types (gypsum, dolomite, sandstone, limestone, and shale). There was no discernible correlation or trends for the partition coefficient values across different types of unconsolidated deposits for Pu , Am, and Se. Pu and Am exhibited similar partition coefficients between unconsolidated and consolidated deposits. The partition coefficients typical of unconsolidated deposits for Se were significantly lower than the partition coefficients in consolidated deposits.

Based on this analysis, we concluded that no reliable correlations could be developed for the elements of

Table 6.85 Correlation between partition coefficient values and composition of the unconsolidated deposits

Element	Description of correlation			
	% Clay	% Silt	% Sand	% Organic
I	indistinguishable	indistinguishable	weak	insignificant
Pb	indistinguishable	NA	NA	indistinguishable
Ru	NA	NA	NA	weak
Ni	weak	indistinguishable	weak	indistinguishable
Fe	indistinguishable	weak	weak	weak
Po	indistinguishable	indistinguishable	indistinguishable	indistinguishable
U	indistinguishable	indistinguishable	indistinguishable	NA
Tc	indistinguishable	indistinguishable	indistinguishable	weak
Co	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Sr	indistinguishable	indistinguishable	weak	indistinguishable
Cd	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Cs	indistinguishable	weak	weak	indistinguishable
Ra	indistinguishable	indistinguishable	indistinguishable	weak
Mn	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Np	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Se	weak	NA	NA	indistinguishable
Th	indistinguishable	NA	NA	NA
Zn	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Cm	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Cr	NA	NA	NA	indistinguishable
Ce	weak	indistinguishable	indistinguishable	indistinguishable

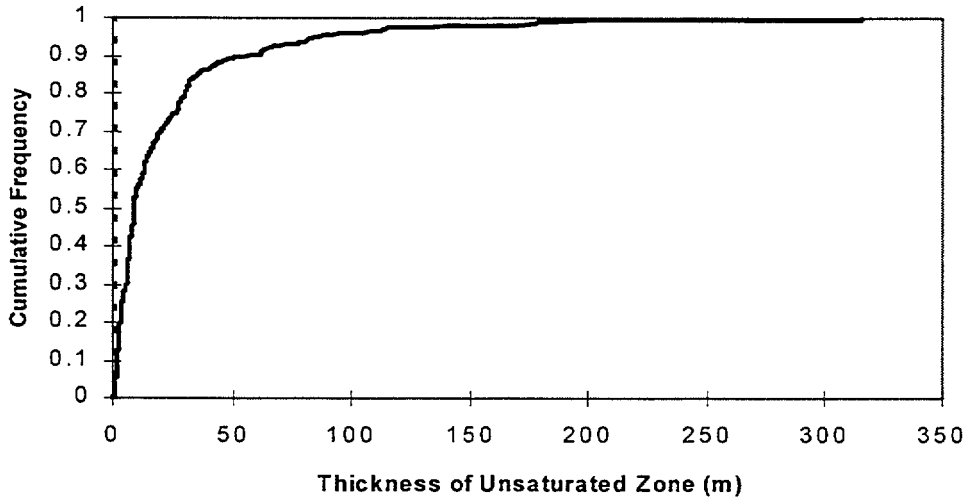

Figure 6.67 Cumulative frequency of sampled H2 values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

interest. The absence of a distinguishable correlation between the composition of the unconsolidated deposits and partition coefficients supports a single probability distribution function for each element based on all data available, rather than separate probability distributions for each element and soil type.

6.4.10.4 Probability Distributions for Partition Coefficients

6.4.10.4.1 Partition Coefficient Probability Distributions Based on Experimental Data for Unconsolidated Deposits

Experimental data on partition coefficients for unconsolidated deposits are available for 34 of the 69 elements of interest. The experimental data from Thibault et al. (1990) were used to develop probability distributions for 15 elements. The experimental data from the NEA SDB (1989) were used for two radionuclides. The experimental data from Thibault et al. were combined with the experimental data from the NEA SDB to develop probability distributions for the 17 remaining elements. Information on data sources and number of samples available for each element is provided in Table 6.86.

The computer code C-FIT (Center for Engineering Research Inc., 1996) was used to develop radionuclide probability distribution functions based on the experimental data. C-FIT provides three different optimization techniques (method of moments, maximum likelihood method, and least squares method) to fit experimental data into16 different possible probability distribution functions. The decision on which distribution provides the best fit can be made either visually based on the comparison of the experimental data histogram and different probability distribution functions and/or based on the results of the goodness-of-fit tests. Two test are available with the software: chi-square test and Kolmogorov-Smirnov test. Both tests calculate significance levels corresponding to the hypothesis that experimental data are sampled from a specified distribution. The higher the significance level, the higher the probability that the experimental data are from this distribution.

The analysis of data for each of 34 elements consisted of plotting the histograms of partition coefficients and logarithms of partition coefficients, and comparing them with the different theoretical distributions. In most of the cases developing distributions for partition coefficients using C-FIT was not successful in that the significance levels from both statistical tests were very low. This is due in part to the variability in the partition coefficient values over many orders of magnitude. To reduce the spread, distributions were fit to the log-transformed partition coefficient data. Using log-transformed data allowed development of histograms with smaller ranges and distributions with higher significance levels.

All three optimization methods were used to search for the best fit. Both statistical goodness-of-fit tests were performed for each run. However, it was found that chi-square test produced a low significance level even in the cases where the experimental data appeared to be in good agreement with the theoretical distribution. Conversely, the Kolmogorov-Smirnov test results were in good agreement with visual analysis of the results. The results of the Kolmogorov-Smirnov test were used to evaluate the goodness of fit.

The summary of the analysis is also included in Table 6.86. This table provides information on type of distribution obtained, parameters that characterize the distribution, the fitting method that provided the highest significance level, and the significance level from the Kolmogorov-Smirnov test. In addition to this information, Table 6.86 provides the corresponding values from NUREG/CR-5512, Vol. 1, and the best estimates of the partition coefficients (logarithmically converted) from the repository performance assessment studies compiled in McKinkley and Scholtis (1991), obtained for soil and surface deposits.

Seven of the 34 elements analyzed (Y, Ba, Eu, Cu, Ca, As, and Sb) did not have enough data (15 or fewer samples) to develop distributions fit to the data. The uncertainty in the log of these Kd values was represented by normal distributions with mean values based on the mean of the experimental data and a standard deviation based on the larger of the standard deviation in the data for that element or the standard deviation in the data for all elements.

For 21 of the 34 elements, the logarithms of the partition coefficients fit a normal distribution. The mean values of these distributions vary from 0.66 (Kd = 4.6 mL/g) for I to 3.83 (Kd = 6761 mL/g) for Cm with an average value of 2.37 (Kd = 234.4 mL/g).

Over the 34 elements, the average standard deviation of the fitted normal distributions is 1.09. However, some distributions have much lower standard deviations (e.g., 0.25 for Se) and some distributions have much higher standard deviations (e.g., 1.93 for Zn). The mean values for Pd, Tc, and Se lay outside of the range of the best estimated values provided in McKinkley and Scholtis (1991). In the cases of Pd and Se this may be related to the small size of the populations considered (nine

Table 6.86 Radionuclide partition coefficient distributions, logarithmic values in mL/g

Element	Data source (*)	Number of samples	Distribution type	Fitting method	Significance level (**)	Distribution parameters				Volume 1 default	PA study range (***)
						mean	std. dev.	other	vari-ance		
Sr	1, 2	539	normal	LS	0.10	1.50	0.92		0.85	1.18	1.0 to 2.0
I	1, 2	109	normal	LS	0.37	0.66	0.95		0.90	0.00	-∞ to 2.0
Cs	1, 2	564	normal	MLM	0.06	2.65	1.01		1.02	2.43	2.0 to 4.0
Tc	1, 2	206	normal	LS	0.65	0.87	1.33		1.77	-1.0	-∞ to 0.7
Ra	1, 2	53	normal	MLM	0.52	3.55	0.74		0.55	2.70	
U	1, 2	60	normal	MLM	0.64	2.10	1.36		1.85	1.18	1.3 to 3.2
Ni	1, 2	52	normal	LS	0.23	1.57	1.48		2.19	2.60	1.0 to 3.0
Po	1	50	normal	LS	0.97	2.26	0.73		0.53	2.18	
Pb	1	18	normal	MOM	0.96	3.38	1.20		1.44	2.43	
Ru	1	47	normal	LS	0.30	3.20	1.36		1.85	1.74	
Cd	1	87	normal	LS	0.22	1.53	1.30		1.69	1.60	
Am	1, 2	219	normal	LS	0.53	3.16	1.37		1.88	3.28	2.0 to 5.0
Pu	1, 2	205	normal	MLM	0.75	2.98	0.82		0.67	2.74	2.5 to 5.0
Pd	2	9	normal	LS	0.92	2.27	1.37		1.88	1.72	0.6 to 2.0
Ce	1, 2	29	normal	LS	0.55	1.93	0.43		0.18	2.70	
Mo	1	24	normal	LS	1.00	1.42	0.75		0.56	1.00	
Th	1	26	normal	MLM	1.00	3.77	1.57		2.46	3.51	2.9 to 4.8
Cr	1	22	normal	LS	0.94	2.01	1.20		1.44	1.48	
Cm	1	23	normal	LS	0.90	3.83	0.79		0.62	3.60	
Zn	1, 2	98	normal	MLM	0.18	3.03	1.93		3.72	2.30	
Se	1	22	normal	MOM	1.00	2.06	0.25		0.06	2.15	0.0 to 1.7
Y	2	15	normal			2.90	1.4			2.28	
Mn	1, 2	127	log-normal	MLM	0.50	1.15	0.70			1.70	
Ag	1, 2	27	log-normal	MOM	0.75	2.04	0.52			1.95	
Eu	1, 2	14	normal			2.98	1.74			2.38	
Ba	1	9	normal			1.65	3.53			1.72	
C	1, 2	66	log-normal	MLM	0.02	1.32	0.79			0.83	-∞ to 2.0
Co	1, 2	292	Gumbel Min	MOM	0.59	3.00		1.18		1.78	
Fe	1	44	Gumbel Min	MLM	0.97	2.95		1.65		2.21	
Np	1, 2	262	Gumbel Max	MLM	0.29	0.85		1.28		0.70	1.0 to 3.0
Cu	1	4	normal			2.25	1.40			1.48	
Ca	1	4	normal			3.17	1.40			0.95	
As	1	4	normal			2.06	1.40			2.04	
Sb	1	4	normal			2.24	1.40			1.65	
Be	3					2.97	1.40			2.38	
F						0.70	1.40			1.94	
P	3					1.41	1.40			0.95	
S						2.00	1.40			1.15	
Cl						0.70	1.40			0.23	-∞ to 2.0
Sc						2.20	1.40			2.49	-∞ to 1.23
Br	3					1.75	1.40			1.15	
Te	3					2.74	1.40			2.15	-∞ to 1.2
La						0.70	1.40			3.08	
Pr						2.20	1.40			2.38	
Nd						2.20	1.40			2.38	
Pm	3					3.70	1.40			2.38	3 to 4
Sm	3					2.97	1.40			2.38	0 to 3.7
Gd						0.70	1.40			2.38	-1.5 to 3.0
Tb						2.20	1.40			2.38	0.8 to 2.9
Ho	3					2.97	1.40			2.38	2.4 to 3.4
W						2.20	1.40			2.00	

Table 6.86 Radionuclide partition coefficient distributions, logarithmic values in mL/g (continued)

Element	Data source (*)	Number of samples	Distribution type	Fitting method	Significance level (**)	Distribution parameters				Volume 1 default	PA study range (***)
						mean	std. dev.	other	vari-ance		
Re	3					1.64	1.40			1.15	
Os						2.20	1.40			2.28	
Ir						2.20	1.40			1.96	
Au						2.20	1.40			1.48	
Rb	3					2.31	1.40			1.72	-1 to 2.2
Zr	3					3.38	1.40			2.76	1.0 to 3.9
Nb	3					2.80	1.40			2.20	0 to 3.7
Rh						2.20	1.40			1.72	
In						2.20	1.40			2.59	
Sn	3					2.70	1.40			2.11	1.7 to 2.9
Hg						2.20	1.40			1.28	
Tl						2.20	1.40			2.59	
Bi	3					2.65	1.40			2.08	1.2 to 2.2
Ac	3					3.24	1.40			2.62	1.0 to 3.7
Pa	3					3.31	1.40			2.71	
Cf						2.20	1.40			2.71	
Na						0.70	1.40			1.88	
K						0.70	1.40			0.10	

(*) - 1 = Thibault *et al.* (1990); 2 = Sorption Data Base(SDB), NEA(1989); 3 = Sheppard and Thibault (1990)
(**) - significance level from Kolmogorov-Smirnov goodness of fitness test
(***) - best estimate value range from the repository performance assessment study, McKinkley and Schottis (1991)

samples for Pd and 22 samples for Se) or the experiment scale since the McKinkley and Scholtis (1991) data are from large scale observations as opposed to the Thibault et al. (1990) data, which are from small scale experiments. In the case of Tc, the size of the population appears to be representative (206 samples) and the observed difference may be related to the experiment scale or the experiment scale since the mean the K_d values for I, Sr, Cs, U, Ni, Am, Pu, and Th are within the range reported by McKinkley and Scholtis (1991).

For three of the 34 elements (Mn, Ag and C), the logarithmic values of the partition coefficients demonstrated the best fit with a log-normal distribution. The log-normal distribution better describes the shift of the logarithms of the experimental data to the lower values. The mean values vary from 0.14 to 2.04. The standard deviation varies from 0.52 to 1.17. The data from McKinkley and Scholtis (1991) are available only for C. The mean value obtained for C is within the best estimate range.

For three other elements (Co, Fe, and Np), the logarithmic values of the partition coefficients demonstrated the best fit with the Gumbel distribution (Gumbel minimum for Co and Fe and Gumbel maximum for Np). The Gumbel distribution better describes the shift of the logarithms of the experimental data to the higher values. In all cases the population sizes (292 samples for Co, 44 samples for Fe, and 262 samples for Np) appear to be large enough to justify these distributions. The standard deviation varies from 0.52 to 1.17.

6.4.10.4.2 Partition Coefficient Probability Distributions for Elements without Data

The remaining 35 of the 69 elements of interest have no data on partition coefficient. In Volume 1, partition coefficients for these and other elements were defined based on plant-to-soil concentration ratio model [Equation (6.95)]. A different approach was taken in this analysis because of the potential for inconsistencies in describing uncertainty in partition coefficient values using concentration ratio data. These difficulties arise in estimating the partition coefficient based on plant uptake, because the concentration in plants is modeled as a function of the concentration ratio and the total soil concentration (which is a function of the partition coefficient).

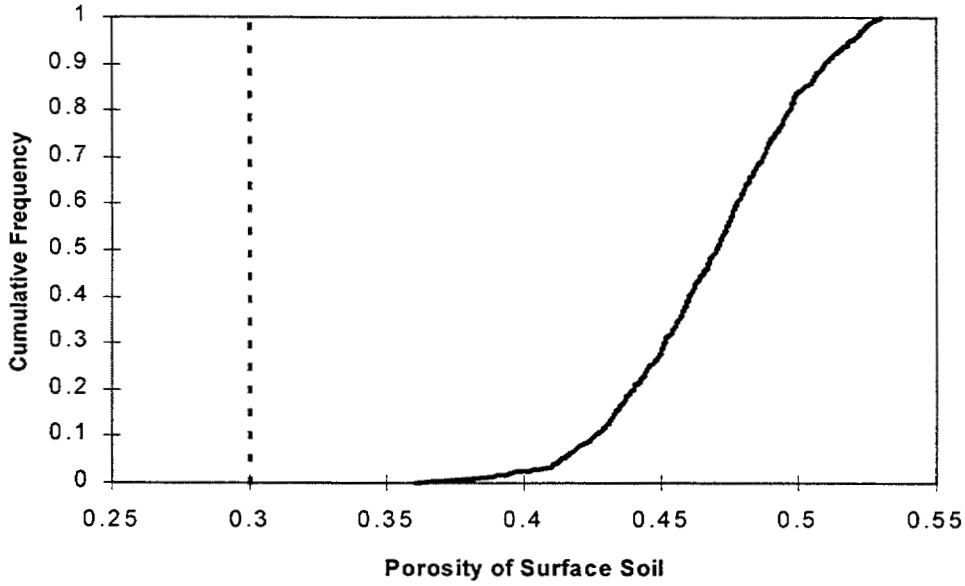

Figure 6.68 Cumulative frequency of sampled N1 values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

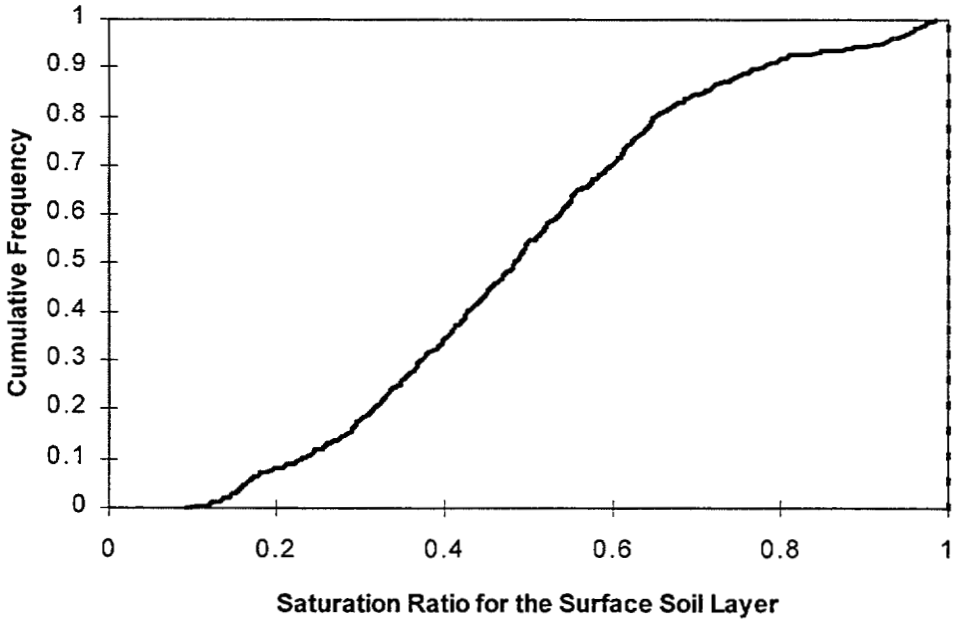

Figure 6.69 Cumulative frequency of sampled f1 values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

We have assumed that the variability in the logarithms of the partition coefficients for elements without experimental data is normally distributed. This assumption is based on the observation that the majority of the distributions fit to experimental data are normally distributed (see Table 6.86). In addition, we have assumed that the standard deviation of these normal distributions will be the same as the standard deviation derived from a distribution of *all* the experimental observations in Table 6.86. To obtain the pooled standard deviation, all the experimental data available for all the radionuclides were combined and analyzed. The resulting distribution is normal with the mean equal to 2.2 and the standard deviation equal to 1.4.

Mean values were based on review of additional literature. Additional information was found in Thibault et al. (1990) for Be, P, Br, Te, Sm, Ho, Re, Rb, Zr, Nb, Sn, Bi, Ac, and Pa. In Thibault et al. (1990), the mean values of the experimental data are presented for each of these 14 radionuclides for each of four types of soil (sand, clay, silt, and organic). Based on these data, the average value over all soil types was used to define the mean of the corresponding normal distributions having standard deviation of 1.4 (Table 6.86).

Eight elements were assumed to behave similarly to iodine: K, Na, F, S, Cl, La, Gd, and Tb (McKinley and Scholtis, 1991). These elements are known to have low sorption capabilities, similar to I, and were therefore assumed to have partition coefficients similar to iodine. The distribution of the log-transformed partition coefficients for these elements was assumed to have the same mean as I (0.7), but a higher standard deviation of 1.4 to account for potential differences (Table 6.86).

No additional information was found for the partition coefficients of the remaining 13 elements: Pm, Sc, Pr, Nd, W, Os, Ir, Au, Rh, In, Hg, Tl, and Cf. The partition coefficient probability distributions for these elements were based on the mean (2.2) and standard deviation (1.4) of all experimental data (Table 6.86).

6.5 Results of the Residential Scenario Parameter Analysis

The procedure described in Section 3.5 was applied to define default values for the residential scenario parameters. This section describes the parameter values produced by this procedure, as well as key intermediate results. Section 6.5.1 summarizes the parameter distributions used in the analysis. Section 6.5.2 describes the way the dose distributions for the individual source nuclides were calculated from these parameter distributions. Section 6.5.3 describes the way potential deterministic default values for the physical parameters were identified. Section 6.5.4 describes the way these potential default values were evaluated to select a particular solution as the set of default values.

6.5.1 Summary of Parameter Type, Variability, Means and Input PDFs

Table 6.87 summarizes the residential scenario model input parameters, including:

- The symbol, description, and units of each parameter;
- The parameter classification as either behavioral (B), physical (P), or metabolic (M);
- Whether the parameter is treated as a constant (C), is sampled from a distribution (S), or is a function of other parameters (F); and
- The mean value of the parameter.

The behavioral parameter values for the AMSG are defined by the mean values of the respective parameter distributions. For the residential scenario, the screening group is defined as adult male resident farmers. Distributions for the behavioral parameters for this group are described in Section 6.2. For these parameters, the average values in Table 6.87 define the default values used in the subsequent dose calculations.

6.5.2 Calculation of Dose Distributions

The dose distributions, which are used to define the default screening analysis, represent the possible site-specific dose values that might result from unit concentrations of each of the 106 potential source radionuclides having half-lives greater than 65 days (see Table 6.88 for a list of these radionuclides). As described in Section 3.5.2, dose distributions were estimated using a stratified Monte-Carlo sampling of the distributions for the physical parameters.

The residential scenario model has 435 physical parameters for which distributions were defined. The distribution functions for each sampled parameter are summarized in Table 6.87. This table contains the distribution definitions as specified to the LHS sampling program, and includes: the parameter description, the parameter symbol, the distribution type, and the values required to define the distribution (for example the mean and standard deviation for the NORMAL distribution type).

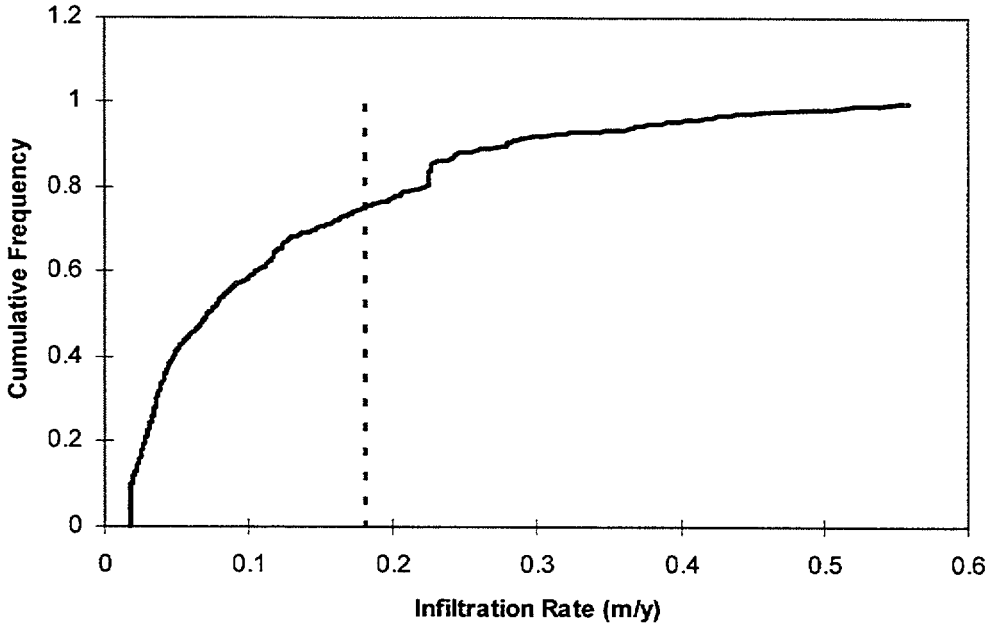

Figure 6.70 Cumulative frequency of sampled IR values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$

Part 1 - Element-independent parameters

Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
TI	Exposure period: indoors	d/y	B	S	2.37E+02	1.75E+02	2.98E+02	240
TX	Exposure period: outdoors	d/y	B	S	4.24E+01	1.69E+01	8.43E+01	40.2
TG	Exposure period:gardening	d/y	B	S	2.97E+00	3.92E-02	1.65E+01	2.92
TTR	Total time in the 1-year exposure period	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
SFI	Indoor shielding factor	-	B	S	5.85E-01	4.79E-01	8.57E-01	0.552
SFO	Outdoor Shielding Factor	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
PD	Floor dust-loading	g/m^2	P	S	1.60E-01	2.03E-02	3.00E-01	0.15986
RFR	Resuspension factor for indoor dust	1/m	P	S	1.20E-05	1.00E-07	7.95E-05	2.82E-06
CDI	Air dust-loading indoors	g/m^3	P	F	6.44E-06	2.84E-08	5.67E-05	1.41E-06
CDO	Air dust-loading outdoors	g/m^3	P	S	1.45E-05	1.01E-07	9.91E-05	3.14E-06
CDG	Air dust-loading gardening	g/m^3	P	S	4.00E-04	1.01E-04	7.00E-04	4.00E-04
VR	Breathing rate: indoors	m^3/h	M	C	9.00E-01	9.00E-01	9.00E-01	0.9
VX	Breathing rate: outdoors	m^3/h	M	C	1.40E+00	1.40E+00	1.40E+00	1.4
VG	Breathing rate: gardening	m^3/h	M	C	1.70E+00	1.70E+00	1.70E+00	1.7
GR	Soil ingestion transfer rate	g/d	B	S	5.00E-02	2.55E-03	9.80E-02	5.00E-02
UW	Drinking water ingestion rate	L/d	B	S	1.31E+00	2.31E-01	5.03E+00	1.31
H1	Thickness of surface-soil layer	m	P	C	1.50E-01	1.50E-01	1.50E-01	0.15
H2	Thickness of unsaturated zone	m	P	S	2.22E+01	3.05E-01	3.16E+02	1.22877
N1	Porosity of surface-soil	-	P	F	4.68E-01	3.61E-01	5.30E-01	0.459923

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
N2	Porosity of unsaturated zone	-	P	F	4.68E-01	3.61E-01	5.30E-01	0.459923
F1	Saturation ratio for the surface-soil layer	-	P	F	4.94E-01	9.24E-02	9.84E-01	0.162572
F2	Saturation ratio for the unsaturated-soil layer	-	P	F	4.94E-01	9.24E-02	9.84E-01	0.162572
VDR	Volume of water for domestic uses	L	B	S	1.18E+05	5.49E+04	2.76E+05	118000
VSW	Volume of water in surface-water pond	L	P	C	1.30E+06	1.30E+06	1.30E+06	1.30E+06
I	Infiltration rate	m/y	P	F	1.19E-01	1.82E-02	5.59E-01	0.252555
AR	Area of land cultivated	m^2	B	F	2.40E+03	5.48E+02	8.64E+03	2400
IR	Irrigation rate	L/m^2-d	B	S	1.29E+00	3.72E-01	9.29E+00	1.29
PS	Soil areal density of surface plow layer	kg/m^2	P	F	2.12E+02	1.87E+02	2.54E+02	214.681
DIET	Fraction of annual diet derived from home-grown foods	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
UV(1)	Human diet of leafy vegetables	kg/y	B	S	2.14E+01	3.58E-02	2.13E+02	21.4
UV(2)	Human diet of other vegetables	kg/y	B	S	4.46E+01	3.41E-01	3.79E+02	44.6
UV(3)	Human diet of fruits	kg/y	B	S	5.28E+01	1.24E-01	6.53E+02	52.8
UV(4)	Human diet of grain	kg/y	B	S	1.44E+01	1.62E-01	9.70E+01	14.4
UA(1)	Human diet of beef	kg/y	B	S	3.98E+01	1.20E-01	2.22E+02	39.8
UA(2)	Human diet of poultry	kg/y	B	S	2.53E+01	5.77E-01	7.29E+01	25.3
UA(3)	Human diet of milk	L/y	B	S	2.33E+02	9.51E-01	1.21E+03	233
UA(4)	Human diet of eggs	kg/y	B	S	1.91E+01	2.62E-01	1.21E+02	19.1
UF	Human diet of fish	kg/y	B	S	2.06E+01	2.12E-01	8.28E+02	20.6
TCV(1)	Food consumption period for leafy vegetables	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCV(2)	Food consumption period for other vegetables	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCV(3)	Food consumption period for fruits	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCV(4)	Food consumption period for grain	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCA(1)	Food consumption period for beef	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCA(2)	Food consumption period for poultry	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCA(3)	Food consumption period for milk	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCA(4)	Food consumption period for eggs	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
THV(1)	Holdup period for leafy vegetables	d	B	C	1.00E+00	1.00E+00	1.00E+00	1
THV(2)	Holdup period for other vegetables	d	B	C	1.40E+01	1.40E+01	1.40E+01	14
THV(3)	Holdup period for fruits	d	B	C	1.40E+01	1.40E+01	1.40E+01	14
THV(4)	Holdup period for grains	d	B	C	1.40E+01	1.40E+01	1.40E+01	14
THA(1)	Holdup period for beef	d	B	C	2.00E+01	2.00E+01	2.00E+01	20
THA(2)	Holdup period for poultry	d	B	C	1.00E+00	1.00E+00	1.00E+00	1
THA(3)	Holdup period for milk	d	B	C	1.00E+00	1.00E+00	1.00E+00	1
THA(4)	Holdup period for eggs	d	P	C	1.00E+00	1.00E+00	1.00E+00	1

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
TGV(1)	Minimum growing period for leafy vegetables	d	P	C	4.50E+01	4.50E+01	4.50E+01	45
TGV(2)	Minimum growing period for other vegetables	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGV(3)	Minimum growing period for fruits	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGV(4)	Minimum growing period for grains	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGF(1)	Minimum growing period for forage consumed by beef cattle	d	P	C	3.00E+01	3.00E+01	3.00E+01	30
TGF(2)	Minimum growing period for forage consumed by poultry	d	P	C	3.00E+01	3.00E+01	3.00E+01	30
TGF(3)	Minimum growing period for forage consumed by milk cows	d	P	C	3.00E+01	3.00E+01	3.00E+01	30
TGF(4)	Minimum growing period for forage consumed by layer hens	d	P	C	3.00E+01	3.00E+01	3.00E+01	30
TGG(1)	Minimum growing period for stored grain consumed by beef cattle	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGG(2)	Minimum growing period for stored grain consumed by poultry	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGG(3)	Minimum growing period for stored grain consumed by milk cows	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGG(4)	Minimum growing period for stored grain consumed by layer hens	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGH(1)	Minimum growing period for stored hay consumed by beef cattle	d	P	C	4.50E+01	4.50E+01	4.50E+01	45
TGH(2)	Minimum growing period for stored hay consumed by poultry	d	P	C	4.50E+01	4.50E+01	4.50E+01	45
TGH(3)	Minimum growing period for stored hay consumed by milk cows	d	P	C	4.50E+01	4.50E+01	4.50E+01	45
TGH(4)	Minimum growing period for stored hay consumed by layer hens	d	P	C	4.50E+01	4.50E+01	4.50E+01	45
RV(1)	Interception fraction for leafy vegetables	-	P	S	3.50E-01	1.00E-01	6.00E-01	0.349508
RV(2)	Interception fraction for other vegetables	-	P	S	3.50E-01	1.00E-01	5.99E-01	0.349765
RV(3)	Interception fraction for fruits	-	P	S	3.50E-01	1.01E-01	5.99E-01	0.349655
RV(4)	Interception fraction for grains	-	P	S	3.50E-01	1.00E-01	6.00E-01	0.349935
RF(1)	Interception fraction for beef cattle forage	-	P	S	3.50E-01	1.01E-01	6.00E-01	0.349497
RF(2)	Interception fraction for poultry forage	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RF(3)	Interception fraction for milk cow forage	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RF(4)	Interception fraction for layer hen forage	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RG(1)	Interception fraction for beef cattle grain	-	P	S	3.50E-01	1.00E-01	6.00E-01	0.34968
RG(2)	Interception fraction for poultry grain	-	P	F	3.50E-01	1.00E-01	6.00E-01	0.34968

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
RG(3)	Interception fraction for milk cow grain	-	P	F	3.50E-01	1.00E-01	6.00E-01	0.34968
RG(4)	Interception fraction for layer hen grain	-	P	F	3.50E-01	1.00E-01	6.00E-01	0.34968
RH(1)	Interception fraction for beef cattle hay	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RH(2)	Interception fraction for poultry hay	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RH(3)	Interception fraction for milk cow hay	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RH(4)	Interception fraction for layer hen hay	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
TV(1)	Translocation factor for leafy vegetables	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TV(2)	Translocation factor for other vegetables	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TV(3)	Translocation factor for fruits	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TV(4)	Translocation factor for grains	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TF(1)	Translocation factor for beef cattle forage	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TF(2)	Translocation factor for poultry forage	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TF(3)	Translocation factor for milk cow forage	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TF(4)	Translocation factor for layer hen forage	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TG(1)	Translocation factor for beef cattle grain	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TG(2)	Translocation factor for poultry grain	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TG(3)	Translocation factor for milk cow grain	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TG(4)	Translocation factor for layer hen grain	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TH(1)	Translocation factor for beef cattle hay	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TH(2)	Translocation factor for poultry hay	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TH(3)	Translocation factor for milk cow hay	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TH(4)	Translocation factor for layer hen hay	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
XF(1)	Fraction of contaminated beef cattle forage	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XF(2)	Fraction of contaminated poultry forage	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XF(3)	Fraction of contaminated milk cow forage	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XF(4)	Fraction of contaminated layer hen forage	-	B	C	1.00E+00	1.00E+00	1.00E+00	1

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
XG(1)	Fraction of contaminated beef cattle grain	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XG(2)	Fraction of contaminated poultry grain	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XG(3)	Fraction of contaminated milk cow grain	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XG(4)	Fraction of contaminated layer hen grain	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XH(1)	Fraction of contaminated beef cattle hay	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XH(2)	Fraction of contaminated poultry hay	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XH(3)	Fraction of contaminated milk cow hay	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XH(4)	Fraction of contaminated layer hen hay	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XW(1)	Fraction of contaminated beef cattle water	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XW(2)	Fraction of contaminated poultry water	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XW(3)	Fraction of contaminated milk cow water	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XW(4)	Fraction of contaminated layer hen water	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
YV(1)	Crop yield for leafy vegetables	kg/m^2	P	S	2.89E+00	2.70E+00	3.09E+00	2.88921
YV(2)	Crop yield for other vegetables	kg/m^2	P	S	2.40E+00	2.30E+00	2.52E+00	2.40002
YV(3)	Crop yield for fruits	kg/m^2	P	S	2.37E+00	2.18E+00	2.55E+00	2.36732
YV(4)	Crop yield for grains	kg/m^2	P	S	3.91E-01	2.86E-01	4.93E-01	0.390429
YF(1)	Crop yield for beef cattle forage	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YF(2)	Crop yield for poultry forage	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YF(3)	Crop yield for milk cow forage	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YF(4)	Crop yield for layer hen forage	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YG(1)	Crop yield for beef cattle grain	kg/m^2	P	F	6.57E-01	3.97E-01	9.18E-01	0.656769
YG(2)	Crop yield for poultry grain	kg/m^2	P	F	6.57E-01	3.97E-01	9.18E-01	0.656769
YG(3)	Crop yield for milk cow grain	kg/m^2	P	F	6.57E-01	3.97E-01	9.18E-01	0.656769
YG(4)	Crop yield for layer hen grain	kg/m^2	P	F	6.57E-01	3.97E-01	9.18E-01	0.656769
YH(1)	Crop yield for beef cattle hay	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YH(2)	Crop yield for poultry hay	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YH(3)	Crop yield for milk cow hay	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YH(4)	Crop yield for layer hen hay	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
WV(1)	Wet/dry conversion factor for leafy vegetables	-	P	S	1.09E-01	3.32E-02	3.24E-01	0.133577
WV(2)	Wet/dry conversion factor for other vegetables	-	P	S	1.09E-01	3.58E-02	3.13E-01	0.162031
WV(3)	Wet/dry conversion factor for fruits	-	P	S	1.09E-01	3.66E-02	3.25E-01	0.284903
WV(4)	Wet/dry conversion factor for grains	-	P	C	8.80E-01	8.80E-01	8.80E-01	0.88

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$ (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
WF(1)	Wet/dry conversion factor for beef cattle forage	-	P	S	2.52E-01	1.83E-01	3.23E-01	0.251767
WF(2)	Wet/dry conversion factor for poultry forage	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WF(3)	Wet/dry conversion factor for milk cow forage	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WF(4)	Wet/dry conversion factor for layer hen forage	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WG(1)	Wet/dry conversion factor for beef cattle grain	-	P	C	8.80E-01	8.80E-01	8.80E-01	0.88
WG(2)	Wet/dry conversion factor for poultry grain	-	P	F	8.80E-01	8.80E-01	8.80E-01	0.88
WG(3)	Wet/dry conversion factor for milk cow grain	-	P	F	8.80E-01	8.80E-01	8.80E-01	0.88
WG(4)	Wet/dry conversion factor for layer hen grain	-	P	F	8.80E-01	8.80E-01	8.80E-01	0.88
WH(1)	Wet/dry conversion factor for beef cattle hay	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WH(2)	Wet/dry conversion factor for poultry hay	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WH(3)	Wet/dry conversion factor for milk cow hay	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WH(4)	Wet/dry conversion factor for layer hen hay	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
QF(1)	Ingestion rate for beef cattle forage	kg/d	P	F	8.53E+00	5.88E+00	1.23E+01	8.133
QF(2)	Ingestion rate for poultry forage	kg/d	P	F	6.60E-02	1.46E-02	1.48E-01	5.62E-02
QF(3)	Ingestion rate for milk cow forage	kg/d	P	F	3.52E+01	2.18E+01	7.68E+01	35.1654
QF(4)	Ingestion rate for layer hen forage	kg/d	P	F	7.52E-02	3.76E-02	1.17E-01	7.55E-02
QG(1)	Ingestion rate for beef cattle grain	kg/d	P	F	2.39E+00	1.94E+00	2.60E+00	2.41877
QG(2)	Ingestion rate for poultry grain	kg/d	P	F	5.53E-02	1.23E-02	9.59E-02	6.30E-02
QG(3)	Ingestion rate for milk cow grain	kg/d	P	F	1.95E+00	1.07E+00	2.99E+00	1.94662
QG(4)	Ingestion rate for layer hen grain	kg/d	P	F	6.33E-02	4.07E-02	7.58E-02	6.10E-02
QH(1)	Ingestion rate for beef cattle hay	kg/d	P	F	1.71E+01	1.09E+01	2.47E+01	16.2535
QH(2)	Ingestion rate for poultry hay	kg/d	P	C	0.00E+00	0.00E+00	0.00E+00	0
QH(3)	Ingestion rate for milk cow hay	kg/d	P	F	2.80E+01	1.69E+01	5.53E+01	26.1089
QH(4)	Ingestion rate for layer hen hay	kg/d	P	C	0.00E+00	0.00E+00	0.00E+00	0
QW(1)	Water ingestion rate for beef cattle	L/d	P	C	5.00E+01	5.00E+01	5.00E+01	50
QW(2)	Water ingestion rate for poultry	L/d	P	C	3.00E-01	3.00E-01	3.00E-01	0.3
QW(3)	Water ingestion rate for milk cows	L/d	P	C	6.00E+01	6.00E+01	6.00E+01	60
QW(4)	Water ingestion rate for layer hens	L/d	P	C	3.00E-01	3.00E-01	3.00E-01	0.3
QD(1)	Soil intake fraction for beef cattle	-	P	C	2.00E-02	2.00E-02	2.00E-02	2.00E-02
QD(2)	Soil intake fraction for poultry	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
QD(3)	Soil intake fraction for milk cows	-	P	C	2.00E-02	2.00E-02	2.00E-02	2.00E-02
QD(4)	Soil intake fraction for layer hens	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
MLV(1)	Mass-loading factor for leafy vegetables	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLV(2)	Mass-loading factor for other vegetables	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLV(3)	Mass-loading factor for fruits	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLV(4)	Mass-loading factor for grains	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
LAMBDW	Weathering rate for activity removal from plants	1/d	P	C	4.95E-02	4.95E-02	4.95E-02	4.95E-02
RHO1	Surface Soil Density	g/mL	P	F	1.41E+00	1.25E+00	1.69E+00	1.4312
RHO2	Unsaturated Zone Soil Density	g/mL	P	F	1.41E+00	1.25E+00	1.69E+00	1.4312
TTG	Total time in gardening period	d	B	C	9.00E+01	9.00E+01	9.00E+01	90
TF	Fish consumption period	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TD	Drinking-water consumption period	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
MLF(1)	Mass-loading factor for beef cattle forage	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLF(2)	Mass-loading factor for poultry forage	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLF(3)	Mass-loading factor for milk cow forage	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLF(4)	Mass-loading factor for layer hen forage	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLG(1)	Mass-loading factor for beef cattle grain	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLG(2)	Mass-loading factor for poultry grain	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLG(3)	Mass-loading factor for milk cow grain	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLG(4)	Mass-loading factor for layer hen grain	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLH(1)	Mass-loading factor for beef cattle hay	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLH(2)	Mass-loading factor for poultry hay	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLH(3)	Mass-loading factor for milk cow hay	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLH(4)	Mass-loading factor for layer hen hay	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TFF(1)	Feeding period for beef cattle forage	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFF(2)	Feeding period for poultry forage	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFF(3)	Feeding period for milk cow forage	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFF(4)	Feeding period for layer hen forage	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFG(1)	Feeding period for beef cattle grain	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFG(2)	Feeding period for poultry grain	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFG(3)	Feeding period for milk cow grain	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFG(4)	Feeding period for layer hen grain	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFH(1)	Feeding period for beef cattle hay	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFH(2)	Feeding period for poultry hay	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$ (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
TFH(3)	Feeding period for milk cow hay	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFH(4)	Feeding period for layer hen hay	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFW(1)	Water ingestion period for beef cattle	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFW(2)	Water ingestion period for poultry	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFW(3)	Water ingestion period for milk cows	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFW(4)	Water ingestion period for layer hens	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
fca(1)	Carbon fraction for beef cattle	-	P	C	3.60E-01	3.60E-01	3.60E-01	0.36
fca(2)	Carbon fraction for poultry	-	P	C	1.80E-01	1.80E-01	1.80E-01	0.18
fca(3)	Carbon fraction for milk cows	-	P	C	6.00E-02	6.00E-02	6.00E-02	6.00E-02
fca(4)	Carbon fraction for layer hens	-	P	C	1.60E-01	1.60E-01	1.60E-01	0.16
fcf(1)	Carbon fraction for beef cattle forage	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fcf(2)	Carbon fraction for poultry forage	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fcf(3)	Carbon fraction for milk cow forage	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fcf(4)	Carbon fraction for layer hen forage	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fch(a)	Carbon fraction for beef cattle hay	-	P	C	7.00E-02	7.00E-02	7.00E-02	7.00E-02
fch(a)	Carbon fraction for poultry hay	-	P	C	7.00E-02	7.00E-02	7.00E-02	7.00E-02
fch(a)	Carbon fraction for milk cow hay	-	P	C	7.00E-02	7.00E-02	7.00E-02	7.00E-02
fch(a)	Carbon fraction for layer hen hay	-	P	C	7.00E-02	7.00E-02	7.00E-02	7.00E-02
fcg(a)	Carbon fraction for beef cattle grain	-	P	C	4.00E-01	4.00E-01	4.00E-01	0.4
fcg(a)	Carbon fraction for poultry grain	-	P	C	4.00E-01	4.00E-01	4.00E-01	0.4
fcg(a)	Carbon fraction for milk cow grain	-	P	C	4.00E-01	4.00E-01	4.00E-01	0.4
fcg(a)	Carbon fraction for layer hen grain	-	P	C	4.00E-01	4.00E-01	4.00E-01	0.4
fcd05	Fraction of carbon in soil	-	P	C	3.00E-02	3.00E-02	3.00E-02	3.00E-02
satac	Specific activity equivalence for livestock	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
fha(1)	Hydrogen fraction for beef cattle	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fha(2)	Hydrogen fraction for poultry	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fha(3)	Hydrogen fraction for milk cows	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fha(4)	Hydrogen fraction for layer hens	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fhv(1)	Hydrogen fraction for leafy vegetables	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhv(2)	Hydrogen fraction for other vegetables	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhv(3)	Hydrogen fraction for fruits	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhv(4)	Hydrogen fraction for grains	-	P	C	6.80E-02	6.80E-02	6.80E-02	6.80E-02
fhf(1)	Hydrogen fraction for beef cattle forage	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhf(2)	Hydrogen fraction for poultry forage	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhf(3)	Hydrogen fraction for milk cow forage	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$ (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
fhf(4)	Hydrogen fraction for layer hen forage	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhh(1)	Hydrogen fraction for beef cattle hay	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhh(2)	Hydrogen fraction for poultry hay	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhh(3)	Hydrogen fraction for milk cow hay	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhh(4)	Hydrogen fraction for layer hen hay	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhg(1)	Hydrogen fraction for beef cattle grain	-	P	C	6.80E-02	6.80E-02	6.80E-02	6.80E-02
fhg(2)	Hydrogen fraction for poultry grain	-	P	C	6.80E-02	6.80E-02	6.80E-02	6.80E-02
fhg(3)	Hydrogen fraction for milk cow grain	-	P	C	6.80E-02	6.80E-02	6.80E-02	6.80E-02
fhg(4)	Hydrogen fraction for layer hen grain	-	P	C	6.80E-02	6.80E-02	6.80E-02	6.80E-02
fhd016	Fraction of hydrogen in soil	-	P	F	1.82E-02	3.49E-03	3.65E-02	5.80E-03
sasvh	Tritium equivalence: plant/soil	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
sawvh	Tritium equivalence: plant/water	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
satah	Tritium equivalence: animal product/intake	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
sh	Moisture content of soil	L/m^3	P	F	1.64E-01	3.14E-02	3.29E-01	5.22E-02

6.5.2.1 Parameter Sample Distributions

Five hundred and eighty samples from these distributions were generated using stratified Monte-Carlo (LHS) sampling. The results of the parameter sampling are illustrated in Figures 6.67 through 6.95. These figures show the cumulative frequency of the physical parameter values based on the LHS sampling. Default parameter values from NUREG/CR-5512, Vol. 1, are indicated for reference. Two of the parameters, partition coefficient and vegetation concentration factor, have a separate distribution for each of 69 chemical elements. Each of these distributions is summarized in Table 6.87. Because of the large number of element-specific parameters, four representative distributions are shown for the partition coefficients and concentration factors. Figures 6.85 through 6.88 show example distributions of concentration factors; Figures 6.92 through 6.95 show example partition coefficient distributions.

6.5.2.2 Dose Modeling Results

For each set of sampled parameter values, dose to the AMSG was calculated for unit concentrations of each of the 106 potential source radionuclides having half-lives greater than 65 days (see Table 6.88). For each source, the distribution describing possible doses to the AMSG was then constructed from these calculated doses. From the resulting dose distributions, the dose quantiles d_{Ci} can be estimated for various values of P_{crit} (see Equation 3.7). These quantiles represent screening dose values for unit concentrations of individual radionuclides, and also define the lower limits on the doses calculated using default parameter values (Equation 3.8). This section describes the calculations used to estimate the dose distributions, and presents the resulting dose quantiles for three selected values of P_{crit}.

6.5.2.2.1 Evaluation of the Mixing Cell Model

Due to the large number of calculations required by this analysis, the mixing cell model described in NUREG/CR-5512, Vol. 1, was used to represent the groundwater pathway. This model results in faster execution time than the more accurate numerical transport model, but introduces some amount of numerical dispersion.

Selected calculations were done with both the mixing cell model and the numerical model of the unsaturated zone to assess the effect of numerical dispersion. Using the mean values for all model parameters, the TEDE for all 106 isotopes was calculated using both the mixing

Table 6.88 Source nuclides used in the parameter analysis

Source ID	Source	Source ID	Source	Source ID	Source
1	3H	87	126Sn+C	180	232Th
2	10Be	89	125Sb	181	232Th+C
3	14C	93	123mTe	183	231Pa
5	22Na	95	127mTe	184	231Pa+C
9	35S	106	129I	187	232U
10	36Cl	114	134Cs	188	232U+C
11	40K	115	135Cs	189	233U
12	41Ca	117	137Cs	190	233U+C
13	45Ca	128	144Ce	191	234U
14	46Sc	132	147Pm	192	235U
16	54Mn	137	147Sm	193	235U+C
18	55Fe	138	151Sm	194	236U
20	57Co	140	152Eu	196	238U
21	58Co	141	154Eu	197	238U+C
22	60Co	142	155Eu	199	237Np
23	59Ni	144	153Gd	200	237Np+C
24	63Ni	145	160Tb	203	236Pu
27	65Zn	146	166mHo	205	238Pu
31	75Se	147	181W	206	239Pu
32	79Se	148	185W	207	240Pu
41	90Sr	150	187Re	208	241Pu
48	93Zr	151	185Os	209	242Pu
49	93Zr+C	153	192Ir	211	244Pu
52	93mNb	156	210Pb	212	241Am
53	94Nb	160	210Po	213	242mAm
58	93Mo	165	226Ra	215	243Am
61	99Tc	166	226Ra+C	216	242Cm
65	106Ru	167	228Ra	217	243Cm
69	107Pd	169	227Ac	218	244Cm
71	110mAg	170	227Ac+C	219	245Cm
73	109Cd	173	228Th	220	246Cm
74	113mCd	174	228Th+C	221	247Cm
81	119mSn	175	229Th	222	248Cm
82	121mSn	176	229Th+C	223	252Cf
84	123Sn	177	230Th		
86	126Sn	178	230Th+C		

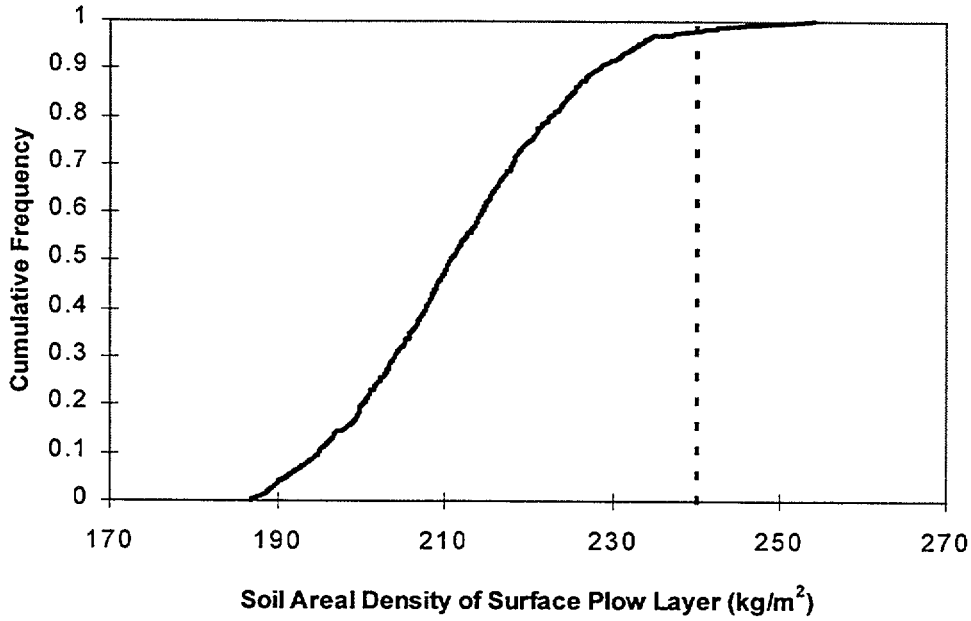

Figure 6.71 Cumulative frequency of sampled Ps values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

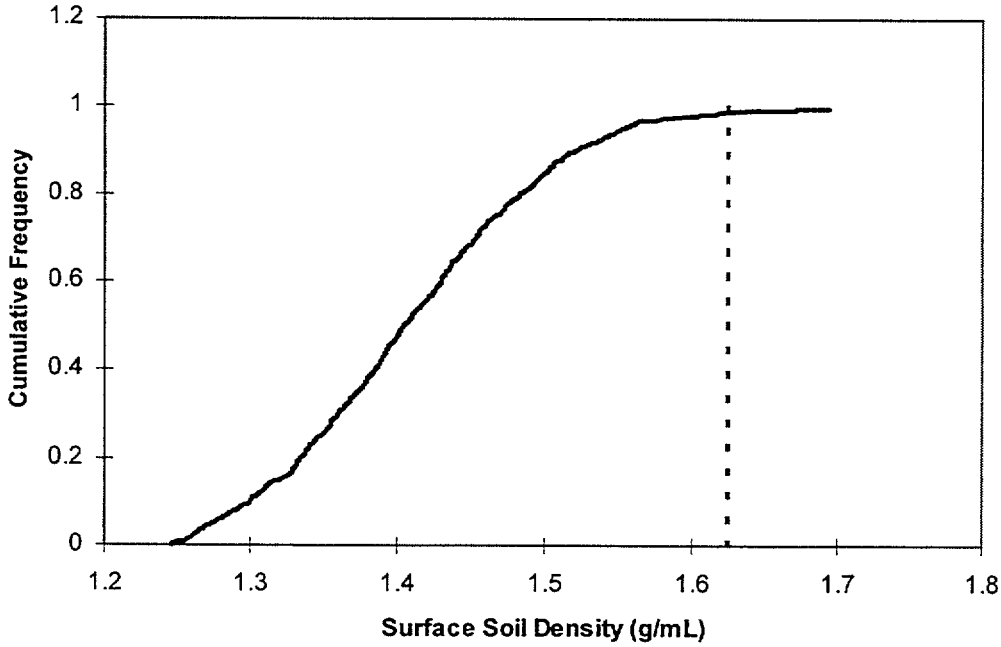

Figure 6.72 Cumulative frequency of sampled ρ values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

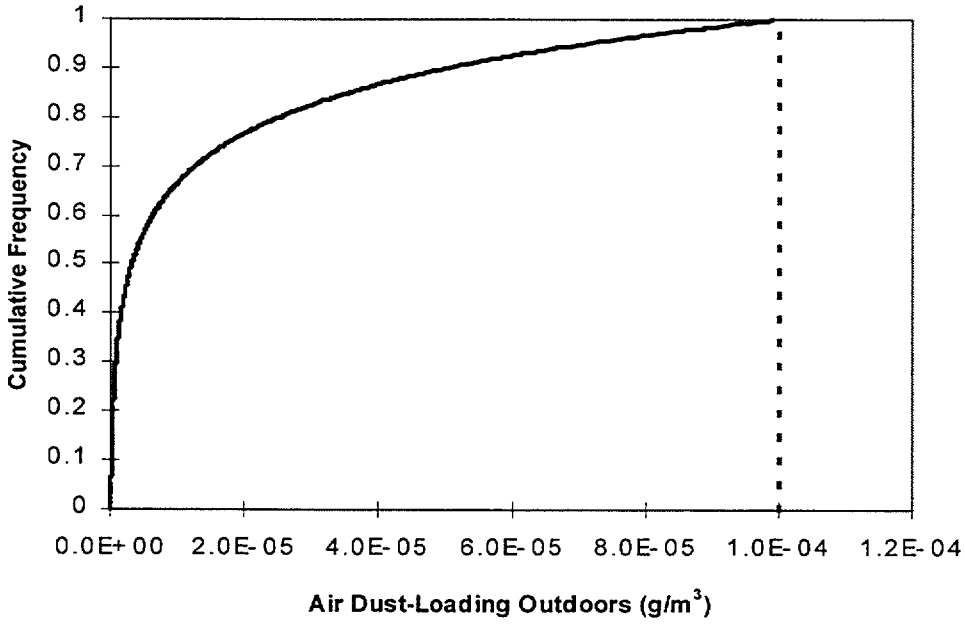

Figure 6.73 Cumulative frequency of sampled CDO values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

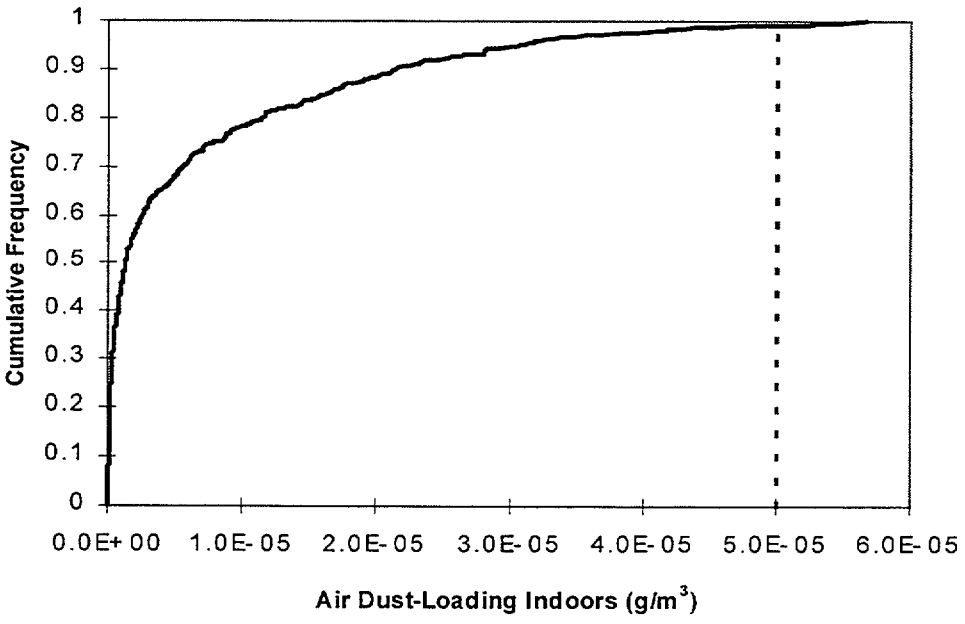

Figure 6.74 Cumulative frequency of CDI values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

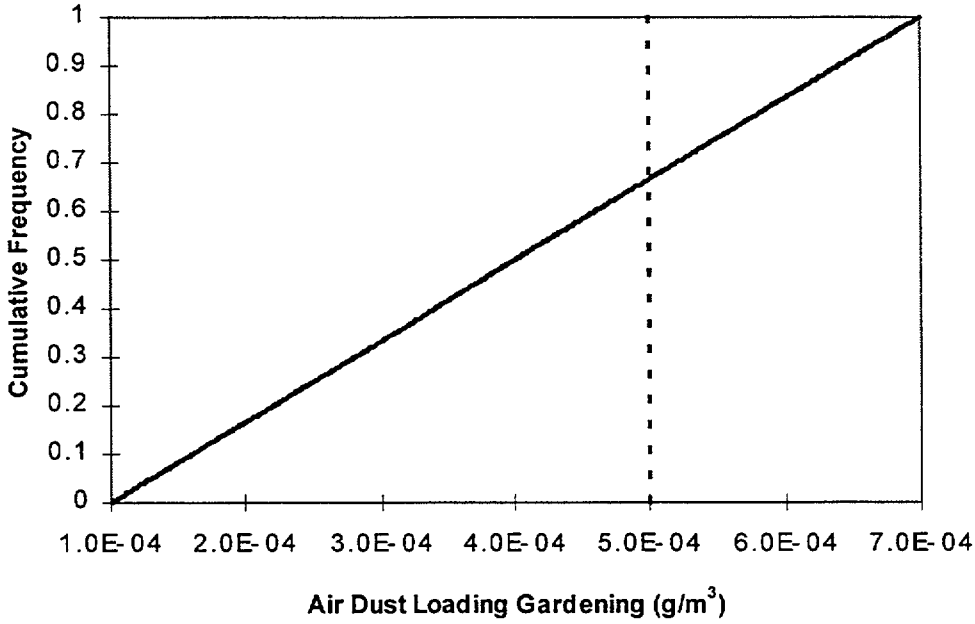

Figure 6.75 Cumulative frequency sampled CDG values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

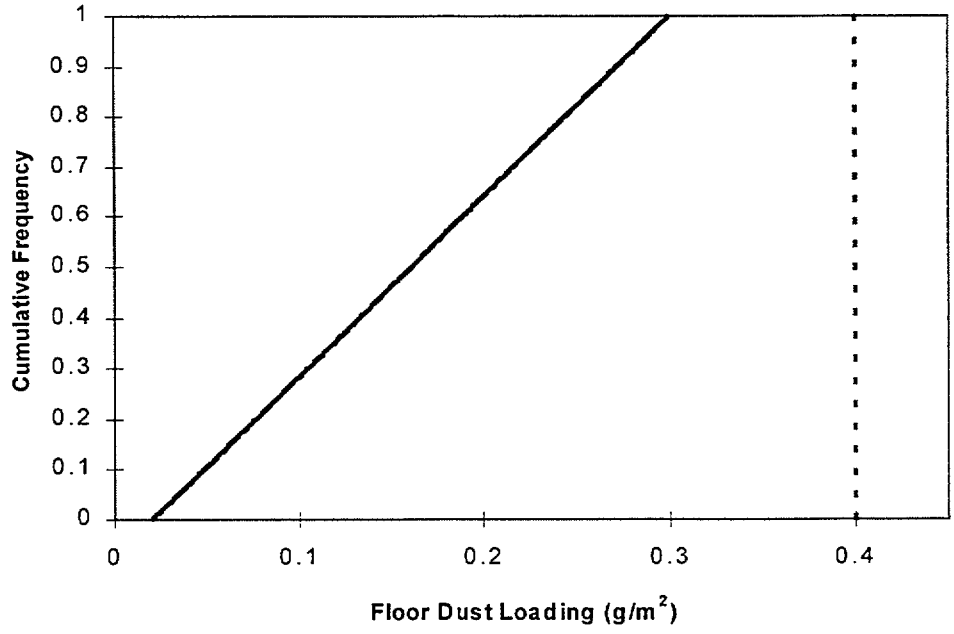

Figure 6.76 Cumulative frequency sampled Pd values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

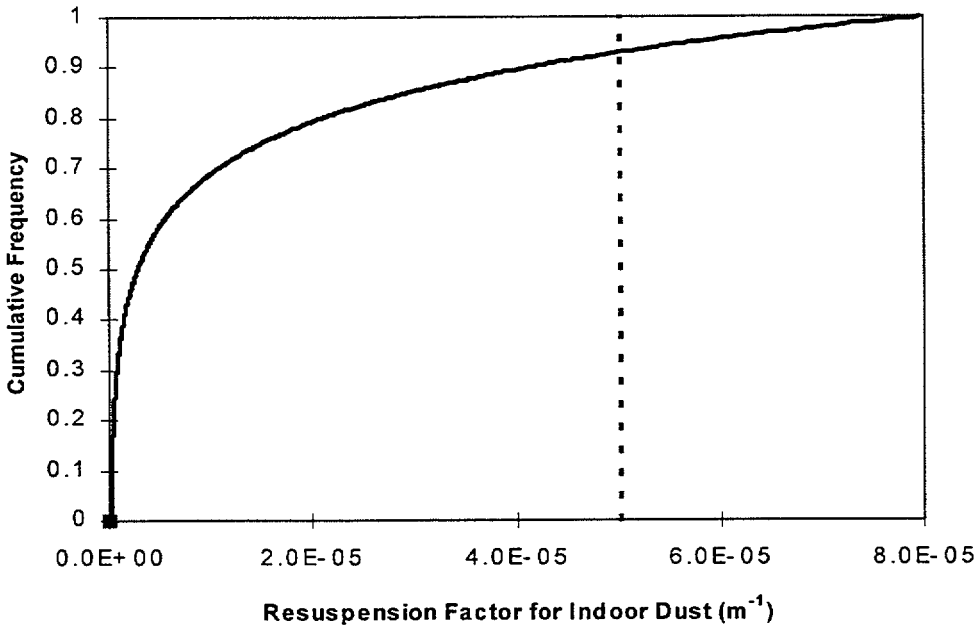

Figure 6.77 Cumulative frequency sampled RFr values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

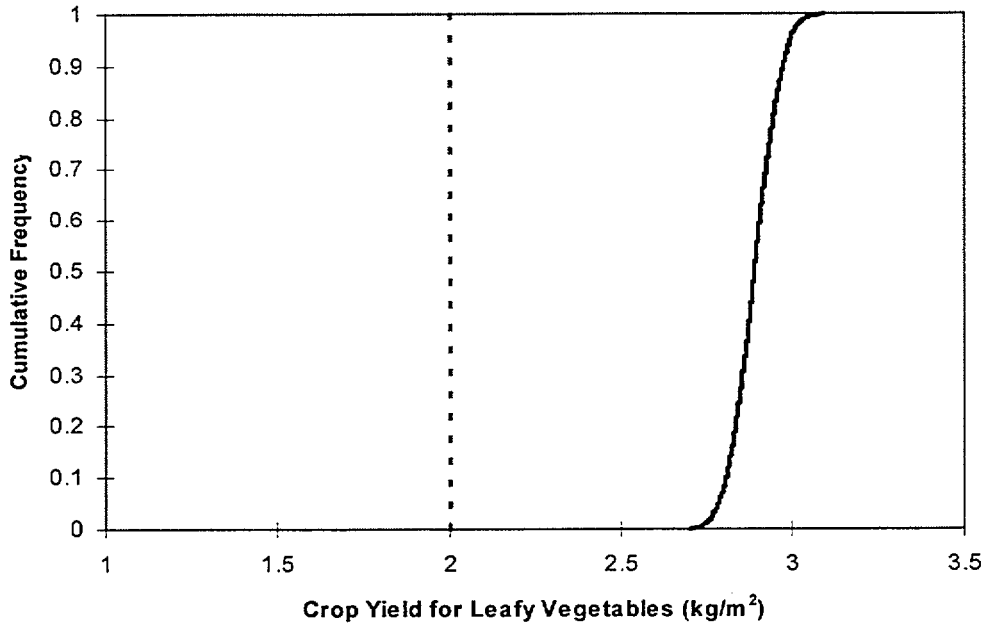

Figure 6.78 Cumulative frequency sampled Yv values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

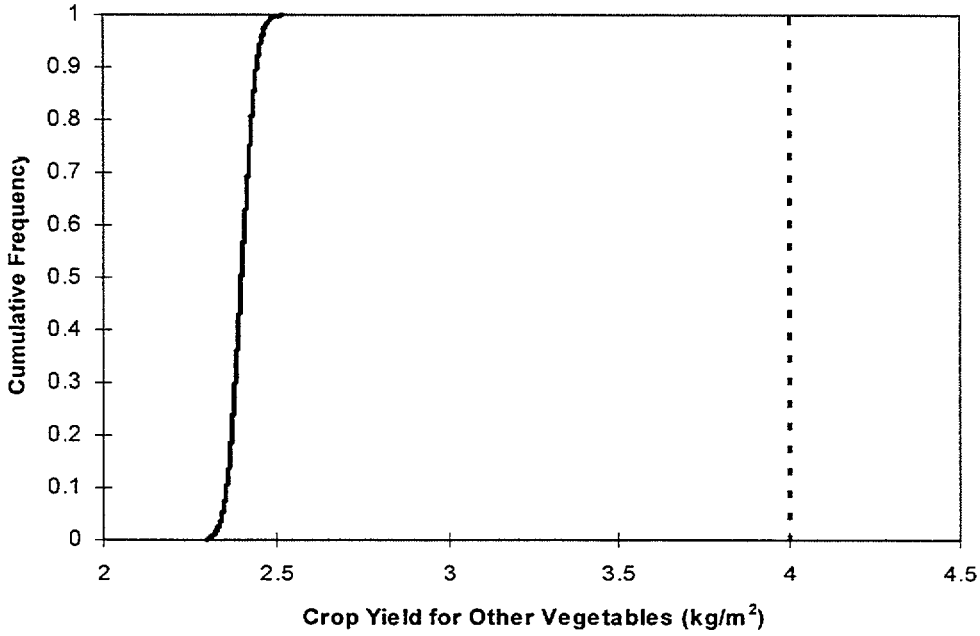

Figure 6.79 Cumulative frequency sampled Yv (other) values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

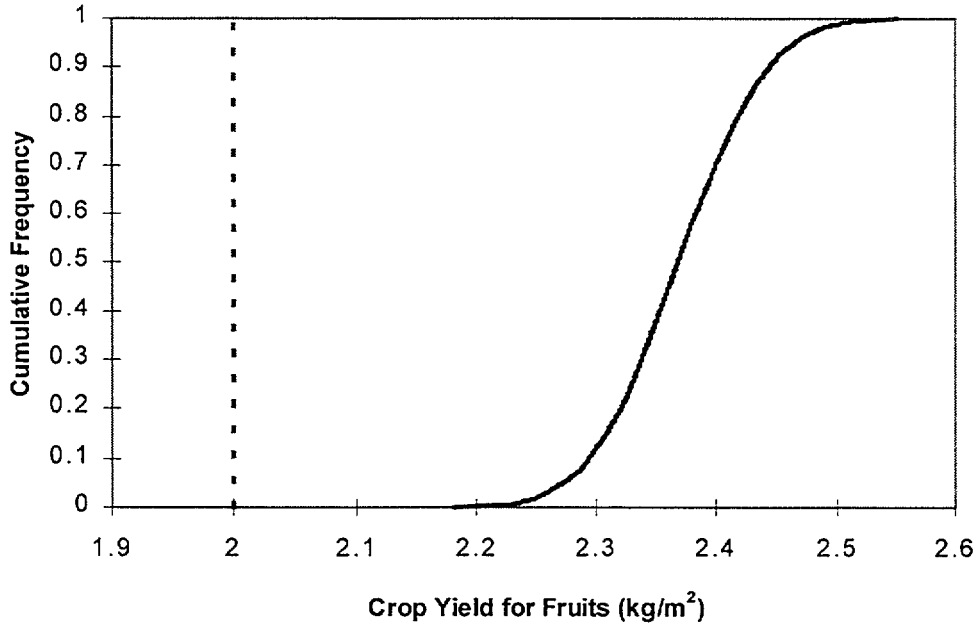

Figure 6.80 Cumulative frequency sampled Yv (fruit) values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

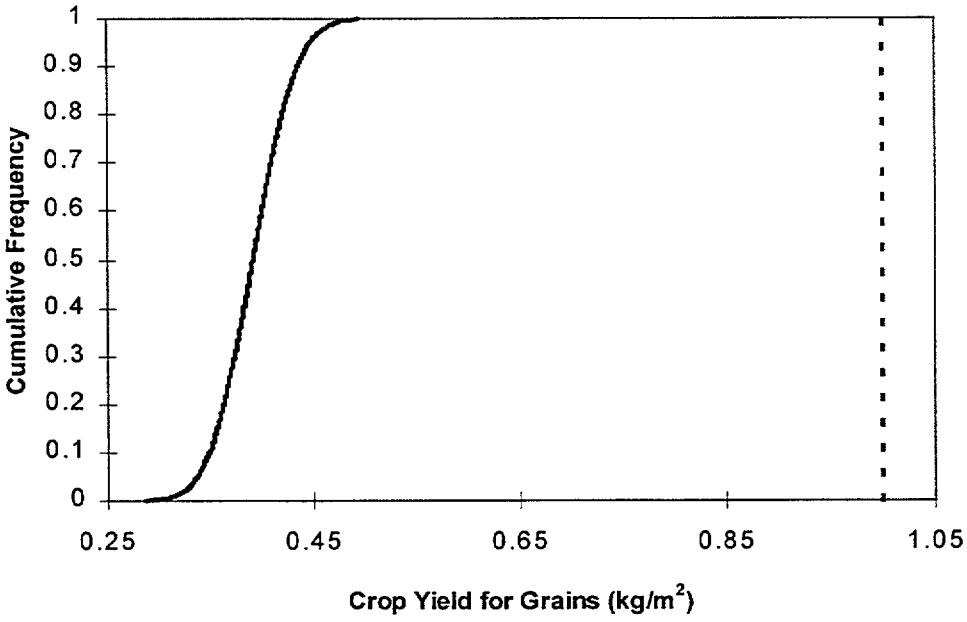

Figure 6.81 Cumulative frequency sampled Yg values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

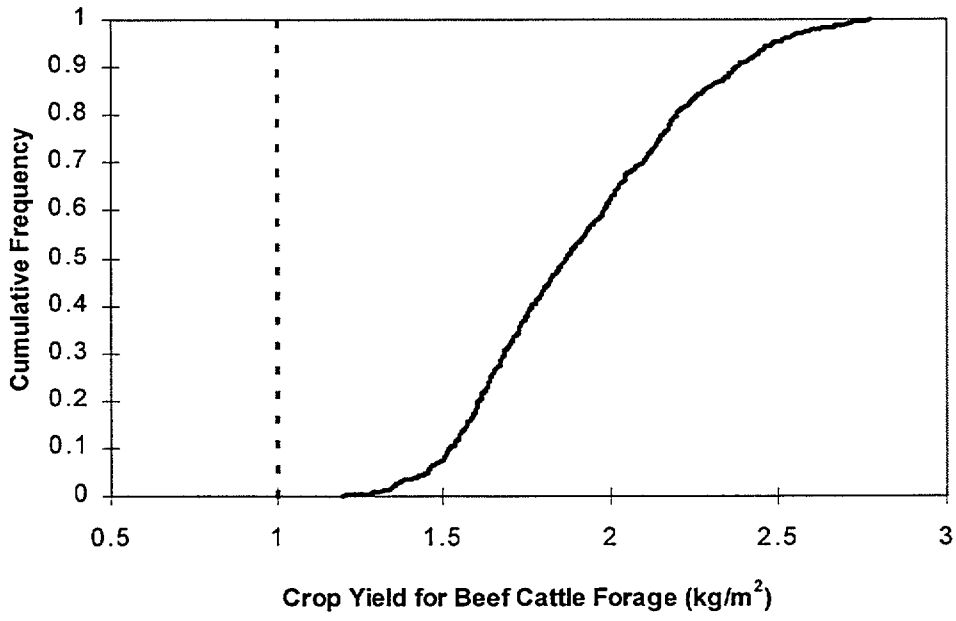

Figure 6.82 Cumulative frequency sampled Yf values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

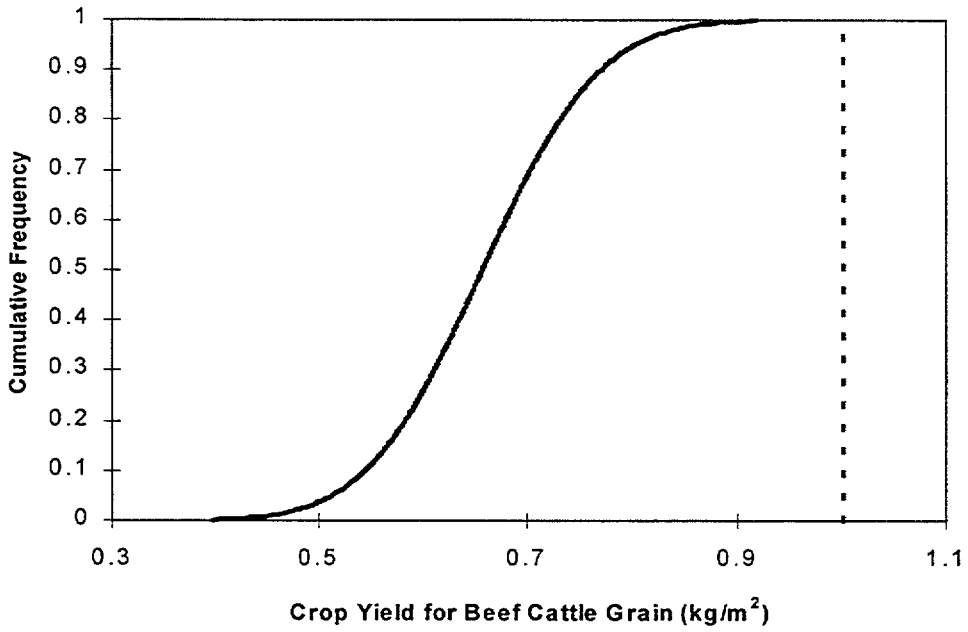

Figure 6.83 Cumulative frequency sampled Yg values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

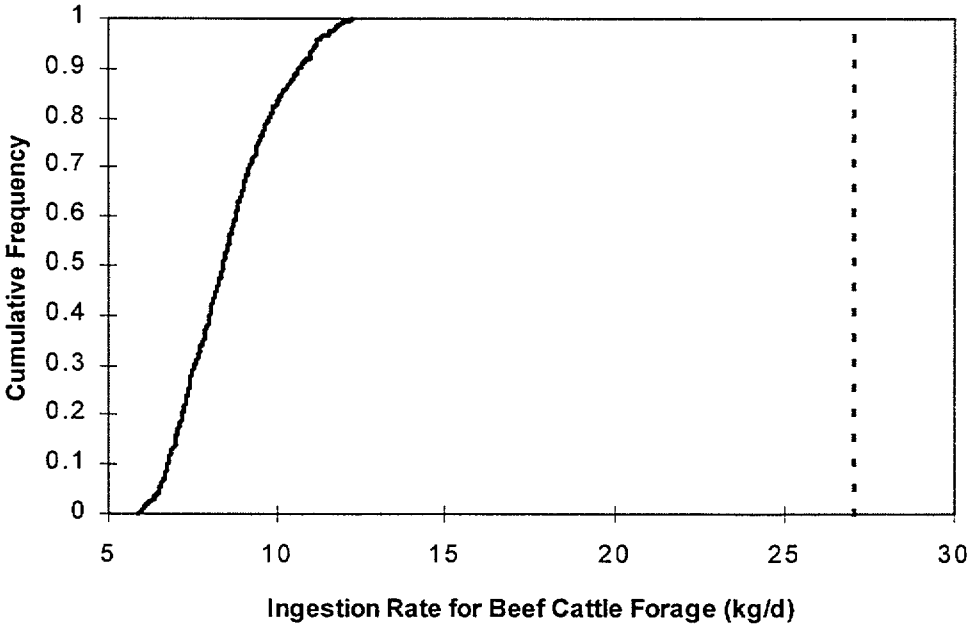

Figure 6.84 Cumulative frequency sampled Qf values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

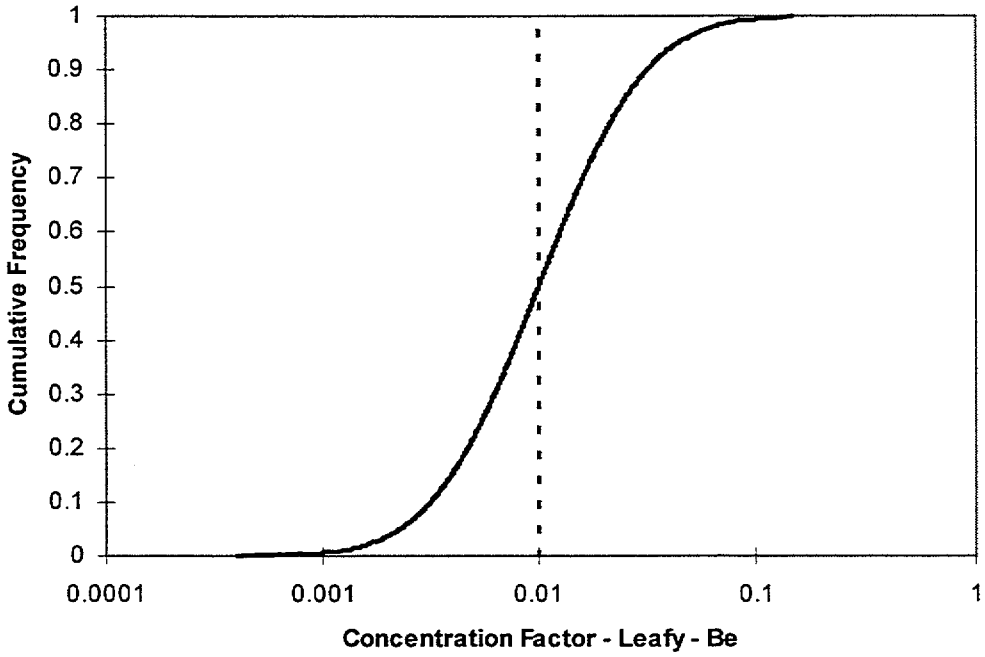

Figure 6.85 Cumulative frequency of sampled Bjv for Be in leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

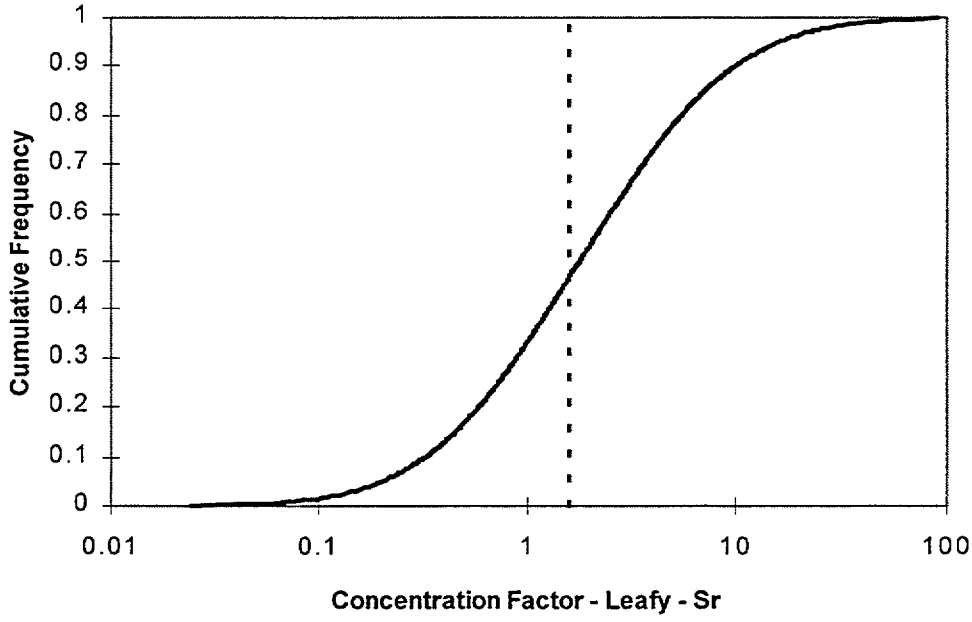

Figure 6.86 Cumulative frequency of sampled Bjv for Sr in leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

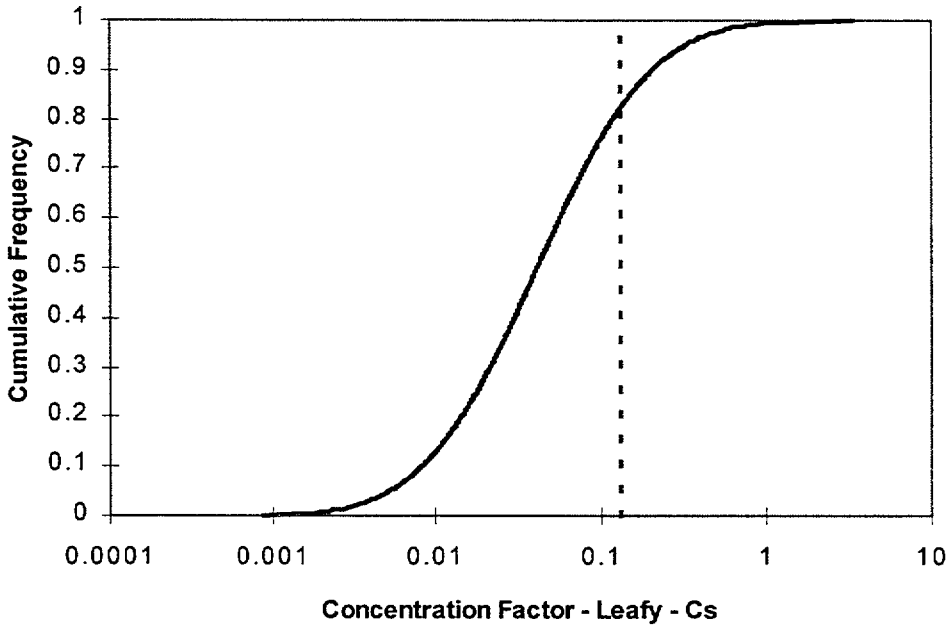

Figure 6.87 Cumulative frequency of sampled Bjv for Cs in leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

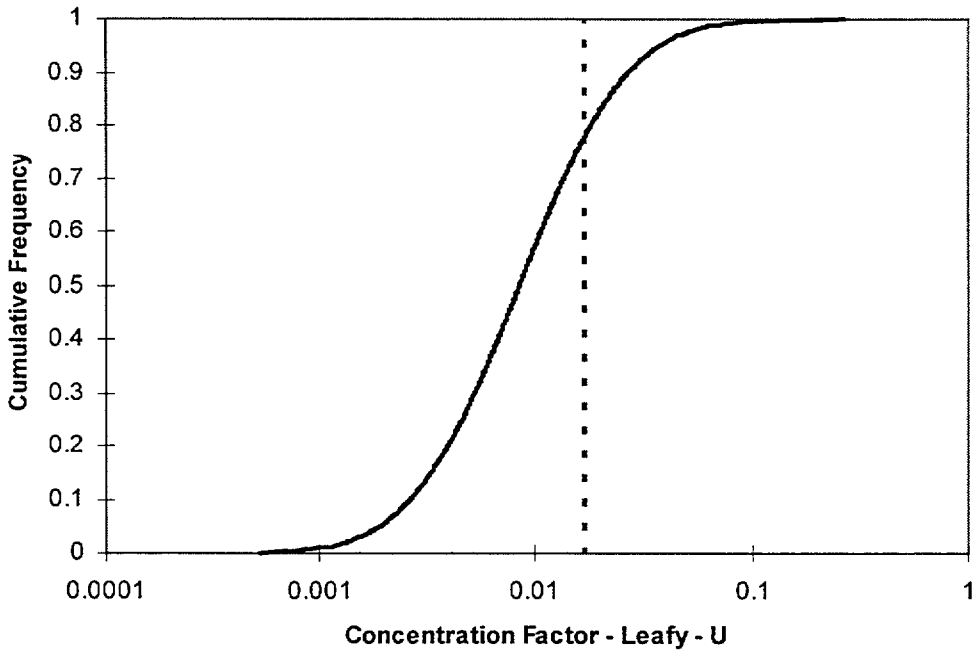

Figure 6.88 Cumulative frequency of sampled Bjv for U in leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

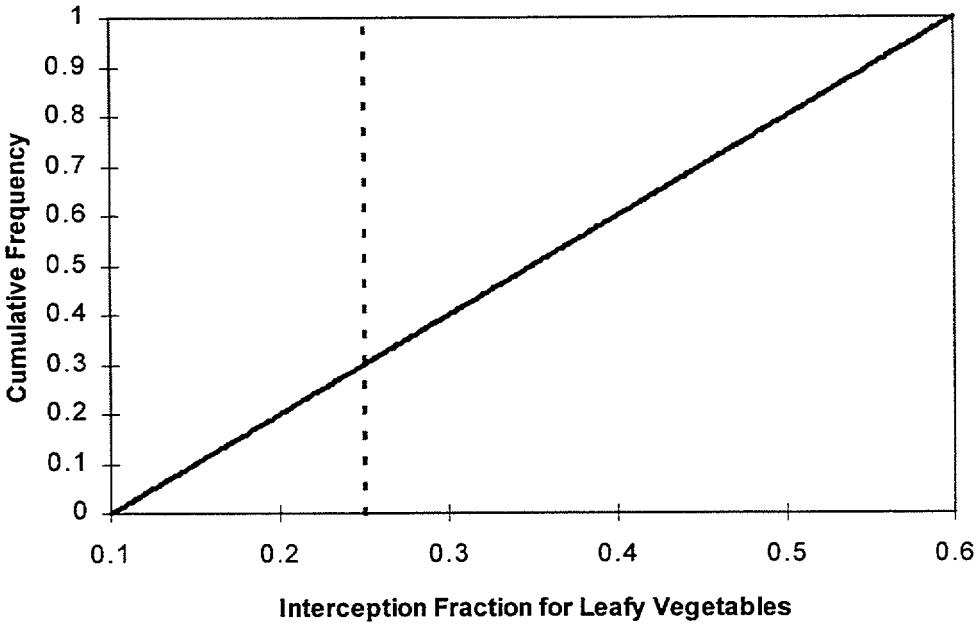

Figure 6.89 Cumulative frequency of sampled r_v for leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

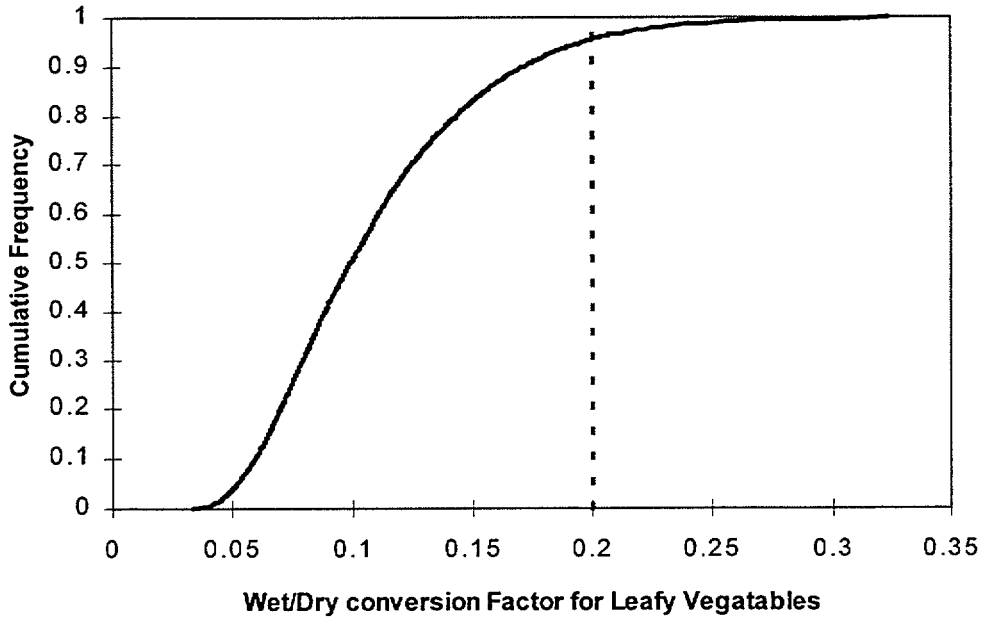

Figure 6.90 Cumulative frequency of sampled Wv for leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

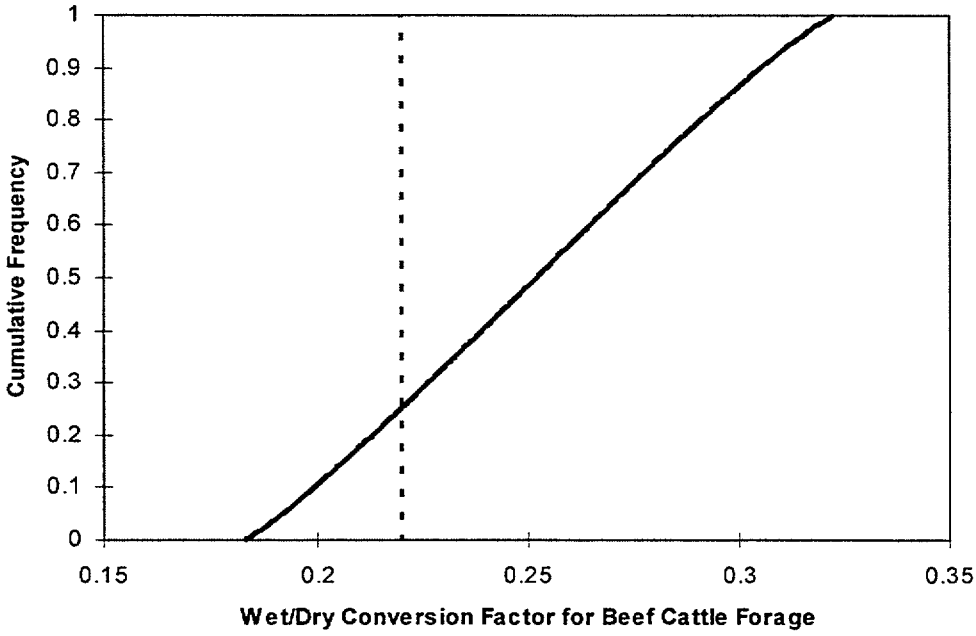

Figure 6.91 Cumulative frequency of sampled Wf for leafy vegetables (dashed vertical line = NUREG/CR 5512, Vol. 1, default)

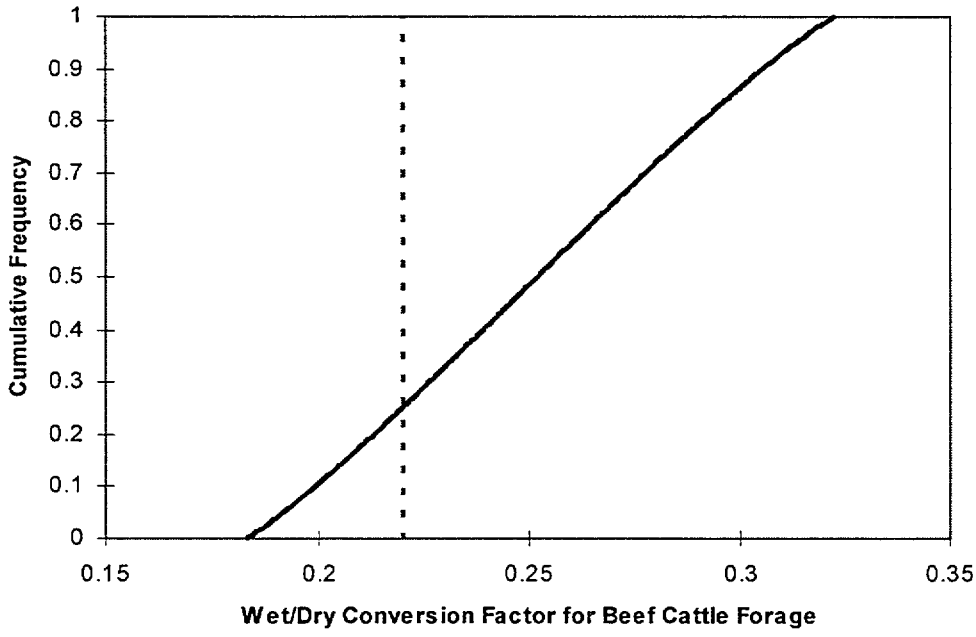

Figure 6.92 Cumulative frequency of sampled Kd for Cs (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

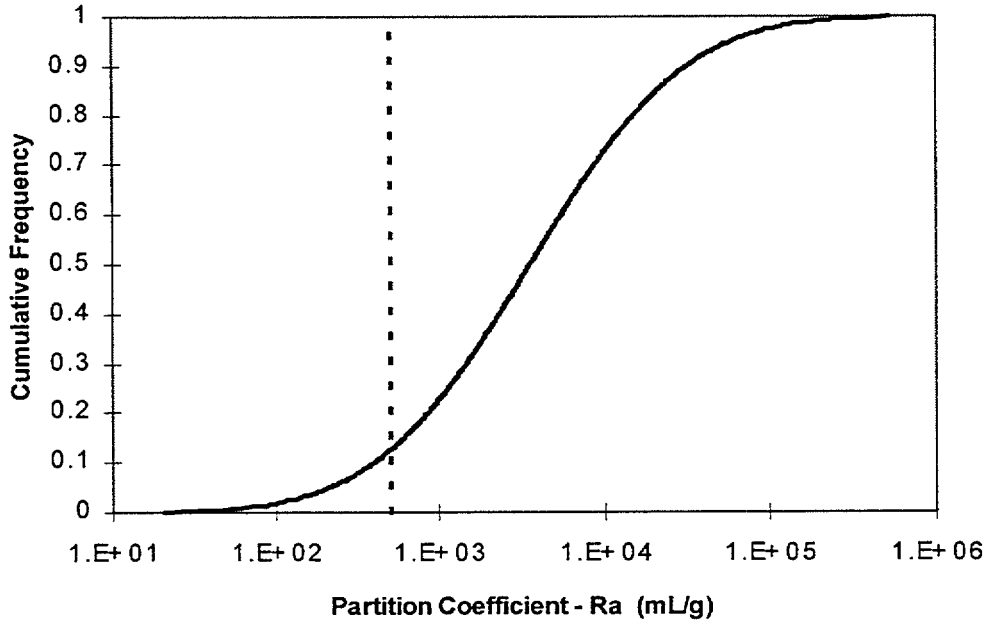

Figure 6.93 Cumulative frequency of sampled Kd for Ra (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

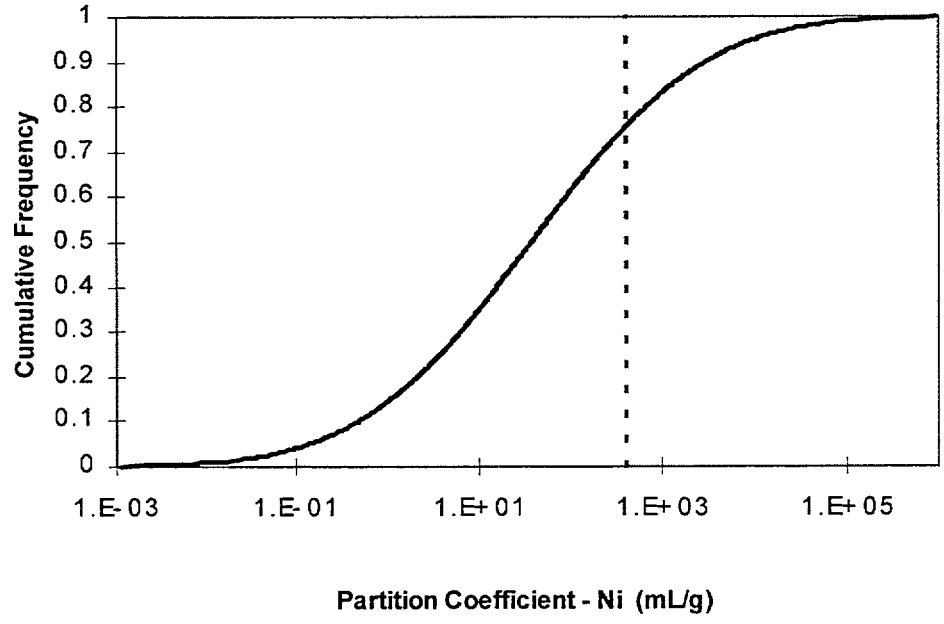

Figure 6.94 Cumulative frequency of sampled Kd for Ni (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

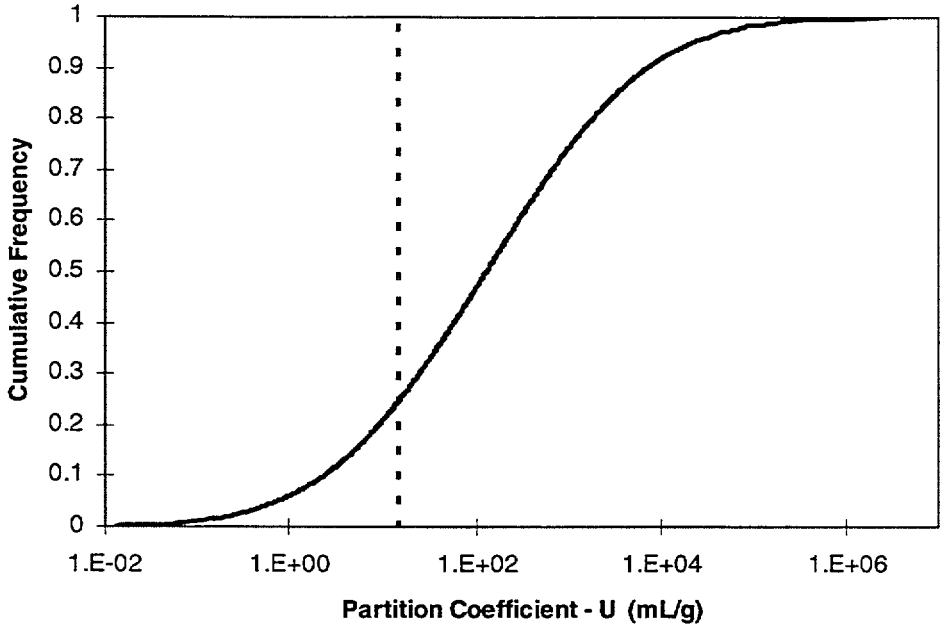

Figure 6.95 Cumulative frequency of sampled Kd for U (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

Table 6.89 Unsaturated zone model error analysis

Radionuclide	H2 (meters)	Unsat'd zone model	TEDE	% Error
Co-60	100	Mixing Cell	6.79e+00	-9.75e-01
	100	Numerical	6.73e+00	
	200	Mixing Cell	6.76e+00	-4.88e-01
	200	Numerical	6.73e+00	
Mo-93	100	Mixing Cell	4.89e-02	-3.03e+00
	100	Numerical	4.75e-02	
	200	Mixing Cell	4.82e-02	-1.52e+00
	200	Numerical	4.75e-02	
Th-230	100	Mixing Cell	1.39e+01	6.35e+00
	100	Numerical	1.49e+01	
	200	Mixing Cell	8.91e+00	6.98e+00
	200	Numerical	9.58e+00	
H-3	100	Mixing Cell	1.61e-01	6.21e-04
	100	Numerical	1.61e-01	
	200	Mixing Cell	1.61e-01	-8.69e-03
	200	Numerical	1.61e-01	
I-129	100	Mixing Cell	6.47e+00	7.37e+00
	100	Numerical	6.98e+00	
	200	Mixing Cell	5.85e+00	-1.18e+01
	200	Numerical	5.24e+00	
U-235	100	Mixing Cell	1.67e+00	6.35e+00
	100	Numerical	1.79e+00	
	200	Mixing Cell	1.46e+00	-9.51e+00
	200	Numerical	1.33e+00	

cell and numerical models. The TEDE for every nuclide was the same to six significant figures except for ^{3}H, ^{75}Se, ^{93}Mo, ^{129}I, ^{226}Ra, $^{226}Ra+C$, ^{230}Th, $^{230}Th+C$, ^{233}U, $^{238}U+C$, ^{245}Cm, and ^{247}Cm. For these radionuclides, the TEDE's from the mixing cell and numerical models were equivalent to three significant digits.

Analyzing these results indicated that the mean radionuclide partition coefficients, most of which are larger than the default values proposed in NUREG/CR-5512, Vol. 1,[3] cause radionuclides to be retained in the unsaturated zone, thereby decreasing the importance of the dose from the ground water pathways. This in turn decreases the sensitivity to the choice of the mixing cell or numerical model for unsaturated zone transport.

To bound the potential error associated with using the mixing cell model instead of the numerical model, calculations were conducted assuming no sorption and a relatively thick unsaturated zone. Results for selected radionuclides are shown in Table 6.89. For each of these radionuclides, the maximum relative error (numerical solution TEDE minus mixing cell solution TEDE divided by the numerical solution TEDE) is less than 12%. TEDE tends to be overestimated by the mixing cell model.

6.5.2.2.2 Dose Distributions

For each source, the distribution describing possible doses to the AMSG was estimated from the dose values calculated using the 580 sampled parameter values. For three alternative values of P_{crit}, and for each source nuclide, the value of d_{Ci} (the quantile of order $1 - P_{crit}$ from Equation 3.7) was determined from the calculated distribution. Table 6.90 lists the values of d_{Ci} for each of the source nuclides, and for the three selected values of P_{crit}. The increase in d_{Ci} for decreasing (more restrictive) values of P_{crit} indicates the spread of the underlying dose distribution. As a further measure of distribution spread, Table 6.90 also shows the ratio of dose at the 99th percentile to the median (50th percentile) dose.

Dose values at the selected quantiles can also be used to calculate the source concentration equivalent to a dose of 25 mrem. Table 6.91 summarizes these concentration values.

[3]The mean of the PDF for Kd for 50 of the 69 elements is greater than the Volume 1 default

6.5.3 Identification of Default Parameter Values

Using the dose quantile values d_{Ci} estimated from the dose distributions, vectors of parameter values $\mathbf{x}_d$ which satisfied Equation 3.8 were identified using the procedure outlined in Section 3.3. This section describes the application of that procedure, and summarizes the solutions obtained.

The initial LHS sample set was examined for solutions to Equation 3.8 at the P_{crit} values of 0.50, 0.25, and 0.10. None were found, and the basic genetic algorithm described in Appendix B was used to construct new sets of parameter vectors, using the solution count values to select parent vectors. After six iterations of the basic genetic algorithm, only two solutions were produced at the least restrictive P_{crit} value of 0.50, and no solution vectors had been produced for the P_{crit} value of 0.10. In addition, the increase in solution counts with successive generations was discouraging. Figure 6.96 shows the distributions of solution counts, for a P_{crit} value of 0.10, for the initial set of sample vectors and the first six iterations of the basic genetic algorithm.

Because of the very slow improvement in solution counts produced by the basic genetic algorithm, the "genetic engineering" algorithm described in Appendix C was applied beginning with the original set of LHS sample vectors. Figure 6.97 show the distribution of solution counts for the sets of sample vectors produced by three successive applications of this algorithm. The third set of vectors contained 63 solutions to Equation 3.8 for a P_{crit} value of 0.10.

6.5.4 Ranking of Solutions

For each of the 63 solution vectors found in the solution search, the joint parameter exceedance probability and the average inversion probability were calculated as described in Appendix B. Given that Equation 3.8 is satisfied, solutions having large values of these measures are preferred to solutions with small values.

Figure 6.98 is a scatter plot showing the values of these measures for the 63 solution vectors. The average inversion probability is confined to a fairly narrow range between 0.013 and 0.03. The maximum theoretical value for the average inversion probability is P_{crit}, which would only be obtained for a parameter vector that satisfied Equation 3.8 as a strict equality for all sources. Such a solution may not exist because of the large number of source term constraints that must be satisfied. The joint parameter exceedance probability, in contrast,

Table 6.90 Selected quantiles of unit-concentrationTEDE distributions for the residential scenario (mrem)

Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$	Dose @ $P_{crit} = 0.01$/ Dose @ $P_{crit} = 0.50$
3H	1.41E-01	2.32E-01	3.10E-01	4.15
10Be	1.48E-02	1.65E-02	1.88E-02	13.17
14C	6.10E-01	2.15E+00	3.85E+00	33.61
22Na	5.49E+00	5.88E+00	6.85E+00	2.98
35S	6.46E-02	9.26E-02	1.20E-01	4.56
36Cl	4.46E+01	6.91E+01	8.54E+01	4.87
40K	2.74E+00	6.94E+00	1.48E+01	19.24
41Ca	2.28E-01	3.77E-01	4.86E-01	6.51
45Ca	2.69E-01	4.41E-01	5.84E-01	6.88
46Sc	1.70E+00	1.70E+00	1.70E+00	1.01
54Mn	1.60E+00	1.69E+00	1.79E+00	1.37
55Fe	2.21E-03	2.43E-03	2.67E-03	10.10
57Co	1.66E-01	1.69E-01	1.73E-01	1.25
58Co	7.17E-01	7.20E-01	7.24E-01	1.05
60Co	6.49E+00	6.60E+00	6.79E+00	1.24
59Ni	2.07E-03	4.51E-03	1.35E-02	39.83
63Ni	5.65E-03	1.19E-02	3.49E-02	39.30
65Zn	1.84E+00	2.32E+00	2.80E+00	3.38
75Se	4.24E-01	4.29E-01	4.32E-01	1.05
79Se	1.05E-01	1.21E-01	1.35E-01	1.92
90Sr	8.80E+00	1.46E+01	2.05E+01	8.42
93Zr	1.82E-02	2.32E-02	3.86E-02	13.38
93Zr+C	9.84E-03	1.33E-02	2.01E-02	12.60
93mNb	1.24E-02	1.38E-02	1.67E-02	7.68
94Nb	4.30E+00	4.32E+00	4.34E+00	1.03
93Mo	5.94E-02	1.17E-01	1.67E-01	11.03
99Tc	8.57E-01	1.34E+00	1.68E+00	5.63
106Ru	4.73E-01	4.94E-01	5.18E-01	1.29
107Pd	2.76E-03	3.89E-03	6.11E-03	12.35
110mAg	4.93E+00	5.08E+00	5.23E+00	1.20
109Cd	1.63E-01	2.35E-01	3.46E-01	10.77
113mCd	2.84E+00	5.05E+00	9.07E+00	19.52
119mSn	6.95E-03	8.10E-03	1.10E-02	14.69
121mSn	1.83E-02	4.39E-02	1.94E-01	61.15
123Sn	2.86E-02	3.24E-02	4.06E-02	5.76
126Sn	5.30E+00	5.32E+00	5.36E+00	2.13
126Sn+C	2.48E+00	2.49E+00	2.53E+00	2.13
125Sb	9.71E-01	9.76E-01	9.82E-01	1.16
123mTe	1.34E-01	1.35E-01	1.36E-01	1.22
127mTe	1.64E-02	1.75E-02	1.88E-02	3.54
129I	1.47E+01	4.65E+01	1.01E+02	49.83
134Cs	4.18E+00	4.40E+00	4.66E+00	1.92
135Cs	8.94E-02	1.36E-01	2.18E-01	29.74
137Cs	2.06E+00	2.27E+00	2.54E+00	5.67

Table 6.90 Selected quantiles of unit-concentration TEDE distributions for the residential scenario (mrem) (continued)

Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$	Dose @ $P_{crit} = 0.01$/ Dose @ $P_{crit} = 0.50$
144Ce	1.29E-01	1.36E-01	1.44E-01	1.36
147Pm	2.75E-03	3.05E-03	3.24E-03	1.92
147Sm	6.07E-01	6.91E-01	8.66E-01	6.61
151Sm	1.24E-03	1.42E-03	1.67E-03	6.26
152Eu	2.88E+00	2.88E+00	2.89E+00	1.01
154Eu	3.12E+00	3.12E+00	3.12E+00	1.01
155Eu	8.75E-02	8.80E-02	8.86E-02	1.07
153Gd	7.66E-02	7.93E-02	8.83E-02	1.66
160Tb	8.29E-01	8.29E-01	8.29E-01	1.02
166mHo	4.49E+00	4.49E+00	4.50E+00	1.01
181W	1.64E-02	1.66E-02	1.77E-02	1.95
185W	1.87E-03	2.43E-03	5.51E-03	27.86
187Re	4.09E-04	5.95E-04	8.25E-04	7.15
185Os	6.48E-01	6.49E-01	6.50E-01	1.03
192Ir	6.04E-01	6.05E-01	6.05E-01	1.01
210Pb	2.63E+01	2.95E+01	3.17E+01	5.37
210Po	2.64E+00	2.82E+00	2.97E+00	1.69
226Ra	3.22E+01	3.60E+01	3.86E+01	5.60
226Ra+C	4.15E+00	4.58E+00	4.85E+00	5.24
228Ra	6.49E+00	6.84E+00	7.05E+00	1.24
227Ac	4.22E+01	4.70E+01	5.16E+01	8.85
227Ac+C	5.28E+00	5.88E+00	6.43E+00	8.83
228Th	5.12E+00	5.29E+00	5.43E+00	1.15
228Th+C	7.37E-01	7.62E-01	7.81E-01	1.15
229Th	1.22E+01	1.35E+01	1.46E+01	5.99
229Th+C	1.53E+00	1.69E+00	1.83E+00	5.98
230Th	1.19E+01	1.36E+01	1.51E+01	9.18
230Th+C	3.88E+00	4.33E+00	4.67E+00	6.32
232Th	2.05E+01	2.21E+01	2.32E+01	3.01
232Th+C	2.12E+00	2.27E+00	2.40E+00	3.15
231Pa	6.82E+01	7.66E+01	9.01E+01	7.49
231Pa+C	8.24E+00	9.38E+00	1.06E+01	7.36
232U	1.01E+01	1.28E+01	4.25E+01	17.79
232U+C	1.43E+00	1.72E+00	5.21E+00	15.34
233U	1.71E+00	2.74E+00	6.76E+00	21.20
233U+C	1.53E+00	1.79E+00	2.55E+00	6.90
234U	1.12E+00	1.89E+00	6.62E+00	22.71
235U	2.22E+00	3.11E+00	7.47E+00	20.57
235U+C	6.99E+00	7.91E+00	9.09E+00	7.19
236U	1.06E+00	1.79E+00	6.27E+00	22.81
238U	1.11E+00	1.80E+00	6.33E+00	21.80
238U+C	3.04E+00	3.51E+00	4.59E+00	7.03
237Np	1.41E+02	2.72E+02	4.30E+02	11.45
237Np+C	1.36E+01	2.55E+01	4.35E+01	10.12

Table 6.90 Selected quantiles of unit-concentration TEDE distributions for the residential scenario (mrem) (continued)

Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$	Dose @ $P_{crit} = 0.01$/ Dose @ $P_{crit} = 0.50$
236Pu	2.74E+00	3.06E+00	3.35E+00	2.87
238Pu	8.88E+00	9.83E+00	1.05E+01	1.93
239Pu	9.88E+00	1.09E+01	1.17E+01	2.47
240Pu	9.88E+00	1.09E+01	1.17E+01	2.46
241Pu	3.02E-01	3.49E-01	5.81E-01	11.58
242Pu	9.38E+00	1.04E+01	1.11E+01	2.47
244Pu	1.03E+01	1.13E+01	1.21E+01	2.23
241Am	1.05E+01	1.20E+01	1.65E+01	10.28
242mAm				
243Am	1.09E+01	1.24E+01	1.68E+01	9.96
242Cm	1.38E-01	1.53E-01	1.61E-01	1.43
243Cm	7.15E+00	7.82E+00	8.26E+00	1.41
244Cm	5.46E+00	6.00E+00	6.34E+00	1.42
245Cm	1.53E+01	1.81E+01	2.12E+01	3.93
246Cm	1.03E+01	1.14E+01	1.20E+01	1.42
247Cm	1.07E+01	1.18E+01	1.24E+01	1.35
248Cm	3.80E+01	4.18E+01	4.41E+01	1.42
252Cf	3.12E+00	3.64E+00	4.42E+00	12.34

Table 6.91 Concentration (pCi/g) equivalent to 25 mrem/y for three values of P_{crit}

Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$	Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$
3H	1.77E+02	1.08E+02	8.06E+01	166mHo	5.57E+00	5.56E+00	5.56E+00
10Be	1.69E+03	1.51E+03	1.33E+03	181W	1.52E+03	1.51E+03	1.41E+03
14C	4.10E+01	1.16E+01	6.50E+00	185W	1.34E+04	1.03E+04	4.54E+03
22Na	4.55E+00	4.25E+00	3.65E+00	187Re	6.12E+04	4.20E+04	3.03E+04
35S	3.87E+02	2.70E+02	2.08E+02	185Os	3.86E+01	3.85E+01	3.85E+01
36Cl	5.61E-01	3.62E-01	2.93E-01	192Ir	4.14E+01	4.13E+01	4.13E+01
40K	9.13E+00	3.60E+00	1.69E+00	210Pb	9.50E-01	8.46E-01	7.90E-01
41Ca	1.10E+02	6.63E+01	5.15E+01	210Po	9.46E+00	8.87E+00	8.41E+00
45Ca	9.29E+01	5.67E+01	4.28E+01	226Ra	7.77E-01	6.94E-01	6.48E-01
46Sc	1.47E+01	1.47E+01	1.47E+01	226Ra+C	6.03E+00	5.45E+00	5.16E+00
54Mn	1.57E+01	1.48E+01	1.39E+01	228Ra	3.85E+00	3.65E+00	3.54E+00
55Fe	1.13E+04	1.03E+04	9.35E+03	227Ac	5.92E-01	5.31E-01	4.85E-01
57Co	1.51E+02	1.48E+02	1.44E+02	227Ac+C	4.74E+00	4.25E+00	3.89E+00
58Co	3.49E+01	3.47E+01	3.45E+01	228Th	4.89E+00	4.73E+00	4.61E+00
60Co	3.85E+00	3.79E+00	3.68E+00	228Th+C	3.39E+01	3.28E+01	3.20E+01
59Ni	1.21E+04	5.54E+03	1.85E+03	229Th	2.04E+00	1.85E+00	1.71E+00
63Ni	4.43E+03	2.11E+03	7.17E+02	229Th+C	1.63E+01	1.48E+01	1.36E+01
65Zn	1.36E+01	1.08E+01	8.93E+00	230Th	2.10E+00	1.83E+00	1.65E+00
75Se	5.89E+01	5.83E+01	5.78E+01	230^{Th}+C	6.44E+00	5.78E+00	5.36E+00
79Se	2.39E+02	2.07E+02	1.85E+02	232Th	1.22E+00	1.13E+00	1.08E+00

Table 6.91 Concentration (pCi/g) equivalent to 25 mrem/y for three values of P_{crit} (continued)

Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05	Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05
90Sr	2.84E+00	1.72E+00	1.22E+00	232Th+C	1.18E+01	1.10E+01	1.04E+01
93Zr	1.38E+03	1.08E+03	6.48E+02	231Pa	3.66E-01	3.27E-01	2.77E-01
93Zr+C	2.54E+03	1.88E+03	1.25E+03	231Pa+C	3.03E+00	2.67E+00	2.36E+00
93mNb	2.02E+03	1.81E+03	1.49E+03	232U	2.47E+00	1.96E+00	5.88E-01
94Nb	5.81E+00	5.79E+00	5.76E+00	232U+C	1.74E+01	1.46E+01	4.80E+00
93Mo	4.21E+02	2.13E+02	1.49E+02	233U	1.47E+01	9.11E+00	3.70E+00
99Tc	2.92E+01	1.87E+01	1.49E+01	233U+C	1.63E+01	1.40E+01	9.81E+00
106Ru	5.28E+01	5.06E+01	4.83E+01	234U	2.23E+01	1.32E+01	3.78E+00
107Pd	9.07E+03	6.43E+03	4.09E+03	235U	1.13E+01	8.04E+00	3.35E+00
110mAg	5.07E+00	4.92E+00	4.78E+00	235U+C	3.58E+00	3.16E+00	2.75E+00
109Cd	1.54E+02	1.06E+02	7.23E+01	236U	2.36E+01	1.40E+01	3.99E+00
113mCd	8.80E+00	4.95E+00	2.76E+00	238U	2.26E+01	1.39E+01	3.95E+00
119mSn	3.60E+03	3.09E+03	2.26E+03	238U+C	8.21E+00	7.13E+00	5.44E+00
121mSn	1.37E+03	5.70E+02	1.29E+02	237Np	1.77E-01	9.18E-02	5.81E-02
123Sn	8.74E+02	7.71E+02	6.16E+02	237Np+C	1.84E+00	9.81E-01	5.75E-01
126Sn	4.72E+00	4.70E+00	4.66E+00	236Pu	9.11E+00	8.17E+00	7.45E+00
126Sn+C	1.01E+01	1.00E+01	9.89E+00	238Pu	2.81E+00	2.54E+00	2.39E+00
125Sb	2.57E+01	2.56E+01	2.55E+01	239Pu	2.53E+00	2.28E+00	2.15E+00
123mTe	1.86E+02	1.85E+02	1.84E+02	240Pu	2.53E+00	2.28E+00	2.15E+00
127mTe	1.52E+03	1.43E+03	1.33E+03	241Pu	8.28E+01	7.16E+01	4.30E+01
129I	1.70E+00	5.38E-01	2.47E-01	242Pu	2.66E+00	2.41E+00	2.26E+00
134Cs	5.98E+00	5.68E+00	5.36E+00	244Pu	2.42E+00	2.22E+00	2.07E+00
135Cs	2.80E+02	1.83E+02	1.15E+02	241Am	2.39E+00	2.08E+00	1.52E+00
137Cs	1.22E+01	1.10E+01	9.83E+00	243Am	2.30E+00	2.01E+00	1.49E+00
144Ce	1.93E+02	1.84E+02	1.74E+02	243mAm			
147Pm	9.08E+03	8.20E+03	7.71E+03	242Cm	1.81E+02	1.64E+02	1.56E+02
147Sm	4.12E+01	3.62E+01	2.89E+01	243Cm	3.50E+00	3.20E+00	3.03E+00
151Sm	2.01E+04	1.76E+04	1.50E+04	244Cm	4.58E+00	4.17E+00	3.94E+00
152Eu	8.68E+00	8.67E+00	8.66E+00	245Cm	1.63E+00	1.38E+00	1.18E+00
154Eu	8.02E+00	8.01E+00	8.00E+00	246Cm	2.42E+00	2.20E+00	2.09E+00
155Eu	2.86E+02	2.84E+02	2.82E+02	247Cm	2.33E+00	2.12E+00	2.02E+00
153Gd	3.27E+02	3.15E+02	2.83E+02	248Cm	6.57E-01	5.98E-01	5.67E-01
160Tb	3.02E+01	3.02E+01	3.02E+01	252Cf	8.00E+00	6.86E+00	5.66E+00

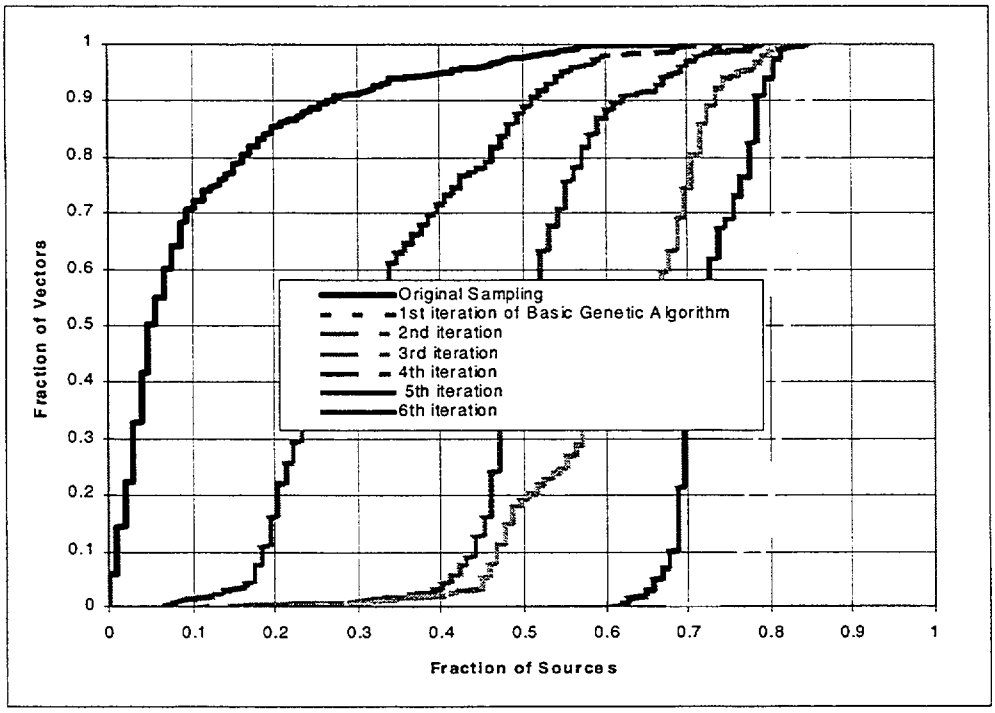

Figure 6.96 Solution count distributions for the original LHS sample set and the first 6 iterations of the basic genetic algorithm

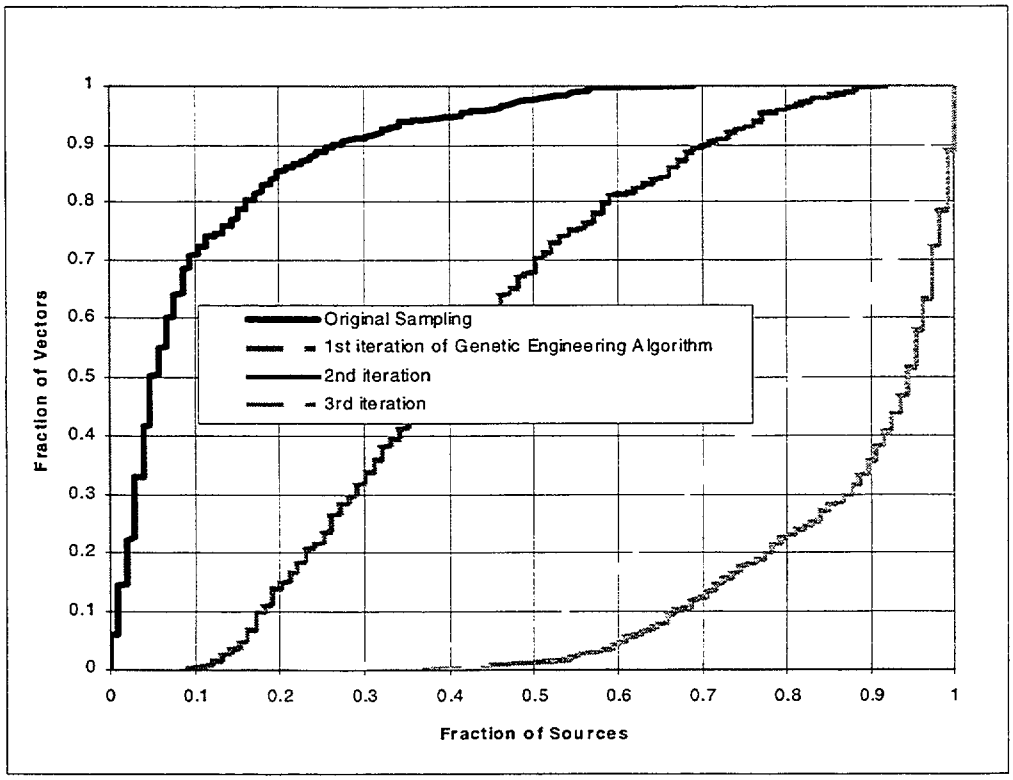

Figure 6.97 Solution count distributions for the original LHS sample set and the first 3 iterations of the genetic engineering algorithm

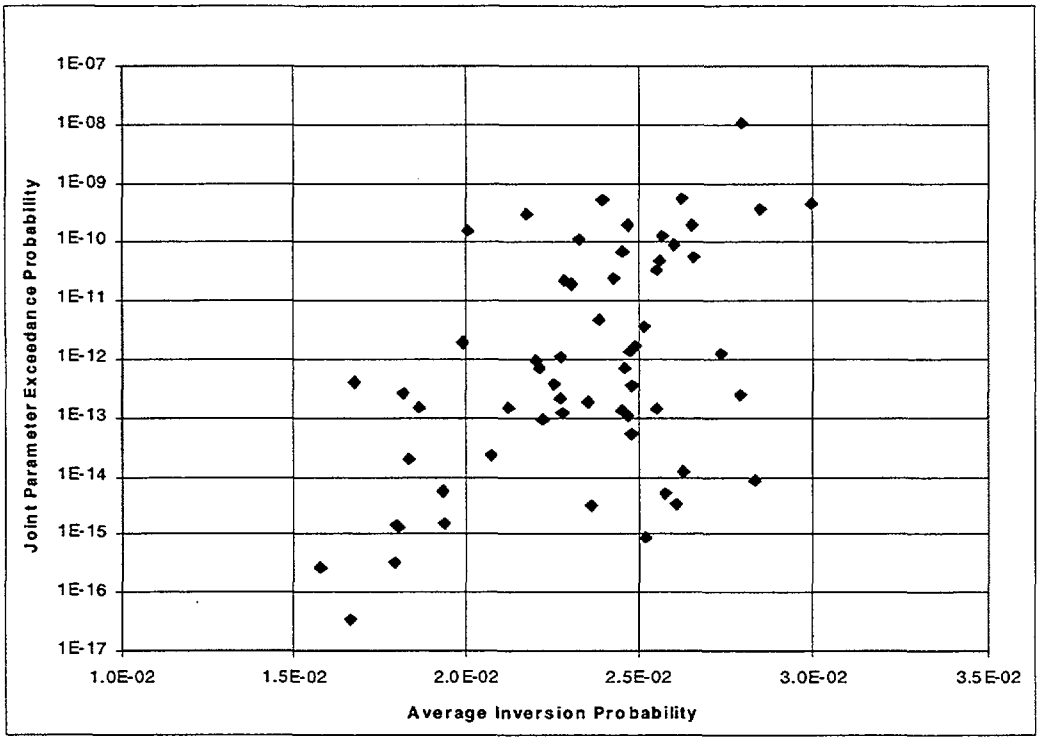

Figure 6.98 Scatterplot of joint parameter exceedance probabilities and average inversion probabilities for 63 solution vectors

varies over several orders of magnitude. The largest observed value is approximately 1×10^{-8}. Because this value is substantially greater than the next largest alternative, and because the average inversion probability for this vector is also relatively large, this solution was selected to define the default parameter values.

Tables 6.92 and 6.93 list the parameter values for this solution. Statistics of the values sampled from the parameter distribution are also included for comparison.

6.5.5 Sensitivity Analysis

The results of the Monte-Carlo dose calculations were processed to identify parameters controlling TEDE for each source. The dependence of TEDE on the model parameter values is potentially complex: total dose may depend non-monotonically on the parameter value, or may be sensitive to the parameter value only within certain limits, or only in conjunction with certain ranges of values for other parameters. Because of these complexities, a linear regression analysis was not used to identify sensitive parameters.

Instead, a robust test which does not rely on monotonicity was employed. For each source nuclide, sensitive parameters were identified by dividing the sample vectors into two groups with equal numbers of samples: vectors having doses above the median dose, and vectors with doses below the median dose. For each parameter, the Kolmogorov-Smirnov (K-S) test was used to assess the significance of the differences in the distributions of parameter values between these two groups. Parameters whose distributions differed at a significance level of 0.0001 were selected. A restrictive value of the significance level is appropriate in this analysis because of the large number of tests performed (580 vectors × 435 sampled parameters), and the correspondingly high prospect of producing low K-S statistic values by random chance.

For each parameter selected, the strength of the dependence of TEDE on the parameter value was calculated by segregating the sample vectors on the basis of the parameter value. This segregation defines two groups of sample vectors: vectors having values for the selected parameter less than a chosen quantile; and vectors having parameter values greater than the chosen quantile. Within each group, the TEDE distribution was estimated using only vectors in that group. The 95th percentile of this distribution was then compared to the 95th percentile of the original TEDE distribution using all sample vectors. The ratio of the 95th percentile TEDE value from the segregated sample to the 95th

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10

Part 2 - Partition coefficients in mL/g (kd)				
Element	Statistics for sampled values			Solution
	Average	Min	Max	Vector 105
H	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Be	9.98E+04	6.84E-02	2.10E+07	**9.29E+02**
C	4.83E+11	2.71E-01	2.80E+14	**4.34E+00**
F	4.50E+02	1.85E-04	7.42E+04	**4.97E+00**
Na	6.54E+02	1.08E-04	1.86E+05	**3.56E-02**
P	2.86E+03	1.85E-03	5.91E+05	**2.57E+01**
S	9.58E+03	4.73E-03	1.88E+06	**9.92E+01**
Cl	4.56E+02	2.87E-05	7.01E+04	**4.95E+00**
K	6.12E+02	1.07E-04	1.59E+05	**5.01E+00**
Ca	1.56E+05	2.97E-02	3.38E+07	**1.47E+03**
Sc	1.54E+04	3.43E-03	2.07E+06	**5.06E-01**
Cr	3.40E+03	1.68E-02	4.00E+05	**1.01E+02**
Mn	4.67E+07	7.60E+00	2.59E+10	**8.41E+01**
Fe	1.10E+03	7.70E-02	1.39E+04	**5.35E+02**
Co	1.91E+03	3.42E-03	4.43E+04	**1.51E+03**
Ni	5.54E+03	1.10E-03	9.47E+05	**3.70E+01**
Cu	1.66E+04	2.90E-03	2.88E+06	**1.76E+02**
Zn	2.09E+06	5.82E-04	5.19E+08	**1.06E+03**
As	1.21E+04	3.38E-03	2.69E+06	**1.14E+02**
Se	1.35E+02	2.13E+01	6.23E+02	**1.15E+02**
Br	6.67E+03	1.55E-03	1.69E+06	**5.62E+01**
Kr	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Rb	3.10E+04	3.49E-03	9.33E+06	**2.02E+02**
Sr	3.62E+02	5.46E-02	7.41E+04	**3.14E+01**
Y	1.09E+05	2.51E-02	3.01E+07	**7.89E+02**
Zr	4.33E+05	1.86E-02	1.59E+08	**4.66E+04**
Nb	2.02E+05	2.84E-02	9.26E+07	**8.26E-01**
Mo	1.30E+02	1.58E-01	1.56E+04	**2.61E+01**
Tc	4.96E+02	1.89E-04	8.34E+04	**7.37E+00**
Ru	1.95E+05	3.51E-03	6.11E+07	**1.58E+03**
Rh	1.85E+04	3.33E-03	4.79E+06	**1.57E+02**
Pd	1.51E+04	7.38E-03	2.88E+06	**1.85E+02**
Ag	8.41E+07	4.07E+00	4.78E+10	**1.91E+02**
Cd	2.19E+03	3.72E-03	4.86E+05	**3.36E+01**
In	1.45E+04	2.25E-03	2.48E+06	**1.58E+02**
Sn	5.86E+04	1.43E-02	1.30E+07	**2.52E+01**
Sb	1.73E+04	9.10E-03	3.36E+06	**6.83E+04**
Te	4.89E+04	1.90E-02	6.91E+06	**5.48E+02**
I	5.07E+01	4.71E-03	7.52E+03	**2.83E-01**
Xe	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Part 2 - Partition coefficients in mL/g (kd)				
Element	Statistics for sampled values			Solution
	Average	Min	Max	Vector 105
Cs	5.78E+03	3.43E-01	5.97E+05	**1.05E+01**
Ba	2.65E+09	1.62E-09	1.16E+12	**4.40E+01**
La	9.25E+02	3.89E-05	3.51E+05	**4.98E+00**
Ce	1.39E+02	4.66E+00	1.97E+03	**8.48E+01**
Pr	8.53E+04	1.21E-02	4.31E+07	**1.57E+02**
Nd	1.34E+04	7.03E-03	2.00E+06	**1.58E+02**
Pm	5.55E+05	1.47E-01	1.25E+08	**5.00E+03**
Sm	1.08E+05	6.02E-02	2.47E+07	**9.30E+02**
Eu	3.25E+06	5.01E-03	1.62E+09	**9.40E+02**
Gd	4.78E+02	2.94E-04	6.67E+04	**1.32E-02**
Tb	1.58E+04	9.63E-03	3.02E+06	**5.32E+01**
Ho	1.59E+05	5.53E-02	5.44E+07	**6.69E+00**
W	1.79E+04	9.09E-03	3.97E+06	**1.56E+02**
Re	5.27E+03	2.32E-03	1.37E+06	**4.35E+01**
Os	1.76E+04	1.26E-02	4.14E+06	**1.57E+02**
Ir	3.95E+04	1.56E-03	1.67E+07	**1.58E+02**
Au	1.85E+04	6.93E-03	3.75E+06	**1.57E+02**
Hg	1.41E+04	1.04E-02	2.08E+06	**1.57E+02**
Tl	1.64E+04	7.60E-03	3.28E+06	**1.58E+02**
Pb	1.61E+05	2.45E-01	5.54E+07	**2.38E+03**
Bi	4.02E+04	3.00E-02	6.36E+06	**4.43E+02**
Po	7.70E+02	3.26E-01	5.59E+04	**2.64E+01**
Rn	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Ra	1.42E+04	2.05E+01	5.18E+05	**3.53E+03**
Ac	3.07E+05	1.96E-02	1.13E+08	**1.73E+03**
Th	1.70E+06	7.02E-02	4.02E+08	**1.19E+02**
Pa	1.87E+05	1.19E-01	2.88E+07	**4.80E+00**
U	1.23E+04	1.30E-02	2.67E+06	**2.18E+00**
Np	7.52E+03	1.97E-01	3.68E+06	**1.36E+01**
Pu	6.16E+03	3.40E+00	7.70E+05	**1.36E+01**
Am	1.24E+05	1.27E-01	2.42E+07	**1.43E+03**
Cm	3.88E+04	5.68E+00	4.82E+06	**1.09E+05**
Cf	2.15E+04	6.65E-04	6.28E+06	**1.58E+02**

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Element	Leafy Statistics for sampled values Average	Min	Max	Solution Vector 105	Root Statistics for sampled values Average	Min	Max	Solution Vector 105
Part 3 - Plant concentration factors (B_{jv}) (leafy and root)								
H	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Be	1.50E-02	4.01E-04	1.47E-01	**1.00E-02**	2.25E-03	9.76E-05	2.52E-02	**1.50E-03**
C	1.05E+00	4.65E-02	1.15E+01	**3.20E-01**	1.05E+00	4.63E-02	1.12E+01	**7.00E-01**
N	4.50E+01	2.12E+00	4.54E+02	**3.00E+01**	4.49E+01	1.62E+00	4.45E+02	**3.00E+01**
F	8.99E-02	3.95E-03	9.51E-01	**6.00E-02**	9.04E-03	3.36E-04	1.24E-01	**6.00E-03**
Na	1.11E-01	2.30E-03	1.35E+00	**7.40E-02**	1.33E-01	2.50E-04	2.64E+00	**2.80E-02**
Mg	1.50E+00	6.16E-02	1.52E+01	**1.00E+00**	8.25E-01	2.70E-02	8.67E+00	**5.50E-01**
Si	5.25E-01	1.90E-02	5.88E+00	**3.50E-01**	1.05E-01	2.96E-03	1.40E+00	**7.00E-02**
P	5.25E+00	2.40E-01	5.57E+01	**3.50E+00**	5.27E+00	2.05E-01	6.56E+01	**3.50E+00**
S	2.25E+00	6.49E-02	2.54E+01	**2.30E+00**	2.25E+00	1.05E-01	2.47E+01	**1.50E+00**
Cl	1.06E+02	4.44E+00	1.59E+03	**1.60E+02**	1.05E+02	4.43E+00	1.32E+03	**7.00E+01**
Ar	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
K	1.51E+00	5.87E-02	2.14E+01	**8.40E+00**	8.25E-01	3.58E-02	8.22E+00	**5.50E-01**
Ca	5.30E+00	1.93E-01	8.22E+01	**1.40E+01**	5.27E-01	2.42E-02	6.58E+00	**3.50E-01**
Sc	9.03E-03	4.09E-04	1.23E-01	**6.00E-03**	1.50E-03	6.33E-05	1.90E-02	**1.00E-03**
Cr	3.03E-02	1.64E-03	4.17E-01	**2.20E-02**	1.81E-01	1.05E-02	2.18E+00	**8.00E-02**
Mn	4.04E+00	3.11E-04	1.10E+03	**3.30E-01**	4.58E+00	5.47E-03	2.08E+02	**1.10E+01**
Fe	1.35E-02	1.00E-04	3.92E-01	**5.60E-03**	1.00E-02	6.07E-05	2.74E-01	**2.60E-03**
Co	2.91E-01	5.54E-04	1.51E+01	**4.00E-02**	3.31E-01	3.00E-03	8.20E+00	**2.90E+00**
Ni	6.63E-02	6.05E-04	1.24E+00	**3.40E-02**	3.44E-01	1.12E-02	4.03E+00	**2.50E+00**
Cu	7.74E-01	2.47E-02	1.15E+01	**4.90E-01**	5.49E+00	2.60E-04	3.30E+02	**2.60E-01**
Zn	9.08E-01	3.53E-02	9.94E+00	**3.10E-01**	3.00E+00	2.02E-02	1.25E+02	**2.40E-01**
Ga	6.00E-03	2.20E-04	6.74E-02	**4.00E-03**	5.99E-04	2.33E-05	5.68E-03	**4.00E-04**
As	6.04E-02	2.38E-03	9.04E-01	**4.00E-02**	9.02E-03	3.70E-04	9.65E-02	**6.00E-03**
Se	3.75E-02	1.69E-03	4.03E-01	**4.90E-02**	3.79E-02	1.38E-03	6.65E-01	**2.50E-02**
Br	2.25E+00	9.95E-02	2.17E+01	**1.50E+00**	2.26E+00	5.98E-02	2.75E+01	**1.50E+00**
Kr	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Rb	1.82E+00	1.34E-02	3.69E+01	**8.10E-01**	1.05E-01	2.24E-03	1.03E+00	**7.00E-02**
Sr	4.31E+00	2.39E-02	9.02E+01	**6.40E+01**	2.00E+00	2.05E-02	6.27E+01	**4.60E-01**
Y	2.24E-02	8.30E-04	2.26E-01	**1.50E-02**	9.15E-03	2.75E-04	1.83E-01	**6.00E-03**
Zr	9.21E-02	6.04E-03	9.87E-01	**7.20E-02**	9.79E-02	1.04E-05	9.48E+00	**4.70E-03**
Nb	3.00E-02	1.24E-03	2.82E-01	**4.60E-02**	7.52E-03	3.36E-04	9.13E-02	**5.00E-03**
Mo	4.48E+00	4.52E-02	1.03E+02	**5.20E+01**	8.98E-02	3.48E-03	8.78E-01	**6.00E-02**
Tc	1.43E+01	6.38E-01	1.79E+02	**3.60E+01**	2.25E+00	8.65E-02	2.48E+01	**1.50E+00**
Ru	2.05E-01	6.25E-04	6.33E+00	**1.80E-02**	5.10E-02	7.41E-05	2.05E+00	**8.60E-03**
Rh	2.26E-01	6.16E-03	3.04E+00	**1.50E-01**	6.02E-02	2.79E-03	6.84E-01	**4.00E-02**
Pd	2.27E-01	5.62E-03	3.41E+00	**1.20E+00**	6.01E-02	2.16E-03	7.15E-01	**4.00E-02**
Ag	6.03E-01	1.88E-02	7.74E+00	**5.50E+00**	1.51E-01	4.90E-03	2.33E+00	**1.00E-01**
Cd	8.29E-01	2.24E-02	1.11E+01	**5.00E+00**	2.24E-01	1.03E-02	2.18E+00	**1.50E-01**
In	5.99E-03	2.05E-04	6.00E-02	**4.00E-03**	6.02E-04	1.17E-05	7.39E-03	**4.00E-04**
Sn	4.50E-02	1.80E-03	4.56E-01	**4.30E-02**	9.07E-03	2.70E-04	1.41E-01	**6.00E-03**
Sb	3.03E-01	1.27E-02	4.76E+00	**9.00E-01**	4.51E-02	1.83E-03	5.56E-01	**3.00E-02**

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Element	Leafy				Root			
	Statistics for sampled values			Solution	Statistics for sampled values			Solution
	Average	Min	Max	Vector 105	Average	Min	Max	Vector 105
	Part 3 - Plant concentration factors (B_{jv}) (leafy and root)							
Te	3.74E-02	1.67E-03	3.56E-01	**1.70E-02**	6.02E-03	2.61E-04	7.49E-02	**4.00E-03**
I	3.46E-01	2.78E-03	6.46E+00	**1.60E-01**	1.70E-01	3.54E-04	7.62E+00	**2.80E-02**
Xe	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Cs	9.18E-02	8.79E-04	3.43E+00	**1.80E-02**	1.70E-01	9.37E-04	1.76E+01	**3.10E-02**
Ba	7.04E-02	8.60E-04	2.23E+00	**3.90E-02**	2.68E-02	3.54E-04	5.74E-01	**8.00E-03**
La	1.50E-02	7.00E-04	1.46E-01	**1.00E-02**	5.99E-03	2.35E-04	6.12E-02	**4.00E-03**
Ce	5.96E-02	1.48E-04	1.84E+00	**6.40E-01**	4.13E-02	1.92E-05	2.58E+00	**4.50E-03**
Pr	1.50E-02	5.61E-04	1.77E-01	**1.00E-02**	5.99E-03	2.70E-04	5.87E-02	**4.00E-03**
Nd	1.52E-02	4.92E-04	2.85E-01	**1.00E-02**	5.99E-03	2.16E-04	5.83E-02	**4.00E-03**
Pm	1.50E-02	6.07E-04	1.58E-01	**1.00E-02**	6.11E-03	2.52E-04	1.23E-01	**4.00E-03**
Sm	1.50E-02	2.81E-04	1.81E-01	**1.00E-02**	6.00E-03	2.81E-04	6.57E-02	**4.00E-03**
Eu	1.50E-02	6.59E-04	1.69E-01	**1.00E-02**	6.00E-03	2.37E-04	6.15E-02	**4.00E-03**
Gd	1.50E-02	6.49E-04	1.46E-01	**1.00E-02**	6.07E-03	2.51E-04	1.04E-01	**4.00E-03**
Tb	1.51E-02	6.20E-04	2.21E-01	**1.00E-02**	6.00E-03	1.79E-04	6.74E-02	**4.00E-03**
Dy	1.50E-02	2.61E-04	1.56E-01	**1.00E-02**	6.06E-03	1.50E-04	9.13E-02	**4.00E-03**
Ho	1.50E-02	6.21E-04	1.49E-01	**1.00E-02**	6.00E-03	2.75E-04	6.59E-02	**4.00E-03**
Er	1.50E-02	6.94E-04	1.52E-01	**1.00E-02**	6.01E-03	2.67E-04	7.03E-02	**4.00E-03**
Hf	5.24E-03	2.14E-04	5.04E-02	**3.50E-03**	1.28E-03	4.91E-05	1.51E-02	**8.50E-04**
Ta	1.52E-02	5.83E-04	2.93E-01	**1.00E-02**	3.79E-03	1.35E-04	6.37E-02	**2.50E-03**
W	6.80E-02	1.67E-03	1.03E+00	**3.10E-01**	1.50E-02	2.13E-04	1.55E-01	**1.00E-02**
Re	2.25E+00	9.72E-02	2.30E+01	**7.50E+00**	5.27E-01	9.81E-03	6.61E+00	**3.50E-01**
Os	2.24E-02	8.99E-04	2.16E-01	**9.40E-02**	5.27E-03	2.38E-04	6.85E-02	**3.50E-03**
Ir	8.26E-02	3.66E-03	9.75E-01	**1.50E-01**	2.26E-02	8.84E-04	2.58E-01	**1.50E-02**
Au	5.99E-01	2.14E-02	5.85E+00	**4.00E-01**	1.50E-01	3.96E-03	1.47E+00	**1.00E-01**
Hg	1.36E+00	5.93E-02	2.01E+01	**9.00E-01**	2.99E-01	1.18E-02	2.83E+00	**2.00E-01**
Tl	6.01E-03	1.89E-04	6.85E-02	**4.00E-03**	6.00E-04	1.71E-05	6.74E-03	**4.00E-04**
Pb	6.78E-02	2.61E-03	8.19E-01	**4.50E-02**	1.35E-02	5.74E-04	1.74E-01	**9.00E-03**
Bi	5.25E-02	2.16E-03	5.67E-01	**3.50E-02**	7.52E-03	3.02E-04	9.05E-02	**5.00E-03**
Po	3.78E-03	1.19E-04	5.76E-02	**2.50E-03**	6.00E-04	2.29E-05	6.30E-03	**4.00E-04**
Rn	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Ra	2.25E-02	9.78E-04	2.64E-01	**1.50E-02**	2.25E-03	8.40E-05	2.15E-02	**1.50E-03**
Ac	5.39E-03	2.39E-04	1.33E-01	**3.50E-03**	5.24E-04	2.37E-05	5.36E-03	**3.50E-04**
Th	1.28E-03	5.98E-05	1.49E-02	**8.50E-04**	1.27E-04	4.98E-06	1.33E-03	**8.50E-05**
Pa	3.75E-03	1.72E-04	4.18E-02	**2.50E-03**	3.75E-04	1.68E-05	4.59E-03	**2.50E-04**
U	1.30E-02	5.31E-04	2.68E-01	**8.50E-03**	6.09E-03	2.57E-04	1.05E-01	**4.00E-03**
Np	4.04E+00	8.30E-03	2.77E+02	**1.90E+01**	1.19E+00	1.98E-02	3.05E+01	**1.90E-01**
Pu	6.75E-04	2.91E-05	7.17E-03	**4.50E-04**	6.92E-05	3.16E-06	1.78E-03	**4.50E-05**
Am	8.29E-03	3.12E-04	1.16E-01	**5.50E-03**	3.76E-04	1.48E-05	4.56E-03	**2.50E-04**
Cm	1.28E-03	5.46E-05	1.69E-02	**8.50E-04**	2.24E-05	9.06E-07	2.16E-04	**1.50E-05**
Cf	1.50E-02	5.60E-04	1.62E-01	**1.00E-02**	1.50E-02	7.03E-04	1.54E-01	**1.00E-02**

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Element	Fruit Statistics for sampled values Average	Min	Max	Solution Vector 105	Grain Statistics for sampled values Average	Min	Max	Solution Vector 105
Part 3 - Plant concentration factors (B_{iv}) (fruit and grain)								
H	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Be	2.25E-03	8.25E-05	2.18E-02	**1.50E-03**	2.26E-03	3.42E-05	3.15E-02	**1.50E-03**
C	1.06E+00	4.52E-02	1.67E+01	**7.00E-01**	1.05E+00	3.88E-02	1.04E+01	**2.20E-01**
N	4.51E+01	1.42E+00	5.03E+02	**3.00E+01**	4.52E+01	1.24E+00	5.77E+02	3.00E+01
F	9.04E-03	3.01E-04	1.11E-01	**6.00E-03**	8.98E-03	2.80E-04	8.79E-02	**6.00E-03**
Na	1.33E-01	5.84E-04	4.04E+00	**1.60E-02**	1.38E-02	5.02E-05	3.59E-01	**5.20E-03**
Mg	8.25E-01	3.65E-02	7.97E+00	**5.50E-01**	8.36E-01	3.52E-02	1.62E+01	**5.50E-01**
Si	1.05E-01	3.88E-03	1.04E+00	**7.00E-02**	1.05E-01	3.34E-03	1.16E+00	**7.00E-02**
P	5.25E+00	2.35E-01	5.97E+01	**3.50E+00**	5.24E+00	2.12E-01	5.56E+01	**3.50E+00**
S	2.30E+00	8.80E-02	5.30E+01	**1.50E+00**	2.25E+00	4.48E-02	2.35E+01	**1.50E+01**
Cl	1.05E+02	4.13E+00	1.07E+03	**7.00E+01**	1.05E+02	3.96E+00	9.99E+02	**1.00E+03**
Ar	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
K	8.25E-01	3.00E-02	9.15E+00	**5.50E-01**	8.23E-01	2.78E-02	7.74E+00	**1.30E+00**
Ca	5.30E-01	2.36E-02	8.51E+00	**3.50E-01**	5.25E-01	2.41E-02	6.33E+00	**1.60E+00**
Sc	1.50E-03	4.23E-05	1.43E-02	**1.00E-03**	1.52E-03	6.87E-05	2.91E-02	**1.00E-03**
Cr	1.80E-01	1.07E-02	1.72E+00	**4.60E-02**	1.87E-02	1.56E-03	1.24E-01	**1.50E-02**
Mn	4.22E+00	5.25E-03	1.53E+02	**4.20E+00**	4.75E-01	1.30E-03	1.97E+01	**1.40E-01**
Fe	9.79E-03	1.17E-04	2.04E-01	**1.50E-03**	1.03E-03	1.14E-05	2.06E-02	**4.80E-04**
Co	3.35E-01	1.82E-03	1.05E+01	**2.20E-02**	3.45E-02	2.41E-04	6.56E-01	**1.10E-02**
Ni	3.44E-01	1.25E-02	3.15E+00	**3.40E-01**	3.61E-02	6.47E-04	3.75E-01	**3.80E-02**
Cu	5.92E+00	4.57E-04	5.80E+02	**1.50E-01**	5.70E-01	2.70E-05	4.23E+01	**4.90E-02**
Zn	2.95E+00	1.55E-02	7.58E+01	**1.10E+00**	3.13E-01	2.04E-03	9.40E+00	**5.50E+00**
Ga	6.01E-04	2.57E-05	6.98E-03	**4.00E-04**	6.01E-04	7.82E-06	6.38E-03	**4.00E-04**
As	8.97E-03	2.95E-04	8.67E-02	**6.00E-03**	8.97E-03	2.89E-04	8.59E-02	**6.00E-03**
Se	3.85E-02	1.35E-03	9.97E-01	**2.50E-02**	3.75E-02	1.53E-03	4.54E-01	**1.60E-01**
Br	2.25E+00	1.06E-01	2.51E+01	**1.50E+00**	2.25E+00	1.03E-01	2.50E+01	**1.50E+00**
Kr	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Rb	1.06E-01	4.97E-03	1.66E+00	**7.00E-02**	1.06E-01	4.71E-03	1.48E+00	**7.00E-02**
Sr	1.93E+00	8.70E-03	4.40E+01	**2.60E-01**	2.06E-01	1.30E-03	5.64E+00	**8.50E-02**
Y	9.10E-03	2.93E-04	1.52E-01	**6.00E-03**	9.03E-03	3.65E-04	1.13E-01	**6.00E-03**
Zr	8.80E-02	7.97E-06	8.47E+00	**2.70E-03**	9.75E-03	7.73E-07	9.41E-01	**8.70E-04**
Nb	7.50E-03	3.03E-04	8.62E-02	**5.00E-03**	7.53E-03	2.77E-04	1.00E-01	**4.30E-03**
Mo	9.14E-02	3.98E-03	1.85E+00	**6.00E-02**	9.00E-02	3.66E-03	8.71E-01	**6.00E-02**
Tc	2.25E+00	1.01E-01	2.30E+01	**1.50E+00**	2.25E+00	7.56E-02	2.57E+01	**7.30E-01**
Ru	5.99E-02	1.81E-04	7.27E+00	**3.00E-01**	5.46E-03	7.30E-06	1.88E-01	**1.60E-03**
Rh	6.01E-02	1.75E-03	6.95E-01	**4.00E-02**	6.01E-02	2.25E-03	6.48E-01	**4.00E-02**
Pd	6.04E-02	2.29E-03	9.35E-01	**4.00E-02**	6.04E-02	2.79E-03	8.67E-01	**1.80E-01**
Ag	1.50E-01	6.39E-03	1.78E+00	**1.00E-01**	1.51E-01	6.70E-03	1.88E+00	**1.00E-01**
Cd	2.26E-01	7.98E-03	2.92E+00	**6.70E-01**	2.25E-01	1.02E-02	2.47E+00	**2.20E-01**
In	6.01E-04	1.97E-05	7.02E-03	**4.00E-04**	6.03E-04	2.63E-05	8.20E-03	**4.00E-04**
Sn	9.03E-03	4.09E-04	1.06E-01	**6.00E-03**	9.08E-03	4.10E-04	1.35E-01	**1.00E-02**
Sb	4.50E-02	1.75E-03	4.68E-01	**3.00E-02**	4.52E-02	7.85E-04	6.42E-01	**3.00E-02**

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Element	Fruit				Grain			
	Statistics for sampled values			Solution	Statistics for sampled values			Solution
	Average	Min	Max	Vector 105	Average	Min	Max	Vector 105
Part 3 - Plant concentration factors (B_{iv}) (fruit and grain)								
Te	6.02E-03	1.37E-04	7.37E-02	**4.00E-03**	5.99E-03	2.74E-04	6.18E-02	**2.50E-03**
I	1.68E-01	2.26E-04	8.52E+00	**1.60E-02**	1.85E-02	3.60E-05	1.24E+00	**5.10E-03**
Xe	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Cs	1.46E-01	6.11E-04	5.37E+00	**1.40E-01**	1.60E-02	5.68E-05	9.62E-01	**6.60E-03**
Ba	2.61E-02	2.67E-04	5.59E-01	**4.60E-03**	2.84E-03	4.75E-05	8.41E-02	**1.50E-03**
La	6.05E-03	2.41E-04	8.51E-02	**4.00E-03**	5.99E-03	2.58E-04	5.68E-02	**4.00E-03**
Ce	5.02E-02	2.31E-05	7.03E+00	**2.00E-03**	4.08E-03	2.81E-06	1.78E-01	**8.20E-04**
Pr	5.99E-03	2.00E-04	5.97E-02	**4.00E-03**	5.99E-03	1.29E-04	6.54E-02	**4.00E-03**
Nd	6.09E-03	1.67E-04	1.20E-01	**4.00E-03**	6.00E-03	2.46E-04	6.02E-02	**4.00E-03**
Pm	6.02E-03	2.33E-04	7.58E-02	**4.00E-03**	5.98E-03	1.50E-04	5.69E-02	**4.00E-03**
Sm	6.02E-03	2.63E-04	7.10E-02	**4.00E-03**	6.00E-03	2.48E-04	5.85E-02	**4.00E-03**
Eu	6.13E-03	2.58E-04	1.38E-01	**4.00E-03**	6.00E-03	1.96E-04	6.77E-02	**4.00E-03**
Gd	6.00E-03	1.90E-04	6.00E-02	**4.00E-03**	5.99E-03	2.09E-04	6.18E-02	**4.00E-03**
Tb	6.08E-03	2.84E-04	1.12E-01	**4.00E-03**	5.99E-03	2.19E-04	5.92E-02	**4.00E-03**
Dy	6.17E-03	2.71E-04	1.60E-01	**4.00E-03**	6.00E-03	2.45E-04	5.96E-02	**4.00E-03**
Ho	6.00E-03	2.67E-04	6.89E-02	**4.00E-03**	6.03E-03	1.90E-04	7.66E-02	**4.00E-03**
Er	6.01E-03	2.24E-04	6.94E-02	**4.00E-03**	5.98E-03	1.85E-04	5.65E-02	**4.00E-03**
Hf	1.28E-03	5.08E-05	1.35E-02	**8.50E-04**	1.27E-03	5.36E-05	1.36E-02	**8.50E-04**
Ta	3.76E-03	1.05E-04	4.32E-02	**2.50E-03**	3.77E-03	1.31E-04	4.53E-02	**2.50E-03**
W	1.50E-02	6.98E-04	1.48E-01	**1.00E-02**	1.50E-02	4.68E-04	1.50E-01	**4.10E-02**
Re	5.25E-01	9.93E-03	5.42E+00	**3.50E-01**	5.28E-01	1.68E-02	8.07E+00	**9.50E-01**
Os	5.31E-03	2.17E-04	8.87E-02	**3.50E-03**	5.24E-03	1.62E-04	5.30E-02	**3.50E-03**
Ir	2.26E-02	9.48E-04	2.86E-01	**1.50E-02**	2.24E-02	9.43E-04	2.15E-01	**1.00E-02**
Au	1.50E-01	5.63E-03	1.52E+00	**1.00E-01**	1.50E-01	7.05E-03	1.49E+00	**1.00E-01**
Hg	3.00E-01	9.97E-03	2.86E+00	**2.00E-01**	3.00E-01	1.01E-02	2.96E+00	**2.00E-01**
Tl	5.99E-04	2.65E-05	5.98E-03	**4.00E-04**	6.00E-04	2.54E-05	6.11E-03	**4.00E-04**
Pb	1.35E-02	4.83E-04	1.31E-01	**9.00E-03**	1.35E-02	5.45E-04	1.48E-01	**9.00E-03**
Bi	7.50E-03	3.03E-04	7.89E-02	**5.00E-03**	7.48E-03	2.70E-04	7.62E-02	**5.00E-03**
Po	6.02E-04	1.64E-05	6.93E-03	**4.00E-04**	6.04E-04	2.45E-05	8.13E-03	**4.00E-04**
Rn	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Ra	2.25E-03	9.86E-05	2.22E-02	**1.50E-03**	2.26E-03	8.50E-05	3.03E-02	**1.50E-03**
Ac	5.24E-04	2.04E-05	5.23E-03	**3.50E-04**	5.34E-04	2.11E-05	1.12E-02	**3.50E-04**
Th	1.28E-04	3.97E-06	1.26E-03	**8.50E-05**	1.28E-04	3.85E-06	1.50E-03	**8.50E-05**
Pa	3.75E-04	1.62E-05	4.12E-03	**2.50E-04**	3.76E-04	1.58E-05	4.70E-03	**2.50E-04**
U	5.99E-03	8.33E-05	5.88E-02	**4.00E-03**	5.99E-03	1.69E-04	5.65E-02	**4.00E-03**
Np	1.18E+00	1.87E-02	4.29E+01	**1.30E-01**	1.24E-01	2.02E-03	2.11E+00	**6.80E-02**
Pu	6.72E-05	2.28E-06	7.05E-04	**4.50E-05**	6.88E-05	3.11E-06	1.43E-03	**4.50E-05**
Am	3.75E-04	1.57E-05	4.28E-03	**2.50E-04**	3.75E-04	1.63E-05	3.84E-03	**2.50E-04**
Cm	2.24E-05	9.50E-07	2.34E-04	**1.50E-05**	2.25E-05	7.49E-07	3.04E-04	**1.50E-05**
Cf	1.51E-02	6.35E-04	2.21E-01	**1.00E-02**	1.51E-02	5.09E-04	2.55E-01	**1.10E-02**

percentile TEDE value from the original sample measures the strength of the relationship between the TEDE and the parameter. This measure of the strength of dependence of dose on parameter value provides a direct indication of the potential for site-specific parameter information (expressed as a revised limit on the parameter value) to change the estimated dose.

Finally, those parameters with "significant" potential to modify the screening dose value were selected based on the calculated strength measure. A threshold value of 0.52 for "significant" reduction of the 95th percentile of the dose distribution was selected. Parameters having strength measures less than this threshold (i.e., with the potential to effect a greater reduction in the 95th percentile) were considered to be strongly and significantly correlated with dose. The threshold strength measure value of 0.52 was selected by noting the spurious associations between parameter values and TEDE that emerged. The indoor shielding factor SFI was identified as significant by the K-S test, and had an associated strength measure of 0.52. This parameter, however, was not used in the calculation, and the reported strength measure is an artifact of sampling error. Strength measure values less than this threshold were assumed to be significant.

Table 6.94 lists, for each source nuclide, the identifiers of the model input parameters identified as having a strong significant relationship to dose due to that nuclide. Some parameters listed in Table 6.94 are an artifact of the functional connection among soil properties and soil type. The fraction of hydrogen in soil, for example, is only used in the tritium model. It appears as a significant parameter for dose due to 129I, however, because of the functional connection between the hydrogen fraction and the soil saturation fraction, F1.

For many source nuclides, no significant controlling parameters were identified. The small range of the dose distribution for some nuclides may make the relationship between parameter values and dose difficult to distinguish from sampling error.

Table 6.93 Model parameters having significant strong correlations with TEDE

Source	Parameter symbol	Parameter description	Relative change in dose
3H	fhd016	Fraction of hydrogen in soil	0.22
	sh	Moisture content of soil	0.22
	F1	Saturation ratio for the surface-soil layer	0.27
	F2	Saturation ratio for the unsaturated layer	0.27
	I	Infiltration rate	0.29
	N1	Porosity of the surface-soil layer	0.40
	N2	Porosity of the unsaturated layer	0.40
	PS	Soil areal density of surface plow layer	0.40
	RHO1	Surface Soil Density	0.40
	RHO2	Unsaturated Zone Soil Density	0.40
14C	F1	Saturation ratio for the surface-soil layer	0.14
	F2	Saturation ratio for the unsaturated layer	0.14
	fhd016	Fraction of hydrogen in soil	0.15
	sh	Moisture content of soil	0.15
	KdC	C Partition Coefficient	0.18
	I	Infiltration rate	0.18
	H2	Thickness of unsaturated zone	0.19
36Cl	B4Cl	Concentration factor: grain Cl	0.48
40K	H2	Thickness of unsaturated zone	0.20
	KdK	K Partition Coefficient	0.22
41Ca	B1Ca	Concentration factor: leafy Ca	0.25
45Ca	B1Ca	Concentration factor: leafy Ca	0.21
59Ni	I	Infiltration rate	0.17

Table 6.93 Model parameters having significant strong correlations with TEDE (continued)

Source	Parameter symbol	Parameter description	Relative change in dose
	KdNi	Ni Partition Coefficient	0.19
63Ni	KdNi	Ni Partition Coefficient	0.20
93Mo	B1Mo	Concentration factor: leafy Mo	0.28
99Tc	B1Tc	Concentration factor: leafy Tc	0.33
107Pd	B1Pd	Concentration factor: leafy Pd	0.50
113mCd	KdCd	Cd Partition Coefficient	0.41
121mSn	KdSn	Sn Partition Coefficient	0.10
129I	F1	Saturation ratio for the surface-soil layer	0.10
	F2	Saturation ratio for the unsaturated layer	0.10
	fhd016	Fraction of hydrogen in soil	0.11
	sh	Moisture content of soil	0.11
	KdI	I Partition Coefficient	0.14
	H2	Thickness of unsaturated zone	0.15
	I	Infiltration rate	0.16
185W	KdW	W Partition Coefficient	0.39
	WV(2)	Wet/dry conversion: nonleafy	0.43
232U	H2	Thickness of unsaturated zone	0.25
	WV(2)	Wet/dry conversion: nonleafy	0.26
	KdU	U Partition Coefficient	0.27
232U+C	WV(2)	Wet/dry conversion: nonleafy	0.29
233U	H2	Thickness of unsaturated zone	0.26
	WV(2)	Wet/dry conversion: nonleafy	0.30
	U	U Partition Coefficient	0.33
234U	U	U Partition Coefficient	0.19
	WV(2)	Wet/dry conversion: nonleafy	0.25
235U	WV(2)	Wet/dry conversion: nonleafy	0.36
	U	U Partition Coefficient	0.37
236U	I	Infiltration rate	0.18
	U	U Partition Coefficient	0.19
	WV(2)	Wet/dry conversion: nonleafy	0.25
238U	U	U Partition Coefficient	0.20
	WV(2)	Wet/dry conversion: nonleafy	0.25

7.0 References

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Appendix A: Equations for Distribution Functions and LHS Calculations

C-Fit Program PDF Equations

The following equations and definitions were taken from the C-Fit™ software (C-Fit, 1996) that was used to fit functions probability for some residential scenario parameters based on supporting data. Among the many distribution types included in C-Fit, normal, log normal, beta, gamma, and Gumbel distributions were used. Distributions were selected based on either the Chi-square or Kolmogorov-Smirnov goodness of fitness tests.

The following equations describe the distribution types used in our analysis, using notation from the C-Fit User Guide.

Normal Distribution

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

where μ and σ are the mean and standard deviation of the variable and are defined as:

$$\text{Mean } \mu_x = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (2)$$

and Standard Deviation is:

$$\sigma_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \mu_x\right)^2} \quad (3)$$

Log Normal

$$f(x;\mu,\sigma,\varepsilon) = \frac{e^{-\frac{1}{2\sigma^2}\left[\log\left(\frac{x-\varepsilon}{\mu}\right)\right]^2}}{(x-\varepsilon)\sigma\sqrt{2\pi}} \quad (4)$$

Gumbel (Extreme Value Type I Max.)

$$f(x;\mu,\alpha) = \alpha e^{\left(\alpha(\mu-x)-e^{\alpha(\mu-x)}\right)} \quad (5)$$

Gamma

$$f(x;\kappa,\lambda,\varepsilon) = \frac{\lambda[\lambda(x-\varepsilon)]^{\kappa-1} e^{-[\lambda(x-\varepsilon)]}}{\Gamma(\kappa)} \quad (6)$$

where:

$$\kappa = \frac{\mu^2}{\sigma^2} \quad \lambda = \frac{\kappa}{\mu} \quad (7)$$

and the gamma function is defined by:

$$\Gamma(\kappa) = \int_0^{\infty} t^{\kappa-1} e^{-t}\, dt \quad (8)$$

Beta

$$f(x;a_1,a_2,\delta_1,\delta_2) = \frac{\left(\frac{x-\delta_1}{\delta_2-\delta_1}\right)^{a_1-1}\left(1-\frac{x-\delta_1}{\delta_2-\delta_1}\right)^{a_2-}}{(\delta_2-\delta_1)B(a_1,a_2)} \quad (9)$$

and the beta function is given by:

$$B(x,y) = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)} = \int_0^1 t^{x-1}(1-t)^{y-1}\, dt \quad (10)$$

LHS Distribution Equations

The LHS program was used to generate samples of parameter values based on the distribution functions assigned to the parameters. The general mathematical forms for the distribution functions used in this analysis are described below, using the notation of the LHS input guide (Iman & Shortencarier, 1984?)

Unbounded Normal Distribution

There are two input parameters required when defining a normal distribution: the mean and the standard deviation. The mean may be any real value; however, the standard deviation must be strictly positive. The normal distribution is defined in terms of the mean μ and standard deviation or by the following density function:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad -\infty < x < \infty \qquad (11)$$

The defining parameters are the same as those used by C-FIT [Equation (1)].

Unbounded Lognormal Distribution

A lognormal distribution is defined by the density function:

$$f(y) = \frac{1}{y\sigma\sqrt{2\pi}} e^{-\frac{(\ln y-\mu)^2}{2\sigma^2}} \quad y>0 \qquad (12)$$

where the mean, variance and median are, respectively:

$$E(y) = e^{\left(\mu+\frac{\sigma^2}{2}\right)} \qquad (13)$$

$$V(y) = e^{2\mu+\sigma^2}\left(e^{\sigma^2}-1\right) \qquad (14)$$

$$\text{Median} = e^{\mu} \qquad (15)$$

In the input to LHS, this distribution is described by the mean and an error factor parameter. The error factor is the ratio of the value at the 95% quantile to the median; it is also the ratio of the median to the 5% quantile. The program collects the input mean and error factor into the mean and standard deviation of the underlying normal distribution using the following relations:

$$\sigma = \frac{\ln(\text{error factor})}{1.645} \qquad (16)$$

$$\mu = \ln(\text{input mean}) - \frac{1}{2}\sigma^2 \qquad (17)$$

The C-FIT formulation for this distribution, Equation (4), includes a displacement parameter ε, and a different definition for the parameter μ.

Uniform Distribution - Uniform Intervals

This distribution samples values uniformly between two specified interval endpoints A and B. It is defined by the following density function:

$$f(x) = \frac{1}{B-A}, \quad A \le x \le B \qquad (18)$$

The mean and variance are:

$$E(x) = \frac{A+B}{2} \quad \text{and} \quad V(x) = \frac{(B-A)^2}{12} \qquad (19)$$

Loguniform Distribution - Uniform Intervals

The logarithm of a variable having a loguniform distribution is uniform between the log base 10 of the specified end points A and B, where A and B are both >0.

The following equations are stated in terms of natural logarithms to simplify the presentation. The density function for this distribution is:

$$f(x) = \frac{1}{x}(\ln A - \ln B), \quad A<x<B \qquad (20)$$

The mean, variance, and median (respectively) are as follows:

$$E(x) = \frac{B-A}{\ln B - \ln A} \qquad (21)$$

$$V(x) = (B-A)\frac{(\ln B - \ln A)(B+A) - 2(B-A)}{2(\ln B - \ln A)^2} \qquad (22)$$

$$\text{Median} = e^{\frac{\ln B + \ln A}{2}} = \sqrt{AB} \qquad (23)$$

Triangular Distribution

The triangular distribution is defined by three parameters a, b, and c. The lower limit a and upper limit c establish bounds beyond which sampling is not to occur. The most likely value is specified by the b parameter. With a < b < c, the density function is:

$$f(x) = \frac{2(x-a)}{(c-a)(b-a)}, \quad a \le x \le b \qquad (24)$$

and,

$$f(x) = \frac{2(c-x)}{(c-a)(c-b)}, \quad b \le x \le c \qquad (25)$$

The mean, variance, and median (respectively) are as follows:

$$E(x) = \frac{a+b+c}{3} \tag{26}$$

$$V(x) = \frac{a(a-b)+b(b-c)+c(c-a)}{18} \tag{27}$$

$$\text{median} = a-\sqrt{\frac{(c-1)(c-b)}{2}}, \quad b \geq \frac{a+c}{2}$$

$$\text{median} = c-\sqrt{\frac{(c-a)(c-b)}{2}}, \quad b \leq \frac{a+c}{2}$$

Beta Distribution

A beta distribution is defined by the limiting endpoints A and B, and shape parameters p and q. The following conditions must be satisfied:

$$p, q \geq 0.001$$
$$0 \leq A < B.$$

The beta distribution is defined by the following density functions:

$$f(\beta) = \frac{\beta}{\int_A^B \beta} \tag{30}$$

where:

$$\beta = x^{p-1}(1-x)^{q-1} \tag{31}$$

User Defined Cumulative Continuous Distribution with Linear Interpolation

A continuous distribution is used when the user knows certain values that the variable will take on, and linearly interpolates between those values. It is commonly used to approximate irregular distributions. The user must specify n, an integer (n > 1) number of ordered pairs to be read in, followed by the n ordered pairs. Within the ordered pairs, the first number is the value of the variable; the second number is the cumulative probability associated with the value. The probabilities in the ordered pairs must increase monotonically starting with 0.0 and ending with 1.0. The variable values must also increase monotonically. LHS then performs a linear interpolation on this distribution function. If only two points are specified, a uniform distribution is generated between the two points.

User Defined Discrete Cumulative Distribution

A discrete cumulative distribution is used when the user has a discrete number of possibilities that may occur. The user must specify an integer, n > 1, which signifies the number of ordered pairs to be read in. The n ordered pairs consist of the value of the variable with the cumulative probability associated with that value. The probabilities in the ordered pairs must increase monotonically starting with a value greater than 0.0 and ending with 1.0. The values must also increase monotonically.

Gamma Distribution

A gamma distribution has a density function defined by

$$\frac{B^{\alpha} X^{\alpha-1} e^{-Bx}}{\Gamma(\alpha)} \tag{32}$$

where

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

In the input to LHS, the user must specify α and β, both of which are real numbers.

Appendix B: Procedure for Defining Deterministic Defaults for Physical Parameters

The default values for the physical model parameters are required to satisfy the mathematical conditions described in Section 3.3. These mathematical conditions, which express the requirement that the parameter values tend to overestimate dose, lead to set of simultaneous inequalities (Equation 3.8):

$$d_{Di} \equiv m\left(\mathbf{x_d}, \mathbf{s}_i\right) \geq d_{Ci} \quad i = 1 \ldots n_s$$

Solving Equation 3.8 requires values for the dose distribution quantile values d_{Ci} for each of the n_s source radionuclides. These quantile values are based on the probability distribution functions F_{Di} for each the n_s radionuclides (Equation 3.7), and these distribution functions depend on the distributions assigned to the model input parameters. Finding defaults therefore entails: 1) identifying parameter distributions; 2) calculating dose distributions; 3) looking for parameter values that solve the inequality constraints in Equation 3.8. If Equation 3.8 has a solution, it will have many solutions. As a final step in defining the default parameters, evaluation functions are defined to help select among alternative solutions identified in Step 3. Details of each of these four steps are provided in this appendix.

Defining Parameter Distributions

For each of the physical parameters of the scenario model, a distribution was developed to describe the variability in the parameter value over all potential site-specific applications of the model based on: guidelines provided in NUREG/CR-5512; the use of the parameter in the model; the relationship between the diverse site conditions and parameter values; and the expected range of site conditions across applications. (The specific distributions defined for each parameter, along with the data and procedures used to define these distributions, are detailed in Section 5.4 and Section 6.4.)

Calculating Dose Distributions for Individual Source Nuclides

A stratified monte-carlo technique, Latin Hypercube Sampling (LHS, Iman and Shortencarier 1984) , was used to estimate the dose distribution functions from the assigned parameter distribution functions. Monte-carlo techniques, in general, are used to estimate the properties of random variables from a set of sample values for those variables. Samples of the dose distribution functions D_{Ti} were generated by creating samples of the input parameter vector **X**, then calculating the dose value resulting from each of those sampled parameter vectors. For each source nuclide, the dose assessment model m produces a possible dose value $d_{Ti,j}$ for each sample of the parameter vector:

$$d_{Ti,j} = m\left(\mathbf{x}_j, \mathbf{s}_i\right) \qquad j = 1 \ldots n_v, \quad i = 1 \ldots n_s \tag{1}$$

where $\mathbf{x}_j$ is the vector of model parameters for sample j, and n_v is the number of sample vectors used to estimate the dose distribution.

LHS is a technique for creating the sample vectors of model parameters based on a stratified sampling of the individual model parameters. For each model parameter, the distribution function for the parameter is used to divide the range of parameter values into n_v intervals such that there is an equal probability of the parameter value occurring in each interval. One sample value is then chosen at random from each interval. Each of the n_v values for a given parameter are then combined with one of the n_v sampled value for all other parameters, producing a set of n_v sample vectors. Each sample vector represents a possible site-specific analysis.

The procedure used to combine parameter values controls the correlations among parameters, or more precisely, among the ranks of the parameter values. This control can be used to insure that accidental (spurious) correlations among parameters are not introduced, or to impose specified correlations among parameters.

Table 1 is a list of the individual radionuclides that might occur in a site source term, including both non-equilibrium and equilibrium (+C) progeny. For each generic source $\mathbf{s}_i$ in Table 1, the TEDE value was calculated using each of the sample vectors generated by LHS, and a unit concentration of the radionuclide.

The resulting set of n_v dose values defines the dose distribution function F_{Di}. The dose quantile values, d_{Ci}, for a particular value of P_{crit} can be directly obtained from this distribution function as the 1 - P_{crit} quantile of F_{Di}.

Identify Default Parameter Values

The calculations used to approximate the dose distribution functions, and to estimate the dose quantile values

d_{Ci} can also be used to search for solutions to Equation 3.8. For each source radionuclide, the LHS calculations provide a value of the function m for each one of the set of parameter sample vectors. For a given value of P_{crit}, the subset of vectors which satisfy Equation 3.8 for each individual source can be identified:

$$\Phi_i = \left\{ \mathbf{x}_j \middle| d_{Ti,j} \geq d_{Ci} \right\} \qquad (2)$$

The sets Φ_i are all subsets of the original set of sample vectors. Different source will produced different subsets because doses due to different sources will tend to be controlled by different parameters.

Any sample vectors that satisfy Equation 3.8 for all sources are in all filtered sets. The set of samples that are solutions to Equation 3.8 is found by taking the intersection of the filtered sets:

$$\Psi = \bigcap_{i=1,n_s} \Phi_i \qquad (3)$$

This approach requires that the same parameter samples be used for each source radionuclide. This requirement is easy to satisfy if the parameter distributions are the same for all sources within the scenario as assumed here (Equation 3.5). If the parameter distributions vary from source to source, it is possible but practically difficult to use a common sample set. This approach only requires simple sorting and searching operations on the initial sample sets.

For a given value of P_{crit}, solutions may not be found in the set of LHS samples used to estimate the dose distribution. This may have one of two causes:

1. No solution exists to Equation 3.8 because the constraints represented by the different sources are incompatible: one constraint requires values for a particular parameter at one end of its range, while another constraint requires values at the other end. Figure 1(a) illustrates this situation for a model using only two parameters, x_1 and x_2.

2. There are no samples in the region where the solution to Equation 3.8 exists: different constraints establish limits on different parameters, and the joint solution space is a small 'corner' of the original sample space. Figure 1(b) illustrates this situation for a two-parameter model.

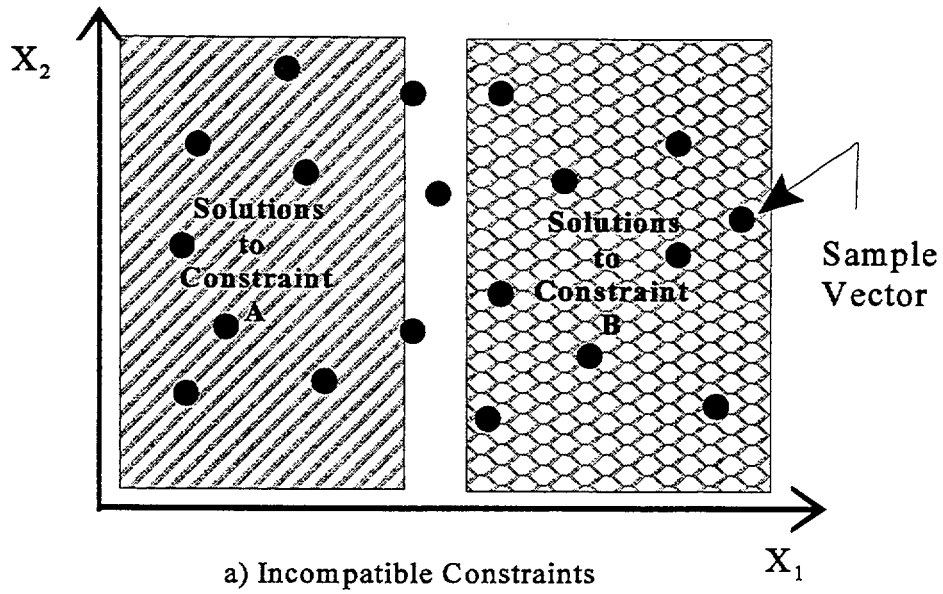
It is important to distinguish between these two cases when the LHS sampling fails to produce a solution. In the first case, it is impossible to define defaults that would be appropriate for all source nuclides, and source-dependent default values are required. A solution exists in the second case, but additional samples must be taken in the region of parameter space where the source-independent solution appears to be located.

The results of the LHS sampling can be interpreted to discover whether the source constraints tend to be conflicting (case 1 above), independent (case 2 above) or redundant (several constraints drive the same parameters in the same direction). For a small number (e.g. 10) of source constraints, the correlation coefficient between the ranks of calculated dose for different source constraints can provide this information. For the large number (>100) of constraints in this problem, however, it is impractical to calculate and examine the rank correlation coefficients for all constraint pairs. A different diagnostic technique was therefore used to characterize the set of constraints as generally incompatible, independent, or redundant.

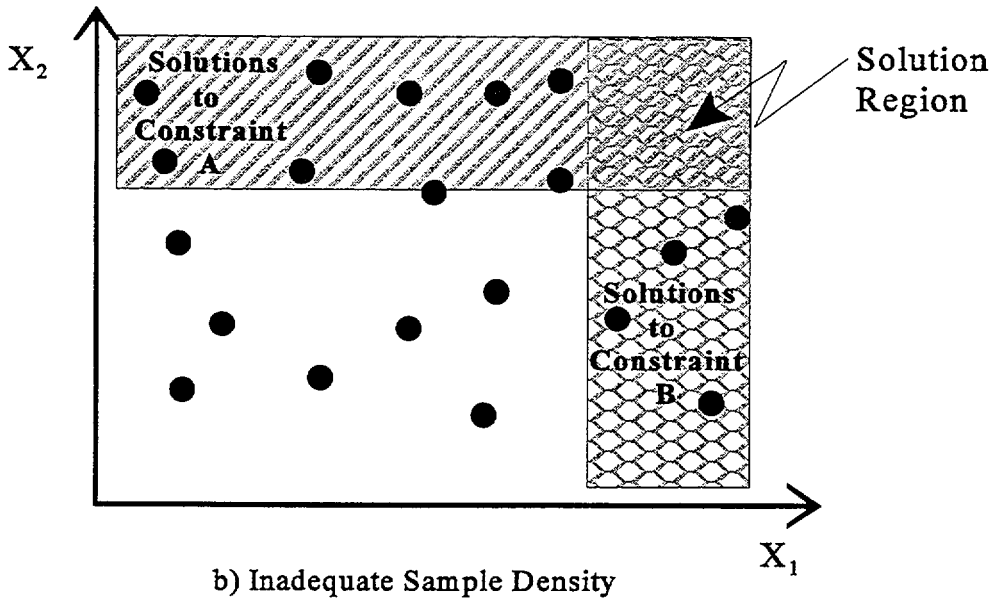
To make this distinction, and to guide the search for parameter vectors that satisfy Equation 3.8 for all sources, the *solution count distribution* (SCD) was generated for the set of sample vectors. For an LHS sample size of n_v, and a given value of P_{crit}, exactly $n_{crit} = P_{crit} \cdot n_v$ sample vectors will satisfy each individual constraint in Equation 3.8. Some vectors will satisfy no constraints, others will satisfy one or more constraints. For each vector, the solution count for that vector is the sum of the number of constraints that it satisfies. If there are n_s constraints, the maximum value for the solution count (indicating that Equation 3.8 is satisfied) is n_s. The minimum value for the solution count is zero. The SCD is the distribution of solution count values over the n_v LHS sample vectors.

If there are n_s constraints, and those constraints are perfectly redundant, then the n_{crit} vectors that satisfy any one constraint also satisfy all remaining constraints. The SCD in this case will show that n_{crit} vectors satisfy exactly n_s constraints, and $n_v - n_{crit}$ vectors satisfy exactly 0 constraints.

If, on the other hand, the n_s constraints are perfectly independent, then any one of the n_{crit} vectors that satisfies the first constraint has the same probability of satisfying the second constraint as any of the $n_v - n_{crit}$ vectors that do not satisfy the first constraint. For a single vector, there is a probability of P_{crit} that it will satisfy the first constraint, a probability of P_{crit} that it will satisfy the second constraint, an so on. Because the n_s constraints are independent, the expected number of constraints satisfied by each vector is $P_{crit} \cdot n_s$. For a set



a) Incompatible Constraints



b) Inadequate Sample Density

Figure 1 Schematic illustration of two situations in which no joint solution is found in the LHS sample set for a model using two input parameters

of independent *sample vectors*, the distribution of the number of constraints satisfied by each vector should approach the Poisson distribution with an expected value of $P_{crit} \cdot n_s$.

If two constraints are incompatible, then the n_{crit} vectors that satisfy the first constraint do not satisfy the second, and *vice versa*. Generalizing to n_s constraints, each vector will satisfy exactly one constraint, but not satisfy any of the other $n_s - 1$ constraints. For $n_s \cdot n_{crit} \leq n_v$, each vector will satisfy either no constraints or one constraint. In contrast, for n_s *independent* constraints described above, some of the vectors would be expected to satisfy 2 or more constraints according to the Poisson distribution. For $n_s \cdot n_{crit} > n_v$, one or more vectors must necessarily satisfy more than one constraint, so that the n_s constraints cannot be mutually perfectly incompatible. The tendency for vectors which satisfy one constraint to be excluded from solutions to other constraints will instead produce a characteristic clustering in the number of constraints satisfied by each vector: most numbers will be near the expected value of $P_{crit} \cdot n_s$, while vectors that satisfy a larger number of constraints will be much less frequent that predicted for the independent (Poisson) case.

Figure 2 is a schematic illustration of the solution count distributions expected for each of the three cases discussed above. Both the density functions and cumulative distribution functions are shown. The distribution for redundant constraints is bi-modal, with values only occurring at 0 and n_s. The distribution for independent constraints is centered around $P_{crit} \cdot n_s$, and follows a Poisson distribution. The distribution for incompatible constraints is also centered around $P_{crit} \cdot n_s$, but is characteristically narrower than the Poisson distribution.

No actual set of constraints is expected to conform exactly to any one of these ideal cases, but comparing the SCD to these prototypes helps judge the prospective existence of a joint solution to all constraints, and the difficulty in finding such solutions if none are produced by the LHS sampling. Any vectors that satisfy all constraints for a given value of P_{crit} occur at the maximum value of x of n_s on the SCD plot. If there are no joint solutions in a given sample set for a specified value of P_{crit}, the distribution density near n_s for the desired P_{crit}, and the density at n_s for larger values of P_{crit}, indicate the "proximity" of the solution to the vectors in the sample set.

If the initial LHS sampling does not contain solutions for a desired value of P_{crit}, but does not appear to be subject to contradictory constraints, the solution to Equation 3.8 can be pursued by using the results of the initial evaluation to generate new parameter values and combinations. There are a number of strategies for using the performance of the initial LHS sampling to guide the search for solutions to Equation 3.8. The large number of simultaneous constraints, the potential for pathway interactions to create a non-monotonic dependence on parameter values, and the potential for abrupt changes in parameter sensitivity due to changes in pathway dominance all suggest that a robust empirical search procedure would be more effective than analytical approaches.

An empirical approach, based on genetic optimization, was therefore used to generate targeted parameter sets preferentially containing solutions for small values of P_{crit}. Genetic algorithms require no assumptions about the functional form, or even continuity, of the response surface m, and have been successfully applied in traditionally difficult non-linear and multimodal optimization problems (Goldberg, 1989).

A basic genetic algorithm creates a new parameter set by combining components from a subset of the original sample set:

1. From the original parameter sample set, a subset of sample vectors is selected based on their solution counts. Vectors having large solution counts are assumed to be "close" to parameter combinations that solve Equation 3.8;

2. To create a new sample vector, a pair of 'parent' vectors from the selected subset is chosen at random, along with a value i_s of a random integer uniformly distributed between 1 and $n_p + 1$, where n_p is the number of components of the parameter vector (i.e. the number of adjustable parameters in the model);

3. The new sample is formed by copying components 1 to $i_s - 1$ from the first parent vector, and components i_s to n_p of the second parent vector.

4. The new sample vectors are also subject to random mutation. A specified percentage of the new vectors are chosen at random. For each chosen vector, a particular parameter is chosen at random,and replaced by a value randomly selected from the original set of sampled values for that parameter.

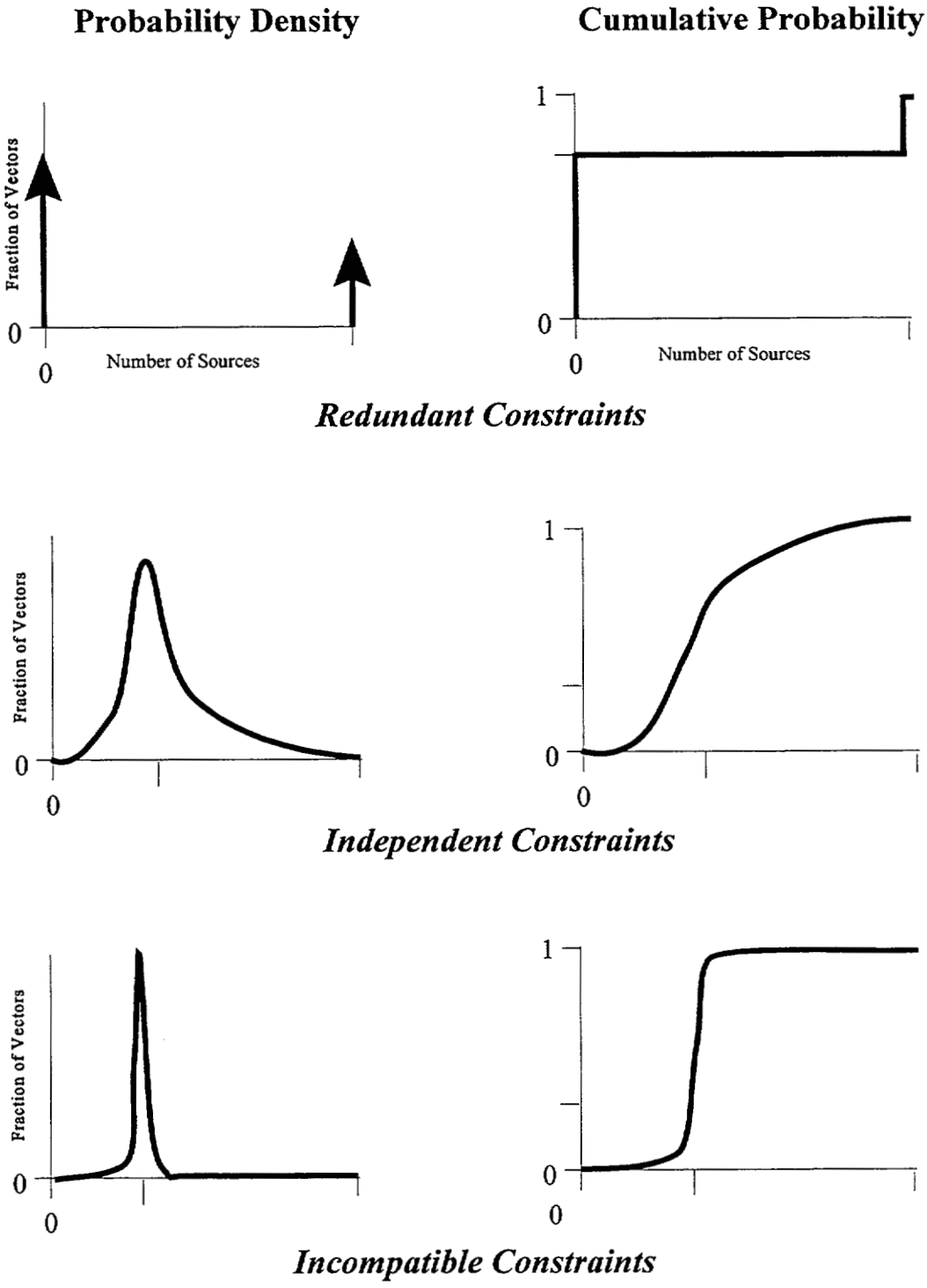


Figure 2 Solution count distributions (SCDs) for three idealized relationships among source constraints

Dose values are then calculated for the new set of sample vectors for each of the source radionuclides, and the set is examined for solutions to Equation 3.8. If none are found, the genetic algorithm can be applied to the second generation of vectors, along with their solution counts. With each iterative application, the algorithm is expected to produce vectors with increasing solution counts, ultimately producing one or more vectors that satisfy Equation 3.8.

The basic genetic algorithm described above rates parameter vectors based on the total number of source nuclides for which the vector is a solution. New vectors are generated based on random combinations of the parameter values of highly-rated vectors. This algorithm was found to produce vectors with large solution counts after a few iterations, but the maximum solution count increased at an unacceptably slow rate during later iterations.

To speed the search for solutions, the algorithm was modified to exploit information that is not used in the basic genetic algorithm. A solution vector must produce a dose value in the selected quantile for each of the source nuclides. For a given nuclide, the dose will be more strongly dependent on some parameters than on others. These features of the problem were used to speed the solution search by modifying the way vectors were selected and combined to produce new candidate vectors. The first 'parent' vector was selected based on the solution count distribution, as in the basic algorithm. The second 'parent' was selected based on a modified solution count, in which only the source nuclides *not* satisfied by the first 'parent' vector are counted. This modified or residual solution count was used to determine the probability of selecting a vector as the second parent.

Once the parents were selected, the parameter values for the new vector were selected by combining the 'important' parameters from each parent, rather than by selecting parameters at random. 'Important' parameters were those whose values were significantly correlated with dose for any of the source nuclides satisfied by the vector. Parameters having no significant correlation with any source nuclide were set to the median values of their distributions.

The resulting 'child' vector has parameter values that were assembled in a way that increases the number of distinct nuclides whose constraints are satisfied. Parents vectors are paired based on their distinctive contributions, and parameter values are chosen to preserve the desirable characteristics of each parent. Compared to the random parameter combination used in the basic genetic algorithm, this 'genetic engineering' algorithm resulted in a much more rapid increase in the solution count values with successive iterations.

The performance of the two algorithms is compared in Figure 3. The distribution of solution counts for the vectors produced using each algorithm is summarized as a function of iteration. After 5 iterations, the largest solution count value produced by the basic genetic algorithm was 92 out of 105 sources. In addition, the rate of increase of the maximum solution count was discouragingly slow given that a solution to Equation 3.8 requires a solution count of 105. In contrast, the genetic engineering algorithm produced 63 vectors with a solution count of 105 after only three iterations.

Ranking Identified Solutions

Equation 3.8, if it has a solution, will in general be solved anywhere in some subdomain of the sample parameter space. If the procedure described above produces multiple solution vectors, additional criteria can be used to rank the solutions as potential default parameter values.

With respect to inversion probability, P_{crit} defines an upper limit, but the actual inversion probability associated with a solution may be much smaller than this limit, as discussed in Section 3.4. Individual source probabilities are not available, so that the inversion probability strictly cannot be calculated using Equation 3.2. The range (over the various source constraints) of conditional inversion probabilities *can* be calculated from Equation 3.3 however, and may be used to discriminate among solution vectors. For a given value of P_{crit}, solutions that tend to have small values of the conditional inversion probability will generally have parameter values that are more 'extreme' than solutions that tend to have large values, (assuming the model is monotonic)[1]. The average inversion probability (AIP) over all sources was used to evaluate alternative solution vectors.

With respect to the parameter values themselves, default values that are generally closer to the center of their distributions may be preferred to values near the tail of their distributions. The probability of obtaining a parameter value 'beyond' the potential default value is an intuitive measure of the reasonableness of the default value. For each parameter in the solution vector,

[1]Solutions that *consistently* have small values of conditional inversion probability are of course also solutions for smaller values of P_{crit}.

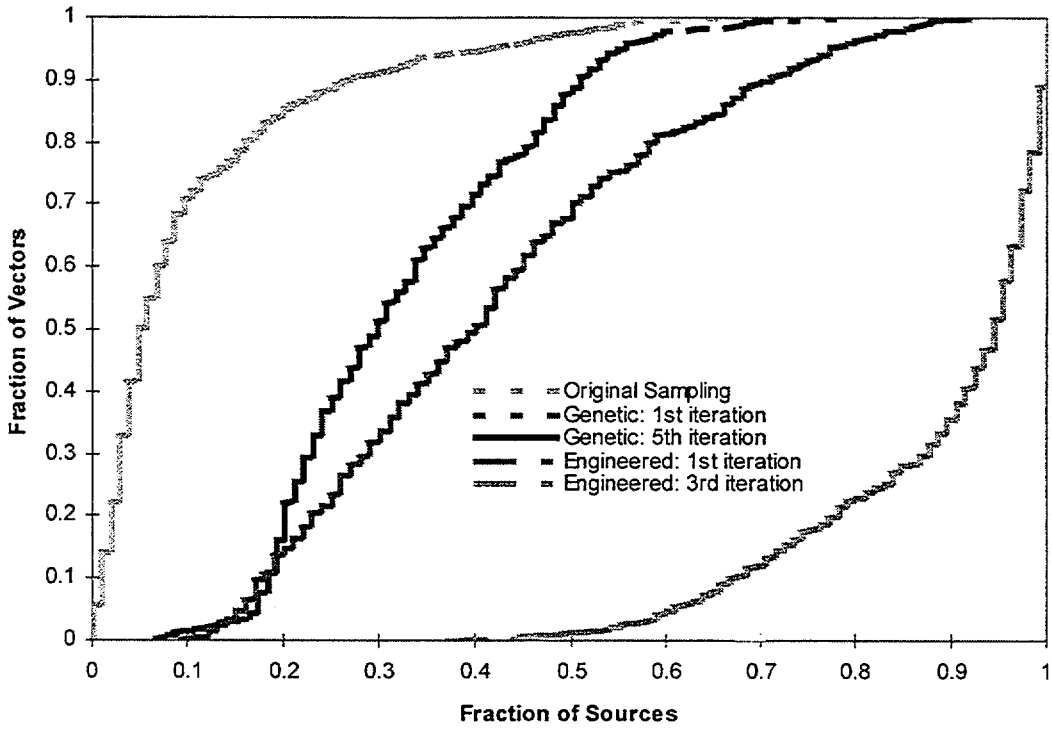


Figure 3 Solution count distributions (SCDs) for sample vector sets generated using the basic genetic and genetic engineering algorithms

the probability of obtaining a more extreme site specific value was calculated using the input parameter distributions. A 'more extreme' value is a larger value for defaults above the median, or a smaller value for defaults below the median. The product of these probabilities over all parameters, called the joint parameter exceedance probability (JPEP), was used as a second measure of reasonableness in evaluating alternative solution vectors. Other global measures might be considered, such as the minimum exceedance probability over all parameters, or the minimum conditional inversion probability over all sources.

Note that it is also possible to incorporate ranking functions into the solution search procedure. The analytical problem is then to maximize the value of the ranking function subject to the constraints defined by the simultaneous inequalities of Equation 3.8, rather than to simply find a combination of parameters that solves these inequalities. It is also possible to use ranking function values, along with solution count values, to control parent selection in the genetic (engineering) algorithm. This approach would require combining, in some way, an absolute requirement based on solution count with a continuous requirement based on the ranking function, and was not explained.

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11. ABSTRACT *(200 words or less)*

NUREG/CR-5512 is a multi-volume report describing a generic model which estimates potential radiation dose from exposure to residual radioactive contamination after the decommissioning of facilities licensed by the U.S. Nuclear Regulatory Commission. Individual volumes describe the generic scenarios, models, and parameter values for screening calculations, and the software that implements these calculations. This third volume describes the analysis used to define default parameter values for the Building Occupancy and Residential scenarios and the results of that analysis. Screening calculations are designed to support dose-based decisions without requiring information about specific site conditions. The range of conditions that might exist at licensed sites was used to develop distributions describing the variability in site-specific parameter values. These distributions were then used to derive distributions of potential dose values for unit concentrations of individual source radionuclides. Parameter values were then identified which produce dose values in the upper quantiles of the distributions for all source radionuclides. The resulting parameter values define a generic screening calculation that has a limited risk of underestimating a site-specific dose calculation based on the generic scenarios, models, and screening group. The distributions that underlie these parameter values provide a basis for developing site-specific parameter values.

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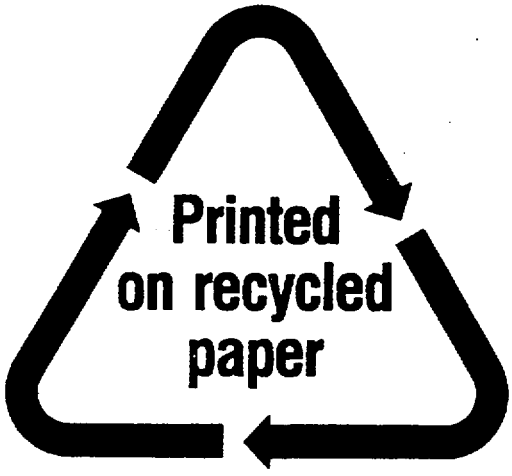

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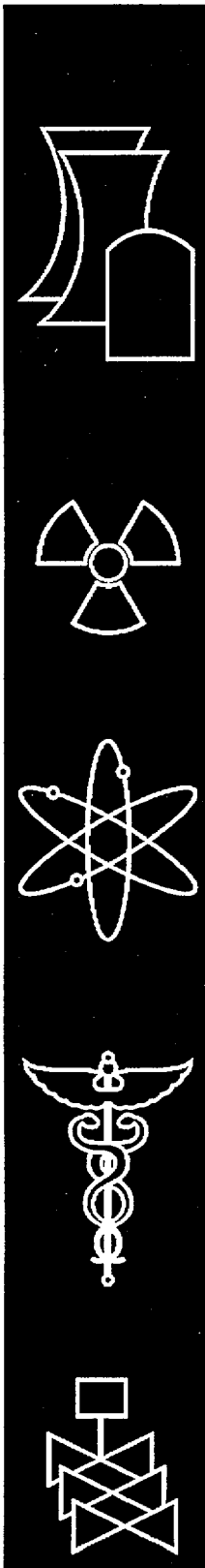

Comparison of the Models and Assumptions used in the DandD 1.0, RESRAD 5.61, and RESRAD-Build 1.50 Computer Codes with Respect to the Residential Farmer and Industrial Occupant Scenarios Provided in NUREG/CR-5512

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Comparison of the Models and Assumptions used in the DandD 1.0, RESRAD 5.61, and RESRAD-Build 1.50 Computer Codes with Respect to the Residential Farmer and Industrial Occupant Scenarios Provided in NUREG/CR-5512

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Abstract

This report provides a detailed comparison of the models, simplifying assumptions and default parameter values implemented by the DandD 1.0, RESRAD 5.61 and RESRAD Build 1.50 computer codes. Each of these codes is a potentially useful tool for demonstrating compliance with the license termination criteria published by the Nuclear Regulatory Commission in the Federal Register on July 21, 1997. The comparison was limited to the industrial occupant and residential farmer scenarios defined in NUREG/CR-5512 (Kennedy and Strenge, 1992). The report is intended to describe where and how the models and default parameter values in each of the codes differ for the specified scenarios. Strengths, weaknesses and limitations of the models are identified. The practical impacts of the identified differences to dose assessment results are discussed.

RESRAD 5.61 and DandD 1.0 were compared based on the residential farmer scenario. The primary differences between the two codes are due to the use of different groundwater and atmospheric transport models, default parameter values and dose rate reporting. Doses related to pathways involving the use of contaminated groundwater tend to be rather different because of fundamental differences in the groundwater models. Another major difference in dose assessments resulted from the apparently large value of default soil plant mass loading factor used in DandD 1.0. In general there were significant differences in doses modeled for scenarios involving carbon-14, tritium and radon because RESRAD 5.61 includes special flux models for simulating the transport of these isotopes from the soil to the atmosphere while DandD 1.0 does not.

RESRAD Build 1.50 and DandD 1.0 were compared based on the industrial occupant scenario. The modeling approach of the two codes is very different. RESRAD Build 1.50 uses kinetic models to assess the dose, while DandD 1.0 does not. When input parameter values are matched, the models provide similar initial dose rates. Time dependencies of the two models are rather different due to fundamental differences in the models.

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FOREWORD

This contractor report, NUREG/CR-5512, Volume 4, was prepared by Sandia National Laboratory under their DOE Interagency Work Order (JCN W6227) with Radiation Protection, Environmental Risk & Waste Management Branch, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission. This report is the fourth volume to be published in the NUREG/CR-5512 series, and provides a detailed comparison of the model structure, assumptions, and parameters used in the Nuclear Regulatory Commission's DandD software code with those used in the Department of Energy's RESRAD 5.61 and RESRAD-Build 1.50 software codes.

NUREG/CR-5512,Volume 1, describes the scenarios and calculational approach for translating residual radioactivity to dose. Volume 2 is the User's guide for the DandD software, which automates the dose calculations described in Volume 1. Volume 2 also contains an appendix which describes the changes that have been made to the models and calculations since the publication of Volume 1. This series of reports is a part of the technical basis for the License Termination Rule (10 CFR 20, Subpart E), and was used to develop implementation guidance for the Rule.

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1. Introduction

This report provides a comparison of the assumptions, models, and default parameters in three environmental dose assessment computer codes that have been used to assess compliance with license termination requirements promulgated by the Nuclear Regulatory Commission (NRC) (NRC, 1997). The computer codes compared were DandD 1.0, RESRAD 5.61, and RESRAD-Build 1.50. The report also includes the results of a number of simulations performed with each model and, to the degree possible, an explanation of why the results differed. The comparison was limited to the residential farmer and industrial occupant exposure scenarios given in NUREG/CR-5512. In the case of the residential farmer scenario, simulations were run for three general sub-cases:

1. Simulations having minimal changes to defaults,

2. Simulations representing a wet climate with effort to make parameters comparable, and

3. Simulations representing a dry climate with effort to make parameters comparable.

This report does not describe every difference between DandD 1.0, RESRAD 5.61, and RESRAD-Build 1.50. However, an effort was made to identify major differences between the computer codes as well as aspects of the codes that may lead to underestimation or gross overestimation of doses for the NUREG/CR-5512 scenarios considered.

Sandia National Laboratories developed the DandD 1.0 computer code. It represents an implementation of the dose assessment screening models given in NUREG/CR-5512 (Kennedy and Strenge, 1992) as modified by Wernig, et al. (1999). DandD 1.0 provides a structured interface that allows users to apply screening models to estimate doses under four distinct exposure scenarios: industrial occupancy, renovation, residential farmer, and drinking water. Default parameters were selected based on a rigorous analysis so that defensible screening calculations can be made using information about the source.

RESRAD 5.61 (Yu et al., 1993) and RESRAD-Build 1.50 (Yu et al., 1994) were developed by Argonne National Laboratories, and are widely used by DOE and other government agencies to estimate doses from residual radioactive material. These programs are flexible modeling platforms, but they are not specifically organized for implementing the four exposure scenarios given in NUREG/CR-5512. RESRAD 5.61 is primarily useful for estimating doses arising from occupancy of land contaminated by radioactive material. RESRAD-Build 1.50 is primarily useful for estimating doses resulting from occupancy of structures that have surfaces or volumes contaminated with radioactive materials.

2. Scenarios

The comparison of the three computer codes was completed for two scenarios: a residential farmer and an industrial occupant. Both of these scenarios are described in detail in NUREG/CR-5512. The scenarios are summarized below.

2.1 Residential Farmer

The residential farmer scenario is intended to allow estimation of radiation doses that may result from radioactive contamination in soil. The contamination is assumed to be present in a 15-cm thick surface layer on property that can be used for residential and light farming activities. The following pathways are considered in the residential farmer scenario given in NUREG/CR-5512:

- External Exposure from Volume Soil Sources While Outdoors and While Gardening,
- External Exposure from Volume Soil Sources While Indoors,
- Inhalation Exposure to Resuspended Soil While Outdoors and While Gardening,
- Inhalation Exposure to Resuspended Soil While Indoors,
- Inhalation Exposure to Resuspended Surface Sources of Soil Tracked Indoors,
- Ingestion of Soil – Direct,
- Inadvertent Ingestion of Soil Tracked Indoors,
- Ingestion of Drinking Water from a Groundwater Source,
- Ingestion of Plant Products Grown in Contaminated Soil,
- Ingestion of Plant Products Grown With Contaminated Groundwater,
- Ingestion of Animal Products Grown On-Site, and
- Ingestion of Fish Grown in a Pond that is Contaminated by Groundwater.

A number of other pathways are not considered in the residential farmer scenario that is described in NUREG/CR5512. These include:

- External exposure to radioactive material tracked indoors,
- External exposure to sources due to submersion in an airborne cloud of radioactive material,
- External exposure related to contaminated surface water,
- Inhalation of radon and radon progeny,
- Ingestion of drinking water from contaminated surface water sources, and
- Dermal absorption of radionuclides.

Of the pathways not considered, inhalation of radon and radon progeny while indoors is apt to be the most significant in cases where the radioactive contaminants are Naturally Occurring Radioactive Materials (NORM) or Atomic Energy Act 11(e)2 byproduct materials[1]. However, the radon inhalation pathway was excluded from the scenario because NRC does not regulate NORM and closure of facilities contaminated by 11(e)2 byproduct material is already covered by existing regulations.

2.2 Industrial Occupant

The industrial occupancy scenario given in NUREG/CR-5512 is intended to allow estimation of the doses resulting from occupancy of a building that contains both fixed and removable surface contamination. It is assumed that the individual simply occupies a commercial facility in a passive manner without deliberately disturbing surface sources of radioactive contamination. The following pathways were considered in the industrial occupancy scenario:

- External exposure due to source,
- Inhalation of airborne radioactive material, and
- Inadvertent ingestion of radioactive material.

[1]Uranium/thorium mill tailings produced as a consequence of extraction of source material.

A number of other pathways are not considered in the industrial occupancy scenario described in NUREG/CR-5512. These include:

- External exposure to sources due to submersion in an airborne cloud of radioactive material,
- Inhalation of radon and radon progeny,
- Dermal absorption of radionuclides.

The pathways not considered in the industrial occupancy scenario are unlikely to be important in most cases, with the possible exception of inhalation of radon and radon progeny, as discussed in section 2.1.

3. Model Comparisons

3.1 DandD 1.0 and RESRAD 5.61

The most fundamental difference between the two codes is that RESRAD 5.61 is a general purpose environmental dose assessment model while DandD 1.0 is specifically designed to model the scenarios given in NUREG/CR-5512.

The pathways considered in DandD 1.0 and RESRAD 5.61 are provided in Table 1.

The major pathway differences can be summarized as follows:

- DandD 1.0 treats inhalation exposure to soil that has been tracked indoors and become airborne as a discrete pathway, while RESRAD 5.61 does not.
- RESRAD 5.61 has a radon diffusion model and treats inhalation of radon and radon progeny as a separate pathway, while DandD 1.0 does not.
- DandD 1.0 treats inadvertent ingestion of soil tracked indoors as a discrete pathway, while RESRAD 5.61 does not.

In addition, there are numerous significant differences between the two models. These are summarized below.

- DandD 1.0 reports doses accrued over a year of exposure, while RESRAD 5.61 reports instantaneous dose rates. Although both of the codes report dose rates in units of mrem/y, they are distinctly different quantities that cannot always be directly compared.
- DandD 1.0 has a larger library of isotopes than RESRAD 5.61. The DandD 1.0 isotope library includes many primary isotopes with half-lives between 10 minutes and 30 days that are not considered by RESRAD 5.61.
- DandD 1.0 and RESRAD 5.61 observe different formalisms concerning treatment of decay chains. These differences are not likely to give rise to significant differences in simulation results, however.
- DandD 1.0 considers ingestion of eggs and poultry, while RESRAD 5.61 does not.
- DandD 1.0 subdivides plant foods consumed by humans into four groups, while RESRAD 5.61 subdivides plant foods into two groups.

Table 1. Residential farmer scenario pathways considered by DandD 1.0 and RESRAD 5.61

Pathway	DandD 1.0	RESRAD 5.61
External Exposure from Volume Soil Sources While Outdoors	yes	yes
External Exposure from Volume Soil Sources While Indoors	yes	yes
Inhalation Exposure to Resuspended Soil While Outdoors	yes	yes
Inhalation Exposure to Resuspended Soil While Indoors	yes	yes
Inhalation Exposure to Resuspended Surface Sources of Soil Tracked Indoors	yes	no
Inhalation – Radon Progeny	no*	yes
Ingestion of soil – Direct	yes	yes
Inadvertent Ingestion of Soil Tracked Indoors	yes	no
Ingestion of Drinking Water from a Groundwater Source	yes	yes
Ingestion of Plant Products Grown in Contaminated Soil	yes	yes
Ingestion of Plant Products Grown With Contaminated Groundwater	yes	yes
Ingestion of Animal Products Grown On-Site	yes	yes
Ingestion of Fish	yes	yes

*Radon-222 is released from radium-226. Radium-226 in uranium mill tailings is regulated through section 11(e) 2 of the Atomic Energy Act as byproduct material. Cleanup requirements for such radium residues are promulgated through the Uranium Mill Tailings Radiation Control Act. Radium-226 in a form other than source material or byproduct material is largely regulated by the states.

- RESRAD 5.61 considers consumption of shellfish and fish, while DandD 1.0 only considers consumption of fish.

- RESRAD 5.61 food consumption rates are based on national averages, while DandD 1.0 food consumption rates are based on consumption rates of home grown foods.

- As a default, RESRAD 5.61 calculates the contamination fraction of foods as a function of the surface area of contamination. DandD 1.0 does not.

- RESRAD 5.61 has a non-dispersion groundwater model (default) and a mass balance groundwater model; DandD 1.0 has a groundwater model that resembles RESRAD 5.61's mass balance groundwater model in some respects.

- DandD 1.0 recycles irrigation water back through the unsaturated zone to the aquifer, while RESRAD 5.61 does not.

- RESRAD 5.61 allows the user to specify whether irrigation water comes from surface water or from groundwater. DandD 1.0 assumes that irrigation water comes from groundwater.

- RESRAD 5.61 allows different water sources to be used for irrigation and watering of livestock. DandD 1.0 does not.

- RESRAD 5.61 considers sorption in the saturated zone, while DandD 1.0 does not.

- Travel times of contaminants to the well are very different for the two models due to different default values for distribution coefficients, and different groundwater model assumptions. This results in different time dependence and dose rates for pathways related to surface water or groundwater usage.

- DandD 1.0 uses the same distribution coefficients for surface soils and the unsaturated zone, while RESRAD 5.61 allows for different distribution coefficients.

- DandD 1.0 assumes that carbon-14 and tritium only become airborne as a component of airborne dust; RESRAD 5.61 contains flux models for these isotopes and it takes into account inhalation of gaseous forms of these isotopes. RESRAD 5.61 also takes into account inhalation of particulate forms of carbon-14.

- DandD 1.0 assumes that conventional soil-to-plant transfer coefficients can be used to model uptake of carbon-14 by plants. RESRAD 5.61 has a carbon-14 model based on the assumption that assimilation of carbon by plants occurs through leaf surfaces and through the root system.

- RESRAD 5.61 models direct gamma doses from soil as a function of thickness and areal extent of contamination, while DandD 1.0 considers only a 6" thick infinite slab of contaminated soil.

- RESRAD 5.61 takes the surface area of contamination into account, while DandD 1.0 does not; this allows RESRAD 5.61 to model doses from "hot spots" of radioactive contamination.

- RESRAD 5.61 allows for the presence of a cover of clean fill over the contaminated area. DandD 1.0 does not.

- RESRAD 5.61 allows the user to select an erosion rate that applies to the cover and contaminated area, while DandD 1.0 does not take erosion into account.

- RESRAD 5.61 uses a conservative correction factor for contamination fraction of dust present in outdoor air that depends on areal extent of contamination, while DandD 1.0 assumes that all dust present in outdoor air is resuspended contaminated soil.

- RESRAD 5.61 models the amount of soil present in plants as the result of a dynamic process involving deposition and removal through weathering. DandD 1.0 addresses this through use of an empirical mass loading factor. The current mass loading factors used by DandD 1.0 appear to be rather high; it is recommended that they be reconsidered.

- RESRAD 5.61 uses a single human respiration rate. DandD 1.0 uses different respiration rates for indoors, gardening, and "other outdoor activities."

- RESRAD 5.61 has a single outdoor air mass loading for inhalation, while DandD 1.0 has separate values of mass loading for gardening and "other outdoor activities."

- DandD 1.0 distinguishes between indoor airborne dust concentrations resulting from infiltration of outdoor air and from resuspension of soil tracked indoors. RESRAD 5.61 does not.

- Throughout the model, RESRAD 5.61 and DandD 1.0 tend to use different values for default parameters.

- DandD 1.0 assumes overhead irrigation, RESRAD 5.61 will model either overhead or ditch irrigation.

3.1.1 Dose Rate Reporting Basis

DandD 1.0 computes average doses that occur over a one-year period of time and reports the value as the maximum annual dose for the time interval of interest. RESRAD 5.61 computes and reports instantaneous dose rates for the times specified by the user as well as the maximal instantaneous dose rate projected during the interval of interest. These are fundamentally different approaches. Both approaches should provide essentially the same annualized dose rate for scenarios involving nuclides having a half-life of a few years or longer and nuclides moving slowly out of the contaminated zone.

The maximal instantaneous dose rate reporting basis of RESRAD 5.61 presents a complication in the interpretation of results for certain isotopes. Cleanup standards in 10 CFR 20, Subpart E, "Radiological Criteria for License Termination," are based on limiting the annual dose to a prescribed value (25 mrem) and not a limitation of the instantaneous dose rate. Substantial differences will result from the dose rate reporting basis alone for isotopes having a half-life between one month and six months and for tritium and carbon-14 because of their rapid movement out of surface soils.

A pair of simulations provided in Appendix A illustrate how rapidly the RESRAD 5.61 instantaneous dose rates change in the case of tritium (Table A.1). In this example, the instantaneous dose rate declines during the first year from an initial (and maximal) value of 5 mrem/y to a final value of 2E-5 mrem/y. Using maximal instantaneous dose rates could be appropriate for screening purposes.

The maximal instantaneous dose rate approach is conservative in most cases. However, it would be desirable to modify RESRAD 5.61 to calculate the dose accrued over a year so that direct comparison with regulatory limits is possible.

3.1.2 Isotopes and Decay Chains

RESRAD 5.61 will operate with either of two isotope libraries. As the default condition, RESRAD 5.61 uses a library of 67 primary isotopes with a half-life of six months or longer. In the default mode it considers any progeny with a half-life shorter than six months to be in equilibrium with the parent isotope. As an option, users can choose to run RESRAD 5.61 with a library of 84 primary isotopes having a half-life of 30 days or longer.

The DandD 1.0 library includes 249 primary isotopes. The half-lives of all primary isotopes in the library are 10 minutes or longer. DandD 1.0 always assumes a short-lived decay product to be in equilibrium with its parent when *both* of the following conditions are met: the decay product has a half-life less than nine hours, *and* the decay product half-life is less than one tenth of the parent.

3.1.3 Human Diet

DandD 1.0 and RESRAD 5.61 subdivide the human diet differently. A comparison of the two is provided in Table 2. DandD 1.0 and RESRAD 5.61 use transfer coefficients assumed to be dependent only on radionuclide for entire classes of foods.

DandD 1.0 subdivides the "plant" foods into four categories while RESRAD 5.61 subdivides "plant" foods into two categories. The higher number of plant subdivisions could make it easier for users of DandD 1.0 to identify suitable alternate soil-to-plant transfer factors from the scientific literature. In practice, taking advantage of the greater flexibility may be difficult. It is noted that default soil-to-plant transfer factor values for many of the isotopes in the DandD 1.0 database have the same value for roots, fruits, and grains.

DandD 1.0 distinguishes between intakes of poultry, eggs, and beef, while RESRAD 5.61 only considers intakes of beef. It is desirable to distinguish between intakes of poultry, eggs, and beef, because:

- cattle and birds are different physiologically,

- foraging birds tend to ingest more soil than do cattle, and

- birds and cattle have different plant-to-animal product transfer factors.

In theory, RESRAD 5.61 users could compensate for the aggregation of intakes of animal products by adjusting the plant-to-animal transfer factors to represent a weighted average of the factors for poultry, eggs, and beef.

Table 3 provides default animal intake rates for fodder, water and soil.

Table 2. How DandD 1.0 and RESRAD 5.61 divide the human diet into food classes

Dietary Component	DandD 1.0	RESRAD 5.61
Beef and Poultry combined	no	yes
Beef	yes	no
Poultry	yes	no
Milk	yes	yes
Eggs	yes	yes
Fish	yes	yes
Mollusks and crustaceans	no	yes
Fruits, non-leafy vegetables, and grains as a group	no	yes
Leafy vegetables	yes	yes
Roots	yes	no
Fruit	yes	no
Grain	yes	no

Table 3. Default animal intake rates for food, water, and soil

Animal Intake Rates	Units	DandD 1.0 Default Value	RESRAD 5.61	Remarks
Beef Forage	kg/day	8.13	NA	
Poultry Forage	kg/day	0.0562	NA	
Milk Cow Forage	kg/day	35.2	NA	
Layer Hen Forage	kg/day	.0755	NA	
Beef Grain	kg/day	2.42	NA	
Poultry Grain	kg/day	0.0630	NA	
Milk Cow Grain	kg/day	1.95	NA	
Layer Hen Grain	kg/day	0.0610	NA	
Beef Hay	kg/day	16.3	NA	
Fodder intake for meat	kg/day	NA	68.0	
Poultry Hay	kg/day	0.00	NA	
Milk Cow Hay	kg/day	26.1	NA	
Milk Cow Fodder	kg/day	NA	55.0	
Layer Hen Hay	kg/day	0.00	NA	
Beef Water	L/day	50.0	NA	
Livestock Water intake for meat	L/day	NA	50	Presumably this is the same as intake for beef.
Poultry Water	L/day	0.30	NA	
Milk Cow Water	L/day	60.0	160	RESRAD 5.61's 160 L/day water intake rate for dairy cattle seems high.
Layer Hen Water	L/day	0.30	NA	

Table 3. Default animal intake rates for food, water, and soil (continued)

Animal Intake Rates	Units	DandD 1.0 Default Value	RESRAD 5.61	Remarks
Beef Period	days	365	NA	
Poultry Period	days	365	NA	
Milk Cow Period	days	365	NA	
Layer Hen Period	days	365	NA	
Beef Soil Ingestion Fraction	None	0.020	NA	
Poultry Soil Ingestion Fraction	None	0.10	NA	
Milk Cow Soil Ingestion Fraction	None	0.020	NA	
Layer Hen Soil Ingestion Fraction	None	0.10	NA	
Livestock soil intake	kg/day	NA	0.05	

RESRAD 5.61 distinguishes between intakes of shellfish and fish, while DandD 1.0 only considers intakes of fish. The higher number of aquatic food subdivisions provides RESRAD 5.61 with additional flexibility in modeling dose from intakes of aquatic foods. This added flexibility of RESRAD 5.61 increases its usefulness as a general environmental dose assessment tool. The shellfish intake pathway is not a component of the residential farmer scenario given in NUREG/CR-5512, so this feature is not directly applicable to the scenarios considered.

An important distinction should be made between DandD 1.0 and RESRAD 5.61 concerning default ingestion rates. The default ingestion rates given in DandD 1.0 are intended to represent the ingestion rates of homegrown foods. These values are intended to be used for screening purposes with a default "DIET" fraction of 1.0. The DIET fraction used in DandD 1.0 could be set to a value of less than 1.0 if only a uniform fraction of the homegrown foods can be grown in the contaminated area (Beyeler, et al., 1998).

The ingestion rate parameters in RESRAD 5.61 represent the total consumption rates for the different food groups based on national averages (Yu, et al., 1993). The default ingestion rate of contaminated foods in RESRAD 5.61 is the product of the total consumption rate and the contamination fraction. The contamination fraction can be set by the user, but by default RESRAD 5.61 calculates a contamination fraction based on the extent of the contamination area. The default method used by RESRAD 5.61 to calculate contamination fraction is given in Table 4. Table 4 provides default ingestion rates for contaminated foods in DandD 1.0 and RESRAD 5.61.

Comparison of the DandD 1.0 values for consumption rates of homegrown foods with RESRAD 5.61 national average consumption rates (see the first page of Table 4) suggests that people may tend to consume what foods are readily available to them or that they tend to raise foods that they prefer to eat.

3.1.4 Fish and Shellfish Bio-Concentration Factors

Table 5 provides default bio-accumulation factors for RESRAD 5.61 and DandD 1.0. Shellfish bio-concentration factors (FWR) used in RESRAD 5.61 tend to be significantly higher than the corresponding fish FWR. In summary, in RESRAD 5.61 the shellfish FWR compare to the fish FWR as follows (noble gases and nitrogen excluded):

shellfish FWR $\leq$ 0.1 $\times$ fish FWR: 4 elements

shellfish FWR $<$ fish FWR: 23 elements

shellfish FWR $=$ fish FWR: 4 elements

shellfish FWR $>$ fish FWR: 45 elements

shellfish FWR $\geq$ 10 $\times$ fish FWR: 34 elements.

The fish bio-accumulation factors used by DandD 1.0 may require modification when the model is applied to scenarios where consumption of shellfish is an exposure pathway.

Table 4. Comparison of the basic residential farmer scenario default parameters of DandD 1.0 and RESRAD 5.61

Parameter	DandD 1.0 Default	RESRAD 5.61 Default	Remarks
Inhalation rate (m**3/hr)	NA	0.9589	
Inhalation rate, indoor (m**3/hr)	0.90	NA	
Inhalation rate, outdoor (m**3/hr)	1.40	NA	
Inhalation rate, gardening (m**3/hr)	1.70	NA	
Mass loading for inhalation, outdoors (g/m**3)	3.14E-6	2.00E-04	
Mass loading for inhalation, indoors (g/m**3)	1.41E-6	NA	
Mass loading for inhalation, gardening (g/m**3)	4.00E-4	NA	
Resuspension factor for indoor dust	2.82E-6	NA	
Floor dust loading g/m^2	0.1599	NA	
Dilution length for airborne dust, inhalation (m)	NA	3.000E+0	
Exposure duration (y)	NA	3.00E+01	
Shielding factor, inhalation	NA	4.000E-01	
Shielding factor, external gamma	0.5512	7.000E-01	
Fraction of time spent indoors	0.6571	5.00E-01	
Fraction of time spent outdoors (on site)	0.1101	2.50E-01	
Fraction of time spent gardening	7.99E-3	NA	
Fruits, vegetables, and grain consumption (kg/yr.)	112	160	DandD 1.0 value is sum of individual annual dietary intakes for food items.
Soil mass loading on plants	0.1		DandD 1.0 rate is high for food crops
Fruits (kg/yr.)	52.8	NA	DandD values are based on average for consumption of home-grown crops
Roots (kg/yr.)	44.6	NA	
Grain (kg/yr.)	14.4	NA	
Leafy vegetable consumption (kg/yr.)	21.4	14	
Milk consumption (L/yr.)	233	92	
Meat and poultry consumption (kg/yr.)	65.1	63	DandD 1.0 value is sum of individual annual dietary intakes for food items.
Beef consumption (kg/yr.)	39.8	NA	
Poultry consumption (kg/yr.)	25.3	NA	
Fish consumption (kg/yr.)	20.6	5.40	
Other seafood consumption (kg/yr.)	NA	0.90	

Table 4. Comparison of the basic residential farmer scenario default parameters of DandD 1.0 and RESRAD 5.61 (continued)

Parameter	DandD 1.0 Default	RESRAD 5.61 Default	Remarks
Soil ingestion rate (g/yr.)	18.2625	36.5	
Drinking water intake (L/yr.)	478.5	510	
Contamination fraction of drinking water	1.0	1.00	
Contamination fraction of household water	1.0	1.00	
Contamination fraction of livestock water	1.0	1.00	
Contamination fraction of irrigation water	1.0	1.00	
Contamination fraction of aquatic food	1.0	0.50	
Contamination fraction of plant food	1.0	0.5, if area > 1000 m^2; area / 2000, if area < 1000 m^2	
Contamination fraction of meat	1.0	1.0 if area > 20,000 m^2; area / 20000, if area < 20000 m^2	
Contamination fraction of milk	1.0	1.0 if area > 20,000 m^2; area / 20000, if area < 20000 m^2	
Mass loading for foliage deposition (g/m**3)	NA	1.00E-04	
Depth of soil mixing layer (m)	NA	0.15	DandD 1.0 only models 15 cm layer of surface soil contamination.
Depth of roots (m)	NA	0.90	
Drinking water fraction from groundwater	1.0	1.0	
Household water fraction from groundwater	1.0	1.0	
Livestock water fraction from groundwater	1.0	1.0	
Irrigation fraction from groundwater	1.0	1.0	
Fraction of grain in beef cattle feed	0.0743	0.8	DandD 1.0 considers balance to be forage and hay.
Fraction of grain in milk cow feed	0.0308	0.2	DandD 1.0 considers balance to be forage and hay.
Storage times of contaminated foodstuffs (days):			
Fruits, non-leafy vegetables, and grain	NA	14.0	
Leafy vegetables	1	1.0	
Roots	14	NA	
Fruit	14	NA	
Grain	14	NA	
Milk	1	1.00	
Eggs	1	NA	

Table 4. Comparison of the basic residential farmer scenario default parameters of DandD 1.0 and RESRAD 5.61 (continued)

Parameter	DandD 1.0 Default	RESRAD 5.61 Default	Remarks
Storage times of contaminated foodstuffs (days):			
Meat and poultry	NA	20.0	
Beef	20	NA	
Poultry	1	NA	
Fish	NA	7.0	DandD 1.0 assumes no hold-up time for this pathway.
Crustacea and mollusks	NA	7.0	DandD 1.0 does not consider dietary intake of freshwater mollusks and crustacea.
Well water	NA	1.0	DandD 1.0 assumes no holdup time for well water.
Surface water	NA	1.0	DandD 1.0 assumes that the residential farmer drinks well water.
Livestock fodder	0	45.0	DandD 1.0 assumes intake of stored feeds to begin at the time of harvest.

Table 5. Default bio-accumulation factors for DandD 1.0 and RESRAD 5.61

Isotope	DandD 1.0, Fish (L/kg)	RESRAD 5.61, Fish (L/kg)	RESRAD 5.61 Crustacea and Mollusks (L/kg)
H	1.0	1.0	1.0
Be	2.0	100.0	10.0
C	4,600.0	50,000.0	9,100.0
N	150,000.0	150,000.0	0.0
F	10.0	10.0	100.0
Na	100.0	20.0	200.0
Al		500.0	1,000.0
P	70,000.0	50,000.0	20,000.0
S	750.0	1,000.0	240.0
Cl	50.0	1,000.0	190.0
Ar		0.0	0.0
K	1,000.0	1,000.0	200.0
Ca	40.0	1,000.0	330.0
Sc	100.0	100.0	1,000.0
Cr	200.0	200.0	2,000.0

Table 5. Default bio-accumulation factors for DandD 1.0 and RESRAD 5.61 (continued)

Isotope	DandD 1.0, Fish (L/kg)	RESRAD 5.61, Fish (L/kg)	RESRAD 5.61 Crustacea and Mollusks (L/kg)
Mn	400.0	400.0	90,000.0
Fe	2,000.0	200.0	3,200.0
Co	330.0	300.0	200.0
Ni	100.0	100.0	100.0
Cu	50.0	200.0	400.0
Zn	2,500.0	1,000.0	10,000.0
Ge		4,000.0	20,000.0
As	100.0	300.0	300.0
Se	170.0	200.0	200.0
Br	420.0	420.0	330.0
Kr		0.0	0.0
Rb	2,000.0	2,000.0	1,000.0
Sr	50.0	60.0	100.0
Y	25.0	30.0	1,000.0
Zr	200.0	300.0	6.7
Nb	200.0	300.0	100.0
Mo	10.0	10.0	10.0
Tc	15.0	20.0	5.0
Ru	100.0	10.0	300.0
Rh	10.0	10.0	300.0
Pd	10.0	10.0	300.0
Ag	2.3	5.0	770.0
Cd	200.0	200.0	2,000.0
In	100,000.0	10,000.0	15,000.0
Sn	3,000.0	3,000.0	1,000.0
Sb	200.0	100.0	10.0
Te	400.0	400.0	75.0
Cs	2,000.0	2,000.0	100.0
Ba	200.0	4.0	200.0
La	25.0	30.0	1,000.0
Ce	500.0	30.0	1,000.0
Pr	25.0	100.0	1,000.0
Nd	25.0	100.0	1,000.0
Pm	25.0	30.0	1,000.0
Sm	25.0	25.0	1,000.0
Eu	25.0	50.0	1,000.0
Gd	25.0	25.0	1,000.0
Tb	25.0	25.0	1,000.0
Ho	25.0	25.0	1,000.0
Ta		100.0	30.0
W	1,200.0	1,200.0	10.0
Re	120.0		
Os	10.0		

Table 5. Default bio-accumulation factors for DandD 1.0 and RESRAD 5.61 (continued)

Isotope	DandD 1.0, Fish (L/kg)	RESRAD 5.61, Fish (L/kg)	RESRAD 5.61 Crustacea and Mollusks (L/kg)
Ir	10.0	10.0	200.0
Au	33.0	35.0	1,000.0
Hg	1,000.0	1,000.0	20,000.0
Tl		10,000.0	15,000.0
Pb	100.0	300.0	100.0
Bi	15.0	15.0	10.0
Po	500.0	100.0	20,000.0
Rn	0.0	0.0	0.0
Ra	70.0	50.0	250.0
Ac	25.0	15.0	1,000.0
Th	100.0	100.0	500.0
Pa	11.0	10.0	110.0
U	50.0	10.0	60.0
Np	250.0	30.0	400.0
Pu	250.0	30.0	100.0
Am	250.0	30.0	1,000.0
Cm	250.0	30.0	1,000.0
Cf	25.0	25.0	1,000.0

3.1.5 Soil-to-Plant Transfer Factors

Default soil-to-plant transfer factors are provided in Table 6. DandD 1.0 subdivides plant-based foods into four categories (leafy vegetables, roots, fruit, and grain). RESRAD 5.61 subdivides plant-based foods into two categories: (1) leafy vegetables and (2) fruits, non-leafy vegetables, and grains.

DandD 1.0, RESRAD 5.61, and other environmental dose screening models make use of soil-to-plant transfer factors. Using generic soil-to-plant transfer coefficients requires the following simplifying assumptions:

- transfer coefficients are independent of the chemical form of the radioactive material,
- transfer coefficients are independent of the soil composition,
- all food plants can be grouped into a small number of classes and a representative transfer factor can be assigned for each radionuclide and food class.

Ng (1982) observed that soil-to-plant transfer coefficients are highly variable. He attributed this to differences among plant characteristics, soil types, and other factors.

3.1.6 Plant-to-Animal Product Transfer Factors.

DandD 1.0, RESRAD 5.61, and other screening models use transfer factors to model the relationship between activity per mass of the animal product and daily intake rate of a radionuclide by the animal. Default values are provided in Table 7.

These transfer factors have been studied in the most detail for the plant-milk pathway (Ng et al., 1978; Ng, 1982). Transfer factors for beef, eggs, and poultry have also been published.

There are a number of assumptions that introduce uncertainty into the derivation of plant-to-animal product transfer factors. These uncertainties are described below:

- Published transfer coefficients are often based on limited duration studies; they may not always provide a reasonable estimate of steady state conditions. Extrapolating these values to steady state conditions results in uncertainty from assumptions that must be made concerning the partitioning among compartments, excretion, and retention of the particular isotope by the animal;

Table 6. Soil-to-plant transfer factors

Element	DandD 1.0 Leafy	DandD 1.0 Root	DandD 1.0 Fruit	DandD 1.0 Grain	RESRAD 5.61 Plant
H	0.00	0.00	0.00	0.00	4.8
Be	1.00E-02	1.50E-03	1.50E-03	1.50E-03	4.00E-03
C	3.20E-01	7.00E-01	7.00E-01	2.20E-01	5.5
N	3.00E+01	3.00E+01	3.00E+01	3.00E+01	7.5
F	6.00E-02	6.00E-03	6.00E-03	6.00E-03	2.00E-02
Na	7.40E-02	2.80E-02	1.60E-02	5.20E-03	5.00E-02
Mg	1.00	5.50E-01	5.50E-01	5.50E-01	
Al					4.00E-03
Si	3.50E-01	7.00E-02	7.00E-02	7.00E-02	
P	3.50	3.50	3.50	3.50	1
S	2.30	1.50	1.50	1.50	6.00E-01
Cl	1.60E+02	7.00E+01	7.00E+01	1.00E+03	20
Ar	0.00	0.00	0.00	0.00	0.00
K	8.40	5.50E-01	5.50E-01	1.30	3.00E-01
Ca	1.40E+01	3.50E-01	3.50E-01	1.60	5.00E-01
Sc	6.00E-03	1.00E-03	1.00E-03	1.00E-03	2.00E-03
Cr	2.20E-02	8.00E-02	4.60E-02	1.50E-02	2.50E-04
Mn	3.30E-01	1.10E+01	4.20	1.40E-01	3.00E-01
Fe	5.60E-03	2.60E-03	1.50E-03	4.80E-04	1.00E-03
Co	4.00E-02	2.90	2.20E-02	1.10E-02	8.00E-02
Ni	3.40E-02	2.50	3.40E-01	3.80E-02	5.00E-02
Cu	4.90E-01	2.60E-01	1.50E-01	4.90E-02	1.30E-01
Zn	3.10E-01	2.40E-01	1.10	5.50	4.00E-01
Ga	4.00E-03	4.00E-04	4.00E-04	4.00E-04	4.00E-01
As	4.00E-02	6.00E-03	6.00E-03	6.00E-03	8.00E-02
Se	4.90E-02	2.50E-02	2.50E-02	1.60E-01	1.00E-01
Br	1.50	1.50	1.50	1.50	7.60E-01
Kr	0.00	0.00	0.00	0.00	0.00
Rb	8.10E-01	7.00E-02	7.00E-02	7.00E-02	1.30E-01
Sr	6.40E+01	4.60E-01	2.60E-01	8.50E-02	3.00E-01
Y	1.50E-02	6.00E-03	6.00E-03	6.00E-03	2.50E-03
Zr	7.20E-02	4.70E-03	2.70E-03	8.70E-04	1.00E-03
Nb	4.60E-02	5.00E-03	5.00E-03	4.30E-03	1.00E-02
Mo	5.20E+01	6.00E-02	6.00E-02	6.00E-02	1.30E-01
Tc	3.60E+01	1.50	1.50	7.30E-01	5
Ru	1.80E-02	8.60E-03	3.00E-01	1.60E-03	3.00E-02
Rh	1.50E-01	4.00E-02	4.00E-02	4.00E-02	1.30E-01
Pd	1.20	4.00E-02	4.00E-02	1.80E-01	1.00E-01
Ag	5.50	1.00E-01	1.00E-01	1.00E-01	1.50E-01

Table 6. Soil-to-plant transfer factors (continued)

Element	DandD 1.0 Leafy	DandD 1.0 Root	DandD 1.0 Fruit	DandD 1.0 Grain	RESRAD 5.61 Plant
Cd	5.00	1.50E-01	6.70E-01	2.20E-01	3.00E-01
In	4.00E-03	4.00E-04	4.00E-04	4.00E-04	3.00E-03
Sn	4.30E-02	6.00E-03	6.00E-03	6.00E-03	2.50E-03
Sb	9.00E-01	3.00E-02	3.00E-02	3.00E-02	1.00E-02
Te	1.70E-02	4.00E-03	4.00E-03	2.50E-03	6.00E-01
I	1.60E-01	2.80E-02	1.60E-02	5.10E-03	2.00E-02
Xe	0.00	0.00	0.00	0.00	0.00
Cs	1.80E-02	3.10E-02	1.40E-01	6.60E-03	4.00E-02
Ba	3.90E-02	8.00E-03	4.60E-03	1.50E-03	5.00E-03
La	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Ce	6.40E-01	4.00E-03	2.00E-03	8.20E-04	2.00E-03
Pr	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Nd	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.40E-03
Pm	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Sm	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Eu	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Gd	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Tb	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.60E-03
Dy	1.00E-02	4.00E-03	4.00E-03	4.00E-03	
Ho	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.60E-03
Er	1.00E-02	4.00E-03	4.00E-03	4.00E-03	
Hf	3.50E-03	8.50E-04	8.50E-04	8.50E-04	
Ta	1.00E-02	2.50E-03	2.50E-03	2.50E-03	2.00E-02
W	3.10E-01	1.00E-02	1.00E-02	4.10E-02	1.80E-02
Re	7.50	3.50E-01	3.50E-01	9.50E-01	
Os	9.40E-02	3.50E-03	3.50E-03	3.50E-03	
Ir	1.50E-01	1.50E-02	1.50E-02	1.00E-02	3.00E-02
Au	4.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01
Hg	9.00E-01	2.00E-01	2.00E-01	2.00E-01	3.80E-01
Tl	4.00E-03	4.00E-04	4.00E-04	4.00E-04	2.00E-01
Pb	4.50E-02	9.00E-03	9.00E-03	9.00E-03	1.00E-02
Bi	3.50E-02	5.00E-03	5.00E-03	5.00E-03	1.00E-01
Po	2.50E-03	4.00E-04	4.00E-04	4.00E-04	1.00E-03
Rn	0.00	0.00	0.00	0.00	0.00
Ra	1.50E-02	1.50E-03	1.50E-03	1.50E-03	4.00E-02
Ac	3.50E-03	3.50E-04	3.50E-04	3.50E-04	2.50E-03
Th	8.50E-04	8.50E-05	8.50E-05	8.50E-05	1.00E-03
Pa	2.50E-03	2.50E-04	2.50E-04	2.50E-04	1.00E-02
U	8.50E-03	4.00E-03	4.00E-03	4.00E-03	2.50E-03

Table 6. Soil-to-plant transfer factors (continued)

Element	DandD 1.0 Leafy	DandD 1.0 Root	DandD 1.0 Fruit	DandD 1.0 Grain	RESRAD 5.61 Plant
Np	1.90E+01	1.90E-01	1.30E-01	6.80E-02	2.00E-02
Pu	4.50E-04	4.50E-05	4.50E-05	4.50E-05	1.00E-03
Am	5.50E-03	2.50E-04	2.50E-04	2.50E-04	1.00E-03
Cm	8.50E-04	1.50E-05	1.50E-05	1.50E-05	1.00E-03
Cf	1.00E-02	1.00E-02	1.00E-02	1.10E-02	1.00E-03

- The fractional uptake of the isotope by the animal is assumed to be the same regardless of the media (water, plant, or soil) ingested;
- Ingested plant material, water, and soils of all types are assumed to have the same bio-availability of radionuclides;
- The transfer factors are assumed to independent of the chemical form of the radionuclide;
- The transfer factors are assumed to be independent of the age of the animal and dietary factors.

3.1.7 Groundwater Models

The groundwater models in DandD 1.0 and RESRAD 5.61 are similar in some respects and different in others. The DandD 1.0 groundwater model is a sequence of unsteady well-mixed linear reservoirs. In this model, the contaminant concentration in each reservoir is proportional to its initial concentration and additional input. The output concentrations are equal to the concentrations in the reservoir. The unsaturated zone is usually represented as one well-mixed linear reservoir. However, it can be represented with as many as 10 reservoirs. These reservoirs all have the same thickness, porosity, moisture saturation, and retardation. The intent of the additional reservoirs is to limit the dispersion that is inherent in this type of model (due to the complete mixing assumption). Additional reservoirs slow down the simulated arrival time of contaminants to the groundwater relative to a single reservoir model.

The RESRAD 5.61 groundwater model has an unsteady well-mixed linear reservoir in the contaminated zone, a travel time model in the unsaturated zone, and either a mass balance model or non-dispersive model in the saturated zone. The unsaturated zone in RESRAD 5.61 can be represented by up to five layers with differing properties. The mass balance or non-dispersive model is user-selectable in RESRAD 5.61.

DandD 1.0 and RESRAD 5.61 use the same leaching model to estimate the concentration of contaminants in groundwater in the unsaturated zone (see Kennedy and Strenge, 1992, p.4.8-4.9 and Yu et al., 1993, p.197-199). The leaching rate is a function of the infiltration rate, moisture content, layer thickness, and retardation coefficient. As a result, the leaching rate is element-specific.

3.1.7.1 DandD 1.0 Groundwater Model

3.1.7.1.1 Contaminated Zone. The contaminated zone in DandD 1.0's groundwater model is modeled as a well-mixed linear reservoir. In DandD 1.0's model implementation, the contaminated zone is referred to as the soil plow layer and is located at land surface. DandD 1.0 allows contaminated water from the aquifer to be pumped to the soil layer for irrigation purposes. The impact would be to continually add radioactive materials to the soil layer. Therefore, the decline in radioactivity in the soil plow layer of DandD 1.0's model is slower than for a case in which no contaminated water is pumped to the soil layer. Contaminants dissolved in the soil layer water move to the unsaturated zone by infiltration. Contaminants left behind are adsorbed onto the soil particles.

DandD 1.0 formulates its model equation for the soil in terms of total activity within a well-mixed linear reservoir. Dissolved activity is transported out of the soil layer box by infiltration. Transport out of the soil layer box is dependent on the infiltration rate, the distribution coefficient, the soil bulk density, the thickness, the porosity, and the moisture saturation. These factors are combined into a transfer term that controls the rate at which contaminants move out of the

Table 7. Plant to animal product transfer factors

Isotope	DandD 1.0 Beef	DandD 1.0 Poultry	RESRAD 5.61 Beef	DandD 1.0 Milk	RESRAD 5.61 Milk	DandD 1.0 Eggs
H	0.0	0.0	1.2E-02	0.0	1.0E-02	0.0
Be	1.0E-03	4.0E-01	1.0E-03	9.0E-07	2.0E-06	2.0E-02
C	0.0	0.0	3.1E-02	0.0	1.2E-02	0.0
N	7.5E-02	1.0E-01	1.0E-02	2.5E-02	1.0E-02	8.0E-01
F	1.5E-01	1.0E-02	2.0E-02	1.0E-03	7.0E-03	2.0
Na	5.5E-02	1.0E-02	8.0E-02	3.5E-02	4.0E-02	2.0E-01
Mg	5.0E-03	3.0E-02		4.0E-03		1.6
Al			5.0E-04		2.0E-04	
Si	4.0E-05	2.0E-01		2.0E-05		8.0E-01
P	5.5E-02	1.9E-01	5.0E-02	1.5E-02	1.6E-02	1.0E+01
S	1.0E-01	9.0E-01	2.0E-01	1.5E-02	2.0E-02	7.0
Cl	8.0E-02	3.0E-02	6.0E-02	1.5E-02	2.0E-02	2.0
Ar	0.0	0.0	0.0	0.0	0.0	0.0
K	2.0E-02	4.0E-01	2.0E-02	7.0E-03	7.0E-03	7.0E-01
Ca	7.0E-04	4.4E-02	1.6E-03	1.0E-02	3.0E-03	4.4E-01
Sc	1.5E-02	4.0E-03	1.5E-02	5.0E-06	5.0E-06	3.0E-03
Cr	5.5E-03	2.0E-01	9.0E-03	1.5E-03	2.0E-03	8.0E-01
Mn	4.0E-04	5.0E-02	5.0E-04	3.5E-04	3.0E-04	6.5E-02
Fe	2.0E-02	1.5E+00	2.0E-02	2.5E-04	3.0E-04	1.3
Co	2.0E-02	5.0E-01	2.0E-02	2.0E-03	2.0E-03	1.0E-01
Ni	6.0E-03	1.0E-03	5.0E-03	1.0E-03	2.0E-02	1.0E-01
Cu	1.0E-02	5.1E-01	1.0E-02	1.5E-03	2.0E-03	4.9E-01
Zn	1.0E-01	6.5	1.0E-01	1.0E-02	1.0E-02	2.6
Ga	5.0E-04	3.0E-01	2.0E-01	5.0E-05	1.0E-02	8.0E-01
As	2.0E-03	8.3E-01	1.5E-03	6.0E-05	1.0E-04	8.0E-01
Se	1.5E-02	8.5	1.0E-01	4.0E-03	1.0E-02	9.3
Br	2.5E-02	4.0E-03	2.0E-02	2.0E-02	2.0E-02	1.6
Kr	0.0	0.0	0.0	0.0	0.0	0.0
Rb	1.5E-02	2.0	1.5E-02	1.0E-02	1.0E-02	3.0
Sr	3.0E-04	3.5E-02	8.0E-03	1.5E-03	2.0E-03	3.0E-01
Y	3.0E-04	1.0E-02	2.0E-03	2.0E-05	2.0E-05	2.0E-03
Zr	5.5E-03	6.4E-05	1.0E-06	3.0E-05	6.0E-07	1.9E-04
Nb	2.5E-01	3.1E-04	3.0E-07	2.0E-02	2.0E-06	1.3E-03
Mo	6.0E-03	1.9E-01	1.0E-03	1.5E-03	1.7E-03	7.8E-01
Tc	8.5E-03	3.0E-02	1.0E-04	1.0E-02	1.0E-03	3.0
Ru	2.0E-03	7.0E-03	2.0E-03	6.0E-07	3.3E-06	6.0E-03
Rh	2.0E-03	5.0E-01	1.0E-03	1.0E-02	5.0E-03	1.0E-01
Pd	4.0E-03	3.0E-04	1.0E-03	1.0E-02	5.0E-03	4.0E-03
Ag	3.0E-03	5.0E-01	3.0E-03	2.0E-02	2.5E-02	5.0E-01
Cd	5.5E-04	8.4E-01	4.0E-04	1.0E-03	1.0E-03	1.0E-01
In	8.0E-03	3.0E-01	4.0E-03	1.0E-04	2.0E-04	8.0E-01
Sn	8.0E-02	2.0E-01	1.0E-02	1.0E-03	1.0E-03	8.0E-01
Sb	1.0E-03	6.0E-03	1.0E-03	1.0E-04	1.0E-04	7.0E-02

Table 7. Plant to animal product transfer factors (continued)

Isotope	DandD 1.0 Beef	DandD 1.0 Poultry	RESRAD 5.61 Beef	DandD 1.0 Milk	RESRAD 5.61 Milk	DandD 1.0 Eggs
Te	1.5E-02	8.5E-02	7.0E-03	2.0E-04	5.0E-04	5.2
I	7.0E-03	1.8E-02	7.0E-03	1.0E-02	1.0E-02	2.8
Xe	0.0	0.0	0.0	0.0	0.0	0.0
Cs	2.0E-02	4.4	3.0E-02	7.0E-03	8.0E-03	4.9E-01
Ba	1.5E-04	8.1E-04	2.0E-04	3.5E-04	5.0E-04	1.5
La	3.0E-04	1.0E-01	2.0E-03	2.0E-05	2.0E-05	9.0E-03
Ce	7.5E-04	1.0E-02	2.0E-05	2.0E-05	3.0E-05	5.0E-03
Pr	3.0E-04	3.0E-02	2.0E-03	2.0E-05	2.0E-05	5.0E-03
Nd	3.0E-04	4.0E-03	2.0E-03	2.0E-05	2.0E-05	2.0E-04
Pm	5.0E-03	2.0E-03	2.0E-03	2.0E-05	2.0E-05	2.0E-02
Sm	5.0E-03	4.0E-03	2.0E-03	2.0E-05	2.0E-05	7.0E-03
Eu	5.0E-03	4.0E-03	2.0E-03	2.0E-05	2.0E-05	7.0E-03
Gd	3.5E-03	4.0E-03	2.0E-03	2.0E-05	2.0E-05	7.0E-03
Tb	4.5E-03	4.0E-03	2.0E-03	2.0E-05	2.0E-05	7.0E-03
Dy	5.5E-03	4.0E-03		2.0E-05		7.0E-03
Ho	4.5E-03	4.0E-03	2.0E-03	2.0E-05	2.0E-05	7.0E-03
Er	4.0E-03	4.0E-03		2.0E-05		7.0E-03
Hf	1.0E-03	6.0E-05		5.0E-06		2.0E-04
Ta	6.0E-04	3.0E-04	5.0E-06	3.0E-06	5.0E-06	1.0E-03
W	4.5E-02	2.0E-01	4.0E-02	3.0E-04	3.0E-04	8.0E-01
Re	8.0E-03	4.0E-02		1.5E-03		4.0E-01
Os	4.0E-01	1.0E-01		5.0E-03		9.0E-02
Ir	1.5E-03	5.0E-01	2.0E-03	2.0E-06	2.0E-06	1.0E-01
Au	8.0E-03	5.0E-01	5.0E-03	5.5E-06	1.0E-05	5.0E-01
Hg	2.5E-01	1.1E-02	1.0E-01	4.5E-04	5.0E-04	2.0E-01
Tl	4.0E-02	3.0E-01	2.0E-03	2.0E-03	3.0E-03	8.0E-01
Pb	3.0E-04	2.0E-01	8.0E-04	2.5E-04	3.0E-04	8.0E-01
Bi	4.0E-04	1.0E-01	2.0E-03	5.0E-04	5.0E-04	8.0E-01
Po	3.0E-04	9.0E-01	5.0E-03	3.5E-04	3.4E-04	7.0
Rn	0.0	0.0	0.0	0.0	0.0	0.0
Ra	2.5E-04	3.0E-02	1.0E-03	4.5E-04	1.0E-03	2.0E-05
Ac	2.5E-05	4.0E-03	2.0E-05	2.0E-05	2.0E-05	2.0E-03
Th	6.0E-06	4.0E-03	1.0E-04	5.0E-06	5.0E-06	2.0E-03
Pa	1.0E-05	4.0E-03	5.0E-03	5.0E-06	5.0E-06	2.0E-03
U	2.0E-04	1.2E+00	3.4E-04	6.0E-04	6.0E-04	9.9E-01
Np	5.5E-05	4.0E-03	1.0E-03	5.0E-06	5.0E-06	2.0E-03
Pu	5.0E-07	1.5E-04	1.0E-04	1.0E-07	1.0E-06	8.0E-03
Am	3.5E-06	2.0E-04	5.0E-05	4.0E-07	2.0E-06	9.0E-03
Cm	3.5E-06	4.0E-03	2.0E-05	2.0E-05	2.0E-06	2.0E-03
Cf	5.0E-03	4.0E-03	6.0E-05	7.5E-07	7.5E-07	2.0E-03

soil layer box. The thickness of the box is set at 0.15 m for DandD 1.0 and cannot be changed. This limitation is an artifact of the volumetric-source committed effective dose equivalent (CEDE) factors, which are dependent on a soil thickness of 0.15 m.

The well-mixed linear reservoir assumption appears reasonable for the 0.15 m soil layer. In most cases, plowing of the surface layer would keep radionuclides mixed with the soil and the soil layer is relatively thin. Mathematical complications would occur if the upper 0.15 m were not assumed to be well-mixed.

3.1.7.1.2 Unsaturated Zone. DandD 1.0 models the contaminants in the unsaturated zone as a well-mixed linear reservoir with one to ten layers. Input activity enters the unsaturated zone as a dissolved species from the soil plow layer, by infiltration, becomes well-mixed in the unsaturated zone box and then exits to the aquifer by infiltration. Species can be adsorbed onto the soil particles in the unsaturated zone. The unsaturated zone model equation is set up in terms of total radionuclide activity.

Usually, the modeling is done with one layer. However, if the unsaturated zone is thick, more than one modeling layer can be used. DandD 1.0's unsaturated zone model treats the unsaturated zone as a single homogenous unit even though there may be several heterogeneous units. Rather than model heterogeneities, the additional layering is used to reduce the numerical dispersion that is inherent in well-mixed linear reservoir models. This numerical dispersion has a tendency to reduce the contaminant arrival times from the contaminated zone to the aquifer relative to the advective velocity and may dilute the peak concentration depending on the system and the contaminants. These effects may be negligible, offset each other, or one may be dominant. The well-mixed linear reservoir assumption is reasonable for thin unsaturated zones or for thin layers in the unsaturated zone.

3.1.7.1.3 Saturated Zone. The saturated zone in DandD 1.0 is also modeled as a well-mixed linear reservoir. At steady state with no radioactive decay, this model resembles the mass balance aquifer model for RESRAD 5.61 (see below).

Input activity enters the aquifer box from the unsaturated zone box by infiltration, becomes well mixed within the aquifer box, and then exits the aquifer box through either one or two means. First, activity can leave the aquifer box by pumpage for irrigation and domestic use. Most of the pumped water with its corresponding activity is returned to the soil plow layer box and is recycled through the system. Recycling is a reasonable assumption for dry climates where irrigation is present. Second, if the recharge rate through the contaminated area to the aquifer box is larger than the pumping rate, activity can be removed from the aquifer box by natural groundwater flow. This activity is essentially lost from the system because it flows down-gradient from the aquifer box. In the case where the recharge rate is less than the pumping rate, up-gradient aquifer water, which is free of activity, mixes with contaminated aquifer water, thus diluting activity within the aquifer. Given no data about the aquifer, these are reasonable assumptions that maintain the water balance and radionuclide mass balance in the aquifer.

Adsorption of radionuclides onto the aquifer sediments is neglected. In most cases, this is a conservative, simplifying assumption. Adsorption reduces concentrations in the aquifer water and retains the radionuclide on the soil sediments. If a radionuclide is capable of being adsorbed onto the aquifer sediments, the no-retardation assumption tends to cause overestimates of doses from pathways related to use of groundwater. This affects doses from all isotopes except tritium.

3.1.7.1.4 Distribution Coefficients, K_d. Sorption in the unsaturated zone is modeled assuming it can be represented as a linear, reversible, equilibrium process. DandD 1.0 does not account for sorption in the saturated zone. Default distribution coefficient values are provided in Table 8.

The K_d values for the unsaturated zone are element-specific. The default values for these parameters, listed in Table 8, were selected based on a systematic parameter analysis (Beyeler, et al., 1998). The DandD 1.0 code allows the user to specify site-specific values for K_d.

3.1.7.2 RESRAD 5.61 Groundwater Model

3.1.7.2.1 Contaminated Zone. RESRAD 5.61's model of the contaminated zone is designed to provide a source term for the unsaturated zone model and, thus, is formulated in terms of a release rate from the contaminated zone. In RESRAD 5.61's model, the contaminated zone is generally buried and covered with a soil layer, but it may sit at land surface. RESRAD 5.61's model treats the contaminated zone as a well-mixed linear reservoir in that the contaminants are well mixed over the contaminated zone. This seems a reasonable assumption as radionuclides are generally either placed over the entire contaminated zone, or plowing of the soil layer keeps radionuclides well mixed. Transport from the contaminated zone is dependent on the same

Table 8. Default values of distribution coefficients in DandD 1.0 and RESRAD 5.61

Element	DandD 1.0 Value (ml/g)	RESRAD 5.61 Value (ml/g)	Basis for RESRAD 5.61 Value
H	0	na	
Be	929	na	
C	4	na	
F	5	na	
Na	0	10	unknown
P	26	na	
S	99	na	
Cl	5	2	concentration ratio model
K	5	5.5	unknown
Ca	1468	50	unknown
Sc	1	na	
Cr	101	na	
Mn	84	200	unknown
Fe	535	1000	Table E.3 mean for clay & soil*
Co	1515	1000	unknown
Ni	37	1000	Table E.3 mean for clay & soil
Cu	176	na	
Zn	1060	0	unknown
As	114	na	
Se	115	na	
Br	56	na	
Kr	0	na	
Rb	202	na	
Sr	31	30	Table E.3 mean for clay & soil
Y	789	na	
Zr	46616	na	
Nb	1	0	unknown
Mo	26	na	
Tc	7	0	unknown
Ru	1580	0	unknown
Rh	157	na	
Pd	185	na	
Ag	191	0	unknown
Cd	34	0	unknown
In	158	na	
Sn	25	na	
Sb	68268	0	unknown
Te	548	na	
I	0	60	concentration ratio model

*Table E.3 of the RESRAD users manual (Yu, et al., 1993).

Table 8. Default values of distribution coefficients in DandD 1.0 and RESRAD 5.61 (continued)

Element	DandD 1.0 Value (ml/g)	RESRAD 5.61 Value (ml/g)	Basis for RESRAD 5.61 Value
Xe	0	na	
Cs	10	1000	unknown
Ba	44	na	
La	5	na	
Ce	85	1000	Table E.3 mean for clay & soil
Pr	157	na	
Nd	158	na	
Pm	4995	na	
Sm	930	na	
Eu	940	na	
Gd	0	na	
Tb	53	na	
Ho	7	na	
W	156	na	
Re	44	na	
Os	157	na	
Ir	158	na	
Au	157	0	unknown
Hg	157	na	
Tl	158	na	
Pb	2377	100	Table E.3 mean for clay & soil
Bi	443	0	unknown
Po	26	na	
Rn	0	na	
Ra	3529	70	Table E.3 mean for clay & soil
Ac	1726	20	unknown
Th	119	60000	Table E.3 mean for clay & soil
Pa	5	50	unknown
U	2	50	Table E.3 mean for clay & soil
Np	14	na	
Pu	14	2000	Table E.3 mean for clay & soil
Am	1432	20	unknown
Cm	109084	na	
Cf	158	na	

parameters and processes as DandD 1.0. However, thickness of the contaminated zone does not have to be fixed at 0.15 m and can be specified to become thinner with time. The model does not allow for irrigation water to be returned to land surface for recycling through the unsaturated zone back to groundwater. This is a reasonable assumption in humid climates, but not in dry ones. It may result in an underestimate of potential dose when attempting to evaluate irrigated agricultural or gardening doses.

3.1.7.2.2 Unsaturated-Saturated Zone Mass Balance Model. For contaminated areas less than 1000 m^2, RESRAD 5.61 can use a mass balance model to calculate groundwater concentrations. This model treats transport in the unsaturated zone with a travel time

model, which is the advection equation (the convective-dispersive equation without the dispersion term). The travel time is the time it takes a radionuclide to reach the top of the aquifer from the bottom of the contaminated zone. In the RESRAD 5.61 model's unsaturated zone, the travel times are called breakthrough times. The breakthrough times are based on infiltration, retardation, and unsaturated zone thickness. Given the travel time rates of radionuclides reaching the aquifer, concentrations based on radioactive decay and in-growth are calculated. Properties of up to five different unsaturated-zone soil-layers can be used in this model.

The mass balance model assumes that a well is pumped from the aquifer in an area located directly below the center of the contaminated area. Because of this assumption, it is further assumed that the travel time of water in the aquifer to the well is zero and the contents of the aquifer are well mixed. This is a reasonable assumption if the saturated zone is small. If volumetric recharge through the contaminated zone is greater than the pumping rate, the concentration in the aquifer is not diluted and is set to the concentration of the infiltrating water, i.e., the dilution factor is 1. However, if the volumetric recharge is less than the pumping rate, then contaminated aquifer water is diluted with enough fresh water that the recharge to the aquifer from infiltration and induced groundwater flow is equal to the pumping rate. In this case, the dilution factor is the ratio of the volumetric infiltration rate to the well pumping rate.

The mass balance is similar to DandD 1.0's well-mixed linear reservoir model for the aquifer.

3.1.7.2.3 Unsaturated-Saturated Zone Non-Dispersive Model. RESRAD 5.61 can use this model for all sizes of contaminated areas. In this groundwater model, transport in the unsaturated zone is calculated in the same manner as for the mass balance model. In the saturated zone, instead of a mass balance, an additional travel time, called a rise time, from the unsaturated-zone/aquifer interface to the well is calculated. This travel time is based on the flow of groundwater and the retardation of radionuclides in the aquifer. The well is assumed to be located in the aquifer at the down-gradient edge of the contaminated area. The additional travel time caused by flow in the saturated zone and neglecting dispersion allows for more radionuclide decay and in-growth before the contaminants reach the well. The non-dispersive assumption maximizes concentration behind the advective front.

The non-dispersive model assumes that the well is pumped from the aquifer at an area located down-gradient from the centerline of the contaminated area. It is assumed that contaminated water entering the well is well mixed and may be diluted with fresh aquifer water if necessary. The degree of dilution is dependent on the aquifer flow rate, the pumping rate, well depth, infiltration rate, and contaminated area size and length. These factors can be combined to calculate a contamination depth and a pumping zone width in the aquifer. Depending on the relationship between contamination depth to the well depth and contamination width to pumping zone width, estimates for a dilution factor can be made. For instance, if the contamination depth is deeper than the well depth and pumping zone width is less than the contaminated zone width, the dilution factor is 1. This reduces to the case where the volumetric recharge is greater than the pumping rate in the mass balance model. However, if the contamination depth is shallower than the well depth and pumping zone is wider than the contaminated zone, the dilution factor is the ratio of the volumetric recharge to the pumping rate. This reduces to the case where the volumetric recharge is less than the pumping rate in the mass balance model. There are two other cases that must be considered and they relate to how the contamination flows through the aquifer. Both cause a dilution of the pumped aquifer water. One depends on the contaminated zone being deeper than the well and the pumping zone being wider than the contaminated zone. The second depends on the contaminated zone depth being shallower than the well depth and the pumping zone width being less than the contaminated zone width.

The RESRAD 5.61 non-dispersive model assumes that dispersion does not occur as a radionuclide travels through the saturated zone to the pumped well. In general, this slows the arrival of a concentration front to the well, but allows for higher concentrations at the well when the travel time is significantly faster than the half-lives of the contaminant. However, since the pumped well is located down-gradient along the centerline of the plume at the edge of the contaminated zone, dispersion may not be significant.

RESRAD 5.61's calculation of the width of the effective pumping zone is a factor of two larger than that predicted by steady-state recharge well theory and the location of the well in relation to the contaminated zone (see Bear, 1979). This calculation is based on an implicit assumption in RESRAD 5.61 that the pumping of the well has no impact on the flow field. In reality, there is a faster, convergent flow as groundwater approaches the pumping well. Potentially, RESRAD 5.61's assumption can produce a pumping zone that is wider than the contaminated zone, while the recharge well theory produces a pumping zone width smaller than the contaminated zone width. As a result, RESRAD

5.61's assumption can produce smaller dilution factors and, thus, an underestimate of groundwater concentrations.

3.1.7.2.4 Distribution Coefficients. Sorption in the unsaturated zone is modeled as a linear, reversible, equilibrium process in the same manner it is in DandD 1.0. In contrast to DandD 1.0, RESRAD 5.61 takes sorption into account in the saturated zone.

The code is designed with default values and allows selection or utilization of four prioritized, alternative models for deriving K_d values. These models, in order of priority, are based on measurements of the groundwater concentration, estimated solubility limits, leach rate, and an empirical model based on the soil-to-plant concentration ratio. Many of the default parameter values appear to be based on the average value for clay and soil as reported in Table E.3 of the RESRAD 5.61 manual (Yu et al., 1993). Some of the K_d values are set to 0, indicating that the radionuclide is not retarded. Others are calculated using the empirical, concentration ratio model.

3.1.8 Surface Water Model

Neither DandD 1.0 nor RESRAD 5.61 model run-off or transport of contaminated sediment to the surface water.

3.1.8.1 DandD 1.0

DandD 1.0's surface water pond model is based on an infinitely fast mass transfer of radionuclides between the aquifer and an aquifer/pond combination. This model restricts the maximum pond concentration to that of the aquifer if the pond volume is small compared to the aquifer volume and prevents the creation of radioactive material if the pond volume is large compared to the aquifer volume.

This model assumes that there are no water sources or losses to the pond that can dilute or concentrate radionuclides from the groundwater. Instead, the pond has a fixed volume with no additional sources or sinks of water or radionuclides. The connection between the aquifer and the pond conserves mass between the two.

3.1.8.2 RESRAD 5.61

The surface water concentration is calculated in a similar manner as the groundwater concentration. The breakthrough and rise times have the same values as those in the groundwater model. The dilution factor is based on the ratio of the contaminated area to the pond watershed area.

The assumptions in this model are that the infiltration through the pond watershed area is the only source of water into the pond, all infiltration reaches the pond, the pond discharge is equal to the infiltration volume, and all radionuclides entering the groundwater reach the pond. The model neglects surface water runoff that would flow into the pond and evaporation from the pond surface. To assume that all radionuclides entering the groundwater will also enter the surface water pond is conservative. It may tend to overestimate contaminant concentration into the pond due to groundwater discharge. It is unclear if this overestimation will be offset by dilution.

3.1.9 Groundwater and Surface Water Model Parameters

Groundwater model parameters are shown in Table 9. Some parameters are common to both DandD 1.0 and RESRAD 5.61. Many are not. In some cases, parameters that are input to DandD 1.0 are calculated in RESRAD 5.61 from other parameters. One example is infiltration rate. Table 9 shows that RESRAD 5.61 requires more parameters than DandD 1.0.

Some parameters that appear similar between DandD 1.0 and RESRAD 5.61 are actually different in some respects. DandD 1.0 has a restriction that the distribution coefficients are the same in both the soil layer and the unsaturated zone. RESRAD 5.61 does not have this restriction. DandD 1.0 does not permit retardation of radionuclides in the saturated zone and RESRAD 5.61 does. RESRAD 5.61 uses a total porosity for retardation coefficient calculations and an effective porosity for velocity calculations. DandD 1.0 does not make this porosity distinction. It uses the same porosity for both the retardation coefficient and the box-to-box transfer coefficient calculations.

3.1.10 Tritium Models

There are a number of significant differences between the tritium models utilized in DandD 1.0 and RESRAD 5.61.

3.1.10.1 Airborne Concentrations

3.1.10.1.1 DandD 1.0. DandD 1.0 assumes that tritium only becomes airborne as a constituent of airborne dust. Setting the dust loading value to zero results in a zero inhalation dose in instances where tritium is the only airborne constituent.

Table 9. Comparison of parameters related to groundwater pathways (Default parameter values are shown in parentheses)

Parameter	DandD 1.0	RESRAD 5.61
Contaminated Zone Thickness	Used to calculate transfer factor from the contaminated zone to the unsaturated zone and the aquifer concentration. It is the depth that a plow can be expected to disturb agricultural soil. This value is restricted to 0.15 m because the volumetric CEDE values are based on this depth.	This is an initial thickness, which is used to calculate the release rate of contaminants from the contaminated zone to the unsaturated zone. The contaminated zone thickness is allowed to erode. See "Contaminated Zone Erosion Rate." (2 m)
Unsaturated Zone Thickness	This is the depth from the bottom of the soil plow layer to the top of the water table. Used to calculate the transfer factor from the unsaturated zone to the aquifer. Larger values reduce the transfer factor. (1.2 m)	Used in the calculation of the breakthrough time though the unsaturated zone. A value is specified for each layer in the unsaturated zone. (4 m)
Number of Unsaturated Zone Layers	Used to divide the unsaturated zone to reduce dispersion. All layers have the same properties. (1)	Data on properties, e.g. porosity, hydraulic conductivity, can be supplied separately for one to five layers. (1)
Contaminated Zone Porosity	Used to calculate the transfer factor between the soil layer and the unsaturated zone and the soil layer retardation coefficient. Not broken down into total and effective porosity. (0.46)	See discussions for the "Contaminated Zone Total Porosity" and "Contaminated Zone Effective Porosity" parameters in this table.
Unsaturated Zone Porosity	Used to calculate the transfer factor between the unsaturated zone and the aquifer and the unsaturated zone retardation coefficient. Not broken down into total and effective porosity (0.46)	See discussions for the "Unsaturated Zone Total Porosity" and "Unsaturated Zone Effective Porosity" parameters in this table.
Contaminated Zone Saturation	Used to calculate the transfer factor between the soil layer and the unsaturated zone and the soil layer retardation coefficient. (0.16)	Not input. Calculated instead. Used to calculate the radionuclide release rate from the soil layer to the unsaturated zone and the soil layer retardation coefficient. Calculated from infiltration rate (which itself is calculated), contaminated zone hydraulic conductivity, and the contaminated zone 'b' parameter. Default value would be about 0.8 based on the other default values.
Unsaturated Zone Saturation	Used to calculate the transfer factor between the soil layer and the unsaturated zone, and the soil layer retardation coefficient. (0.16)	Not input. Calculated instead. Used to calculate the unsaturated zone retardation coefficient, which is used to calculate breakthrough times through the unsaturated zone, and to calculate breakthrough times in the unsaturated zone. Calculated from infiltration rate (which itself is calculated), contaminated zone hydraulic conductivity, and the contaminated zone 'b' parameter. Default value would be about 0.8 based on the other default values

Table 9. Comparison of parameters related to groundwater pathways (continued)

Parameter	DandD 1.0	RESRAD 5.61
Soil Bulk Density for Contaminated Area	Used in the calculation of the transfer factor from the soil layer to the unsaturated zone and in the concentration in the aquifer layer. (1.4 g/cm^3)	Used in the calculation of the contaminated zone retardation coefficient, which is used to calculate the release rate from the contaminated zone to the unsaturated zone, and in the contaminant release rate from the contaminated zone to the unsaturated zone. (1.5 g/cm^3)
Soil Bulk Density for Unsaturated Zone	Used in the calculation of the transfer factor the unsaturated zone to the aquifer. (1.4 g/cm^3)	Used in the calculation of the unsaturated zone retardation coefficient, which is used to calculate the breakthrough time in the unsaturated zone. A value is specified for each layer in the unsaturated zone. (1.5 g/cm^3)
Volume of Water Removed from Aquifer for Domestic Use per Year	Used to calculate volume of aquifer. (118000 L)	Not used. Uses a total pumping rate instead.
Volume of Surface Water Pond	Used in the calculation of the surface water pond concentration. (1300000 L)	Not used. Uses a contaminated zone area and a watershed area to calculate a dilution factor.
Infiltration Rate	Used in the calculation of aquifer volume if annual volumetric infiltration is greater than annual pumped. (0.25 m/y)	Not directly used. Calculated from precipitation, runoff coefficient, evapo-transpiration coefficient, and irrigation rate. Default value would be 0.5 m/y if calculated from other default values.
Land Area	This is cultivated land area, the assumption being that crops are grown on the site's entire contaminated surface area. Used in the calculation of aquifer volume and aquifer concentration. (2400 m^2)	This is contaminated zone area. Used in the calculation of the release rate of radionuclides from the contaminated zone and the dilution factors. (10000 m^2)
Irrigation Rate	Used in the calculation of the aquifer volume and fraction transfer rate from the aquifer to the soil layer. (1.29 L/m^2-d)	Used in the calculation of infiltration rate (0.2 m/y)
Distribution Coefficient	Used in the calculation of the retardation coefficient. Larger values tend to hold radionuclides in the soil layer and the unsaturated zone; smaller values tend to release contaminants to the groundwater. Same value used for soil layer and unsaturated zone. (Different for various radionuclides)	Not used. Uses "Contaminated Zone Distribution Coefficient" and "Unsaturated Zone Distribution Coefficient" instead. See below.

Table 9. Comparison of parameters related to groundwater pathways (continued)

Parameter	DandD 1.0	RESRAD 5.61
Length Parallel to Flow	Not used.	Distance from the up-gradient edge to the down-gradient edge of the contaminated zone in a direction parallel to flow. Used in the calculation of dilution factors for the non-dispersive model. (100 m)
Elapsed Time of Waste Emplacement	Not directly used. This is similar to the start time of the simulation. (0 d)	Time since disposal of radioactive materials. Must be greater than 0 if initial groundwater concentrations will be specified. Used to set time when radionuclide concentrations will be calculated. (0 y)
Cover Depth	Not used.	This is the distance from the top of the contaminated zone to land surface. It is allowed to erode with time. It is used in the decision process of the rise time calculation for the non-dispersive model. (0 m)
Cover Erosion Rate	Not used.	Used to calculate the removal of a cover overlying the contaminated zone. (0.001 m/y)
Contaminated Zone Erosion Rate	Not used.	Used to calculate the removal of the contaminated zone by erosion. Not used until cover is removed. (0.001 m/y)
Contaminated Zone Total Porosity	Not used. See "Contaminated Zone Porosity" above.	Used in the calculation of the contaminated zone retardation coefficient, which is used to calculate contaminant release rate from the contaminated zone to the unsaturated zone. (0.4)
Contaminated Zone Effective Porosity	Not used. See "Unsaturated Zone Porosity" above.	Used in all pathways to calculate water transport breakthrough times (0.2)
Contaminated Zone Hydraulic Conductivity	Not used.	Used in the calculation of the degree of saturation in the contaminated zone, which is used to calculate the contaminant release rate from the contaminated zone to the unsaturated zone. (10 m/y)
Contaminated Zone 'b' Parameter	Not used.	Used in the calculation of the degree of saturation in the contaminated zone, which is used to calculate the contaminant release rate from the contaminated zone to the unsaturated zone. The default value is for a silt loam. (5.3)
Humidity in Air	Not used.	Not used in groundwater model. Used to calculate average equilibrium concentration of hydrogen in air for the special tritium model. (8 g/m3)

Table 9. Comparison of parameters related to groundwater pathways (continued)

Parameter	DandD 1.0	RESRAD 5.61
Evapo-transpiration Coefficient	Not used.	Used in the calculation of the infiltration rate. (0.5)
Precipitation	Not used.	Used in the calculation of the infiltration rate, which is used to calculate the contaminant release rate from the contaminated area to the unsaturated zone and the breakthrough times through the unsaturated zone. Default value is for humid areas. (1 m/y)
Irrigation Mode	Not used. Irrigation is assumed to come from groundwater.	Specifies whether irrigation is overhead or ditch. (Overhead)
Runoff Coefficient	Not used.	Used in calculation of infiltration rate. Default value is for areas characterized by flat, sandy-loam soils. (0.2)
Watershed Area for Nearby Stream or Pond	Not used.	Used to calculated dilution factor for contaminants transferred from contaminated area to surface water. (1000000 m^2)
Density of Saturated Zone	Not used.	Used to calculate retardation coefficient in the saturated zone, which is used to calculate rise times for the non-dispersive model. (1.5 g/cm3)
Saturated Zone Total Porosity	Not used.	Used to calculate retardation coefficient in the saturated zone, which is used to calculate rise times for the non-dispersive model. (0.4)
Saturated Zone Effective Porosity	Not used.	Used in the calculation of saturated zone rise times in the non-dispersive model (0.2)
Saturated Zone Hydraulic Conductivity	Not used.	Used in the calculation of Darcy flow rate in the saturated zone, which is used to calculate saturated zone rise times for the non-dispersive model, and dilution factors for the non-dispersive and mass balance models. Default value is for a silty clay loam or sandy clay loam. (100 m/y)
Saturated Zone Hydraulic Gradient	Not used.	Used in the calculation of Darcy flow rate in the saturated zone, which is used to calculate saturated zone rise times for the non-dispersive model, and dilution factors for the non-dispersive and mass balance models. (0.02)

Table 9. Comparison of parameters related to groundwater pathways (continued)

Parameter	DandD 1.0	RESRAD 5.61
Saturated Zone 'b' Parameter	Not used.	Used if water table drop greater than 0 to calculate properties, e.g. breakthrough time, of new unsaturated zone that is formed. Default value is for a silt loam. (5.3)
Water Table Drop Rate	Not used.	Used to calculate an additional unsaturated zone layer and increase breakthrough times. (0.001 m/y)
Well Pump Intake Depth	Not used.	Used in the calculation of aquifer dilution factors in the non-dispersive model. (10 m below water table)
Non-dispersion or Mass Balance	Not used.	Chooses between the non-dispersive model and the mass balance model for calculating rise times and dilution factors in the saturated zone. (Non-dispersive)
Well Pumping Rate	Not used. Yearly volumes for domestic use and irrigation groundwater are supplied.	Used in the calculation of dilution factors for the mass balance and non-dispersive models. (250 m^3/y)
Unsaturated Zone Total Porosity	Not used. See "Unsaturated Zone Porosity" above.	Used to calculate unsaturated zone degree of saturation, which is used to calculate unsaturated zone breakthrough times. A value is specified for each layer in the unsaturated zone. (0.4)
Unsaturated Zone Effective Porosity	Not used. See "Unsaturated Zone Porosity" above.	Used to calculate unsaturated zone breakthrough times. A value is specified for each layer in the unsaturated zone. (0.2)
Unsaturated Zone Soil Specific 'b' Parameter	Not used.	Used to calculate unsaturated zone degree of saturation, which is used to calculate unsaturated zone breakthrough times. A value is specified for each layer in the unsaturated zone. Default value is for silt loam. (5.3)
Unsaturated Zone Hydraulic Conductivity	Not used.	Used to calculate unsaturated zone degree of saturation, which is used to calculate unsaturated zone breakthrough times. A value is specified for each layer in the unsaturated zone. Default value is for clay. (10 m/y)
Contaminated Zone Distribution Coefficient	See "Distribution Coefficient" above	Used in the calculation of the retardation coefficient in the soil layer. Larger values tend to hold radionuclides in the unsaturated zone, smaller values tend to release contaminants to the unsaturated zone. (Different for various radionuclides)

Table 9. Comparison of parameters related to groundwater pathways (continued)

Parameter	DandD 1.0	RESRAD 5.61
Unsaturated Zone Distribution Coefficient	See "Distribution Coefficient" above	Used in the calculation of the breakthrough times in the unsaturated zone. Larger values tend to increase breakthrough times, thus increasing decay and ingrowth. (Different for various radionuclides)
Saturated Zone Distribution Coefficient	Not used.	Used in the calculation of the rise time for the non-dispersive model. Larger values tend to increase rise times, thus increasing decay and ingrowth. (Different for various radionuclides)
Leach Rates	Not used.	Used to calculated distribution coefficient if distribution coefficient is not supplied and certain other parameters are. (Radionuclide dependent)
Solubility	Not used.	Used to calculated distribution coefficient if distribution coefficient is not supplied and certain other parameters are. (Radionuclide dependent)

3.1.10.1.2 RESRAD 5.61. RESRAD 5.61 assumes that tritium becomes airborne as tritiated water vapor and as particulate.

RESRAD 5.61 assumes that tritium escapes from the soil, enters the atmosphere, and mixes with the ambient air to a height of the "mixing height" (2 m for people, 1 m for vegetation and animals). The average tritium concentration in air above a contaminated site is assumed to decrease as the wind speed increases. RESRAD 5.61 calculates airborne tritiated water vapor concentrations as proportional to:

$$\frac{\text{Tritium flux} \times (\text{Area})^{0.5} \times \text{Source evasion factor}}{\text{Mixing height} \times \text{Average wind speed}}$$

The mixing height concept is useful for setting a reasonable bound for the outdoor airborne concentrations that may result from small areas contaminated with tritiated water. However, this approach will result in very conservative airborne tritiated water vapor estimates for large areas of soil contaminated with tritium, particularly under unstable atmospheric conditions (that cause substantial vertical mixing).

RESRAD 5.61 assumes that tritium leaves the soil at a rate defined by product of the tritium flux and a source evasion factor. In effect, the source evasion factor is assumed to restrict the tritium inventory available for loss to the atmosphere to that initially present in the upper 30 cm of contaminated soil (the reference evasion depth). With a 30 cm thick cover, RESRAD 5.61 predicts a zero tritium flux.

The evasion source factor causes RESRAD 5.61 to calculate what appear to be non-conservative soil guidelines for scenarios involving burial of soil or debris contaminated with tritiated water. For instance, in a scenario where the only exposure pathway would be inhalation, a 0.3 m cover results in a tritium soil guideline that exceeds the specific activity of HTO.

Particularly under arid climatic conditions, the assumption of a 0.3 m reference evasion depth would appear to be unconservatively low. Arid conditions result in high evaporation rates, and surface soils with a low moisture content. Dry surface soils cause loss of moisture from underlying soils through capillary action. This capillary action will cause transfer of moisture to surface soils and to the atmosphere from depths deeper than 0.3 m.

3.1.10.2 Time Dependence of Soil Tritium Concentrations

DandD 1.0 and RESRAD 5.61 will give rather different results for surface soils contaminated with tritium because:

- the tritium content of surface soils decreases quickly with time due to loss of tritiated water from soils to the atmosphere; RESRAD 5.61's tritium flux model takes this into account, while DandD 1.0 does not;

- RESRAD 5.61 assumes that tritium is transferred from the contaminated zone to the saturated zone more quickly than DandD 1.0;

- the groundwater model in DandD 1.0 recycles irrigation water to the groundwater, while the RESRAD 5.61 model does not;

- RESRAD 5.61 calculates instantaneous dose rates, while DandD 1.0 calculates an integrated dose and reports it as an average rate.

3.1.10.3 Tritium Model Default Values

Default values for DandD 1.0 and RESRAD 5.61 are provided in Table 10.

3.1.10.4 Conclusions about Tritium Models

In conclusion, DandD 1.0 and RESRAD 5.61 model tritium differently.

DandD 1.0 ignores inhalation of tritiated water vapor, while RESRAD 5.61 ignores inhalation of tritium associated with airborne dust. Of these two inhalation exposure routes, inhalation of tritiated water vapor should be the more significant means of exposure. DandD 1.0 would appear to underestimate the inhalation dose due to tritium in many situations since it ignores inhalation of water vapor. This difference in the models has little practical impact in the residential farmer scenario, since the doses from the inhalation pathway are smaller than the doses from water related and agricultural pathways; see Table 11 and Tables A.5, A.10, and A.18 in Appendix A.

RESRAD 5.61's use of a 0.3 m reference evasion depth may result in non-conservative residual material burial guidelines for tritiated debris and soil, particularly in arid areas. This could become a concern in scenarios where a 0.3 m (or greater) cover thickness is included over tritium contaminated soil or debris and groundwater exposure pathways are not included in an exposure scenario. However, this does not cause difficulty in the application of the model to the NUREG/CR-5512 residential farmer scenario. This scenario is only concerned with a 15 cm thick surface layer of contamination with no clean soil cover. RESRAD 5.61 should give reasonable estimates of airborne tritiated water vapor concentrations for small areas having exposed tritium contaminated soils. The limited mixing height will cause airborne concentrations estimated by RESRAD 5.61 to become rather conservative for large contamination areas.

RESRAD 5.61's convention of reporting instantaneous dose rates may complicate the interpretation of simulation results for tritium, since the dose rates it calculates change very rapidly with time. In this report, we took the instantaneous dose rate computed by RESRAD 5.61 at the mid-point of the time intervals (e.g., at six months and at 4.5 years) of interest as representative of annual doses for the first and fifth years to provide a comparison over time.

RESRAD 5.61 simulations suggest that tritium moves out of the contaminated zone far more quickly than DandD 1.0 simulations, even when effort is made to provide comparable input parameters for both models. This result is illustrated by Figure 1. The large difference is related to the tritium flux model that RESRAD 5.61 has but DandD 1.0 lacks, and to the differences in the groundwater models.

With the changes to defaults identified in Tables A.3, A.9, and A.16 for the three residential farmer sub-cases, DandD 1.0 gave consistent maximum dose rates that ranged from 306 mrem/y to 317 mrem/y. In each case, DandD 1.0 identified the agricultural pathway as responsible for about 98% of the dose for the year of maximum dose rate, as shown in Table 11.

RESRAD 5.61 simulations exhibited more variability from case to case. With changes to defaults identified in Appendix sections A.2.1 through A.2.3, RESRAD 5.61 simulation results for the wet climate case showed highest maximal dose rate of 131 mrem/y while simulations for the dry climate case yielded a maximal dose rate of 9.3 mrem/y. Drinking water was the dominant exposure pathway in both of these simulations. The RESRAD 5.61 simulation having minimal changes to defaults gave a maximal dose rate of 4.8 mrem/y at time = 0 with agricultural pathways being dominant.

Tritium behaves in a more complex manner than radioactive isotopes of most other elements due to multiphase transport and barometric and hydraulic driving forces. Both models oversimplify the behavior of tritium in the environment and must be used with caution. As a case in point, neither model considers the potential inhalation exposure from tritium that diffuses through a foundation into a structure. In most respects, RESRAD 5.61 presents a more realistic approach to modeling dose from tritium to an actual residential farmer than DandD 1.0.

Table 10. Special model parameters for tritium

Parameter	DandD 1.0 Default	RESRAD 5.61 Default	Remarks
Mass Fraction of Hydrogen in Leafy Vegetables	0.10	0.10	In RESRAD 5.61 these are constants.
Mass Fraction of Hydrogen in Root	0.10	0.10	
Mass Fraction of Hydrogen in Fruit	0.10	0.10	
Mass Fraction of Hydrogen in Grain	0.07	0.10	
Mass Fraction of Hydrogen in Beef	0.10	0.066	RESRAD 5.61 value is calculated based on default value in Table L.1 and equation L.21 in Yu et al. (1993).
Mass Fraction of Hydrogen in Poultry	0.10	0.066	RESRAD 5.61 value is calculated based on default value in Table L.1 and equation L.21 in Yu et al. (1993).
Mass Fraction of Hydrogen in Milk	0.11	0.097	RESRAD 5.61 value is calculated based on default value in Table L.1 and equation L.21 in Yu et al. (1993).
Mass Fraction of Hydrogen in Eggs	0.11	NA	Ingestion of eggs is not considered in RESRAD 5.61
Mass Fraction of Hydrogen in Beef Forage	0.10	0.10	In RESRAD 5.61 these are constants.
Mass Fraction of Hydrogen in Poultry Forage	0.10	0.10	
Mass Fraction of Hydrogen in Milk Cow Forage	0.10	0.10	
Mass Fraction of Hydrogen in Layer Hens Forage	0.10	0.10	
Mass Fraction of Hydrogen in Beef Grain	0.07	0.10	
Mass Fraction of Hydrogen in Poultry Grain	0.07	0.10	
Mass Fraction of Hydrogen in Milk Cow Grain	0.07	0.10	
Mass Fraction of Hydrogen in Layer Hens Grain	0.07	NA	Ingestion of eggs is not considered in RESRAD 5.61
Mass Fraction of Hydrogen in Beef Hay	0.10	0.10	In RESRAD 5.61 these are constants.
Mass Fraction of Hydrogen in Poultry Hay	0.10	0.10	
Mass Fraction of Hydrogen in Milk Cow Hay	0.10	0.10	
Mass Fraction of Hydrogen in Layer Hens Hay	0.10	NA	Ingestion of eggs is not considered in RESRAD 5.61
Mass Fraction of Hydrogen in Soil	5.80E-03	NA	
Tritium/hydrogen ratio in animal products relative to ratio in soil product	1.00	1.00	In RESRAD 5.61 these are constants.
Tritium/hydrogen ratio in plants relative to ratio in soil	1.00	1.00	
Tritium/hydrogen ratio in plants relative to ratio in water	1.00	1.00	
Soil Moisture	0.0522	NA	
Average annual wind speed (m/sec)	NA	2.00	

Table 11. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving tritium

Pathway	Maximum EDE Rate, mrem/y, Minimal Changes to Defaults		Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 1	RESRAD 5.61 Year 0	DandD 1.0 Year 1	RESRAD 5.61 Year 6.9	DandD 1.0 Year 1	RESRAD 5.61 Year 1.46
Inhalation	3.9E-6	0.37	3.9E-6	0.77	3.9E-6	7.9E-7
Plant	NA	3.46	NA	0	NA	1.2E-5
Meat	NA	0.49	NA	0	NA	1.7E-6
Milk	NA	0.44	NA	0	NA	1.6E-6
Soil Ingestion	8.8E-4	1.75E-3	8.8E-4	0	8.8E-4	0
Water	6.04	0	0.10	5.85	3.19	120
Fish / Aquatic	0.13	0	3.9E-3	0.62	0.096	0.74
Irrig water →→ Plant	NA	0	NA	2.93	NA	0
Irrig water →→ Meat	NA	0	NA	0.26	NA	2.13
Irrig water →→ Milk	NA	0	NA	0.49	NA	7.49
Irrigation pathways	5.36	NA	0.091	NA	2.82	NA
Agriculture	305	NA	305	NA	305	NA
Total	317	4.76	306	9.26	311	131

3.1.11 Carbon–14 Model

Both DandD 1.0 and RESRAD 5.61 have special models for carbon-14. Aspects of those models are described in this section.

3.1.11.1 Airborne Concentrations

The airborne concentration models for carbon-14 in DandD 1.0 and RESRAD 5.61 are similar to the tritium models.

3.1.11.1.1 DandD 1.0. DandD 1.0 assumes that carbon-14 only becomes airborne as a constituent of airborne dust. Setting the dust loading values to zero results in zero inhalation dose in instances where carbon-14 is the only airborne constituent.

3.1.11.1.2 RESRAD 5.61. In effect, RESRAD 5.61 assumes that all carbon-14 released to the atmosphere can be in the form of carbon-14 dioxide and also as carbon-14 contaminated particulate. RESRAD 5.61 models flux and airborne concentrations of carbon-14 dioxide using the same basic model it uses for tritium. However, the carbon-14 reference evasion depth is a parameter that can be adjusted by the user in RESRAD 5.61.

3.1.11.2 Time Dependence of Soil Carbon-14 Concentrations

DandD 1.0 and RESRAD 5.61 will give rather different results for soils contaminated with carbon-14 because:

- the carbon-14 content of surface soils decreases due to loss to the atmosphere. RESRAD 5.61 takes this into account while DandD 1.0 does not;
- the groundwater model in DandD 1.0 recycles irrigation water to groundwater, while RESRAD 5.61 does not;
- RESRAD 5.61 calculates an instantaneous dose rate, while DandD 1.0 calculates the average dose received over a year.

The simulation results presented in Appendix A demonstrate that there is a considerable difference in time dependence of carbon-14 doses between DandD 1.0 and RESRAD 5.61 for residential farmer scenarios. These results differences are depicted in Figure 2. DandD 1.0 estimates higher dose rates at years one and five under each of the residential farmer scenarios considered (see Tables A.6, A.11, and A.19). However, RESRAD 5.61 calculates very high maximum instantaneous dose rates under the dry site scenario (62,990 mrem; see Table A.11). In every case, carbon-14

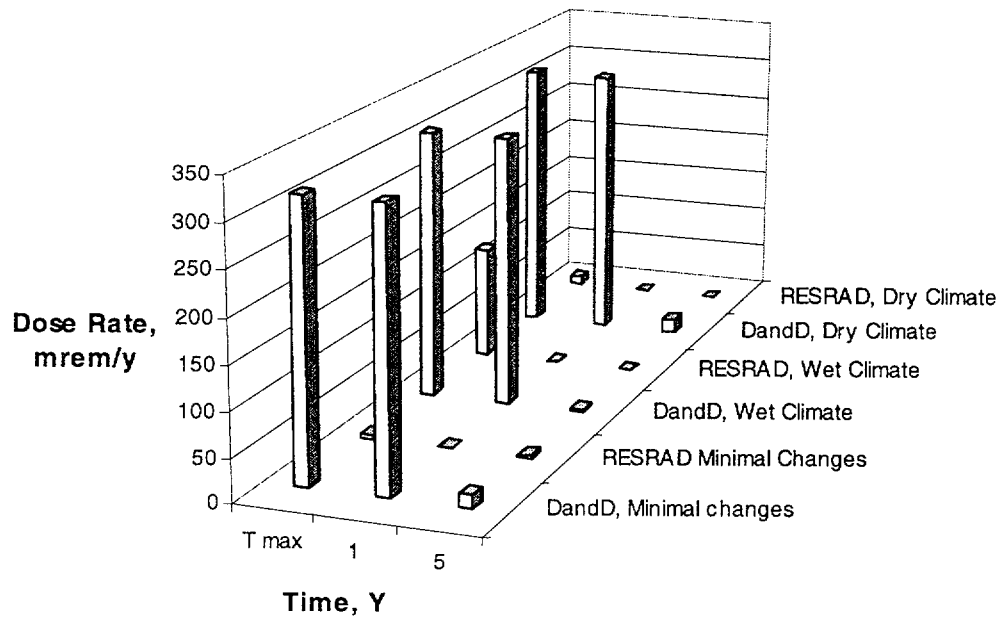

Figure 1. Comparison of tritium results for DandD and RESRAD

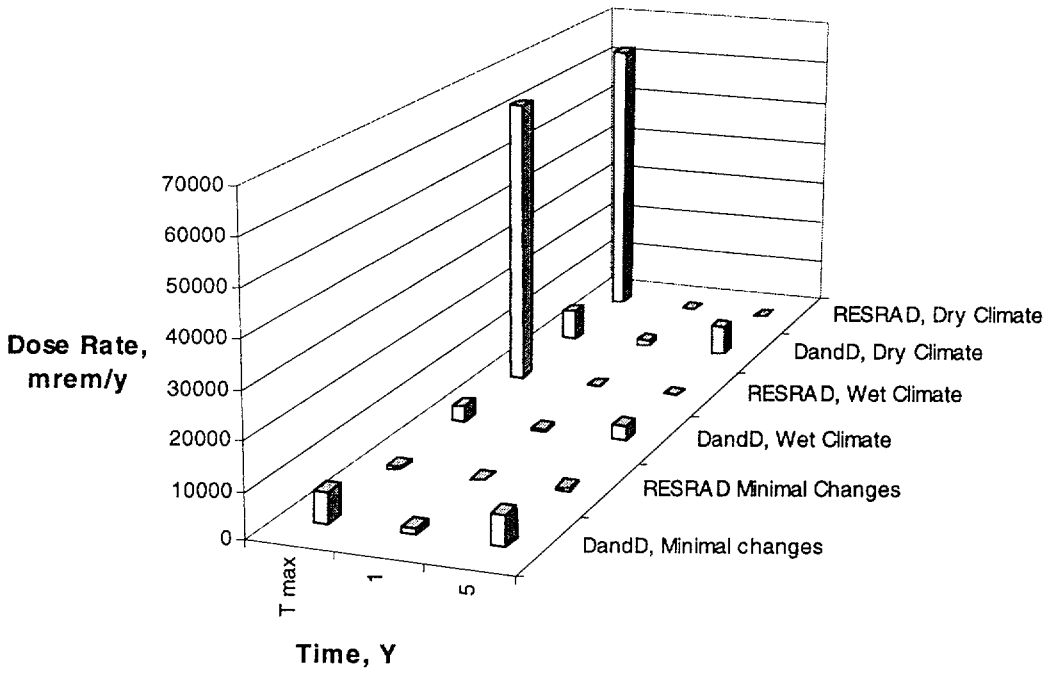

Figure 2. Comparison of Carbon-14 results for DandD and RESRAD

reached the well sooner in DandD 1.0 simulations than in RESRAD 5.61 simulations. With both models, the aquatic pathway was dominant once carbon-14 reached the well.

The maximum dose rates occurring with simulations having minimal changes to defaults occurred at five years (DandD 1.0, 6,460 mrem/y) and at 0 years (RESRAD 5.61 659 mrem/y). The maximum dose rates occurring with simulations representative of a dry climate occurred at 63 years (DandD 1.0, 390 mrem/y) and at 143 years (RESRAD 5.61 62,990 mrem/y).

3.1.11.3 Default Values for the Carbon-14 Models.

Default values for the carbon-14 models in DandD 1.0 and RESRAD 5.61 are provided in Table 12.

3.1.11.4 Carbon-14 Uptake by Plants.

RESRAD 5.61 assumes that carbon assimilated by plants comes primarily from the atmosphere (default 98%) and only a small amount of carbon-14 uptake occurs through the root system (default 2%). The soil-to-plant transfer factor used in RESRAD 5.61 contains terms that take both of these processes into account. The term for uptake from the atmosphere is dominant when default factors are used. In this case, the transfer factor is proportional to the square root of the area of carbon-14 contamination (Yu, et al., 1993).

The RESRAD 5.61 results provided in Table A.19 were obtained with both the reference depth and assimilation fractions set to the default values.

DandD 1.0 makes the simplifying assumption that the soil-to-plant transfer factors are simply a ratio of concentration of carbon-14 in the plant to the concentration in the soil. The DandD 1.0 model assumes that the transfer coefficient is independent of the surface area of the contaminated zone. The RESRAD 5.61 model for carbon-14 soil-to-plant transfer factors is based on the assumption that the soil-to-plant concentration ratio is a function of the surface area of contaminated zone. The approach taken in RESRAD 5.61 that most carbon-14 is assimilated by plants from the atmosphere is more realistic.

3.1.11.5 Conclusions about the Carbon-14 Models

For the purposes of determining compliance with 10 CFR 20 subpart E, the RESRAD 5.61 convention of reporting instantaneous dose rates complicates interpretation of simulation results as annual dose for scenarios involving carbon-14. The dose rate RESRAD 5.61 calculates for carbon-14 changes rapidly with time. Nonetheless, the maximum instantaneous dose rate reported by RESRAD 5.61 should be a conservative estimate of the annual dose.

DandD 1.0 ignores inhalation of gaseous carbon-14 compounds while RESRAD 5.61 considers inhalation of carbon-14 associated with airborne dust and gaseous compounds. Of these two inhalation exposure routes, inhalation of gaseous carbon-14 compounds should be the more significant means of exposure. This difference in the models has little practical impact in the residential farmer scenario of NUREG/CR-5512. In this scenario, the doses due to carbon-14 from water-related and agricultural pathways are much larger than the inhalation doses; see Table 13 and Appendix Tables A.6, A.11, and A.19.

RESRAD 5.61 has a carbon-14 flux model, while DandD 1.0 does not. In RESRAD 5.61 the carbon-14 reference evasion depth can be adjusted by the user. This feature allows RESRAD 5.61 to simulate the natural processes of volatilization and oxidation of carbon-14 compounds in surface soils. Neither model considers the potential inhalation dose that may result from diffusion of carbon-14 compounds through a foundation into an occupied structure, however.

RESRAD 5.61 has a more realistic formulation of soil-to-plant transfer factor than DandD 1.0, since it takes into account that atmospheric carbon dioxide is the principal source of carbon assimilated by plants.

Like tritium, carbon-14 behaves in a more complex manner than radioactive isotopes of most other elements. Because of this complexity, both the special carbon-14 models in RESRAD 5.61 and DandD 1.0 should be used with caution. In most respects, RESRAD 5.61 presents a more realistic approach to modeling dose from carbon-14 to an actual residential farmer than DandD 1.0.

3.1.12 External Exposure from Volume Soil Sources while Outdoors

DandD 1.0 assumes an infinite slab of contamination 6 inches thick. A six-inch-thick infinite area slab of soil contaminated with cesium-137 would have an Effective Dose Equivalent (EDE) rate that is about 89% of the EDE rate of a slab that is infinite in area and thickness (EPA, 1993). Consequently the external dose pathway will give reasonable dose estimates for thicker layers or contaminated soil. For contaminated areas smaller than about 500 m^2 or thinner than 15 cm, DandD 1.0 will

Table 12. Special model parameters for carbon

Parameter	DandD 1.0 Default	RESRAD 5.61 Default	Remarks
C-12 concentration in water (g/cm**3)	NA	2.00E-05	
C-12 concentration in contaminated soil (g/g)	0.03	0.03	
Fraction of vegetation carbon from soil	1.00	2.00E-02	
Fraction of vegetation carbon from air	0.00	9.80E-01	
C-14 evasion layer thickness in soil (m)	NA	3.00E-01	
C-14 evasion flux rate from soil (1/sec)	NA	7.00E-07	
C-12 evasion flux rate from soil (1/sec)	NA	1.00E-10	
Mass Fraction of Carbon in Beef	0.36	0.24	In RESRAD 5.61, these values are constants.
Mass Fraction of Carbon in Poultry	0.18	0.24	
Mass Fraction of Carbon in Milk	0.06	0.07	
Mass Fraction of Carbon in Eggs	0.16	NA	
Mass Fraction of Carbon in Beef Forage	0.11	0.09	
Mass Fraction of Carbon in Poultry Forage	0.11	0.09	
Mass Fraction of Carbon in Milk Cow Forage	0.11	0.09	
Mass Fraction of Carbon in Layer Hen Forage	0.11	0.09	
Mass Fraction of Carbon in Beef Grain	0.40	0.40	
Mass Fraction of Carbon in Poultry Grain	0.40	0.40	
Mass Fraction of Carbon in Milk Cow Grain	0.40	0.40	
Mass Fraction of Carbon in Layer Hen Grain	0.40	0.40	
Mass Fraction of Carbon in Beef Hay	0.07	0.40	
Mass Fraction of Carbon in Poultry Hay	0.07	0.40	
Mass Fraction of Carbon in Milk Cow Hay	0.07	0.40	
Mass Fraction of Carbon in Layer Hen Hay	0.07	0.40	
C-14/C-12 activity in animal products relative to ratio in soil	1	NA	
Average annual wind speed (m/sec)	NA	2.00	

Table 13. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving carbon-14

Pathway	Maximum EDE Rate, mrem/y, Minimal Changes to Defaults		Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 5	RESRAD 5.61 Year 0	DandD 1.0 Year 63	RESRAD 5.61 Year 143	DandD 1.0 Year 8	RESRAD 5.61 Year 27.5
External	5.3E-4	8.0E-3	7.1E-4	0	4.3E-4	0
Inhalation	1.0E-5	0.398	1.4E-5	0	8.5E-6	0
Plant	NA	495	NA	0	NA	0
Meat	NA	115	NA	0	NA	0
Milk	NA	49.1	NA	0	NA	0

Table 13. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving carbon-14 (continued)

Pathway	Maximum EDE Rate, mrem/y, Minimal Changes to Defaults		Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 5	RESRAD 5.61 Year 0	DandD 1.0 Year 63	RESRAD 5.61 Year 143	DandD 1.0 Year 8	RESRAD 5.61 Year 27.5
Soil Ingestion	2.4E-3	0.057	3.2E-3	0	2.0E-3	0
Water	57.5	0	1.84	12.7	24.9	230
Fish / Aquatic	5,580	0	324	62,900	3,440	62,800
Irrig water →→ Plant	NA	0	NA	24.2	NA	0
Irrig water →→ Meat	NA	0	NA	3.51	NA	7.42
Irrig water →→ Milk	NA	0	NA	4.47	NA	27.8
Irrigation pathways	813	NA	53.4	NA	22.9	NA
Agriculture	9.58	NA	12.9	NA	7.88	NA
Total	6,460	659	392	63,000	3,500	63,100

The external exposure model in RESRAD was updated with version 5.50. The external exposure model in an earlier version of RESRAD 5.61 (RESRAD 5.05) is well documented.[1] RESRAD 5.05 contains tables of EDE rates per unit activity for two different soil densities. RESRAD 5.05 estimates dose rates by performing a series of interpolations and by application of the correction factors described in Table 14.

A comparison of external dose rates among DandD 1.0, RESRAD 5.61, and Microshield® 5.03 is presented in Appendix A (Table A.25). For an infinite slab of soil 6 inches (15 cm) thick, all three codes give good agreement when consistent occupancy and shielding factors are used.

3.1.13 External Exposure from Volume Soil Sources while Indoors

Both RESRAD 5.61 and DandD 1.0 model this pathway by applying correction factors to the outdoor external dose rate. Calculation of the external dose rate is described in section 3.1.1 and Table 14. The correction factors applied to the external dose rate include a shielding factor and an occupancy factor. Both models provide default attenuation factors that are assumed to be independent of gamma energy. The correction for exposure occurring indoors is of the same form for both RESRAD 5.61 and DandD 1.0:

Indoor exposure to volume soil sources
$\propto$ Shielding Factor × External Exposure (Eq. 1)

Where the Shielding Factor in Eq. 1 is:

1 - Attenuation Fraction.

In fact, the shielding factor will differ with the method of construction (slab on grade as compared to mobile home or pier and beam), with the materials of construction (wood siding as compared to brick or stone), and with the gamma radiation energy.

Alternative shielding factors may be measured directly or estimated. Estimates of shielding factors can be derived from use of shielding models such as Microshield® 5.03 (Grove Engineering, 1998). Caution should be exercised in deriviation of alternative shielding factors using shielding models. Individual simulations may have a 15% margin of error or more. Deriving structural shielding estimates by modeling involves mathematical manipulation of several simulation results; this may result in shielding factor estimates that contain considerable accumulated error.[2]

3.1.14 Inhalation Exposure to Resuspended Soil while Outdoors

This pathway is described in Table 15.

[1] a description of the new model is on the RESRAD web page http://www.ead.anl.gov/~resrad/

[2] The same is true of other similar shielding codes.

Table 14. External exposure from volume soil sources

Factor	DandD 1.0	RESRAD 5.05
Basic DCF for volume contamination of soil	Infinite layer, 15 cm thick. Effective Dose Equivalent dose conversion factors are taken from FRG-12.	Infinite in depth and areal extent.
Bremstrahlung for beta emitters	Included	Neglected.
Correction for soil density	none	Interpolation or extrapolation based on values tabulated for density = 1.0 g/cm^3 and 1.8 g/cm^3 (Table A.1).
Correction for areal extent	none	Interpolation based on a table of area correction factors that are not dependent on radionuclide or energy. (Table A.2)
Correction for depth of contamination	none	A correction for depth is applied that depends on nuclide. The value of the correction is based on interpolations between values tabulated for two soil densities as well as contamination depths (Table A.3, Equation A.2).
Time dependence for thickness of contaminated zone	none	Erosion of contaminated zone is assumed to occur in a linear fashion once the cover has been eroded away. 1 mm/y default erosion rate. Equation A.4.
Cover attenuation correction outdoors	Default value of 1. Alternate values may be calculated by the user and input into program.	Correction for cover attenuation is interpolated from Table A.3, Equation A.5.
Time dependence for thickness of contaminated zone.	none	Cover is assumed to erode at a linear rate. Default of 1 mm/y is provided.
Correction for attenuation provided by a structure.	A default value of 0.55 is provided. Alternate values must be calculated by user and input into program.	A default value of 0.7 is provided. Alternate values must be calculated by user and input into program.
Correction for fractions of time spent outdoors, indoors and in uncontaminated areas.	Default values of 240 d/y (66%) inside, 40.2 d/y (11%) outside, 2.92 d/y (0.8%) outside engaged in gardening activities, 82.13 d/y (23%) in uncontaminated areas provided.	Default values of 50% inside, 25% outside and 25% in uncontaminated areas are provided.

Table 15. Factors related to EDE resulting from inhalation exposure to resuspended soil while outdoors

Factor	DandD 1.0	RESRAD 5.61
Outdoor airborne dust concentration (non-gardening outdoor activities)	DandD 1.0 currently uses a default airborne dust mass loading value of 3.14 $\mu g/m^3$.	RESRAD 5.61 uses a default outdoor airborne concentration of 200 $\mu g/m^3$.
Outdoor airborne dust concentration (gardening only)	DandD 1.0 currently uses a default airborne dust mass loading value of 400 $\mu g/m^3$.	Not separately considered.
Correction to airborne dust concentration due to finite size of contaminated area.	None	RESRAD 5.61 uses an area factor that represents the fraction of airborne mass loading of dust that is contaminated. The area factor takes the Form: $FA_2 = (Area)^{0.5}/((Area)^{0.5} + DL)$, Where Area is the area that is contaminated and DL is the dilution length. A default dilution length of 3 m is provided.
Allowance for dilution of contaminated soil with a mixing layer	None	Assumes that mixing occurs over the upper 15 cm of soil. When the cover is less than 15 cm thick, mixing of the cover with the contaminated layer is assumed. When no cover is present and the contaminated layer is less than 6 inches thick, mixing with sub-soils is assumed (Yu, 1993, Eq. B.5).
Correction for occupancy	Yes; defaults are 2.92 d/y gardening; 40.2 d/y other outdoor activities.	Yes; a default occupancy factor of 0.25 is provided.
Respiration rate	1.4 m^3/h for non-gardening outdoor activities; 1.7 m^3/h for gardening outdoor activities	Default value of 8400 m^3/y (0.96 m^3/h).

DandD 1.0 assumes that a certain airborne dust concentration is present due to resuspension of contaminated dust, and that the airborne dust concentration is independent of the size of the contaminated area. The default air mass loadings given in Table 4 are reasonable given that gardening is modeled as a distinct outdoor activity.

RESRAD 5.61 assumes that the contaminated fraction of airborne dust is related to the size of the contaminated area; the contaminated fraction is modeled by an empirical formula (Eq. 2).[3]

$$\frac{\text{Area of Contamination}^{1/2}}{\text{Area of Contamination}^{1/2} + \text{Dilution Length}} \quad \text{(Eq. 2)}$$

Using the default dilution length value of 3 meters in Eq. 2 leads to rather high contamination fraction results for small contaminated areas. This becomes apparent when one considers that the terminal settling velocity of 10 μm particles of density 2.3 g/cm^3 is on the order of 0.6 cm/s (Burton, 1984), and the average wind speed at the ground surface is about 2 m/s. This high contamination fraction estimate is of little consequence in the residential farmer scenario unless one is concerned about potential dose from hot spots of residual radioactivity following a remedial action.

The default outdoor mass loading assumed by RESRAD-5.61, 200 $\mu g/m^3$, seems high for a time weighted average

[3] An improved area factor model for airborne concentrations has been incorporated into RESRAD versions 5.75 and later (Chang et al., 1998). The new area factor is based on a Gaussian plume model.

concentration in the breathing zone, particularly for insoluble isotopes whose dose is primarily the result of deposition in the pulmonary region of the lung.[4]

3.1.15 Inhalation Exposure to Resuspended Soil while Indoors, and to Resuspended Surface Sources of Soil Tracked Indoors

Both DandD 1.0 and RESRAD 5.61 model the inhalation exposure to dust occurring indoors. The differences in approach are described in Table 16. To summarize, RESRAD 5.61 models indoor inhalation exposures taking into consideration only the outdoor air mass loading and a scale factor. DandD 1.0 includes two indoor dust inhalation pathways: resuspension of dust tracked indoors, and infiltration of airborne dust from outdoors. DandD 1.0 requires three inputs:

- the floor dust loading factor,
- a resuspension factor, and
- the indoor airborne dust loading from processes other than resuspension of dust tracked into the structure.

The approaches taken by either model should be suitable for dose screening purposes.

3.1.16 Plant – Human Pathways

Assumptions common to all Plant – Human pathways are provided in Table 17. DandD 1.0 assumes that plant foods are held briefly upon harvest, and then consumed over a period of time. RESRAD 5.61 does not take into account that plant foods may be consumed over a period of time. DandD 1.0 also calculates an average dose received over a year while RESRAD 5.61 calculates an instantaneous dose rate.

Default values for Plant—Human pathways are provided in Table 4.

3.1.16.1 Irrigation Water— Plant— Human Pathways

The irrigation water – plant – human pathways include the following:

- Irrigation water – plant – human (retention of irrigation water on leaf surfaces),
- Irrigation water – soil – plant –human.

These pathways are discussed in section 5.4.1 of NUREG/CR 5512 Volume 1 and in Appendix D of the RESRAD manual (Yu et al., 1993). DandD 1.0 and RESRAD 5.61 use the same fundamental approach to modeling the doses due to the irrigation – plant – human pathways. Assumptions common to all irrigation water – plant – human pathways are summarized in Table 18. However, there are important differences in the groundwater models that cause differences in the doses from these pathways. The time dependence and magnitude of dose rates from groundwater related pathways tended to be very different in this study. This affected the doses resulting from the irrigation pathways, the drinking pathway, and the aquatic pathway. In general, DandD 1.0 simulations showed contaminants at the well sooner than RESRAD 5.61 simulations, but maximal dose rates were not always higher with one model or the other.

The irrigation water – soil – plant – human pathway in both DandD 1.0 and RESRAD 5.61 assumes that soil-to-plant transfer factors depend on radioisotope but are independent of soil type and largely independent of the plant species. Soil-to-plant transfer factors may be modified by users in both DandD 1.0 and RESRAD 5.61.

3.1.16.2 Soil—Plant—Human Pathways

The soil – plant – human pathways include the following

- Soil – root uptake by plant – human,
- Soil – resuspension and deposition on plant surfaces – human.

These pathways are discussed in section 5.3.1 of NUREG/CR 5512 Volume 1 and in Appendix D of Yu et al. (1993). DandD 1.0 and RESRAD 5.61 use fundamentally the same approach to modeling the doses due to these pathways.

The basic assumptions in the soil-to-plant (root uptake) pathways are:

- those inherent in the use of soil-to-plant transfer factors (both DandD 1.0 and RESRAD 5.61), and
- the plant concentration for each decay chain member radionuclide is in equilibrium with the soil concentrations at all times.

[4] The default value for outdoor mass loading has been decreased to 100 $\mu g/m^3$ in RESRAD version 5.781 and later.

Table 16. Inhalation exposure to resuspended soil while indoors

Factor	DandD 1.0	RESRAD 5.61
Indoor Airborne Dust Concentration	DandD 1.0 is supplied with a default airborne indoor dust mass loading value of 1.41 $\mu g/m^3$. This value is modeled as independent of the outdoor mass loading value. The concentration does not include the contribution from dust tracked indoors.	RESRAD 5.61 applies a scale factor to outdoor airborne dust loading to obtain the indoor dust loading. The default indoor airborne dust loading is 80 $\mu g/m^3$. This value follows from the default outdoor airborne concentrations of 200 $\mu g/m^3$ and a scale factor of 0.4.
Indoor Airborne Dust Concentration Resulting from Resuspension of Dust Tracked Indoors	DandD 1.0 multiplies a resuspension factor by a floor dust loading to obtain a resuspension concentration. The default values of 2.82E-6 m^{-1} (resuspension) and 0.1599 g/m^2 (floor dust loading) provide an default value of 0.45 $\mu g/m^3$ for Indoor Airborne Dust Concentration Resulting from Resuspension	Not distinguished from the Indoor Airborne Dust Concentration described above.
Total Indoor Airborne Dust Concentration	Sum of the Indoor Airborne Dust Concentration and the Indoor Dust Concentration resulting from resuspension.	RESRAD 5.61 takes the Total Indoor Airborne Dust Concentration to be the product of the Outdoor Airborne Dust Loading and a scale factor. Resuspension of dust tracked indoors is not *explicitly* included.
Correction for occupancy	Yes; default is 240 days per year	Yes, default is 0.5 (equivalent to 182.6 d/yr for 365.25 d simulation).

Table 17. Assumptions related to all plant – human pathways

Factor	DandD 1.0	RESRAD 5.61
Harvested plants are held for a short period of time prior to consumption by humans.	Yes. Radioactive decay during the hold-up period between harvest and commencement of consumption is taken into account. The default values are dependent on the food item. Defaults are provided in Table 2.	Same as DandD.
Radioactive decay over the food consumption period is taken into account	Yes. Food products are assumed to be consumed over a period of one year. This is taken into account by NUREG/CR-5512, Eq. 5.9.	Not accounted for.

Table 17. Assumptions related to all plant – human pathways (continued)

Factor	DandD 1.0	RESRAD 5.61
Corrections for areal extent of contamination and contamination fraction for the plant – human pathway.	There is no specific correction for areal extent of contamination for this pathway. The users can manually enter a single value for contamination fraction, which is applied, to all food types. The default fraction is 1.0.	RESRAD 5.61 uses corrections to account for areal extent of contamination as the default option. The default action has the effect of calculating the contamination fraction of "plant food" ingested (Yu, 1993, Eq D.5). The user may enter a single contamination fraction for "plant food." See Table 4 for the means RESRAD 5.61 uses to calculate a contamination fraction.
Adjustments to the dietary intake of plant foods	The user may specify annual ingestion rates for four different plant groups: leafy vegetables, fruits, roots and grains.	The user may specify separate annual ingestion rates for two different plant groups: (1) leafy vegetables, and (2) fruits, vegetables and grains.
Is equilibrium assumed to continually occur between the radionuclide concentrations in soil and radionuclide concentrations in edible portions of the plant.	Yes.	Yes.
Translocation of material deposited on plant surfaces to edible portions of plant.	Adjustable by user.	Not adjustable in RESRAD 5.61 but can be adjusted in version 5.82.

Table 18. Assumptions related to all irrigation water – plant – human pathways

Factor	DandD 1.0	RESRAD 5.61
Time dependence of the concentration of radionuclides in irrigation water.	Assumed constant over growing season at the average value.	RESRAD 5.61 computes the concentration at an instant in time.
Is there a distinction between overhead irrigation and ditch irrigation?	Yes. The default settings in DandD 1.0 are appropriate for overhead irrigation. To model ditch irrigation, the Translocation Factors should be set to zero.	Yes. Overhead irrigation is the default.

Table 18. Assumptions related to all irrigation water – plant – human pathways (continued)

Factor	DandD 1.0	RESRAD 5.61
Deposition of contaminated irrigation water on foliage.	Yes. The default settings of DandD 1.0 assume that overhead irrigation occurs; that a portion of the radioactivity in irrigation water equal to the interception fraction (r_v) is retained on the plant, and that "translocation" of a portion of this activity (T_v) to edible portions of the plant occurs.	In the case of ditch irrigation, no deposition of contamination from irrigation water onto foliage is assumed to occur. RESRAD 5.61 and DandD 1.0 use the same approach to model overhead irrigation.
Removal of contaminants deposited on plant surfaces from irrigation water.	The translocated activity from overhead irrigation is assumed to be removable through weathering, with a weathering constant of 0.0495 per day.	RESRAD 5.61 and DandD 1.0 use the same approach to modeling the removal of activity deposited by overhead irrigation. RESRAD 5.61 uses a weathering constant of 0.055 per day.
Is radioactivity deposited in the soil from irrigation water removed by both leaching and radioactive decay?	Yes. By decay during the timestep it is deposited (eq. 5.26 NUREG/CR 5512 V1) and by leaching after the deposition timestep.	Yes. For the purposes of this pathway, it is assumed to be removed by both radioactive decay and leaching.
Is mixing of contaminated layer with uncontaminated soil taken into account?	No.	Not applicable to these pathways.

The (soil-to-plant) resuspension and deposition pathway in DandD 1.0 and RESRAD 5.61 differ notably. DandD 1.0 assumes that there is a static ratio between radionuclide concentrations in dried plant foods and in soil on a pCi/kg basis (NUREG/CR 5512, Eq. 5.5); this ratio is called the mass loading factor (ML_v). The default value of 0.1 used by DandD 1.0 suggests that dried foods could be 10% soil by weight. This value seems too high for plant foods consumed by humans. For several isotopes, this value leads to much higher dose agricultural pathway estimates in DandD 1.0 simulations than in RESRAD 5.61 simulations (see Tables 19, 20, and Appendix A).

RESRAD 5.61 assumes a kinetic relationship between these quantities:

- there is a constant deposition rate,
- removal is controlled by a first order weathering constant, and
- deposition and removal occur over the growing season (Yu, et al., 1993).

During the comparison of DandD 1.0 and RESRAD 5.61, it was found that with DandD 1.0 the default mass loading factor dominated the ingestion dose for radionuclides that do not have a high degree of root uptake by plants. This was particularly notable for the thorium-232 (Table 20) and radium-226 decay chains (Table 19).

In reviewing the basis for the default mass loading factors in NUREG/CR 5512 volume 1, it was found that the data used to support the default value are for unwashed produce, roots, leafy vegetables, grain, and forage crops. While these data may be appropriate for estimating animal ingestion of soil, they are not appropriate for estimating human consumption. Sheppard (1995) compiled soil loading data for washed, edible portions of plants and reports that the geometric mean of the data is 0.001 grams of soil per gram of dry plant, indicating that the default mass loading factor for vegetation consumed by humans could be reduced by as much as two orders of magnitude. The data for mass loading reported in Sheppard (1995) for human food products range from a minimum value of 0.00003 for harvested grain to 0.008 for washed root crops. It is

Table 19. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving radium-226 with progeny

Pathway	Maximum EDE Rate, mrem/y, Minimal Changes to Defaults		Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 80	RESRAD 5.61 Year 0	DandD 1.0 Year 1	RESRAD 5.61 Year 0	DandD 1.0 Year 4	RESRAD 5.61 Year 0
External	3,780	5,630	4,610	5,340	4,590	5,340
Inhalation	1.31	23.3	1.98	1.24	1.94	1.24
Radon	NA	25,900	NA	30,800	NA	30,800
Plant	NA	1,830	NA	1,830	NA	1,830
Meat	NA	153	NA	153	NA	153
Milk	NA	113	NA	113	NA	113
Soil Ingestion	80.0	235	123	243	122	243
Water	2,550	0	0.552	0	137	0
Fish / Aquatic	21,900	0	7.05	0	1,520	0
Irrig water →→ Plant	NA	0	NA	0	NA	0
Irrig water →→ Meat	NA	0	NA	0	NA	0
Irrig water →→ Milk	NA	0	NA	0	NA	0
Irrigation pathways	3,290	NA	1.74	NA	11.0	NA
Agriculture	26,200	NA	40,400	NA	39,900 *	NA
Total	57,800	33,900	45,200	38,500	46,300	38,500

* Decreasing the plant mass loading value from 0.1 to 0.01 for plant foods directly consumed by humans decreases the EDE from the agricultural pathway from 39,900 to 8,380 mrem/y.

Table 20. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving thorium-232 with progeny

Pathway	Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 1	RESRAD 5.61 Year 0.17	DandD 1.0 Year 1	RESRAD 5.61 Year 0
External	6,530	7,596	6,530	7,600
Inhalation	122	77.3	122	77.3
Radon	NA	334	NA	334
Plant	NA	891	NA	886
Meat	NA	48.9	NA	48.4
Milk	NA	57.6	NA	57.6
Soil Ingestion	70.5	141	70.5	141
Water	0.058	0	4.35	0
Fish / Aquatic	0.21	0	12.7	0
Irrig water →→ Plant	NA	0	NA	0

Table 20. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving thorium-232 with progeny (continued)

Pathway	Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 1	RESRAD 5.61 Year 0.17	DandD 1.0 Year 1	RESRAD 5.61 Year 0
Irrig water →→ Meat	NA	0	NA	0
Irrig water →→ Milk	NA	0	NA	0
Irrigation pathways	0.20	NA	6.6E-3	NA
Agriculture	19,400	NA	19,400*	NA
Total	26,100	9,150	26,100**	9,141

*Decreasing the plant mass loading value from 0.1 to 0.01 for plant foods directly consumed by humans decreases the EDE from the agricultural pathway from 19,400 to 2,020 mrem/y.
**This value decreases to 9,520 mrem/y if the if the plant mass loading is decreased to 0.01.

recommended that the sources on mass loading data in Sheppard (1995), NUREG/CR 5512, and more recent studies be evaluated to provide a PDF for each class of vegetation and feed crop in the DandD 1.0 model.

3.1.17 Animal Product – Human Pathways

Animal product – human pathways may be subdivided into those involving irrigation water and those involving soil. DandD 1.0 assumes that animal products are held briefly upon harvest, and then consumed over a period of time. RESRAD 5.61 does not take into account that animal products may be consumed over a period of time. DandD 1.0 also calculates an average dose received over a year while RESRAD 5.61 calculates an instantaneous dose rate.

Default values for animal product – human pathways are provided in Table 4.

3.1.17.1 Irrigation Water – Animal Product – Human Pathways

Assumptions common to all these pathways are summarized in Table 21.

Both RESRAD 5.61 and DandD 1.0 allow the user to specify the contamination fraction of irrigation water used for livestock. RESRAD 5.61 also allows the user to specify whether irrigation water is surface water or well water. The irrigation water – animal product – human pathways include the following:

- Irrigation water – forage – animal product – human (Table 22),
- Irrigation water – soil – forage – animal product – human (Table 23),
- Irrigation water – stored hay – animal product – human (Table 24),
- Irrigation water – soil – stored hay – animal product – human (Table 25),
- Irrigation water – stored grain – animal product – human (Table 24),
- Irrigation water – soil – stored grain – animal product – human (Table 25),
- Irrigation water – soil – animal product – human (Table 26)
- Irrigation water – animal product – human,

These pathways are generally discussed in section 5.4.2 of NUREG/CR-5512 Volume 1 and in Appendix D of Yu et al. (1993). DandD 1.0 and RESRAD 5.61 use fundamentally the same approach to modeling the doses due to the irrigation water – animal product – human pathways. However, there are important differences in the groundwater models that cause differences in the doses from these pathways. The time dependence and magnitude of dose rates from groundwater-related pathways tended to be very different in this study. This affected the doses resulting from the irrigation pathways, the drinking pathway, and the aquatic pathway. In general, DandD 1.0 simulations had faster arrival times for contaminant to the well, but the DandD 1.0 maximal dose rates for these pathways were not always higher.

Table 21. Assumptions common to all irrigation water – animal product – human pathways

Factor	DandD 1.0	RESRAD 5.61
Time dependence of concentrations of radionuclides in irrigation water.	Assumed constant over the growing season (i.e. an annual average concentration is used).	RESRAD 5.61 computes the concentration at an instant in time.
Material deposited onto plant surfaces is assumed to be removed at a rate determined by a weathering constant.	Yes. The translocated activity from overhead irrigation is assumed to be removable through weathering, with a weathering constant of 0.0495 per day. The weathering rate may be changed by the user.	Yes. RESRAD 5.61 and DandD 1.0 use the same approach to modeling the removal of activity deposited by overhead irrigation. RESRAD 5.61 uses a weathering constant of 0.055 per day. The weathering rate cannot be changed within the program by the user.*
All irrigation pathways include a radionuclide specific transfer factor termed F_{aj} in NUREG/CR 5512. This factor relates the concentration in an animal product to the daily intake via feed, water, and soil.	Yes. This factor is assumed to be independent of media ingested, but is dependent on the animal product (Kennedy and Strenge, 1992, section 5.4.2).	Yes. This factor is assumed to be independent of media ingested, but is dependent on the animal product (Yu, et al, 1993, Eq. D.15, Table D.4).
Animal products ingested	DandD 1.0 provides separate transfer factors for beef, milk, poultry and eggs. Default values are found in Table 7.	RESRAD 5.61 does not provide separate transfer factors for beef and poultry. RESRAD 5.61 does not consider ingestion of poultry eggs by humans as an exposure pathway. See Table 7 for defaults.
Radionuclide concentrations in soil are assumed to be continuously in equilibrium with radionuclide concentrations in the edible portions of the plant.	Yes.	Yes.
Animals ingest soil while grazing	Yes.	Yes.
The concentrations in animal products are immediately in equilibrium with the concentrations in intake (feed, water, and soil).	Yes, this assumption is made by both DandD 1.0 and RESRAD 5.61. For isotopes that are rapidly cleared from the body, this is a good approximation. However, it will be conservative for elements that are retained in edible tissues for long periods of time. Based on retention data in ICRP 30 and 54, which is based on animal and human studies, the following are likely to take two years or more to reach a steady state concentration in animal flesh: Co-60, Cd-109, Ce-144, Pb-210, Th isotopes, Pu, and transuranics (liver).	
Animal products are harvested continuously over the feeding period and then held for a short time before distribution for human consumption.	Yes	Dose rates are computed based on concentrations present in media at a particular point in time. There is a brief holdup period before consumption by humans.
Source of irrigation water for livestock	Assumed to be well water. User may specify a contamination fraction.	User may choose surface water or well water and specify a contamination fraction.

Table 22. Irrigation water – forage – animal product – human pathway FactorDandD 1.0RESRAD 5.61

Time dependence of radionuclide concentration in forage as a result of irrigation water.	Taken to be the average concentration for the feeding period.	Concentration is evaluated at an instant in time that is specified by the user.
Time dependence of radionuclide concentration in animal product over the forage period.	Taken to be the average concentration for the feeding period. Instantaneous equilibrium between forage and the animal product is assumed via plant to animal product transfer factors.	Concentration is evaluated at an instant in time that is specified by the user.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the forage is taken into account over the holding time	Radionuclide ingrowth and decay in the forage is taken into account over the holding time
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the forage is taken into account over the holding time.	No correction for radioactive ingrowth and decay occurring over the consumption time is considered.

Table 23. Irrigation water – soil – forage – animal product – human pathway

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in soil as a result of irrigation water.	Taken to be the average concentration for the forage period.	Concentration is evaluated at an instant in time that is specified by the user.
Time dependence of radionuclide concentration in forage as a result of irrigation water.	Taken to be the average concentration for the forage period. Concentrations in edible part of plant are assumed to be in equilibrium with soil concentrations via the soil-to-plant transfer factors.	Concentration is evaluated at an instant in time that is specified by the user. Concentrations in edible part of plant are assumed to be in equilibrium with soil concentrations via the soil-to-plant transfer factors.
Time dependence of radionuclide concentration in animal product over the forage period.	Taken to be the average concentration for the feeding period. Instantaneous equilibrium between forage and the animal product is assumed via plant-to-animal product transfer factors.	Concentration is evaluated at an instant in time that is specified by the user. Instantaneous equilibrium between forage and the animal product is assumed via plant-to-animal product transfer factors.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the forage is taken into account over the holding time	Same as DandD 1.0.
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the forage is taken into account over the consumption period.	No correction for radioactive ingrowth and decay occurring over the consumption time is considered.

Table 24. Irrigation water – stored hay or grain – animal product – human pathway

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in stored hay or grain as a result of irrigation water.	Taken to be the concentration at the time of harvest.	Same as DandD 1.0
Length of holding time between when feed is harvested and when it is first used.	Zero.	Fodder is held for a short time before intake by animals.
Time dependence of radionuclide concentration in animal product over the period when the feed is consumed.	Radionuclide ingrowth and decay in the stored hay/grain is taken into account over the stored hay/grain consumption period. Instantaneous equilibrium between stored hay/grain and the animal product is assumed via plant-to-animal product transfer factors.	Not considered.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the stored product is taken into account over the holding time.	A holding time is assumed, see Table 4 for defaults, with decay taken into account.
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the stored hay/grain is taken into account over the consumption period.	Not taken into account.

Table 25. Irrigation water – soil – stored hay/grain – animal product – human pathway

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in soil as a result of irrigation water.	Deposition, ingrowth and decay of radionuclides in soil are assumed to occur over the time the crop is in the field.	Same as DandD 1.0.
Time dependence of radionuclide concentration in the crop as a result of irrigation water.	Concentrations in edible part of plant are assumed to be in equilibrium with soil concentrations via the soil-to-plant transfer factors. Ingrowth and decay of radionuclides in soil is assumed to occur over the time the crop is in the field.	Same as DandD 1.0.
Initial radionuclide concentration in stored hay or grain.	Taken to be the concentrations at the time of harvest. Crop is continuously in equilibrium with soil via soil-to-plant transfer factors.	Same as DandD 1.0.
Length of holding time between when hay/grain is harvested and when it is first used.	Zero.	There is a holding time. Default values provided in Table 4. Decay is accounted for.

Table 25. Irrigation water – soil – stored hay/grain – animal product – human pathway (continued)

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in animal product over the period when stored hay/grain is consumed.	Radionuclide ingrowth and decay in the stored hay/grain is taken into account over the stored hay/grain consumption period. Instantaneous equilibrium between stored hay/grain and the animal product is assumed via plant to animal product transfer factors.	Not considered.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the animal product is taken into account over the holding time. See Table 4 for default values.	Same as DandD 1.0.
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the animal product is taken into account over the consumption period.	Not considered.

Table 26. Irrigation water – soil – animal product – human pathway

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in soil as a result of irrigation water.	Taken to be the average concentration for the forage period.	Concentration is evaluated at an instant in time that is specified by the user.
Time dependence of radionuclide concentration in animal product over the forage period.	Taken to be the average concentration for the feeding period. Instantaneous equilibrium between forage and the animal product is assumed via plant to animal product transfer factors.	Concentration is evaluated at an instant in time that is specified by the user. Instantaneous equilibrium between forage and the animal product is assumed via plant to animal product transfer factors.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the animal product is taken into account over the holding time. See defaults in Table 4.	Same as DandD 1.0.
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the animal product is taken into account over the consumption period.	No correction for radioactive ingrowth and decay occurring over the consumption time is considered.

3.1.17.2 Soil – Animal Product – Human Pathways

Assumptions made by DandD 1.0 that are common to all of these pathways are provided in Table 27. The soil – animal product – human pathways include the following:

- Soil – forage – animal product – human (Table 28),
- Soil – stored hay – animal product – human (Table 29),
- Soil – stored grain – animal product – human (Table 29),
- Soil – animal product – human.

Table 27. DandD 1.0 assumptions common to all soil – animal product – human pathways

Assumption	DandD 1.0	RESRAD 5.61
Fresh forage crops are eaten continuously (starting at time 0) over the entire feeding period of the animal.	yes	yes
Stored feed crops are eaten continuously during a feeding period offset by the stored feed crop's growing period (i.e. feeding begins at harvest).	yes	not specifically assumed
The harvested crops are immediately available for feeding to animals.	yes	Available after a short holding time.
A combination of fresh and stored feeds is assumed for each type of animal product.	yes	yes
Stored feeds may consist of hay or grain.	yes	yes
Instantaneous equilibrium occurs between the radionuclide concentration in the soil and the concentration in the plants (fresh forage and stored feed plants).	yes	yes
Instantaneous equilibrium occurs between daily intake in the feed and the radionuclide concentration in the animal product.	yes	yes
Animal products are harvested (milked, slaughtered, or eggs gathered) continuously over the feeding period and then distributed for consumption.	yes	No. Dose rates from animal products are evaluated at a specific point in time.
The human consumption period is equal in length to the feeding period for each animal product type, offset by the time between harvest and consumption.	yes	not considered
Decay during the hold-up time between animal product harvest and consumption by humans is evaluated.	yes	yes

Table 28. Soil – forage – animal product – human

Assumption	DandD 1.0	RESRAD 5.61
Concentration in soil as a function of time	Declines due to radioactive decay and leaching.	Declines due to radioactive decay and leaching.
Radionuclide concentration in forage crops.	Continuously in equilibrium with soil via soil-to-plant transfer factors.	Continuously in equilibrium with soil via soil-to-plant transfer factors.

Table 28. Soil – forage – animal product – human (continued)

Assumption	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in animal product over the forage period.	Instantaneous equilibrium between forage and the animal product is assumed via plant-to-animal product transfer factors.	Instantaneous equilibrium between forage and the animal product is assumed via plant-to-animal product transfer factors.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the forage is taken into account over the holding time. See Table 4 for defaults.	Same as DandD 1.0.
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the forage is taken into account over the consumption period.	No correction for radioactive ingrowth and decay occurring over the consumption time is considered.

Table 29. Soil – stored hay/grain – animal product – human

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in stored hay or grain as a result of root uptake.	At time of harvest, crop is continuously in equilibrium with soil via soil-to-plant transfer factors.	Same as DandD 1.0.
Length of holding time between when hay/grain is harvested and when it is first used.	Zero.	Held for a short period before consumption, see Table 4.
Time dependence of radionuclide concentration in animal product over the period when stored hay/grain is consumed.	Radionuclide ingrowth and decay in the stored hay/ grain is taken into account over the stored hay/grain consumption period. Instantaneous equilibrium between stored hay/grain and the animal product is assumed via plant to animal product transfer factors.	NA. Dose rates are evaluated at a specific point in time.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the stored animal product is taken into account over the holding time. See Table 4 for defaults.	Same as DandD 1.0
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the animal product is taken into account over the consumption period.	Not considered.

3.1.18 Comparison of RESRAD 5.61 and DandD 1.0 Simulation Results

Three variations of the residential farmer scenario were considered. In the first set of comparisons, RESRAD 5.61 and DandD 1.0 were run with minimal changes to default values for tritium, carbon-14, cesium-137, and radium-226. The changes to default values for these simulations are described in Appendix A, Tables A.3 and A.4. In the second set of comparisons, RESRAD 5.61 and DandD 1.0 parameters were adjusted to represent a residential farmer in an arid climate. The changes to default values that were made for this series of simulations are described in "Comparison of DandD 1.0 and RESRAD 5.61 Results for a Residential Farmer in Dry Climatic Conditions" in Appendix A. In the third set of simulations, parameters were adjusted to represent a residential farmer in a wet climate. The changes to default values that were made for this series of simulations are described in "Comparison of DandD 1.0 and RESRAD 5.6.1 Results for a Residential Farmer in Wet Climatic Conditions" in Appendix A. The dry climate and wet climate simulations were completed for tritium, carbon-14, cesium-137, radium-226, thorium-232, and cobalt-60.

To illustrate the differences in simulation results over time, each set of simulation results are presented for the first year and the fifth year of the scenario in Appendix A, and in Figures 1 through 6. A comparison of maximal dose rates is provided Figures 1 through 6 and in Tables 11, 13, 19, 20, 30, and 31.

It was concluded that the agricultural pathway in DandD 1.0 simulations tends to dominate the Total Effective Dose Equivalent (TEDE) when the default plant mass loading factor is used. The default value for this parameter is that plant foods contain 10% soil on a dry weight basis. Decreasing the value of this factor to 1% results in reasonable agreement between agricultural doses predicted by RESRAD 5.61 and DandD 1.0 for most isotopes. This empirical observation is very evident in two examples, radium-226 plus progeny (Table 19) and thorium-232 plus progeny (Table 20). In the radium case, decreasing the plant mass loading factor in DandD 1.0 from 0.1 to 0.01 results in a decrease in dose from the agricultural pathway from 39,900 mrem/y to 8,380 mrem/y.

Although decreasing the value of the plant mass loading factor to a more realistic value produces closer agreement in the doses simulated using RESRAD 5.61 and DandD 1.0, the models of diet are still dissimilar. Hence, there remain significant differences in the simulated doses for some isotopes. The agricultural pathway in DandD 1.0 corresponds to the sum of the plant, meat, and milk pathways in RESRAD 5.61, which is 2,100 mrem/y. This RESRAD 5.61 result is based on the assumption that one-half of the food consumed is grown in the contaminated area, while the DandD 1.0 result is based on assumption that all of the food grown on-site is grown in the contaminated area. The two diets are not equivalent and as a result, the revised DandD 1.0 agricultural dose of 8,380 mrem/y (with a plant mass loading of 0.01 for plant foods consumed by humans) is about twice the dose calculated by RESRAD 5.61.

As discovered during the parameter analysis for DandD (Beyeler et al., 1998) and based on values found in the literature for soil mass loading on washed plant foods consumed by humans (e.g., Sheppard, 1995), the plant mass loading values in DandD 1.0 for plants foods consumed by humans appear to be implausibly high. It is recommended that the default values for these values be reconsidered.

In this comparison, parameters related to diet were not adjusted in RESRAD 5.61 to match DandD 1.0 values because basic differences in way the computer codes model the ingestion pathway make it difficult to derive parameter values that result in comparable diets. These differences include:

RESRAD uses a single animal soil intake rate. NUREG/CR-5512 and DandD 1.0 have separate soil ingestion rates that are a function of forage intake rate for beef cattle, dairy cattle, poultry and layer hens. The value chosen for RESRAD 5.61 needs to be representative for layer hens, poultry, dairy and beef cattle.

RESRAD does not include intakes of eggs and poultry, NUREG/CR-5512 and DandD 1.0 do. In principle, the contribution of eggs and poultry can be included in the "meat" component of the diet. This leads to the difficulty that transfer coefficients for beef, eggs and poultry are very different for some isotopes.

Examples:

	Beef	Poultry	Eggs
Po-210	3E-4	0.9	7
Pb-210	3E-4	0.2	0.8

Derivation of a composite transfer coefficient that would make the diet in RESRAD 5.61 equivalent to the DandD 1.0 default diet is problematic because of the orders of magnitude difference in the transfer coefficient for beef

Table 30. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving cobalt-60

Pathway	Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 1	RESRAD 5.61 Year 0	DandD 1.0 Year 1	RESRAD 5.61 Year 0
External	6,200	7,570	6,200	7,570
Inhalation	0.013	8.5E-3	0.013	8.51E-3
Plant	NA	30.1	NA	31.1
Meat	NA	23.5	NA	23.5
Milk	NA	3.03	NA	3.03
Soil Ingestion	0.36	0.76	0.36	0.76
Water	2.6E-6	0	1.9E-4	0
Fish / Aquatic	3.3E-5	0	1.9E-3	0
Irrig water →→ Plant	NA	0	NA	0
Irrig water →→ Meat	NA	0	NA	0
Irrig water →→ Milk	NA	0	NA	0
Irrigation pathways	2.0E-5	NA	2.9E-5	NA
Agriculture	667	NA	667	NA
Total	6,870	7,630	6,870	7,630

verses poultry and eggs. If a composite transfer coefficient could be derived, it would need to be changed whenever site-specific variations in diet are made.

RESRAD 5.61 uses a single soil to plant transfer coefficient for all plant foods. The values chosen need to representative for the diets of humans, poultry, layer hens, dairy and beef cattle. This leads to difficulties in choosing a representative value because of differences in diet among these organisms.

RESRAD 5.61 uses a single animal food, fodder. DandD 1.0 uses separate interception fractions, translocation fractions and crop yields for each animal product for forage, grain and hay. Representative values of these parameters would need to be calculated for the diets of layer hens, poultry, dairy and beef cattle.

Wet and dry interception fractions are coupled in RESRAD 5.82 and cannot be independently adjusted. This leads to difficulty in modeling the dose from resuspended soil on plants. In RESRAD 5.82, this can be compensated for, to a degree, by setting the soil mass loading for deposition to zero and increasing the amount of soil directly ingested by animals. DandD 1.0 allows for separate plant mass loading values for hay, forage, and grain for each animal food.

Devising a robust method for matching non-equivalent parameters in these two models was beyond the scope of this analysis.

RESRAD 5.61 and DandD 1.0 tend to agree well for doses resulting from direct irradiation, inhalation, and soil ingestion, provided that an effort is made to match input parameter values. This is due to the fact that the models for these pathways are very similar. The dose from incidental soil ingestion in each of the RESRAD 5.61 simulations summarized in Tables 11, 13, 19, 20, 30, and 31 and in Appendix A is twice as high as in the corresponding DandD 1.0 simulation because of differences in the incidental soil ingestion rates. 100 mg per day was used in the RESRAD 5.61 simulations, while 50 mg/d was used in the DandD 1.0 simulations.

Table 31. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving cesium-137

Pathway	Maximum EDE Rate, mrem/y, Minimal Changes to Defaults		Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 6	RESRAD 5.61 Year 0	DandD 1.0 Year 1	RESRAD 5.61 Year 0	DandD 1.0 Year 11	RESRAD 5.61 Year 0
External	1,380	1,778	1,460	1,690	218	0.065
Inhalation	1.9E-4	0.023	1.96e-3	1.24E-3	2.9E-4	0
Plant	NA	29.0	NA	29.0	NA	1.14E-3
Meat	NA	45.0	NA	45.0	NA	1.73E-3
Milk	NA	15.9	NA	15.9	NA	6.13E-4
Soil Ingestion	0.066	1.37	0.70	1.41	0.10	5.43E-5
Water	562	0	0.099	0	192	511
Fish / Aquatic	23,700	0	7.56	0	11,600	5,460
Irrig water →→ Plant	NA	0	NA	0	NA	0
Irrig water →→ Meat	NA	0	NA	0	NA	47.3
Irrig water →→ Milk	NA	0	NA	0	NA	59.0
Irrigation pathways	3,840	NA	1.40	NA	69.8	NA
Agriculture	53.6	NA	567	NA	84.6	NA
Total	28,300	1,870	2,040	1,780	12,100	6,070

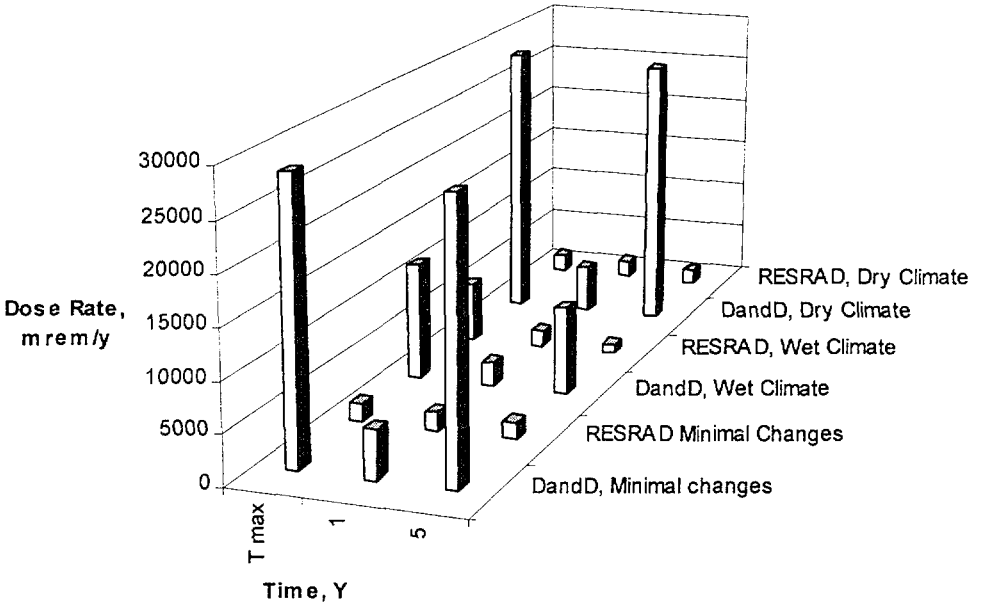

Figure 3. Comparison of Cesium-137 results for DandD and RESRAD

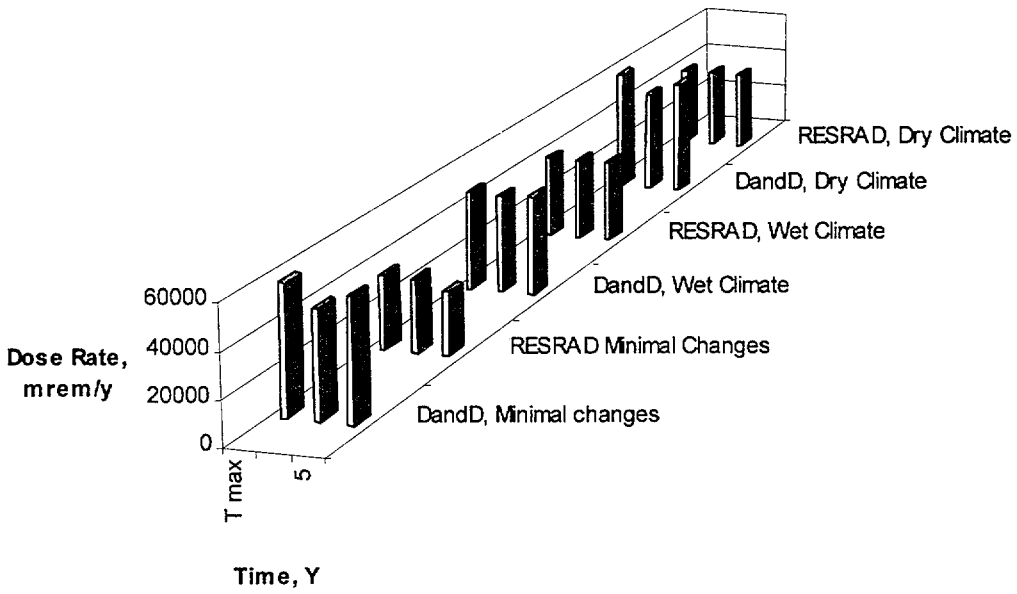

Figure 4. Comparison of Radium-226 + chain results for DandD and RESRAD

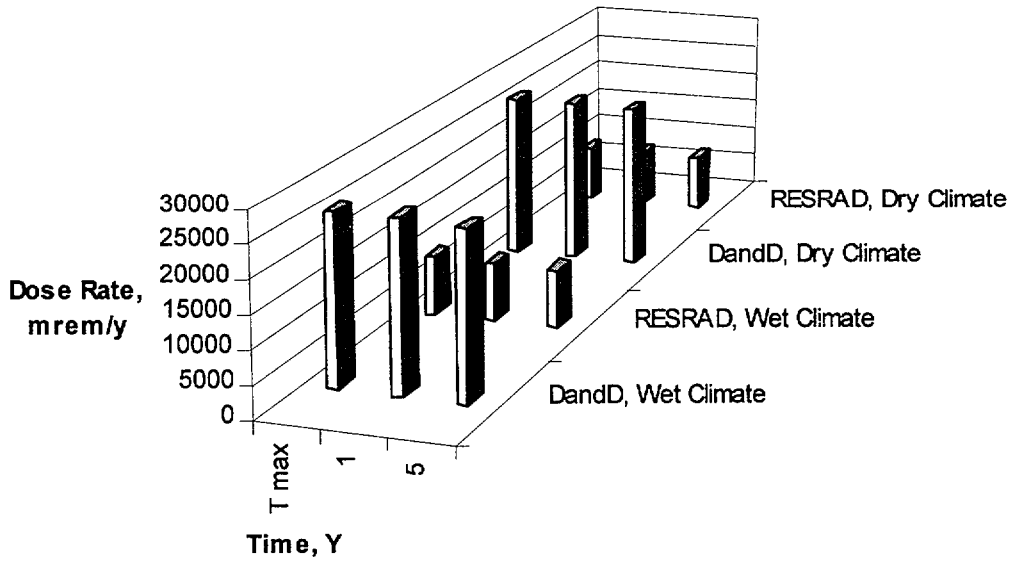

Figure 5. Comparison of Th-232 + chain results for DandD and RESRAD

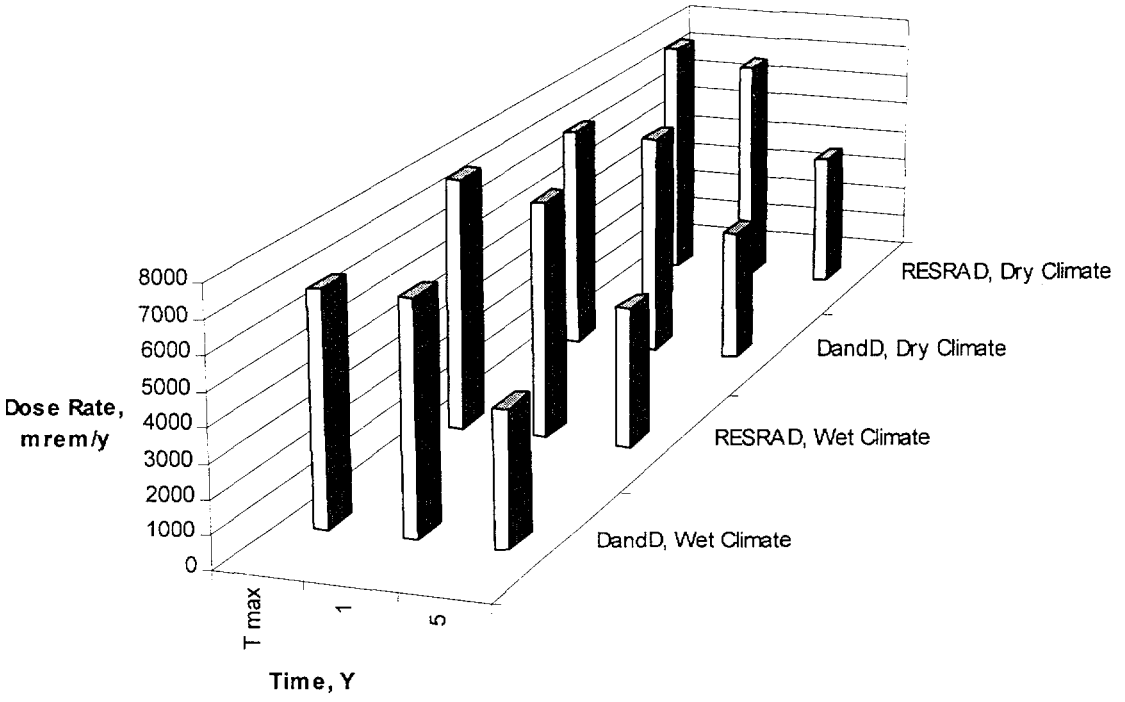

Figure 6. Comparison of Co-60 results for DandD and RESRAD

Because RESRAD 5.61 and DandD 1.0 groundwater models differ in significant ways, the time dependence and magnitude of doses from groundwater pathways tended to be very different when the models are applied to the residential farmer scenario. This affected the doses resulting from the irrigation pathways, the drinking pathway, and the aquatic pathway. In general, contaminants reached the well sooner in DandD 1.0 simulations.

A primary difference in the water pathway calculations performed by DandD 1.0 and RESRAD 5.61 can be attributed to the method in which they model the unsaturated zone. In the unsaturated zone DandD 1.0 uses a well-mixed linear reservoir model, which has inherent, probably large, dispersion due to the mixing assumption. This dispersion causes the arrival time from the contaminated zone to the aquifer to be zero when a single layer is used. Thus, DandD 1.0 simulations show radionuclides reaching the aquifer in a very short time, but at a low mass flow rate.

The concentrations in the aquifer in RESRAD 5.61 are based in part on travel time from the contaminated zone to the aquifer. This means that no radionuclides from the contaminated zone can reach the aquifer until the model simulation time exceeds the travel time. The travel time in RESRAD 5.61 is proportional to the retardation coefficient. A radionuclide, such as tritium, has a retardation coefficient of 1 because it is not adsorbed onto soil particles and, thus, travels through the unsaturated zone at the same speed as water. Carbon-14 and many other radionuclides are retarded and take much longer to reach the water table than tritium in the RESRAD 5.61 model. This is why doses were not seen for water-dependent pathways at one year or five years for isotopes other than tritium in the RESRAD 5.61 code.

Three of the isotopes considered in simulations showed a tendency to enter groundwater readily. This included the isotopes cesium-137, tritium, and carbon-14. With these isotopes, maximum dose rates for water dependent

pathways depend strongly on the values of parameters used.

Three of the isotopes considered in simulations showed little tendency to enter groundwater: radium-226, thorium-232, and cobalt-60. For each of these isotopes, DandD 1.0 and RESRAD 5.61 results were consistent. If a more realistic default plant mass loading values are adopted into DandD 1.0, the differences, in the simulated doses for these isotopes between DandD 1.0 and RESRAD 5.61, would be significantly reduced.

3.2 DandD 1.0 and RESRAD-Build 1.50

DandD 1.0 and RESRAD-Build 1.50 differ in the exposure pathways considered for an industrial occupancy scenario, and they differ in the treatment of those pathways. The pathways considered are provided in Table 32.

The major pathway differences between RESRAD-Build 1.50 and DandD 1.0 for application of the industrial occupant scenario of NUREG/CR-5512 can be summarized as follows:

- RESRAD-Build 1.50 considers dose due to submersion in a cloud of radioactive material, while DandD 1.0 does not.
- RESRAD-Build 1.50 considers external exposure to dust that has been airborne and settled on floors, while DandD 1.0 does not consider this to be a separate exposure pathway.
- RESRAD-Build 1.50 considers dose due to inhalation of radon and radon progeny. DandD 1.0 does not include a radon model.

In addition, there are many significant differences between the two models. These are summarized below.

- RESRAD-Build 1.50 is a dynamic model of a structure, while DandD 1.0 is a static model. This leads to numerous differences in the parameters needed to run the models. DandD 1.0 was designed to model the four scenarios in NUREG/CR-5512 while RESRAD-Build 1.50 is a general purpose dose assessment model for scenarios related to remediation and occupancy of structures.
- RESRAD-Build 1.50 will model dose from finite sources; it addresses area sources, volume sources, point sources, and line sources. The DandD 1.0 industrial occupant scenario only considers dose from infinite area sources.
- RESRAD-Build 1.50 contains a ventilation model, so some of the radioactive material that becomes airborne can be exhausted from the building. DandD 1.0 does not contain a ventilation model.
- In RESRAD-Build 1.50, a structure can be modeled with up to three rooms using numerous sources of contamination. DandD 1.0 assumes that the contamination is present in a single room.
- In RESRAD-Build 1.50, it is necessary to specify the location and occupancy of a receptor relative to each source. The location does not matter with DandD1.0, since the receptor is located on an infinite area source.
- RESRAD-Build 1.50 assumes that a fraction of contamination is removed from the building over a period of time specified by the user through ordinary traffic or housekeeping activities. DandD 1.0 only accounts for loss of material through radioactive decay.

3.2.1 Isotopes Considered

The RESRAD-Build 1.50 library of isotopes contains 67 isotopes having a half-life of six months or longer. RESRAD-Build 1.50 uses the same convention as RESRAD 5.61 for treatment of radioactive progeny (see section 3.1.2 of this report). The isotope library and conventions concerning progeny utilized by DandD 1.0 are described in section 3.1.2. DandD 1.0's isotope library contains 249 primary isotopes. The DandD 1.0 isotope library includes many more short-lived primary isotopes than the RESRAD-Build 1.50 isotope library.

3.2.2 Dose Rate Reporting Basis

The dose rate reporting basis of RESRAD-Build 1.50 is the same as described for RESRAD 5.61 in section 3.1.1 of this report. RESRAD-Build 1.50 calculates instantaneous dose rates while DandD 1.0 calculates dose received over a year.

3.2.3 External Exposure

The only external exposure pathway considered by DandD 1.0 is direct exposure to an infinite area source

Table 32. Industrial occupant scenario exposure pathways considered by DandD 1.0 and RESRAD-Build 1.50

Pathway	DandD 1.0	RESRAD-Build 1.50
External Exposure due to Source	√	√
External Exposure due to Air Submersion		√
External Exposure to Material Deposited on Floor		√
Inhalation of Airborne Radioactive material	√	√
Inhalation of Radon Progeny		√
Inadvertent Ingestion of Radioactive Material	√	√

of contamination. RESRAD-Build 1.50 can model external exposure to:

- sources of contamination in a number of different geometries, area, volume, line, and point. The default geometry is a volume source.
- exposure due to submersion in a infinite cloud of airborne contamination, and
- exposure to radioactivity that has been resuspended, transported via the indoor air quality model, and subsequently deposited on horizontal surfaces.

3.2.3.1 DandD 1.0

DandD 1.0 calculates the EDE to an industrial occupant due to surface contamination using the following basic relationship (Kennedy and Strenge, 1992, Eq 3.15):

External dose (mrem for 1 year) =
[Exposure duration for occupancy] (Eq. 3)
× [Surface Source Dose Rate Factor]
× [Average Surface Activity per Unit Area]

The *Surface Source Dose Rate Factors* are taken from Table III.3 of Federal Guidance Report (FGR)12 (EPA, 1993). These factors represent the EDE rate for exposure to an infinite planar source of the isotope of interest.

In the case where the contaminant is uniformly distributed on a floor, assuming an infinite planar distribution is conservative. In the case of gamma emitters, DandD 1.0 substantially overestimates external dose other than low energy gamma emitters for small rooms that only have contamination on the floor. To estimate how conservative, the Microshield® computer code (Grove Engineering, 1998) was used to compute exposure rates at one meter above different sizes of circular area sources of 0.1 MeV gamma emitters. The ratios of exposure rates for finite disks to disks of effectively infinite radius were estimated from Microshield® simulations. These ratios are presented in Figure 7 as a function of radius. In the case of 0.1 MeV gamma emitters, a disk 50 meters in diameter has roughly one-half of the exposure rate of an infinite planar source.

As indicated above, DandD 1.0 assumes that contamination is distributed on an infinite planar floor. In real structures, the highest contamination levels are usually on the floor and the lower parts of walls. Typically, comparatively little contamination is present on the upper portions of walls and on ceilings. With this pattern of contamination in mind, Microshield® 5.03 was used to estimate external EDE rates for a Cs-137 contaminated room. As a reference case, the external EDE rate was estimated for an infinite planar source. Then the external EDE rates were estimated for circular rooms having a height of 3 meters and diameters of 6 and 12 meters. In each case, the floor was assumed to have the same surface contamination level as the infinite planar source. Walls and ceilings were assumed to have one-half and one-tenth of this surface contamination level respectively. Based on Microshield® simulations, the rooms with 6 and 12 meter diameters had external EDE rates that were 40% and 56% of the reference value for an infinite planar source. Based on this limited evaluation, the assumption of an infinite planar source of contamination is a reasonable screening model for surface contamination of a room having contamination on the walls and ceiling as well as the floor.

Additional commentary is provided in Table 33 that relates to the use of dose conversion factors from FGR 12 for a planar source of radioactive material.

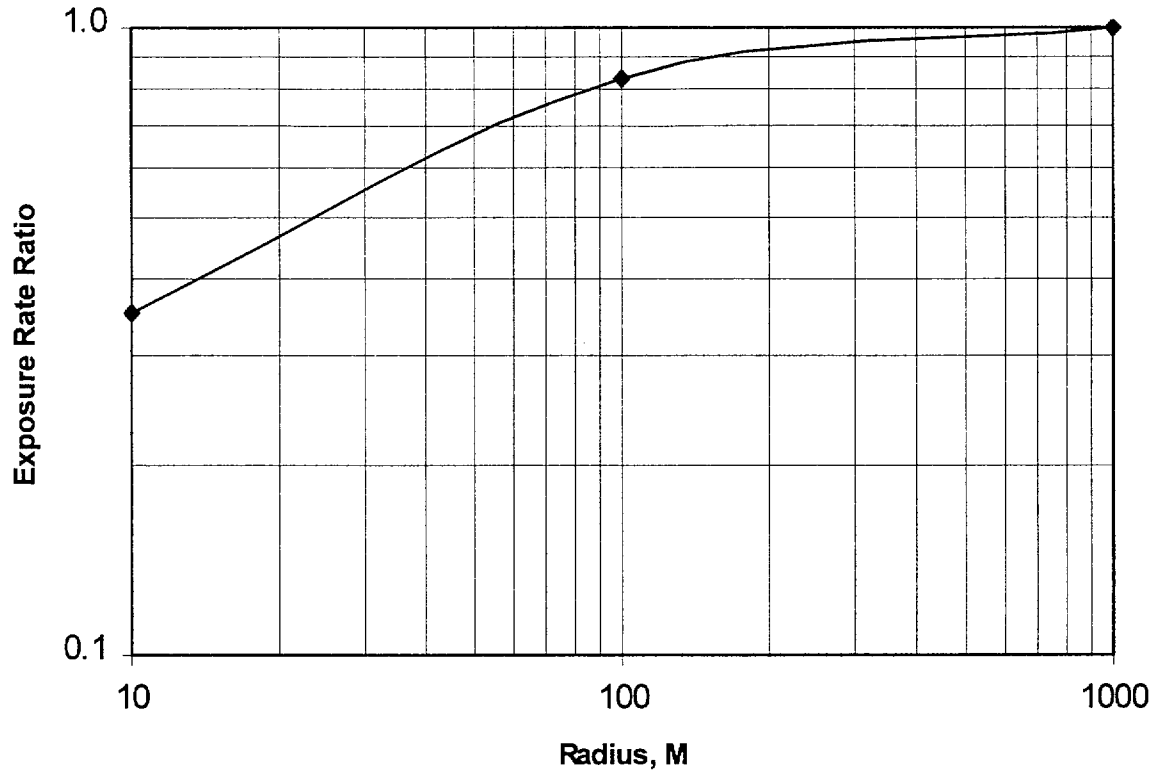

Figure 7. Gamma exposure rate ratio for 0.1 MeV photons: finite disk/infinite plane

3.2.3.2 RESRAD-Build 1.50

RESRAD-Build 1.50 calculates external exposures for a number of geometries: planar source, volume source, line source, and point source. RESRAD-BUILD 1.50's planar source geometry corresponds most closely to the spatial configuration assumed in the building occupant scenario. RESRAD-Build 1.50 external dose coefficients are based on FGR 12 (EPA, 1993).

3.2.3.2.1 Planar Source. RESRAD-Build 1.50 calculates external EDE for planar source geometry in a similar fashion to DandD 1.0, however, RESRAD-Build 1.50 incorporates four correction factors into external EDE estimates (Yu, et al., 1994, Appendix F):

- A correction that takes into account the finite area of the source,
- A correction that takes into account any offset of the receptor from the axis of the disk of contamination,
- A shielding correction that can be applied to account for attenuation by material covering the disk source (e.g. an intervening walls or floors), and
- The distance between the source and the receptor.

Each of these correction factors tends to reduce the estimated EDE from a finite area source in comparison to an infinite area source.

An important difference between the two codes is that DandD 1.0 always assumes the floor is contaminated, while RESRAD-Build 1.50 can be used to model external EDE from to up to 10 sources present on walls, ceiling, floor, in another room, or on another floor. The external dose calculations performed by RESRAD-Build 1.50 are much more complex than those provided by DandD 1.0. RESRAD-Build 1.50 should be capable of providing more accurate estimates of external EDE than DandD 1.0 where site-specific modeling is required. However, to take advantage of the more sophisticated external dose modeling capability afforded by RESRAD-Build 1.50, more site-specific information is required. For example:

- Information concerning the spatial distribution of surface contamination,

Table 33. Discussion of industrial occupant scenario parameters in DandD 1.0 and RESRAD-Build 1.50

Parameter	DandD 1.0	RESRAD-Build 1.50	Comments
Dose Conversion Factor for exposure to a planar source of radioactive material	FGR 12 factors	FGR 12 factors. Factors can be edited from within RESRAD-BUILD 1.50. In RESRAD-BUILD 2.37 these factors cannot be edited by the user.	The assumption of a planar infinitely thin perfectly flat and smooth source of radioactive contamination is a limiting conservative case. In real situations, this value is decreased by a number of factors: surface roughness; residual radioactive contamination largely may be associated with cracks between flooring material so that residual contamination is actually located within the surface. Furniture and building contents provide shielding that serves to reduce external EDE to a building occupant. As photon energies decrease, these factors cause external EDE estimates to become increasingly conservative. Both programs use FGR 12 factors to convert distributed radioactive contamination levels to EDE. However, the Radiological Criteria for License Termination standard is written in terms of TEDE, which is the sum of the deep dose equivalent (measured at a tissue depth of 1 cm) from external radiation sources and the CEDE from intakes of radioactive material. For a given distribution of radioactive materials, the deep dose equivalent usually exceeds the EDE. External dose conversion factors for EDE thus provide a non-conservative estimate of deep dose equivalent. Typically, the deep dose equivalent can exceeds the EDE by 25 to 50% or more (ICRU, 1988, Figure B.16). The difference between deep dose equivalent and EDE from external irradiation increases as the photon energy decreases.
Inhalation Dose Conversion Factors	FGR 11 factors	DOE (1988) factors. Factors can be edited from within RESRAD-BUILD 1.50. RESRAD-BUILD 2.37 uses factors from FGR 11; they cannot be modified by the user.	Both sets of dose conversion factors are based on an assumed of 1 Tm activity median aerodynamic diameter (AMAD). Both FGR 11 and DOE (1988) are based in the same system of dosimetry, ICRP publication 30 (ICRP, 1977), and there should be few substantive differences between the inhalation dose conversion factors used by RESRAD-Build 1.50 and DandD 1.0. The new lung model described in ICRP publication 66 (ICRP 1994) recommends that 5 Tm AMAD particles be assumed for occupational exposures in the absence of site-specific information to the contrary. Newer dose conversion factors found in ICRP 68 (ICRP, 1994) are tabulated for both 1 Tm and 5 Tm AMAD particles. Assuming a 1 Tm particle size distribution instead 5 Tm introduces a conservative bias on the order of 30% for most particulate beta and gamma emitters. For long lived alpha-emitting thorium and plutonium isotopes that are cleared slowly from the lung, 1 Tm AMAD particles produce around twice the EDE per unit concentration as 5 Tm AMAD particles.

Table 33. Discussion of industrial occupant scenario parameters in DandD 1.0 and RESRAD-Build 1.50 (continued)

Parameter	DandD 1.0	RESRAD-Build 1.50	Comments
			The AMAD particle size encountered in occupational exposure situations frequently will exceed 5 μm, introducing additional conservatism into the 1 μm particle size assumption. Where more than one lung clearance class is identified in ICRP publication 30, both DandD 1.0 and RESRAD-Build 1.50 tend to conservatively assume the more restrictive form of the isotope is present. This often provides a conservative estimate of the EDE by less than a factor of two. However this convention becomes rather conservative for a number of isotopes, for example: •Uranium-238, class D versus class Y; factor of 50, •Strontium-90, class D versus class Y; factor of 6, •Technetium-99, class D versus class W; factor of 8.
Ingestion Dose Conversion Factors	FGR 11 factors	DOE (1988) factors. Factors can be edited from within RESRAD-BUILD 1.50. RESRAD-BUILD 2.37 uses factors from FGR 11 (they cannot be modified by the user).	Both FGR 11 and DOE (1988) are based in the same system of dosimetry, ICRP publication 30 (ICRP, 1977), and there should be few substantive differences between the ingestion dose conversion factors used by RESRAD-Build 1.50 and DandD 1.0. In some instances, ICRP publication 30 provides different GI absorption factors for isotopes depending on lung clearance class (uranium is an example). In such cases, both computer codes use the larger value as the default factor. The GI tract absorption factors used in ICRP publication 30 are based on data from animal experimentation and limited human studies. The default factors will be inappropriate for specific chemical forms of some radionuclides. For example, ICRP 30 uses a GI tract absorption factor of 0.10 for barium, but the fractional absorption of barium sulfate via the GI tract is orders of magnitude lower. The factors could be non-conservative for unusual chemical forms of some radionuclides.
Length of the Exposure Period	365.25 days (default). Can be edited within DandD 1.0.	365 days (default) Can be edited within RESRAD-Build 1.50.	
Occupancy Factor	--	50 % (default). Can be edited within RESRAD-Build 1.50.	The high *Occupancy Factor* of RESRAD-Build 1.50 is reflective of the fact that defaults values of its parameters are not specifically based on the industrial occupant scenario of NUREG/CR-5512.

Table 33. Discussion of industrial occupant scenario parameters in DandD 1.0 and RESRAD-Build 1.50 (continued)

Parameter	DandD 1.0	RESRAD-Build 1.50	Comments
Time in Building per Year	97.46 days (default) (i.e. 45 hours/week, 52 weeks/yr.) Can be edited within DandD 1.0	Default values of *Length of Exposure Period* and *Occupancy Factor* correspond to 182.5 days or 84 hours per week.	The value of *Time in Building per Year* is reasonable for the average member of the exposed population. The default values of *Length of Exposure Period* and *Occupancy Factor* in RESRAD-Build 1.50 are very conservative for an industrial occupant scenario.
Resuspension Factor	1.42E-5 m^{-1}		The *resuspension factor* in DandD 1.0 is not directly comparable to the *resuspension rate* used in RESRAD-Build 1.50 because the resuspension models are so different. DandD 1.0 utilizes a static resuspension model while RESRAD-Build 1.50 is based on a dynamic resuspension model.
Resuspension Rate		5E-7 s^{-1}	
Volumetric Breathing Rate	1.4 m^3/h	18 m^3/day	The default volumetric breathing rate for an industrial occupant in the DandD 1.0 computer code is 1.4 m^3/h, which is well within the range of literature values used by the ICRP. For comparison, ICRP publication 2 (1959) assigned *Standard Man* a breathing rate of 1.25 m^3/h while occupationally exposed. ICRP publication 23 (1974) assigned *Reference Man* a breathing rate of 1.2 m^3/h for light activity. ICRP publication 66 assigned breathing rates of 1.2 m^3/h for light work and 1.69 m^3/h for heavy work. The breathing rate of 18 m^3/day used by RESRAD-Build 1.50 is within the range of estimates provided in EPA (1985). However, the breathing rate for an occupational worker involved in light activity is apt to be underestimated (as 0.75 m^3/h) when this average value is used to provide an estimate for an active part of the day. In such cases, a use of a breathing rate of about 30 m^3/day (1.25 m^3/h) in RESRAD-Build 1.50 will provide a more conventional estimate for an industrial occupant.
Effective transfer rate for ingestion (from surfaces to mouth)	1.11E-5 m^2/h	1E-4 m^2/h	These factors are not completely comparable because in RESRAD-Build 1.50 this only represents the transfer rate for material that has been suspended in air and then redeposited. To make the two models comparable, RESRAD-Build 1.50 must also have a non-zero value for direct ingestion of the source.
Air Exchange Rates	NA	0.8 / h (default) in case of one compartment structure.	Users need to recognize that the RESRAD-Build 1.50 IAQ model (Yu, et al., 1994, Appendix A) assumes ideal (complete) mixing behavior of air between compartments and between a compartment and outside air. However, this ideal behavior is seldom approached in real structures. Inefficiencies in mixing of air often result in layering, channeling, and the occurrence of dead air spaces within ventilated structures. These cause the *Effective* Air Exchange Rate to be lower than the ideal Air Exchange Rate. The *Effective* Air Exchange Rate is often 10% to 33% of the Air Exchange Rate (NIOSH, 1973). The *Effective Air Exchange Rate* is the appropriate value for use in RESRAD-Build 1.50.

Table 33. Discussion of industrial occupant scenario parameters in DandD 1.0 and RESRAD-Build 1.50 (continued)

Parameter	DandD 1.0	RESRAD-Build 1.50	Comments
			A default *Air Exchange Rate* of 0.8/h seems rather high considering that it is actually the *Effective Air Exchange Rate* that is of interest. In the 1970s, industrial buildings were built with a design specification of as little as 5 cfm of outdoor air per person (SMACNA, 1988) and some buildings may not have actually performed to specification.
Radon Release Fraction	NA	0.1 (default) for area source	DandD 1.0 Does not compute a dose due to emanated radon from residual radium contamination. Consideration of the dose resulting from emanated radon is not a requirement of the final rule on Radiological Criteria for License Termination (NRC, 1997). RESRAD-Build 1.50s assumes that 10% of the radon present in residual radium contamination is available for release to indoor air. This default value is too low for many chemical forms of surface contamination by radium. It is not unusual for the emanation fraction of surface soils contaminated by uranium mill tailings to emanate 30% of the radon they produce.

- Locations and characteristics of shielding, and
- Occupancy factors for specific locations in the structure.

3.2.3.2.2 Immersion. RESRAD-Build 1.50 conservatively estimates the EDE arising from immersion in an infinite cloud of radioactive material utilizing dose conversion factors from FGR 12 (EPA, 1993). RESRAD-Build 1.50 calculates the immersion EDE as the product of the *airborne concentration* and the *concentration to dose rate conversion factor* for an infinite cloud. The following considerations limit the practical importance of this exposure mechanism in the industrial occupant scenario:

- A person would have to be situated in a very large (football stadium-sized) volume of contaminated air in order for the immersion EDE rate to begin to approach the value that would result from immersion in an semi-infinite cloud of moderate energy to high energy gamma emitters[5]. This point is illustrated by Figure 8.
- In the case of immersion in a cloud of beta emitters, the skin, muscle, and fat tissues receive almost the entire dose equivalent. The dose equivalents to these tissues are not included in the calculation of EDE due to external irradiation.
- For isotopes that are a practical concern, other exposure pathways, such as inhalation or ingestion, would be much more significant than immersion.[6]

3.2.4 Inhalation

The inhalation models of DandD 1.0 and RESRAD-Build 1.50 differ significantly in the means used to compute airborne concentrations. These differences are illustrated in Figure 9; the models are described in the following section.

3.2.4.1 DandD 1.0

DandD 1.0 assumes a simple and static linear relationship between the amount of loose surface contamination

[5] The ratio of dose rates (finite ÷ infinite) for hemispherical clouds of gamma emitters is calculated as:

Ratio = 1- exp(-μ*R), where μ is the linear energy absorption coefficient of air and R is the radius of the cloud (after Member, 1983, eq. 6.40).

[6] Isotopes for which immersion in an infinite cloud causes a higher EDE than inhalation tend to be short-lived activation products and noble gases that are produced during the operation of devices such as nuclear reactors and linear accelerators. However, immersion dose could be important in building decontamination scenarios where respiratory protection is utilized and airborne gamma-emitting isotopes are present in the air at many times the derived air concentration (DAC).

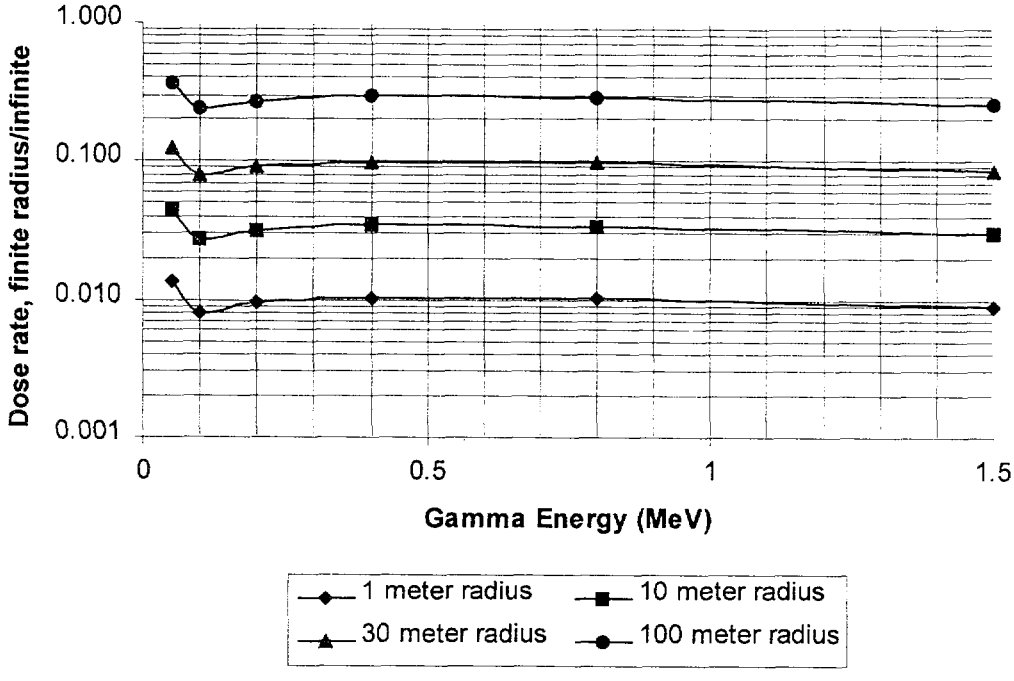

Figure 8. Dose rates from hemispheres of contaminated air having various radii relative to the dose rate from an infinite hemisphere of contaminated air.

and the airborne concentration. Concentrations of airborne radioactive materials are computed by DandD 1.0 as the product of a *resuspension factor*, which has the units of m^{-1}, and the *removable activity per unit area*, which has the units of pCi/m^2 (Kennedy and Strenge, 1992, Eq. 3.17). DandD 1.0 takes into account radioactive ingrowth and decay. No other time dependence is present in the air concentration model. DandD 1.0 uses standard factors based on ICRP publication 30 to convert airborne concentrations to CEDE. Specifically, dose conversion factors used in DandD 1.0 are obtained from FGR 11 (EPA, 1988). In instances where more than one lung clearance class is given in FGR 11, the more conservative (larger) value is used in DandD 1.0.

3.2.4.2 RESRAD-Build 1.50

The airborne concentration model used by RESRAD-Build 1.50 is provided in Appendix A of Yu, et al. (1994). This is a dynamic model that takes into consideration kinetics of the introduction and removal of radioactive material to or from indoor air. Radioactive material may be released into the air from each direct source and also from resuspension of loose radioactive material deposited on horizontal surfaces in each compartment of the structure (Yu, et al., 1994, Eq. D.1). Once airborne, radioactive material is subject to transport among the compartments of the structure, deposition on horizontal surfaces, and removal by air exchange between the structure and outdoor air. Radioactive ingrowth and decay are taken into account.

The user specifies occupancy factors and respiration rates for each receptor. For up to three rooms in the structure, the user also specifies the:

- dimensions of the rooms,
- deposition velocity,
- resuspension rate,
- air exchange rates,
- initial surface contamination level,
- removable fraction of contamination, and
- air release fraction of contamination

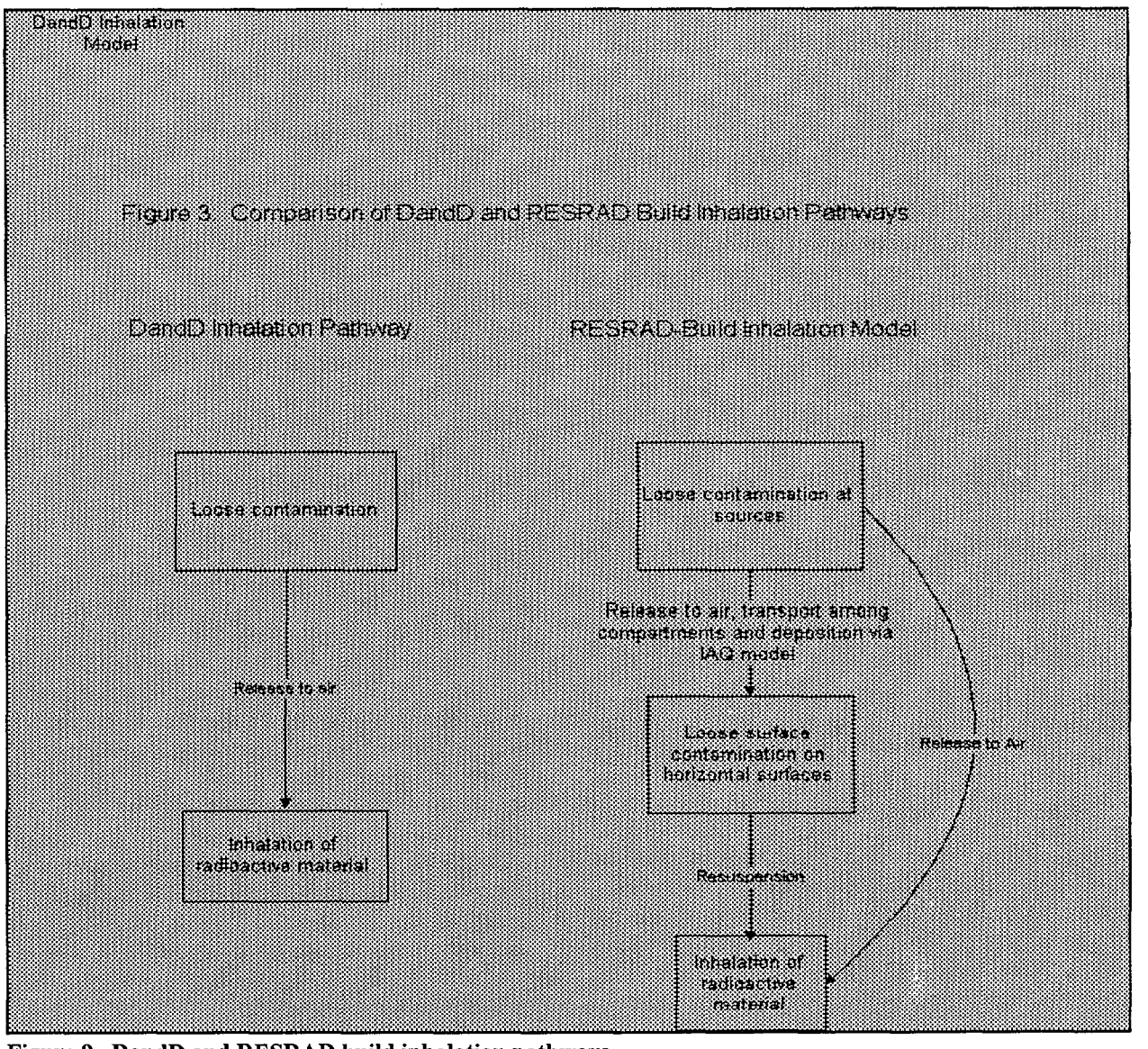

Figure 9. DandD and RESRAD build inhalation pathways

A CEDE is calculated for each receptor. RESRAD-Build 1.50 uses dose conversion factors from DOE (1988).[7] These factors are based on the ICRP-30 system of dosimetry.

The inhalation dose estimates provided by RESRAD-Build 1.50 depend strongly on the relative magnitudes of the *resuspension rate* and *air exchange rates*. Both of these factors will vary by more than an order of magnitude depending on the activities of the building occupants, characteristics of the surface contaminants, and building design and use. Air exchange rates are discussed further in Table 33.

In RESRAD-Build 1.50, the rate of release of radioactive material into a compartment, from a surface, is defined by step functions that are time-dependent. When the elapsed time exceeds a specified value, no loose contamination is assumed to be present, and concentrations of non-radon particulates are assumed to be zero. At lesser times, loose contamination is assumed to be available for release to the air (see Yu, et al., 1994, Eq. D.2).

The step function controlling the rate of release into the structure causes ingestion and inhalation doses estimated

[7]The newer version, RESRAD-BUILD 2.37, uses inhalation coefficients from FGR 11 (EPA, 1998).

by RESRAD-Build 1.50 to have a very different time dependence than DandD 1.0. DandD 1.0 only removes material from the building through radioactive decay. As a consequence, DandD 1.0 ingestion and inhalation dose estimates decline gradually. RESRAD-Build 1.50 ingestion and inhalation doses drop to zero once the time required for removal of loose contamination is exceeded.

The RESRAD-BUILD 1.50 ventilation model also removes a portion of the inventory of radioactive material from the structure, since it assumes that exchange of outdoor air with indoor air occurs. This process removes a portion of airborne radioactive material that would otherwise be redeposited in the structure. RESRAD-BUILD 1.50's ventilation model causes dose rates to drop more quickly than in simulations run in DandD 1.0.

3.2.5 Inhalation – Radon Progeny

The exposure scenario for industrial occupancy given in NUREG/CR-5512 does not address inhalation of radon and radon progeny.

3.2.5.1 DandD 1.0

DandD 1.0 does not directly calculate a dose due to radon progeny released from residual radium contamination.

3.2.5.2 RESRAD-Build 1.50

In the case of an area source, such as that assumed by the occupancy scenario, RESRAD-Build 1.50 assumes a default radon release fraction of 0.1 from an area source. Concentrations of radon progeny are estimated taking into account ingrowth, decay, air exchange rates, attachment, and plate-out (Yu, et al., 1994, Appendix C).

3.2.6 Ingestion

Both DandD 1.0 and RESRAD-Build 1.50 provide estimates of EDE from ingestion of loose surface contamination. However, RESRAD-Build 1.50 models the EDE resulting from this pathway in a more complex manner. It requires additional site-specific data to take advantage of the features of the ingestion dose model. The overall pathways of each model are depicted in Figure 10.

3.2.6.1 DandD 1.0

The DandD 1.0 computer code estimates dose to a building occupant due to incidental ingestion as the product of several factors (Kennedy and Strenge, 1992, Eq. 3.19):

[Dose] = [Exposure duration]

× [Effective Transfer Rate, m^2/h]

× [Ingestion dose factor] (Eq. 4)

× [Average Surface Activity per Unit Area]

The *Effective Transfer Rate* used by DandD 1.0 has the units of m^2/h for the building occupant scenario. Ingestion dose factors are taken from FGR 11 (EPA, 1988). DandD 1.0 computes the final term, Average Surface Activity per Unit Area, from initial concentrations input by the user; it takes into account radioactive decay and ingrowth of radioactive daughters.

3.2.6.2 RESRAD-Build 1.50

RESRAD-Build 1.50 includes two incidental ingestion pathways as described in Appendix E of Yu, et al. (1994). The first means of ingestion depicted in Figure 10 is very similar to the pathway as modeled by DandD 1.0; loose contamination from the original area of contamination is ingested at a specific rate per hour. In RESRAD-Build 1.50, the *Effective Transfer Rate* for this means of ingestion has the units of h^{-1}, while the *Effective Transfer Rate* in DandD 1.0 has the units of m^2/h. The *Effective Transfer Rate* in RESRAD-Build 1.50 multiplied by the area of the contaminated source is comparable to the *Effective Transfer Rate* in DandD 1.0. **Note:** the default *Effective Transfer Rate* for direct ingestion of the source is set to zero in RESRAD-Build 1.50, making this ingestion pathway inactive unless the default is changed by the user.

The second means of ingestion of loose contamination is concerned only with the ingestion of activity that has become airborne, transported throughout the structure via RESRAD-Build 1.50's indoor air quality model, and subsequently deposited on horizontal surfaces (Yu, et al., 1994, Appendices A and B). The *Effective Transfer Rate* for this means of ingestion has the units of m^2/h, which is consistent with DandD 1.0.

The step function discussed in the section 3.2.4 of this report also restricts the ingestion dose to zero for times greater than the time required for removal of loose contamination.

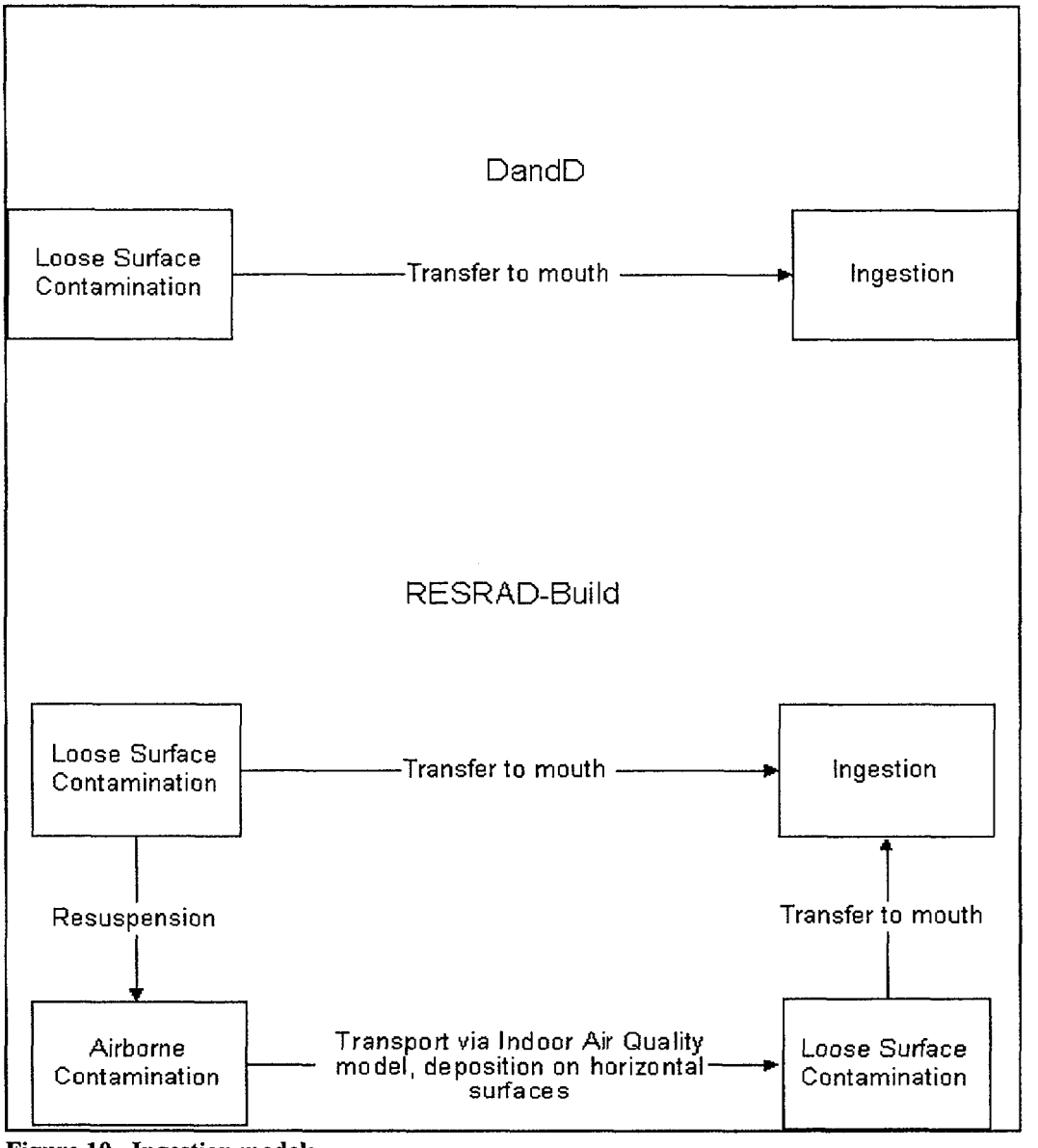

Figure 10. Ingestion models

3.2.7 Industrial Occupant Scenario Parameter Values

To evaluate the building occupancy scenario using DandD 1.0 and RESRAD-Build 1.50, the following parameters are required.

- Dose Conversion Factor for exposure to a planar source of radioactive material,
- Inhalation Dose Conversion Factors,
- Ingestion Dose Conversion Factors,
- Length of the Exposure Period,
- Occupancy Factor (RESRAD-Build 1.50 only),
- Time in Building per Year (DandD 1.0 only),
- Resuspension Factor (DandD 1.0 only),
- Resuspension Rate (RESRAD-Build 1.50 only),
- Volumetric Breathing Rate,

- Effective transfer rate for ingestion (from surfaces to mouth),
- Air Exchange Rates (RESRAD-Build 1.50 only), and
- Radon Release Fraction (RESRAD-Build 1.50 only).

Each of these parameters is provided with default values. Because of differences in the models underlying DandD 1.0 and RESRAD-Build 1.50, not all values are directly comparable. Each of these parameters is discussed in Table 33.

3.2.8 Comparisons of DandD 1.0 and RESRAD Build Simulations for the Industrial Occupant Scenario

3.2.8.1 Approach

A series of 12 DandD 1.0 and RESRAD-Build 1.50 simulations were run to provide a comparison of results when minimal changes are made to default settings and when an effort is made to match input parameters. The following isotopes were included in this evaluation: Pu-238, Pu-239, Cs-137, and Co-60.

Simulations with minimal changes to default values were run with only the following scenario specific changes:

- isotope concentration: 27 pCi/m^2 (1 Bq/m^2), and
- RESRAD-Build 1.50 was set to model surface contamination (volume contamination is the default).

Because RESRAD-Build 1.50 is a kinetic model with many more free parameters than DandD 1.0, undoubtedly there is more than one way to make it resemble DandD 1.0. The changes described below might not have been the best approach to doing this. In the series of simulations where an effort was made to match input data, the following additional changes to default settings were made in RESRAD-Build 1.50:

- Deposition rate = 0
- Resuspension rate = 0,
- Air exchange rate with environment = 14.42 per hour,
- Time for removal of source = 81.59 days,
- Contamination area = building area = 1000 m^2,
- Rate for direct ingestion of source = 1.11E-8 per h,
- Resuspended contamination ingestion rate (e.g. surface ingestion rate) = 0 m^2/h,
- Fraction removable = 1.0,
- Fraction released to air = 1.0,
- Respiration rate = 33.6 m^3/d,
- Fraction of time spent in the building = 0.267.

Selection of these values forced the value of the initial airborne concentration calculated by RESRAD Build to be 1.42E-5 Bq/m^3. This is the concentration that DandD 1.0 would calculate based on a default resuspension factor of 1.42E-5 m^{-1}. It also forced the ingestion rate of surface contamination computed by RESRAD-Build 1.50 to be equal to the DandD 1.0 default value (1.11E-5 m^2/h). The adjustments to the occupancy fraction and volume of air breathed were made to provide consistency with DandD 1.0.

Results of this comparison are provided in Table 34 and depicted in Figures 11, 12, 13, and 14.

3.3 Summary

3.3.1 Residential Farmer Scenario: RESRAD 5.61 and DandD 1.0

RESRAD 5.61 and DandD 1.0 tend to agree for doses resulting from direct irradiation, inhalation, and soil ingestion, provided that an effort is made to match input parameter values.

Because RESRAD 5.61 and DandD 1.0 groundwater models differ in significant ways, the time dependence and magnitude of doses from groundwater pathways tended to be very different in this study. This affected the doses resulting from the irrigation pathways, the drinking pathway, and the aquatic pathway. In general, DandD 1.0 simulations showed contaminants at the well sooner than RESRAD 5.62 simulations, but maximal dose rates were not always higher with one model or the other depending on the relative importance of dispersion and decay on the simulated contaminant concentration. The groundwater models in NUREG/CR-5512 Volume

Table 34. Comparison of results obtained from RESRAD-Build 1.50 and DandD 1.0 simulations for the Industrial Occupant Scenario

Isotope/pathway	RESRAD-Build 1.50 result with minimal changes to defaults, mrem/y	RESRAD-Build 1.50 result with effort to emulate DandD 1.0, mrem/y	DandD 1.0 result, mrem/y	Ratio, DandD 1.0 result to RESRAD-Build 1.50 result (with effort to emulate DandD 1.0)
Cs-137 ingestion	3.28E-4	3.50E-5	3.47E-5	0.99
Cs-137 inhalation	7.89E-5	4.01E-5	3.97E-5	0.99
Cs-137 external	2.45E-4	2.93E-4	4.61E-4	1.57
Cs-137 deposition	1.36E-4	0.0		
Cs-137 total	7.9E-4	3.7E-4	5.36E-4	1.45
Co-60 ingestion	1.51E-4	1.82E-5	1.77E-5	0.97
Co-60 inhalation	3.30E-4	1.88E-4	2.58E-4	1.37
Co-60 external	9.74E-4	1.17E-3	1.85E-3	1.58
Co-60 deposition	4.80E-4	0.0		
Co-60 total	1.9E-3	1.4E-3	2.13E-3	1.52
Pu-238 ingestion	0.0254	2.68E-3	2.24E-3	0.84
Pu-238 inhalation	1.15	0.58	0.49	0.84
Pu-238 external	7.38E-7	6.70E-7	7.02E-7	1.05
Pu-238 deposition	4.18E-7	0.0		
Pu-238 total	1.2	0.58	0.49	0.84
Pu-239 ingestion	0.029	3.01E-3	2.48E-3	0.82
Pu-239 inhalation	1.29	0.64	0.54	0.84
Pu-239 external	4.42E-7	3.00E-7	3.09E-7	1.03
Pu-239 deposition	2.52E-7	0.0		
Pu-239 total	1.32	0.64	0.54	0.84

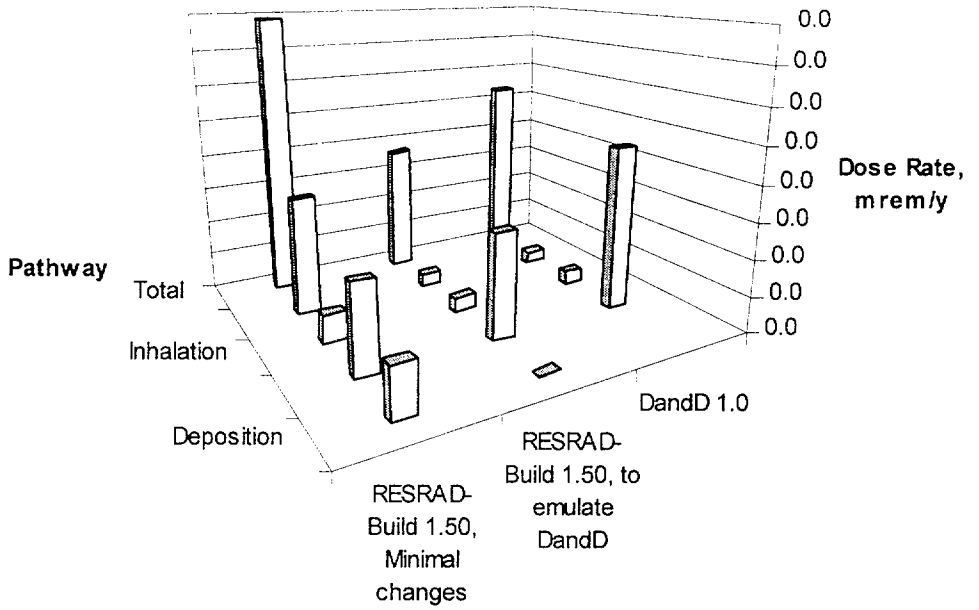

Figure 11. Comparison of RESRAD-Build and DandD results for Cesium-137

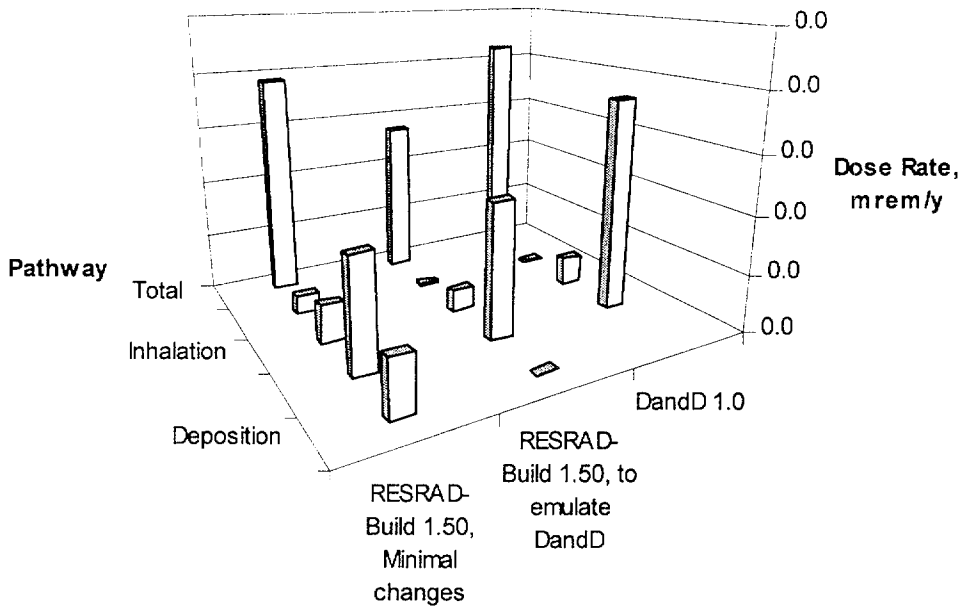

Figure 12. Comparison of RESRAD-Built and DandD results for Cobalt-60

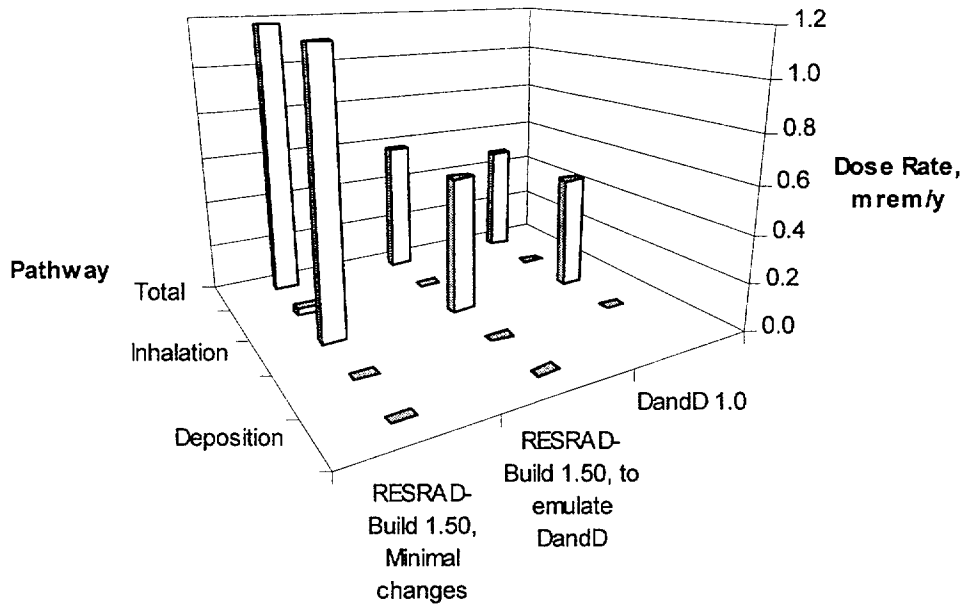

Figure 13. Comparison of RESRAD-Build and DandD results for Pu-238

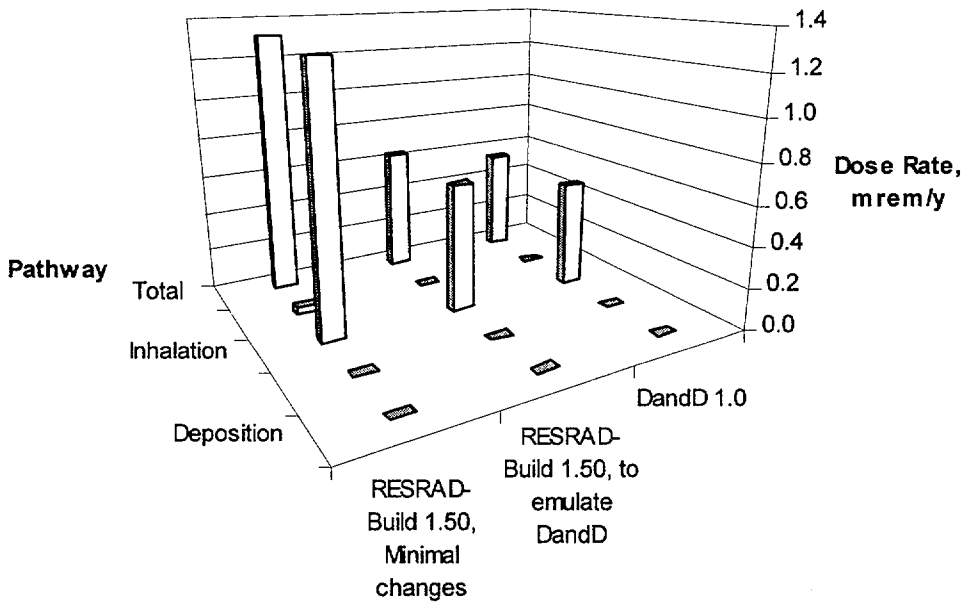

Figure 14. Comparison of RESRAD-Built and DandD results for Pu-239

1 are evaluated in greater detail in NUREG/CR-5621 (Cole et al., 1993).

Tritium and carbon-14 results in DandD 1.0 and RESRAD 5.61 are different, in part because DandD 1.0 lacks a gas or vapor flux model that would deplete the contaminated zone by release of water vapor and volatile carbon compounds to the atmosphere. DandD 1.0 models incorporation of carbon-14 by plants as a root uptake process. In contrast, RESRAD 5.61 assumes that 98% (default) of carbon incorporated into plants is a result of exchange through leaf surfaces.

The lack of a carbon-14 or tritium flux model in DandD 1.0 may cause dose from inhalation to be underestimated. This is a minor exposure pathway for these isotopes in standard residential farmer scenarios, but it could become significant in site-specific scenarios where groundwater is not potable or suitable for irrigation.

Neither DandD 1.0 nor RESRAD 5.61 model the inhalation dose due to diffusion of tritium or carbon-14 from underlying soils into a structure. This potential exposure pathway should be evaluated.

3.3.2 Industrial Occupant Scenario: RESRAD-BUILD 1.50 and DandD 1.0

In the comparison of DandD 1.0 and RESRAD-Build 1.50, there is good agreement between the initial external dose rate results for plutonium isotopes. These isotopes have a low energy 17 KeV x-ray that is rapidly attenuated by air. The size of the contaminated zone used in the comparison, 1000 m^2, is effectively infinite because of this attenuation by air.

The disagreement between initial external dose rate results for cesium-137 and cobalt-60 largely is attributable to the limited size of the contaminated zone. The low attenuation of these gamma rays by air makes a 1000 m^2 area "non-infinite" and this causes RESRAD-Build 1.50 external dose results to be smaller than those predicted by DandD 1.0. The RESRAD-Build 1.50 external dose estimates would be the more realistic.

Initial dose rate estimates for the inhalation and ingestion pathways were in reasonable agreement.

The time dependence of the DandD 1.0 and RESRAD-Build 1.50 models will be very different for two reasons. First, the step function described in section 3.2.5.2 causes all loose (removable) contamination to disappear from the structure after a specified time. Second, the air exchange between the structure and the environment that is included in RESRAD-Build 1.50's indoor air quality model causes removal of loose contamination from the structure.

Both of these factors should cause the dose rate versus time to drop more rapidly in RESRAD-Build 1.50 simulations than in DandD 1.0 simulations.

3.4 Conclusions and Recommendations

This report provides a comparison of the concepts and assumptions in three environmental dose assessment computer codes that have been used to assess compliance with license termination requirements promulgated by the Nuclear Regulatory Commission (NRC) (NRC, 1997). The computer codes compared were DandD 1.0, RESRAD 5.61, and RESRAD-Build 1.50. The comparison was largely limited to two standard exposure scenarios given in NUREG/CR-5512: a residential farmer and an industrial occupant.

The largest source of missed dose in DandD 1.0 simulations is apt to be inhalation of radon and radon-progeny.

DandD 1.0 is specifically designed as a screening model to be used within the NUREG-1549 decision framework. It is not meant to be used to set site-specific clean-up levels. If calculated doses exceed the NRC standard, the user is encouraged not only to change the default parameters to justifiable site-specific values, but more importantly, is directed to consider *site-specific models*. Given that the DandD 1.0 models are both simplistic and defensible with minimal data, site-specific models should virtually always lead to lower doses and higher associated clean up levels and therefore lower costs. The development of default parameter values for DandD 1.0 was based on a systematic, transparent, and quantitative approach that allows the user to bound the risk of making an incorrect decision and at the same time provides a clear starting point for users who need to know the potential value of collecting information prior to collecting it.

Default soil mass loading values in DandD 1.0 for plant foods consumed by humans appear to be implausibly high; the default values for these factors should be reevaluated.

In the residential farmer scenario, DandD 1.0 does not model tritium and carbon-14 in a realistic manner. It neglects inhalation of gaseous forms of these isotopes.

This neglected pathway could be significant in site specific modeling where groundwater is not potable and not suitable for use. Modification of the model to account for gaseous tritium and carbon-14 is recommended.

Neither RESRAD 5.61 nor DandD 1.0 address the inhalation of carbon-14 or tritium that has diffused from underlying soils into structures. The significance of this pathway should be evaluated.

RESRAD 5.61 potentially will provide non-conservative soil guidelines for tritium contaminated debris or soil covered by 30 cm of soil or more. This does not affect RESRAD 5.61's ability to model the residential farmer scenario given in NUREG/CR-5512 however.

RESRAD 5.61 was not specifically designed to evaluate the generic scenarios or criteria for NRC license termination. As a result there are several issues that must be addressed when applying the code to NRC DandD sites, including: translating instantaneous dose rates to average annual dose, irrigation return flow, and appropriateness of parameter values. Because of the large number of options available to the user, NRC should provide guidance to licensees on how RESRAD 5.61 should be set to run simulations on a screening level. This becomes important because some RESRAD 5.61 options, such as the choice of non-dispersive versus mass balance groundwater models, can change the simulation results by more than one order of magnitude.

Both RESRAD 5.61 and RESRAD-Build 1.50 lend themselves to assessing doses to hot-spots of residual contamination more readily than DandD 1.0.

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Appendix A: Comparison of DandD 1.0 and RESRAD 5.61 Simulations

Average Dose Rates Versus Instantaneous Dose Rates

RESRAD 5.61 calculates instantaneous dose rates and reports the result in units of mrem/y. Cleanup standards in 10 CFR 20, Subpart E "Radiological Criteria for License Termination" contain a TEDE criterion for annual dose, and not a limitation of the instantaneous dose rate. The difference between instantaneous dose rates calculated by RESRAD 5.61 and annual average dose should be most marked in the cases of tritium and carbon-14 (which are rapidly lost from surface soils) and short-lived isotopes, such as Zr/Nb-95.

To illustrate the significance of this point, RESRAD 5.61 was run twice for a residential farmer scenario involving tritium. In one instance, the annual dose rate for the first year was taken to be the instantaneous dose rate at 0.5 years (the midpoint). In the other instance, the dose rate for the first year was taken to be the average of the instantaneous dose rates calculated by RESRAD 5.61 at 0 y, 0.2 y, 0.4 y, 0.6 y, 0.8 y, and 1.0 y. The results of the two simulations are provided in Table A.1. Changes from default settings used to run these simulations are provided in Table A.2.

Comparison of the two simulations shows that the RESRAD 5.61 convention of reporting instantaneous rates can lead to difficulties in interpreting the results for the purposes of determining compliance with 10 CFR 20, Subpart E. Using the maximal instantaneous dose rate may result in rather high annual dose estimates for short-lived isotopes and isotopes which are rapidly lost from surface soils. It is suggested that RESRAD 5.61 be modified to report annual dose so that direct comparison with regulatory limits can be made.

Comparison of DandD 1.0 and RESRAD 5.61 Simulations

A comparison of DandD 1.0 and RESRAD 5.61 was completed for residential farmer scenarios for a variety of isotopes. This involved a comparison of :

- time dependence,
- results when only minimal changes were made to default values,
- a series of simulations involving wet climate sites, and
- a series of simulations involving dry climate sites.

The wet and dry climate site comparisons were made with an effort to ensure the input values of the two computer codes were comparable.

The comparison involved the following isotopes:

- Tritium and carbon-14 (both RESRAD 5.61 and DandD 1.0 have special models for these isotopes),
- Cs-137/Ba-137m,
- Radium-226 in equilibrium with radon-222 and progeny (RESRAD 5.61 has a special model for radon while DandD 1.0 does not),
- Thorium-232 in equilibrium with radon-220 and progeny,
- Cobalt-60.

DandD 1.0 simulations were used to estimate doses for the first year (0 – 365.25 days) and the fifth year (1461 – 1826.25 days) to provide a comparison of doses at different time periods. The resulting values were compared directly to RESRAD 5.61 dose rate estimates at 0.5 years and at 4.5 years. Simulations were also run for longer time periods so that each model would provide a maximum dose rate estimate.

Comparison of DandD 1.0 and RESRAD 5.61 Results for a Residential Farmer With Minimal Changes to Default Values

Approach

For this series of comparisons, DandD 1.0 was run with the changes to default values given in Table A.3. RESRAD 5.61 was run with the changes to default values given in Table A.4.

Results

Simulation results are provided in Table A.5 (tritium), Table A.6 (C-14), Table A.7 (Cs-137), and Table A.8 (Ra-226 chain).

Comparison of DandD 1.0 and RESRAD 5.61 Results for a Residential Farmer in Dry Climatic Conditions

Approach

For this series of comparisons, DandD1.0 was run with the changes to default values given in Tables A.3 and A.9. RESRAD 5.61 was run with the changes to default values given in Tables A.2 and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0.

Results

Simulation results are provided in Table A.10 (tritium), Table A.11 (C-14), Table A.12 (Cs-137), Table A.13 (Ra-226 chain), Table A.14 (Th-232), and Table A.15 (Co-60).

Comparison of DandD 1.0 and RESRAD 5.61 Results for a Residential Farmer in Wet Climatic Conditions

Approach

For this series of comparisons, DandD1.0 was run with the changes to default values given in Tables A.3 and A.16. RESRAD 5.61 was run with the changes to default values given in Tables A.4 and A.17. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0.

Results

Simulation results are provided in Table A.18 (tritium), Table A.19 (C-14), Table A.21 (Cs-137), and Table A.22 (Ra-226 chain Th232 and Co60).

Discussion

Groundwater Pathways

A primary difference in the water pathway calculations performed by DandD 1.0 and RESRAD 5.61 can be attributed to the method in which they model the unsaturated zone.

DandD 1.0 uses a well-mixed linear reservoir model, which has an inherent dispersion term in it. This causes the arrival time for radionuclides from the contaminated zone to the aquifer to be zero. Thus, DandD 1.0 simulations show radionuclides reaching the aquifer in a very short time, but at a low mass flow rate.

The unsaturated zone model in RESRAD 5.61 is based on travel time from the contaminated zone to the aquifer. This means that no radionuclides can reach the aquifer until the model simulation time exceeds the travel time. The travel time in RESRAD 5.61 is proportional to the retardation coefficient. A radionuclide, such as tritium, has a retardation coefficient of 1 because it is not adsorbed onto soil particles and, thus, travels through the unsaturated zone at the same speed as water. Carbon-14 and other radionuclides are retarded, so they take much longer to reach the water table in the RESRAD 5.61 model. This is why doses were not seen for water-dependent pathways at one year or five years for isotopes other than tritium.

Soil Ingestion

Soil ingestion doses were twice as high in RESRAD 5.61 simulations than in DandD 1.0 simulations. Upon inspection, it was determined that RESRAD 5.61 soil ingestion rates were set at the default value of 100 mg/day; this is twice as high as the DandD 1.0 default soil ingestion rates (50 mg/d). There would have been no significant difference in doses calculated for soil ingestion if consistent soil ingestion rates had been used in the comparison.

Inhalation

DandD 1.0 inhalation doses were approximately 50% higher than those calculated by RESRAD 5.61 even after the RESRAD 5.61 occupancy factors and the inhalation shielding factor were adjusted for consistency with DandD 1.0. The difference in inhalation doses largely is attributable to the RESRAD 5.61's use of a single respiration rate, while DandD 1.0 uses activity specific respiration rates for indoor, outdoor, and gardening activities.

Inhalation dose results of DandD 1.0 and RESRAD 5.61 are not comparable for radon, carbon-14, and tritium because DandD 1.0 does not have a flux model that simulates release of these isotopes to the atmosphere.

External Dose Rates

In this comparison, the primary differences in external dose rate estimates generated by DandD 1.0 and RESRAD 5.61 resulted from two factors:

- the residential shielding factors in RESRAD 5.61 and DandD 1.0 were not adjusted to be consistent with one another; DandD 1.0 was run with an external shielding factor of 0.5512 (the default value) while RESRAD 5.61 was run with an external shielding factor of 0.7 (the default value);
- DandD 1.0 does not apply a soil density correction to external dose rates; the density of soils in this study were assumed to be 1.431 g/cm^3 while the external dose conversion factor data in DandD 1.0 are based on a soil density of 1.6 g/cm^3 a density to match the value used in RESRAD for the unsaturated zone.

External doses calculated by both RESRAD 5.61 and DandD 1.0 agree well with one another when residential shielding factors and occupancy factors are assigned consistent values. The external dose results of both codes agree well with those calculated by Microshield® version 5.03 (see Table A.25).

Agricultural Pathway Doses

In this study, doses from the agricultural pathways calculated by DandD 1.0 tended to be much higher than those calculated by RESRAD 5.61. This is primarily due to the differences in the plant mass loading assumptions of the two models. RESRAD 5.61 models the plant mass loading as the net result of two processes: (1) deposition of resuspended soil on edible portions of plant foods at a constant rate, and (2) removal of soil from surfaces according to a first order (exponential) process. DandD 1.0 assumes a default plant mass loading of 10%, and this plant mass loading dominates the agricultural pathway for many isotopes.

Smaller differences in the simulated doses in this study are due to the differences in how the diet of food grown on the contaminated site is modeled. These differences occur in both the composition of the diet and transfer factors. The primary difference between DandD 1.0 and RESRAD 5.61 values for consumption rates of homegrown foods are that the DandD 1.0 values are based on production and consumption values for the specified critical group (people who garden), while RESRAD 5.61 values are based on national average consumption rates and the assumption that 50% of the entire diet is grown on site

Tritium

The results for a residential farmer scenario involving tritium, with minimal changes to defaults (see Table A.5), differed by a factor of more than 100,000 for the initial year, with DandD 1.0 providing the higher result. This result is based on the convention used throughout this report of comparing DandD 1.0 annual doses with RESRAD 5.61 mid-year dose rates. For this scenario, agreement is much better between DandD 1.0 annual dose for the first year (317 mrem/y) and the *initial* dose rate calculated by RESRAD5.61(4.8 mrem). For the fifth year of the scenario the results were in reasonable agreement; the DandD 1.0 result was only a factor of 5 higher than the RESRAD 5.61 result. A similar trend is seen in the residential farmer scenario involving tritium under dry climate conditions (see Table A.10) or wet climate conditions (see Table A.18).

It must be remembered that DandD 1.0 estimates the dose received in a year, while RESRAD 5.61 reports an instantaneous dose rate. Because RESRAD 5.61 rapidly transports tritium out of the contaminated zone and the codes have a different dose reporting basis the time dependence of the dose values reported by the two codes are different.

Carbon-14

The results for the residential farmer scenario involving carbon-14, with minimal changes to defaults, differed by a factor of more than 20,000,000 for the initial year, with DandD 1.0 providing the higher result (see Table A.6). For the fifth year of the scenario, the results were in better agreement, although the DandD 1.0 result still was a factor of 13 higher than the RESRAD 5.61 result. The results for the residential farmer scenario for a dry climate (see Table A.11) and wet climate (see Table A.19) obtained from DandD 1.0 and RESRAD 5.61 were not in good agreement for the irrigation, agricultural and aquatic pathways.

For all of the DandD 1.0 simulations involving a residential farmer scenario with carbon-14, the agricultural, irrigation, and aquatic pathways tended to be predominant. This is partly due to the absence of a carbon-14 flux model in DandD 1.0 that would allow loss to the atmosphere.

The results obtained from RESRAD 5.61 depend strongly on the reference evasion depth assumed for carbon-14. This factor determines the maximum depth from which carbon-14 can be lost via flux to the

atmosphere (default 0.3 m). The RESRAD 5.61 results also depend strongly on the relative fractions of carbon assimilated by the plant from the soil and the atmosphere (defaults: soil 2%, plant 98%). The RESRAD 5.61 results provided in Table A.19 were obtained with both the reference depth and assimilation fractions set to the default values.

It is not reasonable to do so, but running RESRAD 5.61 for this scenario with the reference evasion depth set to 0 and the fraction of carbon assimilated from the soil to 100%, improves agreement with DandD 1.0, as shown in Table A.20. These changes to default parameters set the carbon-14 flux to the atmosphere to zero, and set the carbon dioxide absorption rate through leaf surfaces to zero to more closely mimic the model used in DandD 1.0.

The initially higher dose rates due to the aquatic pathway in DandD 1.0 are partly due to the faster transport of carbon-14 to groundwater relative to the transport rate associated with the RESRAD 5.61 mass balance model. Since carbon-14 moves rapidly through environmental media, the different dose rate reporting bases of the two models precludes direct comparison of the results.

Cesium-137

The results for a residential farmer scenario involving cesium-137, with minimal changes to defaults, initially were in reasonable agreement. The result DandD 1.0 provided was a factor of three greater than the RESRAD 5.61 result. However, for the fifth year of the scenario, the difference was much larger. The DandD 1.0 result was about 15 times greater than the RESRAD 5.61 result. This difference primarily is due to the much higher doses calculated for the aquatic and irrigation pathways by DandD 1.0.

Radium-226 in Secular Equilibrium with Progeny

The overall results for a residential farmer scenario involving radium-226 initially were in good agreement. However, there are large differences in the distribution of dose among pathways (see Tables A.8, A.13, and A.22). DandD 1.0 simulations suggested that agricultural pathways were the dominant source of dose to a residential farmer.

In the case of radium-226 in a dry climate, the dose calculated by DandD 1.0 from the agricultural pathway is almost entirely due to soil mass loading on foods. Better agreement between RESRAD 5.61 and DandD 1.0 is obtained for this pathway when plant mass loading is changed in DandD 1.0 from the default value of 0.1 to 0.01.

In the 5.61 simulations doses from inhalation of radon and radon progeny were the dominant exposure pathway. DandD 1.0 does not have a radon gas flux model, this causes DandD 1.0 to underestimate inhalation doses due to radon.

Thorium-232 in Secular Equilibrium with Progeny

The overall results for the residential farmer scenarios involving thorium-232 did not give good agreement when default values of plant mass loading were used. Adjusting the DandD 1.0 plant mass loading value to 0.01 and decreasing the fraction of foods grown onsite from the default values to approximate the diet in RESRAD results in significantly closer results. These adjustments cause the agricultural pathway doses calculated by DandD 1.0 for the residential farmer-dry climate scenario (Table A.14) to drop from 19,400 mrem/y to 1,220 mrem. For comparison, RESRAD 5.61 estimated the doses for this pathway to be 999 mrem/y.

Co-60

The overall results for the residential farmer scenarios involving Co-60 did not give good agreement when default values of plant mass loading were used. Adjusting the DandD 1.0 plant mass loading value to 0.01, and decreasing the fraction of foods grown onsite yields similar results for the agricultural pathway. These adjustments cause the agricultural pathway doses calculated by DandD 1.0 for the residential farmer-dry climate scenario to drop from 667 mrem/y to 292 mrem/y; for comparison, RESRAD 5.61 estimated the doses for this pathway to be 54 mrem/y.

Table A.1. Comparison of annualized dose for a residential farmer for a scenario involving tritium using RESRAD 5.61

Time (y)	Instantaneous Dose Rates (mrem/y)	Instantaneous Dose Rate at Interval Mid-Point (mrem/y)
0.0	5.055	
0.2	0.410	
0.4	3.33E-2	
0.5	--	9.49E-3
0.6	2.70E-3	
0.8	2.20E-4	
1.0	1.78E-5	
Annual estimate*	1.10 (arithmetic mean)	9.49E-3 (mid-point)

* Of course, users of RESRAD 5.61 could use more sophisticated means of estimating annual dose than those presented in Table A-1.

Table A.2. Changes to default settings used to run RESRAD 5.61 for comparison of estimated annualized and instantaneous doses. Scenario: Residential farmer, dry site, mass balance groundwater concentrations

Factor	Setting	Remarks
Contaminated zone thickness, m	0.15	Chosen for consistency with DandD 1.0
Initial Tritium Concentration, pCi/g	1000	Scenario value
Density of all zones, g/cm^3	1.431	Chosen for consistency with DandD 1.0
Total porosity of all zones	0.4599	Chosen for consistency with DandD 1.0
Effective porosity of all zones	0.4599	Chosen for consistency with DandD 1.0
Evapotranspiration coefficient	0.95	Scenario value
Precipitation Rate, m/y	0.2	Scenario value
Irrigation Rate, m/y	1.0	Scenario value
Runoff coefficient	0.4	Scenario value
Watershed area for nearby stream or pond, m^2.	10,000	Scenario value
Thickness of unsaturated zone, m	1.229	Chosen for consistency with DandD 1.0
Well pumping rate, m^3/y	1.012E4	Scenario value
Groundwater model	mass balance	Chosen for consistency with DandD 1.0
Watertable drop rate, m/y	0	Chosen for consistency with DandD 1.0
Mass loading for inhalation, mg/m^3	0.030	Chosen for consistency with DandD 1.0
Inhalation shielding factor	0.062	Chosen for consistency with DandD 1.0
Fraction of time spent indoors	0.6571	Chosen for consistency with DandD 1.0
Fraction of time spent outdoors (onsite)	0.1181	Chosen for consistency with DandD 1.0

Table A.3. DandD 1.0 changes to defaults values in residential farmer scenario

Factor	Value	Remarks
H-3	1,000 pCi/g	

Table A.3. DandD 1.0 changes to defaults values in residential farmer scenario

Factor	Value	Remarks
C-14	1,000 pCi/g	
Cs-137/Ba-137m	1,000 pCi/g	
Ra-226 + chain	1,000 pCi/g	
start time (first year), d	365.25	Times chosen to ensure that DandD 1.0 gave the dose for the time interval of interest.
stop time (first year), d	365.25	
start time (fifth year), d	1461	
stop time (fifth year), d	1826.25	

Table A.4. RESRAD5.61 changes to defaults values in residential farmer scenario

Factor	Value	Remarks
H-3	1,000 pCi/g	
C-14	1,000 pCi/g	
Cs-137/Ba-137m	1,000 pCi/g	
Ra-226 + chain	1,000 pCi/g	
dose rate evaluation time (first year), y	0.5	Time corresponds to midpoint of first year.
dose rate evaluation time (fifth year), y	4.5	Time corresponds to midpoint of fifth year.
Thickness of contaminated zone, m	0.15	Chosen to make source term and geometry comparable to DandD 1.0.

Table A.5. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving tritium, with the changes to default values given in Tables A.3 and A.4

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Inhalation	3.89E-6	0	1.49E-4	0.0
Plant	NA	NA	1.38E-3	0.0
Meat	NA	NA	1.96E-4	0.0
Milk	NA	NA	1.75E-4	0.0
Soil Ingestion	8.81E-4	1.60E-5	6.99E-7	0.0
Water	6.04	5.34	0.0	2.853
Fish / Aquatic	0.127	0.113	0.0	1.76E-4
Irrig water → → Plant	NA	NA	0.0	0.121
Irrig water → → Meat	NA	NA	0.0	6.27E-2
Irrig water → → Milk	NA	NA	0.0	0.188
Irrigation pathways	5.36	4.74	NA	NA
Agriculture	305	5.54	NA	NA
Total	317	15.7	1.92E-3	3.26

Table A.6. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving carbon-14, with the changes to default values given in Tables A.3 and A.4

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6.57E-3	5.27E-4	0	0
Inhalation	1.28E-4	1.03E-5	0	0
Plant	NA	NA	4.31E-5	0
Meat	NA	NA	1.00E-5	0
Milk	NA	NA	4.28E-6	0
Soil Ingestion	2.95E-2	2.37E-3	0	0
Water	10.6	57.5	0	120
Fish / Aquatic	1,030	5,580	0	327
Irrig water → → Plant	NA	NA	0	22.3
Irrig water → → Meat	NA	NA	0	8.01
Irrig water → → Milk	NA	NA	0	18.4
Irrigation pathways	150	813	NA	NA
Agriculture	119	9.58	NA	NA
Total	1,310	6,460	5.74E-5	495

Table A.7. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Cs-137, with the changes to default values given in Tables A.3 and A.4

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	1,460	169	1,750	1,570
Inhalation	1.96E-3	2.27E-4	2.30E-2	2.03E-2
Plant	NA	NA	28.6	25.1
Meat	NA	NA	44.3	38.9
Milk	NA	NA	15.7	13.8
Soil Ingestion	0.70	8.10E-2	1.35	1.18
Water	58.0	550	0	0
Fish / Aquatic	2,440	23,200	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	396	3,760	NA	NA
Agriculture	567	65.6	NA	NA
Total	4,930	27,800	1,840	1,650

Table A.8. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Ra-226 + chain, with the changes to default values given in Tables A.3 and A.4

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	4,610	4,540	5,530	4,830
Inhalation	1.98	1.86	23.0	20.2
Radon	NA	NA	25,450	22,010
Plant	NA	NA	1,800	1,580
Meat	NA	NA	151	133
Milk	NA	NA	111	96.8
Soil Ingestion	123	117	232	205
Water	326	1,110	0	0
Fish / Aquatic	2450	8,870	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	475	1,530	NA	NA
Agriculture	40,400	38,600	NA	NA
Total	48,400	54,700	33,300	28,900

Table A.9. Changes to default parameters used in DandD 1.0 simulations for a residential farmer scenario in a dry climate

Factor	Setting
Surface layer ratio	0.683
Unsaturated zone ratio	0.683
Infiltration rate,	0.056
Cultivated area, m^2	10,000
Irrigation rate, L/m^2d	2.738

Table A.10. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving tritium in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Inhalation	3.89E-6	2.87E-7	1.46E-3	0
Plant	NA	NA	6.33E-3	0
Meat	NA	NA	8.99E-4	0
Milk	NA	NA	8.02E-4	0

Table A.10. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving tritium in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Soil Ingestion	8.81E-4	6.50E-5	3.40E-6	0
Water	1.03E-1	5.67E-1	0	0
Fish / Aquatic	3.93E-3	2.16E-2	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	9.15E-2	5.04E-1	NA	NA
Agriculture	305	22.5	NA	NA
Total	306	23.6	9.49E-3	1.47E-24

Table A.11. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving carbon-14 in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6.57E-3	4.75E-3	0	0
Inhalation	1.28E-4	9.29E-5	5.79E-6	0
Plant	NA	NA	7.22E-3	0
Meat	NA	NA	1.68E-3	0
Milk	NA	NA	7.17E-4	0
Soil Ingestion	2.95E-2	2.14E-2	0	0
Water	2.24E-2	5.14E-1	0	0
Fish / Aquatic	3.93	90.3	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	6.49E-1	1.49	NA	NA
Agriculture	119	86.3	NA	NA
Total	124	192	9.62E-3	0

Table A.12. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving cesium-137 in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	1460	1160	1,650	1,370
Inhalation	1.96E-3	1.55E-3	1.21E-3	1.00E-3
Plant	NA	NA	28.3	23.4
Meat	NA	NA	44.0	36.4
Milk	NA	NA	15.6	12.9
Soil Ingestion	6.99E-1	5.54E-1	1.38	1.14
Water	9.91E-2	2.27	0	
Fish / Aquatic	7.56	173	0	
Irrig water → → Plant	NA	NA	0	
Irrig water → → Meat	NA	NA	0	
Irrig water → → Milk	NA	NA	0	
Irrigation pathways	1.40	31.9	NA	NA
Agriculture	567	449	NA	NA
Total	2040	1820	1,741	1,440

Table A.13. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Ra-226 + chain in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	4610	4600	5,340	5,330
Inhalation	1.98	1.96	1.24	1.24
Radon	NA	NA	30,800	30,700
Plant	NA	NA	1,834	1,830
Meat	NA	NA	153	153
Milk	NA	NA	113	113
Soil Ingestion	123	123	243	243
Water	5.52E-1	2.02	0	0
Fish / Aquatic	7.05	28.5	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	1.74	5.84	NA	NA

Table A.13. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Ra-226 + chain in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0 (continued)

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Agriculture	40,400	40,200	NA	NA
Total	45,200	45,000	38,500	38,400

Table A.14. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Th-232 + chain in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6,530	6,490	7,590	7,560
Inhalation	122	121	77.3	76.6
Radon	NA	NA	338	332
Plant	NA	NA	892	889
Meat	NA	NA	49.0	48.8
Milk	NA	NA	57.6	57.5
Soil Ingestion	70.5	69.8	141	140
Water	0.058	1.45	0	0
Fish / Aquatic	0.21	5.36	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	0.20	5.11	NA	NA
Agriculture	19,400	19,200	NA	NA
Total	26,100	25,900	9,140	9,110

Table A.15. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Co-60 in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6,200	3,660	7,090	4,189
Inhalation	1.3E-2	7.7E-3	8.0E-3	4.7E-3

Table A.15. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Co-60 in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0 (continued)

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Radon	NA	NA	NA	NA
Plant	NA	NA	29.1	17.2
Meat	NA	NA	22.0	13.0
Milk	NA	NA	2.83	1.67
Soil Ingestion	0.36	0.21	0.71	0.42
Water	2.6E-6	4.1E-5	0	0
Fish / Aquatic	3.2E-5	5.2E-4	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	2.0E-5	3.2E-4	NA	NA
Agriculture	667	394	NA	NA
Total	6,870	4,060	7,150	4,220

Table A.16. Changes to default parameters used in DandD 1.0 simulations for a residential farmer scenario in a wet climate

Factor	Setting	Remarks
Surface layer ratio	0.7727	Based on equations given in RESRAD 5.61 users manual (Yu, et al. 1993)
Unsaturated zone ratio	0.7727	Based on equations given in RESRAD 5.61 users manual (Yu, et al. 1993)
Infiltration rate,	0.30	
Cultivated area, m^2	10,000	
Irrigation rate, L/m^2d	0	

Table A.17. Changes to Default settings used to run RESRAD 5.61 simulations for scenarios involving a residential farmer, wet site, mass balance groundwater concentrations

Factor	Setting	Remarks
Contaminated zone thickness, m	0.15	Chosen for consistency with DandD 1.0
Density of all zones, g/cm^3	1.431	Chosen for consistency with DandD 1.0
Total porosity of all zones	0.4599	Chosen for consistency with DandD 1.0
Effective porosity of all zones	0.4599	Chosen for consistency with DandD 1.0
Evapotranspiration coefficient	0.50	

Table A.17. Changes to Default settings used to run RESRAD 5.61 simulations for scenarios involving a residential farmer, wet site, mass balance groundwater concentrations (continued)

Factor	Setting	Remarks
Precipitation Rate, m/y	1.0	
Irrigation Rate, m/y	0.0	
Runoff coefficient	0.4	
Watershed area for nearby stream or pond, m^2	10,000	
Thickness of unsaturated zone, m	1.229	Chosen for consistency with DandD 1.0
Well pumping rate, m^3/y	118	
Groundwater model	mass balance	Chosen for consistency with DandD 1.0
Mass loading for inhalation, mg/m^3	0.030	Chosen for consistency with DandD 1.0
Inhalation shielding factor	0.062	Chosen for consistency with DandD 1.0
Fraction of time spent indoors	0.6571	Chosen for consistency with DandD 1.0
Fraction of time spent outdoors (onsite)	0.1181	Chosen for consistency with DandD 1.0

Table A.18. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving tritium in a wet climate

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Inhalation	3.89E-6	5.20E-16	2.75E-3	0
Plant	NA	NA	4.25E-2	0
Meat	NA	NA	6.04E-3	0
Milk	NA	NA	5.39E-3	0
Soil Ingestion	8.81E-4	1.18E-13	2.58E-5	0
Water	3.19	1.45	0	3.80E-6
Fish / Aquatic	9.58E-2	4.36E-2	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	2.82	1.28	NA	NA
Agriculture	305	4.08E-8	NA	NA
Total	311	2.78	5.66E-2	4.13E-6

Table A.19. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving carbon-14 in a wet climate

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6.57E-3	1.39E-3	0	0
Inhalation	1.28E-4	2.72E-5	5.11E-6	0
Plant	NA	NA	6.38E-3	0

Table A.19. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving carbon-14 in a wet climate

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Meat	NA	NA	1.48E-3	0
Milk	NA	NA	6.34E-4	0
Soil Ingestion	2.95E-2	6.25E-3	0	0
Water	1.55	21.9	0	0
Fish / Aquatic	214	3020	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	1.43	20.1	NA	NA
Agriculture	119	25.3	NA	NA
Total	337	3090	8.51E-3	0

Table A.20. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving carbon-14 in a wet climate. RESRAD 5.61 was run assuming the reference depth for carbon-14 flux to be zero, and that carbon is only assimilated through the root systems of plants

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6.57E-3	1.39E-3	6.64E-3	2.0E-3
Inhalation	1.28E-4	2.72E-5	7.0E-5	2.1E-5
Plant	NA	NA	325	96.2
Meat	NA	NA	75.6	22.3
Milk	NA	NA	32.4	9.57
Soil Ingestion	2.95E-2	6.25E-3	0.051	1.5E-2
Water	1.55	21.9	0	0
Fish / Aquatic	214	3020	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	1.43	20.1	NA	NA
Agriculture	119	25.3	NA	NA
Total	337	3090	433	128

Table A.21. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving cesium-137 in a wet climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	1,460	683	1,570	849
Inhalation	1.96E-3	9.14E-4	1.15E-3	6.22E-4
Plant	NA	NA	26.9	14.6
Meat	NA	NA	41.7	22.6
Milk	NA	NA	14.8	8.01
Soil Ingestion	6.99E-1	3.27E-1	1.31	0.71
Water	7.22	131	0	0
Fish / Aquatic	433	7,890	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	2.62	47.7	NA	NA
Agriculture	567	265	NA	NA
Total	2,470	9,020	1,650	895

Table A.22. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Ra-226 + chain in a wet climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	4,610	4,590	5,340	5,320
Inhalation	1.98	1.94	1.23	1.23
Radon	NA	NA	30,800	30,700
Plant	NA	NA	1,830	1,830
Meat	NA	NA	153	153
Milk	NA	NA	113	112
Soil Ingestion	123	121	243	243
Water	40.2	145	0	0
Fish / Aquatic	410	1610	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	2.97	11.7	NA	NA
Agriculture	40,400	39,800	NA	NA
Total	45,600	46,300	38,500	38,300

Table A.23. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Th-232 + chain in a wet climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6,530	6,360	7,571	7,414
Inhalation	122	116	76.9	73.7
Radon	NA	NA	332	324
Plant	NA	NA	891	878
Meat	NA	NA	48.9	48.1
Milk	NA	NA	57.6	56.8
Soil Ingestion	70.5	67.5	140	136
Water	4.35	107	0	0
Fish / Aquatic	12.7	311	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	6.64E-003	0.165	NA	NA
Agriculture	19,400	18,600	NA	NA
Total	26,100	25,500	9,120	8,930

Table A.24. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Co-60 in a wet climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6,200	3,650	7,090	4,170
Inhalation	1.31E-2	7.71E-3	8.0E-3	4.7E-3
Radon	NA	NA	NA	NA
Plant	NA	NA	29.1	17.1
Meat	NA	NA	21.9	12.9
Milk	NA	NA	2.83	1.67
Soil Ingestion	0.357	2.10E-1	0.71	0.42
Water	1.94E-4	3.13E-3	0	0
Fish / Aquatic	1.92E-3	3.1E-2	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	2.91E-5	4.69E-4	NA	NA
Agriculture	667	393	NA	NA
Total	6,870	4,040	7,140	4,210

Table A.25. Comparison of External Radiation dose results from RESRAD 5.61, DandD 1.0, and Microshield 5.03. Default values are given in parenthesis.

Factor	DandD 1.0	RESRAD 5.61
Indoor exposure time (days)	(240)	240 (182.5)
Outdoor exposure time (days)	(40.2)	43.12 (91.25)
Gardening exposure time (days)	(2.92)	---
Gamma shielding factor	(0.5512)	(0.7)
Cs-137 result (mrem/y) for 1000 pCi/g soil	1,460 (see Table A.7)	1,778 (see Table A.7)
Microshield result (mrem/y) for 1000 pCi/g Cs-137	1,391	1,672
Ra-226 + chain result (mrem/y) for 1000 pCi/g soil	4,610 (see Table A.8)	5,530 (see Table A.8)
Microshield result (mrem/y) for 1000 pCi/g Ra-226 + chain	4,358	5,239

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C. Daily, NRC Project Manager

11. ABSTRACT *(200 words or less)*

This report provides a detailed comparison of the models, simplifying assumptions, and default parameter values implemented by the DandD 1.0, RESRAD 5.61, and RESRAD Build 1.50 computer codes. Each of these codes is a potentially useful tool for demonstrating compliance with the License Termination Rule, 10 CFR 20, Subpart E. The comparison was limited to the industrial occupant and residential farmer scenarios defined in NUREG/CR-5512, Volume 1. This report is intended to describe where and how the models and default parameter values in each of the codes differ for the specified scenarios. Strengths, weaknesses and limitations of the models are identified. The practical impacts of the identified differences to dose assessment results are discussed.

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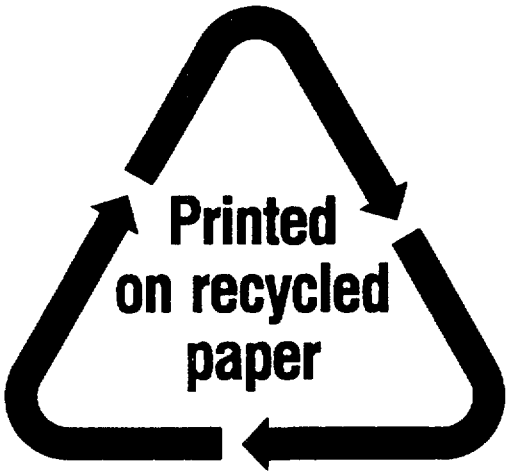

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