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August 2007

Biosphere Model Report

Prepared for:
U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Office of Repository Development
1551 Hillshire Drive
Las Vegas, Nevada 89134-6321

Prepared by:
Sandia National Laboratories
OCRWM Lead Laboratory for Repository Systems
1180 Town Center Drive
Las Vegas, Nevada 89144

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ACKNOWLEDGMENTS

This report describes the biosphere model, which was jointly developed by the biosphere modeling team. The following team members contributed to the development of the biosphere model and its input parameters:

Kaylie E. Rasmuson

Kurt R. Rautenstrauch

Anthony J. Smith

Maryla A. Wasiolek

D. Wesley Wu

The document checking support and helpful comments of Alicia Aragon, Sandia National Laboratories, and of John Arnish, Argonne National Laboratory are gratefully appreciated.

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Model Signature Page/Change History

only applicable items.

1. Total Pages: 720

2. Type of Mathematical Model

☒ Process Model ☐ Abstraction Model ☐ System Model

Describe Intended Use of Model

The biosphere model is used to calculate the groundwater and volcanic biosphere dose conversion factors. The biosphere dose conversion factors are used as inputs to the TSPA model, which allow calculation of annual radiation dose to a defined receptor from radionuclide concentrations in the groundwater and in volcanic ash deposited in surface soil.

3. Title

Biosphere Model Report

4. DI (including Revision No. and Addendum No.):

MDL-MGR-MD-000001 REV 02

	Printed Name	Signature	Date
5. Originator	Maryla A. Wasiolek	[signature]	8-23-07
6. Independent Technical Reviewer	for Jean Younker	[signature]	8/23/07
7. Checker	Anthony J. Smith (Lead Checker)	[signature]	23Aug07
8. QCS/Lead Lab QA Reviewer	Peter Persoff	[signature]	08/23/2007
9. Responsible Manager/Lead	Kenneth R. Rehfeldt	[signature]	08/23/2007
10. Responsible Manager	Stephanie P. Kuzio	[signature]	08/23/2007

11. Remarks

Change History

12. Revision No. and Addendum No.	13. Description of Change
Rev 00	Initial issue
Rev 01	Revised to incorporate Regulatory Integration Team evaluation comments, to provide better transparency and traceability, include specific items from the YMRP, revise citations to reflect most recent documentation, and comply with revisions in procedures. No changes were made to the product output (the model) but changes were too extensive to use step 5.8(f)(1) per AP-SIII.10Q Rev 2 ICN 7.
Rev 02	Revised to incorporate modified surface soil submodel in the model for the groundwater exposure scenario; double source term in the model for the volcanic ash exposure scenario; results of biosphere dose conversion factor calculation for both exposure scenarios; importance and sensitivity analysis for both exposure scenarios; development of dose factors for groundwater protection standards and development of inhalation dose factors for a volcanic event. The entire model documentation was revised; changes were too extensive to use step 6.8.3.A of SCI-PRO-006. Appendix A includes one compact disk read-only memory.

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CONTENTS

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

FIGURES

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

TABLES

Page

TABLES (Continued)

Page

TABLES (Continued)

Page

TABLES (Continued)

Page

TABLES (Continued)

Page

TABLES (Continued)

Page

ACRONYMS

ACM	alternative conceptual model
BDCF	biosphere dose conversion factor
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ERB2A	example reference biosphere 2A
ERMYN	Environmental Radiation Model for Yucca Mountain, Nevada
FEPs	features, events, and processes
FGR	Federal Guidance Report
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
NCRP	National Council on Radiation Protection and Measurements
NRC	U.S. Nuclear Regulatory Commission
RMEI	reasonably maximally exposed individual
TSPA	total system performance assessment
TWP	*Technical Work Plan for Biosphere Modeling*
USDA	U.S. Department of Agriculture
YMRP	Yucca Mountain Review Plan, Final Report

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1. PURPOSE

This report serves multiple functions. The initial purpose of this report is to document the Environmental Radiation Model for Yucca Mountain Nevada (ERMYN), referred to in this report as the biosphere model, which describes radionuclide transport processes in the biosphere and associated human exposure that may arise as the result of radionuclide release into the accessible environment from the geologic repository at Yucca Mountain. This report also presents the results of the biosphere model, the description of their use in Total System Performance Assessment (TSPA), and the pathway and sensitivity analysis for the model results. Also described in this report are other factors and coefficients, developed outside the biosphere model, that are necessary in evaluating compliance with the repository performance standards of 10 CFR 63 [DIRS 173273]. The biosphere model is one of the process models that support the TSPA. The ERMYN provides the capability of performing in TSPA human radiation dose assessments.

The function of the biosphere process model in supporting the TSPA is to provide the tools for calculating annual radiation dose to a receptor defined in the licensing rule from radionuclide concentrations in the groundwater and in volcanic ash deposited in surface soil. The biosphere model thus allows the results of the geosphere transport to be converted to annual dose in a manner that is consistent with the performance assessment requirements specified in the licensing rule (10 CFR 63 [DIRS 173273]). The geosphere-biosphere interface is a combination of agricultural and domestic wells for the radionuclide releases in the groundwater or an erupting volcano for the releases resulting from an extrusive igneous event. For each of these two release modes, a separate biosphere model was constructed that includes conceptual and mathematical representations of an appropriate set of environmental transport and human exposure pathways. Although these two models represent different exposure scenarios, the conceptual and mathematical representations of the majority of environmental transport and exposure pathways are similar. Therefore, throughout this documentation, the two models are frequently referred to as the ERMYN biosphere model, or the biosphere model.

Biosphere model documentation consists of six reports. Figure 1-1 presents a schematic representation of the documentation flow for the biosphere model and its input to TSPA. *Biosphere Model Report* describes the ERMYN conceptual, mathematical, and numerical models and includes modeling results, and their sensitivity and uncertainty analyses. The five input parameter reports, shown to the right of *Biosphere Model Report* in Figure 1-1, contain detailed descriptions of the vast majority of model input parameters and their development. The remaining parameters were developed in this report.

This report of the biosphere model includes:

- Describing the reference biosphere, human receptor, exposure scenarios, and primary radionuclides for each exposure scenario (Section 6.1)
- Developing a biosphere conceptual model using site-specific features, events, and processes (FEPs) (Section 6.2), the reference biosphere (Section 6.1.1), the human receptor (Section 6.1.2), and modeling assumptions (Sections 6.3.1.4 and 6.3.2.4)

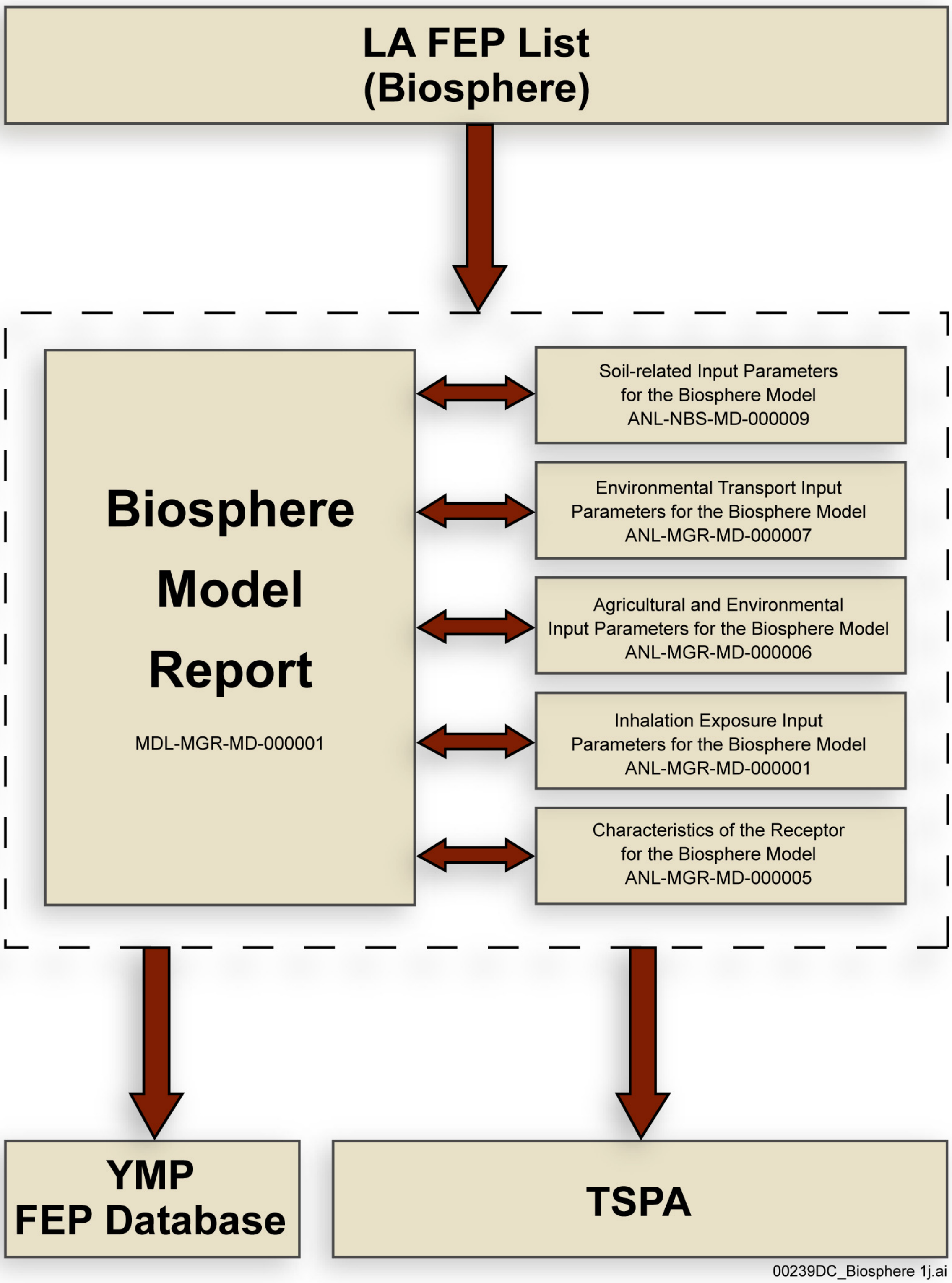

Figure 1-1. Overview of the Yucca Mountain Biosphere Model Documentation

- Building a mathematical model using the biosphere conceptual model (Section 6.3) and published biosphere models (Sections 6.4 and 6.5)
- Summarizing input parameters for the mathematical model, including the uncertainty associated with input values (Section 6.6)
- Addressing disposition of included FEPs in the biosphere model (Section 6.7)
- Constructing a numerical model based on the biosphere mathematical model, using GoldSim stochastic simulation software (Sections 6.8 and 6.9)
- Verifying the ERMYN by comparing output and intermediate results from the software with hand calculations to ensure that the GoldSim implementation is correct (Section 6.10)
- Results of the biosphere model (Sections 6.11 and 6.12)
- Importance and sensitivity analysis for the model results (Sections 6.13 and 6.14)
- Validating the submodels or component process models of ERMYN by corroborating them with those used in published biosphere models; by performing comparisons at the level of conceptual models, mathematical models, and numerical results (Section 7).

The modeling activities described in this report were conducted in accordance with SCI-PRO-006, *Models*, and *Technical Work Plan for Biosphere Modeling* (TWP) (BSC 2006 [DIRS 176938]). This model report revises the previous version of the report with the same title (BSC 2004 [DIRS 169460]). This revision was produced to:

- Develop an enhanced surface soil submodel of the biosphere model to more realistically represent agricultural land use and the long-term effects of irrigation
- Incorporate the enhanced soil submodel into the numerical GoldSim-based biosphere model
- Update biosphere model documentation to reflect changes in other biosphere model documents (Figure 1-1)
- Include the results of the biosphere model, biosphere dose conversion factors (BDCFs), for the groundwater and volcanic ash exposure scenarios previously contained in *Nominal Performance Biosphere Dose Conversion Factor Analysis* (BSC 2005 [DIRS 172814]) and in *Disruptive Event Biosphere Dose Conversion Factor Analysis* (BSC 2005 [DIRS 172812]), respectively
- Incorporate sensitivity and importance evaluations previously contained in *Biosphere Dose Conversion Factor Importance and Sensitivity Analysis* (BSC 2005 [DIRS 173194])

- Provide the TSPA with revised information (input parameters and methods) required to calculate the annual dose to the receptor as identified in 10 CFR 63.311 [DIRS 173273] from the predicted concentrations of identified radionuclides in groundwater and volcanic ash.

The model development activities included validation of the modified biosphere model. One of the post development methods identified in the TWP was the technical review (BSC 2006 [DIRS 176938], Section 2.2.1). The technical review of the modified model was not performed, which constitutes a deviation from the TWP. However, as discussed in Sections 7.1.2 and 7.6, the findings of the previous review remain applicable because the model modifications did not affect the conceptual and mathematical representations of the relevant biosphere processes.

Another deviation from the TWP is the use of ASHPLUME_DLL_LA V2.1 (STN: 11117-2.1-00 [DIRS 178870]) in Appendix G to calculate the thickness of volcanic tephra at the location of the reasonably maximally exposed individual (RMEI). Use of this software was not initially planned (BSC 2006 [DIRS 176938], Section 9). The information on the quantity of deposited tephra was unavailable from other references and had to be calculated for this modeling effort.

ERMYN uses site-specific information, and the environmental pathways and model simplifications are specific to the required characteristics of the reference biosphere (10 CFR 63.305 [DIRS 173273]; 70 FR 53313 [DIRS 178394]) and human receptor, the RMEI (10 CFR 63.312 [DIRS 173273]). The model is used for environmental radiation dose assessments and can calculate radionuclide-specific doses or provide radionuclide-specific BDCFs for a human receptor. A BDCF is equal to the all-pathway annual dose that the RMEI receives under specific biosphere conditions when exposed to radionuclide contamination in environmental media arising from a unit concentration of a radionuclide in a source medium. In the TSPA model, radionuclide-specific BDCFs are combined with the source media radionuclide concentrations to calculate the annual dose to the RMEI. Sections 6.11 and 6.12 describe the BDCF implementation in the TSPA model.

The radionuclides for which the model is developed include all those identified as being potentially important to TSPA in the analysis *Radionuclide Screening* (SNL 2007 [DIRS 177424], Section 7; DTN: MO0701RLTSCRNA.000 [DIRS 179334]). ERMYN is based on biosphere pathways consistent with arid to semi-arid conditions and little or no natural surface water discharge or transport. Limitations of the ERMYN model are discussed in Section 8.2. The model limitations originate primarily from the assessment context, i.e., the purpose and the form of the biosphere component in the performance assessment for the Yucca Mountain repository. In this respect, the biosphere model uses certain assumptions and simplifications, many of which are based on regulatory requirements. These assumptions and simplifications are appropriate for the intended use of the biosphere model. The model only applies within the assessment context for which it was constructed. One of the model limitations is the consideration of only chronic exposure scenarios. The model is not applicable to acute exposures. Because the model is valid for input parameters applicable to arid/semiarid conditions, the use of the model for high precipitation regions may produce invalid results. The volcanic model is limited to cases where the radionuclides are dispersed with fine ash particles. The model is not valid for coarse (or larger) tephra particles or ash flows.

The FEPs considered for the biosphere model (Section 6.2) are included in *FY 07 FEP List and Screening* (DTN: MO0706SPAFEPLA.001 [DIRS 181613]).

In addition to the BDCFs, this report describes the development of conversion factors for calculating quantities required by the groundwater protection standards at 10 CFR 63.331 [DIRS 173273] and inhalation dose factors for evaluating dose from inhalation of contaminated airborne particulates during volcanic ash fallout (Section 6.15).

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2. QUALITY ASSURANCE

Development of this report involves modeling and analysis of data to support performance assessment, as identified in the TWP (BSC 2006 [DIRS 176938]), and thus is a quality-affecting activity in accordance with SCI-PRO-002, *Planning for Science Activities*. Approved quality assurance procedures identified in the TWP (BSC 2006 [DIRS 176938], Section 4), or equivalent, have been used to conduct and document the activities described in this report. Specifically, the governing procedure for the development of this model report was SCI-PRO-006, *Models*. Electronic data used in this analysis were controlled in accordance with the methods specified in the TWP (BSC 2006 [DIRS 176938], Section 8).

The natural barriers and items identified in *Q-List* (BSC 2005 [DIRS 175539]) are not pertinent to this analysis and a safety category per LS-PRO-0203, *Q-List and Classification of Structures, Systems, Components and Barriers*, is not applicable.

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3. USE OF SOFTWARE

ERMYN is implemented using GoldSim stochastic simulation software. This software was selected because it is a graphical, object-oriented computer program for carrying out dynamic, probabilistic simulations (GoldSim Technology Group 2003 [DIRS 166226]). GoldSim allows for visually creating and manipulating data and equations, which are displayed as graphical objects (referred to as graphical elements in GoldSim). This software allows the model developer and user to perform probabilistic analyses in which multiple processes subject to parametric uncertainty are simulated with all uncertainties propagated to the required result. It, therefore, meets the biosphere model requirements of stochastic sampling, data management and manipulation, and calculation. There are no known limitations on outputs from ERMYN due to the use of this software. The use of this software for development of the ERMYN is consistent with the intended use and within the documented validation range of the software described in *Software Validation Test Report for GoldSim V8.02.500* (DOE 2005 [DIRS 174693]).

The GoldSim software (Version 8.02.500) is qualified under the Office of Civilian Radioactive Waste Management Quality Assurance Program for use on the Yucca Mountain Project (software tracking number: 10344-8.02-05; GoldSim V.8.02.500 2005 [DIRS 174650]). Software Configuration Management provided a copy of the GoldSim software and installed it under the Microsoft Windows 2000 operating system. GoldSim is appropriate for constructing the biosphere model, and it is used within the range of validation in accordance with procedure IM-PRO-003, *Software Management*.

In addition, a Monte Carlo analysis was conducted using ASHPLUME_DLL_LA V2.1 (STN: 11117-2.1-00 [DIRS 178870]) and the modeling tool GoldSim V9.60 (STN: 10344-9.60-00 [DIRS 180224]) to provide an estimate of the mean tephra deposit thickness that could occur at the RMEI location 18 km south of the Yucca Mountain (documented in Appendix G). The software was obtained from Software Configuration Management and was appropriate for this application. The use of ASHPLUME_DLL_LA V2.1 (STN: 11117-2.1-00 [DIRS 178870]) constitutes a deviation from the TWP. The information on the quantity of deposited tephra was unavailable from other references and had to be calculated for this modeling effort.

The summary of software used is presented in Table 3-1.

Table 3-1. Computer Software

Software Title/ Version (V)	Software Tracking Number (STN)	Code Usage	Computer Type and Platform
GoldSim Version 8.02.500	10344-8.02-05	This version of GoldSim was used to execute the biosphere model to produce the BDCFs	PC, Windows 2000
ASHPLUME_DLL_LA V.2.1	11117-2.1-00	This software was used for calculation of initial ash/fuel areal concentrations at the location of the RMEI (Appendix G)	PC, Windows XP
GoldSim V9.60	10344-9.60-00	Used in conjunction with ASHPLUME_DLL_LA V.2.1, this software was used for probabilistic simulations (Appendix G)	PC, Windows XP

In addition, Microsoft Excel 2000 (Version 9.0.3821 SR-1) and Microsoft Excel 2003 (Version 11.8134.8132 SP2) were used for data reduction, model verification, and comparisons of the results of ERMYN and other biosphere models. Excel is a commercial, off-the-shelf program, which is exempt form software qualification under IM-PRO-003. Standard functions of Excel were used to calculate values presented in Sections 6 and 7. The Excel files generated in this analysis are described in Appendix A. The formulas and algorithms as well as inputs and outputs for the calculations are included in the Excel files. The results of these calculations do not depend on the software program used.

4. INPUTS

4.1 DIRECT INPUTS

This section describes the direct inputs used in:

- Developing the ERMYN biosphere model
- Calculating groundwater and volcanic BDCFs
- Calculating groundwater protection standards conversion factors
- Calculating inhalation dose factors.

Execution of the biosphere model requires hundreds of input parameters, most of which were developed in the five biosphere model parameter reports (Figure 1-1) and are inputs to this report, as further described in this section. None of the input data used to develop the model were used for model validation.

4.1.1 Direct Inputs Used in the Development of the Biosphere Model

The ERMYN mathematical model was developed using published literature sources. The mathematical representations described in Sections 6.4 and 6.5 were based primarily on a review of published biosphere models. Documents describing the models reviewed are listed in Section 7.1, which identifies models used for, and excluded from, validation. These models are appropriate for the following reasons: (1) they include state-of-the-art methods for radiological assessment models, (2) they include a comprehensive description of the methods available to predict doses from chronic radiation exposure, and (3) at least some part of each model is applicable to the ERMYN conceptual model.

Radionuclides of Interest—Although the mathematical models described in Sections 6.4 and 6.5 apply to any radionuclide (with the exception of special models for ^{14}C and ^{222}Rn), the ERMYN biosphere model focuses on those considered for the TSPA (DTN: MO0701RLTSCRNA.000 [DIRS 179334]). The model output, i.e., the groundwater and volcanic BDCFs, is calculated for only those radionuclides (Section 6.1.3). These radionuclides are listed in Table 6.1-1. The list includes all long-lived radionuclides that could make an important dose contribution during the first million years after establishing a repository at Yucca Mountain; therefore, it is the appropriate list for ERMYN. Many of these primary long-lived radionuclides have short-lived decay products that can contribute to exposure to the RMEI. The ERMYN biosphere model considers these decay products as described in this report (e.g., Sections 6.1.3, 6.3.5, 6.4.7.2, 6.4.8.5, and 6.4.9.6).

4.1.2 Direct Inputs for the Biosphere Model Parameters

As noted before, the biosphere model uses hundreds of input parameters. Most of these parameters were developed in the following five analysis reports (indirect inputs) and are included in the product output data sets (direct inputs), as shown in Table 4.1-1.

Table 4.1-1. Biosphere Model Input Parameter Reports

Report Title and DIRS Number	Product Output DTN
Agricultural and Environmental Input Parameters for the Biosphere Model BSC 2004 [DIRS 169673]	MO0403SPAAEIBM.002 [DIRS 169392]
Characteristics of the Receptor for the Biosphere Model BSC 2005 [DIRS 172827]	MO0407SPACRBSM.002 [DIRS 170677] MO0503SPADCESR.000 [DIRS 172896]
Environmental Transport Input Parameters for the Biosphere Model BSC 2004 [DIRS 169672]	MO0406SPAETPBM.002 [DIRS 170150]
Inhalation Exposure Input Parameters for the Biosphere Model BSC 2006 [DIRS 177101]	MO0605SPAINEXI.003 [DIRS 177172]
Soil-Related Input Parameters for the Biosphere Model SNL 2007 [DIRS 179993]	MO0609SPASRPBM.004 [DIRS 179988]

A few additional biosphere model parameter values were developed and used in this report—annual average irrigation rate for field and garden crops (Section 6.4.1.1), the typical size of the fields and gardens (Section 6.4.6.2), dose coefficients, and radioactive decay data. In addition, two empirical equations are used in the biosphere model. These equations include parameters resulting from fitting a function to the experimental data. The empirical equations were used to quantify the foliar interception fractions of irrigation water (Section 6.4.3.2) and of airborne particulates (Section 6.4.3.3). These empirical equations were qualified for intended use because they include model parameters.

4.1.2.1 Interception Fraction for Wet and Dry Deposition of Contaminants on Plants

The biosphere model uses empirical formulas to calculate the fraction of contaminated water that is intercepted by plants during irrigation and the fraction of interception of suspended soil particles intercepted by crops. Both formulas were reported in the external literature sources. These formulas were qualified for intended use in the biosphere model by using the technical assessment method, which was determined to be the most suitable. The qualification was conducted in accordance with SCI-PRO-001, *Qualification of Unqualified Data* using method 5, *Technical Assessment*. The planning of the data qualification process included the formulation of acceptance criterion used to determine if the data can be considered qualified for intended purpose. In this case, a combination of several attributes were used to determine if the data can be accepted as qualified for the purpose of developing input parameters for the biosphere model. These include the following:

- Extent and reliability of source documentation
- Qualification of personnel or organizations generating the equations
- Prior uses of the data in similar applications
- Availability of corroborating equations, information, or data.

The empirical formula that quantifies the water interception fraction was developed by Hoffman et al. (1989 [DIRS 124110]) at Oak Ridge National Laboratory. The scientists performed a set of experiments involving spraying contamination on the foliage of three types of plants with five radionuclides. Three independent variables were controlled: irrigation intensity, quantity of irrigation per application, and crop standing biomass. The measured dependent variable was the interception fraction for the conditions defined. The authors then fitted an empirical equation (Equation 6.4.3-5) to their data. The methodology used is therefore acceptable. This empirical equation is used in this report with the fitted parameters for beryllium data that provided the highest (conservative) prediction for the interception fraction. The details of these experiments were described in detail in the paper that appeared in a peer-reviewed scientific journal, *Atmospheric Environment,* published by Elsevier. The experiments are further discussed in Section 6.4.3.2.

The primary reason the empirical equation is used in ERMYN is to incorporate variation and uncertainty in irrigation rates and the types of crops grown in the Amargosa Valley. Hoffman et al. (1989 [DIRS 124110]) show that the proportion of radionuclides intercepted differs depending on the size of plants (i.e., aboveground biomass), the rate at which water is applied, the amount of water applied, and the charge carried by the chemical element. A single value of irrigation interception fraction per crop type is not adequate because there are a substantial number of crops per crop type grown in the Amargosa Valley (BSC 2004 [DIRS 169673], Section 7 and Appendix A). The method proposed by Hoffman allows for incorporation of crop variability and represents well the properties of interest because it accounts for differences in irrigation requirements and growth forms of the different crops. It also accounts for differences resulting from climate change. A comparison of the results of this equation with corroborative data summarized in the report by Anspaugh (1987 [DIRS 123696]) is presented in Section 7.3.3.2. It is concluded that the equation results encompass the range of variation in the corroborating data. The empirical formula is thus suitable for the application in the biosphere model and qualified for the intended use. The use of this equation is also justified for its use in the biosphere model by the qualification of the personnel and organizations generating the equations, in addition to the extent to which the equation demonstrates the properties of interest.

An analogous formula that quantifies the interception of dry deposition by plants was obtained from the GENII model. The GENII model uses an empirical relationship between biomass and interception fraction from atmospheric dry deposition that was originally suggested by Chamberlain (Pinder et al. 1988 [DIRS 181310], p. 51) and then expanded by Pinder, Ciravolo, and Bowling (Pinder et al. 1988 [DIRS 181310]). Confidence in the empirical relationship is warranted. The original article describing the method and the results was published in *Health Physics*, a peer-reviewed scientific journal. This method was adopted in the GENII model. The equations used in GENII are documented in the reports describing the original GENII model (Napier et al. 1988 [DIRS 157927], p. 4.69) and GENII Version 2 (Napier et al. 2006 [DIRS 177331], Section 9.4.1.4). The GENII and GENII Version 2 computer codes were developed at Pacific Northwest National Laboratory to incorporate the internal dosimetry models recommended by the International Commission on Radiological Protection (ICRP) into updated versions of existing environmental pathway analysis models. The GENII system was developed to provide a state-of-the-art, technically peer-reviewed, documented set of programs for calculating radiation dose and risk from radionuclides released to the environment. Because this is also the objective of biosphere modeling, the equations match the properties of interest required for use in this model. Although the codes were developed for use at Hanford, they were designed with the flexibility to accommodate input parameters for a wide variety of generic sites. The GENII code has been used extensively for radiological assessments following radionuclide releases into the environment, most notably for the evaluation and licensing of the Waste

Isolation Pilot Plant in New Mexico. GENII model reports (Napier et al. 1988 [DIRS 157927]; Napier et al. 2006 [DIRS 177331]) are also the source of most equations provided in Sections 6.4 and 6.5. The empirical formula for dry deposition interception fraction used in the GENII model represents the properties of interest and is considered suitable for the ERMYN biosphere model by virtue of its representativeness, reliability of the source, the qualifications of the personnel and organizations generating and using the formula. The use of this equation is thus justified and can be considered qualified for intended purpose. The formula is used in Section 6.4.3.3.

4.1.2.2 Annual Average Irrigation Rate for Field and Garden Crops

The annual average irrigation rates for the field and garden crops were developed based on the average annual irrigation rate for the 26 representative crops developed in *Agricultural and Environmental Input Parameters for the Biosphere Model* (BSC 2004 [DIRS 169673], Table 6.5-2). These irrigation rates constitute an intermediate product of that report, were developed specifically for the biosphere model using qualified input data, and are, therefore, qualified and appropriate for the intended use. The field crop irrigation rate was calculated as a weighted average of the alfalfa and other field crop irrigation rates with the weights reflecting the fractions of the land that was used for growing alfalfa and other field crops (other hay, barley, and oats). These fractions were determined based on the data on acres planted in alfalfa and other field crops collected during socioeconomic surveys conducted in Amargosa Valley in the years 1996 through 1999 (CRWMS M&O 1997 [DIRS 101090], Tables 3-12 and 3-13; YMP 1999 [DIRS 158212] Tables 10 and 11). These data were qualified for intended use in accordance with SCI-PRO-001, *Qualification of Unqualified Data*. The data qualification was conducted in accordance with the data qualification plan (included in Appendix F) and is described in Section 6 in accordance with the model documentation outline in SCI-PRO-006, *Models* (Section 6.4.1.1).

4.1.2.3 Average Size of Farms and Gardens

The average size of a farm in Nye County is a parameter that was used in the special ^{14}C model (Section 6.4.6). This parameter was obtained from *Nevada Agricultural Statistics 2003-2004* (USDA 2005 [DIRS 178434]). The report was published by the Nevada Agricultural Statistics Service, which is a division of the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service. The information published by this government agency can be considered established fact, represents the site-specific properties of interest and was appropriate for intended use. The average farm size in Nye County was 2.295×10^6 m^2 (567 acres × 4,047 m^2/acre) (NASS 2005 [DIRS 178434], Section titled "General", p. 11). This datum is used in Section 6.4.6.2.

The size of a home garden was estimated based on the RESRAD model (Yu et al. 2001 [DIRS 159465], p. 2-19). These data were qualified for intended use using the technical assessment method, in accordance with SCI-PRO-001, *Qualification of Unqualified Data*. This qualification method is the most appropriate for the data that were obtained from this external reference. The planning of the data qualification process also included the formulation of acceptance criterion used to determine if the data can be considered qualified. In this case, a combination of several attributes were used to determine if the data can be accepted as qualified for the purpose of developing input parameters for the biosphere model. These included the following:

- Extent and reliability of source documentation
- Qualification of personnel or organizations generating the equations
- Prior uses of the data in similar applications.

The RESRAD code was released in the 1990s to implement the U.S. Department of Energy's (DOE) residual radioactive material guidelines. Since then, as part of the RESRAD quality assurance (QA) program, the RESRAD code has undergone extensive review, benchmarking, verification, and validation. The manual and code have been used widely by the DOE and its contractors, the NRC, U.S. Environmental Protection Agency (EPA), U.S. Army Corps of Engineers, industrial firms, universities, and foreign government agencies and institutions. New features, some in response to comments received from users, have been incorporated into the code to form RESRAD 6, which was used as a source of the data under the evaluation. These improvements have increased RESRAD capabilities and flexibility, and enabled users to interact with the code more easily. With the improvements, the code has become more realistic in terms of the models and default parameters it uses. The RESRAD family of codes was designed and is maintained by the scientific staff of the DOE Argonne National Laboratory, Environmental Science Division. RESRAD 6 represents the sixth major version of the RESRAD code since it was first issued in 1989. By virtue of RESRAD pedigree discussed above (i.e., the reliability of the source of the equations and qualification of personnel or organizations generating the equations) and the prior use of the RESRAD suite of code employing the equations, it is considered suitable for the specific application and qualified for use within this report.

In the RESRAD model it is assumed that for a family to have a garden that provides half of the total plant food diet, the area available for gardens and orchards has to be 0.1 ha or larger. In ERMYN, this area was doubled to 2,000 m^2 (0.2 ha) to account for a possibility of 100% of plant food for a family to be grown locally, which is very conservative considering that only a small fraction of the local population's diet is locally produced (BSC 2005 [DIRS 172827], Section 6.4). The RESRAD model is one of the ERMYN validation models, is referenced throughout this report, and is discussed in more detail in Section 4.1.1. The modeling approaches and data from RESRAD are consistent with those used in ERMYN and the RESRAD information pertaining to home garden size is appropriate and can be considered qualified for intended use.

4.1.2.4 Dose Coefficients and Nuclear Data

Dose coefficients used in the biosphere model were obtained from the Federal Guidance Report No. 13 (FGR 13) (EPA 2002 [DIRS 175544]). This report can be considered a source of established fact data. The federal guidance documents are issued by the EPA for the purpose of providing federal and state agencies with technical information to assist their implementation of radiation protection programs (EPA 1999 [DIRS 175452], p. 1). The EPA indicated in their draft rule that the dosimetric parameters incorporated into Federal Guidance, in order to be considered generally accepted, should be used to calculate the doses for evaluation of compliance with the Public Health and Environmental Radiation Protection Standards for Yucca Mountain

(70 FR 49014 [DIRS 177357], Appendix A). This source is therefore appropriate for the intended use.

FGR 13 was the source of the following dose coefficients used as inputs for the biosphere model:

- Dose coefficient for exposure to soil contaminated to an infinite depth (shown in Table 6.4-4)
- Dose coefficient for exposure to contaminated ground surface (shown in Table 6.5-1)
- Dose coefficients for inhalation (shown in Table 6.4-5)
- Dose coefficients for ingestion (shown in Table 6.4-6).

The radioactive decay data, such as half-lives, branching fractions, and the decay chains were taken from the following three references: Federal Guidance Report No. 12 (FGR 12) (Eckerman and Ryman 1993 [DIRS 107684], Table A.1) was used for the majority of these data; reference by Lide and Frederikse (1997 [DIRS 103178], p. 11-125) was used for ^{210}Tl; and reference by Firestone et al. (1998 [DIRS 178201]) was used for ^{79}Se half-life. The summary of these data is presented in Table 6.3-7. In addition, a general equation that governs chain radioactive decay from Appendix A of the FGR 12 (Eckerman and Ryman 1993 [DIRS 107684], Equation A.2) was used in Section 6.4.1.2. The data can be considered established fact data and were appropriate for the intended use.

All the biosphere model parameters, including their names, values and references, are listed in Table 6.6-3.

4.1.3 Direct Inputs for the Groundwater Protection Standards Conversion Factors

The groundwater protection standards conversion factors were developed using the radionuclide decay data from the following references: Eckerman and Ryman 1993 [DIRS 107684], Table A.1; Lide and Frederikse (1997 [DIRS 103178], p. 11-125); and Firestone et al. (1998 [DIRS 178201]). These established fact data were appropriate for the intended use.

4.1.4 Direct Inputs for the Inhalation Dose Factors

The inhalation dose factors were developed using the same parameter values and equations as those developed for, and used in, the biosphere model.

4.1.5 Other Direct Inputs

4.1.5.1 Gamma Ray Exposure Data

Appendix D considers contributions to exposure from various pathways associated with evaporative coolers. The biosphere model includes the exposure contribution from inhalation of radionuclides transferred from the water to the cooling air stream during the evaporation process. Appendix D demonstrates that the external exposure contribution to dose from build-up of precipitates in the cooler system is negligible to the external dose contribution from radionuclide build-up in irrigated soils. As a result, this pathway is excluded from the evaporative cooler model. This analysis required data of "specific gamma ray dose constants at one meter" for the radionuclides of concern. These data were taken from *The Health Physics and Radiological Health Handbook* (Shleien 1992 [DIRS 127299], Table 6.1.2). This reference handbook serves as a primary source of information for radiation protection professionals. The handbook provides an encyclopedia of radiation health information, with toxicity tables, classification of workplaces, decay schemes, nonionizing radiation, and environmental monitoring programs, as well as extensive glossaries on ionizing radiation, light and lasers, ultrasound, and radiofrequency electromagnetic fields. The data presented in this handbook are therefore considered established fact in the field of health physics and radiological safety. The data used from Table 6.1.2 in the handbook by Shlein (1992 [DIRS 127299]) are suitable for the screening arguments developed in Appendix D and are qualified for that purpose.

4.1.5.2 Dose Coefficients for Air Submersion and Water Immersion

In the evaluation of the air submersion and water immersion pathways (Section 7.4.8), dose coefficients for external exposure were used. The dose coefficients for air submersion were obtained from FRG 13 (EPA 2002 [DIRS 175544]). The dose coefficients for water immersion were obtained from the FGR 12 Dose Assessment Database (DOE 2007 [DIRS 180783], Table III.2) because these data were not included in the FGR 13 data sets. The dose coefficients were expressed in terms of effective dose and used tissue weighting factors consistent with ICRP Publication 60 (ICRP 1991 [DIRS 101836]). FGR 12 (DOE 2007 [DIRS 180783]) and FGR 13 (EPA 2002 [DIRS 175544]) are sources of established fact data and were appropriate for intended use.

4.2 CRITERIA

The requirements that are applicable to the development of biosphere model are listed in Table 4.2-1 (BSC 2006 [DIRS 176938], Section 3.2). These project requirements pertain to compliance with applicable portions of 10 CFR Part 63 [DIRS 173273]. In addition to the requirements listed in Table 4.2-1, definitions of terms in 10 CFR 63.2 [DIRS 173273] and description of concepts in 10 CFR 63.102 [DIRS 173273] that are relevant to biosphere modeling are also applicable.

Table 4.2-1. Requirements Applicable to This Analysis

Requirement Title	Related Regulation
Requirements for Performance Assessment	10 CFR 63.114
Required Characteristics of the Reference Biosphere	10 CFR 63.305
Required Characteristics of the Reasonably Maximally Exposed Individual	10 CFR 63.312

Listed below are the acceptance criteria from *Yucca Mountain Review Plan, Final Report* (YMRP) (NRC 2003 [DIRS 163274]) that are applicable to biosphere modeling activities. The list is based on meeting the requirements of 10 CFR 63.114, 10 CFR 63.305, and 10 CFR 63.312 [DIRS 173273] and their proposed revisions (70 FR 53313 [DIRS 178394]) that relate in whole or in part to the biosphere model.

The acceptance criteria identified in Sections 2.2.1.3.13.3 and 2.2.1.3.14.3 of *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]) are included below. In cases where subsidiary criteria are listed in the YMRP for a given criterion, only the subsidiary criteria addressed by this model report are listed below. Where a subcriterion includes several components, only some of those components may be addressed. How these components are addressed is summarized in Section 8.3 of this report.

Acceptance Criteria from Section 2.2.1.3.13, *Redistribution of Radionuclides in Soil*

Acceptance Criterion 1, System Description and Model Integration are Adequate

(1) Total system performance assessment adequately incorporates important features, physical phenomena and couplings between different models, and uses consistent and appropriate assumptions throughout the abstraction of redistribution of radionuclides in the soil abstraction process;

(2) The total system performance assessment model abstraction identifies and describes aspects of redistribution of radionuclides in soil that are important to repository performance, including the technical bases for these descriptions. For example, the abstraction should include modeling of the deposition of contaminated material in the soil and determination of the depth distribution of the deposited radionuclides; and

(3) Relevant site features, events, and processes have been appropriately modeled in the abstraction of redistribution of radionuclides, from surface processes, and sufficient technical bases are provided.

Acceptance Criterion 2, Data are Sufficient for Model Justification

(1) Behavioral, hydrological, and geochemical values used in the license application are adequately justified (e.g., irrigation and precipitation rates, erosion rates, radionuclide solubility values, etc.). Adequate descriptions of how the data were used, interpreted, and appropriately synthesized into the parameters are provided; and

(2) Sufficient data (e.g., field, laboratory, and natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the abstraction of redistribution of radionuclides in soil in the total system performance assessment.

Acceptance Criterion 3, Data Uncertainty is Characterized and Propagated through the Model Abstraction

(1) Models use parameter values, assumed ranges, probability distributions, and bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, do not result in an under-representation of the risk estimate, and are consistent with the characteristics of the reasonably maximally exposed individual in 10 CFR Part 63;

(2) The technical bases for the parameter values and ranges in the total system performance assessment abstraction are consistent with data from the Yucca Mountain region, e.g., Amargosa Valley survey, studies of surface processes in the Fortymile Wash drainage basin; applicable laboratory testings; natural analogs; or other valid sources of data. For example, soil types, crop types, plow depths, and irrigation rates should be consistent with current farming practices, and data on the airborne particulate concentration should be based on the resuspension of appropriate material in a climate and level of disturbance similar to that which is expected to be found at the location of the reasonably maximally exposed individual, during the compliance time period;

(3) Uncertainty is adequately represented in parameters for conceptual models, process models, and alternative conceptual models considered in developing the total system performance assessment abstraction of redistribution of radionuclides in soil, either through sensitivity analyses, conservative limits, or bounding values supported by data, as necessary. Correlations between input values are appropriately established in the total system performance assessment; and

(4) Parameters or models that most influence repository performance based on the performance measure and time period of compliance, specified in 10 CFR Part 63, are identified.

Acceptance Criterion 4, Model Uncertainty is Characterized and Propagated through the Model Abstraction

(1) Alternative modeling approaches of features, events, and processes are considered and are consistent with available data, and current scientific understanding, and the results and limitations are appropriately considered in the abstraction;

(2) Sufficient evidence is provided that appropriate alternative conceptual models of features, events, and processes have been considered; that the preferred models (if any) are consistent with available data (e.g., field, laboratory, and natural analog) and current scientific understanding; and that the effect on total system performance assessment of uncertainties from these alternative conceptual models has been evaluated; and

(3) Consideration of conceptual model uncertainty is consistent with available site characterization data, laboratory experiments, field measurements, natural analog information and process-level modeling studies; and the treatment of conceptual model uncertainty does not result in an under-representation of the risk estimate.

Acceptance Criterion 5, Model Abstraction Output is Supported by Objective Comparisons

(1) Models implemented in the abstraction provide results consistent with output from detailed process-level models and/or empirical observations (e.g., laboratory testing, field measurements, and/or natural analogs).

Acceptance Criterion from Section 2.2.1.3.14, *Biosphere Characteristics*

Acceptance Criterion 1, System Description and Model Integration are Adequate

(1) Total system performance assessment adequately incorporates important site features, physical phenomena, and couplings, and consistent and appropriate assumptions throughout the biosphere characteristics modeling abstraction process;

(2) The total system performance assessment model abstraction identifies and describes aspects of the biosphere characteristics modeling that are important to repository performance, and includes the technical bases for these descriptions. For example, the reference biosphere should be consistent with the arid or semi-arid conditions in the vicinity of Yucca Mountain; and

(3) Assumptions are consistent between the biosphere characteristics modeling and other abstractions. For example, the U.S. Department of Energy should ensure that the modeling of features, events, and processes, such as climate change, soil types, sorption coefficients, volcanic ash properties, and the physical and chemical properties of radionuclides are consistent with assumption in other total system performance assessment abstractions.

Acceptance Criterion 2, Data are Sufficient for Model Justification

(1) The parameter values used in the license application are adequately justified (e.g., behaviors and characteristics of the residents of the Town of Amargosa Valley, Nevada, characteristics of the reference biosphere, etc.) and consistent with the definition of the reasonably maximally exposed individual in 10 CFR Part 63. Adequate descriptions of how the data were used, interpreted, and appropriately synthesized into the parameters are provided; and

(2) Data are sufficient to assess the degree to which features, events, and processes related to biosphere characteristics modeling have been characterized and incorporated in the abstraction. As specified in 10 CFR Part 63, the U.S. Department of Energy should demonstrate that features, events, and processes, which describe the biosphere, are consistent with present knowledge of conditions in the region, surrounding Yucca Mountain. As appropriate, the U.S. Department of Energy sensitivity and uncertainty analyses (including consideration of alternative conceptual models) are adequate for determining additional data needs, and evaluating whether additional data would provide new information that could invalidate prior modeling results and affect the sensitivity of the performance of the system to the parameter value or model.

Acceptance Criterion 3, Data Uncertainty is Characterized and Propagated through the Model Abstraction

(1) Models use parameter values, assumed ranges, probability distributions, and bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, do not result in an under-representation of the risk estimate, and are

consistent with the definition of the reasonably maximally exposed individual in 10 CFR Part 63;

(2) The technical bases for the parameter values and ranges in the abstraction, such as consumption rates, plant and animal uptake factors, mass-loading factors, and biosphere dose conversion factors, are consistent with site characterization data, and are technically defensible;

(3) Process-level models used to determine parameter values for the biosphere characteristics modeling are consistent with site characterization data, laboratory experiments, field measurements, and natural analog research;

(4) Uncertainty is adequately represented in parameter development for conceptual models and process-level models considered in developing the biosphere characteristics modeling, either through sensitivity analyses, conservative limits, or bounding values supported by data, as necessary. Correlations between input values are appropriately established in the total system performance assessment, and the implementation of the abstraction does not inappropriately bias results to a significant degree; and

(6) Parameters or models that most influence repository performance, based on the performance measure and time period of compliance specified in 10 CFR Part 63, are identified.

Acceptance Criterion 4, Model Uncertainty is Characterized and Propagated through the Model Abstraction

(1) Alternative modeling approaches of features, events, and processes are considered and are consistent with available data and current scientific understanding, and the results and limitations of alternative modeling approaches are appropriately considered in the abstraction. Staff should evaluate alternate conceptual models of the biosphere or biosphere processes, recognizing that 10 CFR 63.305 and 63.312 place a number of constraints on both the biosphere and the characteristics of the reasonably maximally exposed individual. Alternate conceptual models focus on exploring the variability and uncertainty in the physical features, events, and processes, mindful of the regulatory constraints. Evaluation of behavior and characteristics of the reasonably maximally exposed individual emphasizes understanding the characteristics of the current residents of the Town of Amargosa Valley, and uncertainty and variability in the data used to derive mean values.

(2) Sufficient evidence is provided that existing alternative conceptual models of features and processes that are important to waste isolation, such as plant uptake of radionuclides from soil, soil resuspension, and the inhalation dose model for igneous events, have been considered; and

(3) Consideration of conceptual model uncertainty is consistent with available site characterization data, laboratory experiments, field measurements, natural analog

information and process-level modeling studies; and the treatment of conceptual model uncertainty does not result in an under-representation of the risk estimate.

Acceptance Criterion 5, Model Abstraction Output is Supported by Objective Comparisons

(1) Dose calculations pertaining to this total system performance assessment abstraction provide results consistent with output from detailed process-level models and/or empirical observations (e.g., laboratory testing, field measurements, and/or natural analogs).

4.3 CODES, STANDARDS, AND REGULATIONS

No codes, standards, or regulations other than those identified in Section 4.2 and determined to be applicable were used in this analysis.

5. ASSUMPTIONS

SCI-PRO-006 defines an assumption to be “a statement or proposition that is taken to be true or representative in the absence of direct confirming data or evidence, or those estimations, approximations, limitations, and/or decisions made during model development (such as when expanding the range of variables to achieve conservatism).” Attachment 2 to SCI-PRO-006 requires that “this section (Section 5) shall include a description of the assumptions used, in the absence of direct confirming data or evidence, to perform the model activity. Other model assumptions are described in Section 6 of the model report.” No assumptions are made in the absence of direct confirming data or evidence in this report, since parameter input data are mostly developed in supporting reports (Figure 1-1 and Section 4.1). Other model assumptions or approximations are made, discussed, and justified in Section 6.

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6. MODEL DISCUSSION

When constructing a biosphere model, the first step in the determination of the suitable assessment biosphere is defining the context of the performance assessment. The "assessment context" answers fundamental questions about the performance assessment, namely: (a) what are you trying to assess/calculate, and (b) why are you trying to assess it/calculate it? (BIOMASS 2003 [DIRS 168563], p. 13). The overall assessment context defines the role and the form of the biosphere component. The evaluation of the assessment context involves considering a number of issues that define the overall requirements, such as the purpose of the assessment; the calculation endpoint(s); the site and repository context; the radionuclide source term; the geosphere-biosphere interface; the calculation timeframe; basic assumptions about society; and the assessment philosophy (e.g. the level of conservatism to be applied) (BIOMASS 2003 [DIRS 168563], p. 1).

The biosphere model is constructed to evaluate the annual dose to the RMEI, who is a member of a hypothetical community situated at the compliance location specified by the regulator. The hypothetical community is required to have characteristics of the Town of Amargosa Valley. This hypothetical community and the RMEI were defined by the U.S. EPA "to limit speculation about possible futures so that the performance assessments can provide meaningful input into the decision process and the decision process itself is not confounded with speculative alternatives" (66 FR 32074 [DIRS 155216], p. 32,092). The RMEI, who is a member of this community, would be among the most highly exposed individuals downgradient from Yucca Mountain (66 FR 32074 [DIRS 155216], p. 32,093), regardless of the futures of the real population of the region. Because the RMEI and the community the RMEI lives in are hypothetical, the exposure scenarios, as developed in the biosphere model, are stylized and based on the applicable requirements regarding the reference biosphere and the RMEI (Sections 6.1.1 and 6.1.2).

Most of the components of the assessment context for the Yucca Mountain repository are defined in the regulations (10 CFR 63 [DIRS 173273]). The purpose of the assessment is to demonstrate that after permanent closure the repository meets the performance objectives specified in the licensing rule (10 CFR 63 [DIRS 173273]). The assessment, including the geosphere and the biosphere representations, is conducted for a specified site, the geologic repository at Yucca Mountain. The assessment endpoint for demonstrating compliance with the individual protection standard in 10 CFR 63.311 [DIRS 173273] is the annual dose to a defined receptor. For demonstrating compliance with the groundwater protection standards in 10 CFR 63.331, the assessment endpoints are the concentrations of selected radionuclides in groundwater and the annual dose from beta-photon emitting radionuclides resulting from drinking a specified quantity of water. The calculation timeframe is also set in the regulations as the period of geologic stability of the repository system (10 CFR 63. 311 [DIRS 173273]). Within that timeframe, the rule defines how the biosphere and society changes need to be represented (10 CFR 63.305 and 63.312 [DIRS 173273]).

The assessment philosophy broadly defines the approach to the treatment of irreducible uncertainties through basic assessment assumptions and modeling choices. In this regard, the performance assessments and analyses should focus upon the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values (10 CFR 63.101 [DIRS 173273]). However, the rule also points out that the approach to defining factors and parameters used in the performance assessment should be cautious while being reasonable.

The biosphere model is formulated to support the assessment context as described above. The elements of assessment context that are specific to the biosphere model are further discussed in Section 6.1. That section presents the modeling objectives, including a description of the biosphere system. The ERMYN model is based on as much site-specific information as available. The FEPs considered in ERMYN are listed in Section 6.2. Based on characteristics of the biosphere system, the included FEPs, modeling assumptions, and biosphere conceptual models are developed for the two exposure scenarios (Section 6.3). Alternative conceptual models (ACMs), which usually refer to other process models, are considered in the model development (Section 6.3.3) and they are further evaluated at the submodel level.

To quantify the radiation dose to a specific receptor, which in the case of the TSPA is the RMEI, conceptual models for the groundwater and volcanic ash scenarios are represented by a series of mathematical expressions (Sections 6.4 and 6.5 for the groundwater and volcanic ash scenarios, respectively). All input parameters required for the mathematical model, including the uncertainty associated with them, are summarized in Section 6.6. Section 6.7 summarizes disposition of biosphere-related FEPs that were included in the model. Sections 6.8 and 6.9 describe constructing a numerical model, i.e., ERMYN implementation tool based on the biosphere mathematical model, using GoldSim stochastic simulation software. Verification of ERMYN implementation is presented in Section 6.10, where the ERMYN intermediate results and output are compared with hand calculations to ensure that the GoldSim implementation is correct.

The developed biosphere model, built in the GoldSim software (Section 3), produces BDCFs as inputs for the TSPA model. Sections 6.11 and 6.12 present the results of the biosphere model for the groundwater and volcanic ash exposure scenarios, respectively, including a discussion of the TSPA algorithm to calculate annual dose to the RMEI by using the biosphere model inputs. Uncertainty and sensitivity analyses of these results are documented in Sections 6.13 and 6.14, for the two exposure scenarios. Other inputs to the TSPA model developed in this report are presented in Section 6.15.

6.1 MODELING OBJECTIVES

The objective of the biosphere model is to provide capabilities for calculating doses in the TSPA model, i.e., to estimate the annual radiation dose to a specified receptor that would result from unit concentrations of radionuclides in the source (contaminated) media. In general, this biosphere model provides a method for assessing chronic radiation doses with an upper limit to radiation dose of tens of rem per year (Eckerman et al. 1988 [DIRS 101069], Section II). This is because the dose coefficients used in the model apply to chronic intakes and low exposure conditions (continuous exposure to low level contamination), and are not appropriate for acute intakes and high exposure conditions (a few exposures to high contamination).

The radionuclides can be released into different source environmental media, such as water for the groundwater exposure scenario or soil for the volcanic ash exposure scenario (Sections 6.3.1.1 and 6.3.2.1). Because the radionuclide concentration in relevant source medium is developed from other process models, a unit activity concentration is considered as the source term in the biosphere model. This approach, using a biosphere process independent from the radionuclide source, is evaluated in Sections 6.4.10 and 6.5.8. The biosphere model inputs are introduced in Sections 6.4 and 6.5 where the mathematical submodels are presented. All input parameters for generating model outputs are summarized in Section 6.6.

The biosphere model is used to calculate the sets of radionuclide-specific BDCFs that are used in the TSPA model to calculate radiation dose to the RMEI. Between the radionuclide source and the BDCFs is the biosphere model, which contains a representation of radionuclide transfer mechanisms in the biosphere system, along with related assumptions and simplifications, and the representation of the receptor.

It is important to first describe the biosphere system to be modeled and to introduce the related concepts. The two applicable regulatory concepts are those that define the required characteristics of the reference biosphere and the RMEI. Reference biosphere means the description of the environment inhabited by the RMEI (10 CFR 63.2 [DIRS 173273]). The reference biosphere is the model representing, within the performance assessment model, the accessible environment (biosphere) where the average member of the hypothetical community, the RMEI, can receive radiation doses from radionuclide releases from the repository. The reference biosphere is described in Section 6.1.1. The other key concept used in constructing the biosphere model is that of the human receptor, the RMEI, which is described in Section 6.1.2.

6.1.1 Reference Biosphere

The reference biosphere comprises the characteristics and attributes of the biosphere in the Yucca Mountain region and is used in constructing the model representation of that environment. In the modeling space, the reference biosphere represents the environment inhabited by the RMEI along with associated human exposure pathways and parameters (10 CFR 63.102(i) [DIRS 173273]). Required characteristics of the reference biosphere are the following:

- Features, events, and processes that describe the reference biosphere must be consistent with present knowledge of the conditions in the region surrounding the Yucca Mountain site (10 CFR 63.305(a) [DIRS 173273]).

- DOE should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology. In all analyses done to demonstrate compliance with this part, DOE must assume that all of those factors remain constant as they are at the time of submission of the license application (10 CFR 63.305(b) [DIRS 173273]).

- DOE must vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system during the period of geologic stability and consistent with the requirements for performance assessments specified at 10 CFR 63.342 (proposed 10 CFR 63.305(c), 70 FR 53313 [DIRS 178394]).

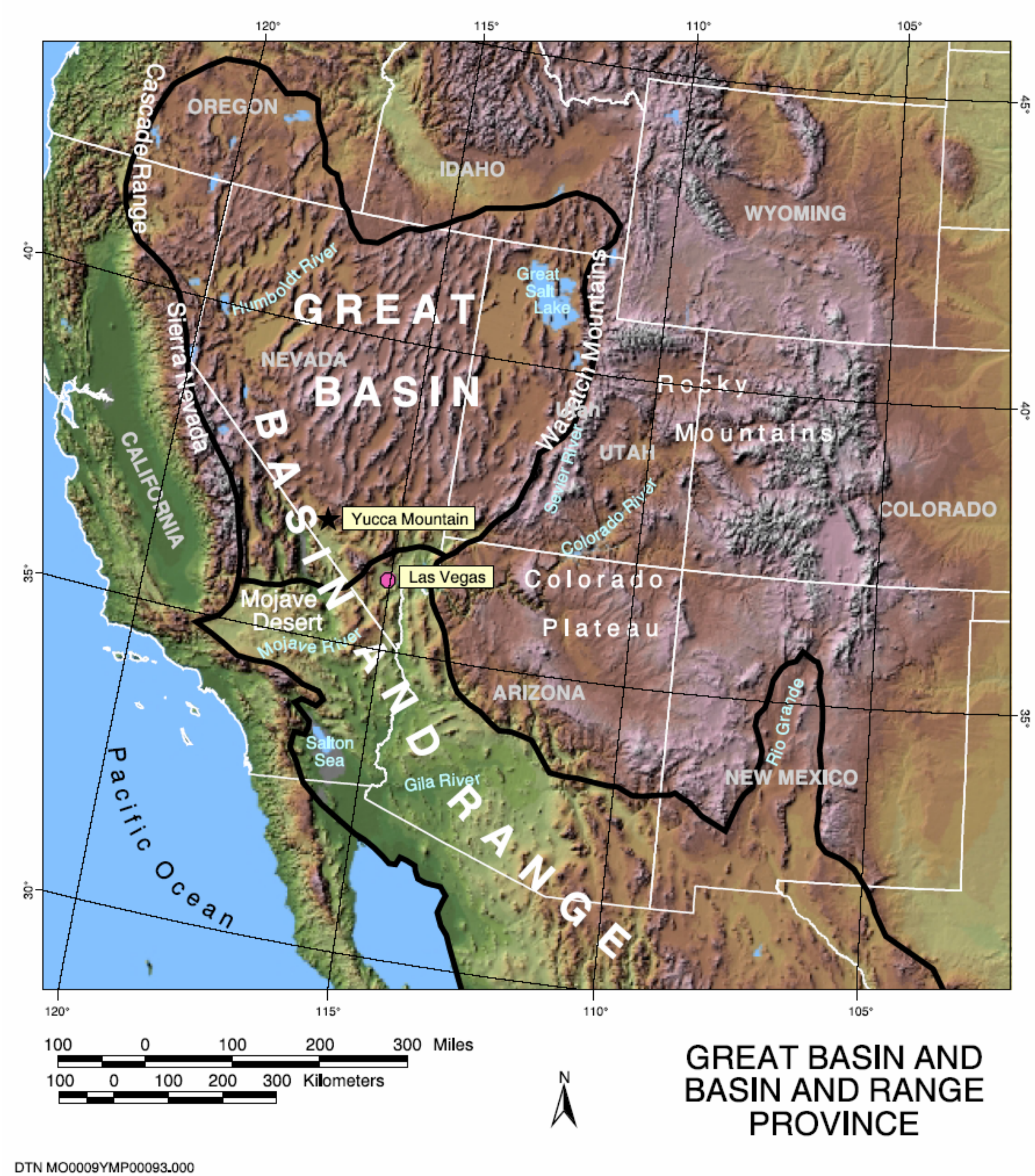
- Biosphere pathways must be consistent with arid or semi-arid conditions (10 CFR 63.305(d) [DIRS 173273]).

The reference biosphere includes characteristics of the geography, geology, physiology, climate, hydrology, and population in the region surrounding the Yucca Mountain site. A brief overview of the reference biosphere is presented in this section. As specified in 10 CFR 63.305 [DIRS 173273], the required characteristics of the reference biosphere include FEPs that are consistent with the present knowledge of the conditions in the region surrounding the Yucca Mountain site (Section 6.2), such as the current conditions of society, biosphere, human biology, and human knowledge (Sections 6.1.1.1 and 6.1.1.3); predicted future conditions of geology, hydrology, and climate (Section 6.1.1.2); and biosphere pathways consistent with arid to semi-arid conditions (Section 6.3). The regional and site information presented in this section provides an overview of the basis for selecting the FEPs and biosphere pathways considered in the ERMYN biosphere model. Other biosphere characteristics, such as those identified by the IAEA international review team (IAEA 2001 [DIRS 155188], Section 4.1), are also considered in the model.

6.1.1.1 Geography, Geology, and Physiography

Yucca Mountain is located in Nye County in southern Nevada, approximately 160 km northwest of Las Vegas, in an arid, sparsely populated region in the transition zone between the Great Basin and the Mojave Deserts. Yucca Mountain and surrounding areas are in the southern-most part of the Great Basin, a subprovince of the Basin and Range Physiographic Province (Figure 6.1-1). The topography is typical of the Great Basin, which is characterized by more or less regularly spaced, north-south trending mountain ranges and intervening alluvial basins that are formed by faulting.

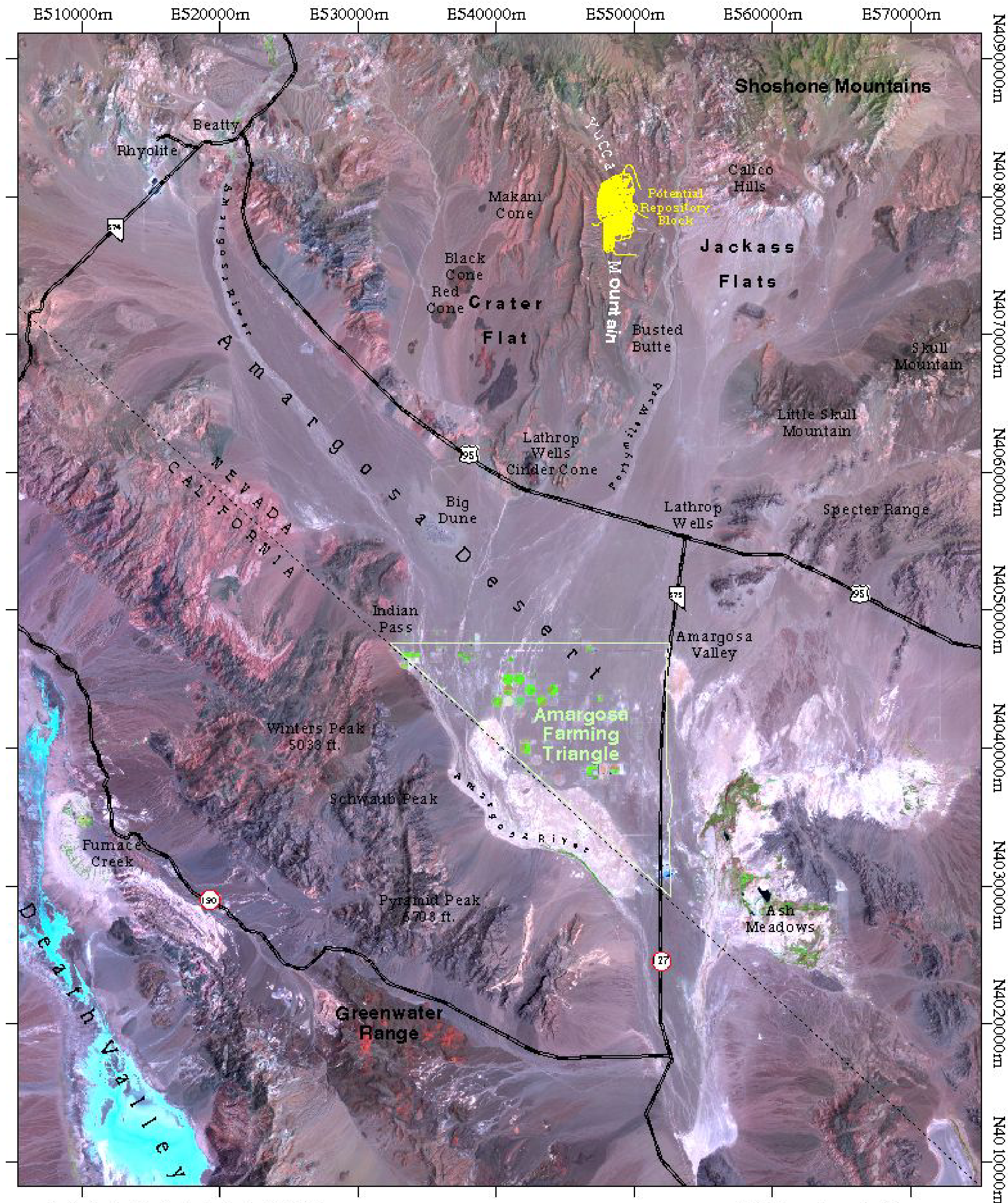
The area surrounding Yucca Mountain can be divided into eight clearly defined physiographic landforms (BSC 2004 [DIRS 169734], Section 2.1.2). The four landforms most relevant to the biosphere conceptual model are Yucca Mountain, Fortymile Wash, Jackass Flats, and the Amargosa Desert (Figure 6.1-2). Yucca Mountain is an irregularly shaped upland, 6 to 10 km wide and about 40 km long. The crest of the mountain reaches elevations of 1,500 to 1,930 m, about 650 m higher than the floors of adjacent washes in Crater Flat and Jackass Flats. Yucca Mountain is composed of fine-grained volcanic rocks and is formed from fault blocks that tilt eastward, such that the fault-bounded west-facing slopes are generally high, steep, and straight, which contrasts with the gentler and often deeply dissected east-facing slopes. Drainage from the west flank of the mountain flows southward down narrow fault-controlled canyons and out into Crater Flat. Drainage from the east flank flows southeastward down Yucca, Drill Hole, and Dune Washes into Fortymile Wash (BSC 2004 [DIRS 169734], Section 3.2.1.1).



Source: DTN: MO0009YMP00093.000 [DIRS 154403].

NOTE: Names of specific geographical points are not necessary to understand the technical content of this document.

Figure 6.1-1. Yucca Mountain in Relation to the Great Basin



NOTE: Names of specific geographical points are not necessary to understand the technical content of this document. This figure is for illustration purposes.

Figure 6.1-2. Regional Map of Yucca Mountain and the Amargosa Valley

There are no perennial streams at Yucca Mountain or northern Amargosa Valley. The ephemeral Amargosa River, which infrequently carries runoff from the Yucca Mountain area via Fortymile Wash, flows southeast along the western edge of the basin, eventually ending in Death Valley (BSC 2004 [DIRS 169734], Sections 3.4.2 and 3.4.3). Fortymile Wash is a large ephemeral wash that drains an approximately 620 km^2 area east and northeast of Yucca Mountain. From its headwaters northeast of Yucca Mountain, it flows southward through Fortymile Canyon and continues down the south-sloping piedmont that forms the west end of Jackass Flats. Along this latter reach, the wash cuts a nearly linear trench through the alluvial deposits, 150 to 600-m wide and up to 25-m deep. This trench gradually decreases downslope until the wash merges with the Amargosa Desert basin.

Jackass Flats is an alluvial basin, 8- to 10-km wide and nearly 20-km long, that lies east of Yucca Mountain and Fortymile Wash. Jackass Flats is formed principally by piedmonts that slope away from highlands to the north, east, and south, merge in the central basin area, and descend gradually westward and southwestward towards Fortymile Wash. The Amargosa Desert is a broad northwest-trending basin approximately 80-km long and up to 30-km wide. The basin is one of the largest in the southern Great Basin. The basin floor slopes gently southeastward from elevations of about 975 m at the north end (near Beatty, Nevada) to about 600 m toward the south end.

The soils on alluvial fans and in stream channels in northern Amargosa Valley generally are deep and well to excessively drained. The surface soil layer generally is less than 20 cm (8 in.) thick and subsurface soils are up to 150 cm (59 in.) deep. Soil textures are very gravelly with fine sands to sandy loams. The soils are calcareous and moderately alkaline. Properties of the Amargosa Valley soils are described in *Soil Survey of Nye County, Nevada, Southwest Part* (USDA 2004 [DIRS 173916], Parts I and II).

6.1.1.2 Climate, Flora, and Fauna

The regional climate is characterized by low precipitation, hot summers, cool winters, and low relative humidity (BSC 2004 [DIRS 169734], Section 6.3). The Sierra Nevada mountain range, a dominant feature in the region, is a major barrier to moist air moving east from the Pacific Ocean and creates a rain shadow. Annual average precipitation in the region ranges from 100 to 200 mm (4 to 8 inches) and decreases from higher to lower elevations. About 50% of the annual precipitation is from frontal storms during November through April. Precipitation during the summer months often occurs as localized thunderstorms that may create floods and runoff. Precipitation often varies between years by a factor of two. Temperatures vary through the year. Average maximum daytime temperatures are about 35°C (95°F) in July and 11°C (52°F) in January. Although the average nighttime temperature in January is above freezing, 2°C (36°F), freezing temperatures do occur. Low precipitation and warm temperatures keep atmospheric humidity low, with an annual average relative humidity of less than 20%.

The combination of low precipitation, warm temperatures, and low humidity results in high rates of evaporation and moisture loss by plants via transpiration. Shrubs adapted to periodic drought and extremes in temperatures dominate the native vegetation in the region (CRWMS M&O 1996 [DIRS 102235]). Shrubs cover 20% to 30% of the ground, depending upon precipitation, and are typical of the northern Mojave Desert, such as creosote bush (*Larrea tridentata*) and white bursage (*Ambrosia dumosa*). There are no forested areas in Amargosa Valley or elsewhere in the region south of Yucca Mountain (DOE 2002 [DIRS 155970], Section 3.1.5.1.1).

Wildlife in the Yucca Mountain region is dominated by species associated with the Mojave Desert, with some species from the Great Basin Desert at higher elevations. Game species found in the region include Gambel's quail (*Callipepla gambelii*), chukar (*Alectoris chukar*), mourning dove (*Zenaida macroura*), and mule deer (*Odocoileus hemionus*) (CRWMS M&O 1999 [DIRS 104593]). Those species are most common in the mountains surrounding Amargosa Valley and Yucca Mountain and in areas where water is available from springs, seeps, and man-made water developments (CRWMS M&O 1999 [DIRS 104593], Section 3.3.2.3; DOE 2002 [DIRS 155970], Section 3.1.5.1.2).

Geological and biological media provide a historical record of the types and periodicity of climate change in the Yucca Mountain region. Future climate predictions for the next 10,000 years indicate that the present-day interglacial climate at Yucca Mountain should persist for another 400 to 600 years. After that, the climate shifts to a warmer and much wetter monsoon climate (lasting 900 to 1,400 years) and then to a cooler and wetter glacial transition climate for 8,000 to 8,700 years (BSC 2004 [DIRS 170002], Section 6.6).

6.1.1.3 Groundwater, Human Activities, and Agriculture

Water in the aquifers beneath Yucca Mountain generally flows from north to south (D'Agnese et al. 1997 [DIRS 100131]). Therefore, groundwater flows from the repository area south to the Amargosa Valley (Figure 6.1-2). If radionuclides are released into the groundwater or the air at Yucca Mountain, groundwater flow and wind patterns suggest that some of these radionuclides would spread south and east into the Amargosa Valley region.

Water used for domestic, municipal, and agricultural purposes in Amargosa Valley comes from groundwater. There are no public water treatment systems in Amargosa Valley, and there is only a small, quasi-municipal water delivery system for which drinking water standards could be enforced (State of Nevada 1997 [DIRS 110951]).

The region surrounding Yucca Mountain is rural and sparsely populated. The nearest human residents to Yucca Mountain (in the direction of groundwater flow) live in the Amargosa Valley. At the time of the 2000 census, it was estimated that 1,176 people in 422 households resided in the approximately 1,300-km^2 Amargosa Valley Census County Division (Bureau of the Census 2001 [DIRS 156858], Tables P1 and H6). Residents living closest to the repository are located at the intersection of U.S. Highway 95 and Nevada State Route 373 (Figure 6.1-2), which is approximately 20 to 21 km south of Yucca Mountain (BSC 2003 [DIRS 168723], Table 1 and Figure 1). Soil conditions at this location generally are similar to those further downgradient where farming currently is practiced (CRWMS M&O 1999 [DIRS 107736]). In 2003, an estimated 23,180 people lived within 84 km (52 mi) of Yucca Mountain. About 80% lived more than 64 km (40 mi) from Yucca Mountain in and near Pahrump, Nevada. About 6% lived in the Amargosa Valley region about 20 to 56 km (12 to 35 mi) south of Yucca Mountain (BSC 2003 [DIRS 168723], Table 1 and Figure 1). Other communities and employment centers in south-central Nevada and the approximate highway distance from the intersection of Highway 95 and State Route 373 are Beatty, 45 km (28 mi); Pahrump, 70 km (43 mi); Indian Springs, 70 km

(43 mi); and Las Vegas, 120 km (75 mi). Part of this information was used to characterize the receptor and the characteristics of the reference biosphere (BSC 2005 [DIRS 172827], Sections 5.1 and 6.1).

In 2004, government and other community and social services in Amargosa Valley included a public library, an elementary school, churches, a community center and park, a senior center, a small medical clinic, an ambulance service, and a post office. There also were small convenience or general stores; restaurants, saloons, or gambling establishments; miscellaneous retail stores; and a motel (Rasmuson 2004 [DIRS 169506], Enclosure 2). Most of the agriculture and the majority of the population are located approximately 30 km south of Yucca Mountain in the Amargosa farming triangle, which is bounded by the Amargosa Farm Road on the north, Nevada State Route 373 on the east, and the California-Nevada border running from northwest to southeast. Most of the major roads in the area are paved. The nearest indoor recreation (e.g., movie theatres, other restaurants), larger stores, and hospitals are in Pahrump; Las Vegas, located farther away, is also a source of such services.

There is a small agricultural industry in Amargosa Valley. Agriculture mainly involves growing feed (e.g., alfalfa) for farm animals; however, gardening and animal husbandry are common (YMP 1999 [DIRS 158212]). Small grains, pistachios, grapes, orchard crops, garlic, and onions are also grown commercially. Commercial agriculture in the Amargosa Valley farming triangle includes a dairy (approximately 5,000 cows) and a fish farm (approximately 15,000 catfish and bass) (YMP 1999 [DIRS 158212], Tables 9 and 11). In 1999 there were approximately 1,400 acres planted in alfalfa, 300 acres in other hay, 100 acres in pistachios, 16 acres in fruit trees, and 10 acres in grapes (YMP 1999 [DIRS 158212], Table 11).

There are no naturally occurring surface waters (i.e., perennial lakes and streams) in the area. Commercial crops are irrigated with groundwater, primarily using center pivot and other overhead sprinkler systems. Local wells provide water for household, agriculture, horticulture, and animal husbandry. Many residences have gardens with vegetable plots and some have a few cattle, sheep, chickens, and other farm animals (CRWMS M&O 1997 [DIRS 101090], Section 3.4; Horak and Carns 1997 [DIRS 124149], pp. 4 to 17; YMP 1999 [DIRS 158212], Section 3.4; BSC 2004 [DIRS 169673], Appendix A).

6.1.2 Human Receptor

The reasonably maximally exposed individual, the RMEI, is the hypothetical individual that represents exposed population for the purpose of performance assessment. The RMEI has a diet and living style characteristics that are average for a hypothetical community with characteristics of the Town of Amargosa Valley that is situated at a specified compliance location. The RMEI is selected to represent those persons in the vicinity of Yucca Mountain who are reasonably expected to receive the greatest exposure to radioactive material released from a geologic repository at Yucca Mountain. Characteristics of the RMEI are to be based on current human behavior and biospheric conditions in the region (10 CRR 63.102(i) [DIRS 173273]).

The RMEI is required to meet the following criteria (10 CFR 63.312 [DIRS 173273]):

- Lives in the accessible environment above the highest concentration of radionuclides in the plume of contamination.

- Has a diet and living style representative of people who now reside in the Town of Amargosa Valley, Nevada. DOE must use projections based upon surveys of the people residing in the Town of Amargosa Valley, Nevada, to determine their current diets and living styles and use the mean values of these factors in the assessments conducted for 10 CFR 63.311 and 10 CFR 63.321.

- Uses well water with average concentrations of radionuclides based on an annual water demand of 3,000 acre-feet.

- Drinks 2 liters of water per day from wells drilled into the groundwater from a point above the highest concentration of radionuclides in the plume of contamination.

- Is an adult with metabolic and physiological considerations consistent with present knowledge of adults.

These requirements are used for developing the external exposure time, inhalation exposure time, and food consumption rates (BSC 2005 [DIRS 172827], Section 6). To determine dietary characteristics of the local population, a food consumption survey of the residents of the Amargosa Valley was conducted (DOE 1997 [DIRS 100332]). The recent census data indicates that, although the Amargosa Valley is a rural community, most of the residents do not work in the agricultural business (Bureau of the Census 2002 [DIRS 159728], Table P49). The following is a summary of information on the people residing in Amargosa Valley used to aid the development of the model.

Diet—Based on a survey of Amargosa Valley residents (DOE 1997 [DIRS 100332]), it was determined that many people in that region consume some locally produced vegetables, fruit, grain, meat, poultry, fish, eggs, and milk (DOE 1997 [DIRS 100332]). This information was used to identify the ingestion pathways in the ERMYN and to develop consumption rates of the locally produced foodstuffs (BSC 2005 [DIRS 172827], Section 6.4).

Use of Evaporative Coolers—About three quarters of Amargosa Valley residents surveyed used evaporative coolers, and they used them for an average of 5 months per year (DOE 1997 [DIRS 100332], Table 2.4.2; BSC 2005 [DIRS 172827], Section 6.3.4). Therefore, the model included exposure to radionuclides resulting from the use of evaporative coolers during part of the year.

Gardens—A little under half Amargosa Valley residents surveyed had gardens (DOE 1997 [DIRS 100332], Table 2.4.2). This and other site-specific information (e.g., Horak and Carns 1997 [DIRS 124149], pp. 5 to 6 and Table 1; Mills et al. [no date] [DIRS 124338]) was used to select the representative crops considered during development of input parameters that characterized irrigation requirements and farming methods (BSC 2004 [DIRS 169673], Section 6 and Appendix A).

Employment—About four in ten Amargosa Valley residents (16 or more years old) were not employed in 1999 (Bureau of the Census 2002 [DIRS 159728], Table P47). Of the residents who were employed, the largest proportion (a quarter) worked in mining and only about one in twenty worked in agriculture (Bureau of the Census 2002 [DIRS 159728], Table P49). This information was used to calculate exposure times and to determine the proportion of the population that worked indoors and outdoors in Amargosa Valley (BSC 2005 [DIRS 172827], Section 6.3).

Commute Time—About two thirds of Amargosa Valley residents (16 or more years old) who worked commuted 10 minutes or more to work one way. About a fifth commuted 35 minutes or more one way (Bureau of the Census 2002 [DIRS 159728], Table P31). This information was used to model the proportion of the Amargosa Valley population who would work in areas where radionuclides may be present and the amount of time that local workers would commute within those areas (BSC 2005 [DIRS 172827], Section 6.3).

Housing Type—About nine out of ten occupied housing units in Amargosa Valley during 2000 were mobile homes, and about the same fraction of the total population lived in mobile homes (Bureau of the Census 2002 [DIRS 159728], Tables H30, H31, and H33). This information was used to select building shielding factors for lightly constructed housing (BSC 2005 [DIRS 172827], Section 6.6) and parameters related to evaporative coolers, house ventilation rates, and equilibrium factors for ^{222}Rn decay products indoors (BSC 2004 [DIRS 169672], Sections 6.5 and 6.6).

Metabolic and Physiological Considerations—The biokinetic and dosimetric characteristics of the RMEI were assumed to be the same as those used to develop dose coefficients in FGR 13 (EPA 1999 [DIRS 175452], Chapters 4 and 5). These models were in part based on a hypothetical 'average' adult person with the anatomical and physiological characteristics defined in *Report of the Task Group on Reference Man* (ICRP 1975 [DIRS 101074]) and used biokinetic models from several ICRP publications (EPA 1999 [DIRS 175452], Chapter 4). Breathing rates used in the biosphere model were based on the biometric results for adult persons used in the respiratory track model developed by the ICRP (ICRP 1994 [DIRS 153705]; BSC 2005 [DIRS 172827], Section 6.3.3).

Although the biosphere model is based on the requirements of 10 CFR Part 63 [DIRS 173273] for the RMEI, it can be used to evaluate doses to human receptors with other dietary and lifestyle characteristics, and can use dosimetric methods other than those of FGR 13 (EPA 1999 [DIRS 175452]) by using appropriate data as input.

6.1.3 Exposure Scenarios and Radionuclides of Interest

In the biosphere model, two human exposure scenarios are considered: the groundwater exposure scenario (groundwater scenario) and the volcanic ash exposure scenario (volcanic scenario). The exposure scenarios are considered separately because the initial radionuclide source terms, as well as some radionuclide transport mechanisms in the biosphere and the human exposure pathways are different.

TSPA considers several scenario classes and modeling cases within these scenarios and these should not be confused with the biosphere exposure scenarios. A biosphere exposure scenario is a well-defined, connected sequence of FEPs that describe characteristics of the biosphere, where radionuclide transport and human exposure occurs and is constructed to evaluate radiological consequences of radionuclide releases to the reference biosphere in a given medium, such as the groundwater, irrespective of the cause of contamination in the groundwater. Therefore, the BDCFs for the groundwater exposure scenario apply to all the TSPA scenarios and modeling cases that result in the release of radionuclides to the groundwater. The BDCFs for the volcanic ash exposure scenario apply only to the volcanic eruption modeling case of the igneous scenario class because this is the only case considered in the TSPA model of radionuclide release to biosphere as a result of an extrusive volcanic event.

For the groundwater scenario, radionuclides enter the biosphere from wells that extract contaminated groundwater from an aquifer. Human exposure arises from using the contaminated water for domestic and agricultural purposes. For the volcanic ash exposure scenario, radionuclides enter the biosphere by means of volcanic tephra that is deposited on or redistributed to the surface soil at the location of the receptor.

As noted previously, each of the biosphere exposure scenarios is a well-defined, connected sequence of FEPs that describe characteristics of the biosphere. The FEPs relevant to biosphere modeling are described in the following section. The details of the exposure scenarios based on these FEPs are provided in Sections 6.3.1.1 and 6.3.2.1 for the groundwater and volcanic ash exposure scenarios, respectively.

The radionuclides of interest (Table 6.1-1) for the TSPA and thus the biosphere model depend on the release type, as discussed in *Radionuclide Screening* (SNL 2007 [DIRS 177424], Section 7). Two exposure scenarios (groundwater and volcanic ash), and, therefore, two lists of radionuclides, are applicable for the biosphere modeling.

Table 6.1-1. Radionuclides of Interest for the TSPA

Radionuclide	Groundwater Scenario		Volcanic Scenario	
	10^2 to 10^4 yr	10^4 to 10^6 yr	10^2 to 10^4 yr	10^4 to 10^6 yr
^{14}C	^{14}C	^{14}C	—	—
^{36}Cl	^{36}Cl	^{36}Cl	—	—
^{79}Se	^{79}Se	^{79}Se	—	—
^{90}Sr	^{90}Sr		^{90}Sr	—
^{99}Tc	^{99}Tc	^{99}Tc	—	^{99}Tc
^{126}Sn	^{126}Sn	^{126}Sn	^{126}Sn	^{126}Sn
^{129}I	^{129}I	^{129}I	—	^{129}I
^{135}Cs	^{135}Cs	^{135}Cs	—	—
^{137}Cs	^{137}Cs	—	^{137}Cs	—
^{210}Pb	—	^{210}Pb	—	^{210}Pb
^{226}Ra	—	^{226}Ra	—	^{226}Ra
^{228}Ra	—	^{228}Ra	—	^{228}Ra
^{227}Ac	—	^{227}Ac	—	^{227}Ac
^{229}Th	^{229}Th	^{229}Th	^{229}Th	^{229}Th
^{230}Th	—	^{230}Th	—	^{230}Th
^{232}Th	—	^{232}Th	—	^{232}Th
^{231}Pa	^{231}Pa	^{231}Pa	—	^{231}Pa
^{232}U	^{232}U	^{232}U	—	—
^{233}U	^{233}U	^{233}U	^{233}U	^{233}U
^{234}U	^{234}U	^{234}U	^{234}U	^{234}U
^{235}U	—	^{235}U	—	—
^{236}U	^{236}U	^{236}U	—	—
^{238}U	^{238}U	^{238}U	—	^{238}U
^{237}Np	^{237}Np	^{237}Np	—	^{237}Np
^{238}Pu	^{238}Pu	—	^{238}Pu	—
^{239}Pu	^{239}Pu	^{239}Pu	^{239}Pu	^{239}Pu
^{240}Pu	^{240}Pu	^{240}Pu	^{240}Pu	^{240}Pu
^{242}Pu	—	^{242}Pu	—	^{242}Pu
^{241}Am	^{241}Am	—	^{241}Am	—
^{243}Am	^{243}Am	^{243}Am	^{243}Am	^{243}Am
Total	23	27	12	20

Source: DTN: MO0701RLTSCRNA.000 [DIRS 179334]

NOTE: In the source document two additional radionuclides are included (^{245}Cm and ^{241}Pu) not because of their direct dose contribution but to include them in the TSPA model as predecessors (sources) of ^{241}Am.

6.2 BIOSPHERE FEATURES, EVENTS, AND PROCESSES

The YMP FEP database (DTN: MO0706SPAFEPLA.001 [DIRS181613]) is the source of FEPs for developing this model. This is a comprehensive list of FEPs that may be applicable to the exposure scenarios that might result from storing spent nuclear fuel and high-level radioactive waste in a geologic repository at Yucca Mountain. This list contains a subset of biosphere-related FEPs that were evaluated for inclusion in the biosphere model. The associated document, *Features, Events, and Processes for the Total System Performance Assessment* (SNL 2007 [DIRS 179476]) contains the screening arguments for excluded FEPs and describes disposition of included FEPs in the documentation that supports the biosphere model. This list of FEPs is appropriate for its intended use because it constitutes a sole source of FEPs that were determined to be relevant to the scenarios and cases considered for evaluation of performance of the Yucca Mountain repository. Further description of the biosphere-related FEPs can be found in Section 6.2 of this report.

Biosphere FEPs describe the reference biosphere and, along with assumptions and simplifications, are the fundamental elements used to build the biosphere conceptual model. The biosphere system and associated chemical, physical, and biological processes are characterized by appropriate FEPs.

Based on the screening of the 51 FEPs designated in the FEP database as related to biosphere transport and exposure, 32 FEPs were determined to be applicable to the current model and were included directly or indirectly in the biosphere model as described in Table 6.2-1. The report *Features, Events, and Processes for the Total System Performance Assessment* (SNL 2007 [DIRS 179476]) presents screening arguments for excluding 19 of the biosphere-related FEPs from consideration in the biosphere model. Most of these FEPs were excluded based on regulations (10 CFR Part 63 [DIRS 173273]), and some are excluded based on low probability of occurrence or low consequence.

The FEPs shown in Table 6.2-1 (referred to as the included FEPs) represent elements of the arid to semi-arid environment in the Yucca Mountain area and the possible processes leading to radionuclide transport and exposure in the environment. These FEPs are presented in Table 6.2-1 with the FEP number, name, and description; and brief comments on how the FEP is incorporated into the model. Detailed information on how each FEP is incorporated into the exposure scenarios is provided in Section 6.3.4. Relationships among the biosphere-related FEPs, the biosphere conceptual model, and the exposure scenarios are more fully examined in Section 6.3. As a tool to illustrate the movement of radionuclides through the biosphere compartments, a radionuclide transfer interaction matrix (Tables 6.3-2 and 6.3-4) links included FEPs in the matrix for each exposure scenario. The description of how the individual included FEPs correspond to the elements of the biosphere conceptual model is presented in Section 6.3.4.

In addition, the disposition of the included FEPs in the biosphere mathematical model, submodels, and associated equations and parameters are discussed in Section 6.7. The disposition of these FEPs in TSPA is collectively through the BDCFs that are inputs for the TSPA model (see Sections 6.11.3 and 6.12.3 for the description of how biosphere inputs are used in the TSPA model).

Table 6.2-1. Description and Consideration of FEPs in the Biosphere Model

FEP Number	FEP Name	FEP Description [a]	FEP Consideration
1.2.04.07.0A	Ashfall	Finely divided waste particles may be carried up a volcanic vent and deposited on the land surface from an ash cloud.	Volcanic ash is the initial source of contamination in the biosphere for the volcanic exposure scenario. Eruptive events involving the intersection of the repository by an eruptive conduit could result in atmospheric release of contaminated tephra from the repository, followed by atmospheric transport, deposition and redistribution of the contaminated tephra by eolian and fluvial processes to the RMEI location. Atmospheric dispersion and deposition of ash are modeled in the ASHPLUME model; the tephra redistribution is modeled in the FAR model. These two models are used in the TSPA model to calculate the radionuclide concentration in the soil, which is the source term in the biosphere component model in the TSPA. Some characteristics of deposited tephra were considered in development of the input parameters for the soil and air submodels.
1.3.01.00.0A	Climate change	Climate change may affect the long-term performance of the repository. This includes the effects of long-term change in global climate (e.g., glacial/interglacial cycles) and shorter-term change in regional and local climate. Climate is typically characterized by temporal variations in precipitation and temperature.	The effects of climate change on BDCFs were evaluated. As a part of this evaluation, separate distributions were developed for input parameters that are directly affected by climate change and separate sets of BDCFs were developed for the present-day and future climate states.
1.3.07.02.0A	Water table rise affects SZ	Climate change could produce increased infiltration, leading to a rise in the regional water table, possibly affecting radionuclide release from the repository by altering flow and transport pathways in the SZ. A regionally higher water table and change in SZ flow patterns might move discharge points closer to the repository.	The biosphere model does not directly consider surface discharge of groundwater. However, the conceptual and mathematical models for the groundwater scenario implicitly included this FEP because BDCFs were calculated per unit activity concentration in the water used in the biosphere, regardless of the water source. If the water from surface discharge resulting from water table rise is used in the biosphere, the model still applies, so long as the use and treatment of water remains unchanged.
1.4.07.01.0A	Water management activities	Water management is accomplished through a combination of dams, reservoirs, canals, pipelines, and collection and storage facilities. Water management activities could have a major influence on the behavior and transport of contaminants in the biosphere.	Water management activities conducted in the Yucca Mountain region (e.g., irrigation, fish farming) were incorporated throughout the conceptual and mathematical model and considered in the development of parameter values for the plant and fish submodels.

Table 6.2-1. Description and Consideration of FEPs in the Biosphere Model (Continued)

FEP Number	FEP Name	FEP Description [a]	FEP Consideration
1.4.07.02.0A	Wells	One or more wells drilled for human use (e.g., drinking water, bathing) or agricultural use (e.g., irrigation, animal watering) may intersect the contaminant plume.	Wells are the source of groundwater for domestic and agricultural uses in the groundwater exposure scenario.
2.2.08.01.0A	Chemical characteristics of groundwater in the SZ	Chemistry and other characteristics of groundwater in the saturated zone may affect groundwater flow and radionuclide transport of dissolved and colloidal species. Groundwater chemistry and other characteristics, including temperature, pH, Eh, ionic strength, and major ionic concentrations, may vary spatially throughout the system as a result of different rock mineralogy.	The source of radionuclides in the biosphere groundwater scenario is the groundwater pumped from wells. The model addresses radionuclide accumulation and transport within and between biosphere compartments culminating in an annual dose to a defined receptor. The model allows the parameters quantifying these transport mechanisms to be represented as probability distributions thereby taking into account localized physical and chemical properties. For the parameters that are dependent on chemical properties of the groundwater and are fixed values (such as dose coefficients for radionuclide intakes), the model assumes parameter values such that the risk to the receptor is not underrepresented.
2.3.02.01.0A	Soil type	Soil type is determined by many different factors (e.g., formative process, geology, climate, vegetation, land use). The physical and chemical attributes of the surficial soils (such as organic matter content and pH) may influence the mobility of radionuclides.	This feature was included through the consideration of the soil characteristics in the reference biosphere in the development of parameter values for the soil, plant, and ^{14}C submodels.
2.3.02.02.0A	Radionuclide accumulation in soils	Radionuclide accumulation in soils may occur as a result of upwelling of contaminated groundwater (leaching, evaporation at discharge location), deposition of contaminated water or particulates (irrigation water, runoff), and/or atmospheric deposition.	Accumulation of radionuclides in soil from deposition of irrigation water and volcanic ash was modeled in the soil submodel.
2.3.02.03.0A	Soil and sediment transport in the biosphere	Contaminated sediments can be transported to and through the biosphere by surface runoff and fluvial processes, and, to a lesser extent, by eolian processes and bioturbation. Sediment transport and redistribution may cause concentration or dilution of radionuclides in the biosphere.	Soil and sediment transport via erosion and resuspension were included in the soil and air submodels.

Table 6.2-1. Description and Consideration of FEPs in the Biosphere Model (Continued)

FEP Number	FEP Name	FEP Description [a]	FEP Consideration
2.3.04.01.0A	Surface water transport and mixing	Radionuclides released from an underground repository might enter the biosphere through discharge of deep groundwater into a lake or river. Transport and mixing within the surface water bodies affects the subsequent behavior and transport of radionuclides in the biosphere. Transport and mixing includes dilution, sedimentation, aeration, streamflow, and river meander.	The groundwater scenario implicitly includes water transport because the model applies to the use of any water containing radionuclides, regardless of the origin, if the reference biosphere, water-use practices, and characteristics of the RMEI remain unchanged. The model does not consider mixing of contaminated and uncontaminated water.
2.3.11.01.0A	Precipitation	Precipitation is an important control on the amount of recharge. It transports solutes with it as it flows downward through the subsurface or escapes as runoff. Precipitation influences agricultural practices of the receptor. The amount of precipitation depends on climate.	Levels of precipitation consistent with current knowledge of the region around the Yucca Mountain site were considered in the development of input parameter distributions for the soil, plant, and ^{14}C submodels.
2.3.13.01.0A	Biosphere characteristics	The principal components, conditions, or characteristics of the biosphere system can influence radionuclide transport and affect the long-term performance of the disposal system. These include the characteristics of the reference biosphere such as climate, soils and microbes, flora and fauna, and their influences on human activities.	The principal components, conditions, and characteristics of the biosphere that influence radionuclide transport were represented in the reference biosphere, including the conceptual and mathematical models. Current knowledge of the conditions in the biosphere was considered in the development of parameter distributions for all submodels.
2.3.13.02.0A	Radionuclide alteration during biosphere transport	Once in the biosphere, radionuclides may be transported and transferred through and between different compartments of the biosphere. Temporally- and spatially-dependent physical and chemical environments in the biosphere may lead to alteration of both the physical and chemical properties of the radionuclides as they move through or between the different compartments of the biosphere. These alterations could consequently control exposure to the human population.	Changes in the physical and chemical form of radionuclides during transfer among biosphere components were incorporated throughout the conceptual and mathematical models. This FEP was also implicitly incorporated through the use of radionuclide-specific transfer factors in the plant and animal submodels.
2.4.01.00.0A	Human characteristics (physiology, metabolism)	This FEP addresses human characteristics. These include physiology, metabolism, and variability among individual humans.	Metabolic and physiologic considerations consistent with present knowledge of adults, as per 10 CFR 63.312 [DIRS 173273], were used in the development of parameter distributions for the external exposure, inhalation, and ingestion submodels.

Table 6.2-1. Description and Consideration of FEPs in the Biosphere Model (Continued)

FEP Number	FEP Name	FEP Description [a]	FEP Consideration
2.4.04.01.0A	Human lifestyle	Human lifestyle, including everyday household activities and leisure activities, will influence the critical exposure pathways to humans.	Activities representative of the living style of the residents of the town of Amargosa Valley were incorporated throughout the conceptual and mathematical model. The living styles of Amargosa Valley residents were considered in the development of parameter distributions for the air, external exposure, inhalation, and ingestion submodels.
2.4.07.00.0A	Dwellings	This FEP addresses human dwellings, and the ways in which dwellings might affect human exposures. Exposure pathways might be influenced by building materials and location.	Characteristics of dwellings representative of the living style of the residents of the town of Amargosa Valley were considered in the development of input parameters for the air, external exposure, and inhalation submodels.
2.4.08.00.0A	Wild and natural land and water use	Human uses of wild and natural lands (forests, bush, coastlines) and water (lakes, rivers, oceans) may affect the long-term performance of the repository. Wild and natural land use will be primarily controlled by natural factors (topography, climate, etc.).	Wild and natural land and water use (e.g., use of natural lands, ingestion of game animals) of the residents of the town of Amargosa Valley was incorporated into the air, external exposure, and ingestion submodels. These lifestyle characteristics were considered in the development of parameters for those submodels.
2.4.09.01.0B	Agricultural land use and irrigation	Agricultural areas exist near Yucca Mountain, particularly in the direction of groundwater flow. Current practices include irrigation, plowing, fertilization, crop storage, and soil modification and amendment. Existing practices may play a significant role in determining exposure pathways and dose.	Agricultural land use and irrigation practices of the residents of the town of Amargosa Valley were incorporated into the soil, air, plant, animal, ^{14}C, and fish submodels. These practices were considered in the development of parameters for those submodels.
2.4.09.02.0A	Animal farms and fisheries	Domestic livestock or fish could become contaminated through the intake of contaminated feed, water, or soil. Such contamination could then enter the food chain.	Animal farms and fisheries practices of the residents of the town of Amargosa Valley were incorporated into the animal and fish submodels. These practices were considered in the development of parameters for those submodels.
2.4.10.00.0A	Urban and industrial land and water use	Urban and industrial uses of land and water (industry, urban development, earthworks, energy production, etc.) may affect the long-term performance of the repository. Urban and industrial land use will be controlled by both natural factors (topography, climate, etc.) and human factors (economics, population density, etc.).	Land and water use in urban and industrial settings of the residents of the town of Amargosa Valley were incorporated into the soil, air, ^{14}C, external exposure, inhalation, and ingestion submodels. These lifestyle characteristics were considered in the development of parameters for those submodels.

Table 6.2-1. Description and Consideration of FEPs in the Biosphere Model (Continued)

FEP Number	FEP Name	FEP Description [a]	FEP Consideration
3.1.01.01.0A	Radioactive decay and ingrowth	Radioactivity is the spontaneous disintegration of an unstable atomic nucleus that results in the emission of subatomic particles. Radioactive species (isotopes) of a given element are known as radionuclides. Radioactive decay of the fuel in the repository changes the radionuclide content in the fuel with time and generates heat. Radionuclide quantities in the system at any time are the result of the radioactive decay and the ingrowth of decay products as a consequence of that decay. Over a 10,000-year performance period, these processes will produce decay products that need to be considered in order to adequately evaluate the release and transport of radionuclides to the accessible environment.	Radionuclide decay and ingrowth in soil was included in the soil submodel. In addition, the effective dose coefficients calculated in the model included dose contributions from the decay products of primary radionuclides.
3.2.10.00.0A	Atmospheric transport of contaminants	Atmospheric transport includes radiotoxic and chemotoxic species in the air as gas, vapor, particulates, or aerosol. Transport processes include wind, plowing and irrigation, degassing, saltation, and precipitation.	The processes of atmospheric transport of radionuclides from soil erosion, resuspension of soil and ash particles, gaseous emission of radionuclides from soil, and generation of aerosols from evaporative coolers were included in the air and ^{14}C submodels.
3.3.01.00.0A	Contaminated drinking water, foodstuffs and drugs	This FEP addresses human diet and fluid intake. Consumption of food, water, soil, drugs, etc., will affect human exposure to radionuclides. Other influences include filtration of water, dilution of diet with uncontaminated food, and food preparation techniques.	Annual consumption rates of contaminated water, soil, locally produced crops, animal products, and fish were included in the ingestion submodel. Consumption rates were based on the diet of the residents of the town of Amargosa Valley and the requirements of 10 CFR 63.312 [DIRS 173273].
3.3.02.01.0A	Plant uptake	Uptake and accumulation of contaminants by plants could affect potential exposure pathways. Plant uptake from contaminated soils and irrigation water is possible. Particulate deposition onto plant surfaces is also possible. These plants may be used as feed for livestock and/or consumed directly by humans.	The process of plant uptake of radionuclides was included in the plant and ^{14}C submodels.
3.3.02.02.0A	Animal uptake	Livestock may accumulate radionuclides as a result of ingestion (water, feed and soil/sediment) and inhalation (aerosols and particulates). Depending on the livestock, they may be used for human consumption directly, or their produce (milk, eggs, etc.) may be consumed.	The animal submodel included the process of radionuclide uptake by farm animals.

Table 6.2-1. Description and Consideration of FEPs in the Biosphere Model (Continued)

FEP Number	FEP Name	FEP Description [a]	FEP Consideration
3.3.02.03.0A	Fish uptake	Uptake and bioaccumulation of contaminants in aquatic organisms could affect potential exposure pathways.	The fish submodel included the bioaccumulation of radionuclides in fish.
3.3.03.01.0A	Contaminated non-food products and exposure	Contaminants may be concentrated in various products: clothing (e.g., hides, leather, linen, wool); furniture (e.g., wood, metal); building materials (e.g., stone, clay for bricks, wood, dung); fuel (e.g., peat), tobacco, and pets.	The external exposure submodel bounded exposure to the few nonfood products known to be produced in Amargosa Valley that may contain radionuclides by assuming that the RMEI would be exposed to the higher activity concentrations in contaminated soil at all times while in the biosphere.
3.3.04.01.0A	Ingestion	Ingestion is human exposure to repository-derived radionuclides through eating contaminated foodstuffs or drinking contaminated water.	The ingestion submodel included ingestion of contaminated food, drinking water, and soil.
3.3.04.02.0A	Inhalation	Inhalation pathways for repository-derived radionuclides should be considered. Two possible pathways are: inhalation of gases and vapors emanating directly from the ground after transport through the far-field; and inhalation of suspended, contaminated particulate matter (e.g., decay products of radon, dust, smoke, pollen, and soil particles).	The inhalation submodel included inhalation of contaminated resuspended particles, aerosols from evaporative coolers, ^{14}C, and radon decay products.
3.3.04.03.0A	External exposure	External exposure is human exposure to repository-derived radionuclides by contact, use, or exposure to contaminated materials.	The external exposure submodel included external exposure to contaminated materials.
3.3.05.01.0A	Radiation doses	The radiation dose is calculated from exposure rates (external, inhalation, and ingestion) and dose coefficients. The latter are based upon radiation type, human metabolism, metabolism of the element of concern in the human body, and duration of exposure.	Calculation of the predicted annual dose, as required by 10 CFR 63.311, for a unit activity concentration of a radionuclide (i.e., BDCF) was conducted in the external exposure, inhalation, and ingestion submodels.
3.3.08.00.0A	Radon and radon decay product exposure	This FEP addresses human exposure to radon and radon decay products. ^{226}Ra occurs in nuclear fuel waste and it gives rise to ^{222}Rn gas, the radioactive decay products of which can result in radiation doses to humans upon inhalation.	Concentrations of ^{222}Rn and ^{222}Rn decay products were calculated in the air submodel. Exposure to ^{222}Rn and decay products was included in the inhalation submodel.

[a] FEP names and descriptions are based on the *FY 07 LA FEP List and Screening* (DTN: MO0706SPAFEPLA.001 [DIRS 181613]), which is considered to be the source of these FEPs.

SZ = saturated zone.

6.3 BIOSPHERE CONCEPTUAL MODELS

In the previous section, the included biosphere-related FEPs, and the methods for including them in the ERMYN model, were discussed. The biosphere conceptual model is constructed by considering these FEPs for a specific exposure scenario. To make it easier to understand, the conceptual model is presented in a logical framework that relates a contamination source to a human radiation dose using all possible mechanisms for radionuclide transport in the environment and human exposure pathways. These transport and exposure pathways are then explicitly represented in the mathematical model. In this section, the biosphere conceptual models for the groundwater (Section 6.3.1) and volcanic ash scenarios (Section 6.3.2) are discussed. Although many transport processes and exposure pathways are the same for both scenarios, they differ because of the different environmental media that are initially contaminated (i.e., groundwater and volcanic ash). Other issues related to the conceptual model are discussed later, including ACMs (Section 6.3.3), individual FEPs applicable to specific exposure scenarios (Section 6.3.4), and the treatment of short-lived decay products of primary radionuclides (Section 6.3.5).

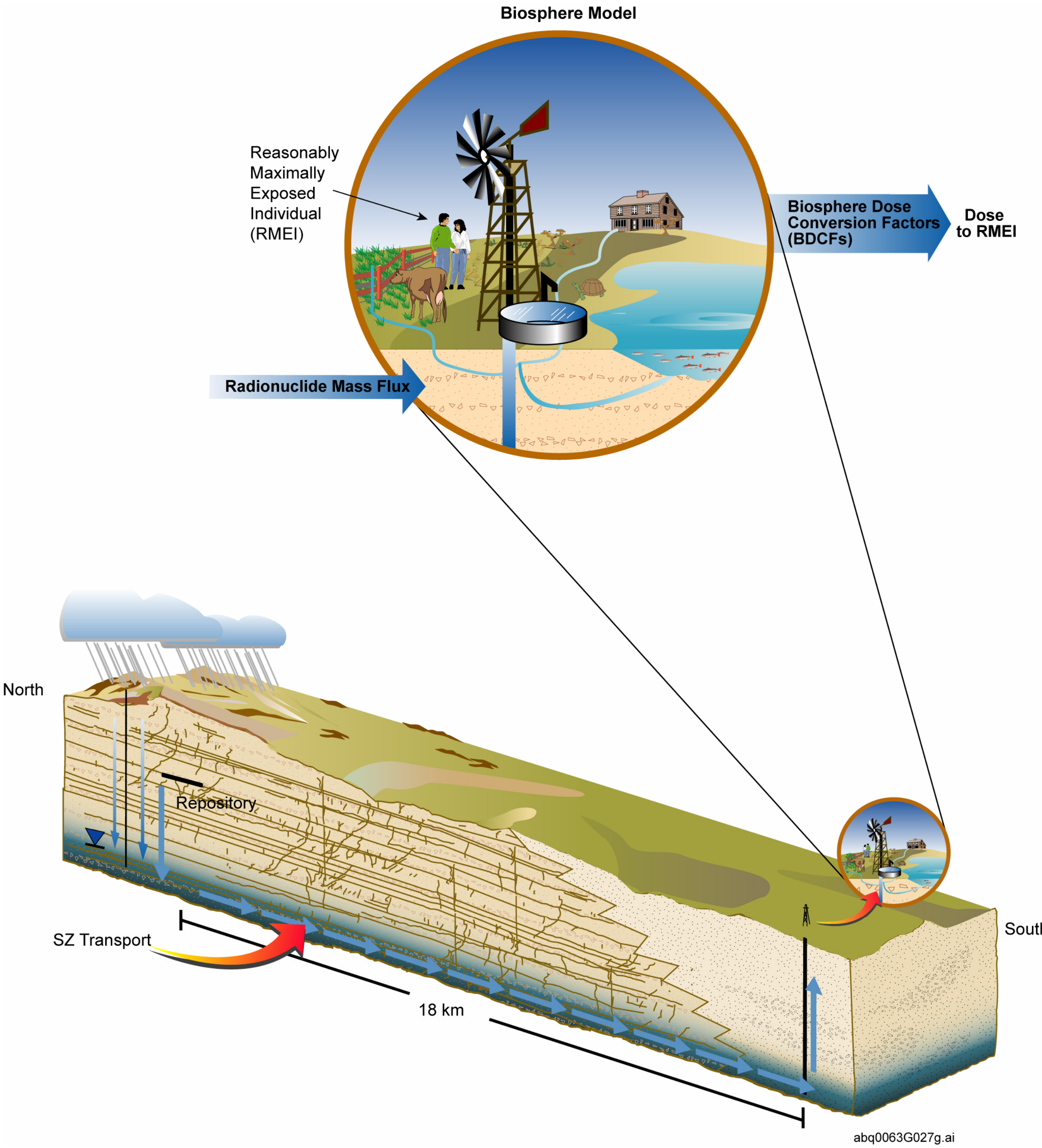
6.3.1 Conceptual Model for the Groundwater Exposure Scenario

An exposure scenario is a well-defined, connected sequence of FEPs that describes the characteristics of the present-day and possible future biosphere where radionuclide transport occurs, as well as circumstances of human exposure. The reference biosphere and the human receptor (Section 6.1) are fundamental concepts of the groundwater exposure scenario, or simply groundwater scenario. The description of the groundwater scenario (Section 6.3.1.1) includes background information on the biosphere system. Based on site-specific information, radionuclide transport in various environmental media is examined using the radionuclide transfer interaction matrix (Table 6.3-2). These environmental media and exposure modes are considered as subsystems of the overall biosphere system.

6.3.1.1 Scenario Description

Under the groundwater exposure scenario, radionuclides would be released into the biosphere from contaminated groundwater drawn from a well. Human exposure, then, would arise when the local community, where the receptor resides, uses the contaminated water for domestic and agricultural purposes. There is no evidence to suggest the widespread use of water treatment in the Amargosa Valley, and there is only a small quasi-municipal system where water standards could be enforced (State of Nevada 1997 [DIRS 110951]). In the model, no credit is taken for water treatment before use, and radionuclide concentrations in the well water are considered to be equal to concentrations in the groundwater. Groundwater is assumed to be the source for all water needs, including drinking water, irrigation, and other domestic uses. The groundwater scenario is used to evaluate the radiological consequences of all TSPA modeling cases that can lead to radionuclide releases into the groundwater.

Environmental transport pathways are the routes by which radionuclides move from the source to the environmental media and among the environmental media. Human exposure pathways arise when people are exposed, internally or externally, to the contaminated media (Figure 6.3-1). The environmental transport pathways, the media, and the exposure pathways are identified in the discussion of biosphere FEPs (Section 6.2). Six environmental media (water, soil, air, plants, animals, and fish) and three principal human exposure pathways (external exposure, inhalation, and ingestion) are considered (Table 6.3-1). These pathways are representative of a rural community in the Yucca Mountain region and consistent with arid to semi-arid conditions.



NOTE: SZ = saturated zone.

Figure 6.3-1. Graphical Representation of the Contaminated Groundwater Release to Biosphere

Table 6.3-1. Exposure Pathways for the Groundwater Scenario

Environmental Medium	Exposure Mode	Exposure Pathways	Examples of Typical Activities
Water	Ingestion	Water intake	Drinking water and water-based beverages and water used in food preparation
Soil	Ingestion	Inadvertent soil ingestion	Recreational activities, occupational activities, gardening, and consumption of fresh fruit and vegetables
Soil	External	External radiation exposure	Activities on or near contaminated soils
Air	Inhalation	Breathing resuspended particles, gases (^{222}Rn and progeny, plus $^{14}CO_2$), and aerosols from evaporative coolers	Outdoor activities, including soil-disturbing activities related to work and recreation. Domestic activities, including sleeping
Plants	Ingestion	Consumption of locally produced crops: leafy vegetables, other vegetables, fruit, and grain	Eating contaminated crop foodstuffs
Animals	Ingestion	Consumption of locally produced animal products: meat, poultry, milk, and eggs	Eating contaminated animal product foodstuffs
Fish	Ingestion	Consumption of locally produced freshwater fish	Eating contaminated fish

The future climate for the region around Yucca Mountain is predicted to be cooler and wetter (BSC 2004 [DIRS 170002]) than the present-day climate. In addressing how the changes that will occur during the period of geologic stability (ending at one million years after disposal) are taken into account in the TSPA, it is required that changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology should not be projected. It must be assumed that all of those factors remain constant as they are at the time of license application submission to the NRC (10 CFR 63.305(b) [DIRS 173273]). In contrast to the direction not to project changes in society, the biosphere, human biology, or human knowledge or technology, 10 CFR 63.305(c) (70 FR 53313 [DIRS 178394]) directs the licensee to vary factors related to climate.

Human activity is defined as a component of the biosphere (10 CFR 63.2 and 63.102 [DIRS 173273]). Many aspects of human activity are determined by the climate; specifically changes in irrigation rates are climate-induced. One thus has to address the question of whether a change in irrigation rates is best viewed as a result of human activity, a factor which section 10 CFR 63.305(b) [DIRS 173273]) directs the DOE not to vary in its performance assessments, or best viewed as a result of climate change, a factor which 10 CFR 63.305(c) (70 FR 53313 [DIRS 178394]) directs the DOE to vary over the period of geologic stability (i.e., one million years). The subject of climate change and its effects on the BDCFs are further investigated in Section 6.11.2.2 and the recommendation regarding the treatment of climate in the TSPA biosphere component model are presented in Section 6.11.3.

To satisfy the requirements of 10 CFR 63.305(c) (70 FR 53313 [DIRS 178394]), climate change is incorporated into the ERMYN model by using different values for input parameters that are influenced by temperature and precipitation (Table 6.6-2). Consequently, different sets of BDCFs are calculated for the present-day and future climate states (see Section 6.11.2 for more information on incorporation of climate change into biosphere model results and Section 6.11.3 for the recommendations for the TSPA). A wetter climate may cause the water table to rise and discharge groundwater at springs in the Yucca Mountain area. The ERMYN biosphere model applies to the discharge of groundwater from springs if use of, and exposure to, water remains the same, and there is no mixing of contaminated and uncontaminated water (or other processes that would cause the radionuclide concentrations in the water to change). There are no permanent rivers or lakes in the immediate region surrounding the Yucca Mountain site. If there were, these features would require additional pathways that are not consistent with the local Amargosa Valley conditions and, therefore, are not included in ERMYN. An example of such pathways is water immersion due to swimming in natural water systems and external exposure due to contaminated sediments. These and other model limitations are summarized in Section 8.2.

6.3.1.2 Identification of Biosphere Model Components

As defined in SCI-PRO-006, a conceptual model is a set of hypotheses consisting of assumptions, simplifications, and idealizations that describes the essential aspects of a system, process, or phenomenon. The biosphere conceptual model provides a description of the biosphere system, the essential components, and the mechanisms of interaction between the biosphere components. It also presents a logical way to evaluate human radiation dose from exposure to radionuclides released from the repository at Yucca Mountain.

As described in Section 6.1, a biosphere system consists of the environment and a human receptor. These elements of the system are represented in the ERMYN model as a reference biosphere and the RMEI, respectively. The number of biosphere components depends on the exposure scenario. For the groundwater scenario, there are seven biosphere components: six representing contaminated environmental media and one for the human receptor:

- **Water**—groundwater from a well is the source of radionuclides in the biosphere
- **Soil**—cultivated soil from farmland and gardens, limited to surface soil down to the tilling depth
- **Atmosphere**—including outdoor air and indoor air
- **Plants**—crops for human and farm animal consumption, grown in the cultivated soil and irrigated with contaminated water
- **Animals**—animal products for human consumption raised by humans using contaminated local fodder and contaminated water
- **Fish**—raised at a fish farm using contaminated groundwater
- **Human Receptor**—exposed through external exposure, inhalation, and ingestion of the contaminated media listed above; for the TSPA, the receptor is the RMEI

The aquifer, the source of groundwater, is not a part of the biosphere; it is part of the geosphere. The biosphere–geosphere interface is through the extraction of well water. The biosphere model does not include processes related to long-range atmospheric transport and dispersion of airborne radionuclides. However, ERMYN considers airborne activity resulting from resuspension of contaminated soil and gaseous emission of radionuclides from soil to air followed by atmospheric dilution. In ERMYN, radionuclides are removed from the biosphere by leaching and erosion, but these transport mechanisms do not provide radionuclide sources in any subsequent model. ERMYN also includes radioactive decay as a radionuclide removal process, but this process is only applied to radionuclide concentrations in the surface soil. The ingrowth in the soil of long-lived decay products of primary radionuclides is also included in the model.

6.3.1.3 Radionuclide Transfer Interaction Matrix

After the components of a biosphere system are defined, radionuclide transport between components is considered. A radionuclide transfer interaction matrix is constructed to identify the important processes leading to radionuclide transfer between biosphere components (Table 6.3-2).

Table 6.3-2. Radionuclide Transfer Interaction Matrix for the Groundwater Scenario

i,j	1	2	3	4	5	6	7
1	**SOURCE** (groundwater)	irrigation	evaporation	irrigation interception	ingestion of water	bio-accumulation (water use in fisheries)	drinking water ingestion
2	leaching [a]	**SURFACE SOIL**	particle resuspension, gas release, soil erosion [a]	root uptake	soil ingestion	—	soil ingestion, external exposure
3	—	dust deposit	**AIR**	dust deposition, photosynthesis	—	—	inhalation of particulates, gases, and aerosols
4	—	weathering, crop debris after harvest removal	—	**PLANTS (crops)**	ingestion of feed	—	crop ingestion
5	—	fertilization	—	—	**ANIMALS (animal products)**	—	animal product ingestion
6	—	—	—	—	—	**FISH**	fish ingestion
7	—	—	—	—	—	—	**HUMAN (receptor)**

[a] Leaching and soil erosion are modeled in the soil submodel only as removal mechanisms within the biosphere. The possibility that the removed radionuclides could become a new source is evaluated elsewhere.

The diagonal elements in the interaction matrix represent the biosphere components (features of the biosphere), and the off-diagonal elements represent the interactions between components (biosphere processes). By convention, the direction of interaction between components is clockwise. For example, in Table 6.3-2, the element in row 2 and column 4 (element [2, 4]), refers to the transfer of radionuclides from the surface soil to the plants via root uptake. Off-diagonal elements with a dash (—) indicate that interactions between the two components are not explicitly modeled in ERMYN. For all off-diagonal elements with stated interactions, radionuclide transfer mechanisms are discussed in the conceptual model section and evaluated quantitatively in the mathematical model section.

6.3.1.4 Conceptual Model Assumptions

The following 11 modeling assumptions are incorporated in the conceptual model for the groundwater exposure scenario. Each is presented as an assumption statement, a rationale providing the basis for the assumption, and the section or sections in this report where the assumption has been applied.

ASSUMPTION 1 – GROUNDWATER SOURCE

Statement—Radionuclide concentrations in the groundwater are constant through time.

Rationale—Radionuclides will accumulate in soil that is irrigated with contaminated groundwater and will build up in the surface soil. The biosphere model calculates doses by taking into consideration radionuclide buildup in surface soil caused by prior irrigation. Therefore, doses calculated for a specified time will be influenced by groundwater radionuclide concentrations prior to that time. The degree of radionuclide buildup in the soil, following irrigation for a certain period of time, varies among the radionuclides and depends on the irrigation duration, and on the physical and chemical properties of the radionuclides. Duration of prior irrigation is one of the biosphere model input parameters and it is developed to be representative of the agricultural land use in the Amargosa Valley. To allow calculations of BDCFs for a given radionuclide concentration in groundwater, i.e., to make them independent on the actual time-dependent radionuclide concentration, it is assumed that concentrations in groundwater are constant at a concentration defined by the user of the model (e.g., unit concentration of 1 Bq/m^3).

Radionuclide concentration in the surface soil is calculated assuming radionuclide buildup over a period of prior irrigation with water containing a constant concentration of radionuclides. If groundwater radionuclide concentrations are increasing, this assumption will result in overestimating the dose for that radionuclide. If concentrations in groundwater are decreasing, the dose may be underestimated. However, it is unlikely that groundwater concentrations would decrease significantly over the period of prior irrigation (Section 6.6).

The assumption of a constant groundwater source allows separate and independent calculations of time-dependent radionuclide concentrations in a TSPA and time-independent BDCFs in the ERMYN. The assumption requires no further confirmation because the compliance dose will not be underestimated.

Applicability—This assumption is applied to the groundwater scenario and is used in Sections 6.3.1.6, 6.4, 6.4.1.1, and 6.4.10.4.

ASSUMPTION 2 – CONSIDERATION OF SHORT-LIVED DECAY PRODUCTS

Statement—Short-lived decay products (half-life less than 180 days) are always in secular equilibrium with the long-lived primary radionuclides.

Rationale—Modeling radionuclide decay and ingrowth in environmental media can be complicated if every decay product is considered as a function of time. This assumption eliminates the need to consider the dynamics of long decay chains for high atomic number (greater than or equal to 82) radionuclides. This assumption is conservative because the activity of a decay product reaches a maximum value when in equilibrium with the long-lived parent radionuclide. This assumption is reasonable because the primary radionuclides have long half-lives (Section 6.3.5), and the primary radionuclides and decay products in the groundwater and the volcanic ash are expected to be in secular equilibrium with the short-lived decay products. If the radionuclides in a decay chain are transferred to the biosphere or between biosphere components, the secular equilibrium could be perturbed because of different transfer characteristics in the biosphere and groundwater (e.g., due to different leaching rates or transfer factors). However, calculations of radionuclide transfer and doses are based on one-year average values, and a new equilibrium will be reached quickly for the short-lived decay products. This assumption is also used in the RESRAD code (Yu et al. 2001 [DIRS 159465], Section 3.1). The developed effective dose coefficients, which are based on this assumption, are compared with results from the RESRAD model to confirm this assumption (Section 7.4.1).

Applicability—This assumption is applied to the groundwater scenario and is used in Sections 6.3.5, 6.4.1.2, 6.4.9, and 7.4.1.

ASSUMPTION 3 – LONG-TERM IRRIGATION, LAND USE, AND CROP ROTATION

Statement—Current land use and irrigation practices continue on agricultural land throughout the period of interest. The average irrigation rate for the crop types is appropriate for calculating radionuclide concentrations in the soil.

Rationale—Based on the present-day and predicted future climates in the Amargosa Valley (BSC 2004 [DIRS 170002]), irrigation will be required for farming and gardening. Because irrigation rates differ among crops (BSC 2004 [DIRS 169673], Section 6.5), radionuclide concentrations in the soil will differ among fields depending on the types of crops grown. Crop rotation is a common agricultural practice in the Amargosa Valley (Horak and Carns 1997 [DIRS 124149], Section 1.b) and crop rotation over long periods will average out the short-term differences in irrigation rates, resulting in an average radionuclide concentration in the surface soil. Therefore, the annual average irrigation rates for the field crops and gardens crops (Assumption 5) are appropriate for calculating the concentration of radionuclides in agricultural soil. The concentration of a radionuclide in the surface soil layer is calculated by assuming uniform radionuclide distributions within the surface soil for the surface soil and for the upper layer of the surface soil that is available for resuspension (Assumption 7). This assumption simplifies the surface soil submodel because the long-term irrigation rate does not depend on each individual crop type. This assumption requires no further confirmation because it is based on common agricultural practices.

Applicability—This assumption is applied to the surface soil submodel for the groundwater scenario and is used in Sections 6.3.1.6, 6.4.1.1, and 6.4.10.4.

ASSUMPTION 4 – CROP HARVEST REMOVAL AND THE USE OF CONTAMINATED MANURE FOR FERTILIZER

Statement—Radionuclides added to the soil due to the use of manure for fertilizer replace radionuclides removed from the soil by harvesting crops.

Rationale—Harvesting crops removes radionuclides from cultivated fields, and fertilizing with contaminated fertilizer returns radionuclides to the fields. It is reasonable to assume that Amargosa Valley farmers will continue to use manure for fertilizer because this is current practice (Horak and Carns 1997 [DIRS 124149], p. 10). This assumption considers the removal of radionuclides from fields, in animal feed and soil, to be balanced by the addition of radionuclides in animal manure on fields where animal feed is grown. Intake of radionuclides by animals is from feed, soil, and water; therefore, drinking water is an additional source of radionuclides in manure not considered by this assumption. However, the contribution of radionuclides to animal intake from drinking water is low (a few percent; Table 6.13-14) compared to that from animal feed and soil. In addition, only a portion of the radionuclides taken in by animals is transferred to animal products. Therefore, these two processes approximately compensate for each other in terms of radionuclide concentration in soil, i.e., annual input to fields from use of manure as fertilizer approximately equals the annual removal less radionuclides retained in animals used for human consumption. The approach is reasonable and reflects possible recycling of radionuclides in the biosphere. Therefore this assumption requires no further confirmation. This assumption eliminates the need to calculate losses from crop harvest removal and gains from animal manure used as fertilizer. Applying this assumption to the entire Amargosa Valley is realistic because alfalfa is planted solely for livestock fodder, and is the major crop grown in Amargosa Valley (CRWMS M&O 1997 [DIRS 101090], pp. 3-18 to 3-19; YMP 1999 [DIRS 158212], Tables 10 and 11).

Applicability—This assumption is applied to the surface soil submodel for the groundwater scenario and is used in Sections 6.3.1.6, 6.4.1.1, and 7.3.1.1.

ASSUMPTION 5 – GARDEN AND FIELD LAND USE

Statement—Two different irrigation patterns for agricultural land are used in the biosphere model: garden irrigation and field irrigation. They result in different radionuclide concentrations in irrigated soils from long-term use of contaminated irrigation water. There are several associated assumptions regarding the biosphere transport and receptor exposure pathways resulting from these two types of land use and irrigation.

(1) Leafy vegetables, other vegetables, and fruit are assumed to be grown in home gardens and thus the garden irrigation is used in the biosphere model for these crops.

(2) Grain (for human and animal consumption) and forage are assumed to be grown in the fields and the field irrigation is used for these crops.

(3) For animal soil ingestion, field soil is used for cattle and milk cows (to calculate radionuclide concentrations in meat and milk); garden soil is used for chickens and hens (to calculate radionuclide concentrations in poultry and eggs).

(4) For human soil ingestion, radionuclide concentration in garden soil is used.

(5) Inhalation and external exposure, while the receptor is in the active outdoor environment (Section 6.4.2.1 for descriptions of the receptor environments), is assumed to occur on field soil. For the other receptor environments (inactive outdoors, active indoors, and asleep indoors), garden soil is used to evaluate inhalation and external exposure.

(6) Radionuclide concentrations in the resuspendable soil layer are assumed to be at equilibrium, regardless of the irrigation duration. If these equilibrium radionuclide concentrations are greater than the concentrations in the surface soil, they are used in calculation of inhalation exposure and deposition of resuspended soil on crops (Section 6.4.1.1).

Rationale—When cultivated lands are irrigated with contaminated groundwater over long periods of time, radionuclides accumulate in the soil. Some radionuclides may reach an equilibrium concentration in surface soil (Section 6.4.1). The time to reach equilibrium depends on the rates of radionuclide addition (i.e., irrigation) and removal from the soil (Equation 6.4.1-2). If a radionuclide builds up in the soil slowly, its concentration will be at a fraction of equilibrium concentration, which depends on the irrigation duration and the addition and removal rates. Irrigation duration of the soil in a home garden that is used to grow garden crops is assumed to be different than the irrigation duration of fields where alfalfa and grains are grown (SNL 2007 [DIRS 179993], Section 5.2). This assumption is based on current agricultural land use and irrigation practices. Other biosphere models, such as BIOMASS example reference biosphere 2A (ERB2A) (BIOMASS 2003 [DIRS 168563], Section C3), assume “constant biosphere conditions”, i.e., are invariant over the period in which contaminants released into the system achieve equilibrium concentration in environmental media. However, such an assumption is inconsistent with the current land use and agricultural practices in Amargosa Valley (SNL 2007 [DIRS 179993], Section 6.7) and thus is inconsistent with the regulatory requirement that the receptor has a living style representative of people who now reside in the Town of Amargosa Valley, Nevada (Section 6.1.2). Using different irrigation durations for field and garden crops divides the reference biosphere into two regions of different radionuclide concentration in the surface soil. Radionuclide concentration in the surface soil is where many of environmental transport and human exposure pathways originate (Table 6.3-2) and thus the choice of garden or field soil has implications on the resulting doses. The choices of soil irrigation listed above in the statement for this assumption are reasonable and consistent with the land use practices in Amargosa Valley and will not underestimate the dose to the receptor. Therefore this assumption does not require further confirmation.

Applicability—The assumption is applied to the surface soil submodel for the groundwater scenario and the associated transport and exposure pathways and is used in Sections 6.3.1.6, 6.4.1.1, 6.4.1.2, 6.4.2.1, 6.4.2.3, 6.4.4.3, and 6.6.2.

ASSUMPTION 6 – CROP WEATHERING LOSS AND SURFACE SOIL GAIN

Statement—All radionuclides in irrigation water are deposited on the surface of the soil, even when overhead irrigation is used and a fraction of the irrigation water is initially intercepted and absorbed by plant leaves.

Rationale—Farmers in the Amargosa Valley, especially the larger commercial operations, irrigate using spray and overhead systems (BSC 2004 [DIRS 169673], Section 6.3.2). When plants are irrigated from above, a portion of water is intercepted and absorbed by the leaves. The total amount of contaminated water eventually deposited on the soil depends on the initial foliar interception fraction, crop weathering, and the crop growing time. This assumption double-counts the radionuclides remaining on the plant and absorbed through plant leaves because they are also treated as deposited on the soil. However, this assumption is reasonable because the amount of radioactive material on and in the plant leaves is low compared to the overall amount applied with the irrigation water. It is estimated that a small fraction of the radioactivity in the irrigation water is transferred to the edible parts of the crops, while the rest is deposited on the soil or remains in the nonedible portion of the plants, and, eventually, is incorporated into the soil from the nonharvested portions of the plants or contaminated manure (Section 7.4.4.1). This assumption is used in other biosphere models such as GENII (Napier et al. 1988 [DIRS 157927], Section 4.7.4) and BIOMASS ERB2A (BIOMASS 2003 [DIRS 168563], Section C3.5.4). This assumption simplifies the mathematical representation of the weathering process, in which a fraction of the intercepted radioactive material is deposited on the soil surface. Based on above discussions, this assumption requires no further confirmation.

Applicability—This assumption is applied to the surface soil submodel for the groundwater scenario in Section 6.3.1.6. It is also discussed in the plant uptake submodel (Sections 6.3.1.6, 6.4.3.2, and 7.3.6) and in Section 7.1.1.

ASSUMPTION 7 – CROP ROOTS IN SURFACE SOIL

Statement—All crop roots are in the surface soil layer down to the tilling depth.

Rationale—In ERMYN, soil in cultivated fields and gardens is divided into two main compartments (surface soil and deep soil), and only the surface layer is considered part of the reference biosphere. Within a surface soil, a thin layer at the soil surface that can become resuspended is modeled separately for some pathways. Although the deep soil could become contaminated due to leaching from the surface soil, radionuclide concentrations in the deep soil are not calculated directly because those radionuclides are considered lost from the reference biosphere. Because many crops require tilling every year, radionuclides would be uniformly distributed throughout the surface soil layer over the long term. Thus, the soil tilling depth fits the concept of a surface soil depth. This assumption is reasonable because 80% to 90% of the plant roots occur in the upper 60% to 75% of the root zone (Jensen et al. 1990 [DIRS 160001], p. 22). Therefore, the assumption requires no further confirmation.

Applicability—This assumption applies to the plant uptake submodel for the groundwater scenario in Sections 6.3.1.6, 6.4.1, 6.4.1.1, 6.4.3.1, and 7.3.3.1.

ASSUMPTION 8 – ANIMAL FEED

Statement—Locally grown fresh forage is the only feed given to beef cattle and dairy cows, and locally produced grain is the only feed given to poultry and laying hens.

Rationale—Farm animals become contaminated by ingesting contaminated feed, water, and soil. Among these, animal feed is an important pathway (Section 7.4.5). In the Amargosa Valley, alfalfa and other hays are the most common crops (YMP 1999 [DIRS 158212], Tables 10 and 11), and dry hay used for livestock feed is produced locally and imported from outside the area (Horak and Carns 1997 [DIRS 124149], p. 12). Although the imported feed would not be contaminated, it is reasonable to assume that all animal feed is contaminated and that it is available year around because of the availability of alfalfa, the main crop grown in the area.

Water is added to locally grown alfalfa hay and commercial feed before feeding it to animals (Horak and Carns 1997 [DIRS 124149], p. 16). It is reasonable to assume that animals are fed locally grown fresh forage rather than dry hay with water added because they are nearly equivalent, and this assumption simplifies the mathematical model. In addition, although poultry and laying hens could be fed with other types of feed, locally produced grain is the only feed considered in the model. This assumption is conservative because it assumes that all animal feed is locally produced and contaminated. This assumption requires no further confirmation. This assumption eliminates the need to consider radionuclide concentrations in other types of feed, the fraction of those feeds, and the fraction of imported uncontaminated feed.

Applicability—The assumption applies to the plant (Sections 6.3.1.6 and 6.4.3) and the animal submodels (Sections 6.3.1.6, 6.4.4, and 7.3.4.1) for the groundwater scenarios.

ASSUMPTION 9 – ANIMAL PRODUCT TYPE

Statement—People consume animal products from four categories: meat, milk, poultry, and eggs. Meat includes beef, pork, lamb, and game animals; milk is from dairy cows, goats, and sheep; poultry includes chicken, turkey, duck, geese, and game hens; and eggs come from laying hens (chickens) and ducks.

Rationale—Farm animals in the Amargosa Valley include cattle, dairy cows, pigs, goats, ostriches, and poultry (YMP 1999 [DIRS 158212], Tables 8 and 9), plus sheep and ducks (Horak and Carns 1997 [DIRS 124149], Tables 5 and 6). There are more cattle than pigs and goats combined, and there are more dairy cows than goats (YMP 1999 [DIRS 158212], Tables 8 and 9). According to the Environmental Protection Agency *Food Ingestion Factors* (EPA 1997 [DIRS 152549], Table 11-9) and the USDA *Census of Agriculture, Nevada State and County Data* (USDA 1999 [DIRS 158643], Tables 20, 29, and 40), beef, milk from cows, chickens, and chicken eggs are the most frequently consumed products or are the most commonly raised and sold products in each category. Therefore, beef and milk from cows are considered representative of the meat and milk categories, respectively, and poultry and chicken eggs are used as general categories in the model. These categories match the categories in the food consumption survey (DOE 1997 [DIRS 100332], Appendix B). This assumption is reasonable because the uncertainty range of transfer coefficients for the selected animal products includes variation in transfer coefficients between selected and unselected animal products. For example, the selected average plutonium transfer coefficient for meat is 1.3×10^{-5} d/kg, with a range of 3.3×10^{-8} to 4.7×10^{-3} d/kg (Table 6.6-3), while the transfer coefficients for pork, mutton, and lamb are 8.0×10^{-5}, 9.4×10^{-5}, and 3.1×10^{-3} d/kg, respectively (IAEA 1994 [DIRS 100458], p. 38). This assumption requires no further confirmation. This assumption reduces the number of animal-product ingestion pathways for humans, and eliminates the need for transfer coefficients for the other types of animal products.

Applicability—This assumption applies to the animal submodel for both exposure scenarios (Sections 6.3.1.6, 6.3.2.4, and 6.4.4).

ASSUMPTION 10 – DOSE COEFFICIENTS FOR EXPOSURE TO CONTAMINATED SOIL

Statement—Dose coefficients for an infinite depth of soil are appropriate for estimating external exposure for the groundwater scenario.

Rationale—The dose coefficients for soil contaminated to an infinite depth (EPA 1999 [DIRS 175452]; EPA 2002 [DIRS 175544]) are based on an infinite isotropic (i.e., a homogeneously contaminated) plane source, located at the air-ground interface or at a specified depth in the soil, and a receptor standing at the air–ground interface (Eckerman and Ryman 1993 [DIRS 107684], p. 11). Under the groundwater scenario, it is reasonable to consider that the contaminated area has an infinite extent because the size of contaminated fields is large relative to the area from which the external exposure generally is received. In addition, noncultivated lands eventually could become contaminated by surface soil transport, although the level of contamination would be lower than that for cultivated land. This assumption is conservative because only a small portion of Amargosa Valley is irrigated (BSC 2006 [DIRS 177101], Section 6.2). Regarding the source depth, using dose coefficients based on an infinite depth is reasonable because deep soil will be contaminated by leaching, although at levels lower than those for surface soil. Dose coefficients for an infinite depth and those for a 15-cm depth differ by less than 10% for most primary radionuclides (EPA 2002 [DIRS 175544]). Only radionuclides with strong gamma emissions, such as ^{226}Ra and ^{137}Cs, have a relatively large difference for the two depths. Because the external exposure to contaminated soil could potentially originate from the depths greater than those for the surface soil, this assumption is reasonable but conservative. This assumption does not underestimate the dose; it does not require further confirmation.

Applicability—The assumption applies to the external exposure submodel for the groundwater scenario (Sections 6.3.1.6 and 6.4.7.1).

ASSUMPTION 11 – EVAPORATIVE COOLER USE AND EXPOSURE TIME

Statement—Evaporative coolers do not cause radionuclides to build up in indoor air, radionuclide concentrations in indoor air are constant on days when coolers are used, and the contribution of contaminated aerosols to the outdoor environments is unimportant.

Rationale—This assumption is necessary to evaluate radiation doses from aerosols generated by evaporative coolers using contaminated water. To be most effective, evaporative coolers require a continuous throughput of air and are therefore operated with an open window or door to let the air flow, thus radionuclides do not build up in indoor air because the large volume of airflow would carry contaminated aerosols out of the house. Radionuclide concentrations in indoor air are assumed constant on days when evaporative coolers are used. Although coolers cycle on and off to maintain the temperature setting, the period when the cooler is temporarily off usually would be relatively short, and decreases in radionuclide concentrations due to decay and air exchange would be insignificant. The contribution of contaminated aerosols generated from evaporative coolers and transferred to the outdoor air is not important and thus is not further considered because the indoor air is diluted and rapidly dispersed in the large outdoor environment. Therefore, this assumption requires no further confirmation.

Applicability—This assumption applies to the air and inhalation submodels for the groundwater scenario (Sections 6.3.1.6, 6.4.2.2, and 6.4.8.2).

6.3.1.5 Submodels for the Groundwater Scenario

To illustrate radionuclide transfer among biosphere components (Figure 6.3-2), the conceptual model is divided into seven parts matching the seven biosphere components (diagonal elements) in the interaction matrix (Table 6.3-2). The human receptor component, however, is further divided into three parts that represent the three major dose pathways. All of these parts are considered as submodels, except for groundwater, which is the source of radionuclides for this scenario. The final box in the figure, "Results: BDCF," is not considered a submodel, rather it represents the output of the biosphere model.

In Figure 6.3-2, arrows point in the direction of radionuclide transfer between biosphere components in the ERMYN model. For example, groundwater is used for human drinking water (to ingestion submodel), animal drinking water (to animal submodel), irrigation water (to soil and plant uptake submodels), fish pond water (to fish submodel), and evaporative cooler water (to air submodel).

The submodels described above are the same for all primary radionuclides, except for ^{14}C. A special submodel is used to calculate ^{14}C concentrations in the surface soil, air, crops, and animal products because the transfer mechanisms for this radionuclide are different from the others in the model. This special submodel is an additional submodel and is discussed separately. The direction of ^{14}C transfer is the same as shown in the radionuclide transfer interaction matrix (Table 6.3-2) and in the relationships among the biosphere submodels (Figure 6.3-2).

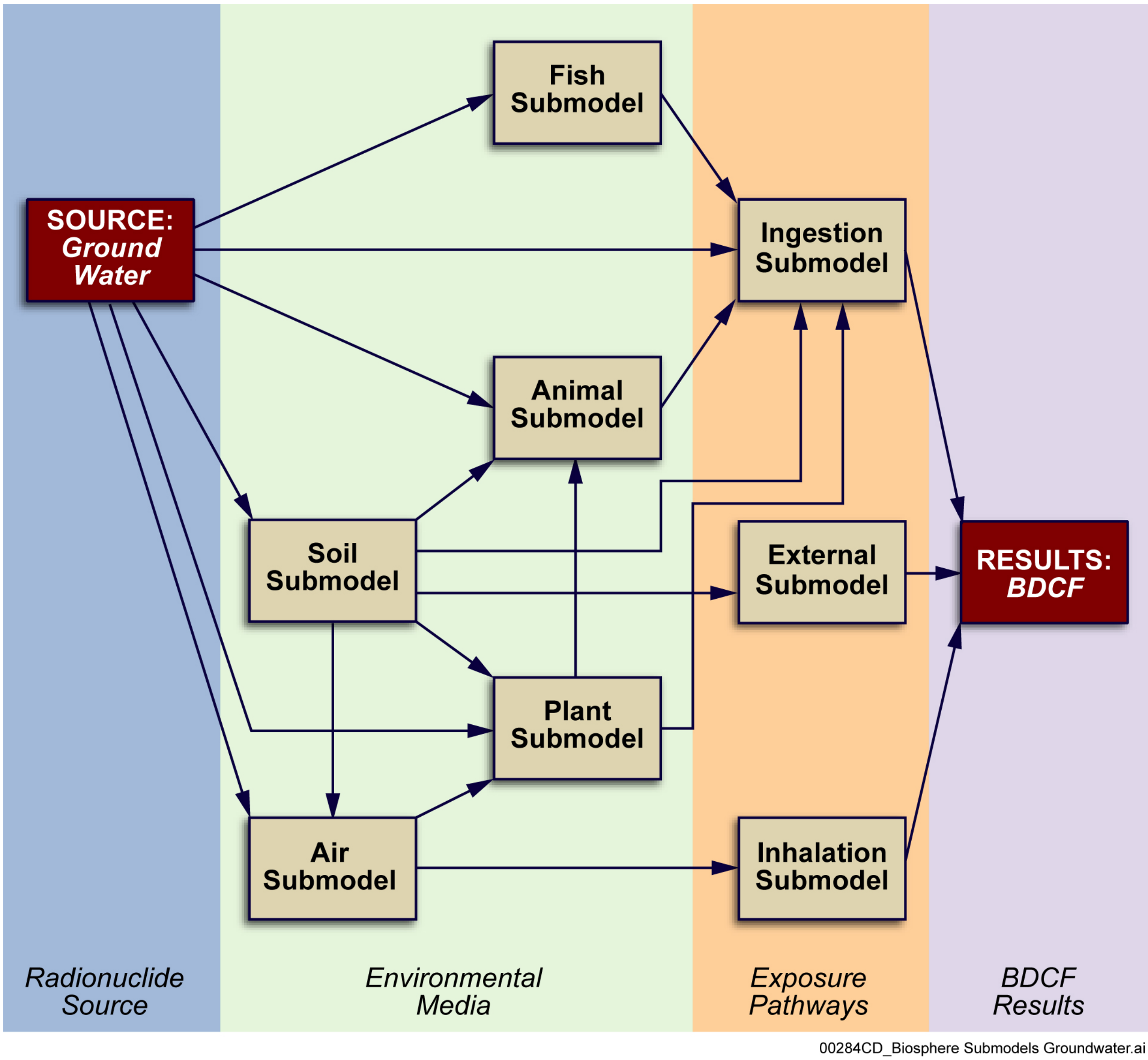


Figure 6.3-2. Relationship among Biosphere Submodels for the Groundwater Scenario

6.3.1.6 Description of Conceptual Model for the Groundwater Scenario

The conceptual model for the groundwater scenario includes groundwater, surface soil, air, plants, animals, fish, and the human receptor. The radionuclide transfer interaction matrix (Table 6.3-2) illustrates the radionuclide transfer mechanisms among the biosphere components. Separation of this model into nine submodels makes the conceptual and mathematical models easier to comprehend.

Groundwater Source—For the groundwater scenario, the source of radionuclides is water from a well ("well water" in 10 CFR 63.312 [DIRS 173273]). The well provides the interface between the geosphere and biosphere. Radionuclide concentrations in the well water are considered to equal the groundwater concentrations (Section 6.3.1.1), so the groundwater can be considered as the source of radionuclides in the biosphere model. To generate BDCFs with the biosphere model, the activity concentration of a radionuclide in groundwater is assumed to be constant at a predetermined concentration (e.g., 1 Bq/m^3; Assumption 1). The groundwater source is not considered a submodel because no radionuclide transport is modeled to or from the groundwater in the biosphere model. The FEP named *Surface water transport and mixing* (FEP 2.3.04.01.0A), is implicitly considered in the conceptual model for the groundwater scenario because the outcome of biosphere modeling (i.e., BDCFs) is insensitive to the source of the groundwater (e.g., well or spring) as long as the reference biosphere and the water use remain unchanged. The biosphere model can use contaminated water from any source for domestic and agricultural purposes. Thus wells and springs are equivalent sources of contamination in the biosphere as long as the concentration of radionuclides in the water remains the same. Mixing of groundwater with uncontaminated surface water is not considered in ERMYN because currently there are no sources of uncontaminated surface water in the biosphere.

Surface Soil Submodel—The purpose of the surface soil submodel, or simply the soil submodel, is to calculate the radionuclide concentration in surface soil (i.e., the root zone or tilling depth). The source of radionuclides in the surface soil is contaminated groundwater used for crop irrigation (Table 6.3-2, element [1, 2]). Based on agricultural practices in Amargosa Valley, groundwater is the only source of irrigation water. Because the objective of the postclosure dose assessment is to predict the future dose from the repository, the biosphere conceptual model assumes long-term irrigation using contaminated groundwater (Assumption 3). This results in the addition of radionuclides to cultivated lands, leading to a buildup of radionuclides in the irrigated soil. When overhead irrigation is used, radionuclides in irrigation water can be intercepted by crop leaves. However, crop weathering by wind and other mechanisms (Table 6.3-2, element [4, 2]) will displace some initially intercepted radionuclides onto the soil. Therefore, the biosphere conceptual model conservatively assumes that all radionuclides in the crop irrigation water reach the soil (Assumption 6).

Besides the groundwater source, contaminated fertilizer (animal manure and nonharvested plant residue) could contribute additional radionuclides to the surface soil (Table 6.3-2, element [5, 2]). However, over the long term, most radionuclides incorporated into crops likely would be recycled in the form of animal manure or the nonedible parts of crops. Therefore, the addition of radionuclides to the surface soil due to contaminated fertilizer is considered to compensate for the removal of radionuclides from the surface soil due to crop harvest removal (Table 6.3-2, element [4, 2]). This assumption is justified in Section 6.3.1.4 (Assumption 4), and it simplifies the mathematical model. Contaminated resuspended dust deposited on the surface of the soil is another possible radionuclide source (Table 6.3-2, element [3, 2]). However, dust deposition on the surface soil could be balanced by particle resuspension (Table 6.3-2, element [2, 3]). Thus, these two mechanisms are not numerically modeled in the surface soil submodel. Furthermore, dust could originate from nonirrigated, uncontaminated soils, such that the radioactivity in the deposited dust would be less than that in the resuspended particles. These two processes (deposition and resuspension) are associated with surface soil erosion, which is a removal mechanism in this submodel, as discussed below.

Processes in the conceptual model that result in the removal of radionuclides from the surface soil are radioactive decay, leaching to the deep soil (Table 6.3-2, element [2, 1]), surface soil erosion (Table 6.3-2, element [2, 3]), and the gaseous release (Table 6.3-2, element [2, 3]) of ^{222}Rn and ^{14}C. Some published biosphere models include crop harvest as a removal mechanism, but the ERMYN model does not, as discussed above. Radionuclides removed by leaching from the root zone were considered unavailable to plants. Although radionuclides eroded from cultivated fields could be deposited elsewhere in the biosphere, the biosphere model only tracked radionuclides in the surface soil of cultivated fields.

As a result of long-term irrigation, radionuclides would build up in the surface soil and some would reach equilibrium concentrations. At equilibrium, additions of radionuclides to the surface soil are balanced by their losses from erosion, leaching, and radioactive decay. Based on the assumption of long-term land use and irrigation practices (Assumption 3), the average irrigation rate of a variety of field and garden crops grown in Amargosa Valley was used to calculate radionuclide concentrations in soil. Radionuclide concentration in surface soil was calculated separately for field and garden crops using different average irrigation rates and durations for a variety of crops in those categories (Assumption 5).

The surface soil conceptual model described above is used to represent radionuclide concentration in the surface soil layer, which extends over the tillage depth, as well as in a much thinner layer of soil at the soil surface. The two soil layers are modeled separately because the radionuclide distribution with soil depth may be different depending on the soil use. The radionuclide concentration in the surface soil is assumed to be uniform due to soil mixing by tilling (Assumption 7). Such a representation is appropriate for modeling the plant root uptake (Table 6.3-2, element [2, 4]) and the external exposure from the radionuclides in the soil (Table 6.3-2, element [2, 7]). For modeling radionuclide concentrations in a very thin soil layer at the soil surface, a somewhat different representation is used, although the underlying model is the same. This is because there is a possibility that the soil would not be tilled for longer periods (e.g., when the land is used for growing alfalfa, fruit trees, or vines) and, consequently, the distribution in the surface soil layer may not be uniform. Radionuclide concentrations in the thin layer at the soil surface that can be resuspended were calculated. The greater of the two concentrations (i.e., the concentration in the surface soil and the concentration in the soil layer that can be resuspended) was used in calculating human and animal soil ingestion (Table 6.3-2, elements [2, 7] and [2, 5], respectively). The greater value was also used to calculate the airborne radionuclides originating from the soil (Table 6.3-2, element [2, 3]), which are subsequently used to estimate foliar deposition of soil particles (Table 6.3-2, element [3, 4]) and human inhalation exposure (Table 6.3-2, element [3, 7]).

Because of the continuous addition of radionuclides to the surface soil with only fractional removals over long periods of time, the concentrations of radionuclides in surface soil increase and eventually may reach equilibrium conditions. Under equilibrium conditions, radionuclide concentrations in the soil would not change with time. In the ERMYN model, the radionuclide concentration in the resuspendable soil layer is modeled based on the assumption that equilibrium conditions have been reached. For the surface soil, the level of radionuclide concentration in the soil relative to the equilibrium concentration depends on the radionuclide and the irrigation duration.

Leaching removal is a function of deep water percolation and soil characteristics, including radionuclide-specific solid-liquid partition coefficients. The initial condition is that water and soil are free of radionuclides from the repository at Yucca Mountain.

The output from the soil submodel is used in most of the remaining submodels (Figure 6.3-2) because the modeling of many environmental transport and exposure pathways depends in some way on the radionuclide concentration in surface soil.

Air Submodel—The air submodel is used to calculate radionuclide concentrations in the air. Inputs to the air submodel come from the surface soil submodel or directly from contaminated water. Three air contamination processes are considered: resuspension of contaminated soil particles (Table 6.3-2, element [2, 3]), generation of contaminated aerosols by evaporative coolers (Table 6.3-2, element [1, 3]), and the gaseous release of radionuclides from the soil (Table 6.3-2, element [2, 3]).

Resuspended particles are assumed to originate from the thin layer at the soil surface (see the description of the surface soil submodel). Resuspension of contaminated soil may be caused by natural forces (e.g., wind) or human activities (e.g., tilling). Radionuclide concentrations in the air depend on particle sizes, mineral composition of the soil particles, and the ability of the soil particles to sorb radionuclides. Resuspended particles deposit on crop leaves (Table 6.3-2, element [3, 4]) and directly on the soil surface (Table 6.3-2, element [3, 2]). Contaminated resuspended particles are a source of radionuclides for human inhalation (Table 6.3-2, element [3, 7]). In the air submodel, contaminated resuspended particles originate from irrigated land, although resuspended particles also could come from uncontaminated soil thus diluting airborne radionuclide concentrations. The most important sources of resuspended particulates would be human dust-generating activities, such as farming (Chow et al. 1993 [DIRS 162999]; Chow 1999 [DIRS 145212]). Therefore, all resuspended particles are considered to originate from contaminated soils. Resuspended particles, transported from the outdoors, are also considered in indoor environments.

The air submodel includes an enhancement factor, which accounts for measured differences between the activity concentration per unit mass of resuspended particles and the average activity concentration per unit mass in the surface soil available for resuspension. For crop deposition, the enhancement factor is taken to be unity, as soil may be transferred to the plant by splashing action from overhead irrigation systems or by farm equipment (the value of the enhancement factor for the conditions when the soil is disturbed, i.e., in the outdoor active environment, is equal to unity, Table 6.6-3). Thus the radionuclide concentrations in airborne particles are considered equal to the concentrations in surface soil per unit of mass. For inhalation, radionuclide concentrations in resuspended particles from wind action can be higher or lower than those in the surface soil and might differ among environments. Therefore, the enhancement factor is environment specific.

Some radionuclides may be released from soil to air as gases. This mechanism is only of concern for radionuclides that are gases, produce gaseous progeny, or form gaseous compounds (e.g., ^{222}Rn and ^{14}C). Radon, a decay product of ^{226}Ra, is a radioactive gas that leads to a chain of short-lived progeny. The release of ^{222}Rn is considered only from accumulated radium in soil because little radon would be released directly from water (Sections 6.4.2.3 and 7.4.3.1). Radon concentrations are considered separately for indoor and outdoor environments. ^{14}C is released from soil as radioactive carbon dioxide gas ($^{14}CO_2$). In this form, the $^{14}CO_2$ could be taken up by plants during photosynthesis and could contribute to human inhalation exposure. Concentrations of gaseous species in the air are affected by atmospheric mixing and dilution. Gases released from the soil contribute to radionuclide concentrations in indoor and outdoor air.

Radionuclide concentrations in indoor air would be affected by the use of contaminated groundwater in evaporative coolers. Evaporative coolers work by forcing air through a wet, porous material (i.e., a pad), resulting in the evaporation of water and the cooling of air. When water evaporates in the coolers, some of the contaminants in the water would be released into indoor air. Radionuclide concentrations in the air would depend on the water evaporation rate, the inlet air flow rate, and the fraction of radionuclides transferred from the water to air (Appendix D). Air leaving the house would carry the radioactive contaminants outdoors, where they would be an unimportant contribution to the outdoor inhalation dose because of atmospheric dilution (Assumption 11). Any radionuclides that are not transferred to the airflow remain in the system, where they are a source of external radiation exposure. This pathway is evaluated in Appendix D where it is shown that the increase of external exposure due to this pathway compared with that from contaminated soil is negligible.

The activity concentrations of radionuclides in the air (as particles, gases, and aerosols) are the outputs of the air submodel. These concentrations are important inputs for calculating the contribution from the inhalation pathways, and they provide inputs for the direct deposition of particles on crop leaves and carbon uptake by photosynthesis in the plant uptake submodel (Figure 6.3-2 and Table 6.3-2).

Plant Uptake Submodel (i.e., the plant submodel)—The purpose of the plant submodel is to calculate radionuclide concentrations in crops consumed by humans and farm animals. The plant submodel receives input from the soil submodel, the air submodel, the ^{14}C submodel, and directly from the contaminated water source. The mechanisms of radionuclide transfer to crops in the submodel are root uptake (Table 6.3-2, element [2, 4]), direct deposition on crop leaves from irrigation water (Table 6.3-2, element [1, 4]), photosynthesis of carbon dioxide containing ^{14}C (Table 6.3-2, element [3, 4]) and deposition of resuspended particles (Table 6.3-2, element [3, 4]).

Root uptake is modeled based on a state of equilibrium between radionuclide concentrations in the soil and crops. It is assumed that plant roots grow only in the surface soil layer down to tillage depth (Assumption 7). Direct deposition of radionuclides from the air on plant surfaces is modeled as a continuous process occurring during the crop growing time, accompanied by the continuous removal of radionuclides by weathering. Two types of direct deposition, irrigation water and resuspended particles, are considered in the submodel. The fraction of irrigation water intercepted by plants depends on irrigation practices and plant biomass. The fraction of resuspended particles intercepted is a function of plant type and biomass. These two processes are modeled using empirical equations. The activity remaining on the crops may be translocated in whole or in part to the edible portion of the plants. Radionuclides removed from crop surfaces by weathering would be eventually incorporated into the soil surface. This process is not separately tracked, as discussed in the surface soil submodel.

For the groundwater scenario (Section 6.1.3), four types of crops are considered for human consumption: leafy vegetables, other vegetables, fruit, and grain. In addition, fresh forage is considered for beef cattle and dairy cow feed. The grain used for human consumption is also considered as the only feed for poultry and laying hens. It is also assumed that fresh forage for beef cattle and dairy cows would be available year around (Assumption 8). Radionuclide concentrations would differ among crop types due to different irrigation rates, growing times, and other agricultural parameters.

The output of the plant submodel, activity concentrations of radionuclides in crops, is used as input to calculate the contribution to the human ingestion pathway from consumption of crop foodstuffs, as well as the contamination of animal products via ingestion of feed (Figure 6.3-2 and Table 6.3-2).

Animal Uptake Submodel (i.e., the animal submodel)—Ingestion of contaminated crops (Table 6.3-2, element [4, 5]), water (Table 6.3-2, element [1, 5]), and soil (Table 6.3-2, element [2, 5]) may contribute to radionuclide uptake by farm animals, and the animal submodel includes these three environmental transport pathways. Radionuclide uptake by inhalation is another potential radionuclide transfer process for animals; however, this is not an important pathway (Section 7.4.5) and is excluded from the submodel.

An equilibrium approach is used to assess radionuclide concentrations in animal products, where the equilibrium is between the rate of animal activity intake and the activity concentration in an animal product. The total animal intake of radionuclides is the sum of intakes from contaminated feed, water, and soil. Four types of animal products (meat, poultry, milk, and eggs) are considered in the submodel, where meat is representative of beef, pork, and lamb; milk is representative of milk from cows and sheep; poultry is representative of chickens, turkeys, ducks, geese, and game hens; and eggs are representative of those from laying hens and ducks (Assumption 9).

The output of the submodel, radionuclide concentrations in animal products, is used as input to calculate the contribution from the consumption of animal products in the human ingestion pathways (Figure 6.3-2 and Table 6.3-2).

Fish Submodel—The fish submodel is used to calculate radionuclide concentrations in farm-raised fish. The ERMYN includes fish because there is a fish farm in the Amargosa Valley with about 15,000 catfish and bass in 1998 and 1999 (YMP 1999 [DIRS 158212], Tables 8 and 9). Radionuclide accumulation in the fish is considered to be caused exclusively by the use of contaminated water in the fishponds.

The radionuclide transfer from water to fish is through a bioaccumulation process (Table 6.3-2, element [1, 6]) that is based on equilibrium conditions between radionuclide concentrations in the water and concentrations in the edible parts of fish. This submodel may be better applied to fish in rivers, lakes, or reservoirs where fish and fish food are in equilibrium with the contaminated water. In the Amargosa Valley, fish were raised using commercial feed (Roe 2002 [DIRS 160674]), which is likely to be uncontaminated because it is not produced locally. Therefore, using bioaccumulation factors results in an upper-bound analysis. Resuspended radioactive particles could be deposited into fishponds, but it is shown that this additional source is small compared to the contaminated water source (Section 6.4.5).

The output for the submodel, activity concentration in fish, is used to calculate the contribution of fish consumption to the human ingestion pathway (Figure 6.3-2 and Table 6.3-2).

Carbon-14 Submodel—The environmental transport pathways of ^{14}C are different from those considered for other radionuclides. While most radionuclides are in solid form, carbon can move in the environment as a gas. Moreover, stable carbon is an abundant and ubiquitous element in the environment. As for the other radionuclides, groundwater is the source of ^{14}C, and the calculation of ^{14}C concentrations in the soil are based on equilibrium conditions between ^{14}C gains and losses from surface soil. The most important process resulting in the loss of this radionuclide from surface soil, gaseous emission, is unique to gases and is not considered for other radionuclides. After it is released into the atmosphere, $^{14}CO_2$ could be incorporated into crops via photosynthesis. The predominant transport pathway to plants is foliar uptake via stomata. The uptake of ^{14}C may also occur via the root system; however, root uptake plays a smaller role than foliar uptake. Following plant uptake, ^{14}C may move into the animal food chain. Consumption of drinking water and soil are additional sources of ^{14}C intake by animals. All of these processes are incorporated into the conceptual model.

Modeling the transport of ^{14}C in the biosphere is carried out using a special ^{14}C submodel. The concentration of ^{14}C in air is calculated based on the equilibrium concentration of ^{14}C in the surface soil, with the rate of loss controlled primarily by the gaseous emission rate of $^{14}CO_2$ from the soil. In the air, ^{14}C is subject to mixing due to atmospheric processes, which are modeled using air movement in a mixing cell of defined dimensions. The uptake of ^{14}C by crops is modeled using the ratios of ^{14}C to stable carbon in soil and air, and the proportion of carbon in crops that is due to transport from these media. The concentration of ^{14}C in animal products is estimated from the ratio of ^{14}C to stable carbon uptake with water, soil, and feed. The bioaccumulation of ^{14}C in fish is assessed using the same method as that used for other radionuclides, which is based on the ratio of concentrations between water and the edible parts of fish. After the media concentrations of ^{14}C are calculated, the dose assessment is carried out using the same approach as is used for other radionuclides.

External Exposure Submodel—The purpose of the external exposure submodel is to calculate the dose resulting from external radiation exposure, which would occur as a result of direct exposure to radiation emitted by radioactive materials outside the human body. For environmental dose assessments, these materials typically include soil, air, and water. The corresponding exposures are referred to as ground exposure, air submersion, and water immersion, respectively. The conceptual model considers only one of these exposure pathways: exposure to emissions from radionuclides in the soil (Table 6.3-2, element [2, 7]). The ERMYN model does not include air submersion or water immersion because they contribute relatively little to the annual dose (Section 7.4.8). Radiation sources of concern in the soil are radionuclides with gamma and high-energy beta rays, which are penetrating and could deposit energy in human organs and tissues. The annual effective dose is calculated for this pathway.

External exposure from other types of media (e.g., building material, furniture, and clothing; FEP 3.3.03.01.0A) also is possible. However, few or no building materials, clothes, or other materials are produced in the Amargosa Valley using contaminated water. Furthermore, it is assumed that the size and depth of contaminated soils are infinite (Assumption 10), and residents are exposed to contaminated soil at all times while within the valley. Thus, the soil exposure, because of the exposure conditions and duration, would be much greater than that for other contaminated media, and, therefore, it is reasonable to not evaluate exposures from these types of media in the ERMYN model.

The external exposure submodel considers indoor and outdoor external exposure to radionuclides in the soil. For outdoor exposures, radiation doses depend on radionuclide concentrations in the soil, the duration of exposure, and the dose coefficients that convert exposure to dose. For indoor exposures, the shielding effect of dwellings reduces the level of exposure. Although the radionuclide concentrations in the soil used as input to this submodel apply to the surface soil, the dose coefficients apply to soil contaminated to an infinite depth. This choice of dose coefficients is considered appropriate because the radiation contributing to external exposure may also originate in the deep soil contaminated due to long-term radionuclide leaching from the surface soil. As indicated in the air submodel discussion on evaporative coolers, the external exposure from cooling systems is evaluated in Appendix D, where it is shown that this specific pathway introduces only a small increase in external exposure from radionuclide accumulation in irrigated soils.

The output of the external exposure submodel, annual dose from external exposure, contributes to the all-pathway dose, which is used to calculate BDCFs (Figure 6.3-2).

Inhalation Submodel—The purpose of the inhalation submodel is to calculate radiation doses due to the inhalation of radionuclides. The 50-year committed effective dose resulting from annual intake of radionuclides by inhalation is calculated for this pathway. The airborne radionuclides that can be inhaled originate from the three sources of contamination considered in the air submodel: resuspension of soil particles, gaseous emissions from the soil, and generation of aerosols by evaporative coolers (Table 6.3-2, element [3, 7]). The air submodel calculates radionuclide concentrations the air resulting from these processes.

In addition to radionuclide concentrations in the air, inhalation doses depend on the duration of inhalation exposure, the breathing rate, and the dose coefficients that convert radionuclide intakes to doses. Human breathing rates and exposure times differ by activity, occupation, work location, and other factors related to the behavior of the receptor. To account for differences and uncertainty in those behaviors, breathing rates and exposure times differ among environments and among population groups (Section 6.4.7.1) that comprise the receptor (RMEI).

The output of the inhalation submodel, annual inhalation dose, contributes to the all-pathway dose, which is used to calculate BDCFs (Figure 6.3-2).

Ingestion Submodel—The ingestion submodel is used to calculate radiation doses due to the ingestion of radionuclides. The 50-yr committed effective dose resulting from the annual intake of radionuclides by ingestion is calculated for this pathway. Inputs to the ingestion submodel are radionuclide concentrations in the groundwater (Table 6.3-2, element [1, 7]), and the outputs from the soil (element [2, 7]), plant (element [4, 7]), animal (element [5, 7]), and fish submodels (element [6, 7]).

Eleven ingestion exposure pathways are considered for the groundwater scenario, including the use of untreated, contaminated groundwater; inadvertent soil ingestion; consumption of four types of plant foodstuffs; consumption of four types of animal products; and consumption of fish. The radionuclide concentrations in these media are combined with the corresponding consumption rates and ingestion dose coefficients, and used to produce ingestion doses.

The output of the ingestion submodel, annual ingestion dose, contributes to the all-pathway dose, which is used to calculate BDCFs (Figure 6.3-2).

BDCFs and ERMYN Results—The all-pathway dose is the sum of the radionuclide-specific annual doses from the external, inhalation, and ingestion exposure pathways. The all-pathway dose is expressed in terms of the committed effective dose from annual intake. The BDCFs, in units of (Sv/yr)/(Bq/m^3), are numerically equal to the all-pathway dose from a unit activity concentration in the groundwater. The calculation of each radionuclide concentration as a function of time in the groundwater is carried out in the TSPA model. The total annual dose is the sum of the products of the radionuclide-specific BDCFs and the time-dependent activity concentrations of radionuclides in the groundwater. It needs to be noted that ERMYN was built using SI units; the TSPA model uses the U.S. customary units to express the radioactivity and doses. The units for the radionuclide concentration in groundwater used in the TSPA model are Ci/m^3 or pCi/L, while ERMYN uses Bq/m^3. Radiation dose in ERMYN is expressed in sieverts (Sv), while the TSPA model uses rems. However, GoldSim, which is used for the TSPA model, is dimentionally-aware and data can be entered and displayed in any units, as long as they are dimentionally consistent.

The conceptual representation of the environmental transport and exposure pathways described in this section is illustrated in Figure 6.3-3.

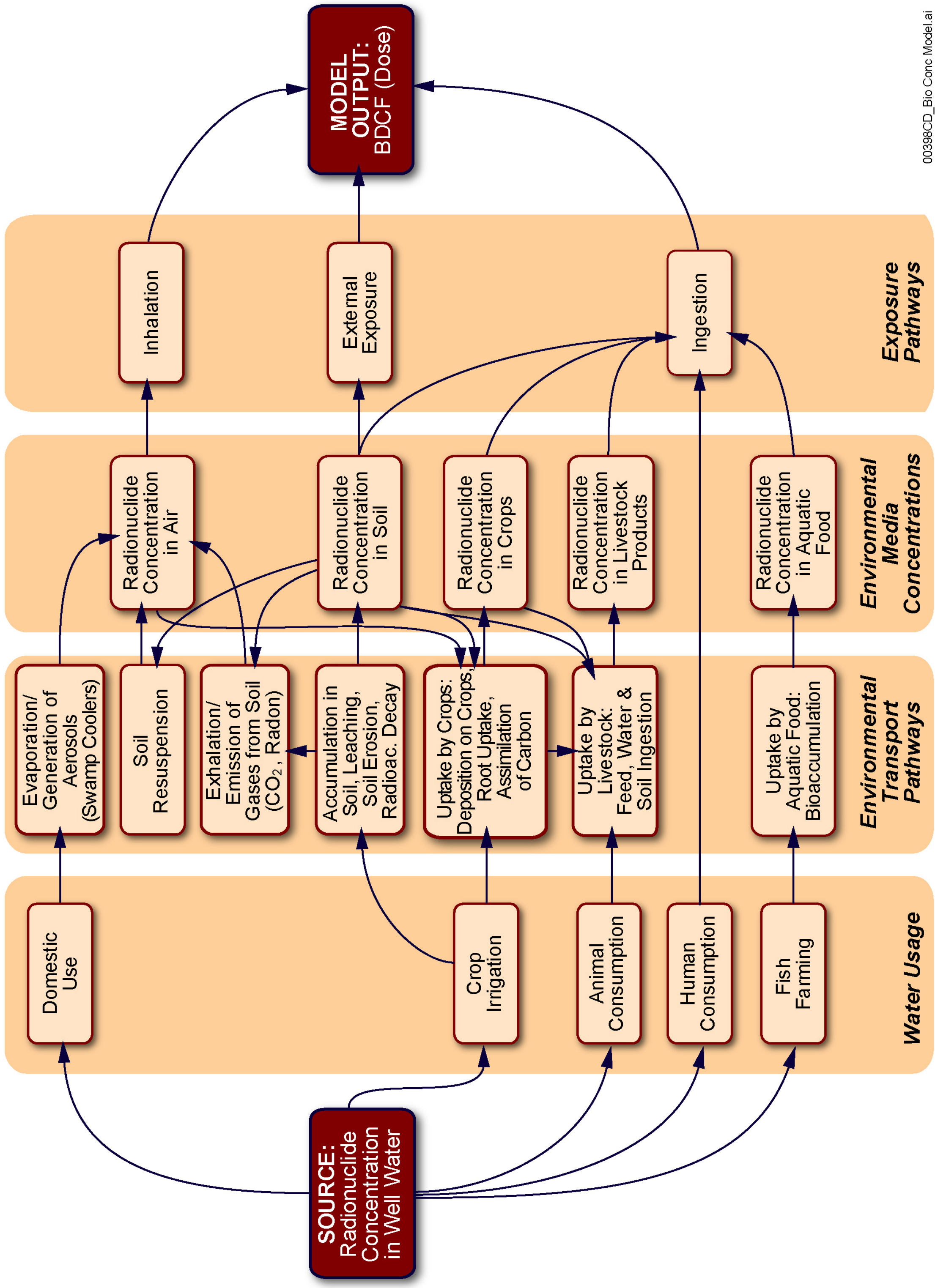


Figure 6.3-3. Conceptual Representation of the Biosphere Model for the Groundwater Exposure Scenario

6.3.2 Conceptual Model for the Volcanic Ash Exposure Scenario

Similar to the groundwater scenario, the volcanic ash exposure scenario (or simply the volcanic scenario) is discussed in this section. The biosphere conceptual model for the volcanic scenario uses the same concepts of reference biosphere and human receptor as the groundwater scenario. The major difference is the radionuclide source, which is contaminated volcanic ash deposited on, and mixed with, the surface soil, rather than contaminated groundwater. In this scenario, water is uncontaminated. Because the radionuclide sources are different, some of the radionuclide transfer mechanisms between biosphere components differ.

6.3.2.1 Scenario Description

The volcanic ash scenario is used to evaluate the radiological consequences of a volcanic eruption at the repository, which is one of the igneous scenario class modeling cases considered for the TSPA.

Eruptive events involving the intersection of the repository by an eruptive conduit could result in atmospheric release of contaminated tephra from the repository, followed by atmospheric transport and deposition of that contaminated tephra on the Earth's surface downwind of the conduit (vent) location, and redistribution of the contaminated tephra by eolian and fluvial processes to the RMEI location. The modeling of the volcanic eruption, as well as the atmospheric dispersal and deposition, are described in a separate model report that provides documentation of the conceptual and mathematical model (ASHPLUME) for atmospheric dispersal and subsequent deposition of ash on the land surface from a potential volcanic eruption at Yucca Mountain, Nevada (SNL 2007 [DIRS 177431]). The ASHPLUME model accounts for incorporation and entrainment of waste fuel particles associated with a hypothetical volcanic eruption through the Yucca Mountain repository and downwind transport and deposition of contaminated tephra. The environmental transport processes occurring after the deposition of contaminated tephra that could bring the radionuclides to or alter the radionuclide concentration in soil at the location of the RMEI are modeled in the FAR model and described in yet another report. That report addresses the redistribution of tephra and waste by geomorphic processes following a potential volcanic eruption at Yucca Mountain (SNL 2007 [DIRS 179347]).

The major processes considered in the tephra redistribution conceptual model are (1) mobilization of contaminated tephra from hillslopes in the Fortymile Wash drainage basin; (2) transport and mixing (dilution) of waste-contaminated tephra with uncontaminated sediments in the Fortymile Wash drainage basin; and (3) emplacement and diffusion of contaminants in the soil at the RMEI location (SNL 2007 [DIRS 179347], Section 1).

The tephra redistribution conceptual model separates the Fortymile Wash drainage into two domains: (1) the drainage basin and (2) the alluvial fan (SNL 2007 [DIRS 179347], Section 6.2). The separation is made at the apex of the alluvial fan. The drainage basin includes the vent location and the hillslopes and tributaries on which the contaminated tephra would be deposited if an eruption through the repository were to occur. The fan consists of the system of active distributary channels and interchannel divides that form the alluvial fan south of the fan apex. The location of the RMEI is considered to be on the alluvial fan and hence, is south of the fan apex (SNL 2007 [DIRS 179347], Section 6.2).

The tephra redistribution model uses a spatially distributed analysis of hillslopes and channels in the Fortymile Wash drainage basin (upstream of the fan apex) to provide an estimate of the mass of contaminated tephra that is transported from the drainage basin to the alluvial fan by hillslope and fluvial processes. Material on slopes greater than a specified critical angle and in active channels is mobilized, mixed and diluted as it is transported toward the RMEI location during flood events. Sediment mixing in channels is accomplished by a scour-dilution-mixing model that explicitly includes the vertical mixing of contaminants with uncontaminated channel sediments within the scour zone, and the model is applicable for both tributary and distributary channels and is, therefore, applicable to the Fortymile Wash system. The mixing depth in channels is defined by the depth to the top of the carbonate and clay-rich soil horizons of reduced permeability compared to the active zone, i.e., the depth to the petrocalcic horizon.

The contaminated tephra transported from the drainage basin and the primary deposit of contaminated tephra at the RMEI location provide the initial conditions for the redistribution of contaminants in the soil column at the RMEI location. The model considers the migration of contaminants in the soil as a diffusion process that includes suspension and redeposition of fine particles by infiltration and physical mixing of soil particles by freeze-thaw cycles and bioturbation. The time-dependent radionuclide concentration in the soil resulting from the diffusion process is combined with the BDCFs in the volcanic ash exposure submodel of the TSPA model to estimate the expected annual dose to the RMEI (SNL 2007 [DIRS 179347], Section 8). The integration of the tephra redistribution model output with the BDCFs is further described in Section 6.12.3. The remainder of this section discusses the biosphere model that is used to calculate the BDCFs for the volcanic ash exposure scenario.

For the volcanic ash exposure scenario, the only source of radionuclides in the biosphere is contaminated volcanic ash deposited on the ground surface as the result of a volcanic eruption and/or redistributed by wind (eolian processes) or flooding (fluvial processes) to the location of the hypothetical community. As noted above, these transport processes are not considered in the ERMYN model. The ERMYN is concerned with radionuclide transport in the biosphere and human exposure resulting from radionuclide concentration in the soil at the RMEI location. On cultivated soils, volcanic ash would mix with surface soil and contaminate crops and animal products, which would contribute to the human ingestion dose. On noncultivated lands, the volcanic ash could remain on the surface of, or mix with, the surface soil; a thin layer of that material could be resuspended into the air, causing human inhalation doses. The volcanic ash also may cause external exposure to humans. The ERMYN model uses predefined, e.g., unit concentrations (areal and mass) of radionuclides in the ash or the soil mixed with ash. A graphical representation of the volcanic ash scenario (Figure 6.3-4) shows dispersion, initial deposition, and radionuclide transport in the biosphere.

In biosphere modeling for the TSPA, volcanic eruptions are conceptually represented by three phases. The first phase, involving eruption, deposition, and redistribution, occurs when the volcanic ash from an erupting volcano undergoes atmospheric and surface transport to the location of the RMEI. The ERMYN model, as noted earlier, does not address this phase. The second phase follows the deposition and redistribution of volcanic ash and is characterized by elevated concentrations of volcanic ash or contaminated soil in the air compared with those experienced before the eruption. The last phase occurs, when particle concentrations in the air return to pre-eruption levels. The inhalation dose during the ash fall is calculated outside the

ERMYN model and is described in Section 6.15.2. The evolution of the posteruption biosphere is modeled in the ERMYN model through time-dependent, multicomponent BDCFs that apply to both posteruption phases.

During the eruption phase, radiation doses to humans mainly result from inhalation. Because exposure conditions depend on the characteristics of the volcanic eruption, radiation doses to the receptor accrued during the eruption phase are calculated in the TSPA using the inhalation dose factors developed for unit activity per unit volume of air (Section 6.15.2).

Volcanic ash deposited on, or redistributed to, cultivated and noncultivated lands is addressed differently in the ERMYN model. The radionuclide transport processes that result in contamination of food products are assumed to originate from the cultivated soil with contamination uniformly distributed throughout by tilling. The other pathways, i.e., inhalation of airborne particulates, inhalation of radon decay products, and external exposure, are assumed to originate from ground surface contamination that is not mechanically mixed with the soil.

The deposition and subsequent redistribution of volcanic ash constitute a sequence of events that are relatively limited in duration. Therefore, long-term radionuclide accumulation in surface soils would not occur. Changes in radionuclide concentrations in volcanic ash and soil mixture in the biosphere due to radionuclide decay, as well as ash redistribution and soil erosion are not considered explicitly in ERMYN. Instead, they are considered in the calculation of the time-dependent source terms (i.e., radionuclide concentrations in the surface soil) in the TSPA model. The source term is then combined with the BDCFs to calculate dose to the receptor.

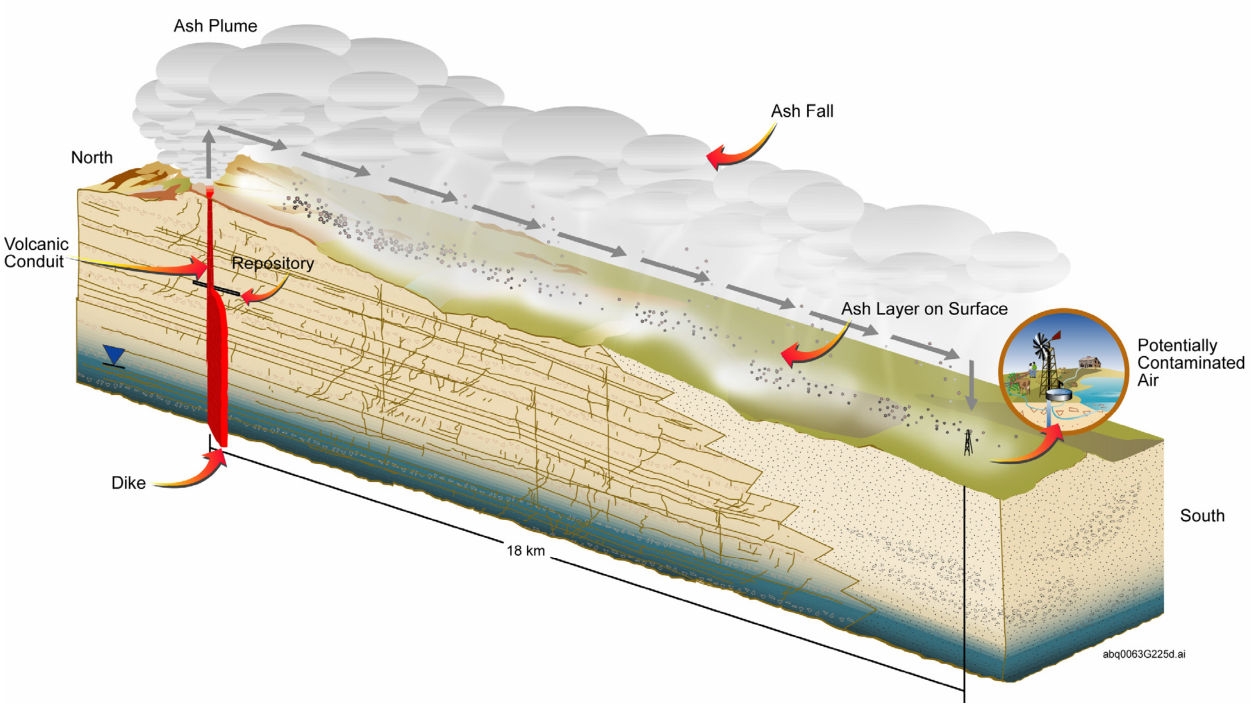


Figure 6.3-4. Representation of a Volcanic Eruption Intersecting the Repository and Radionuclide Release to Biosphere

Similar to the groundwater scenario, human exposure for the volcanic scenario arises from the contamination of environmental media (Table 6.3-3). These environmental media and exposure modes are identified by evaluating the biosphere FEPs (Section 6.2). Only four media (soil, air, plants, and animals) are considered to be contaminated due to volcanic ash deposition. Groundwater is not contaminated in this scenario, and, therefore, fish are considered to be uncontaminated. Even if contaminated ash deposits on the surface of the fish ponds, the activity is not likely to be available for uptake by the fish as readily as if it were dissolved in the groundwater. In addition, inhalation is the dominant pathway under this scenario (Section 6.14), and the fish contribution is likely to be unimportant.

The exposure pathways in the ERMYN model for the volcanic scenario are typical of an area affected by a volcanic eruption, and the biosphere characteristics are consistent with arid to semi-arid conditions. In comparison to the groundwater scenario, fewer exposure pathways are considered in the volcanic scenario because processes and media involving radionuclides in water are only included in the groundwater exposure scenario. As a result, three pathways are eliminated (ingestion of drinking water, ingestion of locally produced fish (Appendix E), and inhalation of indoor aerosols generated by an evaporative cooler). The pathways associated with ^{14}C gas are not considered because ^{14}C is not defined to be a significant contributor to exposure in this scenario (i.e., it is not a primary radionuclide, see Table 6.1-1). For the pathways in both scenarios, the conceptual approach and calculation methods are similar.

Table 6.3-3. Exposure Pathways for the Volcanic Ash Scenario

Environmental Medium	Exposure Mode	Exposure Pathways	Examples of Typical Activities
Soil	Ingestion	Inadvertent soil ingestion	Recreational activities, occupational activities, gardening, consumption of fresh fruit and vegetables with attached soil
Soil	External	External radiation exposure	Activities on or near contaminated soils
Air	Inhalation	Breathing of airborne particulates; breathing of gases (^{222}Rn and progeny)	Outdoor activities, including soil-disturbing activities related to work and recreation. Domestic activities, including sleeping
Plants	Ingestion	Consumption of locally produced crops, including leafy vegetables, other vegetables, fruit, and grain	Eating contaminated crop foodstuffs
Animals	Ingestion	Consumption of locally produced animal products, including meat, poultry, milk, and eggs	Eating and drinking contaminated animal product foodstuffs

6.3.2.2 Identification of Biosphere Model Components

Based on Table 6.3-3, six biosphere components are considered in the conceptual model for the volcanic ash scenario:

- **Volcanic ash**—contaminated ash released from the repository during a volcanic eruption
- **Surface Soil** (soil layer of thickness equal to the tillage depth)—surface soil includes cultivated land and uncultivated land; within the surface soil, a thin layer at the soil surface is distinguished that is the source of airborne soil particles. Volcanic ash becomes deposited on soil surface at, or redistributed to, the location of a community that includes the RMEI (initial source of contamination); the ash may become mixed with the surface soil.
- **Atmosphere**—including outdoor and indoor air
- **Plants**—crops contaminated by ash or foliar uptake from ash for use by human and farm animals; irrigated with uncontaminated water
- **Animals**—animal products for human consumption; animals raised using ash-contaminated local fodder and uncontaminated water
- **Human Receptor (RMEI)**—exposed through external exposure, inhalation, and ingestion of contaminated environmental media.

Contaminated volcanic ash is considered to be mixed with surface soil after initial deposition and redistribution, producing a mixture of contaminated ash and soil. The atmospheric transport of contaminated volcanic ash, followed by deposition and redistribution, is modeled in the TSPA. Consideration of atmospheric transport in ERMYN is limited to modeling airborne activity resulting from the resuspension of contaminated ash (or the ash–soil mixture) and gaseous emission of relevant radionuclides from ash (or the ash–soil mixture).

6.3.2.3 Radionuclide Transfer Interaction Matrix

The radionuclide transfer interaction matrix (Table 6.3-4) for the volcanic scenario is constructed based on the identified biosphere components, radionuclide transfer between the components, and the included FEPs (Section 6.2). A discussion of the interaction matrix concept and notation is presented in Section 6.3.1.3.

Table 6.3-4. Radionuclide Transfer Interaction Matrix for the Volcanic Ash Scenario

(i, j)	1	2	3	4	5	6	7
1	**BIOSPHERE SOURCE (volcanic ash)**	ashfall ash redistribution	—	—	—	—	—
2	—	**REFERENCE BIOSPHERE SOURCE (surface soil)**	particle resuspension, gas release	root uptake	soil ingestion	—	soil ingestion, ground exposure
3	—	particle deposition	**AIR**	particle deposition	—	—	inhalation of particulates and gas
4	—	weathering, harvest removal	—	**PLANTS (crops)**	feed ingestion	—	crop ingestion
5	—	fertilization	—	—	**ANIMALS (animal products)**	—	animal product ingestion
6	—	—	—	—	—	**FISH**	—
7	—	—	—	—	—	—	**HUMAN (receptor)**

In the transfer interaction matrix, the first diagonal element is the source of radionuclides in the biosphere, volcanic ash. This source is outside the reference biosphere. The source of radionuclides in the reference biosphere is the radionuclide concentration in the soil, the second diagonal element of the transfer interaction matrix (element [2, 2]). Calculation of the radionuclide concentration in the soil is external to the biosphere model. Because groundwater is considered to be uncontaminated, the element for fish is not included in the matrix (see Appendix E for a discussion of this exclusion), and there are no intersections of Column 6 with any row in the matrix (Column 6 is retained in the matrix to maintain consistency with Table 6.3-2). All major exposure pathways are considered, including ingestion of contaminated crops and animal products, inhalation of a contaminated ash–soil mixture, and external exposure from contaminated ash on the ground.

6.3.2.4 Conceptual Model Assumptions

As indicated below, of the 11 assumptions listed in Section 6.3.1.4 that are applicable to the conceptual model for the groundwater exposure scenario, five are also applicable to the volcanic ash exposure scenario. Five additional assumptions apply exclusively to the conceptual model for the volcanic ash scenario. The numbering of assumptions in this section is the same as that used for the groundwater biosphere model assumptions in Section 6.3.1.4.

ASSUMPTION 1 – GROUNDWATER SOURCE

This assumption does not apply to the volcanic ash scenario. In the volcanic ash exposure scenario groundwater is not a source of radionuclides in the reference biosphere.

ASSUMPTION 2 – CONSIDERATION OF SHORT-LIVED DECAY PRODUCTS

Statement—Section 6.3.1.4.

Rationale—Section 6.3.1.4.

Applicability—This assumption is applied to the volcanic ash exposure scenario in the same way as it is applied to the groundwater scenario.

ASSUMPTION 3 – LONG-TERM IRRIGATION, LAND USE, AND CROP ROTATION

This assumption does not apply to the volcanic ash exposure scenario. Exclusion of the long-term irrigation is conservative as this process would cause leaching of radionuclides from irrigated soil and thereby reducing radionuclide transport to the other environmental media and receptor exposure to those media.

ASSUMPTION 4 – CROP HARVEST REMOVAL AND THE USE OF CONTAMINATED MANURE FOR FERTILIZER

Statement—Section 6.3.1.4.

Rationale—Section 6.3.1.4.

Applicability—This assumption is applied to the volcanic ash scenario in the same way as it is applied to the groundwater scenario.

ASSUMPTION 5 – GARDEN AND FIELD LAND USE

This assumption does not apply to the volcanic ash exposure scenario.

ASSUMPTION 6 – CROP WEATHERING LOSS AND SURFACE SOIL GAIN

This assumption does not apply to the volcanic ash exposure scenario.

ASSUMPTION 7 – CROP ROOTS IN SURFACE SOIL

Statement—Section 6.3.1.4.

Rationale—Section 6.3.1.4.

Applicability—This assumption is applied to the volcanic ash exposure scenario in the same way as it is applied to the groundwater scenario.

ASSUMPTION 8 – ANIMAL FEED

Statement—Section 6.3.1.4.

Rationale—Section 6.3.1.4.

Applicability—This assumption is applied to the volcanic ash exposure scenario in the same way as it is applied to the groundwater scenario.

ASSUMPTION 9 – ANIMAL PRODUCT TYPE

Statement—Section 6.3.1.4.

Rationale—Section 6.3.1.4.

Applicability—This assumption is applied to the volcanic ash exposure scenario in the same way as it is applied to the groundwater scenario.

ASSUMPTION 10 – DOSE COEFFICIENTS FOR EXPOSURE TO CONTAMINATED SOIL

This assumption does not apply to the volcanic ash exposure scenario. It is superseded by Assumption 12.

ASSUMPTION 11 – EVAPORATIVE COOLER USE AND EXPOSURE TIME

This assumption does not apply to the volcanic ash exposure scenario.

ASSUMPTION 12 – VOLCANIC ASH SOURCE

Statement—There are two volcanic ash source terms used in the biosphere model. The two source terms are the radionuclide concentration in the resuspendable layer of soil in units of mass activity concentration (e.g., Bq/kg) and the depth-integrated (areal) radionuclide concentration in surface soil in units of surface activity concentration (e.g., Bq/m^2). The depth over which the integrated concentrations are determined is the tillage depth. Radionuclide concentration in the layer of soil that can be resuspended is used to calculate inhalation dose from exposure to suspended particulates. Areal radionuclide concentration is used in estimates of doses from the remaining exposure pathways included in the model, i.e., ingestion; inhalation of radon decay products, when applicable; and external exposure. It is also assumed that the addition of ash at the location of the receptor does not significantly affect the soil properties.

Rationale—The volcanic source terms are calculated in the TSPA model using ASHPLUME and FAR outputs for the areas classified as the channels and the interchannel divides. ASHPLUME atmospheric ash dispersal model and the associated computer code calculate ash and radioactive waste concentrations initially deposited in the Yucca Mountain region, including the area occupied by the community that includes the RMEI. FAR model and supporting software evaluate the redistribution of that initially deposited volcanic ash and associated radioactive waste within the Fortymile Wash drainage area and calculates contaminant transport within the soil. FAR segregates the Fortymile Wash alluvial fan into distributary channels and interchannel divides. On interchannel divides, radioactive waste is considered to be deposited only from primary ash fall. Radionuclides within this fallout are initially concentrated at the surface but with time diffuse within the soil profile. In channels, the initial concentration of radioactive waste includes the primary fallout as well as the radionuclides redistributed from the upper basin by fluvial processes. Both of these components will be mixed with channel sediments and native soil by fluvial scour and redeposition. Radionuclides in the distributary channel and interchannel divides are subject to diffusion within the soil (SNL 2007 [DIRS 179347], Section 6.2.3). As noted before, the reference biosphere is divided into agricultural land and non-agricultural land. Regardless of the land use, the radionuclide concentrations in the soil (i.e., the source terms for the biosphere model) are calculated by taking into account the proportion of land occupied by the channels and the divides. In addition to the mixing and diffusion processes occurring in the channels and on the divides, on cultivated land, plowing and irrigation would uniformly mix the ash and surface soil. Therefore, the small anticipated amount or thickness of ash (Appendix G) would not change properties of the soil. This assumption is reasonable and requires no further confirmation.

Applicability—This assumption is applied to the surface soil submodel for the volcanic ash scenario in Sections 6.3.2.6, 6.5.1.1, and 7.3.1.2.

ASSUMPTION 13 – ASH RESUSPENSION

Statement—Resuspended volcanic ash that deposits on plants originates from cultivated land, while ash that contributes to the human inhalation dose originates from noncultivated lands.

Rationale—After a volcanic eruption, much of the local biosphere could be contaminated with ash, and ash available for resuspension would come from two sources: cultivated and noncultivated lands. Most of the resuspended particles that deposit on crops would come from the cultivated lands where the crops are grown; therefore cultivated lands are the appropriate source for these particles. For the human inhalation dose, noncultivated lands are the appropriate source because cultivated lands cover only a small fraction of Amargosa Valley (BSC 2006 [DIRS 177101], Section 6.2). This assumption is intended to ensure that the human inhalation dose is not underestimated in the performance assessment because inhalation is the major exposure pathway in the volcanic ash scenario, and airborne contaminated particulates from noncultivated lands would have a higher radionuclide concentration than those from cultivated land. This assumption could underestimate radionuclide concentrations in the crops if the dust deposited on plants originated primarily from noncultivated areas. However, it is considered unlikely that the majority of foliar deposition would be from non-local sources throughout the plant growing season; although there may be episodes of particulate transport from outside agricultural fields, such as during dust storms. This assumption simplifies calculating radionuclide concentrations in the air, and it requires no further confirmation.

Applicability—This assumption is applied to the air submodel for the volcanic ash scenario in Sections 6.3.2.6, 6.5.1.2, and 6.5.2.1.

ASSUMPTION 14 – TIME DEPENDENT MASS LOADING

Statement—After a volcanic eruption, mass loading (i.e., the concentration of resuspended particulates in the air) decreases with time and eventually returns to levels similar to pre-eruption conditions.

Rationale—A time-dependent mass loading function is used to avoid overestimating the expected inhalation dose after a volcanic eruption that otherwise would be calculated using a constant and high mass loading values based on the measurements taken immediately after a volcanic eruption. This assumption is reasonable because levels of resuspended particulates after volcanic eruptions decrease with time (BSC 2006 [DIRS 177101], Section 6.4). The time-dependent function is implemented in the TSPA model. The time-dependent function is documented in *Inhalation Exposure Input Parameters for the Biosphere Model* (BSC 2006 [DIRS 177101], Section 6.4). This assumption requires no further confirmation because it is based on observed changes in mass loading after volcanic eruptions.

Applicability—This assumption is applied to the air submodel for the volcanic ash scenario in Sections 6.3.2.6 and 6.5.2.1.

ASSUMPTION 15 – RADON GAS RELEASE FROM VOLCANIC ASH

Statement—All ^{222}Rn from ^{226}Ra-contaminated volcanic ash is released into the air where it mixes and is available for inhalation. In the ash/soil mixture, no credit is taken for fractional emanation of radon from the grains of contaminated soil and the subsequent transport processes that may remove radon from soil gas before it is exhaled from the soil. At the same time, short-lived decay products of ^{226}Ra in the soil, including the ^{222}Rn decay products, are assumed to be in equilibrium with ^{226}Ra in the soil to avoid underestimating the dose from the pathways other than inhalation of ^{222}Rn decay products.

Rationale—The thickness of volcanic ash deposited on the ground is anticipated to be relatively thin (Assumption 12). Following the initial deposition, mixing of the ash and soil will occur through atmospheric and mechanical processes affecting the soil surface, and through the downward migration of the contaminant into the soil profile. Because of this mixing, and because the ash thickness is not known a priori in the biosphere modeling, predicting the radium concentration profile in the soil is not a straight-forward process, and estimating the amount of radon released from such a source would require a radon diffusion submodel, for which data are not available. In ERMYN, a simplified method is used in which all radon produced from the contaminated ash is considered to be released to the atmosphere. The relationship between the concentration of ^{226}Ra in the surface soil (Bq/m^2), radon flux density from the soil (Bq/(m^2 s)), and the concentration of ^{222}Rn in the air (Bq/m^3) is derived from available data. This assumption is conservative, as only a fraction of the ^{222}Rn would be exhaled from the soil and released into the air. However, the properties of ash particles with respect to radon emanation power are not known and it is prudent to assume 100% release so the inhalation dose is not underestimated. This assumption requires no further confirmation.

Applicability—This assumption is applied to the air submodel for the volcanic ash scenario in Sections 6.3.2.6, 6.5.2.2, and 7.4.3.1.

ASSUMPTION 16 – EXTERNAL EXPOSURE TO RADIONUCLIDES ON GROUND SURFACE

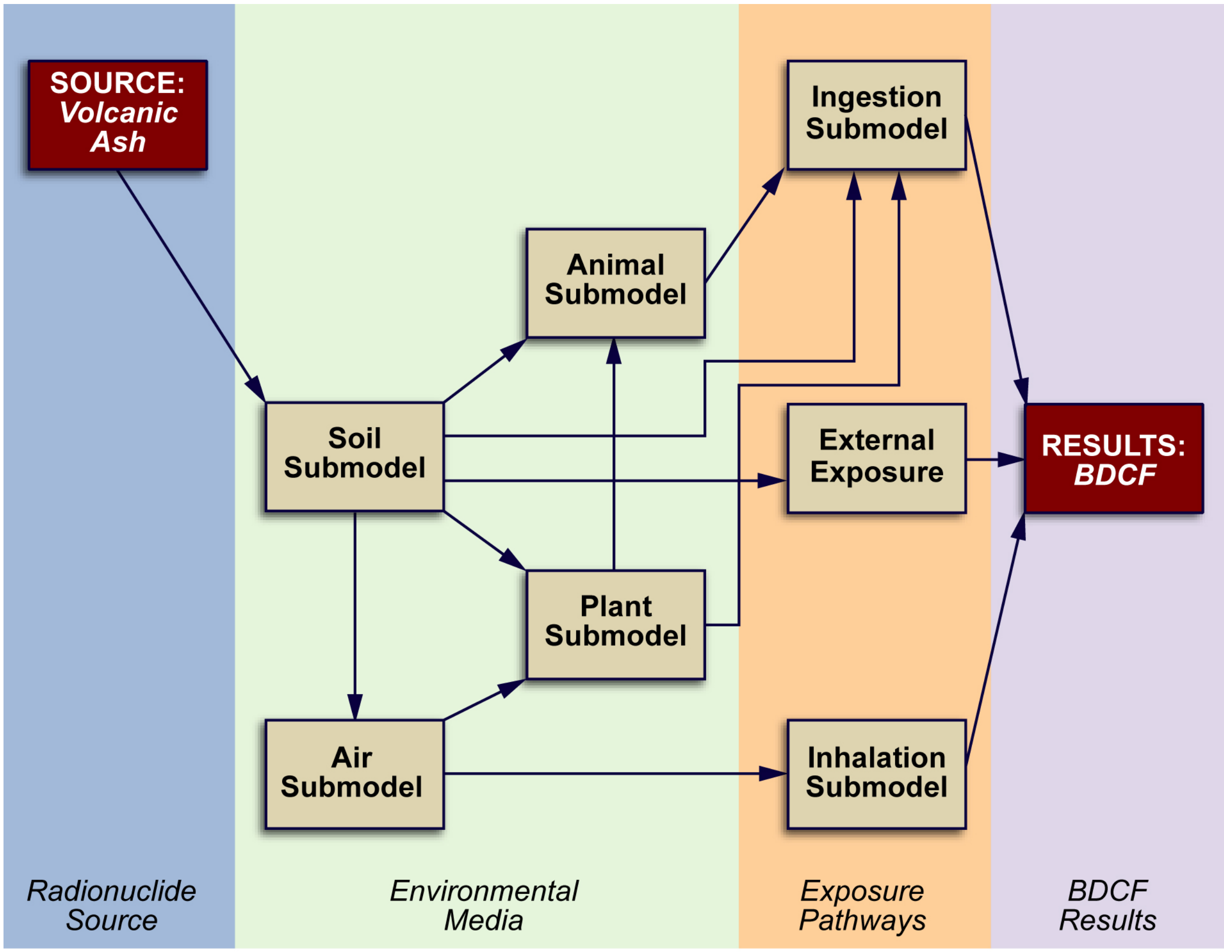
Statement—Radionuclides in the volcanic ash layer are concentrated at the ground surface, and dose coefficients for surficial contaminants are appropriate.

Rationale—Analogous to the inhalation exposure pathway (Assumption 13), external exposure is expected to occur in noncultivated areas where contaminants are not distributed throughout the surface soil layer. This assumption is reasonable because there is considerably more noncultivated land than cultivated land in the Amargosa Valley (BSC 2006 [DIRS 177101], Section 6.2). Therefore, the external exposure submodel used in the biosphere model for the groundwater exposure scenario, which considers long-term irrigation and soil contamination to an infinite depth, does not apply to the volcanic ash exposure scenario. By assuming that radionuclides are primarily concentrated at the ground surface, external exposure can be calculated using surface contamination dose coefficients (Section 6.5.5). In this approach no credit is taken for radiation attenuation in the soil and ash, however the assumed geometry of the contaminant is considered appropriate especially in the initial years after an eruption, before any substantial mixing of contaminant with the soil occurs. This assumption requires no further confirmation. The assumption simplifies calculations of external exposures and eliminates the dependence of external exposure on ash thickness and location.

Applicability—This assumption is applied to the external exposure submodel for the volcanic ash scenario in Sections 6.3.2.6 and 6.5.5.1.

6.3.2.5 Submodels for the Volcanic Ash Scenario

To understand radionuclide transport among biosphere components (Figure 6.3-5), the biosphere conceptual model is divided into the six parts consistent with the biosphere system components in the interaction matrix (Table 6.3-4). Considering the human receptor component to be composed of three exposure pathways (ingestion, inhalation and external exposure), there are eight parts of the model considered. Relationships among these parts or submodels (Figure 6.3-5) show important mechanisms of radionuclide migration from the source through the media to the human receptor. The BDCF box in Figure 6.3-5 is not considered a submodel; rather, it represents the results of the ERMYN model.



NOTE: Atmospheric dispersion, deposition, and redistribution of volcanic ash is modeled outside the ERMYN biosphere model. The source term for ERMYN is the radionuclide concentration in the surface soil.

Figure 6.3-5. Relationship between the Biosphere Submodels for the Volcanic Ash Scenario

6.3.2.6 Description of Conceptual Model for the Volcanic Scenario

The biosphere conceptual model for the volcanic scenario is based on the radionuclide transfer interaction matrix (Table 6.3-4). Because many radionuclide transfer mechanisms are the same in the groundwater and volcanic ash scenarios, the submodels are similar. The following description of the volcanic ash conceptual model focuses on the differences between the two scenarios.

Volcanic Source—The source of radionuclides in the biosphere model is the surface soil contaminated by volcanic ash initially deposited on the ground or redistributed to the location of interest. As described in Section 6.3.2.4 (Assumption 12), ERMYN uses a dual source term approach, with both source terms calculated outside the biosphere model. The two source terms are the radionuclide concentration in the resuspendable layer of soil in units of mass activity concentration (e.g., Bq/kg) and depth-integrated (areal) radionuclide concentration in surface soil in units of surface activity concentration (e.g., Bq/m^2). To calculate the volcanic BDCFs, both source terms are set to a unit radionuclide concentration, so the results of the volcanic biosphere model are independent of the actual radionuclide concentrations in the soil.

Surface Soil Submodel—Unlike the groundwater model, the volcanic biosphere model does not include a submodel that calculates the radionuclide concentration in the surface soil from the geosphere/biosphere releases of radionuclides. This function is carried out outside ERMYN and the radionuclide concentration in the soil is the source term for the volcanic biosphere model (Table 6.3-4, element [2, 2]). There is a surface soil submodel within the volcanic biosphere model structure but its main purpose is to convert areal radionuclide concentrations in the agricultural soil (Bq/m^2) to mass radionuclide concentrations (Bq/kg). Conceptually, this model also accounts for the biosphere radionuclide transport processes involving surface soil that occur on a local scale subsequent to the deposition and redistribution of radionuclides to the location of the receptor, which is why it is identified as a separate biosphere submodel. Because of different soil-mixing mechanisms on cultivated and noncultivated lands, and because of the different contributions to human radiation exposure, the consequences of volcanic ash deposition are calculated differently for these two areas. On cultivated land, volcanic ash would be uniformly mixed with surface soil due to plowing and irrigation. On noncultivated land, ash would be partly mixed with native soil, particularly in the distributary channels, but the distribution of radionuclide concentration with the surface soil depth would not be uniform and may be greater in the top layer of surface soil that may become resuspended. A separate source term of the radionuclide concentration in the resuspendable soil layer, which is used for the evaluation of exposure from inhalation of airborne particulates, ensures that the exposure from this pathway is not underestimated (Assumption 12).

On cultivated lands, volcanic ash would be uniformly mixed with surface soils to the tillage depth. In the model, this ash-soil mixture is treated as native soil except that it is contaminated. The surface soil is the source of contamination for crops and animal products, and it is the source for inadvertent soil ingestion because soil ingestion by humans likely would be from consuming crops, particularly those that would be unwashed or have a residual external contamination.

On noncultivated lands, ash would not be uniformly mixed within surface soil because the land would not be tilled and irrigated. However, the surface processes will cause some degree of mixing, especially in the distributary channels. On the interchannel divides, resuspension and subsequent redeposition would mix the volcanic ash and particles of native soil, and the diffusion processes will cause downward migration of the contaminant through the soil profile. To take into account this type of mixing and radionuclide distribution in the surface soil, a critical thickness (a hypothetical layer of soil from which soil particles would be more readily resuspended) is considered. Radionuclide concentration in that layer is used to evaluate radionuclide concentration in the air in the receptor environments and, subsequently, the inhalation exposure.

As discussed for the groundwater scenario, some radionuclide transfer mechanisms, including harvest removal, fertilization, and crop weathering, are implicitly considered in the biosphere surface soil submodel. Other removal mechanisms (including radionuclide decay and soil erosion) are not considered in the biosphere model but are incorporated in the TSPA model in the calculation of the source term. Unlike the groundwater scenario, where soil contamination could be deep, volcanic ash deposition could be relatively shallow. Thus, the source for external exposure is considered to be the contaminated ground surface (Assumption 16).

There are several outputs from the surface soil submodel. The activity concentration of radionuclides on cultivated lands is used to calculate the contamination of crops and animal products, and it is used to calculate the activity intake from inadvertent soil ingestion. The activity concentrations on noncultivated lands are used to calculate the contamination in the air, which contributes to human inhalation. The surface concentration of radionuclides is used to calculate external exposure and ^{222}Rn exhalation from soil. The relationships among these submodels are shown in Figure 6.3-5.

Air Submodel—The purpose of the air submodel is to calculate radionuclide concentrations in the air from the resuspension of contaminated ash-soil particles and from the gaseous release of ^{222}Rn from deposited volcanic ash (Table 6.3-4, element [2, 3]). Because there would be relatively little cultivated land compared with the total amount of the ash-contaminated land, it is assumed that human inhalation exposure occurs only on noncultivated land (Assumption 13). Soil resuspended from cultivated land is the source of contaminated soil particles for deposition on plants.

An elevated concentration of airborne particulates (mass loading) is expected after a volcanic eruption (BSC 2006 [DIRS 177101], Sections 6.3 and 6.4), but mass loading would decrease with time (Assumption 14) because the ash eventually would settle onto the ground, mix with surface soil, or otherwise become stabilized. Some human activities cause elevated mass loading relative to average levels (BSC 2006 [DIRS 177101], Sections 6.2.1 and 6.3.1). Therefore, mass loading is related to human activity, similar to that for the groundwater scenario. Radon gas released from deposited ash is considered, but the evaluation of ^{222}Rn concentrations in the air is simplified by using a radon release factor from ^{226}Ra–contaminated ground (Assumption 15).

The output of the submodel, the activity concentrations of radionuclides in the air, is used for calculating the radionuclide intake by inhalation of contaminated air and the direct deposition of contaminants on plant surfaces (Figure 6.3-5).

Plant Uptake Submodel—The purpose of the plant uptake submodel (plant submodel) is to calculate radionuclide concentrations in various crops that would be consumed by humans and farm animals. Crop contamination is assumed to occur on cultivated land where deposited volcanic ash and surface soil are uniformly mixed (Assumption 12). Two mechanisms cause the contamination of crops: plant root uptake of contaminants from surface soil (Table 6.3-4, element [2, 4]) and deposition of resuspended particulates on plants (element [3, 4]).

Except for the absence of direct deposition of irrigation water on crop leaves, radionuclide transfer mechanisms from soil to plants and from particulates to plants are the same as those considered in the groundwater scenario. The crop types also are the same in both scenarios.

Output from the submodel, the activity concentrations of radionuclides in crops, is used as input to calculate radionuclide intake by ingestion of contaminated crops and to calculate the contamination of animal products (Figure 6.3-5 and Table 6.3-4).

Animal Uptake Submodel—The purpose of the animal submodel is to calculate radionuclide concentrations in animal products using two radionuclide transfer mechanisms for animal products: ingestion of contaminated soil (Table 6.3-4, element [2, 5]) and feed (element [4, 5]).

Except for ingesting contaminated water, other transfer mechanism for this submodel (including animal product types and equilibrium conditions) are the same as those in the groundwater scenario. The output of the submodel, the activity concentration of radionuclides in animal products, is used to calculate radionuclide intake by ingestion of contaminated animal products (Figure 6.3-5).

External Exposure Submodel—The purpose of the external exposure submodel is to calculate human radiation exposure from contaminated volcanic ash deposited on the ground surface (Table 6.3-4, element [2, 7]). The annual effective dose is calculated for this pathway. As discussed before, for evaluation of external exposure it is assumed that all radionuclides remain on the ground surface (Assumption 16). As in the groundwater scenario, air submersion and other external exposures from contaminated media are not considered in the submodel because they contribute relatively little to the overall external dose to the human receptor, as shown in Section 7.4.8.

The evaluation methods for doses from external exposure to radionuclides on the ground surface are similar to those used in the external exposure submodel of the groundwater scenario, except that the source geometry and the dose coefficients are different. The output of the submodel, the annual doses from external exposure, contributes to the all-pathway dose, which is then used to calculate BDCFs.

Inhalation Submodel—The purpose of the inhalation submodel is to calculate human radiation doses due to the inhalation of radionuclides. The model includes inhalation of resuspended volcanic ash and short-lived decay products of ^{222}Rn (Table 6.3-4, element [3, 7]). The 50-year committed effective dose resulting from annual intake of radionuclides by inhalation is calculated for this pathway.

To account for changes in mass loading over time (discussed for the air submodel), the inhalation dose changes over time as dust levels decrease. The mass loading decrease function quantifying the mass loading decrease is carried into the TSPA model. Similar to the inhalation submodel for the groundwater scenario, the inhalation dose depends on airborne concentrations, breathing rates, and exposure time. Breathing rates and exposure times are related to human activities, and exposure time varies among population groups (Section 6.4.7.1). These parameters are linked to human activities and population groups to incorporate uncertainty from those parameters into the submodel. The output of the inhalation submodel, the annual inhalation dose, contributes to the all-pathway dose, which is used to calculate BDCFs (Figure 6.3-5).

Ingestion Submodel—The purpose of the ingestion submodel is to calculate the radiation dose from ingestion of radionuclides. The 50-year committed effective dose resulting from annual intake of radionuclides by ingestion is calculated for this pathway. The ingestion submodel includes eight contaminated foodstuffs: four types of plants (leafy vegetables, other vegetables, fruit, and grain) (Table 6.3-4, element [4, 7]) and four types of animal products (meat, poultry, milk, and eggs) (element [5, 7]), plus inadvertent soil ingestion (element [2, 7]). Inputs to this submodel are the radionuclide concentrations in foodstuffs and in the soil from the plant, animal, and surface soil submodels. These media concentrations, when combined with the corresponding consumption rates and dose coefficients, are used to produce ingestion doses. The output of the ingestion submodel, the annual ingestion dose, contributes to the all-pathway dose, which is used to calculate BDCFs (Figure 6.3-5).

BDCFs and ERMYN Results——The all-pathway dose is the sum of the radionuclide-specific annual doses from the external, inhalation, and ingestion exposure pathways. The all-pathway dose is expressed in terms of committed effective dose. The BDCFs are numerically equal to the all-pathway dose from a unit activity concentration in the deposited volcanic ash and are expressed in (Sv/yr)/(Bq/kg) for the inhalation of airborne particulates and in (Sv/yr)/(Bq/m^2) for the remaining exposure pathways. The calculation of radionuclide concentrations in the soil is carried out in the TSPA model. The total dose from a volcanic eruption calculated in the TSPA model is the sum of the products of the radionuclide-specific BDCFs, considering changes in mass loading with time, and the time-dependent activity concentrations of radionuclides in the volcanic ash for all of the radionuclides in the TSPA model, as further described in Section 6.4.10.4. As noted in Section 6.3.1.6, the ERMYN model uses SI units, whereas the TSPA model uses the U.S. customary units. However, GoldSim, which is used for the TSPA model, is dimentionally-aware and data can be entered and displayed in any units, as long as they are dimentionally consistent.

The conceptual representation of the environmental transport and exposure pathways described in this section is illustrated in Figure 6.3-6.

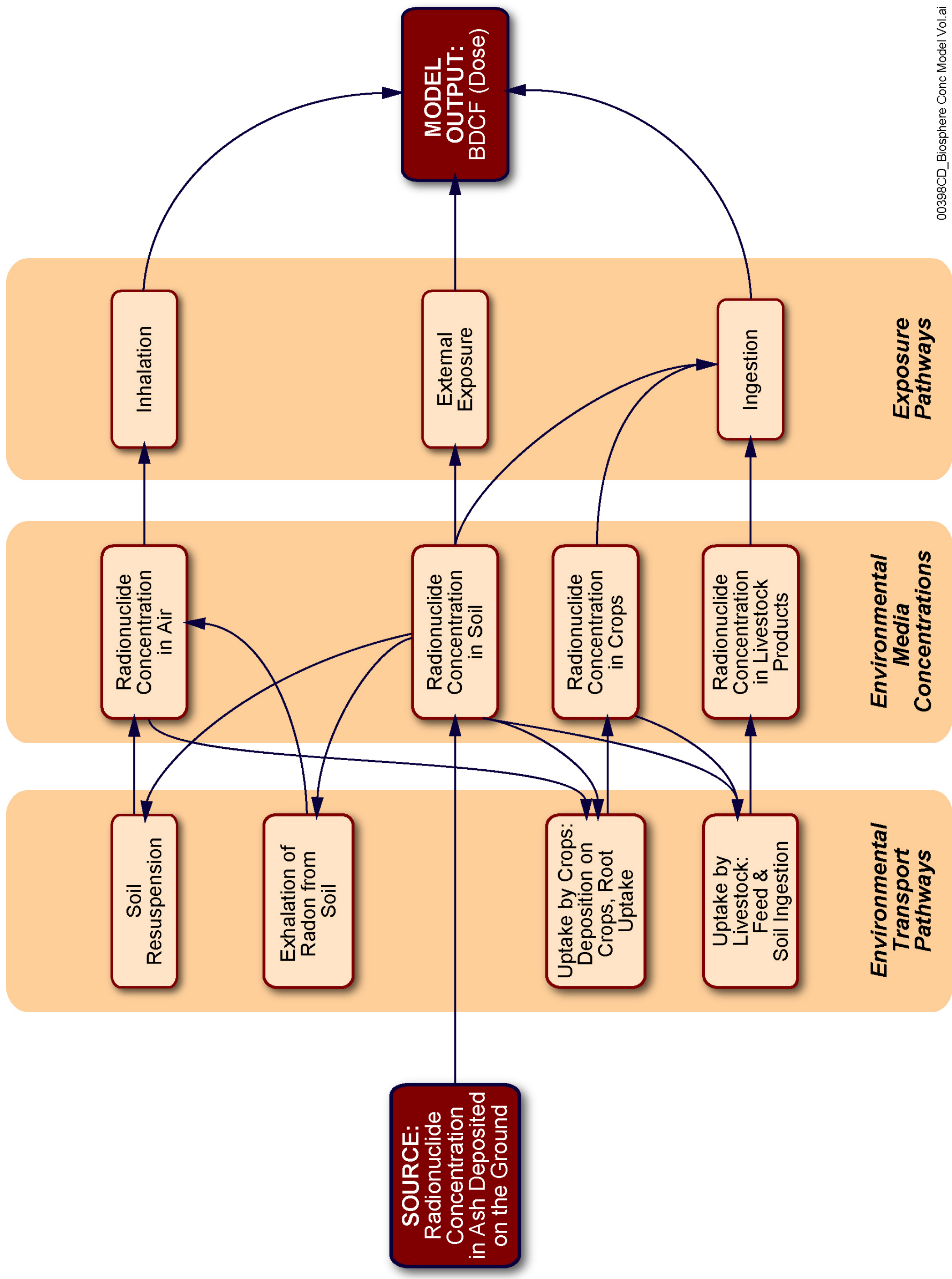


Figure 6.3-6. Conceptual Representation of the Biosphere Model for the Volcanic Ash Exposure Scenario

6.3.3 Alternative Conceptual Models

Performance assessment for a repository at Yucca Mountain must consider ACMs of features and processes that are consistent with available data and current scientific understanding, and must evaluate the effects that ACMs have on the predicted performance of the geologic repository (10 CFR 63.114(c) [DIRS 173273]). From the guidelines for the treatment of ACMs in the TSPA (BSC 2002 [DIRS 158794], Section 2), a conceptual model can only be alternative if it:

- Differs in important ways from the selected conceptual model
- Is consistent with available data and current scientific understanding
- Is reasonable, which has been interpreted as implying that there is some precedent for the alternative, such as prior use by other analysts, and that there is a physical basis for the alternative.

Based on this definition of an ACM, there are no alternative groundwater or volcanic conceptual models applicable to the entire biosphere system. This is because the model of the biosphere system consists of the representations of individual environmental transport processes and pathways, and human exposure pathways, which are modeled independently and then combined to calculate the all-pathway dose. Some of these pathway or process models are site-specific and not usually included in the other models. However, there are ACMs for submodels and process models. This section identifies ACMs from published biosphere models that differ from the corresponding submodel, or parts of the submodel, in ERMYN (Table 6.3-5). These ACMs are screened and evaluated qualitatively and quantitatively, and mathematical representations of these ACMs are presented and compared with those of ERMYN as a part of model validation (Section 7.3). Finally, numerical comparisons between the ACMs and ERMYN are performed, and justifications are provided for why ACMs are not selected (Section 7.4).

The ACMs were obtained from five published biosphere models with corresponding submodels or parts of submodels that are compared with ERMYN as a part of the model validation (Section 7.1.2). These published biosphere models are GENII (Napier et al. 1988 [DIRS 157927]; Leigh et al. 1993 [DIRS 100464], Napier et al. 2006 [DIRS 177331]), BIOMASS ERB2A (BIOMASS 2003 [DIRS 168563]), RESRAD (Yu et al. 2001 [DIRS 159465]), EPRI model, referred to in this document as EPRI-YM, (EPRI 2002 [DIRS 158069]; EPRI 2004 [DIRS 171915]), and NCRP-129 (NCRP 1999 [DIRS 155894]). To be considered as an ACM, submodels or parts of submodels must be conceptually or mathematically different from those in ERMYN. Mathematical simplifications or different treatments, such as numerical or analytical methods, are not considered to be ACMs. Brief descriptions of the seven identified ACMs are presented below and summarized in Table 6.3-5.

ACM 1, Radon Release from Soil (Air Submodel)—The conceptual model for radon selected for implementation in ERMYN is based on a radon release factor for radium contaminated soil. This factor represents the activity concentration of ^{222}Rn in the air per unit of ^{226}Ra activity concentration in the soil. This ACM relies on modeling radon transport in the soil and the atmosphere (Yu et al. 2001 [DIRS 159465]). A numerical comparison between the selected model and the ACM shows that the ^{222}Rn concentrations are comparable (Section 7.4.3.1). Because the ACM required more input data, it was not selected for implementation in ERMYN.

ACM 2, Evaporative Cooler (Air Submodel)—The selected conceptual model for evaporative coolers is based on evenly evaporating contaminated water into the airflow of an evaporative cooler. This ACM calculates radionuclide concentrations based on water evaporation and differences in relative humidity. An evaluation of these two methods shows that they produce equivalent results (Section 7.4.3.2).

ACM 3, Direct Deposition of Irrigation Water (Plant Submodel)—The ERMYN model considers radionuclides in irrigation water to be directly translocated into edible plant parts with accumulation and weathering occurring during the growing period. This conceptual model is also used in published biosphere models (e.g., GENII and RESRAD). This ACM presented in BIOMASS ERB2A considers two processes: transfer of deposited radionuclides from external plant surfaces into the plant tissues and transfer of radionuclides absorbed into plant tissues into edible parts of the crop. This ACM applies weathering to contaminants that remain on external plant surfaces and food-processing losses are included. The model implemented in ERMYN treats the contamination of foodstuffs by radionuclides deposited onto the plant surface as a fraction of activity externally deposited on a plant, without consideration of what route the radionuclides took to arrive at the edible part of the crop. The ACM is conceptually more realistic, but it is not commonly used because the input data that quantify contributing transport processes typically are not available. The two models are evaluated using the same input values or using default data from the BIOMASS ERB2A model (Section 7.4.4.1). This ACM and the approach used in the ERMYN produce comparable results for reasonable input values.

ACM 4, Direct Deposition of Airborne Particulates (Plant Submodel)—In ERMYN, resuspended soil deposited on crop leaves is treated in the same manner as intercepted irrigation water. There are published biosphere models that take a different approach. This ACM is based on a contamination factor for the external contamination of crops, which is similar to a soil-to-plant transfer factor in that it represents radionuclide concentration in the crop per unit radionuclide concentration in the soil. Differences between ERMYN and the ACM are evaluated (Section 7.4.4.3) using the same input values when the parameters are comparable, or using default data from the published ACM. The evaluation shows that ERMYN and the ACM approaches produce comparable results for reasonable input values.

ACM 5, Animal Product Contamination (Animal Submodel)—The ERMYN considers animal contamination resulting from the consumption of contaminated water, soil, and feed. The BIOMASS ERB2A model includes an additional pathway: inhalation of contaminated air by animals. This animal transport pathway is evaluated to determine its relative importance (Section 7.4.5). The inhalation of contaminated dust contributes little to concentrations in meat, and, therefore, it is not included.

ACM 6, ^{14}C Special Submodel (^{14}C Submodel)—The ACM that is evaluated concerns an alternative method of calculating ^{14}C uptake by crops. The conceptual model that is implemented in ERMYN considers two mechanisms of ^{14}C uptake by crops: from the soil through their roots and from the air during photosynthesis. The air concentrations of $^{14}CO_2$ are calculated based on the experimental results of $^{14}CO_2$ emission from soil (Yu et al. 2001

[DIRS 159465], Appendix L). An ACM used in the GENII model only considers the uptake of ^{14}C by roots. The two submodels are compared to evaluate any differences (Section 7.4.7). BIOMASS ERB2A presents another ^{14}C ACM, but it requires additional input parameters that are not provided. For that model, the mathematical representations are compared (Section 7.3.6), but numerical comparisons are not conducted because of the lack of appropriate input values. The GENII ACM is not used because the ERMYN ^{14}C special submodel is more realistic and results in higher ^{14}C concentrations in plants (Section 7.4.7).

ACM 7, Environment-Specific Inhalation Submodel (Inhalation Submodel)—In ERMYN, inhalation exposure is evaluated by dividing the reference biosphere into mutually exclusive environments that were identified based on the conditions of human exposure. Environment-specific sets of input parameter values, dependent on human activities conducted within an environment, are then used to characterize these environments. These include the mass loading, breathing rate, exposure time, and enhancement factor. Similar models, called microenvironmental models, have been used to assess exposure to particulate matter and other contaminants (Duan 1982 [DIRS 162466]; Klepeis 1999 [DIRS 160094]; Mage 1985 [DIRS 162465]). The other biosphere models use one or two environments (Section 7.3.8). An evaluation (Section 7.4.9) numerically compares the ERMYN method with those in the other models. The approaches produce comparable results for reasonable model input values. The environment-specific approach is used in the ERMYN because uncertainty associated with the input parameters can be better addressed.

Table 6.3-5. Alternative Conceptual Models Considered

Alternative Conceptual Model	Overview	Screening Assessment and Basis
Radon release from soil (Air Submodel)	This ACM considers radon transport in the soil and the atmosphere, which requires more input data. ERMYN does not include these processes and uses a simple release factor.	This ACM is screened from the biosphere model based on an analysis (Section 7.4.3.1) showing that the ACM and ERMYN produce comparable results.
Evaporative cooler contribution to indoor air contamination (Air Submodel)	This ACM assesses inhalation dose from aerosols generated from evaporative coolers based on calculating radionuclide concentrations in the air due to an increase in humidity. ERMYN uses a model based on the amount of water evaporated rather than an increase in humidity.	This ACM is screened from the biosphere model based on an analysis (Section 7.4.3.2) showing that this ACM and ERMYN produce comparable results.
Direct deposition of irrigation water on crops (Plant Submodel)	This ACM considers two processes of radionuclide transport in crops, where the deposited radionuclides first move from external plant surfaces into the plant tissues, and then from plant tissues into the edible portion of the crop. Weathering is applied only to contaminants that remain on external plant surfaces. Food processing loss is also considered in the ACM. The ERMYN conceptual model considers the radionuclides in irrigation water to be directly translocated to the edible parts of plants with weathering and accumulation during the growing period, but without food preparation loss.	This ACM is screened from the biosphere model based on an analysis (Section 7.4.4.1) showing that this ACM and ERMYN produce comparable results.

Table 6.3-5. Alternative Conceptual Models Considered (Continued)

Alternative Conceptual Model	Overview	Screening Assessment and Basis
Direct deposition of airborne particulates on crops (Plant Submodel)	This ACM addresses the processes of external crop contamination by soil deposition by using a contamination factor. This contamination factor is conceptually analogous to a soil-to-plant transfer factor. The ERMYN conceptual model treats the direct soil deposition on crops similar to the deposition of irrigation water.	This ACM is screened from the biosphere model based on an analysis (Section 7.4.4.3) showing that this ACM and the ERMYN produce comparable results for reasonable input values.
Animal product contamination (Animal Submodel)	This ACM considers animal inhalation of contaminated air. The ERMYN conceptual model excludes the inhalation of contaminated air as a negligible pathway.	This ACM is screened from the biosphere model based on an analysis (Section 7.4.5) showing that inhalation of contaminated air is not an important contributor to the animal product contamination.
^{14}C special submodel (^{14}C Special Submodel)	This ACM considers root uptake as the only mechanism of ^{14}C transfer to crops. ERMYN also included ^{14}C uptake from air during photosynthesis. In addition to ingestion, ERMYN also includes other pathways that result in human exposure to ^{14}C: external exposure, inhalation of ^{14}C as gas and in soil, as well as soil ingestion.	This ACM is screened from the biosphere model based on an analysis (Section 7.4.7) showing that the ERMYN ^{14}C special submodel considers more processes of ^{14}C transfer to plants than this ACM, which results in a higher ^{14}C concentration in plants.
Environment-specific inhalation submodel (Inhalation Submodel)	This ACM uses average values of input parameters for inhalation exposure. ERMYN considers inhalation exposure as a function of the environment because many model parameters, such as mass loading, breathing rate, and exposure time, differ among environments and activities.	This ACM is screened from the biosphere model based on an analysis (Section 7.4.9) showing that the ACM and the ERMYN produce comparable results. In addition, it is easier to address uncertainty in the input parameters using environment-specific values.

6.3.4 FEPs Considered in the Biosphere Conceptual Model

The radionuclide transfer interaction matrices, Table 6.3-2 for the groundwater scenario and Table 6.3-4 for the volcanic scenario, also serve as a tool to map the included FEPs into the biosphere submodels. To document that the conceptual models address all included FEPs, Table 6.3-6 provides a list of the included FEPs, shows where each FEP is mapped in the interaction matrices (Tables 6.3-2 and 6.3-4), and lists the submodels where each FEP is addressed. The disposition of these FEPs in the biosphere mathematical model, submodels, and associated equations and parameters is discussed in Section 6.7.

Table 6.3-6. Mapping of FEPs to Interaction Matrices and Relevant Submodel

FEP Number	FEP Name	Matrix for Groundwater [a]	Matrix for Volcanic Ash [b]	Biosphere Submodels [c]
1.2.04.07.0A	Ashfall	—	(1,1) (1,2)	Soil, Plant, Air
1.3.01.00.0A	Climate change	(2,2) (4,4) (6,6) (3,7)	(4,4)	Soil, Plant, Fish, ^{14}C, Inhalation
1.3.07.02.0A	Water table rise affects SZ	(1,1)	—	Soil, Air, Plant, ^{14}C, Animal, Fish, Ingestion
1.4.07.01.0A	Water management activities	(1,4) (1,6)	—	Plant, Fish

Table 6.3-6. Mapping of FEPs to Interaction Matrices and Relevant Submodel (Continued)

FEP Number	FEP Name	Matrix for Groundwater [a]	Matrix for Volcanic Ash [b]	Biosphere Submodels [c]
1.4.07.02.0A	Wells	(1,1)	—	Soil, Air, Plant, ^{14}C, Animal, Fish, Ingestion
2.2.08.01.0A	Chemical characteristics of groundwater in the SZ	(1,1)	—	Soil, Plant, Animal, Fish, Ingestion, Inhalation
2.3.02.01.0A	Soil type	(2,2) (4,4)	(2,2) (4,4)	Soil, Plant, ^{14}C
2.3.02.02.0A	Radionuclide accumulation in soils	(1,2) (2,1) (2,2) (3,2) (4,2) (5,2)	(4,2) (5,2)	Soil
2.3.02.03.0A	Soil and sediment transport in the biosphere	(2,3) (3,2)	(2,3) (3,2)	Soil, Air
2.3.04.01.0A	Surface water transport and mixing	(1,1)	—	Soil, Air, Plant, ^{14}C , Animal, Fish, Ingestion
2.3.11.01.0A	Precipitation	(2,2) (4,4)	—	Soil, Plant, ^{14}C
2.3.13.01.0A	Biosphere characteristics	(2,2) (3,3) (4,4) (6,6) (3,7)	(2,2) (3,3) (4,4)	Soil, Air, Plant, Fish, ^{14}C, Inhalation
2.3.13.02.0A	Radionuclide alteration during biosphere transport	(2,2) (2,1) (2,3) (1,4) (2,4) (1,6) (4,2)	(1,4) (2,4) (4,2)	Soil, Air, Plant, Animal, Fish, Inhalation, Ingestion
2.4.01.00.0A	Human characteristics (physiology, metabolism)	(7,7)	(7,7)	External exposure, Inhalation, Ingestion
2.4.04.01.0A	Human lifestyle	(7,7)	(7,7)	Air, External exposure, Inhalation, Ingestion
2.4.07.00.0A	Dwellings	(1,3) (2,7) (3,7)	(2,7) (3,7)	Air, External exposure, Inhalation
2.4.08.00.0A	Wild and natural land and water use	(5,5) (2,7) (5,7)	—	Air, Animal , External exposure, Ingestion
2.4.09.01.0B	Agricultural land use and irrigation	(2,2) (3,3) (4,4) (5,5) (6,6)	(2,2) (3,3) (4,4) (5,5)	Soil, Air, Plant, External exposure, Inhalation, Animal, ^{14}C, Fish
2.4.09.02.0A	Animal farms and fisheries	(5,5) (6,6)	(5,5)	Animal, Fish
2.4.10.00.0A	Urban and industrial land and water use	(2,7)	(2,7)	Soil, Air, ^{14}C, External exposure, Inhalation
3.1.01.01.0A	Radioactive decay and ingrowth	All [d]	All [d]	Surface soil, Air, Plant, Animal, Fish, External exposure, Inhalation, Ingestion
3.2.10.00.0A	Atmospheric transport of contaminants	(1,3) (2,3)	(2,3)	Air, ^{14}C
3.3.01.00.0A	Contaminated drinking water, foodstuffs and drugs	(4,4) (5,5) (6,6)	(4,4) (5,5)	Plant, Animal, Fish, Ingestion
3.3.02.01.0A	Plant uptake	(1,4) (2,4) (3,4)	(2,4) (3,4)	Plant, ^{14}C
3.3.02.02.0A	Animal uptake	(1,5) (2,5) (4,5)	(2,5) (4,5)	Animal, ^{14}C
3.3.02.03.0A	Fish uptake	(1,6)	—	Fish
3.3.03.01.0A	Contaminated non-food products and exposure	(2,7)	(2,7)	External Exposure
3.3.04.01.0A	Ingestion	(1,7) (2,7) (4,7) (5,7) (6,7)	(2,7) (4,7) (5,7)	Ingestion

Table 6.3-6. Mapping of FEPs to Interaction Matrices and Relevant Submodel (Continued)

FEP Number	FEP Name	Matrix for Groundwater [a]	Matrix for Volcanic Ash [b]	Biosphere Submodels [c]
3.3.04.02.0A	Inhalation	(3,7)	(3,7)	Inhalation
3.3.04.03.0A	External exposure	(2,7)	(2,7)	External exposure
3.3.05.01.0A	Radiation doses	(1,7) (2,7) (3,7) (4,7) (5,7) (6,7)	(2,7) (3,7) (4,7) (5,7)	External exposure, Inhalation, Ingestion
3.3.08.00.0A	Radon and radon decay product exposure	(2,3) (3,7)	(2,3) (3,7)	Air, Inhalation

Source: FEP numbers and names are based on the *FY 07 FEP List and Screening* (DTN: MO0706SPAFEPLA.001 [DIRS 181613]).

[a] Elements of the radionuclide transfer interaction matrix for the groundwater scenario shown in Table 6.3-2. Index "i" in (i,j) indicates the row in the matrix, while index "j" in (i, j) indicates the column in the matrix. The linkage between the elements in the matrix and FEPs is based on the biosphere model and the FEP description.

[b] Elements of the radionuclide transfer interaction matrix for the volcanic scenario shown in Table 6.3-4. Index "i" in (i, j) indicates the row in the matrix, while index "j" in (i, j) indicates the column in the matrix.

[c] Relationships among the submodels are shown in Figures 6.3-2 and 6.3-4. Note that ^{14}C has its own special submodel for the groundwater scenario.

[d] "All" means that radionuclide decay is considered in all radionuclide transport in environment media and all human exposure pathways.

SZ = saturated zone; — = not applicable.

6.3.5 Radionuclide Decay and Ingrowth

The TSPA is conducted for the subset of all radionuclides in the radioactive waste inventory that were identified as important contributors to the total dose from radionuclides released from the repository at Yucca Mountain (SNL 2007 [DIRS 177424], Section 7). Consistent with the TSPA, ERMYN considers the same suite of primary radionuclides (Section 6.1.3). The radionuclides identified as primary radionuclides are long-lived and can be accompanied by short-lived decay products, which are included in ERMYN to correctly account for the radiological consequences of the decay chains.

Radionuclides with high atomic numbers (greater than or equal to 82) typically have long chains of radioactive decay products. The consideration of radionuclide decay and ingrowth as a function of time for all members of a decay chain, although conceptually simple, can be computationally intensive and frequently adds little value compared to analyses that only consider long-lived radionuclides. Therefore, in ERMYN, radionuclides with half-lives less than 180 days are treated as if they were always in secular equilibrium with the parent radionuclides (Assumption 2). The secular equilibrium of the parent and progeny applies to the entire biosphere system components (e.g., soil, plants, and animals).

This assumption eliminates the need to consider long decay chains for radionuclides with high atomic numbers. This assumption is reasonable, considering the long time frame of the TSPA modeling. This approach also does not underestimate the concentrations of decay products in the environmental media because the activity concentration of short-lived radionuclides is highest when in secular equilibrium with the long-lived parents (the activity concentrations are equal). The dose contributions of the primary radionuclide and the short-lived decay products can be determined using the activity concentration of the primary radionuclide and the effective dose coefficients for the chain considered. The latter are produced by adding the dose coefficients for the parent radionuclide and those for the short-lived decay products as modified by the branching fraction of the decay products.

The radionuclides of interest for TSPA (Table 6.1-1), with their short-lived (half-life, $T_{1/2}$ less than 180 d) decay products, associated branching fractions, and half-lives, are shown in Table 6.3-7. The radionuclides are arranged into the following five groups listed sequentially in Table 6.3-7:

- Relatively light radionuclides that decay to a stable nuclide or have only one or two radioactive decay products
- Uranium series radionuclides (4n + 2)
- Thorium series radionuclides (4n)
- Actinium series radionuclides (4n + 3)
- Neptunium series radionuclides (4n + 1).

The method of combining dose contributions of decay products with those of their parents is discussed in the sections describing the external exposure (Sections 6.4.7 and 6.5.5), inhalation (Section 6.4.8), and ingestion submodels (Section 6.4.9). In Table 6.3-7, if a primary radionuclide includes a contribution from the short-lived decay products, this is denoted by a D after the radionuclide symbol.

If the half-life of a decay product is longer than 180 d, but not long enough to be considered a primary radionuclide for the TSPA, the decay product is treated in the same way as the long-lived parent. That is, the radionuclide is tracked individually in ERMYN and the BDCF for this radionuclide is calculated. The BDCF for an individually tracked decay product is then added to the BDCF for the parent (Table 6.3-7), assuming the secular equilibrium of the parent and decay products in the source (i.e., groundwater or surface soil). However, following release, the decay product is transported in the environment independently of the parent. For example, ^{232}U decays to ^{228}Th. ^{228}Th is not a primary radionuclide for the TSPA, but the half-life is sufficiently long that it exhibits different environmental transport behaviors, especially as related to leaching, soil-to-plant transfer, and transfer from animal feed to animal products.

Table 6.3-7. Radionuclides of Interest and Their Decay Products

Primary Radionuclide		Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Terminal Nuclide	
Radionuclide	**Half-Life (yr)** [c]		**Nuclide**	**Half-Life (yr)** [c,d]
^{14}C	5730	—	^{14}N	*
^{36}Cl	3.01E+05	—	^{36}Ar (1.9%) ^{36}S (98.1%)	* *
^{79}Se	1.13E+06 [c]	—	^{79}Br	*
^{90}Sr D [a]	29.12	^{90}Y (64.0 h)	^{90}Zr	*
^{99}Tc	2.13E+05	—	^{99}Ru	*
^{126}Sn D	1.0E+05	^{126m}Sb (19.0 min) ^{126}Sb (14%, 12.4 d)	^{126}Te	*
^{129}I	1.57E+07	—	^{129}Xe	*
^{135}Cs	2.3E+06	—	^{135}Ba	*
^{137}Cs D	30.0	^{137m}Ba (94.6%, 2.552 min)	^{137}Ba	*
^{242}Pu	3.763E+05	—	^{238}U	4.468E+09
^{238}U D	4.468E+09	^{234}Th (24.10 d) ^{234m}Pa (99.80%, 1.17 min) ^{234}Pa (0.33%, 6.7 h)[e]	^{234}U	2.445E+05
^{238}Pu	87.74	—	^{234}U	2.445E+05
^{234}U	2.445E+05	—	^{230}Th	7.7E+04
^{230}Th	7.7E+04	—	^{226}Ra	1.60E+03
^{226}Ra	1.60E+03	^{222}Rn (3.8235 d) ^{218}Po (3.05 min) ^{214}Pb (99.98%, 26.8 min) ^{218}At (0.02%, 2 s) ^{214}Bi (19.9 min) ^{214}Po (99.98%, 1.64×10^{-4} s) ^{210}Tl (0.02%, 1.3 min) [c]	^{210}Pb	2.23E+01
^{210}Pb	22.3	^{210}Bi (5.012 d) ^{210}Po (138.38 d)	^{206}Pb	*
^{240}Pu	6.537E+03	—	^{236}U	2.3415E+07
^{236}U	2.3415E+07	—	^{232}Th	1.405E+10
^{232}Th	1.405E+10	—	^{228}Ra	5.75
^{228}Ra	5.75	^{228}Ac (6.13 h)	^{228}Th	1.9131
^{232}U	72	—	^{228}Th	1.9131
^{228}Th [b]	1.9131	^{224}Ra (3.66 d) ^{220}Rn (55.6 s) ^{216}Po (0.15 s) ^{212}Pb (10.64 h) ^{212}Bi (60.55 min) ^{212}Po (64.07%, 0.305 μs) ^{208}Tl (35.93%, 3.07 min)	^{208}Pb	*
^{243}Am	7.38E+03	^{239}Np (2.355 d)	^{239}Pu	2.406E+04
^{239}Pu	2.4065E+04	—	^{235}U	7.038E+08
^{235}U	7.038E+08	^{231}Th (25.52 h)	^{231}Pa	3.276E+04
^{231}Pa	3.276E+04	—	^{227}Ac	2.1773E+01

Table 6.3-7. Radionuclides of Interest and Their Decay Products (Continued)

Primary Radionuclide		Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Terminal Nuclide	
Radionuclide	Half-Life (yr) [c]		Nuclide	Half-Life (yr) [c,d]
^{227}Ac	21.773	^{227}Th (98.62%, 18.718 d) ^{223}Fr (1.38%, 21.8 min) ^{223}Ra (11.434 d) ^{219}Rn (3.96 s) ^{215}Po (1.78 ms) ^{211}Pb (36.1 min) ^{211}Bi (2.14 min) ^{207}Tl (99.72%, 4.77 min) ^{211}Po (0.28%, 0.516 s)	^{207}Pb	*
^{241}Am	432.2	—	^{237}Np	2.14E+06
^{237}Np	2.14E+06	^{233}Pa (27.0 d)	^{233}U	1.585E+05
^{233}U	1.585E+05	—	^{229}Th	7.34E+03
^{229}Th	7.34E+03	^{225}Ra (14.8 d) ^{225}Ac (10.0 d) ^{221}Fr (4.8 min) ^{217}At (32.3 ms) ^{213}Bi (45.65 min) ^{213}Po (97.84%, 4.2 μs) ^{209}Tl (2.16%, 2.2 min) ^{209}Pb (3.253 h)	^{209}Bi	*

[a] "D" indicates that the radionuclide is treated in the model together with the short-lived ($T_{1/2}$ less than 180 d) decay products.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Source: Eckerman and Ryman 1993 [DIRS 107684], Table A.1
Lide and Frederikse 1997 [DIRS 103178], p. 11-125, was used for ^{210}Tl.
Firestone et al. 1998 [DIRS 178201] was used for ^{79}Se half-life.

[d] A "*" denotes a stable nuclide.

[e] The sum of branching fractions for ^{234}Pa and ^{234m}Pa (decay products of ^{234}Th) is greater than one because a fraction of ^{234}Pa undergoes decay to ^{234}Pa. Both of these radionuclides then decay to ^{234}U.

For the groundwater exposure scenario, if a decay product of a primary radionuclide also is a primary radionuclide, the activity of this radionuclide arising from the decay of the parent radionuclide in the soil and the activity that is originally present in the source as a primary radionuclide are tracked independently in the biosphere model. For example, ^{243}Am and ^{239}Pu are primary radionuclides, but ^{243}Am decays to ^{239}Pu, so there are two sources of ^{239}Pu in the environment: ^{239}Pu that was originally in the groundwater and ^{239}Pu that was produced in the soil by the decay of ^{243}Am initially present in the groundwater. If groundwater containing both of these primary radionuclides is used for irrigation, the total activity concentration of ^{239}Pu in the soil results from ^{239}Pu in the groundwater and from ^{239}Pu produced in the soil by the decay of ^{243}Am. These two fractions of ^{239}Pu are independently accounted for in the biosphere model, and the activity concentrations in the soil depend on the concentrations of the primary radionuclides (i.e., ^{239}Pu and ^{243}Am) in the groundwater source. Ingrowth of decay products in the soil is discussed in Section 6.4.1.2. For the volcanic release of radionuclides, TSPA model, specifically the ash redistribution component model, calculates the applicable radionuclide inventory in the soil at the specific time at which dose calculation are required. Therefore, the biosphere model does not include the assessment of the radionuclide buildup or decay in the surface soil.

6.4 MATHEMATICAL MODEL FOR THE GROUNDWATER EXPOSURE SCENARIO

The objective of the biosphere model for the groundwater exposure scenario (Section 6.1) is to calculate BDCFs (Sv/yr)/(Bq/m^3) for the TSPA model. BDCFs for the groundwater exposure scenario are used in calculation of annual dose to the RMEI from radionuclides released from the geosphere to biosphere in groundwater. A BDCF for the groundwater scenario is numerically equal to the all-pathway dose that the RMEI receives under specific biosphere conditions (Section 6.3.1) when the RMEI is exposed to radionuclide contamination in environmental media arising from the use of groundwater containing a unit concentration of the radionuclide. The dimensions of a BDCF are dose per unit time per unit activity concentration in a unit of volume. The source term for the groundwater exposure scenario is the activity concentration of a radionuclide in groundwater (Bq/m^3). This is a time-dependent quantity, calculated outside the biosphere model by the TSPA model, and is unknown until the TSPA model is run. It is assumed in the biosphere model that the radionuclide concentration in groundwater does not change over time (Assumption 1). The radiation dose can then be calculated as a product of the source term (activity concentration in groundwater) and the BDCF, which is source-term independent.

The mathematical model for the groundwater exposure scenario, similar to the biosphere conceptual model for that scenario (Section 6.3.1), is constructed, and presented in this report, as a series of submodels. The relationship among the submodels (Figure 6.3-2) is described in Section 6.3.1. The same notation is used for the same parameter in all submodels so that the linkage between submodels can be traced.

The majority of the individual mathematical representations of processes or pathways described in Sections 6.4 and 6.5 are based on previously published models used for radiological assessment, i.e., the models which analyze radionuclide transport in the biosphere and ensuing human exposure and dose consequences.

The extent to which the equations demonstrate the properties of interest was documented and the following factors were considered in the succeeding sections to evaluate the equations regarding their suitability for intended use:

- Extent and reliability of source documentation
- Qualification of personnel or organizations generating the equations
- Prior uses of the equations
- Availability of corroborating equations, information, or data.

Because ERMYN is largely derived from the GENII biosphere model, the two models share most mathematical equations, which were originally described in the report by Napier et al. (1988 [DIRS 157927]) and then further refined in the report that describes GENII Version 2 (Napier et al. 2006 [DIRS 177331]). For the equations in this section (Section 6.4) and in Section 6.5, based on the GENII/GENII Version 2 model, the source is not specifically referenced; but if the equation is from another source, its source is cited. In Section 7.3, each submodel described in this section is compared with other published biosphere models for model validation, and the sources of equations in the ERMYN are described in detail.

The equations used in GENII are documented in the reports describing the original GENII model (Napier et al. 1988 [DIRS 157927]) and GENII Version 2 (Napier et al. 2006 [DIRS 177331]). The GENII and GENII Version 2 computer codes were developed at Pacific Northwest National Laboratory to provide a state-of-the-art, technically peer-reviewed, documented set of programs for calculating radiation dose and risk from radionuclides released to the environment. Because this is also the objective of biosphere modeling, the equations match the properties of interest required for use in this model. Although the codes were developed for use at Hanford, they were designed with the flexibility to accommodate input parameters for a wide variety of generic sites. The GENII code has been used extensively for radiological assessments following radionuclide releases into the environment, most notably for the evaluation and licensing of the Waste Isolation Pilot Plant in New Mexico. The individual equations used in the GENII model were extensively analyzed in this report and compared with corresponding equations used in other biosphere models for the same processes and properties. This comparison, documented in Sections 7.3 and 7.4, corroborates the appropriateness of the equations from the GENII model for their intended purpose. The equations from this report are, thus, considered suitable for the specific application of developing the biosphere model by virtue of their representativeness, reliability of the source, the qualifications of the personnel and organizations generating the equations, and the prior uses of the equations. Additional sources of equations are described below.

A publication by Lamarsh (1983 [DIRS 149069], Section 2.9) was used as a source for Equation 6.4.1-9. This reference is a textbook for use in university nuclear engineering classes. The equations cited here are simple conservation equations. The first equates the rate of change of the number of atoms of a particular radionuclide in surface soil to the rate of ingrowth from the parent radionuclide less the rate of removal by radioactive decay, leaching, and erosion. The second equation is derived from the first by normalizing to unit area and changing the variable from number of atoms to activity. Being based on the principle of conservation, these equations are considered established fact and do not require further justification.

A report by Eckerman and Ryman (1993 [DIRS 107684], Appendix A, Equation A.2) was used as a source of Equation 6.4.1-10. Equations referred to in this item are the fundamental Bateman equations, which provide radioactive decay chain solutions, in terms of activity or number of atoms, for the chain members.

Baes and Sharp (1983 [DIRS 109606]) (reference used for Equation 6.4.1-28) developed an approximate solution for the annual average leaching rate in soils resulting from overwatering to remove unwanted salt build-up. This equation matches the properties of interest and the intent of the leaching calculations in the soil submodel, as discussed in Section 6.4.1.3, and is, thus, considered qualified for the intended use. This equation for the leaching constant has been used in previous environmental assessment models, most notably the GENII code (Napier et al. 1988 [DIRS 157927]) and GENII Version 2 (Napier et al. 2006 [DIRS 177331]). The same mathematical representation of the leaching process is also used in other biosphere models (BIOMASS 2003 [DIRS 168563]). Its use in the ERMYN biosphere model is identical to the other applications of this equation. The use in the biosphere model is therefore justified.

The National Council on Radiation Protection and Measurements (NCRP) Report No. 129, *Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant* *to Site-Specific Studies* (NCRP 1999 [DIRS 155894], Section 4.3.6) was used for Equation 6.4.2-4. This NCRP report provides screening approaches that can be applied to sites where the surface soil is contaminated with radionuclides to assist with impact evaluations and with making decisions regarding any necessary remediation. The report includes a description of the methods used to arrive at the values of screening factors. These screening approach methods were chosen such that they are conservative under conditions that normally apply to soil contamination, such as those modeled in this report. The description of the methods and the pertinent parameters are useful for developing parameter values for the ERMYN biosphere model. The NCRP calculation used in this model estimates the concentration of radon outdoors from the amount of radon exhaled from the soil. This matches the properties of interest and the intent of the air submodel (Section 6.4.2.3). The specific use of the information in Equation 6.4.2-4 to model the outdoor radon concentration is, therefore, justified.

User's Manual for RESRAD Version 6 (Yu et al. 2001[DIRS 159465]) was used as a source of Equations 6.4.2-5 and 6.4.6-4. That document is the. The equations from this reference are used in the biosphere model to calculate indoor radon concentration and ^{14}C uptake by crops through their roots. This equation matches the properties of interest and the intent of the air (Section 6.4.2.3) and ^{14}C submodels (Section 6.4.6.3). These equations are discussed, compared to other equations representing the same property, and justified for intended use in Sections 7.3.2.2 and 7.3.6.

In the following sections, representative data for many parameters are introduced from the five supporting analyses shown in Figure 1-1. These data are summarized in Table 6.6-3. They are introduced here to provide insight into the various submodel developed in ERMYN, and are also used in Section 7 for model validation.

6.4.1 Surface Soil Submodel

The surface soil submodel is designed to evaluate radionuclide accumulation in, and removal from, the upper layer of the soil (down to the tilling depth) where all plant roots are assumed to be located (Assumption 7) and in the resuspendable layer of the surface soil. For the groundwater scenario, surface soil is contaminated as a result of using contaminated groundwater for irrigation. The surface soil submodel is based on the BIOMASS ERB2A model (BIOMASS 2003 [DIRS 168563], Section C3.5.4).

If contaminated groundwater is used to irrigate cultivated soils, radionuclide concentrations in the soil will build up at a rate determined by the physical and chemical properties of the soil and the contaminant. On land irrigated for a long time, radionuclide concentrations depend on the rate of accumulation and removal, and they will reach equilibrium concentrations when the rates of addition and removal are equal. Long-lived isotopes of elements that sorb readily (i.e., have a large value of the partition coefficient) to soil particles will not reach equilibrium concentrations for thousands of years, whereas relatively short-lived or weakly sorbing radioisotopes will approach equilibrium concentrations after only a few years (Section 7.4.2).

Those radionuclides that reach the biosphere irreversibly attached to colloidal particles will not take part in sorption exchange processes with soil, and will therefore be transported through the soil system without any sorption build-up in soil. As these radionuclides are not in solution, they are not available for plant uptake (via soil to plant transfer). However, in the biosphere model, radionuclide transfer from the soil to crops via root uptake is proportional to the radionuclide concentration in the surface soil (Section 6.4.3.1), i.e., all radionuclides (solutes and colloids) in groundwater are assumed to be in solution and available for plant uptake. This is a conservative approach for cases where colloids are present, because the activity associated with colloids is made available for plant uptake. This conservative approach was adopted because the chemical and biological activity in the surface soil could change the form of the contaminant and allow those contaminants to be subject to sorption (and thereby retarded) by the soil rather then allowing them to be removed.

6.4.1.1 Primary Radionuclides in the Surface Soil

Radionuclides can be removed from the surface soil by leaching into the deep soil, surface soil erosion, crop harvest removal, and radioactive decay. Although crop harvesting may be an important mechanism for radionuclide removal on cultivated lands, this mechanism is not included in the biosphere model because it is considered to compensate for the reintroduction of radionuclides into the soil when contaminated cow manure is used as fertilizer (Assumption 4).

Because irrigation rates differ among crop types, radionuclide concentrations in the surface soil depend on the specific use of cultivated land. In the biosphere model, cultivated land can be used as a home garden or to grow field crops (Assumption 5). However, within each of these land uses, crop rotation over a longer period of time would average out the differing radionuclide concentrations caused by different crop-specific irrigation levels (Assumption 3). Therefore, it is reasonable to use an average annual irrigation rate to estimate long-term radionuclide concentrations in surface soil. The long-term concentration is used to evaluate radionuclide uptake from soil by plants and to evaluate inhalation, inadvertent soil ingestion, and external exposures. Using this simplification, the average activity concentration of a radionuclide in the surface soil does not depend on each individual crop type but only on the general land use (gardens and fields).

The general mathematical representation of the primary radionuclide addition and removal processes in the surface soil is expressed by the following differential equation and the initial condition (based on BIOMASS 2003 [DIRS 168563], Section C3.5.4). Decay product ingrowth in the surface soil is discussed in the next subsection.

$$\begin{cases} \dfrac{dCs_{i,j}}{dt} = Cw_i(t)\ IR_j(t) - (\lambda_{d,i} + \lambda_{l,i} + \lambda_e)\ Cs_{i,j}(t) \\ Cs_{i,j}(t) = 0,\ when\ t = 0 \end{cases} \qquad \text{(Eq. 6.4.1-1)}$$

where

$Cs_{i,j}(t)$	=	activity concentration of radionuclide i in surface soil per unit area at time t (crop type-dependent) (Bq/m^2)
i	=	primary radionuclide index, used for entire biosphere model

t = time variable (yr)

$Cw_i(t)$ = activity concentration of radionuclide i in the groundwater at time t (Bq/m^3)

$IR_j(t)$ = crop-type dependent annual average irrigation rate (annual irrigation rate) (m/yr)

$\lambda_{d,\,i}$ = radioactive decay constant for radionuclide i (1/yr); this can be calculated from radionuclide half-life (Table 6.3-7) using the conversion ln(2)/$T_{d,i}$, where $T_{d,i}$ is half-life of radionuclide i (yr)

$\lambda_{l,\,i}$ = average annual leaching removal rate constant for radionuclide i (1/yr)

λ_e = average annual surface soil erosion removal rate constant (1/yr)

j = crop-type index; j = 1 for leafy vegetables, 2 for other vegetables, 3 for fruit, 4 for grain (consumed by humans and poultry), and 5 for fresh forage feed (used for beef cattle and dairy cows).

When radionuclide concentrations in the surface soil reach equilibrium, they do not change with time, $\frac{dCs_{i,j}(t)}{dt} = 0$, and they are not time dependent $Cs_{i,j}(t) = Cs_{i,j}$. As noted previously, it is assumed in the biosphere model that radionuclide concentrations in groundwater do not change over the time of modeling interest: $Cw_i(t) = Cw_i$ (Assumption 1).

The same equation (Equation 6.4.1-1) can also be used to evaluate the radionuclide concentration in the thin layer of surface soil, from which soil may become resuspended (also referred to in this report as the resuspendable soil layer or the critical thickness of soil). In this case, some of the parameters will have different values from those used for the surface soil, as explained later in this section.

The average irrigation rate for crop type j in Equation 6.4.1-1, $IR_j(t)$, is an annual average irrigation rate, which is developed based on the irrigation rates for individual crop types. Two values of annual average irrigation rates are used in the model: the garden crop irrigation rate (used for leafy vegetables, other vegetables and fruit) and field crop irrigation rate (used for grain and animal forage). The typical range of irrigation rates depends on the climate state and on the crop, and ranges from 0.3 to about 2.3 m/yr (BSC 2004 [DIRS 169673], Section 6.5).

The average irrigation rate is time-dependent because of climate changes predicted for the Yucca Mountain region. However, for a defined climate, the average irrigation rate is not a function of time: $IR_j(t) = IR_j$. As discussed in Section 6.2, climate change does not change the overall biosphere conceptual model as long as the general characteristics of the biosphere are consistent with the arid to semi-arid climate. The model can be adopted for different climates within these boundaries through selection of climate-dependent parameter values, such that they match the desired climate.

The leaching removal rate constant, $\lambda_{l,i}$, is an element-specific input parameter. This important parameter is discussed further in Section 6.4.1.3. The surface soil erosion removal rate constant, λ_e, represents the rate of radionuclide loss from the surface soil due to wind erosion. The value of this radionuclide-independent parameter is strongly site-specific and depends on environmental characteristics and land use. This parameter is further discussed in Section 6.4.1.4.

When the radionuclide concentration in the groundwater and the crop irrigation rate are not time-dependent, the analytical solution of Equation 6.4.1-1 is expressed as:

$$Cs_{i,j}(t) = \frac{Cw_i \; IR_j}{\lambda_{d,i} + \lambda_{l,i} + \lambda_e}\left[1 - e^{-(\lambda_{d,i} + \lambda_{l,i} + \lambda_e)t}\right] \qquad \text{(Eq. 6.4.1-2)}$$

All parameters in Equation 6.4.1-2 are defined in Equation 6.4.1-1. The term $\lambda_{d,i} + \lambda_{l,i} + \lambda_e$ can be replaced with one parameter, the effective removal rate constant, $\lambda_{eff,i}$. In addition, the time variable, t, can be replaced with the irrigation duration, T_{irr}. This parameter quantifies how long an average field was irrigated prior to a year for which a BDCF is calculated. Thus, Equation 6.4.1-2 can be expressed as:

$$Cs_{i,j} = \frac{Cw_i \; IR_j}{\lambda_{eff,i}}\left(1 - e^{-\lambda_{eff,i} T_{irr,j}}\right) \qquad \text{(Eq. 6.4.1-3)}$$

where

$\lambda_{eff,i}$ = effective removal rate constant for radionuclide i (1/yr)

$T_{irr,j}$ = irrigation duration (yr).

$Cs_{i,j}$ is crop-type dependent because the irrigation duration depends on the crop type. Leafy vegetables, other vegetables, and fruit are considered garden crops; grain and fresh forage feed are considered field crops (Assumption 5). This distinction is necessary to select the irrigation duration value.

The effective removal rate constant is an important parameter that determines the rate at which radionuclides approach equilibrium concentrations in the surface soil. For example, the time (t) required for soil concentrations to reach 95% of the equilibrium value can be derived from Equation 6.4.1-3, and is equal to ln(20)/$\lambda_{eff,i}$ (time required to reach 95% equilibrium concentration in surface soil is calculated by making the term in parentheses in Equation 6.4.1-2, representing the fraction of equilibrium, equal to 0.95 and solving for t.) Although it theoretically takes an infinite amount of time to reach equilibrium, the time to reach a fixed percentage of the equilibrium value would be finite, and 95% is a close approximation to equilibrium. It takes about 10 to 2,500 years for the radionuclides considered in the model to reach the 95% equilibrium concentration in surface soils (Section 7.4.2).

If irrigation continued indefinitely, radionuclide concentrations eventually would approach the equilibrium concentration in the surface soil. Within the time period equal to irrigation duration ($T_{irr,j}$), some radionuclides will effectively reach equilibrium concentrations in the surface soil, while the other will be at some fraction of equilibrium concentrations, depending on the value of the effective removal rate constant. The equilibrium concentration in the soil, $Cs_{i,j,equil}$, is expressed as the ratio of the radionuclide addition rate to the removal rate:

$$Cs_{i,\,j,equil} = \frac{Cw_i \; IR_j}{\lambda_{eff,i}}$$
$$Cs_{c,i,j} = \frac{Cw_i IR_j}{\lambda_{eff,c,i}} \qquad \text{(Eq. 6.4.1-4)}$$

As explained later in this section, a thin top layer of the surface soil, called the resuspendable soil layer or the critical thickness, is assumed to always have radionuclide concentrations, $Cs_{c,i,j}$, at equilibrium so the "equil" index is not included in this case. Also, the effective removal rate constant, $\lambda_{eff,c,i}$, is specific for that layer and is calculated as shown in Section 6.4.1.4.

The activity concentration of a radionuclide in surface soil calculated from Equations 6.4.1-3 (or 6.4.1-4) is given in units of activity per unit area (Bq/m^2) and can be converted to activity concentration in Bq per unit mass of surface soil using:

$$Cs_{m,i,j} = \frac{Cs_{i,j}}{\rho_s} \quad or$$
$$Cs_{mc,i,j} = \frac{Cs_{c,i,j}}{\rho_{sc}} \qquad \text{(Eq. 6.4.1-5)}$$

where

$Cs_{m,i,j}$ = crop type-dependent activity concentration of radionuclide i in surface soil per unit mass (Bq/kg)

$Cs_{mc,i,j}$ = crop type-dependent activity concentration of radionuclide i in resuspendable layer of soil per unit mass (Bq/kg)

$Cs_{i,j}$ = crop type-dependent activity concentration of radionuclide i in surface soil per unit area (Bq/m^2) (defined in Equation 6.4.1-3 or 6.4.1-4)

$Cs_{c,i,j}$ = crop type-dependent activity concentration of radionuclide i in resuspendable layer of surface soil per unit area (Bq/m^2) (defined in Equation 6.4.1-4)

ρ_s = areal density of surface soil (kg/m^2)

ρ_{sc} = areal density of the resuspendable soil layer (kg/m^2).

Surface soil density is calculated in the submodel using:

$$\rho_s = \rho \times d \quad or$$
$$\rho_{sc} = \rho \times d_c \qquad \text{(Eq. 6.4.1-6)}$$

where

ρ	=	bulk density of soil (kg/m^3)
d	=	depth of surface soil (m)
d_c	=	depth of the resuspendable soil layer (critical depth) (m).

The soil bulk density ranges from about 1,300 to 1,700 kg/m^3 (Table 6.6-3). The depth of the surface soil is based on tillage depth and ranges from 5 to 30 cm (0.05 to 0.3 m); the depth of the resuspendable soil layer ranges from 1 to 3 mm (0.001 to 0.003 m) (Table 6.6-3).

The soil can be conceptually divided into two compartments: the surface soil layer encompassing the crop root zone, and the deep soil. Only the surface soil layer is modeled in ERMYN. Radionuclides in the deep soil are assumed to be inaccessible to plants (Assumption 7). The depth of the surface soil controls the partition between these two compartments, and, therefore, controls the effective "capacity" of the compartment for the amount of radionuclides available for further mobilization in the biosphere (e.g., by crop uptake).

Within the surface soil layer, where radionuclides are available for transport to the receptor, the general model, as described above, is applied to the entire surface soil layer and to the thin upper layer of surface soil that can be resuspended by natural and mechanical processes. The first of these is used to predict the radionuclide concentrations within the tillage depth (or rooting zone, Assumption 7), where it is available for uptake by crops. The surface soil within the tillage depth is mechanically mixed on a regular basis, so it is reasonable to assume that the radionuclide concentration within this soil layer is uniform (spatially averaged). The other application of the submodel is to predict the radionuclide concentration in the thin layer of surface soil available for atmospheric suspension and subsequent inhalation or deposition or crops and also for inadvertent ingestion intake by humans and animals. Both of these applications make use of Equation 6.4.1-3 with the appropriate removal rates. Because of the differences in the thickness of affected soil layers, the removal rate constants for leaching and soil erosion are different for these two applications of the submodel. Subsequently, for elements with a large partition coefficient, it may take thousands of years to reach equilibrium radionuclide concentration in the surface soil, while it may only take a few years to reach equilibrium in the resuspendable layer of the soil.

Airborne particulates originate from the resuspendable layer of surface soil. To allow for the possibility of longer periods when the soil would not be tilled (e.g., the land used for growing alfalfa, fruit trees, or vines), the equilibrium radionuclide concentration in the resuspendable layer is calculated in the model using Equation 6.4.1-4 and the removal rates characteristic of the resuspendable soil thickness (Assumption 5). This concentration is then compared to the radionuclide concentration in the surface soil, calculated using Equation 6.4.1-3. The greater of these two concentrations is then propagated to the air submodel (Section 6.4.2) to predict atmospheric concentrations of radionuclides, which are then used in the plant submodel (Section 6.4.3) to calculate plant uptake from foliar deposition of soil particles and in the inhalation submodel (Section 6.4.8) to assess doses from inhalation of airborne particulates. The same radionuclide concentration is also used to calculate radionuclide intake by soil ingestion by people and animals. It should be recognized that in some cases the predicted long-term radionuclide concentration in the tillage depth can be greater than the predicted equilibrium concentration in the thin, resuspendable soil layer. Thus taking the greater of the two predictions provides a reasonable value for assessing plant uptake from foliar deposition of contaminated soil, inhalation exposure, and exposure from soil ingestion.

This method of calculating radionuclide concentration in surface soil is considered valid for long-lived radionuclides and for the conditions of long-term irrigation with water containing constant concentrations of given radionuclide (Assumption 1). This approach does not underestimate radionuclide concentrations in surface soil because it is assumed that irrigation continues for an extended period of time and the irrigation duration, which represents an average value for all irrigated land, was developed such that it does not underrepresent the site-specific conditions (Table 6.6-3).

Two irrigation rates, present and future, for field and garden crops were developed based on average annual irrigation rates for 26 representative crops and turf grass for the present-day and upper bound of the glacial transition climate (BSC 2004 [DIRS 169673], Table 6.5-2). The crops were divided into the garden crops and field crops, as shown in Table 6.4-1.

The future climate in Table 6.4-1 refers to the upper bound of glacial transition climate. The average irrigation rate for the garden crops was calculated using irrigation rates for all crops in that category. The standard deviation represents the statistical dispersion around the mean value, i.e., the standard error and was calculated as a ratio of the standard deviation of individual values divided by the square root of the number of garden crops. The distribution of the mean is normal, and the minimum and maximum values of that distribution were calculated at the 99% confidence interval as the mean $\pm$ 2.576 $\times$ standard error.

For the field crops, the average irrigation rate was calculated as a weighted average of irrigation rates of alfalfa and other crops. This was done to take into account that the irrigation rate for alfalfa is higher than that for other crops and that alfalfa is a predominant crop grown in Amargosa Valley. Table 6.4-2 shows the acreage of alfalfa and other field crops in Amargosa Valley in the years from 1996 to 1999.

Table 6.4-1. Average Annual Irrigation Rates for Representative Crops and Turf Grass for Present-Day and Upper Bound Glacial Transition Climate

Garden Crops			Field Crops		
	Irrigation Rate, m/yr			Irrigation Rate, m/yr	
Crop	Present-Day Climate	Future Climate	Crop	Present-Day Climate	Future Climate
Apples	1.82	0.73	Alfalfa	1.94	0.83
Bell peppers	0.72	0.42	Barley	0.84	0.31
Broccoli	0.83	0.64	Feed corn	1.18	0.73
Cabbage	0.91	0.58	Corn silage	0.83	0.69
Carrots	1.00	0.71	Oat feed	0.57	0.55
Cauliflower	0.83	0.44	Oat hay	0.46	0.21
Celery	1.5	0.46	Turf grass	1.62	0.83
Cucumbers	0.50	0.21	Winter wheat	0.94	0.67
Grapes	0.99	0.36			
Head lettuce	0.66	0.63			
Lettuce	0.66	0.46			
Melons	0.84	0.49			
Onions	1.34	0.54			
Potatoes	0.84	0.47			
Spinach	0.51	0.37			
Squash	0.40	0.18			
Strawberries	1.44	0.16	Average, all	1.05	0.60
Sweet corn	0.74	0.52	Average, other	0.92	0.57
Tomatoes	0.69	0.38	St. error, other	0.15	0.09
Average	0.91	0.46	Weighted average	1.78	0.79
Standard error	0.09	0.04	Standard error, all	0.14	0.04
Minimum	0.69	0.36	Minimum	1.41	0.69
Maximum	1.13	0.56	Maximum	2.14	0.89

Source: BSC 2004 [DIRS 169673], Table 6.5-2.

NOTES: The weighted average was calculated based on acreage.
Average, other = average for crops other than alfalfa; st. error, other = standard error for crops other than alfalfa.
See Excel file *Calculation_Annual Irrigation.xls* in Appendix A for details of calculation.

Table 6.4-2. Acres Planted in Field Crops in Amargosa Valley

Crop [a]	Year			
	1996[b]	1997[b]	1998[c]	1999[c]
Alfalfa Hay	1,747	1,822	1,278	1,360
Other Hay	51	68	634	313
Barley	17	32	34	
Oats	45			
Percent of alfalfa acreage	94	95	66	81

[a] Commercial agricultural crop production during spring in Radiological Monitoring Program Grid cells 408, 409, 508, and 509.
[b] Source: CRWMS M&O 1997 [DIRS 101090], Tables 3-12 and 3-13.
[c] Source: YMP 1999 [DIRS 158212], Tables 10 and 11.

The data on acres planted in alfalfa and other field crops were collected during socioeconomic surveys conducted in Amargosa Valley in the years 1996 through 1999 (CRWMS M&O 1997 [DIRS 101090], Tables 3-12 and 3-13; YMP 1999 [DIRS 158212], Tables 10 and 11). The two documents that are the source of these data are the eight and ninth report in a series of annual reports that provide information about spatial distribution of population and agricultural activities within an 84 km radius of Yucca Mountain. The data were collected under the auspices of the Radiological Monitoring Plan by the Regional Studies Department personnel supporting the Yucca Mountain Site Characterization activities. The socioeconomic data collection program under which the data were collected in years 1996 to 1999 evolved in year 2000 into a program subject to Quality Assurance requirements. The data used in the biosphere model concern the commercial agricultural crop production during spring in Radiological Monitoring Program Grid cells 408, 409, 508, and 509 (YMP 1999 [DIRS 158212], Figure 1).

The method used to compile agricultural data in 1998 and 1999 followed the requirements of NWI-RSD-002Q, *Scientific Investigation of Economic, Demographic, and Agricultural Characteristics of the Vicinity of Yucca Mountain*. The description of data collection methods used in years 1996 and 1997 (CRWMS M&O 1997 [DIRS 101090], Section 2.2.2) indicates that they were consistent with the requirement of that procedure. Agricultural data were obtained by examination of agricultural activities within the Radiological Monitoring Program grid. The data collection methods generally consisted of the following steps: (1) previously collected information regarding agricultural activities within the grid was compiled and entered into the database, including the type of agriculture, the number of acres of cropland, and the location of agricultural activity; (2) location of agricultural activities listed in the database was identified on color aerial photographs of southern Nye County; (3) field trips were conducted to verify the existence of, or changes to, previously observed agriculture and to identify any agricultural activity not yet recorded; (4) groundwater pumpage inventories from the Nevada Division of Water Resources were inspected to identify locations of previously unidentified agricultural activities. These data were verified, where possible, with the land owner and other individuals knowledgeable about specific agricultural activities (CRWMS M&O 1997 [DIRS 101090], Sections 1.2 and 2.2.2; YMP 1999 [DIRS 158212], Sections 1.2, 1.3, and 2.3).

The agricultural data on the number of acres of alfalfa and other field crops in Amargosa Valley were evaluated from the perspective of the data collection methods and the intended use of the data. This technical assessment led to a conclusion that the data were appropriate for the intended use and can be considered qualified for the following reasons.

(1) The data collection methods were sound and multi-faceted, and included verification of the data against the independent records maintained by the State of Nevada, Nevada Division of Water Resources and aerial photography.

(2) The procedure that was used to collect the data (NWI-RSD-002Q) was inspected. It was determined that it provides adequate provisions for planning and conduct of the activities, organizing and processing data, and verification of completed work.

(3) The data were used to adjust the annual average irrigation rate for the fraction of the area used for grow alfalfa and other field crops. The desired quantity is independent of the actual area of agricultural land; rather it measures the proportion of various field crops on that land. Because the same methods were used to conduct agricultural surveys in the subsequent years the bias, if present, would be minimized.

The average percentage of fields planted in alfalfa from years 1996 to 1999 was 84% ±14%. The weighted average irrigation for field crops was calculated as:

$$\begin{aligned} \overline{IR_j} &= PA\ IR_{alfalfa} + PO\ IR_{other} \\ &= PA\ IR_{alfalfa} + (1 - PA)\ IR_{other} \\ &= PA\left(IR_{alfalfa} - IR_{other}\right) + IR_{other} \end{aligned} \qquad \text{(Eq. 6.4.1-7)}$$

where

$\overline{IR_j}$ = weighted annual average irrigation rate for field crops (j = 4 and 5) (m/yr)

PA = percent of fields planted in alfalfa

$IR_{alfalfa}$ = annual average irrigation rate for alfalfa (m/yr)

PO = percent of fields planted in other crops, equal to 100% – PA

IR_{other} = annual average irrigation rate for other field crops (m/yr).

The variance in the weighted annual average irrigation rate for field crops was evaluated using the general formula for error propagation (based on Bevington and Robinson 1992 [DIRS 147076], Section 3.2, Equation 3.14, and examples in Section 3.3) as:

$$\begin{aligned} Var_{IR} &= \left(\frac{\partial \overline{IR_j}}{\partial PA}\right)^2 Var_{PA} + \left(\frac{\partial \overline{IR_j}}{\partial IR_{other}}\right)^2 Var_{IR_{other}} \\ &= \left(IR_{alfalfa} - IR_{other}\right)^2 Var_{PA} + (1 - PA)^2 Var_{IR_{other}} \end{aligned} \qquad \text{(Eq. 6.4.1-8)}$$

where

Var_{IR}	=	variance in the weighted annual average irrigation rate for field crops $(m/yr)^2$
Var_{PA}	=	variance in the percent of fields planted in alfalfa (dimensionless)
$Var_{IR_{other}}$	=	variance in the annual average irrigation rate for field crops other than alfalfa $(m/yr)^2$.

The distribution of the weighted annual average irrigation rate for field crops is normal and the standard deviation (square root of variance) of that distribution was calculated using Equation 6.4.1-8 in Excel spreadsheet *Calculation_Annual Irrigation.xls* (Appendix A). The minimum and maximum of the distribution were calculated, analogous to those for the distribution of garden crops irrigation rates, at the 99% confidence interval as the mean ± 2.576 × standard deviation.

6.4.1.2 Radionuclide Decay and Ingrowth in the Surface Soil

This section describes radionuclide decay and ingrowth in surface soil due to introduction of primary radionuclides in irrigation water. As noted in Sections 6.3.1.4 and 6.3.5, short-lived decay products (half-lives less than 180 days) are treated as if they were in secular equilibrium with the parent radionuclide (Assumption 2). The buildup of long-lived decay products (which may also be primary radionuclides) in the surface soil is considered separately from the buildup of parent primary radionuclides (Section 6.4.1.1) because decay product concentrations in the soil are calculated differently. The radiation dose contribution from the decay products is combined with that for the primary radionuclide.

For decay chains in the surface soil, decay products are produced at the rate that the parent radionuclides decay. Removal mechanisms include decay of the decay product, leaching from the surface soil, and removal by soil erosion. The general differential equation (Lamarsh 1983 [DIRS 149069], Section 2.9) describing the rate of change in the number of atoms of the decay product is given by:

$$\begin{cases} \dfrac{dN_0(t)}{dt} = -(\lambda_{d,1} + \lambda_{l,1} + \lambda_e) N_0(t) \\ and\ for\ l \geq 1 \\ \dfrac{dN_l(t)}{dt} = \lambda_{d,l-1} N_{l-1}(t) - (\lambda_{d,l} + \lambda_{l,l} + \lambda_e) N_l(t) \\ N_1(0) = N_l(0) = 0 \end{cases} \qquad \text{(Eq. 6.4.1-9)}$$

where

$N_0(t)$	=	number of atoms for the parent radionuclide in a decay chain in the surface soil
$N_l(t)$	=	number of atoms for the *l*th decay product in a decay chain in the surface soil
$N_{l-1}(t)$	=	number of atoms for the (*l*-1)th decay product in a decay chain in the surface soil
l	=	index of a long–lived radionuclide in the decay chain ($l \geq 1$)
$\lambda_{d,l-1}$	=	radioactive decay constant for the (*l*–1)th decay product (1/yr)
$\lambda_{d,l}$	=	radioactive decay constant for the *l*th decay product (1/yr)
$\lambda_{l,l}$	=	average annual leaching removal rate constant (λ_l) for the *l*th decay product (1/yr)
λ_e	=	average annual surface soil erosion removal rate constant (1/yr).

The sum of removal rate constants in Equation 6.4.1-9 ($\lambda_{d,l} + \lambda_{l,l} + \lambda_e$) can be represented by a single effective removal rate constant, $\lambda_{eff,l}$.

For certain conditions, Equation 6.4.1-9 can be solved analytically, as is discussed later in this section.

By combining short-lived radionuclides with their longer-lived parents (Section 6.3.5), the number of radionuclides in a decay chain can be reduced. However, even if reduced, the number of long-lived (primary) radionuclides in a decay chain could be as high as six (^{242}Pu, Table 6.3-7). The amount of decay products in the soil depend on the decay constants and the effective removal rate constants (Equation 6.4.1-9). Typical effective removal rate constants for the radionuclides of interest to biosphere modeling range from 1×10^{-4}/yr to 1×10^{-1}/yr (Section 7.4.2, Excel file *ERMYN Validation_Soil Model.xls*, Appendix A). If radionuclides have a long half-life (on the order of 1×10^5 year), which corresponds to a small decay constant ($< 1 \times 10^{-5}$/yr), it is not necessary to include them as a decay product of the parent primary radionuclide. Thus, these radionuclides can be considered decay chain "stoppers" for a decay chain originating with a primary radionuclide. The radionuclides that meet this condition are ^{238}U, ^{234}U, ^{236}U, ^{232}Th, ^{235}U, ^{237}Np, and ^{233}U, which effectively terminate the decay chains of ^{242}Pu, ^{238}U/^{238}Pu, ^{240}Pu, ^{236}U, ^{239}Pu, ^{241}Am, and ^{237}Np, respectively (Table 6.3-7).

By combining short-lived decay products with their longer-lived predecessors, and neglecting the contribution from very long-lived decay products and their progeny, the number of decay chain members that are explicitly considered in the ERMYN is significantly reduced. These abridged chains are shown in Table 6.4-3. Only the decay chain for ^{234}U includes a third long-lived decay product (^{210}Pb D; Table 6.4-3). The contribution to the ^{234}U dose from ^{226}Ra, with additional consideration of ^{222}Rn and progeny, is expected to be higher than the dose contribution from ^{210}Pb D and progeny because of the inhalation dose contribution from radon progeny (Table 6.10-3). Therefore, the third decay product, ^{210}Pb D, of the abbreviated ^{234}U decay chain is not considered. This reduces the number of decay products from primary radionuclides that are explicitly modeled in the ERMYN to, at most, two. Consequently, Equation 6.4.1-9 describing kinetics (buildup) of radionuclide concentration in surface soil needs to be solved only for the primary radionuclide and two long-lived decay products.

Table 6.4-3. The Primary Radionuclides and Their Decay Chains for Soil

Primary Radionuclide	1st Long-Lived Decay Product	2nd Long-Lived Decay Product	3rd Long-Lived Decay Product
^{234}U	^{230}Th	^{226}Ra D	^{210}Pb D
^{230}Th	^{226}Ra D	^{210}Pb D	—
^{226}Ra D[a]	^{210}Pb D	—	—
^{232}Th	^{228}Ra D	^{228}Th D	—
^{228}Ra D	^{228}Th	—	—
^{232}U	^{228}Th	—	—
^{243}Am D	^{239}Pu	—	—
^{235}U D	^{231}Pa	^{227}Ac D	—
^{231}Pa	^{227}Ac D	—	—
^{233}U	^{229}Th D	—	—

NOTE: Table entries were derived from Table 6.3-7 using the method discussed in this section.

[a] A "D" after a radionuclide symbol denotes that the radionuclide is treated together with its short-lived (less than 180 d) decay product.

For a single addition of a primary radionuclide into the soil at $t = 0$, $N_1(0)$, the general solution to Equation 6.4.1-9 can be expressed by the Bateman equations as (based on Eckerman and Ryman 1993 [DIRS 107684], Appendix A, Equation A.2):

$$N_n(t) = N_1(0)\prod_{p=1}^{n-1} k_{p,p+1} \sum_{j=1}^{n} \frac{e^{-k_j t}}{\prod_{p=1,\ p\neq j}^{n}(k_p - k_j)} \qquad \text{(Eq. 6.4.1-10)}$$

where

$$\prod_{i=1}^{n} a_i = a_1 \times a_2 \times \ldots \times a_n,\ \ if\ \ n \geq 1$$
$$= 1,\ \ if\ \ n = 0$$

$k_{p,p+1}$ = rate constant that describes production of p+1 radionuclide in the chain from decay of its parent (p) in surface soil, equal to the decay rate of the parent radionuclide ($\lambda_{d,p}$) multiplied by the fraction of the nuclear transformations of chain member p forming member $p+1$. In the chains listed in Table 6.4-3 the branching fractions are equal to 1, so this term is omitted in this and the following equations.

k_j = total rate constant that describes total removal of a jth radionuclide in the chain from surface soil, equal to the effective removal rate constant, $\lambda_{eff,j}$

n = index of radionuclide in the chain; $n = 1$ for the primary radionuclide, $n = 2$ for the first decay product, $n = 3$ for the second decay product.

The subscripts used in Equations 6.4.1-10 through 6.4.1-20 are general indices that do not correspond to other indices used in the biosphere model. They are used here to develop formulas for radionuclide concentrations in the soil for the primary radionuclide and its long-lived decay products.

Specific solutions of Equation 6.4.1-9 are as follows:

For the parent radionuclide ($n = 1$)

$$N_1(t) = N_1(0)\, e^{-\lambda_{eff,1} t} \qquad \text{(Eq. 6.4.1-11)}$$

For the first decay product ($n = 2$)

$$N_2(t) = N_1(0)\lambda_1 \left(\frac{e^{-\lambda_{eff,1} t}}{\lambda_{eff,2} - \lambda_{eff,1}} + \frac{e^{-\lambda_{eff,2} t}}{\lambda_{eff,1} - \lambda_{eff,2}} \right) \qquad \text{(Eq. 6.4.1-12)}$$

For the second decay product ($n = 3$)

$$N_3(t) = N_1(0)\lambda_1\lambda_2 \left(\frac{e^{-\lambda_{eff,1} t}}{(\lambda_{eff,2} - \lambda_{eff,1})(\lambda_{eff,3} - \lambda_{eff,1})} + \frac{e^{-\lambda_{eff,2} t}}{(\lambda_{eff,1} - \lambda_{eff,2})(\lambda_{eff,3} - \lambda_{eff,2})} + \frac{e^{-\lambda_{eff,3} t}}{(\lambda_{eff,1} - \lambda_{eff,3})(\lambda_{eff,2} - \lambda_{eff,3})} \right)$$

(Eq. 6.4.1-13)

These solutions represent the impulse response of the system to a single instantaneous addition of radionuclides in a very short time at $t = 0$, $N_1(0)$. A continuous addition of radionuclide to soil can be interpreted as a series of independent infinitesimal discrete contributions. Because the principle of superposition holds in linear systems and the model of the biosphere system is linear (Section 6.4.10.2), the response due to a continuous addition of a radionuclide with an addition rate of $f(t)$ can be obtained by summing (integrating) the infinitesimal contributions (Polig 2001 [DIRS 178418], p. 494).

For the parent radionuclide, the number of atoms at time t is:

$$N_1(t) = \int_0^t f(\tau)\, e^{-\lambda_{eff,1}(t-\tau)} d\tau \qquad \text{(Eq. 6.4.1-14)}$$

If the rate of addition is constant, $f(\tau) = f$, Equation 6.4.1-14 can be solved as:

$$N_1(t) = f \int_0^t e^{-\lambda_{eff,1}(t-\tau)}\, d\tau = \frac{f}{\lambda_{eff,1}} \left(1 - e^{-\lambda_{eff,1} t}\right) \qquad \text{(Eq. 6.4.1-15)}$$

Equations 6.4.1-12 and 6.4.1-13 can be integrated in a similar manner to obtain the number of atoms of the first and second decay product, $N_2(t)$ and $N_3(t)$. The solutions of these equations are:

$$N_2(t) = f\lambda_1 \int_0^t \left(\frac{e^{-\lambda_{eff,1}(t-\tau)}}{\lambda_{eff,2} - \lambda_{eff,1}} + \frac{e^{-\lambda_{eff,2}(t-\tau)}}{\lambda_{eff,1} - \lambda_{eff,2}} \right) d\tau =$$

$$\frac{f\lambda_1}{\lambda_{eff,2} - \lambda_{eff,1}} \int_0^t e^{-\lambda_{eff,1}(t-\tau)} d\tau + \frac{f\lambda_1}{\lambda_{eff,1} - \lambda_{eff,2}} \int_0^t e^{-\lambda_{eff,2}(t-\tau)} d\tau = \qquad \text{(Eq. 6.4.1-16)}$$

$$\frac{f\lambda_1}{\lambda_{eff,1}\left(\lambda_{eff,2} - \lambda_{eff,1}\right)}\left(1 - e^{-\lambda_{eff,1}t}\right) + \frac{f\lambda_1}{\lambda_{eff,2}\left(\lambda_{eff,1} - \lambda_{eff,2}\right)}\left(1 - e^{-\lambda_{eff,2}t}\right)$$

and

$$N_3(t) = f\lambda_1\lambda_2 \int_0^t \left(\frac{e^{-\lambda_{eff,1}(t-\tau)}}{\left(\lambda_{eff,2} - \lambda_{eff,1}\right)\left(\lambda_{eff,3} - \lambda_{eff,1}\right)} + \frac{e^{-\lambda_{eff,2}(t-\tau)}}{\left(\lambda_{eff,1} - \lambda_{eff,2}\right)\left(\lambda_{eff,3} - \lambda_{eff,2}\right)} + \frac{e^{-\lambda_{eff,3}(t-\tau)}}{\left(\lambda_{eff,1} - \lambda_{eff,3}\right)\left(\lambda_{eff,2} - \lambda_{eff,3}\right)} \right) d\tau =$$

$$\frac{f\lambda_1\lambda_2}{\left(\lambda_{eff,2} - \lambda_{eff,1}\right)\left(\lambda_{eff,3} - \lambda_{eff,1}\right)} \int_0^t e^{-\lambda_{eff,1}(t-\tau)} d\tau + \frac{f\lambda_1\lambda_2}{\left(\lambda_{eff,1} - \lambda_{eff,2}\right)\left(\lambda_{eff,3} - \lambda_{eff,2}\right)} \int_0^t e^{-\lambda_{eff,2}(t-\tau)} d\tau +$$

$$\frac{f\lambda_1\lambda_2}{\left(\lambda_{eff,1} - \lambda_{eff,3}\right)\left(\lambda_{eff,2} - \lambda_{eff,3}\right)} \int_0^t e^{-\lambda_{eff,3}(t-\tau)} d\tau = \frac{f\lambda_1\lambda_2}{\lambda_{eff,1}\left(\lambda_{eff,2} - \lambda_{eff,1}\right)\left(\lambda_{eff,3} - \lambda_{eff,1}\right)}\left(1 - e^{-\lambda_{eff,1}t}\right) +$$

$$\frac{f\lambda_1\lambda_2}{\lambda_{eff,2}\left(\lambda_{eff,1} - \lambda_{eff,2}\right)\left(\lambda_{eff,3} - \lambda_{eff,2}\right)}\left(1 - e^{-\lambda_{eff,2}t}\right) + \frac{f\lambda_1\lambda_2}{\lambda_{eff,3}\left(\lambda_{eff,1} - \lambda_{eff,3}\right)\left(\lambda_{eff,2} - \lambda_{eff,3}\right)}\left(1 - e^{-\lambda_{eff,3}t}\right)$$

(Eq. 6.4.1-17)

Equations 6.4.1-15 to 6.4.1-17 can be expressed in terms of activity, $A_i(t)$, rather than the number of atoms, $N_i(t)$, by multiplying both sides of these equations by the appropriate radioactive decay constant. In Equations 6.4.1-18 to 6.4.1-20, the parameter $F = f\lambda_1$ represents the activity addition rate for the parent radionuclide.

$$A_1(t) = \frac{F}{\lambda_{eff,1}}\left(1 - e^{-\lambda_{eff,1}t}\right) \qquad \text{(Eq. 6.4.1-18)}$$

$$A_2(t) = \frac{F\lambda_2}{\lambda_{eff,1}\left(\lambda_{eff,2} - \lambda_{eff,1}\right)}\left(1 - e^{-\lambda_{eff,1}t}\right) + \frac{F\lambda_2}{\lambda_{eff,2}\left(\lambda_{eff,1} - \lambda_{eff,2}\right)}\left(1 - e^{-\lambda_{eff,2}t}\right) \qquad \text{(Eq. 6.4.1-19)}$$

$$A_3(t) = \frac{F\lambda_2\lambda_3}{\lambda_{eff,1}\left(\lambda_{eff,2} - \lambda_{eff,1}\right)\left(\lambda_{eff,3} - \lambda_{eff,1}\right)}\left(1 - e^{-\lambda_{eff,1}t}\right) +$$

$$\frac{F\lambda_2\lambda_3}{\lambda_{eff,2}\left(\lambda_{eff,1} - \lambda_{eff,2}\right)\left(\lambda_{eff,3} - \lambda_{eff,2}\right)}\left(1 - e^{-\lambda_{eff,2}t}\right) + \frac{F\lambda_2\lambda_3}{\lambda_{eff,3}\left(\lambda_{eff,1} - \lambda_{eff,3}\right)\left(\lambda_{eff,2} - \lambda_{eff,3}\right)}\left(1 - e^{-\lambda_{eff,3}t}\right) \qquad \text{(Eq. 6.4.1-20)}$$

The rate of activity addition of a parent radionuclide, *F*, can now be expressed in terms of the irrigation rate, *IR*, and radionuclide concentration in groundwater, *Cw*, analogous to the method used in Section 6.4.1.1 (Equations 6.4.1-2 to 6.4.1-3). The product of these two quantities represents activity added annually to a unit area of the soil. If *F* in Equations 6.4.1-18 to 6.4.1-20 is replaced by a product of *IR* and *Cw*, then the left side of these equations becomes equal to the areal radionuclide concentration in surface soil, *Cs(t)*, as shown in Equations 6.4.1-21 to 6.4.1-23. Equations 6.4.1-21 to 6.4.1-23 return to the biosphere model indexing with respect to the parent radionuclide (*i*) and the long-lived decay products (l = 1 for first decay product, l = 2 for second decay product).

$$Cs_i(t) = \frac{Cw_i IR_j}{\lambda_{eff,i}}\left(1 - e^{-\lambda_{eff,i}t}\right) \quad \text{(Eq. 6.4.1-21)}$$

$$Cs_{l=1}(t) = \frac{Cw_i IR_j\ \lambda_{d,l=1}}{\lambda_{eff,i}\left(\lambda_{eff,l=1} - \lambda_{eff,i}\right)}\left(1 - e^{-\lambda_{eff,i}t}\right) + \frac{Cw_i IR_j\ \lambda_{d,l=1}}{\lambda_{eff,l=1}\left(\lambda_{eff,i} - \lambda_{eff,l=1}\right)}\left(1 - e^{-\lambda_{eff,l=1}t}\right) = \frac{Cw_i IR_j\ \lambda_{d,l=1}}{\left(\lambda_{eff,l=1} - \lambda_{eff,i}\right)}\left[\frac{\left(1 - e^{-\lambda_{eff,i}t}\right)}{\lambda_{eff,i}} - \frac{\left(1 - e^{-\lambda_{eff,l=1}t}\right)}{\lambda_{eff,l=1}}\right] \quad \text{(Eq. 6.4.1-22)}$$

$$\begin{aligned} Cs_{l=2}(t) = {} & \frac{Cw_i IR_j\ \lambda_{d,l=1}\lambda_{d,l=2}}{\lambda_{eff,i}\left(\lambda_{eff,l=1} - \lambda_{eff,i}\right)\left(\lambda_{eff,l=2} - \lambda_{eff,i}\right)}\left(1 - e^{-\lambda_{eff,i}t}\right) + \\ & \frac{Cw_i IR_j\ \lambda_{d,l=1}\lambda_{d,l=2}}{\lambda_{eff,l=1}\left(\lambda_{eff,i} - \lambda_{eff,l=1}\right)\left(\lambda_{eff,l=2} - \lambda_{eff,l=1}\right)}\left(1 - e^{-\lambda_{eff,l=1}t}\right) + \frac{Cw_i IR_j\ \lambda_{d,l=1}\lambda_{d,l=2}}{\lambda_{eff,l=2}\left(\lambda_{eff,i} - \lambda_{eff,l=2}\right)\left(\lambda_{eff,l=1} - \lambda_{eff,l=2}\right)}\left(1 - e^{-\lambda_{eff,l=2}t}\right) = \\ & Cw_i IR_j\ \lambda_{d,l=1}\lambda_{d,l=2}\left[\frac{\left(1 - e^{-\lambda_{eff,i}t}\right)}{\lambda_{eff,i}\left(\lambda_{eff,l=1} - \lambda_{eff,i}\right)\left(\lambda_{eff,l=2} - \lambda_{eff,i}\right)} + \frac{\left(1 - e^{-\lambda_{eff,l=1}t}\right)}{\lambda_{eff,l=1}\left(\lambda_{eff,i} - \lambda_{eff,l=1}\right)\left(\lambda_{eff,l=2} - \lambda_{eff,l=1}\right)} + \right. \\ & \left. \frac{\left(1 - e^{-\lambda_{eff,l=2}t}\right)}{\lambda_{eff,l=2}\left(\lambda_{eff,i} - \lambda_{eff,l=2}\right)\left(\lambda_{eff,l=1} - \lambda_{eff,l=2}\right)}\right] \end{aligned}$$

(Eq. 6.4.1-23)

When the activity concentration in the soil is at equilibrium for the primary radionuclides and the decay products; that is, $\frac{dCs_i(t)}{dt} = 0$ and $\frac{dCs_l(t)}{dt} = 0$, the solution for the primary radionuclide is as shown in Equation 6.4.1-4 and the solutions for the decay products can be expressed as:

$$Cs_{l,equil} = \frac{\lambda_{d,l}}{\lambda_{eff,l}} Cs_{l-1,equil} \quad \text{(Eq. 6.4.1-24)}$$

where

$Cs_{l,\,equil}$ = equilibrium activity concentration of a decay product l in surface soil (Bq/m^2)

$Cs_{l-1,\,equil}$ = equilibrium activity concentration of a primary radionuclide if $l = 1$, or a decay product (l–1) in surface soil (Bq/m^2)

$\lambda_{d,l}$ = radioactive decay constant for the lth decay product (1/yr)

$\lambda_{eff,l}$ = effective removal rate constant for the lth decay product (1/yr).

In Section 7.4.2.2, the radionuclide decay chains used in GENII-S and ERMYN are compared to verify that all of the decay products are properly considered.

For the surface soil, Equations 6.4.1-21 to 6.4.1-23 describe relationships among activity concentrations for consecutive members of decay chains produced by the decay of primary radionuclides. For short-lived decay products, the effective removal rate constant (λ_{eff}) is approximately equal to the decay constant (λ_d), and the activity concentration in the soil is the same as that for the immediate predecessor, thereby, demonstrating that for short-lived radionuclides, the secular equilibrium is not perturbed by the other physical removal processes.

For a given irrigation duration, $T_{irr,\,j}$, radionuclide concentrations in surface soil can be expressed as:

$$Cs_{i,j} = \frac{Cw_i IR_j}{\lambda_{eff,i}}\left(1 - e^{-\lambda_{eff,i} T_{irr,j}}\right) \quad \text{(Eq. 6.4.1-25)}$$

$$Cs_{l=1,j} = \frac{Cw_i IR_j\ \lambda_{d,l=1}}{\lambda_{eff,i}\left(\lambda_{eff,l=1} - \lambda_{eff,i}\right)}\left(1 - e^{-\lambda_{eff,i} T_{irr,j}}\right) + \frac{Cw_i IR_j\ \lambda_{d,l=1}}{\lambda_{eff,l=1}\left(\lambda_{eff,i} - \lambda_{eff,l=1}\right)}\left(1 - e^{-\lambda_{eff,l=1} T_{irr,j}}\right) = \frac{Cw_i IR_j\ \lambda_{d,l=1}}{\left(\lambda_{eff,l=1} - \lambda_{eff,i}\right)}\left[\frac{\left(1 - e^{-\lambda_{eff,i} T_{irr,j}}\right)}{\lambda_{eff,i}} - \frac{\left(1 - e^{-\lambda_{eff,l=1} T_{irr,j}}\right)}{\lambda_{eff,l=1}}\right] \quad \text{(Eq. 6.4.1-26)}$$

$$\begin{aligned} Cs_{l=2,j} = {} & \frac{Cw_i IR_j\ \lambda_{d,l=1}\lambda_{d,l=2}}{\lambda_{eff,i}\left(\lambda_{eff,l=1} - \lambda_{eff,i}\right)\left(\lambda_{eff,l=2} - \lambda_{eff,i}\right)}\left(1 - e^{-\lambda_{eff,i}\, T_{irr,j}}\right) + \\ & \frac{Cw_i IR_j\ \lambda_{d,l=1}\lambda_{d,l=2}}{\lambda_{eff,l=1}\left(\lambda_{eff,i} - \lambda_{eff,l=1}\right)\left(\lambda_{eff,l=2} - \lambda_{eff,l=1}\right)}\left(1 - e^{-\lambda_{eff,l=1}\, T_{irr,j}}\right) + \frac{Cw_i IR_j\ \lambda_{d,l=1}\lambda_{d,l=2}}{\lambda_{eff,l=2}\left(\lambda_{eff,i} - \lambda_{eff,l=2}\right)\left(\lambda_{eff,l=1} - \lambda_{eff,l=2}\right)}\left(1 - e^{-\lambda_{eff,l=2}\, T_{irr,j}}\right) = \\ & Cw_i IR_j\ \lambda_{d,l=1}\lambda_{d,l=2}\left[\frac{\left(1 - e^{-\lambda_{eff,i}\, T_{irr,j}}\right)}{\lambda_{eff,i}\left(\lambda_{eff,l=1} - \lambda_{eff,i}\right)\left(\lambda_{eff,l=2} - \lambda_{eff,i}\right)} + \frac{\left(1 - e^{-\lambda_{eff,l=1}\, T_{irr,j}}\right)}{\lambda_{eff,l=1}\left(\lambda_{eff,i} - \lambda_{eff,l=1}\right)\left(\lambda_{eff,l=2} - \lambda_{eff,l=1}\right)} + \right. \\ & \left. \frac{\left(1 - e^{-\lambda_{eff,l=2}\, T_{irr,j}}\right)}{\lambda_{eff,l=2}\left(\lambda_{eff,i} - \lambda_{eff,l=2}\right)\left(\lambda_{eff,l=1} - \lambda_{eff,l=2}\right)}\right] \end{aligned}$$

(Eq. 6.4.1-27)

Radionuclide concentrations calculated using Equations 6.4.1-25 to 6.4.1-27 depend on the irrigation duration and crop-dependent annual average irrigation rate and thus are crop-type dependent (different irrigation duration is used for field and garden crops; Assumption 5).

6.4.1.3 Radionuclide Leaching from the Surface Soil

The residence time of radionuclides in the soil can influence their contribution to the total exposure of the receptor. Therefore, the biosphere assessment must account for the removal of radionuclides by leaching from the surface soil to the deep soil as well as from the resuspendable soil layer to the rest of the surface soil and the deep soil.

In the first case, radionuclides removed from the surface soil by leaching would no longer be available to many of the environmental transport and receptor exposure pathways. In an arid climate, leaching may be enhanced by overwatering, which is a common practice to prevent the soil buildup of salts from irrigation water (BSC 2004 [DIRS 169673], Section 6.9). Under wetter conditions, such as those predicted to occur in the future at Yucca Mountain, leaching also would occur when excess precipitation flows through the surface soil, primarily during the winter.

The process of leaching contaminants from the surface soil is evaluated using element-specific leaching coefficients. Leaching coefficients are calculated using a relationship developed by Baes and Sharp (1983 [DIRS 109606], p. 18). This equation is used in other biosphere models as discussed in the model comparison section (Section 7.3.1.1). The equation for the leaching removal rate constant for the surface soil, $\lambda_{l,i}$, is expressed as:

$$\lambda_{l,i} = \frac{OW}{d \times \theta \left(1 + \frac{\rho}{\theta} Kd_i\right)} \qquad \text{(Eq. 6.4.1-28)}$$

where

OW = crop overwatering rate (infiltration rate) (m/yr)

θ = volumetric water content of soil (dimensionless)

Kd_i = solid-liquid partition coefficient for radionuclide i in surface soil $(Bq/kg_{\ solid})/(Bq/m^3_{\ liquid}) = (m^3_{\ liquid}/kg_{\ solid})$

and the other parameters are defined in Equations 6.4.1-1 and 6.4.1-6.

In arid regions, the overwatering rate usually is determined by calculating the amount of water required to flush accumulated salts out of the surface soil to maintain productivity. The value of this parameter is on the order of 10 cm/yr (BSC 2004 [DIRS 169673], Section 7.1). The volumetric water content of soil is defined as the fraction of the soil volume representing water-filled porosity. The value of this parameter depends on soil texture and ranges from less than 0.1 (dry soils) to 0.4 to 0.5 (water-saturated soils), with typical values of about 0.2 to 0.3 (SNL 2007 [DIRS 179993], Section 6.6). The partition coefficients depend on soil characteristics, with average values ranging over several orders of magnitude (i.e., 10^{-4} to 10 m^3/kg; SNL 2007 [DIRS 179993], Section 6.3).

In the case of the soil available for atmospheric suspension, the layer of soil is much thinner than the tillage depth; typical thicknesses are on the order of a few millimeters (Table 6.6-3). Although the processes and, therefore, modeling of the radionuclide build-up is the same as that for the surface soil, the parameters in Equation 6.4.1-28 that are used to calculate the leaching removal rate constant are different from those used for the surface soil. The soil thickness is equal to the thickness of the resuspendable soil layer, d_c, (also called the critical thickness). Equation 6.4.1-28 thus becomes:

$$\lambda_{lc,i} = \frac{OW_c}{d_c \times \theta \left(1 + \frac{\rho}{\theta} Kd_i\right)} \quad \text{(Eq. 6.4.1-29)}$$

The overwatering term, OW_c, is calculated as the average annual irrigation rate adjusted for the amount of water retained in the resuspendable soil layer after irrigation. This can be expressed as:

$$OW_c = IR_j - \left(IR_j - OW\right)\frac{d_c}{d} \quad \text{(Eq. 6.4.1-30)}$$

where

OW_c = overwatering rate for the resuspendable (critical) thickness of soil (m/yr)

and the other parameters were defined in Equations 6.4.1-1, 6.4.1-6 and 6.4.1-28.

6.4.1.4 Surface Soil Erosion

Under natural conditions, the rate of soil removal by erosion, generally, is in approximate equilibrium with the rate of soil development from soil forming processes, and under these conditions, soil depth is relatively constant (Troeh et al. 1980 [DIRS 110012], p. 4). Human activities tend to accelerate the rate of soil removal. The removal of surface soil by erosion would result in the loss of radionuclides attached to the soil particles. The rate of radionuclide removal from surface soils is quantified in ERMYN using a surface soil erosion removal rate constant (λ_e), as introduced in Equation 6.4.1-1. The erosion rate is developed in *Soil-Related Input Parameters for the Biosphere Model* (SNL 2007 [DIRS 179993], Section 6.4), and the surface soil erosion removal rate constant is evaluated as:

$$\lambda_e = \frac{ER}{d \times \rho} \quad \text{(Eq. 6.4.1-31)}$$

where

ER = average annual erosion rate for the surface soil (kg/(m^2 yr))

and the other parameters are defined in Equations 6.4.1-1 and 6.4.1-6.

To calculate the erosion removal rate constant for the resuspendable soil layer, the thickness of surface soil, d, in Equation 6.4.1-31 is replaced with the critical soil thickness, d_c:

$$\lambda_{ec} = \frac{ER_c}{d_c \times \rho} \qquad \text{(Eq. 6.4.1-32)}$$

where

λ_{ec} = average annual soil erosion removal rate constant for the resuspendable soil layer (1/ yr)

ER_c = average annual erosion rate for the resuspendable surface soil layer (kg/(m^2 yr))

and the other parameters are defined in Equation 6.4.1-6.

For the resuspendable soil thickness, the effective removal rate constant $\lambda_{eff,c,i}$ is thus expressed as:

$$\lambda_{eff,c,i} = \lambda_{d,i} + \lambda_{lc,i} + \lambda_{ec} \qquad \text{(Eq. 6.4.1-33)}$$

6.4.2 Air Submodel

The air submodel addresses the transport of radionuclides from contaminated water and soil to the air. Particle transport from soil to air is considered to occur primarily via resuspension. The release of radioactive gases from the soil for species such as radon or carbon dioxide results predominantly from diffusion caused by concentration gradients at the soil-air interface. The transport of radionuclides from water to air also may result from the use of evaporative coolers (for a discussion of the rationale for including this pathway see Appendix D).

6.4.2.1 Resuspended Particles from Surface Soil

Resuspension is the process by which material deposited from the atmosphere onto the ground is subsequently returned to the atmosphere. In ERMYN, radionuclide concentrations in the air are used to estimate the inhalation dose (Section 6.4.8) and crop contamination by the deposition of resuspended particles onto plant surfaces (Section 6.4.3). Radionuclide concentrations in the air are different for inhalation exposure and for particulate deposition on crops, primarily because of the differences in mass loading among environments but also because of the different irrigation duration of the garden and field soils.

For direct deposition on crops, the activity concentration of resuspended particles is linked to the activity concentration in the local surface soil. The relationship between these quantities is expressed as:

$$Ca_{p,i,j} = S\, Cs_{m,i,j} = \frac{S}{\rho_s} Cs_{i,j} \qquad \text{(Eq. 6.4.2-1)}$$

where

$Ca_{p,i,j}$ = crop type-dependent activity concentration of radionuclide i in the air from soil resuspension (Bq/m^3)

$Cs_{m,i,j}$ = crop type-dependent activity concentration of radionuclide i in the soil per unit mass (Bq/kg) (Equation 6.4.1-5)

S = mass concentration of resuspended particles; mass loading (kg/m^3)

$Cs_{i,j}$ = crop type-dependent activity concentration of radionuclide i in the surface soil per unit area (Bq/m^2) (Equation 6.4.1-3)

ρ_s = areal density of surface soil (kg/m^2) (Equation 6.4.1-6).

The mass loading of resuspended particulates, S, (Equation 6.4.2-1), is characteristic of cultivated fields, and is developed based on annual average values (BSC 2006 [DIRS 177101], Section 6.2.5). It should be noted that the above equation implies that an enhancement factor of unity was used for the resuspended activity (i.e., the activity per unit mass of resuspended particulates is the same as that of surface soil). This is appropriate because the mechanical actions of weeding (hoeing), cropping, and water splash will cause the average soil activity to be transferred to the plant. This is in contrast to inhalation of resuspended particles, where the transport mechanisms in different receptor environments may cause the differences between the activity concentrations in soil and that of resuspended particulates (SNL 2007 [179993], Section 6.5).

The radionuclide concentration in soil, $Cs_{m,i,j}$, is the greater of the crop type-specific radionuclide concentrations in the resuspendable layer of soil or in the surface soil (with thickness equal to the tillage depth). The radionuclide concentration in the resuspendable layer of soil is assumed to be at equilibrium, as described in Section 6.4.1.1.

The activity concentration of resuspended particles, used for the assessment of inhalation doses, is calculated for the five environments associated with the human activities and depends on the radionuclide concentration in the surface soil and on the atmospheric mass loading in that environment. In addition, the enhancement factor for the activity concentration of resuspended particulates, $f_{enhance}$, is defined as the ratio of activity concentration of resuspended particles (Bq/kg) to the surface soil activity concentration for a given radionuclide (Bq/kg). The enhancement factor accounts for the fact that the activity concentration of resuspended particulates may be different from that of the soil where they originated. For example, for soil particles contaminated by irrigation water, the contaminant would be adsorbed onto particles in the form of a thin film on the particle surface. The surface coating would result in an increased activity concentration for smaller particles compared to that of larger particles because surface area per unit mass is greater for smaller particles. The enhancement factor is discussed in *Soil-Related Input Parameters for the Biosphere Model* (SNL 2007 [DIRS 179993], Section 6.5).

To account for variation and uncertainty in the characteristics of the RMEI and concentrations of radionuclides in the biosphere, the ERMYN uses a micro-environmental modeling approach to calculate inhalation dose and external exposure. In micro-environmental models, the total exposure environment (i.e., the biosphere) is divided into segments, or environments, with different conditions of exposure to contaminants. The contaminant concentration in the environmental media, time spent exposed to the contaminant, and intake rate or exposure factor (e.g., breathing rate and shielding factor) is determined for each environment, and the total dose is calculated as the sum of the dose from all environments (Mage 1985 [DIRS 162465], pp. 409 and 410). Micro-environmental models are commonly used to evaluate exposure to particulate matter and other contaminants (Duan 1982 [DIRS 162466]; Mage 1985 [DIRS 162465]; Klepeis 1999 [DIRS 160094]). Radionuclide concentrations in the air are calculated as:

$$Ca_{h,i,n} = f_{enhance,n} \; Cs_{m,i,n} \; S_n = f_{enhance,n} \frac{S_n}{\rho_s} Cs_{i,n} \qquad \text{(Eq. 6.4.2-2)}$$

where

$Ca_{h,i,n}$ = activity concentration of radionuclide *i* in the air from soil resuspension for the assessment of human inhalation exposure in environment *n* (Bq/m^3)

$f_{enhance,n}$ = enhancement factor for the activity concentration of resuspended particulates in environment *n* (dimensionless)

S_n = concentration of total resuspended particulates (mass loading) for evaluation of inhalation exposure for environment *n* (kg/m^3)

n = index of the environments (see below)

$Cs_{m,i,n}$ = environment-dependent activity concentration of radionuclide *i* in the soil per unit mass (Bq/kg), calculated using Equation 6.4.1-5 with the crop indices (*j*) replaced with the environment indices (*n*), as explained below

$Cs_{i,n}$ = environment-dependent activity concentration of radionuclide *i* in the surface soil per unit area (Bq/m^2) (calculated using Equation 6.4.1-3 with the crop indices (*j*) replaced with the environment indices (*n*), as explained below)

and the other parameter is defined in Equation 6.4.2-1.

Five environments associated with different human activities are considered in the ERMYN, four in the contaminated area: active outdoors ($n = 1$), inactive outdoors ($n = 2$), active indoors ($n = 3$), asleep indoors ($n = 4$), and outside of the contaminated area ($n = 5$). The activity concentration in the air outside the contaminated area is zero. These mutually exclusive environments represent behavioral and environmental combinations of conditions under which the receptor would receive a substantially different inhalation and external exposure (BSC 2005 [DIRS 172827], Section 6.2).

1. **Active Outdoors**—This environment is representative of conditions that occur when a person is outdoors in the contaminated environment conducting dust-generating activities. It encompasses potentially contaminated locations outdoors where the RMEI would conduct activities that would resuspend soil, including dust-generating

activities while working (e.g., plowing, excavating, livestock operations), driving on unpaved roads, and performing other outdoor recreational activities (e.g., gardening, landscaping, riding horses, riding motorbikes, and walking on uncompacted soil). Because dust concentrations decrease rapidly after dust-disturbing activities cease (Pinnick et al. 1985 [DIRS 159577], pp. 103 and 104), this category is limited to conditions during and shortly after dust-generating activities.

2. **Inactive Outdoors**—This environment includes outdoor locations within potentially contaminated areas where the RMEI is not conducting soil-disturbing activities. In this environment, the RMEI would spend time outdoors engaged in activities that would not resuspend soil (e.g., sitting, swimming, walking on turf or compacted/covered surfaces, driving on paved roads, barbecuing, and equipment maintenance) in areas where radionuclides may be present. This environment also includes time spent commuting within the contaminated area because the major roads in Amargosa Valley are paved.

3. **Active Indoors**—This environment includes locations indoors in areas that may contain radionuclides where the RMEI would spend time active, including working. This environment is representative of conditions indoors within the contaminated area when people are at home or at a place of business, including conditions when they are sedentary or active.

4. **Asleep (Inactive) Indoors**—This environment includes locations where the RMEI would spend time sleeping indoors in areas that may contain radionuclides.

5. **Away from Potentially Contaminated Area**—This environment encompasses locations that would not contain radionuclides released from the repository, including commuting routes to work as well as work and other locations outside of contaminated areas.

When different values of irrigation duration are used in the surface soil submodel for field and garden crops, radionuclide concentration in surface soil is not the same for all irrigated land. Garden crop irrigation was developed in the context of home gardens, so the resulting radionuclide concentration in soil is appropriate for representing the exposure conditions while indoors and inactive outdoors (Assumption 5). Field crop irrigation is representative of work conditions and it is used for estimating inhalation and external exposure of the receptor while in the active outdoor environment (Assumption 5). The crop type dependent radionuclide concentrations in the surface soil correspond to the following environment-dependent radionuclide concentrations in the surface soil: n = 1 (active outdoors) corresponds to any field crop, e.g., j = 5 (forage); n = 2, 3, and 4 correspond to any garden crops, e.g., j = 1 (leafy vegetables).

In Equation 6.4.2-2, the receptor environment-dependent radionuclide concentration in soil, $Cs_{m,i,n}$, is the greater of the radionuclide concentrations in the resuspendable layer of soil or in the surface soil (with thickness equal to the tillage depth). As noted before, the radionuclide concentration in the resuspendable layer of soil is assumed to be at equilibrium.

The mass concentration of resuspended particulates in the air, S_n, depends on the environment and the type of activities conducted there. Values of mass loading range over several orders of magnitude, from 10^{-8} kg/m^3 for asleep indoors to 10^{-5} kg/m^3 for dusty outdoor environments (BSC 2006 [DIRS 177101], Section 7.1).

6.4.2.2 Aerosols from Evaporative Cooler Operation

About 73% of the residents in Amargosa Valley used evaporative coolers during the year 1997 (DOE 1997 [DIRS 100332], p. 20), and these coolers might transfer water-borne contaminants to the indoor air. Thus, ERMYN must include an estimate of the radionuclide concentrations in indoor air when evaporative coolers are in operation so that the radiation dose to the human receptor inhaling the contaminated air can be evaluated. A search of the scientific literature did not find environmental assessments that considered this transport process from water to indoor air. Rather than ignore the process, as had been done in previous assessments, a model was developed to incorporate the process into ERMYN. Based on how evaporative coolers operate and the conservation of radioactivity (i.e., activity transferred to air is equal to the loss of activity from water), the equation $(Ca_{e,i})(F_{air}) = (f_{evap})(M_{water})(Cw_i)$ is rearranged, and radionuclide concentrations in indoor air are estimated as:

$$Ca_{e,i} = f_{evap} \frac{M_{water}}{F_{air}} Cw_i \qquad \text{(Eq. 6.4.2-3)}$$

where

$Ca_{e,i}$	=	activity concentration of radionuclide i in the air resulting from the operation of an evaporative cooler (Bq/m^3)
f_{evap}	=	fraction of radionuclides in water transferred to indoor air (dimensionless)
M_{water}	=	water evaporation rate (water use) for an evaporative cooler (m^3/h)
F_{air}	=	air flow rate for an evaporative cooler (m^3/h)
Cw_i	=	activity concentration of radionuclide i in the groundwater (Bq/m^3).

The fraction of radionuclides that remain in the reservoir, bleed-off water, or in the pads of the evaporative cooler are not further modeled because the associated exposure pathways do not contribute significantly to the RMEI dose, as shown in Appendix D. Evaporation and air flow rates are estimated based on specifications of residential evaporative cooling units. The typical evaporation rate is about 20 L/h, and typical air flow rates range from 2,000 to 10,000 m^3/h (BSC 2004 [DIRS 169672], Section 6.5). The fraction of radionuclides transferred from the water to the indoor air is an important parameter that is not available in the literature, but the theoretical range is from 0 to 1 (BSC 2004 [DIRS 169672], Section 6.5).

Radon, primarily ^{222}Rn, released from evaporative coolers is not considered in this submodel, and justification is provided in Section 7.4.3.1. The calculation of activity concentrations in the air resulting from evaporative coolers does not include consideration of radionuclide buildup in the indoor air. This is because the air flow associated with the use of these coolers would result in dilution and elimination of the airborne radionuclides (Assumption 11).

6.4.2.3 Radon Exhalation from Surface Soil

The inhalation of radon decay products is a major, and in many cases, the dominant dose contributor of internal radiation when radium isotopes are present in the soil (Yu et al. 2001 [DIRS 159465], p. C-3). ^{222}Rn, a decay product of ^{226}Ra (a primary radionuclide; Table 6.3-7), is the most common radon isotope. Other radon isotopes, such as ^{220}Rn and ^{219}Rn, are typically less important. The dose contribution from ^{220}Rn is evaluated in Section 7.4.3.1 and, as the result of the evaluation, is not included in the biosphere model. The dose contribution from inhalation of ^{219}Rn decay products is usually neglected in the radiological assessments because of the very short half-life of this radionuclide (3.9 s), which inhibits exhalation of this radionuclide from the soil. Thus, ^{222}Rn is the only radon isotope considered in ERMYN. Concentrations of ^{222}Rn were calculated separately for indoor and outdoor air. The radon level outdoors was estimated from the calculated concentration of ^{226}Ra in the surface soil and the relationship between the concentration of ^{226}Ra in the soil and the corresponding concentration of ^{222}Rn in the air. This relationship is called the release factor. The release factor used in the biosphere model is based on a global average value of the concentration ratio of ^{222}Rn activity in air to ^{226}Ra in soil (BSC 2004 [DIRS 169672], Section 6.6.1). Based on the U.S. Geological Survey assessment (EPA 2007 [DIRS 180709]) the geologic radon potential of Southern Nevada is low to moderate. Therefore, using the average value did not result in an underestimation of risk to the RMEI.

Outdoor Radon Concentration—The concentration of radon outdoors is estimated from the amount of radon exhaled from the soil. A screening calculation, based on the concentration ratio (i.e., the release factor of ^{222}Rn) of ^{222}Rn activity in the air to ^{226}Ra activity in the soil (NCRP 1999 [DIRS 155894], Section 4.3.6) is used to estimate the concentration of radon in outdoor air as:

$$Ca_{g,Rn-222,n=1\&2} = f_{m,Rn-222}\ Cs_{m,Ra-226} \qquad \text{(Eq. 6.4.2-4)}$$

where

$Ca_{g,Rn\text{-}222,n=1\&2}$ = activity concentration of ^{222}Rn in outdoor air (n = 1 and 2 for active outdoor and inactive outdoor environments; environments are defined following Equation 6.4.2-2) (Bq/m^3)

$f_{m,\ Rn\text{-}222}$ = concentration ratio of ^{222}Rn activity in the air to ^{226}Ra activity in soil (radon release factor) (kg/m^3)

$Cs_{m,Ra\text{-}226}$ = activity concentration of ^{226}Ra in surface soil (Bq/kg).

Using an average outdoor ^{222}Rn concentration value of 10 Bq/m^3 and an average concentration of naturally occurring ^{226}Ra in the soil of 40 Bq/kg (NCRP 1999 [DIRS 155894], Section 4.3.6), the release factor for ^{222}Rn would be 0.25 (Bq/m^3)/(Bq/kg). This value is large compared to the resuspension contribution for ^{226}Ra. For example, using a typical mass loading of about 1×10^{-8} to 1×10^{-6} kg/m^3 (Table 6.6-3) and a ^{226}Ra concentration in the soil of 1 Bq/kg, the

^{226}Ra concentration in the air due to resuspension would be 1×10^{-8} to 1×10^{-6} Bq/m^3, whereas the ^{222}Rn concentration in the air would be 0.25 Bq/m^3.

Indoor Radon Concentration—The method for calculating the indoor concentration of radon, taken from RESRAD (Yu et al. 2001 [DIRS 159465], Equation C.12), was developed for a single-story house built on contaminated soil, assuming steady-state conditions between the rate of radon entry into the house and the rate of removal. The main sources of indoor radon are the soil beneath the house and the entry of outdoor air. The surface soil beneath the house contains the concentration of ^{226}Ra, consistent with the garden use of the irrigated land (Assumption 5). Indoor radon concentration is expressed as:

$$Ca_{g,Rn-222,n=3\&4} = \frac{J_{indoor}}{v\ H} + Ca_{g,Rn-222,n=1\&2} \qquad \text{(Eq. 6.4.2-5)}$$

where

$Ca_{g,Rn\text{-}222,n=3\&4}$ = activity concentration of ^{222}Rn in indoor air ($n = 3$ and 4 for active indoor and asleep indoor; defined in Equation 6.4.2-2) (Bq/m^3)

J_{indoor} = radon flux density from the house floor (Bq/(m^2 s))

H = interior wall height of the house (m)

v = house ventilation rate, or air exchange rate (1/s). This parameter had two values: a normal rate (v_n) for the conditions when evaporative cooling system is not operating and a different rate used when evaporative coolers are in operation (v_e)

and the other parameters are defined in Equation 6.4.2-4.

The radon flux density from the floor of the house can be expressed as a proportion of the total radon flux density from contaminated outdoor soil as:

$$J_{indoor} = f_{house} \times J_{outdoor} \qquad \text{(Eq. 6.4.2-6)}$$

where

$J_{outdoor}$ = radon flux density from outdoor contaminated soil (Bq/(m^2 s))

f_{house} = fraction of radon released into a house from soil beneath the house (dimensionless).

By combining Equations 6.4.2-5 and 6.4.2-6, the indoor radon concentration for times when evaporative cooling system is not operating can be calculated as:

$$Ca_{g,\,Rn-222,n=3\&4} = Ca_{g,\,Rn-222,n=1\&2}\left(\frac{f_{house}}{v_n\ \ H}\frac{J_{outdoor}}{Ca_{g,Rn-222,n=1\&2}}+1\right)$$
$$= Ca_{g,\,Rn-222,n=1\&2}\left(\frac{f_{house}}{CF_{Rn-222}\ v_n\ \ H}+1\right) \qquad \text{(Eq. 6.4.2-7)}$$
$$= Ca_{g,\,Rn-222,n=1\&2}\ \ IF_{n,Rn-222}$$

where

$CF_{Rn\text{-}222}$ = ratio of ^{222}Rn concentration in outdoor air to ^{222}Rn flux density from outdoor soil (s/m)

$IF_{n,Rn\text{-}222}$ = indoor ^{222}Rn increase factor for normal ventilation rate (dimensionless)

and the other parameters are defined in Equations 6.4.2-5, and 6.4.2-6.

During operation of an evaporative cooler, the increase in indoor radon concentration relative to the outdoor concentration would be relatively low because of the high ventilation rate. The indoor radon concentration during that period can be estimated by:

$$Ca_{g,\,Rn-222,e} = Ca_{g,\,Rn-222,n=1\&2}\left(\frac{f_{house}}{CF_{Rn-222}\ v_e\ \ H}+1\right) \qquad \text{(Eq. 6.4.2-8)}$$
$$= Ca_{g,\,Rn-222,n=1\&2}\ \ IF_{e,Rn-222}$$

where

$Ca_{g,Rn\text{-}222,e}$ = activity concentration of ^{222}Rn in indoor air during evaporative cooler operation (Bq/m^3)

$IF_{e,Rn\text{-}222}$ = indoor ^{222}Rn increase factor for a high ventilation rate during evaporative cooler operation (dimensionless)

and the other parameters are defined in Equation 6.4.2-5 and 6.4.2-6.

Radon enters the indoor space through cracks and other openings in the floor and foundations. The fraction of radon released into a house from soil would depend on the type and number of such openings in the floor in the house (typical range of 0.10 to 0.25; Table 6.6-3). The fraction retained in the house would primarily depend on the ventilation rate. Ventilation rates would depend on ambient temperatures because during cold weather, residents would be expected to close up their houses to retain heat, but during warmer weather, they would be expected to open their houses to allow natural or forced ventilation. Natural ventilation rates range from about 0.3 to 3 air exchanges per hour. However, when evaporative coolers are in operation, house air exchange rates range from 1 to 30 exchanges per hour (BSC 2004 [DIRS 169672], Section 6.6.2). Similar to the radon release factor, $f_{m,\ Rn\text{-}222}$, the ratio of the concentration of ^{222}Rn in outdoor air to ^{222}Rn flux density from radium contaminated outdoor soil is based on a global average value, about 300 s/m (10 Bq/m^3 to 0.033 Bq/(m^2 s)) (BSC 2004 [DIRS 169672], Section 6.6). Because of evaporative coolers, indoor radon concentrations must be considered separately when the cooler is turned on or off, as discussed in Section 6.4.8.4.

The radon contribution from evaporative coolers and household water use is excluded from ERMYN, as justified in Section 7.4.3.1.

6.4.3 Plant Submodel

If groundwater is contaminated, irrigated crops become contaminated by the deposition of radionuclides onto the above-ground plant parts and through root uptake of radionuclides from the soil. The plant submodel includes both processes.

Radionuclides would be deposited on plant surfaces from contaminated irrigation water and from resuspension of contaminated surface soil. Some of the radionuclides intercepted by crops would be retained on, or in, the plant and some would be removed by weathering. Contamination of plants by direct deposition would be important for elements that have low rates of root uptake (e.g., actinides: plutonium, neptunium, and americium). For environmentally mobile elements (e.g., technetium, iodine, and chlorine), root uptake usually is more important than direct deposition (see values of transfer factors; Table 6.6-3). Radionuclide concentrations in the surface soil are considered in the surface soil submodel (Section 6.4.1), and radionuclide concentrations in the air are considered in the air submodel (Section 6.4.2).

Soil splash due to irrigation or rain is an additional mechanism used in some biosphere models (e.g., BIOMASS 2003 [DIRS 168563], Section C3.5.2). However, the process of soil splash is considered equivalent to direct deposition of resuspended particles on plant surfaces (Section 6.4.3.3). Therefore, soil splash is not considered separately in the ERMYN. Furthermore, none of the published biosphere models considers dust deposition combined with irrigation or rain splash. For model validation, this ACM 4 (direct deposition of airborne particulates; Section 6.3.3) is compared with the methods used in the plant submodel (Section 7.4.4.3).

Based on the typical approach used in assessments of environmental radionuclide releases, ERMYN includes four types of crops consumed by humans: leafy vegetables, other vegetables, fruit, and grain. Leafy vegetables include plants such as lettuce, spinach, and cabbage, the edible portions of which (i.e., the leaves) grow aboveground, are exposed, and can be eaten directly with little processing (Napier et al. 1988 [DIRS 157927], Section 4.7.4). Other vegetables include root crops (e.g., carrots and potatoes) and crops, like legumes, where the edible parts are unlikely to be exposed directly (e.g., peas and beans that grow inside pods). Fruits include a variety of products such as berries, grapes, currants, melons, pomes (e.g., apples and pears), and drupes (e.g., peaches, plums, and cherries). Grains include seed-producing crops such as wheat, corn, and barley.

In addition to crops consumed by humans, crops consumed by animals are also considered in the plant submodel. Fresh forage (e.g., alfalfa) consumed by beef cattle and dairy cows, and grain fed to poultry and egg-laying hens are considered (see Assumption 8 about animal diets). The mathematical submodel presented in this section applies to all types of crops, but some input parameters are crop-type specific.

The plant submodel does not include radionuclide decay following harvest because the radionuclides of interest are long-lived and decay little during short-term storage. The activity concentration in crops is calculated for the wet weight of the edible plant portions. The three environmental transport processes (roots, water, and dust) are considered independent, and the total activity concentration in crops is the sum of the three contributions, estimated as:

$$Cp_{i,j} = Cp_{root,i,j} + Cp_{water,i,j} + Cp_{dust,i,j} \qquad \text{(Eq. 6.4.3-1)}$$

where

$Cp_{i,j}$ = activity concentration of radionuclide *i* in crop type j (Bq/kg $_{wet}$)

j = crop-type index; *j* = 1 for leafy vegetables, 2 for other vegetables, 3 for fruit, 4 for grain (consumed by humans and poultry), and 5 for fresh forage feed (used for beef cattle and dairy cows)

$Cp_{root,i,j}$ = activity concentration of radionuclide *i* in crop type *j* contributed from plant root uptake (Bq/kg $_{wet}$)

$Cp_{water,i,j}$ = activity concentration of radionuclide *i* in crop type *j* contributed from direct deposition on crop leaves due to interception of contaminated irrigation water (Bq/kg $_{wet}$)

$Cp_{dust,i,j}$ = activity concentration of radionuclide *i* in crop type *j* contributed from the direct deposition on crop leaves due to interception of resuspended particles from contaminated soil (Bq/kg $_{wet}$).

6.4.3.1 Root Uptake

The radionuclides from the contaminated irrigation water would be transferred to the surface soil and, subsequently, to the crops through root uptake. The extent to which plant roots absorb radionuclides from the soil depends on the physiology of the plant, the properties of the soil, and the characteristics of the radionuclide. The uptake of radionuclides by plants usually is considered proportional to radionuclide concentrations in the soil.

The surface soil submodel is used to calculate radionuclide concentrations in the surface layer of the soil. It is assumed that all roots remain in the surface layer, which maximizes the uptake of radionuclides in the submodel (Assumption 7). This approach eliminates the need to determine the fraction of roots in the surface soil. If radionuclides are taken up by the plant roots, the contamination will be internal to the plants and not subject to removal by weathering or food processing. The activity concentration of radionuclides in crops from root uptake is estimated as:

$$Cp_{root,i,j} = Cs_{m,i}\ F_{s \to p,i,j}\ DW_j \qquad \text{(Eq. 6.4.3-2)}$$

where

$Cs_{m,i,j}$ = crop type-dependent activity concentration of radionuclide i in surface soil (Bq/kg $_{\text{dry soil}}$)

$F_{s \rightarrow p,i,j}$ = soil-to-plant transfer factor for radionuclide i and crop type j (Bq/kg $_{\text{dry plant}}$ per Bq/kg $_{\text{dry soil}}$)

DW_j = dry-to-wet weight ratio for edible parts of crop type j (kg $_{\text{dry plant}}$ /kg $_{\text{wet plant}}$).

The soil-to-plant transfer factor is defined as the ratio of activity concentration of a given radionuclide in dry soil to the activity concentration in dry plants. Observed values of transfer factors for a given element vary widely, mainly because of different soils, vegetation types, and environmental conditions (UNSCEAR 2000 [DIRS 158644], p. 39). Because the values of transfer factors represent crop types, rather than the individual crop species, there is uncertainty associated with this parameter. The values of element-specific and crop-type-specific soil-to-plant transfer factors are developed in *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2004 [DIRS 169672], Section 6.2), which also includes a more detailed discussion of the transfer factors. The dry-to-wet weight ratio is represented by the fraction of dry weight of foodstuff in the total (wet) weight of the foodstuff. Typical values range from a few percent for leafy vegetables to about 90% for grain (BSC 2004 [DIRS 169673], Section 6.2).

6.4.3.2 Uptake Following Foliar Interception of Irrigation Water

Radionuclide transfer to plants through foliar uptake involves three processes: interception, translocation, and retention (IAEA 1994 [DIRS 100458], Section 2). Interception is the process by which radionuclide contaminants in the atmosphere are deposited on plant surfaces in wet (irrigation water) or dry (resuspended soil) forms. The plant submodel includes two mechanisms of radionuclide uptake from the deposition of contaminants on plants: leaf uptake following interception of irrigation water (this section) and leaf uptake following interception of resuspended particles (Section 6.4.3.3).

Translocation is the process by which chemical elements, initially deposited on the leaf surface, move from the site of deposition to the edible parts of the plant, including parts not directly affected by deposition. The fraction of radionuclides translocated depends on the plant species, the chemical and physical forms of the radionuclides, the stage of plant development, and weathering conditions. In this submodel, translocation refers to that portion of activity initially deposited on a plant surface that contributes to activity in edible parts of the plant, regardless of the external or internal nature of contamination.

Retention is the process in which a fraction of the radionuclides initially intercepted by foliage is detached from plant surfaces and deposited on the ground and a remaining fraction is retained by a plant. The radionuclide detachment from plants occurs because of weathering and other field losses. In ERMYN, the calculation of activity deposited on leaves is based on daily average irrigation rates per crop type, and is carried out within the plant submodel. The activity deposited on the ground is calculated based on the average annual irrigation rate for garden and field crops, which incorporate crop rotation and some land use changes, and is carried out within the soil submodel. The annual average and daily irrigation rates are linked, as the activity deposited on the ground is not depleted by foliar deposition (Assumption 6).

In the arid to semi-arid region at Yucca Mountain, crops must be irrigated frequently. Therefore, deposition of radionuclides on plant surfaces by irrigation is modeled as a quasi continuous process throughout the plant growing season. Radionuclide concentrations in crops due to leaf uptake from contaminated irrigation water sprayed on plants is expressed as:

$$Cp_{water,i,j} = \frac{Dw_{i,j}\ f_{o,j}\ Rw_j\ T_j}{\lambda_w\ Y_j}\left(1 - e^{-\lambda_w\ t_{g,j}}\right) \qquad \text{(Eq. 6.4.3-3)}$$

where

$Dw_{i,j}$ = deposition rate of radionuclide *i* due to application of irrigation water on crop type *j* (Bq/(m^2 d))

$f_{o,j}$ = fraction of irrigation applied using overhead methods for plant type *j* (dimensionless)

Rw_j = interception fraction of irrigation water for crop type *j* (dimensionless)

T_j = translocation factor for crop type *j* (dimensionless)

λ_w = weathering constant (1/d), which can be calculated from weathering half-life (T_w in units of d) by $\lambda_w = \ln(2) / T_w$

$t_{g,j}$ = crop growing time for crop type *j* (d)

Y_j = crop yield or wet biomass for crop type *j* (kg$_{\text{wet weight}}$/m^2).

For overhead irrigation (i.e., sprinkler or spray), the rate of radionuclide deposition onto the crops, $Dw_{i,j}$, is the product of the irrigation rate and the radionuclide concentration in the water. In this submodel, the radionuclide deposition rate from irrigation water is estimated as:

$$Dw_{i,j} = Cw_i\ IRD_j \qquad \text{(Eq. 6.4.3-4)}$$

where

IRD_j = daily average irrigation rate for crop type *j* during the growing season (m/d)

and the other parameter is defined in Equation 6.4.1-1.

The daily irrigation rates for crops vary during the growing season; therefore, a daily average rate over the entire growing season is used in the plant submodel. As noted previously, the daily average irrigation rate for a crop (Equation 6.4.3-4) and the annual average irrigation rate on land (Equation 6.4.1-1) serve different purposes. The daily average irrigation rate for a crop type is used to calculate activity deposited on the crop leaves in the plant submodel. The annual average irrigation rate is used to calculate the activity deposited on surface soil. The two irrigation rates are determined based on overwatering requirements, precipitation, and evapotranspiration in *Agricultural and Environmental Input Parameters for the Biosphere Model* (BSC 2004 [DIRS 169673], Section 6.5).

The fraction of water applied using overhead irrigation methods, $f_{o,j,}$ is not considered in other biosphere models. However, the rate of contaminant deposition on leaves depends on how irrigation water is applied, and some irrigation methods (e.g., flood and drip irrigation) that cause little foliar deposition are used in the Amargosa Valley (BSC 2004 [DIRS 169673], Section 6.3). Thus, this parameter, which is crop-type specific with values ranging from about 0.25 to one, is used to incorporate variation related to site-specific irrigation methods (BSC 2004 [DIRS 169673], Section 6.3).

The interception fraction for irrigation water, Rw_j, quantifies the initial fraction of radionuclides deposited on plant surfaces following irrigation with contaminated water. The possible range for this parameter is 0 to 1. Values for the irrigation interception fraction can be determined using empirical equations or values from the literature. In this submodel, the interception fraction is estimated using an empirical equation (Hoffman et al. 1989 [DIRS 124110], Section 3) based on crop biomass and the amount and intensity of precipitation and irrigation. The empirical equation was developed using multiple regression analysis on data from experiments where simulated rain was applied to three types of plants: clover, fescue, and mixed grasses. The simulated rain contained five radionuclides: ^{131}I, ^{7}Be, ^{141}Ce, ^{95}Nb, and ^{85}Sr. ^{131}I and ^{7}Be were applied in the form of dissolved species in irrigation water, but the remaining radionuclides were used as tracers in the form of insoluble polystyrene microspheres (Hoffman et al. 1992 [DIRS 124114], pp. 3,313 and 3,314). Because the majority of radioactive contaminants in the Yucca Mountain groundwater would be soluble, the results of the ^{131}I and ^{7}Be experiments are of interest for the groundwater scenario.

The experiments indicate that anionic ^{131}I, present as periodate (IO_4^-), is essentially removed with water after the vegetation surface became saturated, and that cationic $^{7}Be^{2+}$ is adsorbed to, or settles out on, the plant surfaces. The discrepancy between the behavior of the anionic and cationic species is consistent with a negative charge on the plant surface. Hoffman et al. (1995 [DIRS 124120]) show similar experimental results involving six soluble radionuclides, including ^{51}Cr (as CrO_4^{2-}), ^{85}Sr (as Sr^{2+}), ^{109}Cd (as Cd^{2+}), ^{7}Be (as Be^{2+}), ^{131}I (as I^-), and ^{35}S (as SO_4^{2-}). The results indicate that ^{7}Be and ^{109}Cd have the highest, and comparable in value, interception fractions, while ^{131}I has the lowest.

The empirical equation for the interception fraction, *Rw*, from Hoffman et al. (1989 [DIRS 124110], Section 3), which is based on the results of experiments with ^{7}Be and ^{131}I, is expressed as:

$$Rw_j = K_1 \, DB_j^{\,K_2} \, IA_j^{\,K_3} \, I^{K_4} \qquad \text{(Eq. 6.4.3-5)}$$

where

Rw_j = interception fraction of irrigation water for crop type j (dimensionless)

$K_1, K_2, K_3,$ *and* K_4	=	empirical constants (K_1 is in units of $(\mathrm{kg/m^2})^{-K2}$ $(\mathrm{mm})^{-K3}$ $(\mathrm{cm/h})^{-K4}$, and K_2,, K_3,, *and* K_4 are dimensionless)
DB_j	=	standing biomass of crop type *j* (in units of $\mathrm{kg}_{\text{dry weight}}/\mathrm{m}^2$)
IA_j	=	amount of irrigation per application event for crop type *j* (value in units of mm)
I	=	irrigation intensity (value in units of cm/h).

Because this is a regression equation from experimental data, values for the input parameters must be used in the units specified above. The empirical constants in Equation 6.4.3-5, developed based on given parameter units for standing biomass, irrigation amount, and irrigation intensity, depend on the plant type and contaminant form. The recommended values (Hoffman et al. (1989 [DIRS 124110], Table 3.1) are:

K_1 = 2.29	for beryllium (Be^+);	K_1 = 1.54	for iodine (I^-) (values for clover)
K_2 = 0.695	for beryllium (Be^+);	K_2 = 0.697	for iodine (I^-)
K_3 = –0.29	for beryllium (Be^+);	K_3 = –0.909	for iodine (I^-)
K_4 = –0.341	for beryllium (Be^+);	K_4 = –0.049	for iodine (I^-).

Because radionuclides in the groundwater may be present as different species, the empirical constants cannot be determined unequivocally. Therefore, ERMYN uses a simplified approach based on the empirical constants for beryllium. This approach results in the highest values of the irrigation interception fraction because the experimental results indicate that beryllium cations, Be^{2+}, in the simulated rain water have the highest interception fraction among the species tested (Hoffman et al. (1989 [DIRS 124110]; Hoffman et al. (1995 [DIRS 124120]).

The standing biomass of the growing crop, *DB*, is a crop type-specific parameter that represents the capacity of the plants to intercept irrigation water. A typical range for dry biomass is 0.1 to 1.0 kg/m^2 (BSC 2004 [DIRS 169673], Section 6.1).

The amount of irrigation per irrigation event, *IA*, in the experiment ranged from 1 to 30 mm, while the experimental irrigation (or rain) intensity, *I*, ranged from 1.4 to 12.2 cm/h (Hoffman et al. 1995 [DIRS 124114], pp. 3,313 and 3,314). Some parameter values representative of crop irrigation in arid to semi-arid environments exceed the ranges used in these experiments (BSC 2004 [DIRS 169673], Section 6.7). Therefore, a numerical evaluation is used to ensure that the use of this equation is valid (Section 7.4.4.2).

The translocation factor, T_j (Equation 6.4.3-3), is the ratio of the activity on 1 m^2 of edible plant parts at harvest (Bq/m^2) to the activity retained on 1 m^2 of foliage at the time of deposition (Bq/m^2) (IAEA 1994 [DIRS 100458], p. 12). This factor is equal to the fraction of a chemical element initially deposited on the leaf surface that is retained and translocated to the edible plant parts. The possible range for this parameter is zero to one (BSC 2004 [DIRS 169672], Section 6.2).

Radionuclide concentrations on vegetation may be reduced by a variety of processes (e.g., the actions of wind, washout, surface abrasion, volatilization, and growth of new tissue) other than by radioactive decay. These processes can be described by a first order removal submodel with an aggregated weathering removal rate constant or weathering rate (IAEA 2001 [DIRS 158519], Section 5.1.1.2). Similar to radionuclide half-life and decay constants, the relationship between the weathering half-life, T_w, and the weathering removal rate constant, λ_w, is $T_w = \ln 2/\lambda_w$. The weathering half-life describes the time that it would take for the amount of contaminant deposited on a plant to be reduced to one-half of the initial value. The range of values for the weathering half-life reported in the literature is 6 to 56 d (Till and Meyer 1983 [DIRS 101895], p. 5-36). A typically used value for the weathering half-life is 14 d (BSC 2004 [DIRS 169672], Section 6.2.2.3). The weathering half-life may depend on the plant type and the radionuclide (EPRI 2002 [DIRS 158069], Tables 8-9 to 8-24); however, this dependence usually is not included in biosphere models.

The crop growing time, $t_{g,j}$ depends on the crop type and climatic conditions (BSC 2004 [DIRS 169673], Section 6.4). The crop growing time and weathering rate are used in the exponential term in Equation 6.4.3-3. Because the typical value of the weathering half-life is 14 d, the system is considered to reach equilibrium after about three weathering half-lives, a period typically shorter than the crop growing time. Therefore, calculations of activity concentration in crops resulting from the foliar interception of contaminant usually are insensitive to the value of the crop growing time.

The wet yield of crops, Y_j, is used to describe the mass of edible plant parts grown per unit area of farmland. This is a crop type-specific parameter. The range of crop yields for agricultural and garden crops typically grown in southern Nevada is about 0.6 kg/m^2 for grain to about 4 kg/m^2 for other vegetables (BSC 2004 [DIRS 169673], Section 6.11).

6.4.3.3 Uptake by Foliar Interception of Airborne Particulates

The other environmental transport pathway leading to radionuclide contamination of plant surfaces is deposition of resuspended soil, particularly on foliar surfaces. The mathematical representation of this process is similar to that used to represent plant uptake by foliar interception of irrigation water (Equation 6.4.3-3). The radionuclide concentration in crops contributed from uptake by foliar interception of airborne particulates is expressed as:

$$Cp_{dust,\,i,j} = \frac{Da_i \, Ra_j \, T_j}{\lambda_w \, Y_j}\left(1 - e^{-\lambda_w \, t_{g,j}}\right) \quad \text{(Eq. 6.4.3-6)}$$

where

Da_i = deposition rate of radionuclide i with resuspended particulates (Bq/(m^2 d))

Ra_j = interception fraction for airborne particulates for crop type j (dimensionless); Equation 6.4.3-8

and the other parameters are defined in Equations 6.4.3-1 and 6.4.3-3.

The deposition rate of contaminated airborne particles, Da_i, quantifies the combined effect of contaminant removal from the atmosphere by several processes, such as gravitational settling, diffusion, and turbulent transport. The deposition rate, which can be derived by letting a uniform volumetric activity fall with an average velocity representative of the assembly of particulates for a defined period of time, is mathematically represented as:

$$Da_i = 8.64 \times 10^4 \, Ca_{p,i,j} V_d \quad \text{(Eq. 6.4.3-7)}$$

where

$Ca_{p,i,j}$ = activity concentration of radionuclide i in the air used for evaluation of activity deposition on crops (Bq/m^3), Equation 6.4.2-1

V_d = dry deposition velocity for airborne particulates (m/s)

8.64×10^4 = unit conversion factor (s/d).

The dry deposition velocity for airborne particulates, V_d, is a function of particle size and the conditions in the atmospheric boundary layer near the soil surface. For climatic conditions in the Amargosa Valley, the appropriate velocity ranges from 5×10^{-4} to 3×10^{-2} m/s (BSC 2004 [DIRS 169672], Section 6.2.2.1).

The interception fraction for airborne particulates, Ra_j, quantifies the initial fractional deposition of radionuclides on plant surfaces from dry deposition. This parameter is crop-type dependent with a range from zero to one. The value of this parameter can be selected from the literature or calculated using an empirical formula. An empirical formula, selected to estimate the value of the interception fraction for airborne particulates, is:

$$Ra_j = 1.0 - e^{-a_j \, DB_j} \quad \text{(Eq. 6.4.3-8)}$$

where

a_j = an empirical factor for crop type j (m^2/kg$_{\text{dry biomass}}$)

and the other parameters are defined in Equations 6.4.3-5 and 6.4.3-6.

This empirical equation, including the values of the empirical factor is adopted from the GENII model. The recommended values for this factor are 2.9 for leafy vegetables, fresh forage feed, and grain; and 3.6 for root, other vegetables, and fruit (Napier et al. 1988 [DIRS 157927], p. 4.69; Napier et al. 2006 [DIRS 177331], Section 9.4.1.4). This empirical formula is modified to use dry biomass (BSC 2004 [DIRS 169673], Section 6.1) rather than wet standing biomass of growing vegetation times the dry-to-wet biomass ratio (Section 7.3.3.3).

6.4.4 Animal Submodel

The animal food chain involves the transfer of radionuclides from animal feed, water, and soil to animal products, which are subsequently consumed by the receptor. In this submodel, four animal food categories, commonly used in radiological assessments, are modeled: meat, poultry, milk, and eggs (see references in Section 7.1.3) (Assumption 9). The regional food consumption survey (DOE 1997 [DIRS 100332]), the basis for calculating consumption rates of locally produced animal products in the Amargosa Valley (BSC 2005 [DIRS 172827], Section 6.4), also includes these four categories. This submodel does not consider the inhalation of contaminated air by animals (Section 7.4.5).

Beef is the representative animal product for all meat (including beef, pork, wild game, and other meat; Assumption 9). To incorporate the use of wild and natural land and water (FEP 2.4.08.00.0A), consumption rates for local game were obtained from the Amargosa Valley food consumption survey (DOE 1997 [DIRS 100332]). The consumption rate for meat is then calculated by combining the consumption rates for wild game and all other meats (BSC 2005 [DIRS 172827], Section 6.4.2). This is done because game animals could eat crops from irrigated farmlands and drink from irrigation canals and fish ponds. Milk from cows is the representative milk product, chickens are the representative poultry, and chicken eggs are the representative type of eggs (Assumption 9).

Beef cattle and dairy cows are raised using locally grown fresh forage, and poultry and laying hens are fed locally grown grain (Assumption 8). Animals drink contaminated groundwater. Radionuclide concentrations in the soil consumed by animals are based on the long-term concentration obtained using the annual average irrigation rate for field crops (Section 6.4.1). Radionuclide decay is not considered in the animal submodel because of the long half-life of the primary radionuclides (Table 6.3-7).

Radionuclide concentrations in animal products are calculated based on a media equilibrium model that uses transfer coefficients to relate the daily radionuclide intake by animals to radionuclide concentrations in animal products. The transfer coefficient represents the fraction of daily radionuclide intake (Bq/d) that transfers into the animal product (based on mass, Bq/kg, or volume, Bq/L). The daily radionuclide intake includes contributions from feed, water, and ingested soil. Radionuclide concentrations in animal products ($Cd_{i,k}$) are estimated as:

$$Cd_{i,k} = Cd_{feed\ i,k} + Cd_{water\ i,k} + Cd_{soil\ i,k} \qquad \text{(Eq. 6.4.4-1)}$$

where

$Cd_{i,k}$ = activity concentration of radionuclide i in animal product k (Bq/kg $_{\text{fresh weight}}$ or Bq/L for milk)

k = animal product index; $k = 1$ for beef, 2 for milk, 3 for poultry, 4 for eggs

$Cd_{feed\ i,k}$ = activity concentration of radionuclide i in animal product k due to ingestion of contaminated animal feed (Bq/kg or Bq/L for milk)

$Cd_{water\ i,k}$ = activity concentration of radionuclide i in animal product k due to ingestion of contaminated water (Bq/kg or Bq/L for milk)

$Cd_{soil\ i,k}$ = activity concentration of radionuclide i in animal product k due to ingestion of contaminated soil (Bq/kg or Bq/L for milk).

The density of milk is close to 1 g/cm^3; it ranges from 1.028 to 1.035 g/cm^3 (Weast 1977 [DIRS 106266], p. F-3). Therefore, omitting the correction for milk density and reporting the results in Bq/kg instead of Bq/L introduces about 3% positive (conservative) bias in the calculations of radionuclide concentrations in milk. This discrepancy is small relative to the uncertainty in the value of this quantity resulting from the variance in the other input parameters, such as the transfer coefficients.

6.4.4.1 Animal Feed

The radionuclide concentrations in specific animal products from the ingestion of contaminated feed is given by:

$$Cd_{feed\ i,k} = Fm_{i,k}\ Cp_{i,j}\ Qf_k \qquad \text{(Eq. 6.4.4-2)}$$

where

$Fm_{i,k}$ = animal intake-to-animal product transfer coefficient for radionuclide *i* and animal product *k* (d/kg $_{\text{fresh weight}}$ or d/L for milk)

$Cp_{i,j}$ = activity concentration of radionuclide *i* in animal feed *j* (Bq/kg $_{\text{fresh weight}}$)

j = animal feed index; $j = 5$ fresh forage for beef ($k = 1$) and milk ($k = 3$), while $j = 4$ grain for poultry ($k = 2$) and egg hens ($k = 4$)

k = animal product index; see above

Qf_k = animal consumption rate of feed (kg/d).

The radionuclide concentrations in animal feed are taken from the plant submodel. The transfer coefficients for individual animal products depend on the element, the chemical form, and the type of animal product. Direct measurements of transfer coefficients are scarce (IAEA 1994 [DIRS 100458], p. 38). Many published values are derived from sources other than explicit experimental data, such as stable element concentrations in feed and animal tissues, extrapolation from single dose tracer experiments, and the approximation of analogous behavior by chemically similar elements. Therefore, uncertainty in the transfer coefficient values is considerable for most elements. The range of values for transfer coefficients span orders of magnitude (e.g., 10^{-5} to 10^{-1} d/kg or d/L) and are dependent on the element and product type (BSC 2004 [DIRS 169672], Section 6.3).

The animal feed consumption rates depend on the species, mass, age, growth rate, and other variables. The values used in biosphere models are for mature animals. Variation in consumption rates reported in the literature is relatively low. Typical values for animal feed are 30 to 70 kg/d for beef cattle and dairy cows, and about 0.12 to 0.4 kg/d for poultry and laying hens (BSC 2004 [DIRS 169672], Section 6.3).

6.4.4.2 Animal Drinking Water

Radionuclide concentrations in animal products contributed from ingestion of contaminated drinking water is estimated as:

$$Cd_{water\ i,k} = Fm_{i,k}\ Cw_i\ Qw_k \qquad \text{(Eq. 6.4.4-3)}$$

where

Cw_i = activity concentration of radionuclide *i* in the groundwater (Bq/L)

Qw_k = animal consumption rate of drinking water (L/d)

and the other parameters are defined in Equation 6.4.4-2.

As with animal feed, consumption rates for drinking water are based on mature animals, they are animal-type specific, and the data in the literature show little variation. Typical consumption rates from the literature are 50 to 160 L/d for beef cattle and dairy cows and about 0.3 L/d for poultry and laying hens (BSC 2004 [DIRS 169672], Section 6.3).

6.4.4.3 Animal Soil Ingestion

Ingestion of contaminated soil is another source of radionuclide intake for animals. This pathway is important because of the high soil concentrations for some radionuclides. The radionuclide concentration in animal products contributed from the ingestion of contaminated soil is estimated as:

$$Cd_{soil,l,k} = Fm_{l,k} Cs_{m,l,j} Qs_k \qquad \text{(Eq. 6.4.4-4)}$$

where

$Cs_{m,i,j}$ = radionuclide concentration of radionuclide *l* in the soil per unit mass (*l* = *i* for a primary radionuclide) (Bq/kg)

Qs_k = animal consumption rate of soil (kg/d)

and the other parameters are defined in Equation 6.4.4-2.

The radionuclide concentration in soil, $Cs_{m,i,j}$, is the greater of the crop type-specific radionuclide concentration in the resuspendable layer of soil or in the surface soil (with thickness equal to the tillage depth). The radionuclide concentration in the resuspendable layer of soil is assumed to be at equilibrium, as described in Section 6.4.1.1.

As for the feed and water intake, inadvertent soil ingestion is estimated for mature animals, and the values are animal-type specific. Typical consumption rates for beef cattle and dairy cows are 1 kg/d or less (BSC 2004 [DIRS 169672], Section 6.3.2). The radionuclide concentration in the surface soil is taken from the surface soil submodel. To calculate radionuclide concentration in soil ingested by beef cattle and milk cows, field crop irrigation is used; for ingestion of soil by chickens, garden crop irrigation is used (Assumption 5).

6.4.5 Fish Submodel

The ERMYN includes radionuclide transport through an aquatic food chain because there is a fish farm in Amargosa Valley (YMP 1999 [DIRS 158212], Tables 8 and 9), which was fully operational from 1988 until at least 1999 (Roe 2002 [DIRS 160674]). The primary customer for the catfish was the Nevada Division of Wildlife, which used the fish to stock ponds and lakes in southern Nevada. The farm owner also allowed individuals, including residents of Amargosa Valley, to fish the ponds.

Most models for assessing radionuclide transport in aquatic systems are based on the observation that aquatic organisms assimilate radionuclides proportional to radionuclide concentrations in the water (Napier et al. 1998 [DIRS 157927]; Yu et al. 2001 [DIRS 159465]). These models are based on equilibrium systems and use equilibrium concentration ratios (also called bioaccumulation factors) to quantify the uptake of radionuclides by aquatic organisms. The bioaccumulation factor is the ratio of the activity concentration in edible portions of animal tissue to that in the water (Bq/kg_{wet} to Bq/L). In natural aquatic systems, fish take in radionuclides directly from water and feed. In the Amargosa Valley fish farm, the fish consume commercial feed, which is produced outside the Amargosa Valley and, presumably, is uncontaminated (Roe 2002 [DIRS 160674]. Therefore, models based on equilibrium concentrations in various components of the aquatic system provide an upper bound for the activity concentration in Amargosa Valley fish. Radionuclide concentrations in fish are expressed as:

$$Cf_i = Cw_{f,i} \, BF_i \qquad \text{(Eq. 6.4.5-1)}$$

where

Cf_i = activity concentration of radionuclide i in fish (Bq/kg_{wet})

$Cw_{f,i}$ = activity concentration of radionuclide i in fishpond water, at the time of harvest (Bq/L)

BF_i = bioaccumulation factor for radionuclide i in freshwater fish (L/kg).

The bioaccumulation factors are element- and species-specific, and for a given element and species, bioaccumulation factors range over several orders of magnitude (BSC 2004 [DIRS 169672], Section 6.4; IAEA 2001 [DIRS 158519], p. 72).

The calculation of radionuclide bioaccumulation in farm-raised fish uses the activity concentration in pond water at the time of harvest. Due to the need to replace water lost by evaporation and the relatively long fish-breeding cycle, the activity concentration in pond water may be higher than that in the groundwater used to fill the ponds. Therefore, a water concentration-modifying factor is used to account for the increase in activity concentration due to evaporation. The fish submodel parameters are developed in *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2004 [DIRS 169672], Section 6.4). The activity concentration in the fish is calculated as:

$$Cf_i = Cw_i \ MF_i \ \ BF_i \qquad \text{(Eq. 6.4.5-2)}$$

where

Cw_i = activity concentration of radionuclide i in groundwater (Bq/L)

MF_i = water concentration modifying factor for radionuclide i (dimensionless)

and the other parameters are defined in Equation 6.4.5-1.

Radionuclides also might enter the fish ponds by the deposition of resuspended soil particles. The total amount of deposited material is estimated using a submodel similar to that for direct deposition on crops (plant submodel; Equation 6.4.3-7). Equation 6.4.3-7 uses an equation from the air submodel (Equation 6.4.2-1). Using the highest value of the radionuclide concentration in the resuspendable layer of soil of 3 Bq/kg (the value for ^{226}Ra) (Table 7.4-5) and typical values for the other parameters, $V_d = 0.008$ m/s, and $S = 1 \times 10^{-7}$ kg/m^3 (Table 6.6-3), the annual deposition rate for contaminated airborne particles is $Da = 0.08$ Bq/(m^2 yr). This deposition rate is lower than the activity added annually to the fishponds per unit surface area to replace the water lost by evaporation, which is about 2 Bq/(m^2 yr). This value was calculated based on a unit concentration in water ($Cw = 1$ Bq/m^3) and an annual evaporation rate of 2 m/yr (BSC 2004 [DIRS 169672], Section 6.4). Water evaporation from the fishponds is incorporated into the water concentration-modifying factor (*MF*).

6.4.6 ^{14}C Special Submodel

^{14}C is a primary radionuclide for the groundwater scenario (Section 6.1.3). Because carbon is so common in the environment and because the ^{14}C transport pathways differ from those of other radionuclides, ^{14}C transport in the biosphere is considered differently than other radionuclides. Possible ^{14}C transport pathways include emission from the soil, uptake by crops through roots, uptake by crops through leaves (via photosynthesis), and accumulation in animal products. The ERMYN models environmental transport of ^{14}C in the ^{14}C special submodel for the groundwater scenario. The primary function of this submodel is to calculate ^{14}C concentration in the environmental media (soil, air, crops, and animal products).

In the groundwater scenario, ^{14}C initially is introduced into the soil from contaminated irrigation water. Subsequently, a fraction of the ^{14}C is released by gaseous emission into the atmosphere as $^{14}CO_2$. In the atmosphere, $^{14}CO_2$ becomes incorporated into crops via photosynthesis, resulting in increased levels of ^{14}C in the crops. The uptake of ^{14}C in crops may also occur via the root system; however, root uptake is less important than foliar uptake during photosynthesis (Yu et al. 2001 [DIRS 159465], p. L-18).

The RESRAD (Yu et al. 2001 [DIRS 159465], Appendix L) and BIOMASS ERB2A (BIOMASS 2000 [DIRS 154522], Appendix A) models include ^{14}C special submodels that address the transport of gaseous carbon species from soil through the atmosphere and into plants. These ^{14}C special submodels are based on experimental results, which indicated that ^{14}C is quickly released from the soil as $^{14}CO_2$. The BIOMASS model also considers the direct absorption of ^{14}C by plant leaves from intercepted irrigation water.

The ERMYN ^{14}C special submodel is based on RESRAD (Yu et al. 2001 [DIRS 159465], Appendix L). This submodel comparison is discussed in Section 7.3.6. The following are considered for developing the ^{14}C special submodel:

- The ^{14}C special submodel should calculate radionuclide concentrations in the same environmental media that are used to evaluate exposure for the other radionuclides.
- For inhalation exposure, the airborne sources of ^{14}C include gaseous species of carbon released from the soil following irrigation with ^{14}C-contaminated groundwater. This pathway of ^{14}C transport from the surface soil to the air is in addition to the resuspension of soil contaminated by ^{14}C. Both pathways are the sources for inhalation exposure.
- To assess the activity concentration of ^{14}C gas in the air, it is assumed that a finite area is irrigated at the specified average annual irrigation rate. The size of the area and the irrigation rate depend on the type of crops. The resulting activity concentration in the air is required to evaluate the inhalation dose and plant leaf uptake.
- Due to the two different transport processes, ^{14}C in the air may be present in the gaseous (carbon dioxide) and solid (particulate) form. Two different inhalation dose coefficients are used in the model to account for different chemical forms of ^{14}C.
- Long-term accumulation of ^{14}C in the soil is not considered because of the rapid loss of ^{14}C from the soil primarily by emission of $^{14}CO_2$.

6.4.6.1 ^{14}C in Surface Soil

Mechanisms of ^{14}C loss from soil include leaching, soil erosion, and radioactive decay, similar to the other radionuclides. However, ^{14}C transport in the environment is controlled by an additional loss mechanism, emission loss, which is not applicable to other radionuclides. Due to the volatility of ^{14}C in soil, it is quickly released via gaseous emission as $^{14}CO_2$. Sheppard et al. (1991 [DIRS 159545]) measured the rate of ^{14}C loss from soil in outdoor lysimeter experiments. Carbon loss from the soil, quantified by the emission rate (the term “evasion rate” is used in RESRAD), is 12/yr for clay and loamy soils, and 22/yr for sandy and organic soils (Yu et al. 2001 [DIRS 159465], p. L-16). Thus, ^{14}C concentrations in surface soil reach equilibrium within 1 to 2 months. Emission is the dominant mechanism for removing ^{14}C from the soil. In comparison, losses due to leaching, radioactive decay, and soil erosion are slight (Table 7.4-5).

The calculation of ^{14}C concentration in the soil is based on equilibrium conditions between ^{14}C gains and losses. Using a differential equation similar to Equation 6.4.1-1 and the solution similar to Equation 6.4.1-4, the concentration of ^{14}C in the soil is expressed as:

$$Cs_{C-14,j} = \frac{Cw_{C-14} IR_j}{\lambda_{d,C-14} + \lambda_{l,C-14} + \lambda_e + \lambda_{a,C-14}}$$
$$Cs_{c,C-14,j} = \frac{Cw_{C-14} IR_j}{\lambda_{d,C-14} + \lambda_{lc,C-14} + \lambda_{ec} + \lambda_{a,C-14}} \qquad \text{(Eq. 6.4.6-1)}$$

where

$Cs_{C\text{-}14,j}$ = activity concentration of ^{14}C in surface soil for the crop type or exposure pathway j (Bq/m^2)

$Cs_{c,C\text{-}14,j}$ = activity concentration of ^{14}C in resuspendable soil layer for the crop type or exposure pathway j (Bq/m^2)

j = crop-type or pathway index; $j = 1$ for leafy vegetables, 2 for other vegetables, 3 for fruit, 4 for grain, and 5 for fresh forage

$Cw_{C\text{-}14}$ = activity concentration of ^{14}C in irrigation water (Bq/m^3)

IR_j = crop irrigation rate; $j = 1$ to 5 for individual crop types; daily irrigation rate IRD_j is used to calculate soil concentration of ^{14}C for plant uptake; annual average irrigation rate is used for inhalation, soil ingestion, and external exposure pathways (m/yr)

$\lambda_{d,C\text{-}14}$ = radioactive decay constant for ^{14}C (1/yr)

$\lambda_{l,C\text{-}14}$ = leaching removal rate constant for the surface soil for ^{14}C (1/yr)

$\lambda_{lc,C\text{-}14}$ = leaching removal rate constant for ^{14}C for the critical thickness (1/yr)

λ_e = surface soil erosion removal rate constant for the surface soil (1/yr)

λ_{ec} = surface soil erosion removal rate constant for the critical thickness (1/yr)

$\lambda_{a,C\text{-}14}$ = emission rate constant of ^{14}C from the soil to the air (1/yr).

Equation 6.4.6-1 is used to calculate ^{14}C concentration in the surface soil and ^{14}C concentration in the resuspendable soil layer (critical thickness). These two concentrations are used in the similar manner as for the other radionuclides except that the ^{14}C concentration in the surface soil is also used to calculate ^{14}C concentration in air for the $^{14}CO_2$ uptake by crops and $^{14}CO_2$ inhalation by the receptor. The only difference is the values of the leaching removal and erosion removal rate constants. Because crops take up ^{14}C from the local soil and air, and because ^{14}C is released rapidly from the soil, irrigation in the ^{14}C submodel is considered locally and only during the crop growing season. Therefore, the daily average irrigation rate for crop type j, IRD_j, introduced in the plant submodel (Section 6.4.3), is considered appropriate. The same input parameter is used in the ^{14}C submodel with a simple conversion of units from m/d to m/yr. This conversion is needed because all other removal rate constants are in units of 1/yr. Modifying this equation to convert all removal rates to units of per day gives the same results. The average annual irrigation rate for farmland, IR_j, introduced in the surface soil submodel (Section 6.4.1) is used for calculating the ^{14}C concentration in the surface soil for assessment of doses from inhalation, soil ingestion, and external exposure.

Equation 6.4.6-1 is analogous to Equation 6.4.1-4, except that the effective removal rate constant, λ_{eff}, includes an additional loss term to account for gaseous emission. The ^{14}C emission rate constant depends on the soil type, but not strongly (Yu et al. 2001 [DIRS 159465] p. L-16).

6.4.6.2 ^{14}C in Air

Due to the volatility of ^{14}C, the activity concentration of this radionuclide in the air has to include the contribution from release of carbon dioxide from soil. A separate submodel for the gaseous release of ^{14}C from the soil (as CO_2) is used to predict ^{14}C concentrations in the air from this process. The flux density of gaseous ^{14}C from soil to air is estimated as:

$$EVSN_j = Cs_{C-14,j} \ \lambda_{a,C-14} \qquad \text{(Eq. 6.4.6-2)}$$

where

$EVSN_j$ = average flux density of gaseous ^{14}C from contaminated soil for the crop exposure pathway j (Bq/(m^2 yr))

and the other parameters are defined in Equation 6.4.6-1.

If $Cs_{C-14,j}$ in Equation 6.4.6-2 is substituted using Equation 6.4.6-1, the flux density of gaseous ^{14}C from the soil is almost equal to the total deposition rate of ^{14}C ($Cw_{C-14,j} \times IR_j$) because the emission rate constant ($\lambda_{a,C-14}$ = 22/yr; Table 6.6-3) is much greater than the remaining components of the effective removal rate constant ($\lambda_{d,C-14} + \lambda_{l,C-14} + \lambda_e$ = 0.01/yr; Table 7.4-5). This indicates that the atmosphere, rather than the soil, is the main source of ^{14}C available for further dispersion in the environment. It must be recognized that the gaseous ^{14}C flux from soil, of concern to biosphere modeling, originates from irrigated land only. After it is released into the air, ^{14}C is diluted by mixing with uncontaminated air. The ^{14}C concentration in the air above cropland irrigated by contaminated groundwater is estimated using the total ^{14}C release rate and the potential mixing volume of air as:

$$Ca_{g,C-14,j} = \frac{EVSN_j \ A_j}{3.16\times10^7 \ H_{mix} U \sqrt{A_j}} = \frac{EVSN_j \ \sqrt{A_j}}{3.16\times10^7 \ H_{mix} U} \qquad \text{(Eq. 6.4.6-3)}$$

where

$Ca_{g,C-14,j}$ = activity concentration of ^{14}C in the air for the crop type or exposure pathway j (Bq/m^3)

A_j = surface area of irrigated land, which is estimated for garden (j = 1, 2, and 3) and field (j = 4 and 5) crops (m^2)

H_{mix} = mixing height of $^{14}CO_2$ (m)

U = annual average wind speed (m/s)

3.16×10^7 = unit conversion factor from year to seconds based on 1 yr = 365.25 d (s/yr)

and the other parameters are defined in Equation 6.4.6-2.

The airborne concentration of ^{14}C depends on crop types. The surface area of irrigated land, A_j, is estimated from the size of farms and gardens. The average size of a farm in Nye County is 2.295×10^6 m^2 (567 acres $\times$ 4,047 m^2/acre) (USDA 2005 [DIRS 178434], p. 11). This value was used as a surface area for field crops ($A_{j=4\&5}$). The size of a home garden was estimated based on RESRAD model (Yu et al. 2001 [DIRS 159465], p. 2-19). In that model it is assumed that for a family to have a garden that provides half of the total plant food diet, the area available for gardens and orchards has to be 0.1 ha (1,000 m^2) or larger. In ERMYN, this area was conservatively doubled to 2,000 m^2 (0.2 ha).

The square root of irrigated area, A_j, can be used as a measure of the linear dimension of a field of area A_j, irrespective of the actual shape. The concept of mixing cell (a volume of air where mixing of $^{14}CO_2$ with ambient air occurs) with dimensions of A_j and mixing height H_{mix} is then introduced to estimate dilution. The effective average concentration of ^{14}C in the mixing cell is not underestimated relative to the value that would be calculated by solving the transport equations due to the limited size of the cell. The mixing height of gaseous ^{14}C, H_{mix}, is less for crop uptake than for human uptake because human air intake (breathing) would typically occur at a greater height than plant uptake. The same is true for the annual average wind speed, U, which is less close to the ground in the plant growing zone than it is in the human breathing zone. Values for the other parameters in Equation 6.4.6-3 are developed in *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2004 [DIRS 169672], Section 6.7).

The RESRAD model (Yu et al. 2001 [DIRS 159465], p. L-15) uses an additional parameter to account for the fraction of time when wind is blowing over the contaminated area and towards the receptor. In the RESRAD model, the value of this parameter is 0.5 because the receptor is located at the edge of a relatively small, contaminated area. In ERMYN, the receptor is located within the contaminated area, where wind blowing from any direction exposes the receptor. Therefore, correction for wind direction is not considered in ERMYN.

The ^{14}C concentrations in the air from release of carbon dioxide are up to three orders of magnitude greater than the concentrations due to soil resuspension (Section 6.10). Therefore, deposition of resuspended soil does not need to be included as a source of ^{14}C for uptake by plants. ^{14}C concentrations in the air from soil resuspension are necessary for calculation of inhalation exposure. This is because the inhalation dose coefficients for ^{14}C present in air in particulate form can be up to three orders of magnitude greater than that for carbon dioxide. Therefore, concentrations of ^{14}C in air from resuspension of soil are calculated and carried forward to the inhalation submodel. They are evaluated in a manner analogous to that described in Section 6.4.2.1.

6.4.6.3 ^{14}C in Crops

In the environment, the transport of ^{14}C follows that of stable carbon (Yu et al. 2001 [DIRS 159465], p. L-15). Two transport pathways are considered for the uptake of ^{14}C by plants: direct root uptake of ^{14}C and leaf uptake of $^{14}CO_2$ released from soil to the atmosphere by gaseous emission. The latter mechanism is dominant because plants acquire most carbon from the atmosphere during photosynthesis (Yu et al. 2001 [DIRS 159465], p. L-18). In the biosphere model, the activity concentration of ^{14}C in crops resulting from root uptake is calculated as:

$$Cp_{root\,C-14,j} = \frac{Cs_{C-14,j}}{\rho_s} \frac{Fs \times fc_{plant,j}}{fc_{soil}} \quad \text{(Eq. 6.4.6-4)}$$

where

$Cp_{root\ C\text{-}14,j}$ = activity concentration of ^{14}C in the edible parts of crop type j resulting from root uptake (Bq/kg $_{wet\ weight}$)

j = crop-type index; which is the same as that defined in Equation 6.4.6-1

$Cs_{C\text{-}14,j}$ = activity concentration of ^{14}C in surface soil for crop type j (Bq/m^2)

ρ_s = areal density of surface soil (kg/m^2)

$fc_{plant,j}$ = fraction of stable carbon in crop type j (dimensionless, based on kg $_{carbon}$/kg $_{wet\ crop}$)

Fs = fraction of soil-derived carbon in plants (dimensionless)

fc_{soil} = fraction of stable carbon in soil (dimensionless, based on kg $_{carbon}$/kg $_{soil}$).

The fraction of stable carbon in the soil, fc_{soil}, is defined as the mass of carbon per unit mass of soil. The fraction varies depending on soil type, with a typical value on the order of a few percent (BSC 2004 [DIRS 169672], Section 6.7). A value of 0.03 is recommended for the RESRAD model (Yu et al. 2001 [DIRS 159465], p. L-17).

The activity concentration of ^{14}C in crops resulting from the uptake through the leaves via photosynthesis is estimated as:

$$Cp_{leaf\ C-14,j} = Ca_{g,C-14,j} \frac{Fa \times fc_{plant,j}}{fc_{air}} \quad \text{(Eq. 6.4.6-5)}$$

where

$Cp_{leaf\ C\text{-}14,j}$ = activity concentration of ^{14}C in edible parts of crop type j resulting from leaf uptake (Bq/kg $_{wet\ weight}$)

$Ca_{g,C\text{-}14,j}$ = activity concentration of ^{14}C in the air for the crop type j (Bq/m^3)

Fa = fraction of air-derived carbon in plants (dimensionless)

fc_{air} = concentration of stable carbon in the air (kg $_{carbon}$/m^3).

The concentration of stable carbon in the air, fc_{air}, can be derived from the average global value, about 1.8×10^{-4} kg/m^3 (BSC 2004 [DIRS 169672], Section 6.7). By combining Equation 6.4.6-4 and Equation 6.4.6-5, Equation 6.4.6-6, the total concentration of ^{14}C in plants, can be obtained as:

$$Cp_{C-14,j} = fc_{plant,j}\left[\left(Fa\,\frac{Ca_{g,C-14,j}}{fc_{air}}\right)+\left(Fs\,\frac{Cs_{C-14,j}}{\rho_s\ fc_{soil}}\right)\right] \qquad \text{(Eq. 6.4.6-6)}$$

where

$Cp_{C\text{-}14,j}$ = activity concentration of ^{14}C in edible parts of crop type *j* (Bq/kg $_{\text{wet weight}}$)

and the other parameters are defined in Equations 6.4.6-4 and 6.4.6-5.

Vegetation incorporates most of its carbon from the atmosphere during photosynthesis (Yu et al. 2001 [DIRS 159465], p. L-18). A value of $Fa = 0.98$ is recommended for the RESRAD model (Yu et al. 2001 [DIRS 159465], p. L-20). The fraction of carbon in plants derived from soil, *Fs*, is complementary to the fraction of carbon in plants derived from air (i.e., $Fs = 1 - Fa$), with a value of about 0.02 (Yu et al. 2001 [DIRS 159465], p. L-20).

The fraction of stable carbon in plants, $fc_{plant,j}$, is crop-type specific, and defined as the mass of carbon per unit wet mass of a plant. Default values for this parameter in the RESRAD and GENII-S models are 0.09 for fruits, vegetables, and fresh forage; and 0.40 for grain (BSC 2004 [DIRS 169672], Section 6.7).

6.4.6.4 ^{14}C in Animal Products

The activity concentration of ^{14}C in animal products is derived from animal feed, soil, and drinking water. The transfer of ^{14}C from feed to animal products is modeled using the same route as that of stable carbon. The ^{14}C activity concentration in animal products is calculated as:

$$Cd_{C-14,k} = \frac{(Cp_{C-14,j}\times Qf_k)+(Cw_{C-14}\times Qw_k)+(Cs_{C-14,j}\times Qs_k)}{(fc_{plant,j}\times Qf_k)+(fc_{water}\times Qw_k)+(fc_{soil}\times Qs_k)}\times fc_{anim,k} \qquad \text{(Eq. 6.4.6-7)}$$

where

$Cd_{C\text{-}14,k}$ = activity concentration of ^{14}C in animal product *k* (Bq/kg; Bq/L for milk)

$Cw_{C\text{-}14}$ = activity concentration of ^{14}C in groundwater (Bq/L)

fc_{water} = concentration of stable carbon in water (kg/L)

$fc_{anim,\,k}$ = fraction of stable carbon in animal product *k* (dimensionless, based on kg $_{\text{carbon}}$/kg $_{\text{animal product}}$)

and the other parameters are defined in Equations 6.4.4-1 to 6.4.4-4, 6.4.6-1, 6.4.6-4, and 6.4.6-6.

The concentration of stable carbon in water, fc_{water}, is on the order of 1×10^{-5} kg/L (BSC 2004 [DIRS 169672], Section 6.7). The fraction of stable carbon in animal products, $fc_{anim,\,k}$, is animal-product dependent. The GENII and RESRAD models use 0.24 for beef, 0.2 for poultry, 0.07 for milk, and 0.15 for eggs (BSC 2004 [DIRS 169672], Section 6.7).

By comparing the three ^{14}C sources (feed, water, and soil), the main source for animal ^{14}C intake is from feed, as there is only a small amount of carbon in water and soil (Napier et al. 1988 [DIRS 157927] p. 4.89).

6.4.6.5 ^{14}C in Fish

The activity concentration of ^{14}C in fish is calculated using the method developed for other radionuclides, as discussed in Section 6.4.5.

6.4.7 External Exposure Submodel

The dose received from external sources of radiation is attributed to high energy beta- and gamma-emitting radionuclides in contaminated media such as soil, air, and water. For external exposure, radiation emitters are external to the human body, and, therefore, exposure occurs only when a person is near or in direct contact with the contaminated media. The primary external exposure pathways include exposure to contamination on or in the ground (ground exposure), air submersion, and water immersion.

External exposure of the human receptor can be evaluated using radionuclide media concentrations, exposure times, and dose coefficients. Dose coefficients, tabulated in FGR 13 (EPA 2002 [DIRS 175544]), convert media concentrations into effective dose per unit exposure time. In this section, the effective dose from external exposure is referred to as dose from external exposure.

6.4.7.1 Exposure to Contaminated Soil

The dose coefficients for external exposure to contaminated soils given in the FGR 13 (EPA 2002 [DIRS 175544]) are derived for a source, which when seen from the location of an exposed individual, is uniform and effectively semi-infinite in extent (Eckerman and Ryman 1993 [DIRS 107684], p. 2). For consistency, it is assumed that the same exposure geometry applies to the human receptor in the ERMYN (Assumption 10). For the groundwater scenario, the irrigated area is limited in extent, and, although noncultivated areas could become contaminated by surface soil transport, the contamination levels would be lower than those on the irrigated land. Due to crop rotation and changes in land use over the long period considered for evaluation of repository performance, areas not farmed at any given time may have been irrigated previously and, thus, could also be contaminated to a varying degree. Therefore, it is reasonable but conservative to assume that the surface soil, to which the receptor is exposed, is always contaminated, except for the receptor environment away from the contaminated area (see the surface soil submodel, Section 6.4.1).

The annual dose to a receptor from external exposure to primary radionuclide i in contaminated soil may include contributions from other primary radionuclides formed in the soil as a result of radioactive decay of radionuclide i, as explained in Section 6.3.5. The combined dose from the primary radionuclide and its decay products is estimated as:

$$D_{ext,i} = \sum_l D_{ext,l} = \sum_l EDCi_{soil,l} \frac{Cs_l}{d} \left[\sum_n f_{ext,l,n} \left(\sum_m PP_m \, (3600 \times t_{n,m}) \right) \right] \quad \text{(Eq. 6.4.7-1)}$$

where

$D_{ext,i}$ = annual dose from external exposure to primary radionuclide *i* in soil (Sv/yr)

$D_{ext,l}$ = dose from external exposure to long-lived radionuclide *l* (Table 6.4-3) in a decay chain of a primary radionuclide *i* (Sv/yr)

l = index of long-lived radionuclide in a decay chain; $l = 0$ for primary radionuclide

$EDCi_{soil,l}$ = effective dose coefficient for exposure to soil contaminated to an infinite depth for a long-lived radionuclide *l* in a decay chain of a primary radionuclide *i* (Sv/s per Bq/m^3). Calculation of effective dose coefficients is discussed in Section 6.4.7.2.

$Cs_{\,l}$ = activity concentration in surface soil for a long-lived radionuclide *l* in a decay chain of a primary radionuclide *i* (Bq/m^2)

d = depth of surface soil (m)

$f_{ext,l,n}$ = external shielding factor for exposure to radionuclide *l* in the soil at environment *n* (dimensionless)

n = environment index; $n = 1$ for active outdoors, 2 for inactive outdoors, 3 for active indoors, 4 for asleep indoors, and 5 for away from the contaminated area

m = population group index; $m = 1$ for local outdoor workers, 2 for local indoor workers, 3 for commuters, and 4 for nonworkers

PP_m = fraction of total population in population group *m* (population proportion) (dimensionless)

$t_{n,m}$ = exposure times of population group *m* spent in environment *n* (exposure time) (h/yr)

3,600 = unit conversion of hours to seconds; 3,600 (s/h).

To account for variation and uncertainty in the amount of time the receptor would spend in environment *n*, four mutually exclusive population groups, *m*, are considered (Section 6.4.2.1). These groups represent the range of behaviors that would most influence the amount of time that people are exposed to radionuclides via external exposure and inhalation. For these exposure pathways, variation in radiation exposure among individuals is influenced primarily by the amount of time they spent in various environments indoors and outdoors within contaminated areas (and the amount of time they spent away from contaminated areas). For adults, variation among these time factors primarily is a function of occupational characteristics, as people working outside the contaminated area, generally, would experience less exposure than people who remain within the area, and people who work outdoors would be exposed at a different level than those who remained indoors. Therefore, the categories are based on work location and type of occupation. Estimates of the proportion of the adult population of Amargosa Valley in each group are developed in *Characteristics of the Receptor for the Biosphere Model* (BSC 2005 [DIRS 172827], Section 6.3.1).

The following four receptor groups are included in the biosphere model:

Local Outdoor Workers—This group includes residents who work outdoors and disturb (and therefore resuspend) contaminated soil.

Local Indoor Workers—Local indoor workers are residents who work indoors (or outdoors in enclosed vehicles) in areas contaminated by groundwater or ash. The proportion of the population in this group is calculated as the proportion not in the other groups.

Commuters—This group includes residents who work outside the contaminated area.

Nonworkers—Nonworkers are residents who are unemployed or otherwise not in the labor force, including retired persons.

The effective dose coefficient for exposure to soil contaminated to an infinite depth, $EDCi_{soil,\,l}$, is a radionuclide-specific parameter. Unlike the submodels for crop contamination, the external exposure submodel uses an infinite depth of contaminated soil, rather than the depth of the surface soil. This difference accounts for emissions from radionuclides that leach out of the surface soil into the deep soil, but that still could contribute to the radiation field above the air-ground interface. Radionuclide concentrations in the surface soil are used to calculate the external exposure, even though radionuclide concentrations in the deep soil might not be contaminated at the same high level. As discussed in Section 6.3.5, the short-lived decay products are assumed to be in equilibrium with the long-lived parent radionuclides, and their dose coefficients are combined with the parent dose coefficient to produce an effective dose coefficient. The development of effective dose coefficients, which includes contributions from the short-lived decay products, is discussed in Section 6.4.7.2.

The activity concentration of radionuclide i and its decay product l in soil, Cs_i and Cs_l, respectively, are calculated using Equations 6.4.1-3 (or 6.4.1-25), 6.4.1-26, and 6.4.1-27, which are discussed in the surface soil submodel (Section 6.4.1).

In the external exposure submodel, an external shielding factor, $f_{ext,l,n}$, is used to account for the reduction in external exposure provided by dwellings. For the outdoor environments (n = 1, 2, and 5), where normally there would be no shielding, the value for $f_{ext,l,n}$ is equal to one. For indoor environments (n = 3 and 4), shielding is radionuclide dependent because of radiation characteristics. Shielding factor values range from 0 to 1; however, the typical values, even for the most penetrating radiation emissions, do not exceed 0.4 (BSC 2005 [DIRS 172827], Section 6.6). Radionuclides with penetrating (high-energy) gamma emissions have a higher shielding factor than radionuclides with low-energy gamma or beta emissions.

The external exposure time, $t_{n,m}$, is the annual duration that population group m spends in environment n (BSC 2005 [DIRS 172827], Section 6.3.2). The fraction of the total population in population group m, PP_m, is based on current Amargosa Valley census data (BSC 2005 [DIRS 172827], Section 6.3.1). The fractional exposure time for the active-indoor environment and the proportion of indoor-workers are calculated as one minus the sum of the other fractional exposure times and population proportions, respectively. The method is provided in *Characteristics of the Receptor for the Biosphere Model* (BSC 2005 [DIRS 172827], Sections 6.3.1 and 6.3.2), and calculations are carried in ERMYN to incorporate the uncertainty of these parameters.

The external exposure submodel does not include air submersion exposure because air contamination is a secondary process following the resuspension of contaminated surface soil. Because most of the radionuclides of interest are long-lived alpha emitters, the inhalation dose is higher than any subsequent air submersion dose. The external exposure submodel does not include water immersion exposure because of the emission characteristics of the radionuclides involved (primarily long-lived alpha emitters) and the relatively short exposure times expected in water. Justification for excluding these two pathways is presented in the validation section (Section 7.4.8). In addition, the external exposure arising from accumulation of activity in evaporative coolers is not considered, as justified in Appendix D.

6.4.7.2 Effective Dose Coefficients for Exposure to Contaminated Soil

Dose coefficients for exposure to soil contaminated to an infinite depth were taken from FGR 13 (EPA 2002 [DIRS 175544]). These dose coefficients represent effective dose per unit time per unit radionuclide concentration in the soil and were developed using tissue weighting factors consistent with ICRP Publication 60 (ICRP 1991 [DIRS 101836]). As discussed in Section 6.3.5, the dose contributions from short-lived decay products are combined with those of their long-lived parent radionuclides. The development of the combined, or effective, dose coefficients is shown in Table 6.4-4. The first column in the table contains the names of the primary radionuclides, followed by a "D" if short-lived decay products are included. The second column lists the short-lived decay products, the dose contributions of which are combined with those of the parent radionuclide. Dose coefficients for the individual radionuclides are shown in the third column. The effective dose coefficients, calculated by summing the dose coefficients for all short-lived decay products under a long-lived radionuclide, with consideration of the branching fraction, are given in the last column of the table. The calculation method can be expressed as:

$$EDCi_{soil.j} = \sum_{s} DCi_{soil,s} \times BN_s \qquad \text{(Eq. 6.4.7-2)}$$

where

$DCi_{soil,s}$ = dose coefficient for exposure to soil contaminated to an infinite depth for short-lived radionuclide s in the decay chain of long-lived radionuclide l; for a primary radionuclide $l = i$ (Sv/s per Bq/m^3)

s = index of short-lived radionuclide decay chain under a radionuclide l

BN_s = branching fraction for short-lived radionuclide s in the decay chain of radionuclide l (dimensionless)

and the other parameter is defined in Equation 6.4.7-1.

The values of effective dose coefficients shown in Table 6.4-4 are for demonstration purposes only (they are not used as model inputs). ERMYN uses branching fractions and dose coefficients as inputs to calculate effective dose coefficients (Section 6.8).

Table 6.4-4. Dose Coefficients and Effective Dose Coefficients for Exposure to Soil Contaminated to an Infinite Depth

Primary Radionuclide [a,b]	Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Dose Coefficient (DCi_{soil}) [d] (Sv/s)/(Bq/m^3)	Effective Dose Coefficient ($EDCi_{soil}$) (Sv/s)/(Bq/m^3)
^{14}C	—	5.90E–23	5.90E–23
^{36}Cl	—	1.33E–20	1.33E–20
^{79}Se	—	8.21E–23	8.21E–23
^{90}Sr D 	 ^{90}Y (64.0 h)	3.46E–21 2.15E–19	2.18E–19
^{99}Tc	—	5.81E–22	5.81E–22
^{126}Sn D	 ^{126m}Sb (19.0 min) ^{126}Sb (14%, 12.4 d)	6.97E–19 4.67E–17 8.60E–17	5.94E–17
^{129}I	—	5.14E–20	5.14E–20
^{135}Cs	—	1.72E–22	1.72E–22
^{137}Cs D	 ^{137m}Ba (94.6%, 2.552 min)	4.47E–21 1.81E–17	1.71E–17
^{242}Pu	—	5.32E–22	5.32E–22
^{238}U D	 ^{234}Th (24.10 d) ^{234m}Pa (99.80%, 1.17 min) ^{234}Pa (0.33%, 6.7 h)	4.27E–22 1.14E–19 5.28E–19 5.83E–17	8.34E–19
^{238}Pu	—	6.25E–22	6.25E–22
^{234}U	—	1.84E–21	1.84E–21
^{230}Th	—	5.73E–21	5.73E–21
^{226}Ra D	 ^{222}Rn (3.8235 d) ^{218}Po (3.05 min) ^{214}Pb (99.98%, 26.8 min) ^{218}At (0.02%, 2 s) ^{214}Bi (19.9 min) ^{214}Po (99.98%, 1.64 × 10^{-4} s) ^{210}Tl (0.02%, 1.3 min)	1.56E–19 1.17E–20 2.85E–22 6.65E–18 2.61E–20 4.99E–17 2.59E–21 0.00E+00	5.67E–17
^{210}Pb D	 ^{210}Bi (5.012 d) ^{210}Po (138.38 d)	1.06E–20 2.92E–20 2.64E–22	4.01E–20
^{240}Pu	—	6.03E–22	6.03E–22
^{236}U	—	9.53E–22	9.53E–22
^{232}Th	—	2.44E–21	2.44E–21
^{228}Ra D	 ^{228}Ac (6.13 h)	0.00E+00 3.03E–17	3.03E–17

Table 6.4-4. Dose Coefficients and Effective Dose Coefficients for Exposure to Soil Contaminated to an Infinite Depth (Continued)

Primary Radionuclide [a,b]	Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Dose Coefficient (DCi_{soil}) [d] (Sv/s)/(Bq/m^3)	Effective Dose Coefficient ($EDCi_{soil}$) (Sv/s)/(Bq/m^3)
^{232}U	—	4.25E–21	4.25E–21
^{228}Th D		3.85E–20	5.18E–17
	^{224}Ra (3.66 d)	2.53E–19	
	^{220}Rn (55.6 s)	1.15E–20	
	^{216}Po (0.15 s)	5.26E–22	
	^{212}Pb (10.64 h)	3.46E–18	
	^{212}Bi (60.55 min)	5.96E–18	
	^{212}Po (64.07%, 0.305 µs)	0.00E+00	
	^{208}Tl (35.93%, 3.07 min)	1.17E–16	
^{243}Am D		6.66E–19	4.36E–18
	^{239}Np (2.355 d)	3.69E–18	
^{239}Pu	—	1.41E–21	1.41E–21
^{235}U D		3.53E–18	3.70E–18
	^{231}Th (25.52 h)	1.72E–19	
^{231}Pa	—	9.44E–19	9.44E–19
^{227}Ac D		2.40E–21	1.00E–17
	^{227}Th (98.62%, 18.718 d)	2.57E–18	
	^{223}Fr (1.38%, 21.8 min)	9.71E–19	
	^{223}Ra (11.434 d)	2.96E–18	
	^{219}Rn (3.96 s)	1.53E–18	
	^{215}Po (1.78 ms)	5.06E–21	
	^{211}Pb (36.1 min)	1.56E–18	
	^{211}Bi (2.14 min)	1.27E–18	
	^{207}Tl (99.72%, 4.77 min)	1.23E–19	
	^{211}Po (0.28%, 0.516 s)	2.40E–19	
^{241}Am	—	1.99E–19	1.99E–19
^{237}Np D		3.73E–19	5.41E–18
	^{233}Pa (27.0 d)	5.04E–18	
^{233}U	—	6.77E–21	6.77E–21
^{229}Th D		1.55E–18	7.92E–18
	^{225}Ra (14.8 d)	4.63E–20	
	^{225}Ac (10.0 d)	3.09E–19	
	^{221}Fr (4.8 min)	7.56E–19	
	^{217}At (32.3 ms)	8.86E–21	
	^{213}Bi (45.65 min)	3.83E–18	
	^{213}Po (97.84%, 4.2 µs)	0.00E+00	
	^{209}Tl (2.16%, 2.2 min)	6.56E–17	
	^{209}Pb (3.253 h)	4.04E–21	

[a] A “D” indicates that the radionuclide is treated with its short-lived (less than 180 d) decay products.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Branching fractions and half-lives are from Table 6.3.7.

[d] Dose coefficient source: EPA 2002 [DIRS 175544].

Source: Effective dose coefficients were calculated in Excel spreadsheet *Calculation_Effective Dose Coefficients.xls* (Appendix A).

6.4.8 Inhalation Exposure Submodel

The inhalation submodel is used to calculate radiation doses caused by the inhalation of contaminated air. The inhalation dose is estimated using radionuclide concentrations in the air, parameters describing conditions of human exposure, and dose coefficients for inhalation exposure that convert radionuclide intake to the committed effective dose. Activity concentrations in the air are discussed in Section 6.4.2 (air submodel). In contrast to external exposure, where emissions arise from outside the human body, inhalation and ingestion exposures arise from radiation emitted inside the body, and the exposure continues for as long as the radionuclides are in the body. Therefore, inhalation and ingestion doses are presented in terms of the committed dose. Committed dose is the sum of all doses projected to be received in the future from an intake in the current year. For the adult person, this sum is by convention taken over the 50-year period following intake. Committed dose makes no assumption about future intake, but does account for the dose in the future arising from intake in the current year. Analogous to the external exposure submodel, the committed effective dose is referred to in this report as the dose or the annual dose. The inhalation submodel includes calculation of intakes and doses from three types of air contamination: resuspension of contaminated soil (Section 6.4.2.1), aerosols from evaporative coolers (Section 6.4.2.2), and gaseous emissions from soil, which includes exhalation of ^{222}Rn (Section 6.4.2.3) and gaseous emission of ^{14}C (Section 6.4.6.2). The total inhalation dose is the sum of the doses resulting from these three inhalation exposure pathways, expressed as:

$$D_{inh,i} = D_{inh,p,i} + D_{inh,e,i} + D_{inh,g,i} \qquad \text{(Eq. 6.4.8-1)}$$

where

$D_{inh,i}$ = annual dose from inhalation exposure to radionuclide i (Sv/yr)

$D_{inh,p,i}$ = annual dose from inhalation exposure to radionuclide i in resuspended particles (Sv/yr)

$D_{inh,e,i}$ = annual dose from inhalation exposure to radionuclide i in air resulting from the operation of an evaporative cooler (Sv/yr)

$D_{inh,g,i}$ = annual dose from inhalation exposure to radionuclide i in air resulting from gaseous emission from the soil (Sv/yr). This term applies only to the inhalation of ^{222}Rn decay products and the inhalation of $^{14}CO_2$.

6.4.8.1 Inhalation of Resuspended Particles

Exposure from the inhalation of radionuclides in resuspended particles depends on a number of factors, including activity concentrations in air, indoor and outdoor exposure times, the particle size distribution, the radionuclide, the chemical form of the radionuclide, and the breathing rate of the receptor. Although the resuspension pathway usually is not an important contributor to long-term exposure for most locations, it is potentially important in the dusty environments associated with some human activities (NCRP 1999 [DIRS 155894], p. 59).

As discussed in Section 6.4.2 (air submodel), radionuclide concentrations in the air, $Ca_{h,i,n}$, are calculated for five environments associated with human activities and characterized by different concentrations of resuspended particles. The receptor used for the performance assessment of the repository is the RMEI, the characteristics of which are based on the lifestyles and behaviors of people residing in the Amargosa Valley. Evaluation of the inhalation exposure to the RMEI involves considering various population groups within the Amargosa Valley population. Therefore, parameter values for inhalation exposure pathway depend on the environment and on the population group. The inhalation submodel includes five receptor environments, four in the contaminated area (active outdoors, inactive outdoors, active indoors, and asleep indoors) and one away from the contaminated area. The population groups include commuters, local outdoor workers, local indoor workers, and nonworkers (Section 6.4.7).

Annual doses resulting from the inhalation of primary radionuclides should also include exposure to radionuclides in the decay chain (as discussed for the surface soil submodel; Section 6.4.1.2) because the resuspended particles originate from the surface soil where radionuclides build up during long-term irrigation. The combined dose from a primary radionuclide and its long-lived decay products is estimated as:

$$D_{inh,p,i} = \sum_{l} D_{inh,p,l} = \sum_{l} EDCF_{inh,l} \left[\sum_{n} Ca_{h,l,n} \; BR_n \sum_{m} \left(PP_m \; t_{n,m} \right) \right] \qquad \text{(Eq. 6.4.8-2)}$$

where

$D_{inh,p,i}$ = annual dose from inhalation exposure to primary radionuclide i in resuspended particles (Sv/yr)

$D_{inh,p,l}$ = annual dose from inhalation exposure to long-lived radionuclide l in a decay chain of primary radionuclide i in resuspended particles (Sv/yr)

l = radionuclide index for a decay chain, $l = 0$ for primary radionuclide, 1 for the first long-lived decay product, 2 for the second long-lived decay product

$EDCF_{inh,l}$ = effective dose coefficient for inhalation of long-lived radionuclide l in a decay chain of primary radionuclide i (Sv/Bq). Calculation of effective dose coefficients is discussed in Section 6.4.8.5.

n = environment index; $n = 1$ for active outdoors, 2 for inactive outdoors, 3 for active indoors, 4 for asleep indoors, and 5 for away from the contaminated area

$Ca_{h,l,n}$ = activity concentration of radionuclide l in a decay chain of primary radionuclide i in air for environment n (Bq/m^3)

BR_n = breathing rate for environment n (m^3/h)

m = population group index; $m = 1$ for local outdoor workers, 2 for local indoor workers, 3 for commuters, and 4 for nonworkers

PP_m = fraction of the total population in population group *m* (population proportion) (dimensionless)

$t_{n,m}$ = annual amount of time that population group *m* spends in environment *n* (exposure time) (h/yr).

The effective dose coefficients for inhalation of radionuclide *l*, $EDCF_{inh,l}$ includes contributions from the short-lived decay products. The development of this parameter is described in Section 6.4.8.5. The inhalation exposure time, $t_{n,m}$, is the annual amount of time that population *m* spends in environment *n*, depending upon the characteristics of the receptor (BSC 2005 [DIRS 172827], Section 6.3.2). The breathing rate, BR_n varies among environments.

6.4.8.2 Inhalation of Aerosols from Evaporative Coolers

In 1997, about 73% of surveyed Amargosa Valley residents used evaporative coolers (DOE 1997 [DIRS 100332], p. 20). Therefore, this submodel addresses the inhalation of radionuclides introduced into indoor air by coolers as an exposure pathway. During the operation of evaporative coolers, the indoor air exchange rate is high, the residence time for the air inside the dwelling is short, and only the primary radionuclides and decay products in secular equilibrium in the groundwater are considered in this portion of the submodel.

Evaporative coolers are not expected to result in a large transport of outdoor particulates into the indoor space because the cooler pads filter out the particulates. The potential contribution of contaminated indoor air to the outdoors and to outdoor inhalation exposure is not incorporated in the submodel because the dilution of that air would be large.

Evaporative coolers are not usually operated year-round; most people use them only during the hotter months (BSC 2005 [DIRS 172827] Section 6.3.4.2). Therefore, the indoor inhalation exposure time is modified by an evaporative cooler use factor that represents the fraction of time when evaporative coolers are used. Even during the use period, evaporative coolers are not operated continuously. However, it is assumed that indoor radionuclide concentrations do not decrease when an evaporative cooler is temporarily turned off (Assumption 11).

The inhalation dose attributable to evaporative cooler operation is estimated, using a formula similar to Equation 6.4.8-2, as:

$$D_{inh,e,i} = EDCF_{inh,i}\; Ca_{e,i}\; f_{cooler}\; f_{use} \sum_{n=3}^{4} BR_n \left(\sum_{m} PP_m\, t_{n,m} \right) \qquad \text{(Eq. 6.4.8-3)}$$

where

$D_{inh,e,i}$ = annual dose from inhalation of primary radionuclide *i* from evaporative cooler operation (Sv/yr)

$EDCF_{inh,i}$ = effective dose coefficient for inhalation of radionuclide *i* (Sv/Bq)

$Ca_{e,i}$ = activity concentration of radionuclide i in indoor air attributable to the evaporative cooler operation (Bq/m^3)

n = environment index (n = 3 or n = 4 denotes an indoor environment)

f_{cooler} = fraction of houses with evaporative coolers (dimensionless)

f_{use} = annual evaporative cooler use factor (dimensionless)

and the other parameters are defined in Equation 6.4.8-2.

The activity concentration of radionuclides in indoor air attributable to the operation of evaporative coolers is discussed in the air submodel (Section 6.4.2.2). The annual evaporative cooler use factor and the fraction of houses with evaporative coolers are developed based on a site-specific survey in Amargosa Valley (DOE 1997 [DIRS 100332]) and temperatures representative of present-day and future predicted climatic conditions there, as documented in *Characteristics of the Receptor for the Biosphere Model* (BSC 2005 [DIRS 172827], Section 6.3.4).

6.4.8.3 Inhalation of ^{14}C

The inhalation submodel includes another potential inhalation exposure pathway: the inhalation of gaseous ^{14}C released from irrigated soil. After ^{14}C is released from soil as $^{14}CO_2$, it is dispersed in the outdoor and indoor environments. There are no mechanisms that would greatly change the indoor concentration of ^{14}C relative to the outdoor concentration, so both are considered the same. The inhalation dose from $^{14}CO_2$ is calculated using a method similar to that used to calculate the inhalation dose from resuspended particulates (Section 6.4.8.1):

$$\begin{aligned} D_{inh,g,C-14} &= \sum_n D_{inh,g,C-14,n} \\ &= DCF_{inh,C-14}\, Ca_{g,C-14} \sum_n BR_n \left(\sum_m PP_m\, t_{n,m} \right) \end{aligned} \quad \text{(Eq. 6.4.8-4)}$$

where

$D_{inh,g,C-14}$ = annual dose from inhalation of gaseous ^{14}C (Sv/yr)

$D_{inh,g,C-14,n}$ = annual dose from inhalation of gaseous ^{14}C for environment n (Sv/yr)

$Ca_{g,C-14}$ = activity concentration of ^{14}C in air (Bq/m^3)

$DCF_{inh,C-14}$ = dose coefficient for inhalation of $^{14}CO_2$ (Sv/Bq)

and the other parameters are defined in Equation 6.4.8-2.

As noted in Section 6.4.6.2, the doses from inhalation of ^{14}C as carbon dioxide and ^{14}C in particulate form are combined in the inhalation model.

6.4.8.4 Inhalation of Radon Decay Products

The release of ^{222}Rn from the soil is a result of ^{226}Ra decay in the soil. ^{222}Rn subsequently decays in the air through a series of short-lived decay products, which can be inhaled. In the soil, ^{226}Ra is considered to have originated from irrigation water or from radioactive decay of other primary radionuclides initially present in irrigation water (Section 6.4.1.2).

The dose due to inhalation of radon decay products in indoor environments is evaluated separately when evaporative coolers are off and when they are in operation because of the increase in ventilation caused by the operation of coolers. The total radon dose from ^{222}Rn decay products is evaluated as:

$$\begin{aligned} D_{inh,g,Rn-222} &= \sum_n D_{inh,g,Rn-222,n} \\ &= \sum_{n=1}^{5} Ca_{g,Rn-222,n}\, F_n\, DCF_{inh,Rn-222,n}\, BR_n \left(\sum_m PP_m\, t_{n,m} \right) + \\ &\quad \sum_{n=3}^{4} Ca_{g,Rn-222,e}\, f_{cooler}\, f_{use}\, DCF_{inh,Rn-222,n}\, BR_n \left(\sum_m PP_m\, t_{n,m} \right) \end{aligned} \qquad \text{(Eq. 6.4.8-5)}$$

where

$D_{inh,g,Rn\text{-}222}$ = annual dose from inhalation of ^{222}Rn decay products (Sv/yr)

$D_{inh,g,Rn\text{-}222\ n}$ = annual dose from inhalation of ^{222}Rn decay products for environment n (Sv/yr)

$Ca_{g,Rn\text{-}222,n}$ = activity concentration of ^{222}Rn in environment n (Bq/m^3)

F_n = correction factor to account for the use of evaporative coolers in indoor environment n (dimensionless), 1 for n =1 & 2, and (1 - $f_{cooler} \times f_{use}$) for n = 3 & 4

$Ca_{g,Rn\text{-}222,e}$ = activity concentration of ^{222}Rn in indoor air at a high ventilation rate during evaporative cooler in operation (Bq/m^3)

$DCF_{inh,Rn\text{-}222,n}$ = dose coefficient for inhalation of ^{222}Rn decay products for environment n (Sv/Bq)

and the other parameters are defined in Equations 6.4.8-1, 6.4.8-2, and 6.4.8-3.

The dose coefficient for the inhalation of ^{222}Rn decay products for environment n can be further expressed as:

$$DCF_{inh,Rn-222,n} = DCF_{inh,Rn-222}\, EF_{Rn-222,n} \qquad \text{(Eq. 6.4.8-6)}$$

where

$EF_{Rn\text{-}222,\,n}$	=	equilibrium factor for ^{222}Rn decay products for environment n (dimensionless)
$DCF_{inh,\,Rn\text{-}222}$	=	dose coefficient for inhalation of ^{222}Rn decay products in equilibrium with ^{222}Rn (Sv/Bq).

The equilibrium factor permits estimating the potential alpha energy concentration from the measurement of radon gas (here ^{222}Rn), and is defined as the ratio of the actual potential alpha energy concentration to that prevailing if all decay products in the ^{222}Rn series are in equilibrium with the parent radon. The equilibrium factor depends on the environment, such as indoors and outdoors, primarily due to the availability of the surfaces for plateout of radon decay products unattached or attached to ambient aerosols (BSC 2004 [DIRS 169672], Section 6.6). By combining Equations 6.4.8-5 and 6.4.8-6, the inhalation dose from the ^{222}Rn decay products is evaluated as:

$$\begin{aligned} D_{inh,g,Rn-222} &= \sum_n D_{inh,g,Rn-222,n} \\ &= DCF_{inh,Rn-222} \sum_{n=1}^{5} Ca_{g,Rn-222,n}\ F_n\ EF_{Rn-222,n}\ BR_n \left(\sum_m PP_m\ t_{n,m} \right) + \\ &\quad DCF_{inh,Rn-222} \sum_{n=3}^{4} Ca_{g,Rn-222,e}\ f_{cooler}\ f_{use}\ EF_{Rn-222,n}\ BR_n \left(\sum_m PP_m\ t_{n,m} \right) \end{aligned} \qquad \text{(Eq. 6.4.8-7)}$$

where the parameters are defined in Equations 6.4.8-3, 6.4.8-5, and 6.4.8-6.

^{222}Rn is a decay product of ^{226}Ra and the dose from inhalation of ^{222}Rn decay products is added to the BDCF for ^{226}Ra or to the BDCF of radionuclides that include ^{226}Ra as a long-lived decay product (Table 6.4-3).

The calculation of dose from radon decay products is based on the indoor and outdoor concentrations of radon gas. The indoor radon concentration is equal to outdoor radon concentration plus a contribution of radon from soil beneath the house, which depends on the house ventilation rate. Two ventilation rates are considered in the submodel: a high rate when coolers are in use, and a low rate when coolers are not in use. When evaporative coolers are in use, the contribution of radon from soil beneath the house would be limited because the high ventilation rate would prevent radon buildup. However, when evaporative coolers are not in operation, or for houses that had no evaporative cooler, a higher radon contribution from soil beneath the house would be expected. Radon from household water use (e.g., showers and evaporative coolers), typically, is of minor importance (Section 7.4.3.1). Therefore, the inhalation submodel does not include this pathway.

6.4.8.5 Effective Dose Coefficients for Inhalation

The effective inhalation dose coefficients used in ERMYN are based on dose coefficients obtained from FGR 13 (EPA 2002 [DIRS 175544]). These dose coefficients represent committed effective dose per unit radionuclide intake by inhalation and were developed using tissue weighting factors consistent with ICRP Publication 60 (ICRP 1991 [DIRS 101836]). The dose coefficients for intakes of radionuclides used in the biosphere model are those for adults, consistent with the requirement of 10 CFR 63.312(d) [DIRS 173273] that the RMEI be an adult, and use the commitment period of 50 years. As discussed in Section 6.3.5, the dose contributions from short-lived decay products are combined with those of the long-lived parent radionuclide to produce effective dose coefficients. The effective inhalation dose coefficients are shown in Table 6.4-5. The calculation method can be expressed as:

$$EDCF_{inh,l} = \sum_{s} DCF_{inh,s} \times BN_s \qquad \text{(Eq. 6.4.8-8)}$$

where

$DCF_{inh,s}$ = dose coefficient for inhalation for short-lived radionuclide s in the decay chain of long-lived radionuclide l; for a primary radionuclide $l = i$ (Sv/Bq)

s = index of short-lived radionuclide decay chain under a radionuclide l

BN_s = branching fraction for short-lived radionuclide s in the decay chain of radionuclide l (dimensionless)

and the other parameter is defined in Equation 6.4.8-2.

Similar to Table 6.4-4, the values of effective dose coefficients in Table 6.4-5 are for demonstration purposes only and are not used as the model input. ERMYN uses branching fractions and dose coefficients as inputs to calculate the effective dose coefficients (Section 6.8).

The inhalation dose coefficients depend on the element and the chemical and physical form in which it is inhaled. For a given radionuclide and a given physical form (e.g., the particle size distribution) inhalation dose coefficients have different values depending on the rate of dissolution of a specific compound and the level of absorption to blood. Three default absorption types are used in the source reference (EPA 1999 [DIRS 175452]): Type F (fast dissolution and high level of absorption to blood), Type M (an intermediate rate of dissolution and an intermediate level of absorption to blood), and Type S (slow dissolution and low level of absorption to blood) (EPA 1999 [DIRS 175452], p. 146). Because the chemical form of radionuclides in all environmental media included in the reference biosphere is not known and one value of dose coefficient is used in the biosphere model for all environmental media, the highest values of inhalation dose coefficients from among those available in the source reference (EPA 1999 [DIRS 175452]; EPA 2002 [DIRS 175544]) were chosen as biosphere model input. These values are listed in Table 6.4-5.

Table 6.4-5. Dose Coefficients and Effective Dose Coefficients for Inhalation

Primary Radionuclide [a,b]	Absorption Type	Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Dose Coefficient (DCF_{inh}) [d] Sv/Bq	Effective Dose Coefficient ($EDCF_{inh}$) Sv/Bq
^{14}C	(CO_2)	—	6.24E–12	6.24E–12
	S	—	5.73E–09	5.73E–09
^{36}C	S	—	3.80E–08	3.80E–08
^{79}Se	S	—	6.77E–09	6.77E–09
^{90}Sr D	S S	 ^{90}Y (64.0 h)	1.57E–07 1.50E–09	1.59E–07
^{99}Tc	S	—	1.33E–08	1.33E–08
^{126}Sn D	S S S	 ^{126m}Sb (19.0 min) ^{126}Sb (14%, 12.4 d)	1.55E–07 1.96E–11 3.24E–09	1.55E–07
^{129}I	F	—	3.59E–08	3.59E–08
^{135}Cs	S	—	8.53E–09	8.53E–09
^{137}Cs D	S —	 ^{137m}Ba (94.6%, 2.552 min)	3.92E–08 0.00E+00	3.92E–08
^{242}Pu	F	—	1.13E–04	1.13E–04
^{238}U D	S S — S	 ^{234}Th (24.10 d) ^{234m}Pa (99.80%, 1.17 min) ^{234}Pa (0.33%, 6.7 h)	8.04E–06 7.69E–09 0.00E+00 4.16E–10	8.05E–06
^{238}Pu	F	—	1.08E–04	1.08E–04
^{234}U	S	—	9.40E–06	9.40E–06
^{230}Th	F	—	1.02E–04	1.02E–04
^{226}Ra D	S — — S — S — —	 ^{222}Rn (3.8235 d) ^{218}Po (3.05 min) ^{214}Pb (99.98%, 26.8 min) ^{218}At (0.02%, 2 s) ^{214}Bi (19.9 min) ^{214}Po (99.98%, 1.64×10^{-4} s) ^{210}Tl (0.02%, 1.3 min)	9.51E–06 0.00E+00 [e] 0.00E+00 1.47E–08 0.00E+00 1.54E–08 0.00E+00 0.00E+00	9.54E–06
^{210}Pb D	S S S	 ^{210}Bi (5.012 d) ^{210}Po (138.38 d)	5.61E–06 1.33E–07 4.27E–06	1.00E–05
^{240}Pu	F	—	1.19E–04	1.19E–04
^{236}U	S	—	8.74E–06	8.74E–06
^{232}Th	F	—	1.10E–04	1.10E–04
^{228}Ra D	S S	 ^{228}Ac (6.13 h)	1.60E–05 1.46E–08	1.60E–05
^{232}U	S	—	3.70E–05	3.70E–05
^{228}Th D	S S — — S S — —	 ^{224}Ra (3.66 d) ^{220}Rn (55.6 s) ^{216}Po (0.15 s) ^{212}Pb (10.64 h) ^{212}Bi (60.55 min) ^{212}Po (64.07%, 0.305 μs) ^{208}Tl (35.93%, 3.07 min)	3.97E–05 3.36E–06 0.00E+00 0.00E+00 1.90E–07 3.32E–08 0.00E+00 0.00E+00	4.33E–05

Table 6.4-5. Dose Coefficients and Effective Dose Coefficients for Inhalation (Continued)

Primary Radionuclide [a,b]	Absorption Type	Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Dose Coefficient (DCF_{inh}) [d] Sv/Bq	Effective Dose Coefficient ($EDCF_{inh}$) Sv/Bq
^{243}Am D	F S	 ^{239}Np (2.355 d)	9.57E–05 1.03E–09	9.57E–05
^{239}Pu	F	—	1.19E–04	1.19E–04
^{235}U D	S S	 Th-231 (25.52 h)	8.47E–06 3.34E–10	8.47E–06
^{234}Pa	F	—	2.30E–04	2.30E–04
^{227}Ac D	F S S S — — S — — —	 ^{227}Th (98.62%, 18.718 d) ^{223}Fr (1.38%, 21.8 min) ^{223}Ra (11.434 d) ^{219}Rn (3.96 s) ^{215}Po (1.78 ms) ^{211}Pb (36.1 min) ^{211}Bi (2.14 min) ^{207}Tl (99.72%, 4.77 min) ^{211}Po (0.28%, 0.516 s)	1.56E–04 1.04E–05 1.21E–08 8.68E–06 0.00E+00 0.00E+00 1.20E–08 0.00E+00 0.00E+00 0.00E+00	1.75E–04
^{241}Am	F	—	9.64E–05	9.64E–05
^{237}Np D	F S	 Pa-233 (27.0 d)	4.97E–05 3.86E–09	4.97E–05
^{233}U	S	—	9.59E–06	9.59E–06
^{229}Th D	F S S — — S — — S	 ^{225}Ra (14.8 d) ^{225}Ac (10.0 d) ^{221}Fr (4.8 min) ^{217}At (32.3 ms) ^{213}Bi (45.65 min) ^{213}Po (97.84%, 4.2 μs) ^{209}Tl (2.16%, 2.2 min) ^{209}Pb (3.253 h)	2.39E–04 7.73E–06 8.49E–06 0.00E+00 0.00E+00 3.20E–08 0.00E+00 0.00E+00 6.10E–11	2.55E–04

[a] A "D" indicates that the radionuclide is treated with its short-lived (less than 180 d) decay products.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Branching fractions and half-lives are from Table 6.3.7.

[d] Dose coefficient source: EPA 2002 [DIRS 175544].

[e] Dose coefficient for inhalation of short-lived decay products of ^{222}Rn (alpha emitters) is calculated separately and is equal to 6.62×10^{-9} Sv/Bq (BSC 2005 [DIRS 172827], Section 6.5.4).

Source: Effective dose coefficients were calculated in Excel spreadsheet *Calculation_Effective Dose Coefficients.xls* (Appendix A).

6.4.9 Ingestion Exposure Submodel

When contaminated groundwater is used to produce food for humans or farm animals, the ingestion of that food could result in a radiation dose. Inadvertent ingestion of contaminated soil also results in a radiation dose. The ingestion submodel addresses human doses from ingesting contaminated drinking water, four types of crops (leafy vegetables, other vegetables, fruits, and grain), four types of animal products (meat, poultry, milk, and eggs), freshwater fish, and soil.

The ingestion dose, analogous to the inhalation dose, is calculated as the committed effective dose for the 50-year committed period resulting from 1 year of intake.

The methods for calculating activity concentrations in contaminated soil, crops, animal products, and fish are discussed in Sections 6.1.4 (surface soil submodel), 6.4.3 (plant submodel), 6.4.4 (animal submodel), and 6.4.5 (fish submodel). The source of water for human consumption, animal consumption, irrigation, and fish farming is untreated groundwater. The soil ingestion is considered to be inadvertent; purposeful soil ingestion is excluded from the model. The total ingestion dose for a radionuclide includes contributions from all of these sources, and is expressed as:

$$D_{ing,i} = D_{ing,w,i} + D_{ing,p,i} + D_{ing,d,i} + D_{ing,f,i} + D_{ing,s,i} \qquad \text{(Eq. 6.4.9-1)}$$

where

$D_{ing\ i}$ = annual dose from ingestion of radionuclide *i* (Sv/yr)

$D_{ing,w,i}$ = annual dose from ingestion of radionuclide *i* in drinking water (Sv/yr)

$D_{ing,p,i}$ = annual dose from ingestion of radionuclide *i* in crops (Sv/yr)

$D_{ing,d,i}$ = annual dose from ingestion of radionuclide *i* in animal products (Sv/yr)

$D_{ing,f,i}$ = annual dose from ingestion of radionuclide *i* in fish (Sv/yr)

$D_{ing,s,i}$ = annual dose from inadvertent ingestion of radionuclide *i* in surface soil (Sv/yr).

These ingestion pathways are discussed in detail in the following subsections.

All short-lived radionuclides (half-life less than 180 d) are assumed to be in equilibrium with the long-lived primary radionuclides, and the effective dose coefficients for the long-lived primary radionuclides include their dose contribution (Assumption 2). In addition, for pathways such as ingestion of crops, animal products, and soil, the contribution due to radionuclide decay and ingrowth in surface soil is added into the primary radionuclides. The method is discussed in Section 6.4.1.2.

6.4.9.1 Ingestion of Drinking Water

The drinking water pathway, generally, is an important ingestion pathway for the groundwater scenario (Section 6.13.2). The primary radionuclides in groundwater are assumed to be accompanied by their short-lived decay products. The annual dose from ingestion of radionuclides in drinking water is expressed as:

$$D_{ing,w,i} = EDCF_{ing,i}\ Cw_i\ Uw \qquad \text{(Eq. 6.4.9-2)}$$

where

$EDCF_{ing,i}$ = effective dose coefficient for ingestion of radionuclide i (Sv/Bq); calculation of effective dose coefficients for ingestion is discussed in Section 6.4.9.6

Cw_i = activity concentration of radionuclide i in groundwater (Bq/L)

Uw = annual consumption rate of contaminated drinking water by the receptor (L/yr).

The development of effective ingestion dose coefficients is discussed in Section 6.4.9.6. The annual water consumption rate for the receptor is specified in 10 CFR 63.312(d) [DIRS 173273] as 2 L/d (730 L/yr).

6.4.9.2 Ingestion of Crop Foodstuffs

Ingestion of crops also is an important pathway for the groundwater scenario (Section 6.13.2). Radionuclide decay during storage (between harvest and consumption) is not considered because only long-lived primary radionuclides are of concern for the biosphere model. The annual dose to a receptor from ingestion of primary radionuclide i in foodstuffs should include all radionuclides (l) in a decay chain (if one exists), as discussed in the surface soil submodel (Section 6.4.1.2). The annual dose from ingestion of contaminated crops is expressed as:

$$D_{ing,p,i} = \sum_l D_{ing,p,l} = \sum_l \left[EDCF_{ing,l} \sum_j \left(Cp_{l,j} \, Up_j \right) \right] \qquad \text{(Eq. 6.4.9-3)}$$

where

$D_{ing,p,i}$ = annual dose from ingestion of primary radionuclide i in crops (Sv/yr)

$D_{ing,p,l}$ = annual dose from ingestion of long-lived radionuclide l in decay chain of primary radionuclide i in crops (Sv/yr)

l = index of radionuclide decay chain $l = 0$ for primary radionuclide

$EDCF_{ing,\,l}$ = effective dose coefficient for ingestion of radionuclide l in decay chain of primary radionuclide i (Sv/Bq)

$Cp_{l,j}$ = activity concentration of primary radionuclide l in the crop type j (Bq/kg)

j = index of crop type, $j = 1$ for leafy vegetables, 2 for other vegetables, 3 for fruit, and 4 for grain

Up_j = annual consumption rate of locally produced crop type j (kg/yr)

and the other parameter is defined in Equation 6.4.9-2.

The calculation of radionuclide concentrations in crops is discussed in the plant submodel (Section 6.4.3). The consumption rates used in Equation 6.4.9-3 apply only to locally produced crops (BSC 2005 [DIRS 172827], Section 6.4.2); imported crops are considered to be uncontaminated.

6.4.9.3 Ingestion of Animal Products

Animal product foodstuffs may become contaminated if animals are raised using contaminated feed and water. This submodel does not include radionuclide decay during storage of feed. Contributions from the members of radionuclide decay chains are included, as described previously. For animals, all feed and water is contaminated. The annual dose from ingestion of contaminated animal products is expressed as:

$$D_{ing,d,i} = \sum_{l} D_{ing,d,l} = \sum_{l} \left[EDCF_{ing,l} \sum_{k} \left(Cd_{l,k}\ Ud_{k} \right) \right] \qquad \text{(Eq. 6.4.9-4)}$$

where

$D_{ing,d,i}$ = annual dose from ingestion of primary radionuclide i (Sv/yr)

$D_{ing,d,l}$ = annual dose from ingestion of radionuclide l in decay chain of primary radionuclide i in animal products (Sv/yr)

$Cd_{l,k}$ = activity concentration of primary radionuclide l in the animal product type k (Bq/kg)

k = index of animal products, $k = 1$ for meat, 2 for poultry, 3 for milk, and 4 for eggs

Ud_k = annual consumption rate of locally produced animal product type k (kg/yr)

and the other parameters are defined in Equations 6.4.9-2 and 6.4.9-3.

The calculations of radionuclide concentrations in animal products are discussed in the animal submodel (Section 6.4.4). The consumption rates in Equation 6.4.9-4 apply only to locally produced animal products (BSC 2005 [DIRS 172827], Section 6.4.2); imported animal products are considered to be uncontaminated.

6.4.9.4 Ingestion of Fish

The ingestion of locally produced fish is another potential exposure pathway in the groundwater exposure scenario. As discussed for the fish submodel (Section 6.4.5), groundwater is used as a source of water for fishponds. Radionuclide decay and ingrowth in the ponds is not considered because fishpond water is not expected to be used for very long (Roe 2002 [DIRS 160674]). All short-lived decay products are considered to be in equilibrium with the long-lived parent radionuclide (Section 6.4.5). Contaminated groundwater is assumed to be the only water source for raising fish. The annual dose from ingestion of contaminated fish is calculated as:

$$D_{ing,f,i} = EDCF_{ing,i}\ Cf_i\ Uf \qquad \text{(Eq. 6.4.9-5)}$$

where

$D_{ing,f,i}$ = annual dose from ingestion of primary radionuclide i in fish (Sv/yr)

Cf_i = activity concentration of primary radionuclide i in fish (Bq/kg)

Uf = annual consumption rate of locally produced fish (kg/yr)

and the other parameter is defined in Equation 6.4.9-2.

The parameter, $EDCF_{ing,i}$, is defined in Equation 6.4.9-2. Activity concentrations in fish are discussed in the fish submodel (Section 6.4.5). The consumption rates used in Equation 6.4.9-5 apply only to locally produced fish (BSC 2005 [DIRS 172827], Section 6.4.2); imported fish that the receptor might consume is considered to be uncontaminated.

6.4.9.5 Inadvertent Soil Ingestion

In the groundwater exposure scenario, soils can become contaminated as a result of long-term irrigation and the accumulation of primary radionuclides and their decay products. As a result, in the reference biosphere surface soils contain more radioactivity than any other biosphere component. To account for radionuclide intake with contaminated soil, ERMYN includes inadvertent soil ingestion as one of the receptor exposure pathways. Modeling activity concentrations in the soil involves tracking the accumulation and loss of the primary radionuclide and all decay products of a primary radionuclide (Section 6.4.1.2). The annual dose from inadvertent ingestion of contaminated soil is calculated as:

$$D_{ing,s,i} = \sum_l D_{ing,s,l} = \sum_l \left(EDCF_{ing,l}\ Cs_{m,l}\ Us\right) \qquad \text{(Eq. 6.4.9-6)}$$

where

$D_{ing,s,i}$ = annual dose from ingestion of primary radionuclide i in the surface soil (Sv/yr)

$D_{ing,s,l}$ = annual dose from ingestion of long-lived radionuclide l in the decay chain of a primary radionuclide i in the surface soil (Sv/yr)

$Cs_{m,l}$ = mass-based activity concentration of primary radionuclide l in the soil (Bq/kg)

Us = annual consumption rate of contaminated soil (kg/yr)

and the other parameter is defined in Equations 6.4.9-2.

Radionuclide concentrations in the surface soil are discussed in the surface soil submodel (Section 6.4.1). The radionuclide concentration in soil, $Cs_{m,l}$, is the greater of the garden radionuclide concentrations in the resuspendable layer of soil or in the surface soil (with thickness equal to the tillage depth). The radionuclide concentration in the resuspendable layer of soil is assumed to be at equilibrium, as described in Section 6.4.1.1.

Estimates of soil ingestion rates usually have wide uncertainty distributions, and typical values for adults are on the order of several tens to a few hundred milligrams per day (BSC 2005 [DIRS 172827], Section 6.4.3).

6.4.9.6 Effective Dose Coefficients for Ingestion

The effective ingestion dose coefficients used in ERMYN are based on dose coefficients from FGR 13 (EPA 2002 [DIRS 175544]). These dose coefficients represent committed effective dose per unit radionuclide intake by ingestion and were developed using tissue weighting factors consistent with ICRP Publication 60 (ICRP 1991 [DIRS 101836]). The dose coefficients for intakes of radionuclides used in the biosphere model are those for adults, consistent with the requirement of 10 CFR 63.312(d) [DIRS 173273] that the RMEI be an adult, and use the commitment period of 50 years. As discussed in Section 6.3.5, dose contributions from short-lived decay products are combined with those of the long-lived parent radionuclide to produce effective dose coefficients. The dose coefficients and effective dose coefficients for ingestion are shown in Table 6.4-6. The calculation method can be expressed as:

$$EDCF_{ing,l} = \sum_{s} DCF_{ing,s} \times BN_s \qquad \text{(Eq. 6.4.9-7)}$$

where

$DCF_{ing,s}$ = dose coefficient for ingestion for short-lived radionuclide s in the decay chain of primary radionuclide I; for a primary radionuclide $l = i$ (Sv/Bq)

s = index of short-lived radionuclide decay chain under a radionuclide l

BN_s = branching fraction for short-lived radionuclide s in the decay chain of a radionuclide l (dimensionless)

and the other parameter is defined in Equation 6.4.9-2.

Similar to Tables 6.4-4 and 6.4-5, the values in Table 6.4-6 are for demonstration purposes only. ERMYN uses branching fractions and dose coefficients as inputs to calculate the effective dose coefficients (Section 6.8).

The ingestion dose coefficients for some radionuclides have several values, depending on fraction of radionuclide intake that is absorbed to blood, which depends on the chemical form of the radionuclide. Because the chemical form of radionuclides in all environmental media included in the reference biosphere is not known and one value of dose coefficient is used in the biosphere model for all environmental media, the highest values of dose coefficients for ingestion from among those available in the source reference (EPA 2002 [DIRS 175544]) were chosen as biosphere model input. These values are listed in Table 6.4-6.

Table 6.4-6. Dose Coefficients and Effective Dose Coefficients for Ingestion

Primary Radionuclide [a,b]	Fractional Uptake to Blood	Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Dose Coefficient (DCF_{ing}) [d] Sv/Bq	Effective Dose Coefficient ($EDCF_{ing}$) Sv/Bq
^{14}C	1.0	—	5.81E–10	5.81E–10
^{36}Cl	1.0	—	9.29E–10	9.29E–10
^{79}Se	8E–01	—	2.89E–09	2.89E–09
^{90}Sr D	3E–01 1E–04	 ^{90}Y (64.0 h)	2.77E–08 2.69E–09	3.04E–08
^{99}Tc	5E–01	—	6.42E–10	6.42E–10
^{126}Sn D	2E–02 1E–01 1E–01	 ^{126m}Sb (19.0 min) ^{126}Sb (14%, 12.4 d)	4.77E–09 3.60E–11 2.46E–09	5.15E–09
^{129}I	1.0	—	1.06E–07	1.06E–07
^{135}Cs	1.0	—	2.00E–09	2.00E–09
^{137}Cs D	1.0 —	 ^{137m}Ba (94.6%, 2.552 min)	1.36E–08 0.00E+00	1.36E–08
^{242}Pu	5E–04	—	2.38E–07	2.38E–07
^{238}U D	2E–02 5E–04 — 5E–04	 ^{234}Th (24.10 d) ^{234m}Pa (99.80%, 1.17 min) ^{234}Pa (0.33%, 6.7 h)	4.45E–08 3.40E–09 0.00E+00 5.24E–10	4.79E–08
^{238}Pu	5E–04	—	2.28E–07	2.28E–07
^{234}U	2E–02	—	4.95E–08	4.95E–08
^{230}Th	5E–04	—	2.14E–07	2.14E–07
^{226}Ra D	2E–01 — — 2E–01 — 5E–02 — —	 ^{222}Rn (3.8235 d) ^{218}Po (3.05 min) ^{214}Pb (99.98%, 26.8 min) ^{218}At (0.02%, 2 s) ^{214}Bi (19.9 min) ^{214}Po (99.98%, 1.64 × 10^{-4} s) ^{210}Tl (0.02%, 1.3 min) [e]	2.80E–07 0.00E+00 0.00E+00 1.39E–10 0.00E+00 1.12E–10 0.00E+00 0.00E+00	2.80E–07
^{210}Pb D	2E–01 5E–02 5E–01	 ^{210}Bi (5.012 d) ^{210}Po (138.38 d)	6.96E–07 1.31E–09 1.21E–06	1.91E–06
^{240}Pu	5E–04	—	2.51E–07	2.51E–07
^{236}U	2E–02	—	4.69E–08	4.69E–08
^{232}Th	5E–04	—	2.31E–07	2.31E–07
^{228}Ra D	2E–01 5E–04	 ^{228}Ac (6.13 h)	6.97E–07 4.01E–10	6.97E–07
^{232}U	2E–02	—	3.36E–07	3.36E–07
^{228}Th D	5E–04 2E–01 — — 2E–01 5E–02 — —	 ^{224}Ra (3.66 d) ^{220}Rn (55.6 s) ^{216}Po (0.15 s) ^{212}Pb (10.64 h) ^{212}Bi (60.55 min) ^{212}Po (64.07%, 0.305 μs) ^{208}Tl (35.93%, 3.07 min)	7.20E–08 6.45E–08 0.00E+00 0.00E+00 5.98E–09 2.59E–10 0.00E+00 0.00E+00	1.43E–07

Table 6.4-6. Dose Coefficients and Effective Dose Coefficients for Ingestion (Continued)

Primary Radionuclide [a,b]	Fractional Uptake [d]	Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Dose Coefficient (DCF_{ing}) [d] Sv/Bq	Effective Dose Coefficient ($EDCF_{ing}$) Sv/Bq
^{243}Am D	5E–04 5E–04	 ^{239}Np (2.355 d)	2.03E–07 7.99E–10	2.04E–07
^{239}Pu	5E–04	—	2.51E–07	2.51E–07
^{235}U D	2E–02 5E–04	 ^{231}Th (25.52 h)	4.67E–08 3.36E–10	4.70E–08
^{231}Pa	5E–04	—	4.79E–07	4.79E–07
^{227}Ac D	5E–04 5E–04 1.0 2E–01 — — 2E–01 — — —	 ^{227}Th (98.62%, 18.718 d) ^{223}Fr (1.38%, 21.8 min) ^{223}Ra (11.434 d) ^{219}Rn (3.96 s) ^{215}Po (1.78 ms) ^{211}Pb (36.1 min) ^{211}Bi (2.14 min) ^{207}Tl (99.72%, 4.77 min) ^{211}Po (0.28%, 0.516 s)	3.23E–07 9.02E–09 2.36E–09 1.04E–07 0.00E+00 0.00E+00 1.78E–10 0.00E+00 0.00E+00 0.00E+00	4.36E–07
^{241}Am	5E–04	—	2.04E–07	2.04E–07
^{237}Np D	5E–04 5E–04	 ^{233}Pa (27.0 d)	1.07E–07 8.78E–10	1.08E–07
^{233}U	2E–02	—	5.13E–08	5.13E–08
^{229}Th D	5E–04 2E–01 5E–04 — — 5E–02 — — 2E–01	 ^{225}Ra (14.8 d) ^{225}Ac (10.0 d) ^{221}Fr (4.8 min) ^{217}At (32.3 ms) ^{213}Bi (45.65 min) ^{213}Po (97.84%, 4.2 μs) ^{209}Tl (2.16%, 2.2 min) ^{209}Pb (3.253 h)	5.00E–07 9.95E–08 3.85E–08 0.00E+00 0.00E+00 1.98E–10 0.00E+00 0.00E+00 5.67E–11	6.38E–07

[a] A "D" after a radionuclide symbol denotes that the radionuclide is treated together with the short-lived (less than 180 d) decay products.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Branching fractions and half-lives are from Table 6.3-7.

[d] Source: EPA 2002 [DIRS 175544].

Source: Effective dose coefficients were calculated in Excel spreadsheet *Calculation_Effective Dose Coefficients.xls* (Appendix A).

6.4.10 All-Pathway Dose and Biosphere Dose Conversion Factor Calculations

Biosphere model input to the TSPA consists of radionuclide-specific BDCFs. BDCFs for the groundwater exposure scenario are numerically equal to all-pathway annual doses to the receptor for a unit activity concentration of a specific radionuclide in groundwater. This section explains how the BDCFs are calculated.

6.4.10.1 All-Pathway Doses

The all-pathway annual dose for an individual primary radionuclide is the sum of the effective dose from annual external exposure and the committed effective dose from the annual radionuclide intake into the body by ingestion and inhalation. The annual dose for a radionuclide *I* includes any contributions from the decay products, and is calculated as:

$$D_{all,i} = D_{ext,i} + D_{inh,i} + D_{ing,i} \qquad \text{(Eq. 6.4.10-1)}$$

where

$D_{all,i}$ = all-pathway annual dose from internal and external exposure to primary radionuclide *i* (Sv/yr)

$D_{ext,i}$ = annual dose from external exposure to primary radionuclide *i* (Sv/yr)

$D_{inh,i}$ = annual dose from inhalation exposure to radionuclide *i* (Sv/yr)

$D_{ing,i}$ = annual dose from ingestion exposure to radionuclide *i* (Sv/yr).

6.4.10.2 Biosphere Dose Conversion Factors for the Groundwater Exposure Scenario

Contaminated groundwater is the only source of radionuclides in the biosphere under the groundwater exposure scenario. The dose from all exposure pathways discussed in previous sections is linearly proportional to this source, as summarized in Table 6.4-7. As shown in Table 6.4-7, all quantities calculated in the submodels, including radionuclide concentrations in the environmental media and the dose from various exposure pathways, are proportional to the radionuclide concentration in the groundwater. Thus, the biosphere model contribution to the dose assessment (i.e., BDCFs) can be separated from the source (i.e., radionuclide concentration in the groundwater).

In ERMYN, all-pathway doses could be calculated for any concentration of radionuclides in the water. To calculate the BDCFs, the all-pathway doses are divided by their respective radionuclide concentrations in the water. Thus, the BDCF for a radionuclide is numerically equal to the dose for a unit activity concentration of this radionuclide in the water. For the groundwater scenario, the BDCFs are calculated as:

$$BDCF_i = \frac{D_{all,i}}{Cw_i} \qquad \text{(Eq. 6.4.10-2)}$$

where

$BDCF_i$ = BDCF for radionuclide *I* in the groundwater scenario (Sv/yr per Bq/m^3)

$D_{all,i}$ = all-pathway annual dose for radionuclide *i* (Sv/yr)

Cw_i = activity concentration of radionuclide *i* in groundwater (Bq/m^3).

To support the dose calculations, different sets of BDCFs are generated for the present-day and the future climate states.

Table 6.4-7. Summary of the Biosphere Submodels for the Groundwater Scenario

Submodel	Quantity Calculated in Submodel	Section	Simplified Equation [a]	Equation Number
Soil	Activity concentration of a primary radionuclide in surface soil	6.4.1.1	$Cs_i = K1\ Cw_i$	6.4.1-3
	Activity concentration of a decay product in surface soil	6.4.1.2	$Cs_l = K2\ Cs_i = K2\ K1\ Cw_i$	6.4.1-26, 6.4.1-27
	Activity concentration of a primary radionuclide in resuspendable soil layer	6.4.1.1	$Cs_i = K1'\ Cw_i$	6.4.1-3 6.4.1.4
	Activity concentration of a decay product in resuspendable soil layer	6.4.1.2	$Cs_l = K2'\ Cs_i = K2'\ K1'\ Cw_i$	6.4.1-24 6.4.1-26, 6.4.1-27
Air	Activity concentration of a radionuclide in air from soil resuspension	6.4.2.1	$Ca_i = K3\ Cs_i = K3\ K1\ Cw_i$ *or* $Ca_i = K3\ Cs_i = K3\ K1'\ Cw_i$	6.4.2-1, 6.4.2-2
	Activity concentration of a radionuclide in air from operation of evaporative cooler	6.4.2.2	$Ca_i = K4\ Cw_i$	6.4.2-3
	Activity concentration of radon gas in air	6.4.2.3	$Ca_{Rn-222} = K5\ Cs_{Ra-226}$ $= K5\ K1\ Cw_{Ra-226}$	6.4.2-4
Plant	Activity concentration of a radionuclide in crops from root uptake	6.4.3.1	$Cp_i = K6\ Cs_i = K6\ K1\ Cw_i$	6.4.3-2
	Activity concentration of a radionuclide in crops from foliar interception of irrigation water	6.4.3.2	$Cp_i = K7\ Cw_i$	6.4.3-3, 6.4.3-4
	Activity concentration of a radionuclide in crops from foliar interception of resuspended soil	6.4.3.3	$Cp_i = K8\ Ca_i = K8\ K3\ K1\ Cw_i$	6.4.3-6, 6.4.3-7
Animal	Activity concentration of a radionuclide in animal product from animal feed	6.4.4.1	$Cd_i = K9\ Cp_i = K9\ K10\ Cw_i$	6.4.4-2
	Activity concentration of a radionuclide in animal product from drinking water	6.4.4.2	$Cd_i = K11\ Cw_i$	6.4.4-3
	Activity concentration of a radionuclide in animal product from soil ingestion	6.4.4.3	$Cd_i = K12\ Cs_i = K12\ K1\ Cw_i$ *or* $Cd_i = K12\ Cs_i = K12\ K1'\ Cw_i$	6.4.4-4
Fish	Activity concentration of a radionuclide in fish	6.4.5	$Cf_i = K13\ Cw_i$	6.4.5-2
^{14}C	Activity concentration of ^{14}C in soil	6.4.6.1	$Cs_{C-14} = K14\ Cw_{C-14}$	6.4.6-1
	Activity concentration of ^{14}C in air	6.4.6.2	$Ca_{C-14} = K15\ Cs_{C-14} = K15\ K1\ Cw_{C-14}$	6.4.6-2, 6.4.6-3
	Activity concentration of ^{14}C in crops	6.4.6.3	$Cp_{C-14} = K16\ Cs_{C-14}$ $+ K17\ Ca_{C-14} = K18\ Cw_{C-14}$	6.4.6-6
	Activity concentration of ^{14}C in animal products	6.4.6.4	$Cd_{C-14} = K19\ Cp_{C-14} + K20\ Cw_{C-14} +$ $K21\ Cs_{C-14} = K22\ Cw_{C-14}$	6.4.6-7
External Exposure	External exposure dose	6.4.7.1	$D_{ext,\ l} = K23\ Cs_i = K23\ K1\ Cw_i$	6.4.7-1

Table 6.4-7. Summary of the Biosphere Submodels for the Groundwater Scenario (Continued)

Submodel	Quantity Calculated in Submodel	Section	Simplified Equation [a]	Equation Number
Inhalation	Inhalation dose from airborne particulates	6.4.8.1	$D_{inh,\,i}$ = K24 Ca_i = K24 K3 K1 Cw_i or $D_{inh,\,i}$ = K24 Ca_i = K24 K3 K1' Cw_i	6.4.8-2
	Inhalation dose from evaporative cooler operation	6.4.8.2	$D_{inh,\,i}$ = K25 Ca_i = K25 K4 Cw_i	6.4.8-3
	Inhalation dose from ^{14}C	6.4.8.3	$D_{inh,\,C\text{-}14}$ = K26 $Ca_{C\text{-}14}$ = K27$Cw_{C\text{-}14}$	6.4.8-4
	Inhalation dose from radon decay products	6.4.8.4	$D_{inh,\,Rn\text{-}222}$ = K28 $Ca_{Rn\text{-}222}$ = K29 $Cw_{Ra\text{-}226}$	6.4.8-7
Ingestion	Ingestion dose from water	6.4.9.1	$D_{ing,\,i}$ = K30 Cw_i	6.4.9-2
	Ingestion dose from crops	6.4.9.2	$D_{ing,\,i}$ =K31 Cp_i = K31 K32 Cw_i	6.4.9-3
	Ingestion dose from animal products	6.4.9.3	$D_{ing,\,i}$ = K33 Cd_i = K34 Cw_i	6.4.9-4
	Ingestion dose from fish	6.4.9.4	$D_{ing,\,i}$ = K35 Cf_i =K35 K13 Cw_i	6.4.9-5
	Ingestion dose from soil	6.4.9.5	$D_{ing,\,i}$ = K36 Cs_i = K36 K1 Cw_i or $D_{ing,\,i}$ = K36 Cs_i = K36 K1' Cw_i	6.4.9-6

[a] The proportionality constants, *K1, K2*, … in this table can be derived from the equation identified in the last column. These constants are used to show that the dose is proportional to the source, Cw_i, the groundwater concentration.

6.4.10.3 Pathway Contribution to Dose

The all-pathway dose is the sum of doses from all exposure pathways in the ERMYN, which are addressed in Sections 6.4.7, 6.4.8, and 6.4.9. Therefore, the ERMYN can be used to determine the importance of individual exposure pathways (Section 6.13). The annual all-pathway dose is the sum of the component pathway doses, expressed as:

$$\begin{aligned} D_{all,i} &= \sum_p D_{p,i} = D_{ext,i} + D_{inh,i} + D_{ing,i} \\ &= D_{ext,i} + D_{inh,p,i} + D_{inh,e,i} + D_{inh,g,i} + D_{ing,w,i} + D_{ing,p,i,1} + D_{ing,p,i,2} + D_{ing,p,i,3} \\ &\quad + D_{ing,p,i,4} + D_{ing,d,i,1} + D_{ing,d,i,2} + D_{ing,d,i,3} + D_{ing,d,i,4} + D_{ing,f,i} + D_{ing,s,i} \end{aligned} \qquad \text{(Eq. 6.4.10-3)}$$

where

$D_{all,i}$ = annual all-pathway dose for primary radionuclide *i* (Sv/yr)

$D_{p,i}$ = annual dose from exposure pathway *p* for primary radionuclide *i* (Sv/yr)

and the other parameters are defined in Equations 6.4.7-1, 6.4.8-1, and 6.4.9-2 to 6.4.9-6.

In $D_{ing,p,i,j}$, *j* is the index of crop type, *j* = 1 for leafy vegetables, 2 for other vegetables, 3 for fruit, and 4 for grain. In $D_{ing,d,i,k}$, *k* is the index of animal products, *k* = 1 for meat, 2 for poultry, 3 for milk, and 4 for eggs.

By analogy, the all-pathway BDCF for individual radionuclides are calculated as the sum of pathway BDCFs, which can be expressed, using Equation 6.4.10-2, as:

$$BDCF_i = \sum_p BDCF_{p,i} \quad \text{(Eq. 6.4.10-4)}$$

where

$BDCF_{p,\,i}$ = BDCF of individual pathway p for radionuclide *i* (Sv/yr per Bq/m^3)

and the other parameters are defined in Equations 6.4.10-2 and 6.4.10-3.

The ERMYN can be used to calculate doses and BDCFs for individual long-lived radionuclides in the decay chain of a primary radionuclide, which can provide insight into the importance of individual members of the decay chain following long-term irrigation and radionuclide buildup in surface soil.

6.4.10.4 Use of BDCFs in the Total System Performance Assessment Model

The assessment of annual doses is carried out in the TSPA model using the BDCFs as input parameters. The TSPA model is used to calculate groundwater concentrations at the source of the groundwater in the biosphere (the well or spring) for each radionuclide. Annual doses from individual radionuclides can be estimated as:

$$D_{all,i}(t) = BDCF_i \times Cw_i(t) \quad \text{(Eq. 6.4.10-5)}$$

where

$D_{all,i}(t)$ = time dependent all-pathway annual dose for radionuclide *i* (Sv/yr)

$Cw_i(t)$ = time dependent activity concentration of radionuclide *i* in groundwater (Bq/m^3)

and the other parameter is defined in Equation 6.4.10-2.

The total annual dose is the sum of annual doses from the individual radionuclides tracked by the TSPA model. These individual radionuclides, referred to as primary radionuclides, include the contribution from the short-lived decay products (half-life less than 180 d). The annual dose, the final output from the TSPA model, is used to determine compliance with individual protection standard. The total annual dose is calculated in the TSPA as:

$$D_{total}(t) = \sum_i D_{all,i}(t) \quad \text{(Eq. 6.4.10-6)}$$

where

$D_{total}(t)$ = time-dependent total annual dose to a defined receptor resulting from radionuclides released from the repository, including contributions from all radionuclides considered in the TSPA (Sv/yr)

and the other parameter is defined in Equation 6.4.10-5.

Equation 6.4.10-6 is based on a linear relationship between radionuclide concentrations in the groundwater and the resulting dose. BDCFs are calculated based on a constant activity concentration of radionuclides in groundwater (Assumption 1) and a defined period of continuous prior irrigation with contaminated groundwater resulting in radionuclide buildup in the surface soil. The annual dose for a point in time, *t*, is calculated using activity concentrations in the groundwater at time *t*, *Cw(t)*. Therefore, the product of the groundwater concentration and the BDCF represents the dose that would result if the same radionuclide concentration in the water persisted before time *t* for the defined period of prior irrigation. This calculation is conservative if radionuclide concentrations in the groundwater increase. If radionuclide concentrations in the groundwater decrease quickly with time, the decrease in the true radionuclide buildup in the soil would be slower (i.e., the activity concentration in the soil would be higher) than might be predicted by the surface soil submodel. However, the dose calculated in such a case would be lower than the dose calculated for the times before the radionuclide conentration in the groundwater began to decrease, and thus would not be used for evaluation of compliance with the individual performance standards.

6.5 MATHEMATICAL MODEL FOR THE VOLCANIC ASH EXPOSURE SCENARIO

The mathematical model described in this section is based on the conceptual model for the volcanic ash exposure scenario (Section 6.3.2). Similar to the groundwater exposure scenario, the purpose of the model is to calculate BDCFs for the TSPA model. Because calculation of radionuclide concentrations in deposited or redistributed volcanic ash is not part of the biosphere model, BDCFs are calculated for a unit radionuclide concentration in the source medium. The TSPA model calculates radiation dose as a product of the time-dependent source term and the source-independent BDCF. The time-dependent source term is subject to radioactive decay and various surface processes that can cause redistribution of volcanic ash deposited on the ground and affect radionuclide concentration in the source media.

Analogous to the conceptual model, the mathematical model consists of individual submodels. The relationship among the submodels is shown in Figure 6.3-4 and described in Section 6.3.2. In the mathematical model, linkages among the submodels can be traced by the consistent use of notation among submodels. As described in Section 6.3.2.6, there are seven submodels in the biosphere model for the volcanic ash exposure scenario, two fewer than for the groundwater exposure scenario (the fish and ^{14}C submodels are not relevant). The main difference between the two scenarios is the source of contamination in the reference biosphere. In the groundwater exposure scenario, the source of contamination is the groundwater. In the volcanic ash exposure scenario, the surface soil contaminated by volcanic ash is the source of radionuclides in the reference biosphere. The radionuclide transfers among the environmental media, reflected in the links between the submodels, are similar, and, therefore, many of the modeling assumptions and simplifications for the groundwater exposure scenario apply to the volcanic ash exposure scenario. The final dose calculations, the BDCFs, and their use in the TSPA model, are discussed in Section 6.5.8.

6.5.1 Surface Soil Submodel

The surface soil submodel for the volcanic ash scenario differs from that for the groundwater scenario (Section 6.4.1) primarily because a volcanic eruption and the subsequent ash redistribution would disperse contaminated ash over a large area, while irrigating would contaminate the relatively small farming area. The scenarios also differ because during a volcanic event radionuclides would be deposited nearly instantaneously and would not accumulate in the surface soil. Unlike the groundwater scenario, radionuclides would not be continuously added to the environment, as is the case when contaminated water is used for irrigation. The source of radionuclides for this scenario is volcanic ash containing radioactive waste that is deposited on the ground surface or redistributed to the location occupied by the community that includes the RMEI. The surface soil in this scenario is a mixture of volcanic ash and native soil. The biosphere model for the volcanic ash exposure scenario does not calculate the radionuclide concentration in the soil, unlike the model for the groundwater scenario. This function is carried out outside the biosphere model and the soil is the source (primary) contaminated environmental medium in the biosphere model, similar to the groundwater being the source of contamination in the biosphere model for the groundwater exposure scenario.

The model for the volcanic ash exposure scenario uses two source terms. The two source terms are the radionuclide concentration in the resuspendable layer of soil, $Cs_{m,i}(t)$, in units of mass activity concentration (e.g., Bq/kg) and tillage depth-integrated (areal) radionuclide concentration in surface soil, $Cs_i(t)$, in units of surface activity concentration (e.g., Bq/m^2). The depth over which the integrated concentrations are determined is the tillage depth. Radionuclide concentration in the resuspendable layer of soil is used to calculate inhalation dose from exposure to suspended particulates. Depending on the thickness of ash deposit, time after eruption, and the location, this layer may consist of soil mixed with ash or of only ash. Areal radionuclide concentration is used in estimates of doses from the remaining exposure pathways included in the model, i.e., various ingestion pathways; inhalation of radon decay products, when applicable; and external exposure.

Both source terms, $Cs_i(t)$ and $Cs_{m,i}(t)$, are time dependent because of radionuclide decay and the processes that cause volcanic ash redistribution or removal. These time-dependent source terms are calculated by the disruptive events process model and are not directly used in ERMYN. To calculate the BDCFs, the source terms are separated into two parts, such that:

$$\begin{aligned} Cs_i(t) &= Cs_i \times ST_i(t) \\ Cs_{mc,i}(t) &= Cs_{mc,i} \times ST_{mc,i}(t) \end{aligned} \qquad \text{(Eq. 6.5.1-1)}$$

where

$Cs_i(t)$ = time dependent, depth-integrated (areal) activity concentration of radionuclide i in surface soil (Bq/m^2)

$Cs_{mc,i}(t)$ = time dependent mass activity concentration of radionuclide i in resuspendable layer of surface soil (Bq/kg)

i	=	index of primary radionuclide
Cs_i	=	depth-integrated (areal) activity concentration of radionuclide i in surface soil (Bq/m^2)
$Cs_{mc,i}$	=	mass activity concentration of radionuclide i in resuspendable layer of surface soil (Bq/kg)
$ST_i(t)$	=	time function of volcanic ash source term for depth-integrated (areal) activity concentration of radionuclide i in surface soil (dimensionless)
$ST_{mc,i}(t)$	=	time function of volcanic ash source term for mass activity concentration of radionuclide i in resuspendable layer of surface soil (dimensionless).

Equation 6.5.1-1 is a mathematical treatment of the volcanic ash source, such that the time dependent component is separated from the time-independent component, so radionuclide concentrations in surface soil could be considered constant. The BDCFs are calculated for such constant radionuclide concentrations; specifically, they are calculated for a unit radionuclide concentration. For a unit source, the time function of the volcanic ash source term, $ST_i(t)$ (or $ST_{mc,i}(t)$), is numerically equal to $Cs_i(t)$ (or $Cs_{mc,i}(t)$).

The reference biosphere for the volcanic ash scenario is divided into two areas: cultivated land and noncultivated land. Land use is an important factor considered in the surface soil submodel because the radionuclide concentration in surface soil, and, consequently, the concentration of resuspended radionuclides in air, would differ on cultivated and uncultivated lands. On agricultural and other cultivated land (e.g., gardens), volcanic ash would be uniformly mixed with surface soil during tilling. Such a mechanical mixing would not occur on uncultivated land, although natural surface processes would cause radionuclide redistribution from the original deposits, e.g., during fluvial episodes, and by migration into the soil.

Radionuclide decay and ingrowth in the source are a function of time. Short-lived decay products (half-life less than 180 d) are assumed to be in equilibrium with parent radionuclides (Assumption 2), similar to the groundwater scenario (Section 6.3.5). Dose contributions from short-lived decay products are included with their parent long-lived primary radionuclides. For a long-lived decay product that also is a primary radionuclide, the ERMYN does not consider ingrowth; rather, ingrowth would be considered in the time-dependent source term. For a relatively long-lived decay product that is not a primary radionuclide (e.g., ^{228}Th from decay of ^{232}U), the BDCF of the decay product is initially developed based on secular equilibrium with the long-lived primary radionuclide in volcanic ash source, and then it is added to the BDCF for the primary radionuclide.

6.5.1.1 Cultivated Land

On cultivated lands, tilling and irrigation would uniformly mix the volcanic ash within the surface soil. In the biosphere model, the surface soil extends down to the tilling depth, where all plant roots are assumed to be located (Section 6.4.1 and Assumption 7). It is assumed that the density of surface soil mixed with volcanic ash is the same as that of local native soil (Assumption 12). The source term for the cultivated land is the areal radionuclide concentration in the surface soil. This quantity is calculated outside the biosphere model as a depth-integrated radionuclide concentration. Tilling depth is used in these calculations, consistent with the depth of surface soil in the biosphere model. Unlike the groundwater exposure scenario, no credit is taken in the biosphere model for the radionuclide loss by leaching due to irrigation. Other mechanisms that influence the transport and concentrations of radionuclides in the soil are modeled in the ash redistribution model, FAR, and documented in *Redistribution of Tephra and Waste by Geomorphic Processes Following a Potential Volcanic Eruption at Yucca Mountain, Nevada* (SNL 2007 [DIRS 179347]).

Areal radionuclide concentrations in the surface soil are converted to radionuclide mass concentrations in the surface soil, similar to the groundwater soil submodel. Because it is anticipated that in most realizations, atmospheric dispersion and deposition of volcanic ash will result in a relatively thin layer of ash compared with the thickness of surface soil and that redistributed ash is mixed with native soil, the soil bulk density is assumed to remain unchanged after it is mixed with volcanic ash (Assumption 12). This assumption allows surface soil density to be considered as an independent input parameter that is not a function of the amount of ash contained in the surface soil. The activity concentration in surface soil mass can then be calculated as:

$$Cs_{m,i} = \frac{Cs_i}{\rho \times d} = \frac{Cs_i}{\rho_s} \qquad \text{(Eq. 6.5.1-2)}$$

where

$Cs_{m,i}$ = activity concentration of radionuclide *i* in a mixture of soil and ash on cultivated land (Bq/kg)

ρ = bulk density of the surface soil (kg/m^3)

d = depth of the surface soil in the cultivated land, i.e., the tilling depth (m)

ρ_s = areal density of surface soil (kg/m^2)

and the other parameters are defined in Equation 6.5.1-1.

These soil-related parameters are expected to be the same as those used for the groundwater scenario (SNL 2007 [DIRS 179993]). The radionuclide concentration in a mixture of soil and ash on cultivated land is used to estimate radionuclide transfers to plant foodstuffs and animal products, and transfers directly to the receptor by inadvertent soil ingestion. These processes are modeled in the plant, animal, and ingestion submodels, respectively.

6.5.1.2 Noncultivated Land

On noncultivated lands, only natural processes would cause redistribution and mixing of volcanic ash deposited on the ground, so the assumption of uniform distribution of radionuclide concentration in surface soil is not used. Since the majority of land in Amargosa Valley is not farmed, but would still be affected by a deposition or redistribution of volcanic ash, it is assumed that the source of resuspended particulates for calculation of inhalation dose is a thin layer of surface soil, called the critical thickness, originating in noncultivated land. The critical thickness is the layer from which particles are resuspended, which is, at most, a few millimeters thick (BSC 2004 [DIRS 169672], Section 6.8). Radionuclide concentration in this layer, with dimensions of activity per unit mass, is calculated outside the biosphere model and is the source term for the dose calculations (Equation 6.12-1). Unlike the cultivated land, it cannot be assumed that the density of the material within the critical thickness is that of the soil because ash may constitute a significant fraction of that layer, up to 100%. The density of this layer is, therefore, calculated outside the biosphere model using the information on the amount of ash deposited and redistributed to the area of interest.

The mass radionuclide concentration in the resuspendable layer of soil for noncultivated land, $Cs_{mc,i}$, is used to calculate the radionuclide concentration in air, as shown in Equation 6.5.2-2, which then is used to estimate the human inhalation dose using Equation 6.5.6-2 (Assumption 13).

The areal radionuclide concentration in surface soil, i.e., activity integrated to a depth of surface soil, is used to calculate BDCF contribution from external exposure and from inhalation of radon decay products. This quantity does not depend on the distribution of radionuclides in the surface soil and is thus independent on the land use, i.e., whether the land is cultivated or not. To calculate the BDCF contributions from these two pathways, it is assumed that the radionuclides are located at the soil surface (Assumptions 15 and 16).

6.5.2 Air Submodel

The air submodel for the volcanic ash exposure scenario addresses two processes: the resuspension of particles and the exhalation of radon gas from contaminated soil. Because groundwater is not contaminated in the volcanic ash scenario, radionuclide transfer into indoor air from evaporative coolers is not considered. This submodel also does not consider ^{14}C in the air because ^{14}C is not included, on consequence grounds, as a radionuclide of interest to TSPA for the volcanic scenario (DTN: MO0701RLTSCRNA.000 [DIRS 179334]) (Section 6.1.3).

6.5.2.1 Resuspension of Contaminated Soil Particles

As discussed in Section 6.5.1, volcanic ash would settle on cultivated and noncultivated lands. On cultivated lands, ash would typically be well mixed with uncontaminated soil to the depth of the surface soil. On noncultivated lands, contaminated volcanic ash would be more likely to remain closer to or at the soil surface. Radionuclide concentrations in the air are estimated separately for these two cases. For the deposition of resuspended particles onto plant surface (Section 6.5.3.2), radionuclide concentration in air is predicted using the radionuclide concentration in the surface soil on cultivated lands (Section 6.5.1.1). For the assessment of inhalation exposure (Section 6.5.6.1), radionuclide concentration in the resuspendable soil layer from noncultivated land is used (Section 6.5.1.2).

For resuspended particles deposited on crops, only particles from the local farm fields or gardens would be deposited on the plants (Assumption 13). Therefore, the submodel uses the same mass concentration of radionuclides for the surface soil and for the airborne particles:

$$Ca_{p,i} = Cs_{m,i}\, S \qquad \text{(Eq. 6.5.2-1)}$$

where

$Ca_{p,i}$ = activity concentration of radionuclide i in the air for dust deposition on crops (Bq/m^3)

S = concentration of total resuspended particulates (mass loading) for direct deposition on crops (kg/m^3)

and the other parameter is defined in Equation 6.5.1-2.

The mass loading, S, is characteristic of cultivated areas in an arid or semi-arid climate after a volcanic eruption. The value for crop mass loading used in the volcanic biosphere model is different from the value used in the groundwater model (BSC 2006 [DIRS 177101], Section 7.1).

The formula used to calculate of airborne activity concentrations to determine the inhalation dose is similar to that used in the groundwater model. The formula includes the enhancement factor, defined as the ratio of radionuclide concentration in airborne particles (Bq/kg) to the average surface soil concentration (Bq/kg). Similar to Equation 6.4.2-2, radionuclide concentrations in the air inhaled by the receptor are calculated as:

$$Ca_{h,i,n}(t,T) = f_{enhance,n}\, Cs_{mc,i}(t)\, S_n(t,T) \qquad \text{(Eq. 6.5.2-2)}$$

where

$Ca_{h,i,n}(t)$ = activity concentration of radionuclide i in the air for environment n at time t after a volcanic eruption (Bq/m^3)

n = receptor environment index, $n = 1$ for active outdoors; 2 for inactive outdoors; 3 for active indoors; 4 for asleep indoors; and 5 for away from the contaminated area

$f_{enhance,n}$ = enhancement factor for the activity concentration of resuspended particles for environment n (dimensionless)

$S_n(t)$ = average annual mass loading (the concentration of total resuspended particulates in the air) in environment n at time t following a volcanic eruption (kg/m^3)

T = time of volcanic eruption after repository closure (yr)

and the other parameter is defined in Equation 6.5.1-1.

Mass loading would be higher for some time after a volcanic eruption because there would be more unconsolidated, fine particles on the soil surface that would be readily resuspended by wind, human activity, or other disturbances. Over time, the ash would be consolidated into the soil or removed by erosion, and mass loading would return to levels experienced before the eruption (i.e., nominal mass loading; Assumption 14). This assumption is based on measurements of mass loading after the eruption of Mount St. Helens and other volcanoes (BSC 2006 [DIRS 177101], Sections 6.3 and 6.4). To account for the mass loading reduction effect, radionuclide concentrations in the air used for the calculation of inhalation dose are calculated as a sum of the nominal mass loading and the additional, post-volcanic component. The nominal mass loading corresponds to the pre-eruption conditions as well as the conditions after ash stabilization. The other component corresponds to a time-dependent increase of mass loading, above the nominal level, following a volcanic eruption.

For the volcanic eruption occurring at time T, the mass loading at time t-T after a volcanic eruption and time t after repository closure ($t > T$) is expressed as:

$$S_n(t,T) = S_n + S_{n,v} f(t-T) \qquad \text{(Eq. 6.5.2-3)}$$

where

S_n = nominal annual average mass loading (the concentration of total suspended particulates in air) in environment n (kg/m^3)

$S_{n,v}$ = post-volcanic (v) annual average mass loading in environment n, in addition to S_n, during the first year following a volcanic eruption (kg/m^3)

$f(t\text{-}T)$ = mass loading time function, which describes the rate of change in mass loading at time t after a volcanic eruption at time T, where $f(0) = 1$ and $f(\infty) = 0$

and the other parameter is defined in Equation 6.5.2-2.

Mass loading is an important parameter for the inhalation pathway because the radionuclide concentration in air is proportional to mass loading. Mass loading depends on the environment and human activities, and its values range from about 1×10^{-8} to 1×10^{-5} kg/m^3 (BSC 2006 [DIRS 177101], Section 7.1). Mass loading in indoor environments is considerably lower than in some outdoor environments. Mass loading distributions for nominal conditions, S_n, are the same as in the groundwater scenario (Equation 6.4.2-2). The additional component for post-volcanic conditions, $S_{v,n}$, represents the initial mass loading increase over the nominal levels and is also receptor environment-dependent (BSC 2006 [DIRS 177101], Sections 6.3 and 6.4). The mass loading time function, $f(t)$, is carried into the TSPA model to evaluate the final dose (Section 6.5.8).

By combining Equations 6.5.2-2 and 6.5.2-3, radionuclide concentrations in the air used for the assessment of inhalation dose can be expressed as:

$$\begin{aligned} Ca_{h,i,n}(t,T) &= f_{enhance,n} Cs_{mc,i}(t) S_n(t,T) \\ &= f_{enhance,n} Cs_{mc,i}(t)\big(S_n + S_{n,v} f(t-T)\big) \qquad \text{(Eq. 6.5.2-4)} \\ &= Ca_{nc,i,n}(t) + Ca_{v,i,n}(t,T) \end{aligned}$$

where

$Ca_{nc,i,n}(t)$ = radionuclide concentration of radionuclide *i* in the air for the nominal annual average mass loading in environment *n* at time *t* after repository closure (Bq/m^3)

$Ca_{v,i,n}(t, T)$ = radionuclide concentration of radionuclide *i* in the air for the post-volcanic (*v*) annual average mass loading in environment *n* at time *t* after repository closure conditional upon volcanic eruption at time *T* ($t > T$) (Bq/m^3).

6.5.2.2 Exhalation of Radon from the Ground Surface

One of the environmental transport pathways included in the volcanic ash exposure scenario is the release of radon from volcanic ash deposited on the ground surface. Because the layer of contaminated volcanic ash is expected to be relatively thin (less than 10 cm, Assumption 12 and Appendix G), the use of a radon release factor developed for the groundwater scenario (Section 6.4.2.3), $f_{m,Rn\text{-}222}$ = 0.25 (Bq/m^3)/(Bq/kg), is not valid because it is based on a thickness of ^{226}Ra-contaminated soil that is infinite with respect to radon transport (^{222}Rn diffusion length is on the order of 1 m (UNSCEAR 2000 [DIRS 158644], p. 99)). In the case of volcanic ash, the distribution of radium concentration in the surface soil would be different in the distributary channels and interchannel divides; in addition, on the divides, contaminated volcanic ash would be initially concentrated at the soil surface as a result of primary deposition from the eruption (SNL 2007 [DIRS 179347], Section 6.2). Radon exhalation from soil could be evaluated by using a radon diffusion model. However, a simplified method for estimating radon concentration in the air can be used that is similar to the method described in Section 6.4.2.3. This method uses the relationship between the concentration of ^{226}Ra in the surface soil (Bq/m^2), ^{222}Rn flux density from soil (Bq/(m^2 s)), and ^{222}Rn concentration in the air (Bq/m^3). It is assumed that ^{226}Ra is concentrated in a thin layer on the ground surface and that all of the ^{222}Rn that is produced within that layer is released into the air (Assumption 15).

If the ^{226}Ra concentration on the ground surface were 1 Bq/m^2, then one atom of ^{226}Ra/m^2/s would decay to ^{222}Rn. Based on this assumption, 100% of ^{222}Rn would be released into the air and the ^{222}Rn flux density from soil would be one atom/m^2/s. To convert the number of ^{222}Rn atoms ($N_{Rn\text{-}222}$) into activity of ^{222}Rn ($A_{Rn\text{-}222}$), a half-life ($T_{1/2,Rn\text{-}222}$) of 3.8235 d (3.3×10^5 s, Table 6.3-7) is used as:

$$A_{Rn-222} = \frac{\ln(2)}{T_{1/2,Rn-222}} N_{Rn-222} = \frac{\ln(2)}{3.3\times10^{5}\,(s)} \times 1\,(atom) = 2\times10^{-6}\,(Bq) \quad \text{(Eq. 6.5.2-5)}$$

This indicates that N atoms of ^{222}Rn, where N>>1, has an activity of about N × 2×10^{-6} Bq. Then, ^{222}Rn flux density per 1 Bq/m^2 of ^{226}Ra from the ground surface is expressed as:

$$FD_{Rn-222} = \frac{1\,(atom/(m^2 s))_{Rn-222}}{1\,(Bq/m^2)_{Ra-226}} = 2\times10^{-6}\,\frac{Bq/(m^2 s)}{Bq/m^2} \quad \text{(Eq. 6.5.2-6)}$$

where

FD_{Rn-222} = radon release factor for the volcanic ash scenario, defined as flux density of ^{222}Rn per unit ^{226}Ra-activity on the ground surface ((Bq/(m^{2}s))/(Bq/m^2) = 1/s).

Using the ratio of ^{222}Rn activity concentration in the air to the flux density, CF_{Rn-222}, from a large contaminated area outdoors (which is introduced in the air submodel for the groundwater scenario for calculating the indoor radon concentration; Section 6.4.2.3), the release factor of ^{222}Rn from ^{226}Ra surface concentration is estimated as:

$$f_{s,Rn-222} = FD_{Rn-222} \times CF_{Rn-222} \quad \text{(Eq. 6.5.2-7)}$$

where

$f_{s,Rn-222}$ = ratio of ^{222}Rn activity concentration in the air to the ^{226}Ra activity concentration on the ground surface ((Bq/m^3)/(Bq/m^2) = 1/m)

CF_{Rn-222} = ratio of ^{222}Rn concentration in air to flux density from soil for outdoors ((Bq/m^3)/(Bq/(m^2 s)) = (s/m)

and the other parameter is defined in Equation 6.5.2-6.

Using the release factor for ^{222}Rn ($f_{s,Rn-222}$) and an equation similar to Equation 6.4.2-5, the activity concentration of radon in air is estimated as:

$$\begin{aligned} Ca_{g,Rn-222} &= f_{s,Rn-222}\, Cs_{Ra-226} \\ &= FD_{Rn-222}\, CF_{Rn-222}\, Cs_{Ra-226} \end{aligned} \quad \text{(Eq. 6.5.2-8)}$$

where

$Ca_{g,Rn-222}$ = activity concentration of ^{222}Rn in air (Bq/m^3)

Cs_{Ra-226} = activity concentration of ^{226}Ra in surface soil (Bq/m^2)

and the other parameters are defined in Equation 6.5.2-7.

Using a typical value of CF_{Rn-222} = 300 s/m (BSC 2004 [DIRS 169672], Section 6.6.1), the radon release factor is about 0.0006 (Bq/m^3)/(Bq/m^2). This estimate is an upper bound because all of the radon in the ash is released into the air.

Unlike the groundwater scenario, indoor radon concentrations for the volcanic ash scenario are considered to be the same as the outdoor radon concentration because there is no additional radon source from the soil gas entering the home. Even if new houses were built on contaminated land, the release of ^{222}Rn from soil gas would be negligible because the thin layer of ash would be removed or mixed with the surface soil during home construction. Because an upper bound value for outdoor concentrations is used, it is not necessary to consider an additional indoor radon source.

6.5.3 Plant Submodel

Under the volcanic ash exposure scenario, ash contaminates surface soil and surface water. The biosphere model does not include permanent surface waters (e.g., rivers, lakes, or reservoirs; Section 6.3.1.1), other than the fish pond discussed earlier, and it does not consider surface water contamination. Groundwater could become contaminated if radionuclides from volcanic ash leached into the deep soil, but this process is outside the scope of the biosphere model. Further, no account is taken in the biosphere model of the leaching of radionuclides from irrigated agricultural soils. Radionuclide migration in soil by diffusion is included in the ash redistribution model that is used to generate radionuclide concentrations in the soil (SNL 2007 [DIRS 179347], Section 6.2.3). Therefore, the plant submodel for this scenario only considers root uptake of contaminants from the soil and dust deposition from the air (from resuspended soil).

The plant submodel for the volcanic ash scenario is similar to that for the groundwater scenario. The discussions in Section 6.4.3 on crop type, mechanisms of crop contamination, and radionuclide removal processes are valid for the volcanic ash scenario. Equations presented in this section are the same as those in Section 6.4.3, except that the contaminated water pathway is not considered. The radionuclide concentrations in specific plant foodstuffs are estimated as:

$$Cp_{i,j} = Cp_{root\ i,j} + Cp_{dust\ i,j} \qquad \text{(Eq. 6.5.3-1)}$$

where

$Cp_{i,j}$ = activity concentration of radionuclide *i* in crop type *j* (Bq/kg)

j = crop-type index; j = 1 for leafy vegetables, 2 for other vegetables, 3 for fruit, 4 for grain (used for both human and animals), and 5 for fresh forage feed (used for beef cattle and dairy cows)

$Cp_{root\ i,j}$ = activity concentration of radionuclide *i* in crop type *j* contributed from plant root uptake (Bq/kg)

$Cp_{dust\ i,j}$ = activity concentration of radionuclide *i* in crop type *j* contributed from plant leaf uptake due to the deposition of resuspended particulates on plant surfaces (Bq/kg).

6.5.3.1 Root Uptake

Root uptake is estimated using the same methods as those for the groundwater scenario (Section 6.4.3). It is assumed that all plant roots are in the surface soil (to the tilling depth) to maximize radionuclide uptake (Assumption 7). This approach eliminates the need for determining the fraction of roots in a defined thickness of surface soil. Radionuclides taken up by plant roots are internal to the plants and not subject to removal by weathering or food processing. The activity concentration of radionuclides in crops contributed from root uptake is expressed as:

$$Cp_{root,i,j} = Cs_{m,i}\ F_{s\rightarrow p,i,j}\ DW_j \qquad \text{(Eq. 6.5.3-2)}$$

where

$Cp_{root,i,j}$ = activity concentration of radionuclide i in crop type j contributed from root uptake (Bq/kg$_{wet\ weight}$ of edible portions of the plant)

$Cs_{m,i}$ = activity concentration of radionuclide i in surface of cultivated soil (Bq/kg$_{dry\ soil}$)

$F_{s\rightarrow p,i,j}$ = soil-to-plant transfer factor for radionuclide i and crop type j (Bq/kg$_{dry\ plant}$ per Bq/kg$_{dry\ soil}$)

DW_j = dry-to-wet weight ratio for edible parts of crop type j (kg$_{dry\ plant}$ /kg$_{wet\ plant}$).

The activity concentration of radionuclides in surface soil, $Cs_{m,i}$, is calculated using Equation 6.5.1-2. The soil-to-plant transfer factor and the dry-to-wet weight ratio (Section 6.4.3.1) are expected to be the same for the groundwater and volcanic ash scenarios (BSC 2004 [DIRS 169672], Section 7.1; BSC 2004 [DIRS 169673], Section 7.1).

6.5.3.2 Uptake from Resuspended Soil

The second mechanism of crop contamination is the deposition of resuspended soil on plant surfaces. It should be noted that no account is taken for foliar deposition from the ash fall event. Similar to the groundwater scenario (Section 6.4.3.3), radionuclide concentrations in plant foodstuffs from uptake by foliar interception of airborne particulates are expressed as:

$$Cp_{dust,i,j} = \frac{Da_i\ Ra_j\ T_j}{\lambda_w\ Y_j}\left(1 - e^{-\lambda_w\ t_{g,j}}\right) \qquad \text{(Eq. 6.5.3-3)}$$

where

Da_i = deposition rate of radionuclide i in resuspended soil (Bq/(m^2 d)).

Ra_j = interception fraction for resuspended soil (dimensionless)

T_j = translocation factor (dimensionless)

λ_w = weathering constant (per d), calculated from the weathering half-life (T_w in units of d) by $\lambda_w = \ln(2)/T_w$

$t_{g,j}$ = crop growing time (d)

Y_j = crop biomass or wet yield (kg$_{wet}$/m^2)

and the other parameter is defined in Equation 6.5.3-1.

The translocation factor, weathering constant, crop growing time, and crop biomass are expected to be the same in the groundwater and volcanic ash exposure scenarios (BSC 2004 [DIRS 169672], Section 7.1; BSC 2004 [DIRS 169673] Section 7.1). The deposition rate of contaminated resuspended soil, Da_i, quantifies the combined effect of contaminant removal from the atmosphere by several processes, such as gravitational settling, diffusion, and turbulent transport. The deposition rate is expressed as:

$$Da_i = 8.64 \times 10^4 \, Ca_{p,i} \, V_d \qquad \text{(Eq. 6.5.3-4)}$$

where

$Ca_{p,\,i}$ = activity concentration of radionuclide i in the air used for evaluation of activity deposition on the crops (Bq/m^3).

V_d = deposition velocity for resuspended soil (m/s)

8.64×10^4 = unit conversion factor (s/d).

Activity concentrations of radionuclides in the air are calculated using Equation 6.5.2-1. The deposition velocity for resuspended soil, V_d, is a function of particle size and the environmental parameters that characterize the boundary layer at the soil-atmosphere interface. The value of this parameter is developed considering site-specific conditions in the Yucca Mountain region (BSC 2004 [DIRS 169672] Section 6.2.2).

The interception fraction for resuspended soil, Ra_j, quantifies the initial fractional deposition of radionuclides on plant surfaces from dry deposition. This parameter is crop-type dependent and ranges in value from zero to one. Values for this parameter are estimated using an empirical formula as:

$$Ra_j = 1.0 - e^{-a_j \, DB_j} \qquad \text{(Eq. 6.5.3-5)}$$

where

a_j = an empirical factor (m^2/kg$_{\text{dry biomass}}$)

DB_j = the dry standing biomass of crop type j (kg $_{\text{dry weight}}$/m^2)

and the other parameter is defined in Equation 6.5.3-3.

This empirical equation is adopted from the GENII-S model, including the values of the empirical factor. The recommended values of the empirical factor are 2.9 for leafy vegetables, fresh forage feed, and grain, and 3.6 for root and other vegetables plus fruit (Napier et al. 1988 [DIRS 157927], p. 4.69). The empirical formula is modified for this submodel to use dry biomass rather than wet standing biomass of growing vegetation multiplied by the dry-to-wet weight ratio (Sections 6.4.3.3 and 7.3.3.3).

6.5.4 Animal Submodel

The animal product submodel is used to evaluate the accumulation of radionuclides in animal products that later would be consumed by humans. Four animal products are included in this submodel (Assumption 9). Two pathways are considered for the contamination of animal products: ingestion of contaminated feed and soil. Inhalation of contaminated air is not considered in the submodel because it is much less important than ingestion (Section 7.4.5).

Discussions presented for the groundwater scenario (Section 6.4.4) are valid for the volcanic ash scenario. In addition, as mentioned in the plant submodel, only locally grown fresh forage is considered as feed for beef cattle and dairy cows, and only locally grown stored grain is considered as feed for poultry and laying hens.

Radionuclide decay is not considered in this submodel because the growing time and storage time (time between harvest and consumption) for animal feed are short compared with the half-life of the radionuclides of interest. The radionuclide concentration in animal products ($Cd_{i,k}$) is evaluated as:

$$Cd_{i,k} = Cd_{feed,i,k} + Cd_{soil,i,k} \quad \text{(Eq. 6.5.4-1)}$$

where

$Cd_{i,k}$ = activity concentration of radionuclide i in animal product k (Bq/kg $_{\text{fresh weight}}$ or Bq/L for milk)

k = animal product index; k = 1 for beef, 2 for poultry, 3 for milk, and 4 for eggs

$Cd_{feed,i,k}$ = activity concentration of radionuclide i in animal product k due to ingestion of contaminated animal feed (Bq/kg or Bq/L)

$Cd_{soil,i,k}$ = activity concentration of radionuclide i in animal product k due to ingestion of contaminated soil (Bq/kg or Bq/L).

6.5.4.1 Animal Feed

The radionuclide concentrations in animal products, resulting from the ingestion of contaminated animal feed, is evaluated as:

$$Cd_{feed,i,k} = Fm_{i,k}\ Cp_{i,j}\ Qf_k \quad \text{(Eq. 6.5.4-2)}$$

where

$Fm_{i,k}$ = animal intake-to-animal product transfer coefficient for radionuclide i and animal product k (d/kg $_{\text{fresh weight}}$ or d/L)

$Cp_{i,j}$ = activity concentration of radionuclide i in animal feed j (Bq/kg $_{\text{fresh weight}}$)

j = animal feed index; j = 5 for fresh forage, j = 4 for grain

k = animal product index; k = 1 for beef, 2 for milk, 3 for poultry, and 4 for eggs

Qf_k = animal consumption rate of feed for animal producing product k (kg $_{\text{fresh weight}}$/d).

Radionuclide concentrations in animal feed are calculated in the plant submodel (Section 6.5.3). The transfer coefficients for the animal products and animal consumption rates are considered to be the same in the volcanic ash and groundwater scenarios (BSC 2004 [DIRS 169672], Section 7.1).

6.5.4.2 Animal Soil Ingestion

Animal soil ingestion is an important environmental transport pathway (Section 7.4.5) because soil is the initial source of contamination in the volcanic ash exposure scenario. For consistency with the methods used for the contamination of foodstuffs, radionuclide concentrations in the contaminated soil that an animal ingests are calculated using radionuclide concentrations developed for cultivated land (Equation 6.5.1-2). Radionuclide concentrations in animal products from the ingestion of contaminated soil are evaluated as:

$$Cd_{soil,i,k} = Fm_{i,k} Cs_{m,i} Qs_k \qquad \text{(Eq. 6.5.4-3)}$$

where

$Cs_{m,i}$ = activity concentration of radionuclide i in contaminated soil (Bq/kg)

Qs_k = animal consumption rate of soil (kg/d)

and the other parameters are defined in Equation 6.5.4-2.

Inadvertent soil ingestion by animals is estimated for mature animals, and the values are animal-type specific. Typical literature values for beef cattle and dairy cows are about 1 kg/d (BSC 2004 [DIRS 169672], Section 6.3.2).

6.5.5 External Exposure Submodel

As in the groundwater scenario, the external exposure submodel for the volcanic ash scenario considers a human receptor exposed only to contaminated soil. Other external exposure pathways, air submersion and water immersion, are excluded because of the low contribution likely from air submersion (Section 7.4.8) and the lack of a contaminated source for water immersion. Air submersion could be important during a volcanic eruption, but the ERMYN does not consider any scenarios during a volcanic eruption. Dose from external exposure is calculated as the annual effective dose.

6.5.5.1 External Exposure to Contaminated Ground Surface

Under the volcanic ash scenario, a layer of contaminated volcanic ash would be deposited on the surface of the ground during an eruption. Ash could also be redistributed to the location of the receptor from some other locations. The thickness of the contaminated layer may vary in space and in time. The consequences of a volcanic eruption are the greatest in the first year after an eruption, before the mixing of contaminated ash with uncontaminated soil and the diffusion of contaminants into the soil take place. Because of this, and to simplify the calculations, it was assumed (Assumption 16) that, regardless of the actual distribution of waste within the contaminated soil layer, for calculation of external doses, exposure to contaminated ground surface (infinite, isotropic plane source) is used. The annual external exposure, based on a modification of Equation 6.4.7-1 for the groundwater scenario, is evaluated as:

$$D_{ext,i} = EDCs_{soil,i}\ Cs_i \sum_n f_{ext,i,n} \left(\sum_m PP_m\ (3600 \times t_{n,m}) \right) \qquad \text{(Eq. 6.5.5-1)}$$

where

$D_{ext,i}$ = dose from external exposure to radionuclide i in deposited volcanic ash (Sv/yr)

$EDCs_{soil,i}$ = effective dose coefficient for exposure to a contaminated ground surface for radionuclide i (Sv/s per Bq/m^2); calculation of effective dose coefficients for contaminated ground is discussed in Section 6.5.5.2

Cs_i = activity concentration of radionuclide i in deposited volcanic ash (Bq/m^2)

$f_{ext,i,n}$ = external shielding factor for exposure to radionuclide i in the ground at environment n (dimensionless)

n = environment index; $n = 1$ for active outdoors, 2 for inactive outdoors, 3 for active indoors, 4 for asleep indoors, and 5 for away from contaminated area

m = population group index; $m = 1$ for local outdoor workers, 2 for local indoor workers, 3 for commuters, and 4 for nonworkers

PP_m = fraction of total population in population group m (population proportion) (dimensionless)

$t_{n,m}$ = time spent by population group m in environment n (exposure time) (h/yr).

3600 = unit conversion of hours to seconds; 3,600 (s/h).

Similar to the methods discussed in Section 6.4.7 for the source expressed as activity per unit volume, the short-lived decay products are assumed to be in equilibrium with their long-lived parent radionuclides. This assumption (Assumption 2) is used to calculate the effective dose coefficients for contaminated ground surface. Development of the effective dose coefficients is discussed below.

The external shielding factor, $f_{ext,i,n}$, accounts for the reduction in external exposure provided by dwellings. Outdoors ($n = 1$, 2, and 5), there is no shielding reduction and the value of $f_{ext,i,n}$ is considered to be one. For indoor environments ($n = 3$ and 4), the shielding factor is radionuclide dependent (e.g., strong gamma-ray emitters would be more penetrating and have a higher factor than would weak gamma emitters). Although, the shielding factor can range from zero to one, typical values, even for the most penetrating radiation emissions, do not exceed 0.4. The shielding factor values used in the volcanic ash exposure scenario are the same as those used in the groundwater exposure scenario (BSC 2005 [DIRS 172827], Section 6.6).

The exposure time, $t_{n,m}$, the amount of time spent annually in environment n by population m, depends on the lifestyle of the receptor. The fraction of the total population in population group m, PP_m, is based on Amargosa Valley census data (BSC 2005 [DIRS 172827], Section 6.3). Because the spatial distribution of contamination differs between the two exposure scenarios, the fraction of the population that works outside the contaminated area (i.e., commuters) and the time it would take them to leave the area differs among the exposure scenarios. Consequently, different values for exposure times and population proportions must be used for the two scenarios.

6.5.5.2 Effective Dose Coefficients for Contaminated Ground Surface

The source of dose coefficients for exposure to a contaminated ground surface is FGR 13 (EPA 2002 [DIRS 175544]). Dose contributions from short-lived decay products are combined with those of the long-lived parent radionuclides (Section 6.3.5). Effective dose coefficients (Table 6.5-1) are calculated as the sum of the dose coefficients for a long-lived radionuclide and the short-lived decay products, with consideration of the branching fractions. The calculation formula is expressed as:

$$EDCs_{soil,i} = \sum_{s} DCs_{soil,s} \times BN_s \qquad \text{(Eq. 6.5.5-2)}$$

where

$DCs_{soil,s}$ = dose coefficient for exposure to a contaminated ground surface for radionuclides in a decay chain of radionuclide i (Sv/s per Bq/m^2).

s = index of short-lived radionuclide decay chain under a primary radionuclide i

BN_s = branching fraction for short-lived radionuclide s in the decay chain of primary radionuclide i (dimensionless)

the other parameter is defined in Equation 6.5.5-1.

The values of the effective dose coefficients in Table 6.5-1 are for demonstration purposes only and are not used as inputs to the biosphere model. ERMYN uses branching fractions and dose coefficients as inputs to calculate the effective dose coefficients (Section 6.9).

Table 6.5-1. Dose Coefficients and Effective Dose Coefficients for Exposure to Contaminated Ground Surface

Primary Radionuclide [a,b]	Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Dose Coefficient [d] (*DCs_{soil}*) (Sv/s)/(Bq/m^2)	Effective Dose Coefficient (*$EDCs_{soil}$*) (Sv/s)/(Bq/m^2)
^{90}Sr D	 ^{90}Y (64.0 h)	1.64E–18 1.10E–16	1.12E–16
^{99}Tc	—	6.49E–20	6.49E–20
^{126}Sn D	 ^{126m}Sb (19.0 min) ^{126}Sb (14%, 12.4 d)	4.83E–17 1.54E–15 2.71E–15	1.97E–15
^{137}Cs D	 ^{137m}Ba (94.6%, 2.552 min)	2.99E–18 5.78E–16	5.50E–16
^{242}Pu	—	4.98E–19	4.98E–19
^{238}U D	 ^{234}Th (24.10 d) ^{234m}Pa (99.80%, 1.17 min) ^{234}Pa (0.33%, 6.7 h)	4.24E–19 7.50E–18 1.08E–16 1.80E–15	1.22E–16
^{238}Pu	—	6.26E–19	6.26E–19
^{234}U	—	5.86E–19	5.86E–19
^{230}Th	—	6.37E–19	6.37E–19
^{226}Ra D	 ^{222}Rn (3.8235 d) ^{218}Po (3.05 min) ^{214}Pb (99.98%, 26.8 min) ^{218}At (0.02%, 2 s) ^{214}Bi (19.9 min) ^{214}Po (99.98%, 1.64 × 10^{-4} s) ^{210}Tl (0.02%, 1.3 min)	6.11E–18 3.82E–19 8.64E–21 2.40E–16 3.65E–18 1.44E–15 7.91E–20 0.00E+00	1.69E–15
^{210}Pb D	 ^{210}Bi (5.012 d) ^{210}Po (138.38 d)	2.13E–18 3.51E–17 8.07E–21	3.72E–17
^{240}Pu	—	6.01E–19	6.01E–19
^{236}U	—	5.03E–19	5.03E–19
^{232}Th	—	4.55E–19	4.55E–19
^{228}Ra D	 ^{228}Ac (6.13 h)	0.00E+00 9.38E–16	9.38E–16
^{232}U	—	8.08E–19	8.08E–19
^{228}Th D	 ^{224}Ra (3.66 d) ^{220}Rn (55.6 s) ^{216}Po (0.15 s) ^{212}Pb (10.64 h) ^{212}Bi (60.55 min) ^{212}Po (64.07%, 0.305 μs) ^{208}Tl (35.93%, 3.07 min)	2.13E–18 9.15E–18 3.69E–19 1.61E–20 1.35E–16 2.25E–16 0.00E+00 2.97E–15	1.44E–15
^{243}AmD	 ^{239}Np (2.355 d)	4.80E–17 1.54E–16	2.02E–16

Table 6.5-1. Dose Coefficients and Effective Dose Coefficients for Exposure to Contaminated Ground Surface (Continued)

Primary Radionuclide [a,b]	Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Dose Coefficient [d] (*DCs_{soil}*) (Sv/s)/(Bq/m²)	Effective Dose Coefficient (*EDCs_{soil}*) (Sv/s)/(Bq/m²)
^{239}Pu	—	2.84E–19	2.84E–19
^{235}U D	 ^{231}Th (25.52 h)	1.40E–16 1.56E–17	1.56E–16
^{231}Pa	—	3.78E–17	3.78E–17
^{227}Ac D	 ^{227}Th (98.62%, 18.718 d) ^{223}Fr (1.38%, 21.8 min) ^{223}Ra (11.434 d) ^{219}Rn (3.96 s) ^{215}Po (1.78 ms) ^{211}Pb (36.1 min) ^{211}Bi (2.14 min) ^{207}Tl (99.72%, 4.77 min) ^{211}Po (0.28%, 0.516 s)	1.41E–19 9.81E–17 7.76E–17 1.21E–16 5.28E–17 1.68E–19 9.49E–17 4.40E–17 5.56E–17 7.41E–18	4.66E–16
^{241}Am	—	2.33E–17	2.33E–17
^{237}Np D	 ^{233}Pa (27.0 d)	2.52E–17 1.86E–16	2.11E–16
^{233}U	—	6.00E–19	6.00E–19
^{229}Th D	 ^{225}Ra (14.8 d) ^{225}Ac (10.0 d) ^{221}Fr (4.8 min) ^{217}At (32.3 ms) ^{213}Bi (45.65 min) ^{213}Po (97.84%, 4.2 μs) ^{209}Tl (2.16%, 2.2 min) ^{209}Pb (3.253 h)	7.90E–17 1.07E–17 1.47E–17 2.84E–17 2.92E–19 1.68E–16 0.00E+00 1.92E–15 3.19E–18	3.46E–16

[a] A "D" after a radionuclide symbol denotes that the radionuclide is treated together with the short-lived (less than 180 d) decay product.
[b] Indented radionuclides are long-lived decay products considered separately from the parents.
[c] Branching fractions and half-lives are from Table 6.3-7.
[d] Dose coefficients source: EPA 2002 [DIRS 175544].

Source: Effective dose coefficients were calculated in Excel spreadsheet *Calculation_Effective Dose Coefficients.xls* (Appendix A).

6.5.6 Inhalation Submodel

The inhalation submodel for the volcanic ash exposure scenario is different than that for the groundwater scenario because radionuclide concentrations in air vary with time after a volcanic eruption (Equation 6.5.2-4). Unlike most other equations presented in Section 6.5, equations related to the inhalation pathway explicitly show the time variables t and T, representing the time after the repository closure and the time of the volcanic eruption, respectively. The inhalation dose is calculated as the annual committed effective dose for the 50-year committed period resulting from annual intake of radionuclides by inhalation. Two sources of contamination in air are considered: resuspended particles (Section 6.5.2.1) and radon gas (Section 6.5.2.2). The total inhalation dose is the sum of the doses from both sources, which is evaluated as:

$$D_{inh,i}(t,T) = D_{inh,p,i}(t,T) + D_{inh,g,i}(t) \qquad \text{(Eq. 6.5.6-1)}$$

where

$D_{inh,i}(t, T)$ = annual dose from inhalation of radionuclide i at time t after repository closure conditional upon a volcanic eruption at time T, where $t > T$ (Sv/yr)

$D_{inh,p,i}(t, T)$ = annual dose from inhalation of radionuclide i resulting from exposure to resuspended particles (p) at time t conditional upon a volcanic eruption at time T (Sv/yr)

$D_{inh,g,i}(t)$ = annual dose from inhalation of radionuclides resulting from gaseous emission (g) of radionuclide i in the ash at time t (Sv/yr).

6.5.6.1 Inhalation of Resuspended Particles

The inhalation dose is calculated considering specific environments associated with human activities and population groups. For this scenario, there are two components to the radionuclide concentrations in the air, one related to nominal mass loading and one related to post-volcanic, time-dependent, mass loading (Section 6.5.2.1). The inhalation dose can be calculated as a sum of the inhalation doses for the nominal mass loading and for the post volcanic increase in mass loading, as:

$$\begin{aligned} D_{inh,p,i}(t,T) &= EDCF_{inh,i} \sum_n Ca_{h,i,n}(t,T) BR_n \left(\sum_m PP_m t_{n,m} \right) \\ &= EDCF_{inh,i} \sum_n f_{enhance} Cs_{mc,i}(t) S_n BR_n \left(\sum_m PP_m t_{n,m} \right) \\ &+ EDCF_{inh,i} \sum_n f_{enhance} Cs_{mc,i}(t) S_{n,v} f(t-T) BR_n \left(\sum_m PP_m t_{n,m} \right) \\ &= D_{inh,p,i}(t) + D_{inh,v,i}(t) f(t-T) \end{aligned} \qquad \text{(Eq. 6.5.6-2)}$$

where

$D_{inh,p,i}(t)$ = annual dose from inhalation of radionuclide i resulting from exposure to resuspended particles at time t after repository closure, conditional on a volcanic eruption at time T, where $t > T$ (Sv/yr)

$EDCF_{inh,i}$ = effective dose coefficient for inhalation of primary radionuclide i (Sv/Bq)

n = environment index; $n = 1$ for active outdoors, 2 for inactive outdoors, 3 for active indoors, 4 for asleep indoors, and 5 for away from the contaminated area

BR_n = breathing rate for environment n (m^3/h)

m = population group index; $m = 1$ for local outdoor workers, 2 for local indoor workers, 3 for commuters, and 4 for nonworkers

PP_m = proportion of population in group m (dimensionless)

$t_{n,m}$ = time spent by population group m in environment n (exposure time) (h/yr)

$D_{inh,p,i}(t)$ = annual dose from inhalation of radionuclide i resulting from exposure to nominal mass loading (p) at time t after repository closure (Sv/yr)

$D_{inh,v,i}(t)$ = annual dose from inhalation of radionuclide i resulting from exposure to post-volcanic mass loading (v) in addition to nominal mass loading during the first year following a volcanic eruption at time t after repository closure (Sv/yr)

and the other parameters are defined in Equations 6.5.2-2, 6.5.2-3 and 6.5.2-4.

The effective dose coefficients for inhalation are discussed in Section 6.4.8.5 and shown in Table 6.4-5. The inhalation exposure time, $t_{n,m}$, is the annual amount of time that population group m spends in environment n, and depends on the lifestyle of the receptor (BSC 2005 [DIRS 172827], Section 6.3.2). The breathing rate, BR_n, varies with the environment. The fraction of the total population in population group m, PP_m, is based on Amargosa Valley census data (BSC 2005 [DIRS 172827], Section 6.3.1).

6.5.6.2 Inhalation of Radon Decay Products

The only gaseous radionuclide considered in the inhalation submodel for the volcanic ash exposure scenario is ^{222}Rn, which would be released from ^{226}Ra in volcanic ash. The radon concentration in the air is estimated using a conversion factor between ^{226}Ra activity concentration on ground and ^{222}Rn activity concentration in air (Section 6.5.2.2). The indoor ^{222}Rn concentration is the same as the outdoor ^{222}Rn concentration (Section 6.5.2.2). For the ^{222}Rn inhalation dose calculation for the volcanic ash scenario, increased home ventilation resulting from operating an evaporative cooler does not need to be taken into account because there is not an additional source of radon entering the house from soil gas. Using the radon inhalation dose coefficient (Section 6.4.8.5), the radon inhalation dose is evaluated as:

$$\begin{aligned} D_{inh,g,Rn-222}(t) &= Ca_{g,Rn-222}(t)\sum_n DCF_{inh,Rn-222,n} BR_n\left(\sum_m PP_m t_{n,m}\right) \\ &= Ca_{g,Rn-222}(t) DCF_{inh,Rn-222}\sum_n EF_{Rn-222,n} BR_n\left(\sum_m PP_m t_{n,m}\right) \end{aligned} \quad \text{(Eq. 6.5.6-3)}$$

where

$D_{inh,g,Rn\text{-}222}(t)$ = annual dose from inhalation of ^{222}Rn decay products at time t after repository closure (Sv/yr)

$DCF_{inh,Rn\text{-}222,n}$ = dose coefficient for inhalation of ^{222}Rn decay products in environment n (Sv/Bq)

$DCF_{inh,Rn\text{-}222}$ = dose coefficient for inhalation of ^{222}Rn decay products at 100 % equilibrium with ^{222}Rn gas

$EF_{Rn\text{-}222,\,n}$ = equilibrium factor for ^{222}Rn decay products in environment n (dimensionless)

and the other parameters are defined in Equations 6.5.2-8 and 6.5.6-2.

The radon inhalation dose contribution is included in the BDCF for ^{226}Ra.

By combining Equations 6.5.6-1 and 6.5.6-2, Equation 6.5.6-1 can be rewritten as:

$$D_{inh,i}(t,T) = D_{inh,p,i}(t) + D_{inh,v,i}(t)\,f(t-T) + D_{inh,g,i}(t) \qquad \text{(Eq. 6.5.6-4)}$$

where all parameters are defined in Equations 6.5.6-1, 6.5.6-2, and 6.5.6-3.

6.5.7 Ingestion Submodel

Because groundwater is not contaminated in the volcanic ash scenario, the ingestion submodel only considers contaminated crops (leafy vegetables, other vegetables, fruits, and grain), contaminated animal products (meat, poultry, milk, and eggs), and inadvertent ingestion of contaminated soil. The ingestion dose, analogous to the inhalation dose, is calculated as the committed effective dose for the 50-year committed period resulting from the annual intake of radionuclides by ingestion. Calculation of radionuclide concentration in the contaminated foodstuffs are discussed in the plant (Section 6.5.3) and animal submodels (Section 6.5.4). The total ingestion dose includes contributions from all these sources, and for an individual radionuclide is expressed as:

$$D_{ing,i} = D_{ing,p,i} + D_{ing,d,i} + D_{ing,s,i} \qquad \text{(Eq. 6.5.7-1)}$$

where

$D_{ing,i}$ = annual dose from ingestion of radionuclide i (Sv/yr)

$D_{ing,p,i}$ = annual dose from ingestion of radionuclide i in crops (Sv/yr)

$D_{ing,d,i}$ = annual dose from ingestion of radionuclide i in animal products (Sv/yr)

$D_{ing,s,i}$ = annual dose from inadvertent ingestion of radionuclide i in surface soil (Sv/yr).

These ingestion pathways are discussed in detail in the following subsections.

6.5.7.1 Ingestion of Crop Foodstuffs

The ingestion of contaminated crops is an important pathway for the volcanic scenario, similar to the groundwater scenario, and includes four types of crop foodstuffs. The storage time from harvest to consumption is not considered because only long-lived radionuclides are of concern in the biosphere model. Annual doses from the ingestion of contaminated crops are evaluated as:

$$D_{ing,p,i} = EDCF_{ing,i} \sum_{j} \left(Cp_{i,j} \; Up_{j} \right) \qquad \text{(Eq. 6.5.7-2)}$$

where

$D_{ing,p,i}$ = annual dose from ingestion of primary radionuclide *i* in crops (Sv/yr)

$EDCF_{ing,i}$ = effective dose coefficient for ingestion of primary radionuclide *i* (Sv/Bq)

$Cp_{i,j}$ = activity concentration of primary radionuclide *i* in crop type *j* (Bq/kg)

j = index of crop type, *j* = 1 for leafy vegetables, 2 for other vegetables, 3 for fruit, and 4 for grain

Up_j = annual consumption rate of locally produced contaminated crop type *j* (kg/yr).

The effective dose coefficients for ingestion are discussed in Section 6.4.9.6 and shown in Table 6.4-6. The activity concentrations of radionuclides in crops are discussed in the plant submodel (Section 6.5.3). The consumption rates used in Equation 6.5.7-2 apply only to locally produced crops (BSC 2005 [DIRS 172827], Section 6.4.2).

6.5.7.2 Ingestion of Animal Products

The ingestion of animal products includes the same four animal product exposure pathways used for the groundwater scenario. The storage time from harvest to consumption is not considered. Annual doses from the ingestion of contaminated animal products are evaluated as:

$$D_{ing,d,i} = EDCF_{ing,i} \sum_{k} \left(Cd_{i,k} \; Ud_{k} \right) \qquad \text{(Eq. 6.5.7-3)}$$

where

$D_{ing,d,i}$ = annual dose from ingestion of primary radionuclide *i* in animal products (Sv/yr)

$Cd_{i,k}$ = activity concentration of primary radionuclide *i* in animal product *k* (Bq/kg)

k = index of animal products, *k* = 1 for meat, 2 for poultry, 3 for milk, and 4 for eggs

Ud_k = annual consumption rate of locally produced animal product *k* (kg/yr)

and the other parameter is defined in Equation 6.5.7-2.

The activity concentrations of radionuclides in animal products are discussed in the animal submodel (Section 6.5.4). The consumption rates used in Equation 6.5.7-3 apply only to locally produced animal products; imported animal products are considered to be uncontaminated (BSC 2005 [DIRS 172827], Section 6.4.2).

6.5.7.3 Inadvertent Soil Ingestion

Inadvertent soil ingestion may be an important pathway for the volcanic ash scenario because contaminated ash deposited on the soil surface and mixed with the soil is the source of contamination. Annual doses from inadvertent ingestion of radionuclides in contaminated soil is evaluated as:

$$D_{ing,s,i} = EDCF_{ing,i}\, Cs_{m,i}\, Us \qquad \text{(Eq. 6.5.7-4)}$$

where

$D_{ing,s,i}$ = annual dose from inadvertent ingestion of primary radionuclide i in the surface soil (Sv/yr)

$Cs_{m,i}$ = activity concentration of a primary radionuclide i in the surface soil of cultivated land (Bq/kg)

Us = annual consumption rate of contaminated soil (kg/yr)

and the other parameter is defined in Equation 6.5.7-2.

The activity concentration of radionuclides in the surface soil is discussed in the surface soil submodel (Section 6.5.1). Estimates of soil ingestion rates have wide uncertainty distributions, with typical values for adults on the order of several tens to a few hundred milligrams per day (BSC 2005 [DIRS 172827], Section 6.4.3).

6.5.8 All-Pathway Dose and Biosphere Dose Conversion Factor Calculation

Under the volcanic ash exposure scenario, contaminated volcanic ash deposited on the soil surface and redistributed to the location of the receptor is the source of radionuclides in the biosphere. Two sources are used for the volcanic ash scenario to model the annual dose to the receptor: the mass radionuclide concentration in the resuspendable soil layer, and the integrated, areal radionuclide concentration in the surface soil. The former is used to calculate the annual dose from inhalation of airborne particulates and the dose from this exposure pathway depends linearly on this source. The areal radionuclide concentration is used as the source for all the remaining pathways and, similarly, the doses from those pathways depend linearly on this source.

6.5.8.1 All-Pathway Dose

The all-pathway annual dose for an individual primary radionuclide is the sum of the annual effective dose from external exposure and the committed effective dose from the annual radionuclide intake into the body by ingestion and inhalation, and is evaluated as:

$$\begin{aligned} D_{all,i}(t,T) &= D_{ext,i}(t) + D_{inh,i}(t,T) + D_{ing,i}(t) \\ &= D_{ext,i}(t) + D_{ing,i}(t) + D_{inh,g,i}(t) + D_{inh,v,i}(t) f(t-T) + D_{inh,p,i}(t) \\ &= D_{ext,ing,Rn,i}(t) + D_{inh,v,i}(t) f(t-T) + D_{inh,p,i}(t) \end{aligned} \quad \text{(Eq. 6.5.8-1)}$$

where

$D_{all,i}(t,T)$ = all-pathway annual dose from internal and external exposure to radionuclide i at time t after repository closure conditional upon a volcanic eruption occurring at time T, where $t > T$ (Sv/yr)

$D_{ext\ ing,Rn,i}(t)$ = annual dose from external exposure, ingestion, and inhalation of radon decay products for radionuclide i at time t (Sv/yr)

and the other parameters are defined in Equations 6.5.5-1, 6.5.6-1, 6.5.6-2, 6.5.6-4, and 6.5.7-1.

6.5.8.2 Biosphere Dose Conversion Factors for the Volcanic Ash Scenario

The linear dependence of the pathway doses on the source terms is summarized in Table 6.5-2.

Table 6.5-2. Summary of the Biosphere Submodels for the Volcanic Ash Scenario

Submodel	Quantity Calculated in Submodel	Section	Simplified Equation	Equation Number
Soil	Activity concentration of a primary radionuclide on cultivated lands	6.5.1.1	$Cs_{m,i} = K1\ Cs_i$	6.5.1-2
	Activity concentration of a primary radionuclide on noncultivated lands	6.5.1.2	$Cs_{mc,i} = K2\ Cs_i$	6.5.1-2
Air	Activity concentration of a radionuclide in air for dust deposition on crops	6.5.2.1	$Ca_{p,i} = K3\ Cs_i$	6.5.2-1
	Activity concentration of a radionuclide in air from soil resuspension after volcanic eruption (for inhalation)	6.5.2.1	$Ca_{h,i}=L1Cs_{mc,i}$	6.5.2-2
	Activity concentration of radon gas in air after volcanic eruption	6.5.2.2	$Ca_{Rn\text{-}222} = K4\ Cs_{Ra\text{-}226}$	6.5.2-8
Plant	Activity concentration of a radionuclide in crops from root uptake	6.5.3.1	$Cp_i = K5\ Cs_i$	6.5.3-2
	Activity concentration of a radionuclide in crops from foliar interception of resuspended soil	6.5.3.2	$Cp_i = K6\ Ca_i = K6\ K3\ Cs_i$	6.5.3-3 6.5.3-4
Animal	Activity concentration of a radionuclide in animal product from animal feed	6.5.4.1	$Cd_i = K7\ Cp_l = K8\ Cs_i$	6.5.4-2
	Activity concentration of a radionuclide in animal product from soil ingestion	6.5.4.2	$Cd_i = K9\ Cs_i$	6.5.4-3

Table 6.5-2. Summary of the Biosphere Submodels for the Volcanic Ash Scenario (Continued)

Submodel	Quantity Calculated in Submodel	Section	Simplified Equation	Equation Number
External Exposure	External exposure dose	6.5.5.1	$D_{ext,\,i}$ = $K10\ Cs_i$	6.5.5-1
Inhalation	Inhalation dose from airborne particulates	6.5.6.1	$D_{inh,\,i}$ = $L2\ Ca_{h,i}$ = $L1L2\ Cs_{mc,i}$	6.5.6-2
	Inhalation dose from radon decay products	6.5.6.2	$D_{inh,Rn\text{-}222}$ = $K11\ Ca_{Rn\text{-}222}$ = $K11\ K4\ Cs_{Ra\text{-}226}$	6.5.6-3
Ingestion	Ingestion dose from crops	6.5.7.1	$D_{ing,\,i}$ = $K12\ Cp_i$ = $K13\ Cs_i$	6.5.7-2
	Ingestion dose from animal products	6.5.7.2	$D_{ing,\,i}$ = $K14\ Cd_i$ = $K15\ Cs_i$	6.5.7-3
	Ingestion dose from soil	6.5.7.3	$D_{ing,\,i}$ = $K16\ Cs_i$	6.5.7-4

NOTE: The constants in this table are specific to the volcanic ash scenario and are not the same as the constants in Table 6.4-7.

In the simplified equations shown in Table 6.5-2, the proportionality constants (e.g., K1, K2, … to K16 and L1 to L3) can be derived from the referenced equations. The dose from inhalation of particulate matter is proportional to the mass radionuclide concentration in the resuspendable layer of surface soil, $Cs_{mc,i}$ (Bq/kg); the dose from all the remaining exposure pathways are proportional to the activity concentration of radionuclide i in surface soil per unit area, Cs_i (Bq/m^2). The BDCF components can thus be calculated as:

$$BDCF_{ext,ing,Rn,i} = \frac{D_{ext,ing,Rn,i}}{Cs_i}$$

$$BDCF_{inh,v,i} = \frac{D_{inh,v,i}}{Cs_{mc,i}} \qquad \text{(Eq. 6.5.8-2)}$$

$$BDCF_{inh,p,i} = \frac{D_{inh,p,i}}{Cs_{mc,i}}$$

and the annual dose can be calculated as

$$D_{all,i}(t) = BDCF_{ext,ing,Rn,i}\ Cs_i + \left(BDCF_{inh,v,i}\, f(t) + BDCF_{inh,p,i}\right) Cs_{mc,i} \qquad \text{(Eq. 6.5.8-3)}$$

where

$BDCF_{ext,ing,Rn,i}$ = BDCF component for radionuclide i for external exposure, ingestion, and inhalation of radon decay products (Sv/yr per Bq/m^2)

$BDCF_{inh,v,i}$ = BDCF component for radionuclide i for inhalation of particulates at post-volcanic mass loading in addition to nominal mass loading following a volcanic eruption (Sv/yr per Bq/kg)

$BDCF_{inh,p,i}$ = BDCF component for radionuclide i for inhalation of particulates at nominal mass loading following a volcanic eruption (Sv/yr per Bq/kg)

and the other parameters are defined in Equations 6.5.1-1 and 6.5.8-1.

Thus, the biosphere contribution (and input to the TSPA model) can be separated from the source terms. The three radionuclide-specific BDCF components, shown in Equations 6.5.8-2 and 6.5.8-3, are the outputs from the biosphere model for the volcanic ash exposure scenario and are used as inputs in the TSPA model. The two BDCF components for inhalation of airborne particulates, $BDCF_{inh,v,i}$ and $BDCF_{inh,p,i}$, are used with the source term expressed as radionuclide concentration in the resuspendable layer of surface soil. The BDCF component for all the remaining exposure pathways, $BDCF_{ext,ing,Rn,i}$, is combined with the source term expressed as the areal radionuclide concentration in the surface soil.

The biosphere model input to the TSPA includes several additional parameters. These are discussed in Section 6.11.3, which describes the integration of the biosphere model and the TSPA model.

6.6 CONSIDERATION OF MODEL AND PARAMETER UNCERTAINTY

The ERMYN is based on the included FEPs, but it includes many assumptions, simplifications, and idealizations, and, therefore, uncertainties must be considered. Uncertainty in the results of models comes from the conceptual model (e.g., from decisions concerning the inclusion or exclusion of pathways), the mathematical model (e.g., from the use of simplified analytical methods), and the input parameters (e.g., when represented by distributions of parameter values). When models are executed, the conceptual and mathematical model uncertainties are fixed, but if input distributions are used and multiple model simulations are realized, the output will be a range of values that can be used to characterize uncertainty distributions for the output values. The ERMYN has capabilities for simulating biosphere processes using variable inputs. In this section, uncertainty in the ERMYN from the conceptual model, mathematical model, and input parameters are discussed.

6.6.1 Conceptual Model Uncertainty

Uncertainty generated by the conceptual model comes from decisions regarding FEPs screening, assumptions, and the selection of ACMs, but this uncertainty cannot be quantitatively evaluated. However, if a model is constructed carefully from individual submodels, the conceptual model uncertainty usually will be unimportant to overall model uncertainty. In the biosphere model, many submodels have the simple form of *radionuclide concentration in media X = constant of proportionality* × *radionuclide concentration in media Y*, where the constant of proportionality is empirically determined. These constants are generally represented by distributions based on reported variability of measured values, thereby incorporating model uncertainty into the data uncertainty.

FEPs Screening—The biosphere model is based on the comprehensive list of the included FEPs; however, screening decisions to include or exclude FEPs could contribute to model uncertainty. Although this uncertainty is not evaluated quantitatively, it is likely that these decisions add little additional uncertainty because all included FEPs are either explicitly or implicitly represented in the conceptual model (Section 6.7).

Human Receptor—The characteristics of the RMEI are defined by regulation (10 CFR 63.312 [DIRS 173273]). These regulations substantially reduce uncertainty about the dietary and lifestyle characteristics of the receptor and the selection of environmental transport and exposure pathways that are applicable to the receptor. Development of the attributes and behavioral characteristics of the RMEI involves uncertainties related to site-specific information. These uncertainties are considered in input parameter uncertainty (discussed below), rather than conceptual model uncertainty.

Consideration of Human Exposure Pathways—All applicable pathways are considered during development of the conceptual model (Sections 6.3.1 and 6.3.2), and only applicable pathways shown to have little influence on the results are excluded. For example, air submersion and water immersion pathways are not included because numerical comparisons made between dose coefficients and typical exposure times indicate that they are not important when compared with the included pathways (Section 7.4.8). The increase in overall uncertainty in the ERMYN results from not considering pathways with demonstrable inconsequential contributions to the BDCFs is small.

Environmental Transport of Radionuclides—Interaction matrices (Table 6.3-2, groundwater scenario; Table 6.3-4, volcanic ash scenario; Table 6.3-6, verification) are used to summarize radionuclide transfers between biosphere model components (environmental media). Because applicable, important FEPs are considered in the interaction matrices, it is expected that the important radionuclide transfer mechanisms are considered during development of the ERMYN. Of the transfer mechanisms considered, only those shown to have little influence on model results (e.g., inhalation of resuspended particles by livestock; Section 7.4.5) are excluded from the model. Therefore, uncertainty due to omission or exclusion of radionuclide transfer mechanisms is low.

Alternative Conceptual Model—ACMs are discussed in Section 6.3.3. Based on evaluations (Section 7.4), the selected submodels and components are considered more reasonable than the excluded ACMs, and the main uncertainties associated with the ACMs are captured in the ERMYN. Therefore, screening of ACMs added little uncertainty to the final results.

Future Conditions—Regulation 10 CFR 63.305 [DIRS 173273] states that the DOE should not project changes in society, the biosphere (other than climate), human biology, and increases or decreases in human knowledge and technology. Therefore, uncertainty due to changes in the lifestyle and biology of the receptor, or conditions in the biosphere other than climate, is not considered in the ERMYN.

6.6.2 Mathematical Model Uncertainty

Uncertainty associated with mathematical models comes from how accurately a conceptual model is represented by the mathematical equations. Selection of the mathematical model used to express a conceptual model is mainly based on the appropriateness of the model representation and on data availability. When data are not available, assumptions, approximations and simplifications are used to develop a reasonable mathematical model so that the processes can be quantitatively evaluated. Uncertainty associated with the assumptions, approximations and simplifications becomes part of mathematical model uncertainty. Mathematical model uncertainty usually cannot be quantitatively evaluated unless it is included in the input parameters (see discussion on mathematical representation in Section 6.6.1).

Uncertainty for all of the modeling assumptions discussed in Sections 6.3.1.4 and 6.3.2.4 are summarized in Table 6.6-1. The assumptions are constructed to be conservative, i.e., will not underestimate the dose to the RMEI, but not overly conservative, with respect to the implications of compounding conservatism in the ERMYN results. When an assumption is reasonable, uncertainty about how the assumption represents reality is expected to be relatively small. However, assumptions, approximations, and simplifications are necessary to reduce the numerical requirements of the mathematical model and the details required in the associated input data. The tradeoff between model uncertainty and simplified methods is considered acceptable if the dose estimates are not substantially underestimated. This section does not quantitatively evaluate uncertainty associated with the assumptions; rather, it discusses the qualitative uncertainty due to using the assumptions.

The mathematical representations of transport and exposure pathways used in the ERMYN were developed from a review of applicable methods in numerous biosphere and radiological assessment models. Appropriate methods were chosen from among those reviewed and, if necessary, adapted to match site-specific conditions, the requirements of 10 CFR Part 63 [DIRS 173273], and the needs of the TSPA (Sections 6.4, 6.5, 7.1, and 7.3). For the few processes for which no appropriate method had been previously used (e.g., increase in radionuclide concentrations in fish ponds from water evaporation and transfer of radionuclides from water to air during the operation of evaporative coolers), assumptions or new methods were developed generally based on mass conservation arguments (Sections 5, 6.4, and 6.5).

The mathematical model was validated by comparing the computational methods used in the ERMYN to the methods of five published biosphere and radiological assessment models (Section 7). To validate the model, the methods and calculations used in each submodel were compared to the analogous methods and calculations in the validation models. In almost all cases, the methods used by those models produced the same or very similar results to those from the ERMYN. Therefore, it is concluded that the methods used in the ERMYN are well documented and accepted by the scientific community and that the results are consistent with output from other process-level models. Based on the comparisons conducted for model validation, it is concluded that the uncertainty associated with the mathematical methods used to calculate BDCFs is similar to that in other biosphere models.

Table 6.6-1. Uncertainty Considerations for All Assumptions Used in the Model

No.	Assumption Description	Uncertainty Consideration	Conclusion
1	Radionuclide concentrations in the groundwater are constant.	Radionuclide buildup in the soil with time depends on the difference between the rate of radionuclide addition and the rate of removal. Changes in groundwater concentrations over the duration of continuing irrigation may lead to uncertainty in the dose predictions. The uncertainty in the final conditions regarding the radionuclide concentration in the soil would depend on the individual radionuclide and on the time evolution of the radionuclide concentration in groundwater. See also Assumption 5.	Low uncertainty for most radionuclides, higher uncertainty for radionuclides that take a long time to reach equilibrium. This uncertainty is limited by the anticipated slow changes in the groundwater concentration of radionuclides over typical irrigation durations.
2	Short-lived (less than 180 d) decay products are in equilibrium with the long-lived primary radionuclide.	For dose assessment of long-lived radionuclides, this assumption has low uncertainty because even if short-lived decay products are not in secular equilibrium, they will be close.	Low uncertainty biased towards overestimating dose.
3	Radionuclide concentrations in the air are calculated using an annual average irrigation rate.	It is more reasonable to assume crop rotation than to assume single crops are grown forever on a single farm field. By using a distribution for the long-term irrigation input parameter, model uncertainty is considered in input parameter uncertainty.	Input parameters include uncertainty.
4	Harvest removal is compensated by the use of cow manure for fertilizer.	These mechanisms are not modeled because of a lack of input data. This assumption is considered conservative. Uncertainty introduced by this assumption is not evaluated quantitatively.	Uncertainty is not evaluated mathematically but will not underestimate dose.
5	Radionuclides in surface soil are calculated by two methods depending on the specific use of the results in the subsequent steps of the model.	See discussions below under 5a and 5b.	See conclusions below under 5a and 5b.
5a	Radionuclides in tillage depth surface soil are at an average concentration as predicted by the build-up equations over the finite period of continuing irrigation.	For most radionuclides of interest, it takes less than a few hundred years to reach equilibrium in irrigated soil so the precise details of buildup history are of no consequence. For these radionuclides, uncertainty in accumulation is low because the irrigation period is longer than the time required for reaching equilibrium. However, a few radionuclides take thousands of years to reach equilibrium, but the surface soil model takes into account the degree to which equilibrium conditions are achieved. Thus the ERMYN results do include a measure of this uncertainty.	Low uncertainty for most radionuclides, slightly higher uncertainty for radionuclides that take a long time to reach equilibrium in the surface soil. See 5b for the discussion of the effect on resuspended activity.

Table 6.6-1. Uncertainty Considerations for All Assumptions Used in the Model (Continued)

No.	Assumption Description	Uncertainty Consideration	Conclusion
5b	Radionuclides in the upper part of surface soil that is available for resuspension (critical depth) are at equilibrium concentrations, i.e., the rate of addition of activity from irrigation is balanced by the rate of removal by various mechanisms.	For most radionuclides of interest, it takes less than a few years to reach equilibrium in the top few millimeters of irrigated soil. In general, the uncertainty in accumulation is low because the time between mixing (tilling) is longer than the time required to reach equilibrium. However, a few radionuclides take tens of years to reach equilibrium, and, although uncertainty can be estimated for these radionuclides, the ERMYN results do not include this uncertainty.	Low uncertainty for most radionuclides, higher uncertainty for radionuclides that take a long time to reach equilibrium throughout the critical depth. However, uncertainty would be reduced because buildup in thin top layer of soil (e.g., 3 mm for resuspension) could be more rapid.
6	Radionuclides in irrigation water initially deposited on the crop leaf surface, although subject to weathering, are not removed from the quantity reaching the soil surface.	Mathematical evaluation of interception and subsequent weathering of deposited radionuclides is not conducted because crops only retain a fraction of the contaminants from irrigation water (Section 7.4.4). This assumption contributes little uncertainty to the results.	Low uncertainty with bias to overestimate dose.
7	Crop roots are contained in the upper layer of the surface soil (tillage depth), regardless of the actual tillage depth and rooting depth.	Radionuclide concentration in the surface soil at the end of the continuing irrigation period is generally not too dependent on the tillage depth. Further, the majority of the root mass facilitating radionuclide uptake would be within the tillage depth. This assumption contributes little uncertainty.	Low uncertainty
8	Bovines are fed with forage; chickens are fed with grain, both of which are considered to be locally grown.	Animal feeds are based on site-specific information. The plant submodel includes variation in radionuclide concentrations in feed, which partially accounts for uncertainty in the types of animal feed.	Input parameters partially include uncertainty.
9	Animal product types (meat, milk, poultry and eggs) appropriately represent individual food products within a food type.	Each animal product type in the ERMYN model may include more than one product. The most common animal products are selected to represent the groups, and variation is incorporated into input parameter uncertainty.	Input parameters include uncertainty.
10	Dose coefficients for exposure to soil are those for soil contaminated to an infinite depth.	Differences between dose coefficients for infinite and limited soil depths are compared for two sets of dose coefficients (EPA 2002 [DIRS 175544]). The differences are small (10%), and uncertainty due to this assumption is low.	Low uncertainty

Table 6.6-1. Uncertainty Considerations for All Assumptions Used in the Model (Continued)

No.	Assumption Description	Uncertainty Consideration	Conclusion
11	Radionuclide concentration in indoor air does not build up from the use of contaminated water in evaporative coolers; coolers do not affect outdoor air concentrations of radionuclides.	Radionuclide accumulation in indoor air is unlikely because a large volume of air would be circulated. Radionuclide decay is possible, but unlikely because the residence time of the air would be short, even if the evaporative coolers are temporarily turned off. The usage of coolers will not affect outdoor concentrations because of the large mixing volume of outdoor air. Therefore, uncertainty due to this assumption is low.	Low uncertainty
12	The mixing of volcanic ash and surface soil depends on land use.	This assumption allows realistic considerations of volcanic ash mixing with surface soil. Thus, it contributes little uncertainty to the results.	Low uncertainty
13	Resuspended ash deposited on plants comes from cultivated lands, while ash for human inhalation comes from uncultivated lands.	This assumption eliminates considering the mixing of resuspended particles from different lands, as there is no information to evaluate how the mixing occurs. Because inhalation is the predominant pathway, it is conservative to assume that ash is undiluted or only slightly diluted. However, this uncertainty could not be evaluated quantitatively.	Uncertainty not evaluated mathematically.
14	Atmospheric mass loading of particulate matter is time dependent.	Mass loading used for calculation of inhalation dose decreases with time after a volcanic eruption, but the specific decrease rate depends on many factors. Uncertainty due to this assumption is accounted for using a distribution function to describe the decrease rate. Mass loading used for the calculation of radionuclide deposition on crops from soil resuspension is not time dependent. Because inhalation is the predominant pathway, this conservatism is not likely to affect the model result or its uncertainty.	Input parameter includes uncertainty.
15	All radon gas is released from volcanic ash on the ground surface into the atmosphere.	It is conservative to assume that all ^{222}Rn from ^{226}Ra is released into the air. However, uncertainty is not evaluated quantitatively because of dynamic changes in the thickness of contaminated soil and in the radon emanation properties of the contaminated media (soil and ash).	Uncertainty not evaluated mathematically.
16	External exposure for the volcanic scenario is due to contaminated ground surface.	It is conservative to assume that radionuclides deposited on or redistributed to the location of the RMEI as a result of a volcanic event are concentrated on the ground surface. However, uncertainty is not evaluated quantitatively because of dynamic changes in the distribution of the contaminant throughout the soil thickness.	Uncertainty not evaluated mathematically.

6.6.3 Input Parameter Uncertainty

The mathematical models for the groundwater (Section 6.4) and volcanic ash (Section 6.5) scenarios require many input parameters. Typically, parameter uncertainty is represented by probability distribution functions. General considerations of uncertainty in the input parameters is discussed below followed by a list of the input parameters and further discussions of the general parameter uncertainty.

Site-Specific Data—Site-specific and regional information was used to develop parameter distributions in the supporting data documents shown in Figure 1-1. Where necessary, gaps in that information were filled by data published in scientific literature for locations with similar environmental conditions to those in the Amargosa Valley. The resulting parameter distributions, developed to describe the FEPs in the reference biosphere, were ensured to be consistent with the current conditions in the Yucca Mountain region. The consistency was achieved by defining parametric uncertainties to include the range of compatibility with conditions in regions comparable to that surrounding Yucca Mountain.

Parameter Distributions—All ERMYN input parameters can be represented by probability distributions, but fixed values are used for a few parameters. Discussion of parameter uncertainty represented by distribution functions is presented in Section 6.6.3.2.

Fixed Parameter Values—Justification is provided if a fixed value is used for a parameter. In general, fixed values are used for parameters that have little influence on the modeling results or are associated with limited uncertainty and variation. Therefore, parameters with fixed values have relatively minor contributions, and likely add little additional uncertainty to the final BDCF results. An exception is the suite of dose coefficients for intakes of radionuclides. There is a considerable uncertainty associated with their values; however, it is not customary to include uncertainty in dose coefficients in dose assessments conducted for the purpose of demonstrating compliance with regulatory requirements.

Parameter Correlation—For parameters defined by distributions, the probability density functions are considered to vary independently unless information indicates that pairs of parameters are correlated. When parameters are correlated, correlation coefficients are developed, although information on parameter correlation is limited. In general, the effect of neglecting covariance is to imprecisely estimate variability in the results. In the case where results are given by a sum of parameter product (which applies to the majority of the mathematical relations in the biosphere model), for positively correlated parameters, neglecting correlation typically results in underestimating variation in the ERMYN results, and for negatively correlated parameters, neglecting correlation typically results in overestimating variation in the results.

6.6.3.1 List of Input Parameters

Parameter definitions are given in the sections of this report where parameters are introduced in the submodels. A complete list of input parameters, including their use in the groundwater and volcanic ash scenarios, is provided in Table 6.6-2. The table indicates whether the same or different values of a parameter should be used for present-day or future climate conditions and to which scenario the parameter applies. These parameters are grouped based on the submodels for the two scenarios. Because of simplifications in the table, the parameter names may not be exactly the same as those used when the parameter is first described. The parameter notations, shown in the third column, are exactly the same as those used in the appropriate mathematical equation identified in the column labeled “Eqn.”. The characterization of uncertainty is shown, and either a fixed value or a distribution is given. Further discussion of parameter uncertainty is provided in the following sections. The number of values used in each parameter, array, or matrix (e.g., five types of crops, climate change impacts for many agricultural related parameters, and scenario change impacts for some particle resuspension related parameters) is presented, as is a DIRS reference to the report where parameter values are determined and discussed. To be consistent with the requirements of 10 CFR 63.305(b) [DIRS 173273] and 10 CFR 63.305(c) (70 FR 53313 [DIRS 178394]), only those parameters that would be affected by a future change in climate have different values for future conditions.

Table 6.6-2. Summary of Parameters Used in the ERMYN for the Two Scenarios

Submodel	Parameter Name	Symbol	Eqn. [a]	Dist.	Array No. [b]	Climate Change [c]	Scenario Change [d]	Ref. [e]
Surface Soil	Radionuclide concentration in groundwater	Cw_i	6.4.1-1	Fixed	28	Same	Water	Unit source
	Annual irrigation rate	IR	6.4.1-1	Dist.	1 × 2	Different	Water	[DIRS 169673]
	Radionuclide half-life	$T_{d,i}$	6.4.1-1	Fixed	31	Same	Same	Section 6.3.5
	Surface soil erosion rate	ER	6.4.1-31 6.4.1-32	Dist.	1	Same	Water	[DIRS 179993]
	Soil bulk density	ρ	6.4.1-6	Dist.	1	Same	Same	[DIRS 179993]
	Surface soil depth	d	6.4.1-6	Dist.	1	Same	Same	[DIRS 169673]
	Resuspendable soil layer thickness	d_c	6.4.1-6	Dist.	1	Same	Water	[DIRS 169672]
	Soil solid-liquid partition coefficient	Kd_i	6.4.1-28 6.4.1-29	Dist.	17	Same	Water	[DIRS 179993]
	Overwatering rate	OW	6.4.1-28 6.4.1-29	Dist.	1 × 2	Different	Water	[DIRS 169673]
	Volumetric water content	θ	6.4.1-28 6.4.1-29	Dist.	1	Same	Water	[DIRS 179993]
	Radionuclide concentration in ash deposited on the ground	Cs_i	6.5.1-3	Fixed	23	Same	Ash	Unit source
Air	Mass loading for crops	S	6.4.2-1 6.5.2-1	Dist.	1 × 2	Same	Different	[DIRS 177101]
	Mass loading for receptor environments at nominal condition	S_n	6.4.2-2	Dist.	5	Same	Same	[DIRS 177101]
	Mass loading for receptor environments at post-volcanic condition	$S_{v,\,n}$	6.5.2-3	Dist.	5	Same	Ash	[DIRS 177101]
	Resuspension enhancement factor	$f_{enhance,n}$	6.4.2-2 6.5.2-2	Dist.	5 × 2	Same	Different	[DIRS 179993]
	Fraction of radionuclide from water to air	f_{evap}	6.4.2-3	Dist.	1	Same	Water	[DIRS 169672]
	Water evaporation rate	M_{water}	6.4.2-3	Dist.	1	Same	Water	[DIRS 169672]
	Evaporative cooler air flow rate	F_{air}	6.4.2-3	Dist.	1	Same	Water	[DIRS 169672]
	Radon release factor	$f_{m,\,Rn\text{-}222}$	6.4.2-4	Dist.	1	Same	Water	[DIRS 169672]

Table 6.6-2. Summary of Parameters Used in the ERMYN for the Two Scenarios (Continued)

Submodel	Parameter Name	Symbol	Eqn. [a]	Dist.	Array No. [b]	Climate Change [c]	Scenario Change [d]	Ref. [e]
Air (Continued)	Interior wall height	H	6.4.2-5	Dist.	1	Same	Water	[DIRS 169672]
	House ventilation rate (for normal or evaporative condition)	v	6.4.2-5	Dist	1×2	Same	Water	[DIRS 169672]
	Fraction of radon from soil entering into the house	f_{house}	6.4.2-6	Dist.	1	Same	Water	[DIRS 169672]
	Ratio of ^{222}Rn concentration in air to flux density from soil	CF_{Rn-222}	6.4.2-7	Dist.	1	Same	Same	[DIRS 169672]
Plant	Soil-to-plant transfer factor	$F_{s \rightarrow p,i,j}$	6.4.3-2	Dist.	16×5	Same	Same	[DIRS 169672]
	Dry-to-wet weight ratio	DW_j	6.4.3-2	Dist.	5	Same	Same	[DIRS 169673]
	Translocation factor	T_j	6.4.3-3	Dist./Fixed	5	Same	Same	[DIRS 169672]
	Fraction of overhead irrigation	$f_{o,j}$	6.4.3-3	Dist.	5	Same	Water	[DIRS 169673]
	Weathering half-life	T_w	6.4.3-3	Dist.	1	Same	Same	[DIRS 169672]
	Crop growing time	$t_{g,\ j}$	6.4.3-3	Fixed	5×2	Different	Same	[DIRS 169673]
	Crop wet yield	Y_j	6.4.3-3	Dist.	5	Same	Same	[DIRS 169673]
	Daily irrigation rate	IRD_j	6.4.3-4	Dist.	5×2	Different	Water	[DIRS 169673]
	Crop dry biomass	DB_j	6.4.3-5	Dist.	5	Same	Same	[DIRS 169673]
	Irrigation amount per application	IA_j	6.4.3-5	Dist.	5×2	Different	Water	[DIRS 169673]
	Irrigation intensity	I	6.4.3-5	Dist.	1	Same	Water	[DIRS 169673]
	Dry deposition velocity	V_d	6.4.3-7	Dist.	1	Same	Same	[DIRS 169672]
Animal	Animal product transfer coefficient	$Fm_{\ i,k}$	6.4.4-2	Dist.	16×4	Same	Same	[DIRS 169672]
	Animal consumption rate of feed	Qf_k	6.4.4-2	Dist.	4	Same	Same	[DIRS 169672]
	Animal consumption rate of water	Qw_k	6.4.4-3	Dist./Fixed	4	Same	Water	[DIRS 169672]
	Animal consumption rate of soil	Qs_k	6.4.4-4	Dist.	4	Same	Same	[DIRS 169672]
Fish	Bioaccumulation factor	BF_i	6.4.5-1	Dist.	17	Same	Water	[DIRS 169672]
	Water concentration modifying factor	MF_i	6.4.5-2	Dist.	17×2	Different	Water	[DIRS 169672]
^{14}C	^{14}C emission rate constant	$\lambda_{a,C-14}$	6.4.6-1	Fixed	1	Same	Water	[DIRS 169672]

Table 6.6-2. Summary of Parameters Used in the ERMYN for the Two Scenarios (Continued)

Submodel	Parameter Name	Symbol	Eqn. [a]	Dist.	Array No. [b]	Climate Change [c]	Scenario Change [d]	Ref. [e]
^{14}C (Continued)	Annual average wind speed (for crops or inhalation)	U	6.4.6-3	Dist.	1×2	Same	Water	[DIRS 169672]
	^{14}C mixing height (for crops or inhalation)	H_{mix}	6.4.6-3	Fixed	1×2	Same	Water	[DIRS 169672]
	Fraction of soil-derived carbon in plants	Fs	6.4.6-4	Fixed	1	Same	Water	[DIRS 169672]
	Fraction of stable carbon in plants	$Fc_{plant,j}$	6.4.6-4	Fixed	5	Same	Water	[DIRS 169672]
	Fraction of air-derived carbon in plants	Fa	6.4.6-5	Fixed	1	Same	Water	[DIRS 169672]
	Fraction of stable carbon in soil	fc_{soil}	6.4.6-4	Fixed	1	Same	Water	[DIRS 169672]
	Concentration of stable carbon in air	fc_{air}	6.4.6-5	Fixed	1	Same	Water	[DIRS 169672]
	Concentration of stable carbon in water	Fc_{water}	6.4.6-7	Fixed	1	Same	Water	[DIRS 169672]
	Fraction of stable carbon in animal product	$Fc_{anim,\ k}$	6.4.6-7	Fixed	4	Same	Water	[DIRS 169672]
External Exposure	Population proportion	PP_m	6.4.7-1	Dist.	4	Same	Different	[DIRS 172827]
	Exposure time by population group and environment	$t_{n,m}$	6.4.7-1	Dist.	5×4	Same	Different	[DIRS 172827]
	Building shielding factor	$f_{ext\ i,n}$	6.4.7-1	Fixed	31	Same	Same	[DIRS 172827]
	Branching fraction	BN_s	6.4.7-2	Fixed	75	Same	Same	Section 6.3.5
	Dose coefficient for exposure to soil contaminated to an infinite depth	$DCi_{soil,\ i}$	6.4.7-2	Fixed	75	Same	Water	Section 6.4.7.2
	Dose coefficient for exposure to contaminated ground surface	$DCs_{soil,\ i}$	6.5.5-2	Fixed	75	Same	Ash	Section 6.5.5.2
Inhalation	Breathing rate	BR_n	6.4.8-2	Fixed	5	Same	Same	[DIRS 172827]
	Fraction of houses with evaporative coolers	f_{cooler}	6.4.8-3	Dist.	1	Same	Water	[DIRS 172827]
	Evaporative cooler use factor	f_{use}	6.4.8-3	Dist.	1	Different	Water	[DIRS 172827]
	Equilibrium factor for ^{222}Rn decay products	$EF_{Rn\text{-}222,\ n}$	6.4.8-6	Dist.	5	Same	Same	[DIRS 169672]
	Dose coefficient for inhalation of ^{222}Rn decay products at 100% equilibrium	$DCF_{inh,\ Rn\text{-}222}$	6.4.8-6	Fixed	1	Same	Same	[DIRS 172827]
	Dose coefficient for inhalation	$DCF_{inh,s}$	6.4.8-8	Fixed	75	Same	Same	Section 6.4.8.5
Ingestion	Consumption rate of water	Uw	6.4.9-2	Fixed	1	Same	Water	[DIRS 172827]

Table 6.6-2. Summary of Parameters Used in the ERMYN for the Two Scenarios (Continued)

Submodel	Parameter Name	Symbol	Eqn. [a]	Dist.	Array No. [b]	Climate Change [c]	Scenario Change [d]	Ref. [e]
Ingestion (Continued)	Consumption rate of locally produced crop foodstuffs	Up_j	6.4.9-3	Dist.	4	Same	Same	[DIRS 172827]
	Consumption rate of locally produced animal products	Ud_k	6.4.9-4	Dist.	4	Same	Same	[DIRS 172827]
	Consumption rate of locally produced fish	Uf	6.4.9-5	Dist.	1	Same	Water	[DIRS 172827]
	Inadvertent soil ingestion rate	Us	6.4.9-6	Dist.	1	Same	Same	[DIRS 172827]
	Dose coefficient for ingestion	$DCF_{ing,s}$	6.4.9-7	Fixed	75	Same	Same	Section 6.4.9.6

[a] Equation number where the parameter is introduced. The equation for the groundwater scenario is listed unless the parameter is only for the volcanic ash scenario.

[b] The number of values for the parameter, which depends on the radionuclides and elements (i = 31 primary radionuclides included in the ERMYN for the groundwater scenario (fewer for the volcanic scenario); these radionuclides result from total of 75 radionuclides including short-lived radionuclides, 17 elements corresponding to primary radionuclides, 16 elements for transfer factors and coefficients because carbon is a special element), crop types (j = 5 including forage; 4 used for plant ingestion pathways), animal products (k = 4), population groups (m = 4), environments (n = 5), climate conditions (n = 2), and exposure scenarios (n = 2).

[c] Indicates if the parameter values change due to climate conditions, “Same” means the same value is used for all climate states, “Different” means different values are used in different climate states.

[d] Indicates where the parameter is used. “Same” means it is used in both scenarios with the same value, “Different” means it is used in both scenarios with different values, “Water” means it is used only in the groundwater scenario, and “Ash” means it is used only in the volcanic ash scenario.

[e] Reference number for the reports where the parameter values are developed: BSC 2004 [DIRS 169673], SNL 2007 [DIRS 179993], BSC 2006 [DIRS 177101], BSC 2005 [DIRS 172827], and BSC 2004 [DIRS 169672].

6.6.3.2 Consideration of Parameter Uncertainty

As discussed in the previous section, sources of data for parameter development vary with the input parameter types and the available information. 10 CFR 63.114(b) [DIRS 173273] requires that the performance assessment must “account for uncertainties and variabilities in parameter values and provide the technical basis for parameter ranges, probability distributions, or bounding values used in the performance assessment.” This section briefly describes how uncertainties and variabilities in parameter values are accounted for in the parameter distributions and provides the technical bases for the ranges, distributions, or bounding parameter values. Detailed discussions of how parameter values, including uncertainty distributions, were developed can be found in the input parameter source documents (for references, see Table 6.6-3).

Several probability distribution functions are considered. Some distributions that adequately fit available data have ranges that extend beyond the physical or realistic values, e.g., they include negative lengths or ventilation rates. In such cases the distribution has to be truncated to eliminate the possibility of selecting a physically unrealistic value.

When a parameter for a group is developed based on the mean characteristics derived from a sample of a group, the distribution of the parameter represents variation and uncertainty in the mean value. For normal distributions, such parameters are characterized using the mean as the reasonable estimate and the standard error as a measure of variance or parameter range (the second type described above). Based on the requirements in 10 CFR 63.305 [DIRS 173273], parameters in this category include the diet and lifestyle of the RMEI (e.g., consumption rates and time spent in various environments), which primarily are used in the external exposure, inhalation, and ingestion submodels.

When parameters describe processes or properties of a group, even if the processes or properties are constant over time or space, the distribution is selected to represent the entire range of variation among individuals within the group. For normal distributions, the distributions are characterized using the mean as a reasonable estimate and the standard deviation as a measure of variance (the first type described above). For many parameters, lognormal distributions better describe the variation, and a geometric mean can be used for a reasonable estimate and the geometric standard deviation can be used for describing the spread in parameter values. Parameters in this category generally span a large range of values and include many environmental transport and agricultural parameters (e.g., transfer factors, irrigation rates, biomass, and dry-wet weight ratio) that are used in the plant, animal, and fish submodels.

If evidence indicates that a parameter contributes little to the dose from a given radionuclide, or if it has little impact on model uncertainty, then a fixed value may be used for the input parameter. Parameters in this category include the transfer of ^{14}C among soil, air, crop, and animal product components, which are evaluated in the ^{14}C special submodel. Fixed values are also used for quantities, such as dose coefficients, whose values are selected from the available data sets, rather then measured or estimated from the experimental data. The dose coefficients are inherently uncertain quantities, however, when used in the process of assessing compliance, are selected as fixed values and are assumed not to be uncertain.

Cumulative distributions, or piece-wise linear distributions, are used for some model input parameters. A cumulative distribution is defined as a set of input values and corresponding cumulative probabilities developed based on empirical data points. The probability density function for this type of distribution may contain distinct, irregular peaks.

This section provides a brief summary of parameter uncertainty consideration because every parameter is developed separately based on available information. Details concerning development of the input parameters are presented in the five parameter reports (BSC 2004 [DIRS 169673]; SNL 2007 [DIRS 179993]; BSC 2006 [DIRS 177101]; BSC 2005 [DIRS 172827]; BSC 2004 [DIRS 169672]), as discussed in Section 1 and Figure 1-1.

6.6.3.3 Summary of Parameter Uncertainty

A summary of representative parameter values and probability distribution functions are presented in Table 6.6-3. The table includes parameter values and uncertainty information taken from the five parameter reports (Figure 1-1), including the distribution type, the mean or mode, standard deviation or standard error, range (minimum and maximum), and brief notes describing uncertainty considerations. The parameter values in Table 6.6-3 are shown in accordance with the ERMYN parameters shown in Table 6.6-2. To show all parameter values and distributions, every individual value for the parameters with subscript indices in the mathematical model is shown in Table 6.6-3.

The parameter values listed in Table 6.6-3 use the same units as the data reports (Figure 1-1). The units may not be the same as those in the equations shown in Sections 6.4 and 6.5. This is not a discrepancy between the model and inputs, as the GoldSim software automatically converts the units used for the data to those used on the underlying equations and verifies that the dimensions of the parameters used are correct.

6.6.4 Uncertainty of Model Results

When models that use parameters with distribution functions are realized, parameter values are sampled from the range of possible values. For each realization, the values are fixed for the run to produce one deterministic calculation for the entire model. However, the realized parameter values change for each realization, and, therefore, the model results differ for each realization. After many realizations, the results yield a distribution of possible outcomes (i.e., a distribution function) commensurate with the uncertainty in input parameters, thereby capturing the uncertainty in the result. This simulation method, built into the GoldSim software, includes two sampling methods: Monte Carlo and Latin Hypercube; the biosphere model makes use of the latter. A detailed description of the software is presented below.

Uncertainty in the ERMYN results is considered for all of the input parameters that are represented by uncertainty distributions. Uncertainty from conservative assumptions, approximations, and simplifications cannot be evaluated quantitatively.

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Surface Soil	Radionuclide concentration in groundwater		Fixed	Bq/m^3	1	—	—	—	Unit activity concentration – used as a source term for the groundwater scenario
	Annual average irrigation rate, all crops [e]	Present-day climate/ Lower bound monsoon climate	Normal	m/yr	0.95	0.08	0.74	1.16	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
		Upper bound glacial transition climate			0.50	0.04	0.40	0.60	
		Lower bound glacial transition climate	Fixed	m/yr	0.88	—	—	—	
		Upper bound monsoon climate			0.52				
	Annual average irrigation rate, garden crops, present-day climate[f]		Normal	m/yr	0.91	0.09	0.69	1.13	Section 6.4.1.1
	Annual average irrigation rate, field crops, present-day climate		Normal	m/yr	1.78	0.14	1.41	2.14	Section 6.4.1.1
	Annual average irrigation rate, garden crops, future climate[f]		Normal	m/yr	0.46	0.04	0.36	0.56	Section 6.4.1.1
	Annual average irrigation rate, field crops, future climate		Normal	m/yr	0.79	0.04	0.69	0.89	Section 6.4.1.1
	Irrigation duration, garden crops		Triangular	yr	25	—	25	250	DTN: MO0609SPASRPBM.004 SNL 2007 [DIRS 179993]
	Irrigation duration, field crops		Triangular	yr	100	—	100	1,000	DTN: MO0609SPASRPBM.004 SNL 2007 [DIRS 179993]
	Radionuclide half-life		Fixed	yr	See reference	—	—	—	Table 6.3-7
	Surface soil erosion rate		Triangular	$kg/(m^2\ yr)$	0.2 (mode)	—	0.2	1.1	DTN: MO0609SPASRPBM.004 SNL 2007 [DIRS 179993]
	Soil bulk density		Triangular	kg/m^3	1500 (mean and mode)	—	1,300	1,700	DTN: MO0609SPASRPBM.004 SNL 2007 [DIRS 179993]
	Surface soil depth (equal to tillage depth)		Uniform	m	0.25	—	0.05	0.30	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
	Depth of resuspendable soil layer		Uniform	m	0.002	—	0.001	0.003	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Surface Soil (Continued)	Soil solid-liquid partition coefficient	Carbon	Lognormal	L/kg	1.8E+01	6.0E+00	5.3E–01	6.2E+02	DTN: MO0609SPASRPBM.004 SNL 2007 [DIRS 179993] Lognormal distributions of partition coefficients are given in terms of geometric mean and standard deviation. Partition coefficients are correlated with the soil-to-plant transfer factors. The rank correlation coefficient is –0.8.
		Chlorine			1.4E–01	6.0E+00	1.3E–03	1.4E+01	
		Selenium			1.5E+02	6.0E+00	4.4E+00	5.1E+03	
		Strontium			2.0E+01	5.5E+00	7.2E–01	5.6E+02	
		Technetium			1.4E–01	6.0E+00	1.3E–03	1.4E+01	
		Tin			4.5E+02	6.0E+00	1.3E+01	1.5E+04	
		Iodine			4.5E+00	7.4E+00	8.9E–02	2.3E+02	
		Cesium			4.4E+03	3.7E+00	1.6E+02	1.3E+05	
		Lead			1.6E+04	4.1E+00	1.0E+03	2.5E+05	
		Radium			3.6E+04	2.2E+01	8.3E+01	1.6E+07	
		Actinium			1.5E+03	6.0E+00	4.3E+01	5.0E+04	
		Thorium			3.0E+03	8.2E+00	4.9E+01	1.8E+05	
		Protactinium			1.8E+03	6.0E+00	5.3E+01	6.2E+04	
		Uranium			3.3E+01	2.5E+01	6.3E–01	1.8E+04	
		Neptunium			2.5E+01	3.3E+00	2.3E+00	2.6E+02	
		Plutonium			1.2E+03	3.3E+00	1.2E+02	1.3E+04	
		Americium			2.0E+03	1.4E+01	1.2E+01	3.3E+05	
	Overwatering rate	Present-day climate	Cumulative	m/yr	0.079	—	0.009 0.030 0.045 0.077 0.129 0.233 0.275	0% 19% 38% 57% 76% 95% 100%	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
		Future climate	Cumulative	m/yr	0.067	—	0.004 0.02 0.047 0.072 0.104 0.15 0.177	0% 19% 38% 57% 76% 95% 100%	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Surface Soil (Continued)	Volumetric water content		Uniform	—	0.20	—	0.15	0.28	DTN: MO0609SPASRPBM.004 SNL 2007 [DIRS 179993]
	Radionuclide concentration in ash deposited on ground surface		Fixed	Bq/m^2	1	—	—	—	Unit areal activity concentration – a source term for the volcanic ash scenario
	Radionuclide concentration in resuspendable layer of soil		Fixed	Bq/kg	1	—	—	—	Unit mass activity concentration – a source term for the volcanic ash scenario
Air	Mass loading for crops	Nominal	Triangular	mg/m^3	0.12	—	0.025	0.200	DTN: MO0605SPAINEXI.003 BSC 2006 [DIRS 177101]
		Post-volcanic			0.24	—	0.050	0.600	
	Mass loading for receptor environments at nominal conditions	Active outdoors	Triangular	mg/m^3	3.00	—	1.000	10.000	DTN: MO0605SPAINEXI.003 BSC 2006 [DIRS 177101] Used for the groundwater scenario and for the long-term inhalation component for the volcanic ash scenario
		Inactive outdoors			0.06	—	0.025	0.100	
		Active indoors			0.10	—	0.060	0.175	
		Asleep indoors			0.03	—	0.010	0.050	
	Mass loading for receptor environments at post-volcanic condition	Active outdoors	Triangular	mg/m^3	3.00	—	0.000	5.000	DTN: MO0605SPAINEXI.003 BSC 2006 [DIRS 177101] Used for short-term inhalation component for the volcanic ash scenario
		Inactive outdoors			0.06	—	0.025	0.200	
		Active indoors			0.10	—	0.060	0.175	
		Asleep indoors			0.03	—	0.010	0.050	
	Mass loading function f(t) = $S_0 e^{-\lambda t}$, λ = mass loading decrease rate constant λ for all ash depths		Triangular	1/yr	0.20	—	0.125	1.0	DTN: MO0605SPAINEXI.003 BSC 2006 [DIRS 177101] This decay function is used in the TSPA model, not in the biosphere model.
	Enhancement factor groundwater scenario	Active outdoors	Triangular	—	1 (mode)	—	0.4	1.5	DTN: MO0609SPASRPBM.004 SNL 2007 [DIRS 179993]
		Inactive outdoors	Triangular		4 (mode)	—	2	7	
		Active indoors							
		Asleep indoors							

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Air (Continued)	Enhancement factor volcanic scenario	Active outdoors	Lognormal	—	2.9 (GM)	1.8 (GSD)	0.9	9.4	
		Inactive outdoors	Lognormal		1.2 (GM)	2.0 (GSD)	0.3	4.6	
		Active indoors							
		Asleep indoors							
	Fraction of radionuclides transferred in evaporative cooler from water into air		Uniform	—	0.5	—	0	1	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
	Water evaporation (use) rate of evaporative cooler		Lognormal	L/h	17 (GM)	1.7 (GSD)	—	—	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Airflow rate is correlated with water evaporative rate (correlation coefficient = 0.8)
	Air flow rate of evaporative cooler		Cumulative	m^3/h	8,300 (median)	—	1,700 8,300 10,200	0 % 50 % 100 %	
	Radon release factor		Fixed	$(Bq/m^3)/(Bq/kg)$	0.25	—	—	—	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
	Interior wall height		Cumulative	m	2.3 (median)	—	2.1 2.3 2.7	0 % 50 % 100 %	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
	House ventilation rate	When evap. cooler is off	Lognormal	1/h	1 (AM)	1.1 (ASD)	0.35	2.9	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
		When evap. cooler is on	Uniform		15.5	—	1	30	
	Fraction of radon from soil entering into the house		Uniform	—	0.175	—	0.10	0.25	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
	Ratio of ^{222}Rn concentration in air to flux density from soil		Fixed	$(Bq/m^3)/(Bq/(m^2\ s))$	300	—	—	—	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]

Table 6.6-3.Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant	Soil-to-plant transfer factor for leafy vegetables	Chlorine	Lognormal	$(Bq/kg_{plant})/(Bq/kg_{soil})$	6.4E+01	2.0	1.1E+01	3.8E+02	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Transfer factors are given in terms of geometric mean and geometric standard deviation. Soil-to-plant transfer factors are correlated with the partition coefficients. The rank correlation coefficient is –0.8.
		Selenium			4.6E–02	3.8	1.4E–03	1.4E+00	
		Strontium			1.7E+00	2.0	2.9E–01	1.0E+01	
		Technetium			4.6E+01	2.6	3.8E+00	5.5E+02	
		Tin			3.8E–02	2.0	6.4E–03	2.3E–01	
		Iodine			2.6E–02	9.9	7.2E–05	9.7E+00	
		Cesium			8.5E–02	2.5	7.7E–03	9.4E–01	
		Lead			1.5E–02	4.6	3.0E–04	7.7E–01	
		Radium			6.8E–02	2.7	5.1E–03	9.2E–01	
		Actinium			4.3E–03	2.0	7.2E–04	2.6E–02	
		Thorium			4.3E–03	2.8	3.2E–04	5.9E–02	
		Protactinium			4.6E–03	3.8	1.4E–04	1.4E–01	
		Uranium			1.1E–02	2.0	1.8E–03	6.6E–02	
		Neptunium			5.9E–02	4.4	1.3E–03	2.6E+00	
		Plutonium			2.9E–04	2.0	4.9E–05	1.7E–03	
		Americium			1.2E–03	2.5	1.2E–04	1.3E–02	
	Soil-to-plant transfer factor for other vegetables	Chlorine	Lognormal	$(Bq/kg_{plant})/(Bq/kg_{soil})$	6.4E+01	2.0	1.1E+01	3.8E+02	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Transfer factors are given in terms of geometric mean and geometric standard deviation. Soil-to-plant transfer factors are correlated with the partition coefficients. The rank correlation coefficient is –0.8.
		Selenium			4.6E–02	3.8	1.4E–03	1.4E+00	
		Strontium			7.9E–01	2.0	1.4E–01	4.5E+00	
		Technetium			4.4E+00	3.7	1.5E–01	1.2E+02	
		Tin			1.5E–02	3.6	5.3E–04	4.0E–01	
		Iodine			3.2E–02	4.4	7.0E–04	1.5E+00	
		Cesium			5.0E–02	2.0	8.4E–03	3.0E–01	
		Lead			9.0E–03	3.1	5.0E–04	1.6E–01	
		Radium			1.2E–02	5.3	1.6E–04	8.6E–01	
		Actinium			1.1E–03	4.9	1.8E–05	6.6E–02	
		Thorium			4.4E–04	5.6	5.3E–06	3.6E–02	
		Protactinium			1.1E–03	10.0	3.0E–06	4.3E–01	
		Uranium			6.0E–03	2.8	4.2E–04	8.5E–02	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant (Continued)	Soil-to-plant transfer factor for other vegetables	Neptunium	Lognormal	$(Bq/kg_{plant})/(Bq/kg_{soil})$	3.1E–02	4.9	5.0E–04	1.9E+00	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
		Plutonium			1.9E–04	2.0	3.3E–05	1.1E–03	
		Americium			4.0E–04	2.6	3.5E–05	4.6E–03	
	Soil-to-plant transfer factor for fruit	Chlorine	Lognormal	$(Bq/kg_{plant})/(Bq/kg_{soil})$	6.4E+01	2.0	1.1E+01	3.8E+02	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Transfer factors are given in terms of geometric mean and geometric standard deviation. Soil-to-plant transfer factors are correlated with the partition coefficients. The rank correlation coefficient is –0.8.
		Selenium			4.6E–02	3.8	1.4E–03	1.4E+00	
		Strontium			2.9E–01	2.3	3.6E–02	2.4E+00	
		Technetium			4.3E+00	4.6	8.7E–02	2.1E+02	
		Tin			1.5E–02	3.6	5.3E–04	4.0E–01	
		Iodine			5.7E–02	2.8	4.1E–03	7.9E–01	
		Cesium			5.6E–02	2.8	3.8E–03	8.1E–01	
		Lead			1.2E–02	3.3	5.8E–04	2.6E–01	
		Radium			7.3E–03	4.3	1.6E–04	3.2E–01	
		Actinium			8.5E–04	3.4	3.7E–05	2.0E–02	
		Thorium			2.9E–04	4.9	4.8E–06	1.7E–02	
		Protactinium			1.1E–03	10.0	3.0E–06	4.3E–01	
		Uranium			6.3E–03	2.9	3.9E–04	1.0E–01	
		Neptunium			3.4E–02	6.9	2.3E–04	5.0E+00	
		Plutonium			1.8E–04	3.4	7.8E–06	4.2E–03	
		Americium			5.4E–04	2.3	6.5E–05	4.5E–03	
	Soil-to-plant transfer factor for grain	Chlorine	Lognormal	$(Bq/kg_{plant})/(Bq/kg_{soil})$	2.4E+01	8.4	1.0E–01	5.8E+03	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Transfer factors are given in terms of geometric mean and geometric standard deviation. Soil-to-plant transfer factors are correlated with the partition coefficients. The rank correlation coefficient is –0.8.
		Selenium			2.9E–02	2.0	4.8E–03	1.7E–01	
		Strontium			1.7E–01	2.0	2.8E–02	1.0E+00	
		Technetium			1.6E+00	4.3	3.8E–02	6.8E+01	
		Tin			9.2E–03	2.0	1.5E–03	5.5E–02	
		Iodine			2.5E–02	10.0	6.6E–05	9.4E+00	
		Cesium			2.0E–02	2.2	2.7E–03	1.6E–01	
		Lead			5.5E–03	2.1	8.2E–04	3.8E–02	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant (Continued)	Soil-to-plant transfer factor for grain	Radium	Lognormal	$(Bq/kg_{plant})/(Bq/kg_{soil})$	3.1E–03	4.0	8.8E–05	1.1E–01	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Transfer factors are given in terms of geometric mean and geometric standard deviation. Soil-to-plant transfer factors are correlated with the partition coefficients. The rank correlation coefficient is –0.8.
		Actinium			5.4E–04	2.9	3.6E–05	8.0E–03	
		Thorium			1.7E–04	5.2	2.4E–06	1.2E–02	
		Protactinium			9.5E–04	7.2	5.9E–06	1.5E–01	
		Uranium			1.1E–03	3.6	4.1E–05	3.1E–02	
		Neptunium			4.4E–03	6.9	3.1E–05	6.3E–01	
		Plutonium			1.9E–05	4.2	4.8E–07	7.8E–04	
		Americium			7.5E–05	3.2	3.8E–06	1.5E–03	
	Soil-to-plant transfer factor for forage	Chlorine	Lognormal	$(Bq/kg_{plant})/(Bq/kg_{soil})$	7.5E+01	2.0	1.3E+01	4.5E+02	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Transfer factors are given in terms of geometric mean and geometric standard deviation. Soil-to-plant transfer factors are correlated with the partition coefficients. The rank correlation coefficient is –0.8.
		Selenium			1.5E–01	5.5	1.9E–03	1.3E+01	
		Strontium			2.1E+00	2.1	3.2E–01	1.3E+01	
		Technetium			2.7E+01	2.7	2.1E+00	3.5E+02	
		Tin			1.6E–01	5.8	1.7E–03	1.5E+01	
		Iodine			4.0E–02	10.0	1.1E–04	1.5E+01	
		Cesium			1.3E–01	3.3	6.3E–03	2.8E+00	
		Lead			1.8E–02	7.0	1.2E–04	2.8E+00	
		Radium			8.2E–02	3.0	4.9E–03	1.4E+00	
		Actinium			1.7E–02	5.4	2.2E–04	1.3E+00	
		Thorium			1.0E–02	4.2	2.5E–04	3.9E–01	
		Protactinium			1.9E–02	6.7	1.4E–04	2.5E+00	
		Uranium			1.7E–02	6.1	1.6E–04	1.9E+00	
		Neptunium			5.8E–02	5.6	6.8E–04	4.9E+00	
		Plutonium			1.0E–03	10.0	2.7E–06	3.9E–01	
		Americium			2.1E–03	10.0	5.5E–06	7.9E–01	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant (Continued)	Dry-to-wet weight ratio	Leafy vegetables	Cumulative	kg_{dry}/kg_{wet}	0.070	—	0.041 0.054 0.06 0.078 0.081 0.084 0.093	0% 17% 33% 50% 67% 83% 100%	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
		Other vegetables			0.103	—	0.035 0.063 0.078 0.08 0.103 0.122 0.24	0% 17% 33% 50% 67% 83% 100%	
		Fruit			0.120	—	0.062 0.084 0.102 0.155 0.194	0% 25% 50% 75% 100%	
		Grain			0.903	—	0.891 0.896 0.906 0.918	0% 33% 67% 100%	
		Forage			0.220	—	0.182 0.227 0.238	0% 75% 100%	

Table 6.6-3.Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name			Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant (Continued)	Translocation factor		Leafy vegetables	Fixed	—	1.0	—	—	—	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
			Other vegetables	Cumulative	—	0.1	—	0.05 0.10 0.30	0% 50% 100%	
			Fruit							
			Grain							
			Forage	Fixed	—	1.0	—	—	—	
	Fraction of overhead irrigation		Leafy vegetables	Normal	—	0.75	0.10	0.49	1.0	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
			Other vegetables			0.75	0.10	0.49	1.0	
			Fruit			0.50	0.10	0.24	1.0	
			Grain			0.90	0.05	0.77	1.0	
			Forage			0.90	0.05	0.77	1.0	
	Weathering half-life			Cumulative	d	14	—	5 14 30	0% 50% 100%	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
	Crop growing time	Present-day climate	Leafy vegetables	Fixed	d	75	—	—	—	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
			Other vegetables			80	—	—	—	
			Fruit			160	—	—	—	
			Grain			200	—	—	—	
			Forage			75	—	—	—	
		Future climate	Leafy vegetables	Fixed	d	75	—	—	—	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
			Other vegetables			100	—	—	—	
			Fruit			105	—	—	—	
			Grain			185	—	—	—	
			Forage			90	—	—	—	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant (Continued)	Crop wet yield	Leafy vegetables	Cumulative	kg/m^2	3.30	—	1.08 1.46 1.78 2.01 2.98 3.25 3.83 7.79 7.85	0% 5% 20% 35% 50% 65% 80% 95% 100%	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
		Other vegetables			4.13	—	2.8 3.37 3.56 3.64 4.92 5.15 6.61	0% 5% 28% 51% 72% 95% 100%	
		Fruit			2.75	—	0.73 1.51 2.67 2.92 3.00 3.63 6.89	0% 5% 28% 51% 72% 95% 100%	
		Grain			0.59	—	0.27 0.28 0.44 0.54 1.1 1.22	0% 5% 35% 65% 95% 100%	
		Forage			2.14	—	0.69 1.02 1.87 5.78 6.28	0% 5% 73% 95% 100%	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant (Continued)	Crop dry biomass	Leafy vegetation	Cumulative	kg/m^2	0.21	—	0.10 0.13 0.14 0.15 0.16 0.18 0.30 0.42 0.50	0% 5% 20% 35% 50% 65% 80% 95% 100%	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
		Other vegetation			0.43	—	0.30 0.40 0.41 0.43 0.44 0.46 0.60	0% 5% 28% 51% 73% 95% 100%	
		Fruit			0.62	—	0.10 0.56 0.60 0.65 0.68 1.30	0% 5% 35% 65% 95% 100%	
		Grain			1.13	—	0.50 0.61 0.74 1.20 1.97 2.20	0% 5% 35% 65% 95% 100%	
		Forage			0.48	—	0.10 0.23 0.34 1.38 1.50	0% 5% 73% 95% 100%	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name			Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant (Continued)	Daily irrigation rate	Present-day climate	Leafy vegetables	Cumulative	mm/d	5.41	—	4.00 5.11 5.19 5.21 5.38 5.48 6.00 7.08	0% 5% 20% 35% 50% 80% 95% 100%	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
			Other vegetables			7.71	—	5.00 6.07 6.65 6.93 7.67 8.36 9.03 9.26 10.93	0% 5% 20% 35% 50% 65% 80% 95% 100%	
			Fruit			7.41	—	4.00 5.40 7.02 7.59 8.38 8.67 10.23	0% 5% 28% 51% 72% 95% 100%	
			Grain			4.64	—	3.00 3.44 3.58 3.87 7.69 9.07	0% 5% 35% 65% 95% 100%	
			Forage			6.55	—	5.00 5.85 6.18 9.02 10.64	0% 5% 73% 95% 100%	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name			Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant (Continued)	Daily irrigation rate (cont.)	Future climate	Leafy vegetables	Cumulative	mm/d	3.81	—	3.00 3.34 3.51 3.86 3.92 4.02 4.18 4.93	0% 5% 20% 50% 65% 80% 95% 100%	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
			Other vegetables			3.84	—	2.00 2.73 3.08 3.48 4.08 4.16 4.43 4.95 5.84	0% 5% 20% 35% 50% 65% 80% 95% 100%	
			Fruit			3.90	—	2.00 2.51 3.48 4.33 4.38 4.79 5.65	0% 5% 28% 51% 72% 95% 100%	
			Grain			3.36	—	1.00 1.99 3.42 3.93 4.11 4.85	0% 5% 35% 65% 95% 100%	
			Forage			4.14	—	3.00 3.64 4.01 5.03 5.94	0% 5% 73% 95% 100%	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name			Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant (Continued)	Irri-gation amt. per appli-cation	Present-day climate	Leafy vegetables	Cumulative	mm	14.7	—	6.0 7.5 8.4 10.0 10.9 20.8 22.0 23.5 27.7	0% 5% 20% 35% 50% 65% 80% 95% 100%	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
			Other vegetables			26.0	—	8.0 9.1 18.9 19.8 21.2 33.3 34.8 44.7 52.7	0% 5% 20% 35% 50% 65% 80% 95% 100%	
			Fruit			33.9	—	5.0 6.0 30.3 35.4 48.4 49.4 58.3	0% 5% 28% 51% 72% 95% 100%	
			Grain			56.7	—	43.0 48.6 50.1 50.4 77.9 91.9	0% 5% 35% 65% 95% 100%	
			Forage			57.8	—	50.0 56.3 57.6 60.0 71.0	0% 5% 72% 95% 100%	

Table 6.6-3.Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name			Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant (Continued)	Irri-gation amt. per appli-cation (cont.)	Future climate	Leafy vegetables	Cumulative	mm	14.6	—	7.0 7.8 8.0 9.0 10.1 19.3 22.0 26.1 30.8	0% 5% 20% 35% 50% 65% 80% 95% 100%	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
			Other vegetables			25.0	—	10.0 11.3 14.4 17.7 20.1 34.1 37.2 40.3 47.6	0% 5% 20% 35% 50% 65% 80% 95% 100%	
			Fruit			34.2	—	6.0 7.3 31.4 34.6 43.2 54.4 64.2	0% 5% 28% 51% 72% 95% 100%	
			Grain			51.3	—	28.0 32.2 46.2 59.9 66.7 78.7	0% 5% 35% 65% 95% 100%	
			Forage			53.5	—	43.0 48.3 52.5 61.9 73.0	0% 5% 73% 95% 100%	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Plant (Continued)	Irrigation intensity		Uniform	cm/h	4.3	—	1.0	7.5	DTN: MO0403SPAAEIBM.002 BSC 2004 [DIRS 169673]
	Dry deposition velocity		Cumulative	m/s	8E–03	—	3E–04 1E–03 8E–03 3E–02 3E–01	0 % 16 % 50 % 84 % 100 %	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
Animal	Animal product transfer coefficients for meat	Chlorine	Lognormal	d/kg	4.6E–02	2.0	7.7E–03	2.7E–01	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Transfer coefficients are given in terms of geometric mean and geometric standard deviation.
		Selenium			8.8E–02	5.8	9.6E–04	8.0E+00	
		Strontium			1.4E–03	4.4	3.1E–05	6.2E–02	
		Technetium			1.1E–03	7.2	6.9E–06	1.8E–01	
		Tin			1.9E–02	4.6	3.8E–04	9.9E–01	
		Iodine			1.0E–02	2.8	6.8E–04	1.5E–01	
		Cesium			2.4E–02	2.6	2.1E–03	2.7E–01	
		Lead			6.3E–04	2.6	5.4E–05	7.5E–03	
		Radium			8.1E–04	2.1	1.1E–04	5.7E–03	
		Actinium			7.9E–05	8.2	3.5E–07	1.8E–02	
		Thorium			1.1E–04	10.0	2.8E–07	4.0E–02	
		Protactinium			6.6E–05	10.0	1.8E–07	2.5E–02	
		Uranium			4.8E–04	3.0	2.9E–05	7.8E–03	
		Neptunium			3.4E–04	8.8	1.3E–06	9.0E–02	
		Plutonium			1.3E–05	10.0	3.3E–08	4.7E–03	
		Americium			3.4E–05	9.0	1.2E–07	9.9E–03	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Animal (Continued)	Animal product transfer coefficients for milk	Chlorine	Lognormal	d/L	1.8E–02	2.0	2.9E–03	1.0E–01	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Transfer coefficients are given in terms of geometric mean and geometric standard deviation.
		Selenium			5.7E–03	2.5	5.5E–04	6.0E–02	
		Strontium			1.7E–03	2.0	2.8E–04	1.0E–02	
		Technetium			2.1E–03	6.0	2.0E–05	2.1E–01	
		Tin			1.1E–03	2.0	1.8E–04	6.3E–03	
		Iodine			9.1E–03	2.0	1.5E–03	5.4E–02	
		Cesium			7.7E–03	2.0	1.3E–03	4.6E–02	
		Lead			1.7E–04	3.0	1.0E–05	2.9E–03	
		Radium			5.8E–04	2.0	1.0E–04	3.4E–03	
		Actinium			7.6E–06	4.1	2.0E–07	2.9E–04	
		Thorium			4.4E–06	2.0	7.4E–07	2.6E–05	
		Protactinium			4.4E–06	2.0	7.4E–07	2.6E–05	
		Uranium			4.9E–04	2.0	8.1E–05	2.9E–03	
		Neptunium			6.3E–06	2.0	1.0E–06	3.9E–05	
		Plutonium			2.3E–07	7.7	1.2E–09	4.4E–05	
		Americium			1.6E–06	4.2	3.9E–08	6.3E–05	
	Animal product transfer coefficients for poultry	Chlorine	Lognormal	d/kg	3.0E–02	2.0	5.0E–03	1.8E–01	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Transfer coefficients are given in terms of geometric mean and geometric standard deviation.
		Selenium			5.1E+00	3.6	1.9E–01	1.4E+02	
		Strontium			3.1E–02	5.8	3.4E–04	2.9E+00	
		Technetium			6.3E–02	10.0	1.7E–04	2.4E+01	
		Tin			3.5E–02	10.0	9.4E–05	1.3E+01	
		Iodine			5.5E–02	9.7	1.6E–04	1.9E+01	
		Cesium			2.6E+00	9.8	7.2E–03	9.3E+02	
		Lead			2.5E–02	10.0	6.6E–05	9.3E+00	
		Radium			1.7E–02	10.0	4.4E–05	6.3E+00	
		Actinium			4.0E–03	2.0	6.7E–04	2.4E–02	
		Thorium			5.9E–03	8.0	2.7E–05	1.3E+00	
		Protactinium			3.0E–03	2.0	5.1E–04	1.8E–02	
		Uranium			2.4E–01	10.0	6.5E–04	9.2E+01	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Animal (Continued)		Neptunium			3.6E–03	2.0	6.0E–04	2.1E–02	
		Plutonium			1.2E–03	10.0	3.2E–06	4.6E–01	
		Americium			1.8E–03	10.0	4.8E–06	6.7E–01	
	Animal product transfer coefficients for eggs	Chlorine	Lognormal	d/kg	4.4E–02	10.0	1.2E–04	1.7E+01	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Transfer coefficients are given in terms of geometric mean and geometric standard deviation.
		Selenium			7.3E+00	2.0	1.2E+00	4.4E+01	
		Strontium			2.7E–01	2.0	4.5E–02	1.6E+00	
		Technetium			2.4E+00	2.0	4.0E–01	1.4E+01	
		Tin			8.7E–02	10.0	2.3E–04	3.3E+01	
		Iodine			2.6E+00	2.0	4.4E–01	1.6E+01	
		Cesium			3.5E–01	5.8	3.7E–03	3.3E+01	
		Lead			5.6E–02	10.0	1.5E–04	2.1E+01	
		Radium			3.9E–04	10.0	1.0E–06	1.5E–01	
		Actinium			2.9E–03	2.3	3.4E–04	2.5E–02	
		Thorium			3.5E–03	7.3	2.0E–05	5.9E–01	
		Protactinium			2.0E–03	2.0	3.4E–04	1.2E–02	
		Uranium			6.3E–01	2.5	6.0E–02	6.7E+00	
		Neptunium			3.4E–03	2.4	3.4E–04	3.3E–02	
		Plutonium			1.7E–03	7.4	9.7E–06	2.9E–01	
		Americium			4.9E–03	2.0	8.2E–04	2.9E–02	
	Animal consumption rate of feed	Meat	Uniform	kg/d	48.5	—	29	68	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
		Milk			61.5	—	50	73	
		Poultry			0.26	—	0.12	0.40	
		Eggs			0.26	—	0.12	0.40	
	Animal consumption rate of water	Meat	Fixed	L/d	60	—	—	—	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
		Milk	Uniform		80	—	60	100	
		Poultry	Fixed		0.5	—	—	—	
		Eggs	Fixed		0.5	—	—	—	
	Animal consumption rate of soil	Meat	Uniform	kg/d	0.7	—	0.4	1.0	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
		Milk			0.95	—	0.8	1.1	
		Poultry			0.02	—	0.01	0.03	
		Eggs			0.02	—	0.01	0.03	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Fish	Bioaccumulation factor	Carbon	Lognormal	L/kg	4.6E+03	3.2	2.3E+02	9.2E+04	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672] Bioaccumulation factors are given in terms of geometric mean and geometric standard deviation.
		Chlorine			2.2E+02	5.6	2.6E+00	1.9E+04	
		Selenium			2.3E+02	2.0	3.9E+01	1.4E+03	
		Strontium			4.6E+01	2.0	7.8E+00	2.8E+02	
		Technetium			2.0E+01	2.0	3.3E+00	1.2E+02	
		Tin			2.5E+03	2.0	4.2E+02	1.5E+04	
		Iodine			4.5E+01	2.6	3.8E+00	5.3E+02	
		Cesium			3.5E+03	2.2	4.7E+02	2.5E+04	
		Lead			2.9E+02	2.5	2.7E+01	3.1E+03	
		Radium			6.7E+01	2.2	9.2E+00	5.0E+02	
		Actinium			2.9E+01	3.0	1.7E+00	5.0E+02	
		Thorium			1.1E+02	2.5	1.0E+01	1.2E+03	
		Protactinium			1.2E+01	2.0	2.0E+00	7.1E+01	
		Uranium			1.4E+01	3.0	8.4E–01	2.3E+02	
		Neptunium			3.0E+01	2.9	1.9E+00	4.7E+02	
		Plutonium			4.1E+01	4.7	7.9E–01	2.2E+03	
		Americium			5.2E+01	2.3	5.8E+00	4.6E+02	
	Modifying factor for present-day climate	Carbon	Fixed	—	1	—	—	—	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
		Other elements	Uniform	—	4.15	—	2.2	6.1	
	Modifying factor for future climate	Carbon	Fixed	—	1	—	—	—	
		Other elements	Uniform	—	2.4	—	1.5	3.3	
^{14}C	^{14}C emission rate constant		Fixed	1/yr	22	—	—	—	
	Typical field size		Fixed	m^2	2.295E+06	—	—	—	Section 6.4.6.2
	Typical garden size		Fixed	m^2	2,000				Section 6.4.6.2
	Annual average wind speed	For inhalation (at 2 m)	Uniform	m/s	2.45	—	2.1	2.8	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
		For crops (1 m)			1.9	—	1.5	2.3	
	^{14}C mixing height	For inhalation	Fixed	m	2	—	—	—	
		For crops			1	—	—	—	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name			Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
^{14}C (Continued)	Fraction of air-derived C in plants			Fixed	—	0.98	—	—	—	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
	Fraction of soil-derived C in plants			Fixed	—	0.02	—	—	—	
	Fraction of stable C in plant		Leafy vegetation	Fixed	—	0.09	—	—	—	
			Other vegetation			0.09	—	—	—	
			Fruit			0.09	—	—	—	
			Grain			0.40	—	—	—	
			Forage			0.09	—	—	—	
	Fraction of stable C in soil			Fixed	—	0.03	—	—	—	
	Concentration of stable C in air			Fixed	kg/m^3	1.8E–4	—	—	—	
	Concentration of stable C in water			Fixed	kg/L	2.0E–5	—	—	—	
	Fraction of stable C in animal product		Meat	Fixed	—	0.24	—	—	—	
			Milk			0.07	—	—	—	
			Poultry			0.20	—	—	—	
			Eggs			0.15	—	—	—	
External Exposure	Population proportion for groundwater scenario		Outdoor workers	Uniform	%	5.5	2.6	2.9	8.1	DTN: MO0407SPACRBSM.002 BSC 2005 [DIRS 172827], Table 6-5
			Indoor workers[d]			16.1[d]	[d]	—	—	
			Commuters			39.2	5.3	33.9	44.5	
			Nonworkers			39.2	4.8	34.4	44.0	
	Population proportion for volcanic ash scenario		Outdoor workers	Uniform	%	5.5	2.6	2.9	10.7	
			Indoor workers[d]			42.8[d]	[d]	—	—	
			Commuters			12.5	3.8	4.9	16.3	
			Nonworkers			39.2	4.8	34.4	44.0	
	For GW	Exposure time for outdoor workers	Active outdoors	Lognormal	h/d	3.1	0.2	2.6	3.7	DTN: MO0407SPACRBSM.002 BSC 2005 [DIRS 172827] Time spent active indoors is calculated in the submodel as 24 h/d minus the sum of times in the other four environments.
			Inactive outdoors			4.0	0.3	3.3	4.8	
			Active indoors[d]			6.6[d]	[d]	—	—	
			Asleep indoors			8.3	0.1	8.0	8.6	
			Away			2.0	0.4	1.2	3.3	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name			Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
External Exposure (Continued)	For GW	Exposure time for indoor workers	Active outdoors	Lognormal	h/d	0.3	0.1	0.1	0.7	DTN: MO0407SPACRBSM.002 BSC 2005 [DIRS 172827] Time spent active indoors is calculated in the submodel as 24 h/d minus the sum of times in the other four environments.
			Inactive outdoors			1.3	0.2	0.9	1.9	
			Active indoors[d]			12.1[d]	[d]	—	—	
			Asleep indoors			8.3	0.1	8.0	8.6	
			Away			2.0	0.4	1.2	3.3	
		Exposure time for com-muters	Active outdoors	Lognormal	h/d	0.3	0.1	0.1	0.7	
			Inactive outdoors			1.4	0.2	1.0	2.0	
			Active indoors[d]			6.0[d]	[d]	—	—	
			Asleep indoors			8.3	0.1	8.0	8.6	
			Away			8.0	0.5	6.8	9.4	
		Exposure time for non workers	Active outdoors	Lognormal	h/d	0.3	0.1	0.1	0.7	
			Inactive outdoors			1.2	0.2	0.8	1.8	
			Active indoors[d]			12.2[d]	[d]	—	—	
			Asleep indoors			8.3	0.1	8.0	8.6	
			Away			2.0	0.4	1.2	3.3	
	For VA	Exposure time for outdoor workers	Active outdoors	Lognormal	h/d	3.1	0.2	2.6	3.7	DTN: MO0407SPACRBSM.002 BSC 2005 [DIRS 172827] Time spent active indoors is calculated in the submodel as 24 h/d minus the sum of times in the other four environments.
			Inactive outdoors			4.2	0.3	3.5	5.0	
			Active indoors[d]			6.4[d]	[d]	—	—	
			Asleep indoors			8.3	0.1	8.0	8.6	
			Away			2.0	0.4	1.2	3.3	
		Exposure time for indoor workers	Active outdoors	Lognormal	h/d	0.3	0.1	0.1	0.7	
			Inactive outdoors			1.5	0.2	1.1	2.1	
			Active indoors[d]			11.9[d]	[d]	—	—	
			Asleep indoors			8.3	0.1	8.0	8.6	
			Away			2.0	0.4	1.2	3.3	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name			Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
External Exposure (Continued)	For VA	Exposure time for com-muters	Active outdoors	Lognormal	h/d	0.3	0.1	0.1	0.7	DTN: MO0407SPACRBSM.002 BSC 2005 [DIRS 172827] Time spent active indoors is calculated in the submodel as 24 h/d minus the sum of times in the other four environments.
			Inactive outdoors			2.0	0.2	1.5	2.6	
			Active indoors[d]			5.1[d]	[d]	—	—	
			Asleep indoors			8.3	0.1	8.0	8.6	
			Away			8.3	0.6	6.9	10.0	
		Exposure time for non workers	Active outdoors	Lognormal	h/d	0.3	0.1	0.1	0.7	
			Inactive outdoors			1.2	0.2	0.8	1.8	
			Active indoors[d]			12.2[d]	[d]	—	—	
			Asleep indoors			8.3	0.1	8.0	8.6	
			Away			2.0	0.4	1.2	3.3	
	Building shielding factor		^{14}C	Fixed	—	0.2	—	—	—	DTN: MO0407SPACRBSM.002 BSC 2005 [DIRS 172827]
			^{36}Cl			0.4	—	—	—	
			^{79}Se			0.1	—	—	—	
			^{90}Sr D			0.4	—	—	—	
			^{99}Tc			0.2	—	—	—	
			^{126}SnD			0.4	—	—	—	
			^{129}I			0.1	—	—	—	
			^{135}Cs			0.1	—	—	—	
			^{137}CsD			0.4	—	—	—	
			^{242}Pu			0.1	—	—	—	
			^{238}UD			0.4	—	—	—	
			^{238}Pu			0.1	—	—	—	
			^{234}U			0.2	—	—	—	
			230Th			0.3	—	—	—	
			^{226}RaD			0.4	—	—	—	
			^{210}PbD			0.4	—	—	—	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
External Exposure (Continued)	Building shielding factor (Continued)	^{240}Pu	Fixed	—	0.1	—	—	—	DTN: MO0407SPACRBSM.002 BSC 2005 [DIRS 172827]
		^{236}U			0.1	—	—	—	
		^{232}Th			0.2	—	—	—	
		^{228}RaD			0.4	—	—	—	
		^{232}U			0.3	—	—	—	
		^{228}ThD			0.4	—	—	—	
		^{243}AmD			0.4	—	—	—	
		^{239}Pu			0.3	—	—	—	
		^{235}UD			0.4	—	—	—	
		^{231}Pa			0.4	—	—	—	
		^{227}Ac D			0.4	—	—	—	
		^{241}Am			0.2	—	—	—	
		^{237}NpD			0.4	—	—	—	
		^{233}U			0.4	—	—	—	
		^{229}ThD			0.4	—	—	—	
	Dose coefficient for exposure to soil contaminated to an infinite depth		Fixed	(Sv/yr)/(Bq/m^3)	See reference	—	—	—	Table 6.4-4
	Dose coefficient for exposure to contaminated ground surface		Fixed	(Sv/yr)/(Bq/m^2)	See reference	—	—	—	Table 6.4-4
	Branching fraction		Fixed	—	See reference	—	—	—	Table 6.3-7
Inhalation	Breathing rate	Active outdoors	Fixed	m^3/h	1.57	—	—	—	DTN: MO0407SPACRBSM.002 BSC 2005 [DIRS 172827]
		Inactive outdoors			1.08	—	—	—	
		Active indoors			1.08	—	—	—	
		Asleep indoors			0.39	—	—	—	
		Away			1.08 [g]	—	—	—	
	Dose coefficients for inhalation		Fixed	Sv/Bq	See reference	—	—	—	Table 6.4-5
	Fraction of houses with evaporative coolers		Binomial	—	0.738	Sample size = 187	—	—	DTN: MO0407SPACRBSM.002 BSC 2005 [DIRS 172827]

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name		Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Inhalation (Continued)	Evaporative cooler use factor	Present-day climate	Uniform	—	0.39	—	0.32	0.46	
		Future climate			0.085	—	0.03	0.14	
	Equilibrium factor for ^{222}Rn decay products	Outdoors	Uniform	—	0.6	—	0.5	0.7	DTN: MO0406SPAETPBM.002 BSC 2004 [DIRS 169672]
		Indoors	Uniform	—	0.4	—	0.3	0.5	
	Dose coefficient for inhalation of ^{222}Rn decay products		Fixed	Sv/Bq	6.62E–9	—	—	—	DTN: MO0503SPADCESR.000 BSC 2005 [DIRS 172827]
Ingestion	Consumption rate of water		Fixed	L/d	2	—	—	—	Required by 10 CFR 63.312 [DIRS 173273]
	Consumption rate of locally produced crop foodstuffs	Leafy vegetables	Lognormal	kg/yr	3.78	0.88	—	—	DTN: MO0407SPACRBSM.002 BSC 2005 [DIRS 172827] Lognormal distributions are given in terms of arithmetic mean and standard deviation.
		Other vegetables			4.73	0.67	—	—	
		Fruit			12.68	1.36	—	—	
		Grain			0.23	0.11	—	—	
	Consumption rate of locally produced animal products	Meat	Lognormal	kg/yr	2.85	0.65	—	—	
		Milk			4.66	1.68	—	—	
		Poultry			0.42	0.13	—	—	
		Eggs			5.30	0.83	—	—	
	Consumption rate of locally produced fish		Lognormal	kg/yr	0.23	0.10	—	—	

Table 6.6-3. Summary of Biosphere Model Input Parameter Values and Their Distributions (Continued)

Sub-model	Parameter Name	Distribution Type	Units	Mean, Mode, Average [a]	SD/SE [a]	Min. [b]	Max. [b]	Reference/Notes [c]
Ingestion (Continued)	Inadvertent soil ingestion rate	Cumulative	mg/d	100	—	50 100 200	0% 50% 100%	DTN: MO0407SPACRBSM.002 BSC 2005 [DIRS 172827]
	Dose coefficients for ingestion	Fixed	Sv/Bq	See reference	—	—	—	Table 6.4-6

[a] The "Mean, Mode, Average" column contains representative fixed value for the distribution, e.g., the mean for a normal or lognormal distribution, the mode for a triangular distribution. For the distributions that do not require a mean, mode, or average to define in GoldSIm, such as a uniform distribution or cumulative distribution, the values in this column are taken from the source references calculated as the 50th-percentile value. The representative values may not agree with the GoldSim averages for the corresponding distributions. Data in this column are used in model verification (Section 6.10) and model validation (Sections 7.3 and 7.4). "SD/SE" represents the standard deviation or standard error for the described input parameter distribution, such as normal distribution and lognormal distribution. For the transfer factors, transfer coefficients, and partition coefficients the "Mean, Mode, Average" represents the geometric mean and SD/SE represents geometric standard deviation for their lognormal distributions.

[b] "Min." represents the lower bounding value, and "Max." represents the upper bounding value for most distribution types, except for cumulative distributions, in which the "Min." column is the value, and the "Max." column is the corresponding accumulative percentage.

[c] Source of the data. In some instances, the representative or mean values, which are not used as inputs but provide additional information about the parameter distribution, may not be included in the output DTNs and instead were obtained from the source report.

[d] Within the block of parameters, this parameter is the dependent variable whose expected value and distribution is determined by the defined distribution of the remaining parameters in the block and the necessary boundary conditions (such as 24 h/d, percentage total having to be 100%).

[e] These values are not used in the model runs but rather are used to calculate the scaling factors for developing BDCFs for the monsoon and the glacial transition climates.

[f] Throughout this table, present day climate = modern interglacial climate; future climate = upper bound of the glacial transition climate.

[g] Breathing rate away from the contaminated area is an assumed value; it is inconsequential regarding the annual dose to the RMEI because the inhalation exposure away from the contaminated area is zero.

GW=groundwater scenario;,SD=standard deviation; SE=standard error; TSPA=total system performance assessment; VA=volcanic ash scenario.

6.7 DISPOSITION OF FEPS WITHIN THE BIOSPHERE MODEL

The FEPs considered in the biosphere conceptual model are discussed in Section 6.3.4. Table 6.7-1 describes how those FEPs are dispositioned in the mathematical model. Many of the FEPs (primarily features) are represented through the input parameters. For these FEPs, the related input parameters are identified and the disposition of the FEP through development and use of the input parameters is described (Table 6.7-1). Other FEPs (primarily events and processes) are incorporated into the equations described in Sections 6.4 and 6.5. For these FEPs, the submodels and equations related to the FEPs are identified, and the associated model parameters are listed. Some parameters address several FEPs, and one FEP may be linked to several parameters. Based on the evaluation, all FEPs considered in the conceptual model (Section 6.3.4) are adequately dispositioned in the ERMYN mathematical model.

Table 6.7-1. Disposition of the Included FEPs within the Biosphere Mathematical Model

FEP Number and FEP Name	Biosphere Submodel [a]	Model Parameters that Address the FEP [b]	Disposition within ERMYN
1.2.04.07.0A Ashfall	Soil Plant	Radionuclide concentration in ash deposited on ground surface Soil to plant transfer factor	Volcanic ash is the initial source of contamination for the volcanic ash exposure scenario (Sections 6.3.2 and 6.5.1).
	Air	Mass loading for crops Mass loading for receptor environments Mass loading time function	Initial ashfall depth is considered in development of the mass loading parameters (BSC 2006 [DIRS 177101], Sections 6.3 and 6.4).
1.3.01.00.0A Climate change	Soil	Annual irrigation rate Overwatering rate	Separate distributions are developed for listed parameters based on present-day and predicted future climatic conditions (BSC 2004 [DIRS 169673], Sections 6.4, 6.5, 6.7, 6.8 and 6.9; BSC 2004 [DIRS 169672], Sections 6.4 and 6.7; BSC 2005 [DIRS 172827], Section 6.3.4.2). Separate sets of BDCFs are developed for the present-day and future climates.
	Plant	Growing time Irrigation amount per application Daily irrigation rate	
	Fish	Water concentration modifying factor	
	^{14}C	Annual irrigation rate Daily irrigation rate Surface area of irrigated land	
	Inhalation	Evaporative cooler use factor	
1.3.07.02.0A Water table rise affects SZ	Soil, Air, Plant, ^{14}C, Animal, Fish, Ingestion	Radionuclide concentration in groundwater	Conceptual and mathematical models for the groundwater scenario are applicable to surface water flowing from a spring or other discharge point as the source of contaminants (Section 6.3.1).
1.4.07.01.0A Water management activities	Air	Evaporative cooler parameters: Air flow rate Water use rate Water concentration modifying factor	Distributions for the values of the listed parameters are developed based in part on the types of water distribution, use, and storage systems in Amargosa Valley for crop irrigation (BSC 2004 [DIRS 169673], Sections 6.3 and 6.6; SNL 2007 [DIRS 179993], Section 6.7), evaporative cooler usage (BSC 2004 [DIRS 169672], Section 6.5), and fish farming (BSC 2004 [DIRS 169672], Section 6.4).
	Soil	Irrigation duration	
	Plant	Fraction of overhead irrigation Irrigation intensity	
	Fish	Water concentration modifying factor	

Table 6.7-1. Disposition of the Included FEPs within the Biosphere Mathematical Model (Continued)

FEP Number and FEP Name	Biosphere Submodel [a]	Model Parameters that Address the FEP [b]	Disposition within ERMYN
1.4.07.02.0A Wells	Soil, Air, Plant, ^{14}C, Animal, Fish, Ingestion	Radionuclide concentration in groundwater	A well is initial source of contaminated groundwater for the groundwater scenario (Section 6.3.1).
2.2.08.01.0A Chemical characteristics of groundwater in the SZ	Soil	Partition coefficients	Parameter distributions are developed to bound possible variations due to chemical characteristics of groundwater in the SZ (BSC 2004 [DIRS 169672], Sections 6.2, 6.3, and 6.4; SNL 2007 [DIRS 179993], Section 6.3; this report, Sections 6.4.1, 6.4.3, 6.4.4).
	Plant	Soil-to-plant transfer factors Irrigation interception fraction Translocation factor	
	Animal Fish	Animal product transfer coefficients Bioaccumulation factors	
	Ingestion	Dose coefficients	Where multiple dose coefficients are defined, the highest value is used to eliminate the possibility of underestimating dose (Sections 6.4.8.5 and 6.4.9.6).
	Inhalation	Dose coefficients	
2.3.02.01.0A Soil type	Air	Enhancement factors	Distributions for listed parameters are developed based in part on characteristics of the soil types in northern Amargosa Valley (BSC 2004 [DIRS 169673], Sections 6.6, 6.10 and 6.12; SNL 2007 [DIRS 179993], Sections 6.2 to 6.6; and (BSC 2004 [DIRS 169672], Section 6.7.1).
	Soil	Surface soil depth (tillage depth) Soil partition coefficient Soil bulk density Surface soil erosion rate Volumetric water content	
	Plant	Irrigation Intensity	
	^{14}C	^{14}C emission rate constant	
2.3.02.02.0A Radionuclide accumulation in soils	Soil	Annual irrigation rate Irrigation duration Overwatering rate Surface soil depth (tillage depth) Soil solid-liquid partition coefficient Soil bulk density Volumetric water content Surface soil erosion rate Critical thickness for the resuspension	The soil submodel includes the accumulation of radionuclides in the soil from irrigation water (Equations in Section 6.4.1.1 and 6.4.1.2). The parameter values used in the mathematical representation of radionuclide accumulation in soil were developed in several reports (BSC 2004 [DIRS 169673], Sections 6.9 and 6.10; SNL 2007 [DIRS 179993], Sections 6.2, 6.3, 6.4, 6.6, and 6.7; BSC 2004 [DIRS 169672], Section 6.8).
2.3.02.03.0A Soil and sediment transport in the biosphere	Soil	Surface soil erosion rate Soil bulk density Dry deposition velocity Critical thickness for resuspension Enhancement factor Tillage depth	The soil submodel includes soil loss and gain on farm fields (Sections, 6.4.1.1, 6.4.1.4, 6.4.3.3 and 6.5.2.1). The relevant model parameters were developed in the following reports: SNL 2007 [DIRS 179993], Sections 6.2, 6.4, and 6.5; BSC 2004 [DIRS 169672], Sections 6.2 and 6.8; BSC 2004 [DIRS 169673], Section 6.10.
	Air	Mass loading decrease constant in mass loading time function	Selected distribution is based in part on the influence of ash redistribution on changes in mass loading through time (BSC 2006 [DIRS 177101], Section 6.4).

Table 6.7-1. Disposition of the Included FEPs within the Biosphere Mathematical Model (Continued)

FEP Number and FEP Name	Biosphere Submodel [a]	Model Parameters that Address the FEP [b]	Disposition within ERMYN
2.3.04.01.0A Surface water transport and mixing	Soil, Air, Plant, ^{14}C Animal, Fish Ingestion	Radionuclide concentration in groundwater	The conceptual and mathematical models for the groundwater scenario are applicable to water discharged to the surface, and the subsequent transport of radionuclides in surface water. Mixing is not considered because currently there are no sources of uncontaminated water in the biosphere (Section 6.3.1).
2.3.11.01.0A Precipitation	Soil	Annual irrigation rate Overwatering rate	Distributions of parameters are developed based in part on variation and uncertainty in precipitation for the present-day and predicted future climate (BSC 2004 [DIRS 169673], Sections 6.5, 6.7, 6.8, and 6.9; this report, Section 6.4.1.1).
	Plant	Irrigation amount per application Daily irrigation rate	
	^{14}C	Daily irrigation rate Annual irrigation rate	
2.3.13.01.0A Biosphere characteristics	Soil	Annual irrigation rate Overwatering rate Tillage depth Erosion rate	Distributions of parameters are developed based in part on variation and uncertainty in site-specific characteristics in the biosphere, such as temperature, wind speed, and evaporation rate (BSC 2004 [DIRS 169673], Sections 6.4, 6.5, 6.6, 6.7, 6.8, and 6.9); BSC 2005 [DIRS 172827], Sections 6.3.4.2; BSC 2004 [DIRS 169672], Sections 6.2.2.1, 6.4.3, 6.5.2, and 6.7.2). Some other biosphere characteristics are covered by other FEPs, such as soil type (2.3.02.01.0A) and precipitation (2.3.11.01.0A).
	Air	Water evaporation rate	
	Plant	Dry deposition velocity Daily irrigation rate Irrigation application Irrigation intensity Growing time	
	Animal	Animal consumption rates	
	Fish	Water concentration modifying factor	
	^{14}C	Annual average wind speed Emission rate constant	
	Inhalation	Evaporative cooler use factor	
2.3.13.02.0A Radionuclide alteration during biosphere transport	Soil	Partition coefficient	Parameter distributions are developed to reflect possible variations due to chemical characteristics of groundwater in the SZ (BSC 2004 [DIRS 169672], Sections 6.2, 6.3, and 6.4; SNL 2007 [DIRS 179993], Section 6.3; this report, Sections 6.4.1, 6.4.3, 6.4.4).
	Plant	Soil-to-plant transfer factor	
	Animal Fish	Animal product transfer coefficient Bioaccumulation factors	
	Ingestion	Dose coefficients	Where multiple dose coefficients are defined, the highest value is used to eliminate the possibility of underestimating dose (Sections 6.4.8.5 and 6.4.9.6).
	Inhalation	Dose coefficients	
2.4.01.00.0A Human characteristics (physiology, metabolism)	External exposure	Dose coefficients for exposure to soil contaminated to an infinite depth Dose coefficients for exposure to contaminated ground surface	Physiology and metabolism of the human receptor are considered in developing the listed parameters (this report, Sections 6.4.7.2, 6.4.8.5, 6.4.9.6, 6.5.5.2; BSC 2005 [DIRS 172827], Sections 6.3.3, 6.5.4, and 6.5.5).
	Inhalation	Breathing rate Dose coefficients for inhalation Dose coefficient for inhalation of radon decay products	
	Ingestion	Dose coefficients for ingestion	

Table 6.7-1. Disposition of the Included FEPs within the Biosphere Mathematical Model (Continued)

FEP Number and FEP Name	Biosphere Submodel [a]	Model Parameters that Address the FEP [b]	Disposition within ERMYN
2.4.04.01.0A Human lifestyle	Air	Mass loading for receptor environments	Distributions are based, in part, on variation and uncertainty of the lifestyles and characteristics of people living in Amargosa Valley (BSC 2006 [DIRS 177101], Sections 6.2 to 6.4; BSC 2005 [DIRS 172827], Sections 6.3 and 6.4). Influence of human lifestyle on external exposure is considered in Sections 6.4.7 for the groundwater scenario and in Section 6.5.5 for the volcanic ash scenario. Influences on inhalation pathway are considered in Eqs. 6.4.8-2 to 6.4.8-7 for the groundwater scenario and in Eqs. 6.5.6-2 and 6.5.6-3 for the volcanic ash scenario. Influences on the ingestion pathway are considered in Eqs. 6.4.9-2 to 6.4.9-6 for the groundwater scenario and in Eqs. 6.5.7-2 to 6.5.7-4 for the volcanic ash scenario.
	External exposure	Population proportion Exposure time	
	Inhalation	Population proportion Exposure time Fraction of houses with evaporative coolers Evaporative cooler usage factor by climate	
	Ingestion	Consumption rate of water Consumption rate of locally produced crop foodstuffs Consumption rate of locally produced animal products Consumption rate of locally produced fish Inadvertent soil ingestion rate	
2.4.07.00.0A Dwellings	Air	Water evaporation rate Evaporative cooler air flow rate Interior wall height House ventilation rate	Distributions are based in part on uncertainty and variation in the characteristics of types of dwellings in northern Amargosa Valley (BSC 2005 [DIRS 172827], Sections 6.3.4.1, 6.3.4.2, and 6.6; BSC 2004 [DIRS 169672], Sections 6.5.2 and 6.6.2).
	External exposure	Building shielding factor	
	Inhalation	Fraction of houses with evaporative coolers Evaporative cooler use factor	
2.4.08.00.0A Wild and natural land and water use	Air	Mass loading for receptor environments	Distributions are based in part on uncertainty and variation in the use of wild and natural lands and the rate of consumption of wild game by the receptor (BSC 2006 [DIRS 177101], Sections 6.2 to 6.4; BSC 2005 [DIRS 172827], Sections 6.3.2 and 6.4.2).
	External exposure	Exposure time	
	Inhalation	Exposure time	
	Ingestion	Annual consumption rate of locally produced animal products	
2.4.09.01.0B Agricultural land use and irrigation	Soil	Annual irrigation rate Overwatering rate Irrigation duration	The listed parameters are developed based, in part, on variation and uncertainty in cultivated land and water use practices in Amargosa Valley (BSC 2006 [DIRS 177101], Section 6.2 to 6.4; BSC 2004 [DIRS 169673], Sections 6.3 to 6.9; BSC 2005 [DIRS 172827], Section 6.3.2; BSC 2004 [DIRS 169672], Sections 6.3.2, 6.4.3, and 6.7.2). Agricultural use of water is included in the soil (Eq. 6.4.1-2), plant (Eqs. 6.4.3-3 to 6.4.3-5), animal (Eq. 6.4.4-3), fish (Eq. 6.4.5-2), and ^{14}C (Eq. 6.4.6-1) submodels of the groundwater scenario.
	Air	Mass loading for receptor environments Mass loading for crops	
	Plant	Fraction of overhead irrigation Crop growing time Irrigation intensity Tillage depth Irrigation amount per application Daily irrigation rate	

Table 6.7-1. Disposition of the Included FEPs within the Biosphere Mathematical Model (Continued)

FEP Number and FEP Name	Biosphere Submodel [a]	Model Parameters that Address the FEP [b]	Disposition within ERMYN
2.4.09.01.0B Agricultural land use and irrigation (Continued)	External exposure	Exposure time	
	Inhalation exposure	Exposure time Enhancement factor	
	Animal	Animal consumption rate of water	
	^{14}C	Annual irrigation rate Daily irrigation rate Overwatering rate Surface area of irrigated land	
	Fish	Water concentration modifying factor	
2.4.09.02.0A Animal farms and fisheries	Animal	Animal consumption rate of feed Animal consumption rate of water Animal consumption rate of soil	Parameters are developed based, in part, on variation and uncertainty in animal and fish farming practices (BSC 2004 [DIRS 169672], Sections 6.3.2, 6.4.3, and 6.4.5).
	Fish	Water concentration modifying factor	
2.4.10.00.0A Urban and Industrial land and water use	Soil	Annual Irrigation rate	Distributions are developed based, in part, on uncertainty and variation in land and water use practices in residential and industrial settings in Amargosa Valley (BSC 2006 [DIRS 177101], Sections 6.2 to 6.4; BSC 2005 [DIRS 172827], Section 6.3.2; BSC 2004 [DIRS 169672], Section 6.5). Use of contaminated water in residential and urban environments is included in soil (Eq. 6.4.1-2) and air (Eq. 6.4.2-3) submodels of the groundwater scenario.
	Air	Mass loading for receptor environments Water evaporation rate Evaporative cooler water use rate	
	^{14}C	Annual Irrigation rate	
	External exposure	Exposure time	
	Inhalation	Exposure time	
3.1.01.01.0A Radioactive decay and ingrowth	Soil, Air, Plant, Animal, Fish	Activity concentration of a decay product in soil, air, plants, and animal products	Radionuclide decay and ingrowth in surface soils is included in the soil (equations in Section 6.4.1.2), external exposure (Eq. 6.4.7-1), inhalation (Eqs. 6.4.8-2 to 6.4.8-7), and ingestion (Eqs. 6.4.9-3 to 6.4.9-6) submodels of the groundwater scenario. It is also included in the external exposure (Eq. 6.5.5-1), inhalation (Eqs. 6.5.6-2 to 6.5.6-4), and ingestion (Eqs. 6.5.7-2 to 6.5.7-4) submodels of the volcanic ash scenario. Also included in associated dose coefficients (Sections 6.4.7.2, 6.4.8.5, 6.4.9.6, and 6.5.5.2).
	External exposure	Dose coefficients for exposure to soil contaminated to an infinite depth Dose coefficients for exposure to contaminated ground surface	
	Inhalation	Dose coefficients for inhalation Dose coefficient for inhalation of radon decay products	
	Ingestion	Dose coefficients for ingestion	

Table 6.7-1. Disposition of the Included FEPs within the Biosphere Mathematical Model (Continued)

FEP Number and FEP Name	Biosphere Submodel [a]	Model Parameters that Address the FEP [b]	Disposition within ERMYN
3.2.10.00.0A Atmospheric transport of contaminants	Air	Mass loading for crops Mass loading for receptor environments Soil bulk density Tillage depth Resuspension enhancement factor Fraction of radionuclide transfer from water to air Water evaporation rate Evaporative cooler air flow rate Radon release factor Interior wall height House ventilation rate Fraction of ^{222}Rn from soil entering the house Ratio of ^{222}Rn concentration in air to flux density from soil	The process of atmospheric transport is included in the air submodel for the groundwater scenario (Eqs. 6.4.2-1 to 6.4.2-8), the air submodel for the volcanic ash scenario (Eqs. 6.5.2-1 to 6.5.2-8), and the ^{14}C special submodel for the groundwater scenario (Eqs. 6.4.6-2 and 6.4.6-3).
	^{14}C	^{14}C emission rate constant Surface area of irrigated land Annual average wind speed ^{14}C mixing height Concentration of stable carbon in air	
3.3.01.00.0A Contaminated drinking water, foodstuffs and drugs	Plant, Animal, Fish, Ingestion	Consumption rates of locally produced crop foodstuffs Consumption rates of locally produced animal products Consumption rates of locally produced fish Consumption rate of water Inadvertent soil ingestion rate	The listed parameters quantify intake of locally produced food and locally obtained water. Distributions of intake of locally produced food are based on a survey of the people of Amargosa Valley (BSC 2005 [DIRS 172827], Section 6.4). The ingestion submodel includes the intake of food, water, and soil (groundwater scenario, Eqs. 6.4.9-2 to 6.4.9-6; volcanic ash scenario, Eqs. 6.5.7-2 to 6.5.7-4). Calculated radionuclide concentrations in foodstuffs (Sections 6.4.3, 6.4.4, 6.4.5, 6.4.6, 6.5.3, 6.5.4) also address this FEP.
3.3.02.01.0A Plant uptake	Plant	Soil-to-plant transfer factor Dry-to-wet weight ratio Fraction of overhead irrigation Translocation factor Weathering half-life Crop growing time Crop wet yield Daily irrigation rate Crop dry biomass Irrigation amount per application Irrigation intensity Dry deposition velocity	The process of plant uptake of radionuclides is included in the plant submodel for the groundwater (Eqs. 6.4.3-1 to 6.4.3-8) and volcanic ash scenarios (Eqs. 6.5.3-1 to 6.5.3-5), and in the ^{14}C special submodel for the groundwater scenario (Eqs. 6.4.6-4 and 6.4.6-6).

Table 6.7-1. Disposition of the Included FEPs within the Biosphere Mathematical Model (Continued)

FEP Number and FEP Name	Biosphere Submodel [a]	Model Parameters that Address the FEP [b]	Disposition within ERMYN
3.3.02.01.0A Plant uptake (Continued)	^{14}C	Soil bulk density Fraction of air-derived carbon in plants Fraction of soil-derived carbon in plants Fraction of stable carbon in crops Fraction of stable carbon in soil Concentration of stable carbon in air	
3.3.02.02.0A Animal uptake	Animal	Animal product transfer coefficient Animal consumption rate of feed Animal consumption rate of water Animal consumption rate of soil	The animal submodel includes the processes of radionuclide uptake by farm animals (groundwater scenario, Eqs. 6.4.4-1 to 6.4.4-4; volcanic ash scenario, Eqs. 6.5.4-1 to 6.5.4-3), the ^{14}C special submodel for the groundwater scenario also includes these processes (Eq. 6.4.6-7).
	^{14}C	Fraction of stable carbon in animal product Animal consumption rate of feed Animal consumption rate of water Animal consumption rate of soil Fraction of stable carbon in crops Concentration of stable carbon in water	
3.3.02.03.0A Fish uptake	Fish	Bioaccumulation factor Water concentration modifying factor	The fish submodel includes the bioaccumulation of radionuclides in fish (groundwater scenario, Eqs. 6.4.5-1 and 6.4.5-2). The accumulation of radionuclides in farm animals is considered in the animal uptake FEP (3.3.02.02.0A).
3.3.03.01.0A Contaminated non-food products and exposure	External exposure	See parameter list under FEP 3.3.04.03.0A	The external exposure submodel implicitly considers the FEP because these contaminated products cause external exposure that is no worse than exposure of contaminated soil.
3.3.04.01.0A Ingestion	Ingestion	Dose coefficients for ingestion Consumption rate of water Consumption rate of locally produced crop foodstuffs Consumption rate of locally produced animal products Consumption rate of locally produced fish Inadvertent soil ingestion rate	The ingestion submodel includes ingestion of contaminated food, drinking water, and contaminated soil (groundwater scenario, Eqs. 6.4.9-1 to 6.4.9-6; volcanic ash scenario, Eqs. 6.5.7-1 to 6.5.7-4).

Table 6.7-1. Disposition of the Included FEPs within the Biosphere Mathematical Model (Continued)

FEP Number and FEP Name	Biosphere Submodel [a]	Model Parameters that Address the FEP [b]	Disposition within ERMYN
3.3.04.02.0A Inhalation	Inhalation	Dose coefficients for inhalation Breathing rates Exposure times Population proportions Equilibrium factor for ^{222}Rn decay products Dose coefficient for inhalation of ^{222}Rn decay products Critical thickness for resuspension Fraction of dwellings with evaporative cooling systems Evaporator cooler usage factor	The inhalation submodel includes inhalation of contaminated resuspended particles, aerosols from evaporative coolers, ^{14}C, and radon decay products (groundwater scenario, Eqs. 6.4.8-1 to 6.4.8-7; volcanic ash scenario, Eqs. 6.5.6-1 to 6.5.6-4).
3.3.04.03.0A External exposure	External exposure	Dose coefficients for exposure to soil contaminated to an infinite depth Dose coefficients for exposure to contaminated ground surface Exposure time Population proportions Building shielding factor	The external exposure submodel includes external exposure to contaminated materials (groundwater scenario, Eq. 6.4.7-1; volcanic ash scenario, Eq. 6.5.5-1).
3.3.05.01.0A Radiation doses	External exposure, Inhalation, Ingestion	Dose coefficients for exposure to soil contaminated to an infinite depth Dose coefficients for exposure to contaminated ground surface Dose coefficients for inhalation Dose coefficients for ingestion BDCFs	Calculation of the predicted annual dose to the receptor for a unit activity concentration of a radionuclide (i.e., BDCF) is described in Eq. 6.11-5 for the groundwater scenario and 6.12-1 to and 6.12-4 for the volcanic ash scenario.
3.3.08.00.0A Radon and radon decay product exposure	Air, Inhalation	Radon release factor Interior wall height House ventilation rate Fraction of ^{222}Rn from soil entering the house Ratio of ^{222}Rn concentration to flux density for outdoors Equilibrium factor for ^{222}Rn decay products Fraction of radionuclide transfer from water to air Dose coefficient for radon decay products	The air submodels include radon concentrations (groundwater scenario, Eqs. 6.4.2-4 to 6.4.2-8; volcanic ash scenario, Eqs. 6.5.2-5 to 6.5.2-8). The inhalation submodel includes the consequences of inhaling radon and the decay products (groundwater scenario, Eqs. 6.4.8-5 to 6.4.8-7; volcanic ash scenario, Eqs. 6.5.6-3 and 6.5.6-4).

[a] Relationships among submodels shown in Figures 6.3-2 and 6.3-4. Mathematical representations described in Sections 6.4 and 6.5.
[b] Model parameters for each submodel presented in Sections 6.4 and 6.5; also summarized in Section 6.6

6.8 NUMERICAL MODEL (GOLDSIM IMPLEMENTATION) OF THE BIOSPHERE MODEL FOR THE GROUNDWATER EXPOSURE SCENARIO

The ERMYN model was built using GoldSim probabilistic simulation environment. GoldSim is a highly graphical, object-oriented computer program for carrying out probabilistic simulations. A simulation refers to creating a model that represents an existing or a future system in order to predict a system behavior and to identify those factors that control the system. In the model of the biosphere system, many controlling parameters are uncertain and a few are poorly understood. Probabilistic simulation is the process of explicitly representing this uncertainty by specifying inputs as probability distributions.

The GoldSim software supports 13 stochastic distributions: uniform, normal, lognormal, triangular, cumulative, discrete, Poisson, beta, gamma, Weibull, binomial, Student's *t*, and Boolean distributions. The most frequently used distributions in ERMYN are lognormal, normal, uniform, and cumulative distributions.

Only the eight basic GoldSim elements are used in ERMYN (Figure 6.8-1). The Data element is used for the input of fixed data or to combine several stochastic inputs into a data array. Sometimes, a simple calculation is done in the Data element. The Stochastic element is used to input distribution data. The one-dimensional Table element is used to store all radionuclide-related input parameters so that they can be accessed later. The Expression element, the most frequently used element, is used for all calculations. The Sum element is used for some simple additions. The Data and Expression elements accept data arrays, which are used to simplify calculation expressions. The Selector element is used to select parameter values from a database. The Result element is used to present the final distribution results. The Container box is used to separate submodels and calculation tasks.

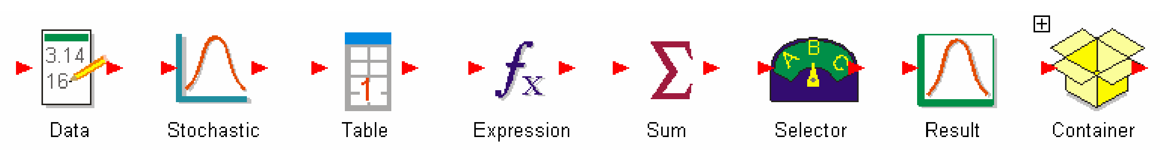


Figure 6.8-1. Basic Elements in the GoldSim Environment

For transparency, the biosphere models for the two exposure scenarios are built separately. This section describes the implementation of the ERMYN model for the groundwater scenario in GoldSim and shows the overall model algorithm and submodel structures. The GoldSim file (*ERMYN_GW_Rev01.gsm*) is part of the model output, which is listed in Appendix A. As discussed in Section 6.4, *ERMYN_GW_Rev01* is structured as a series of submodels. Under each submodel, the linkage of GoldSim elements to the submodel input parameters in an equation is tabulated in this section. Color coding is used in GoldSim to aid in distinguishing among items displayed on the computer screen. Text descriptions are shown in green. Element names are shown in black for calculated quantities and in blue for input parameters. If the name of a container box is shown in blue, it contains at least one input parameter. The title page for the *ERMYN_GW_Rev01.gsm* simulation tool for biosphere modeling (Figure 6.8-2) shows the title and one container box, *Biosphere_Model*, with the name shown in blue to indicate that it contains at least one input parameter.

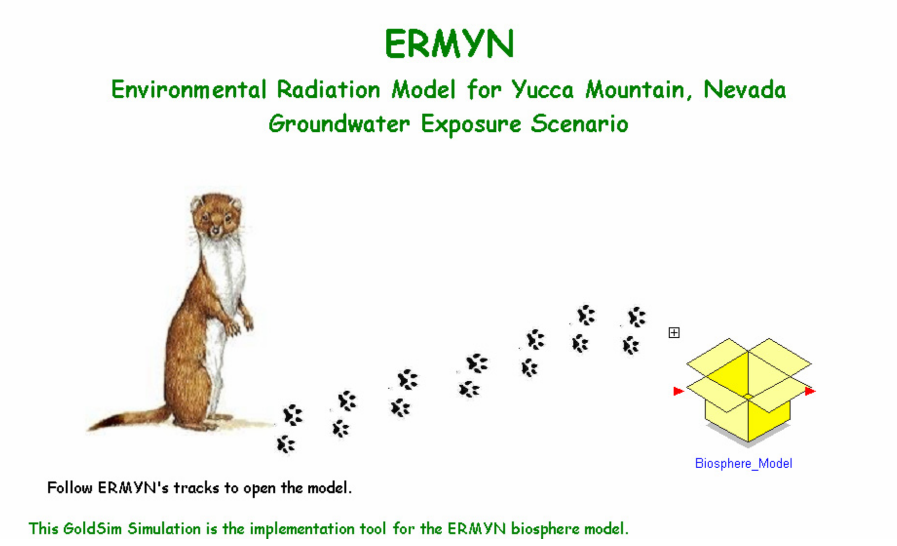


Figure 6.8-2. Title Page for the *ERMYN_GW_Rev01* Model in GoldSim

The *Biosphere_Model* container shown in Figure 6.8-2 holds the submodel containers and the radionuclide data (Figure 6.8-3). GoldSim is an object-oriented graphical program, and the overall model structure looks much like the block diagram of the conceptual model for the groundwater scenario shown in Figure 6.3-2. Each container in GoldSim corresponds to a submodel or to a component model if a container is at a lower level.

Ten containers, including eight submodels (^{14}C does not have a specific box), one results box, and one radionuclide database box are shown in Figure 6.8-3. Each container is discussed in detail in the following subsections. Only two input parameters can be changed at this level: *Radionuclide* and *Water_Source*. *Radionuclide* can be selected only from the data element of *Radionuclide_List* (index i in the equations) that is built in the *Nuclide_Database* container. *Water_Source* is the radionuclide concentration in the groundwater (Cw_i in the equations), which has a default value of 1 Bq/m^3. GoldSim can run in deterministic or stochastic modes by adjusting settings in the *MasterClock*. Master Clock controls simulation settings such as the simulation run mode, number of realizations and the sampling method. If the stochastic mode is chosen, the number of realizations, the sampling method (Monte Carlo or Latin Hypercube), and a random seed number is set. Because the BDCFs are not a function of time, the time option is disabled in ERMYN.

As discussed in Section 6.4, other than the surface soil submodel, the biosphere model involves radionuclides linearly transported from one environmental medium to another, primarily through the use of the media concentration ratios, such as the partition coefficients, transfer factors, and transfer coefficients. The model algorithm uses the submodels and is described here in the order discussed in Section 6.4. The results calculated in one submodel are then used in the next applicable submodel. The arrows in Figure 6.8-3 indicate the relationships and calculation logic flow among submodels.

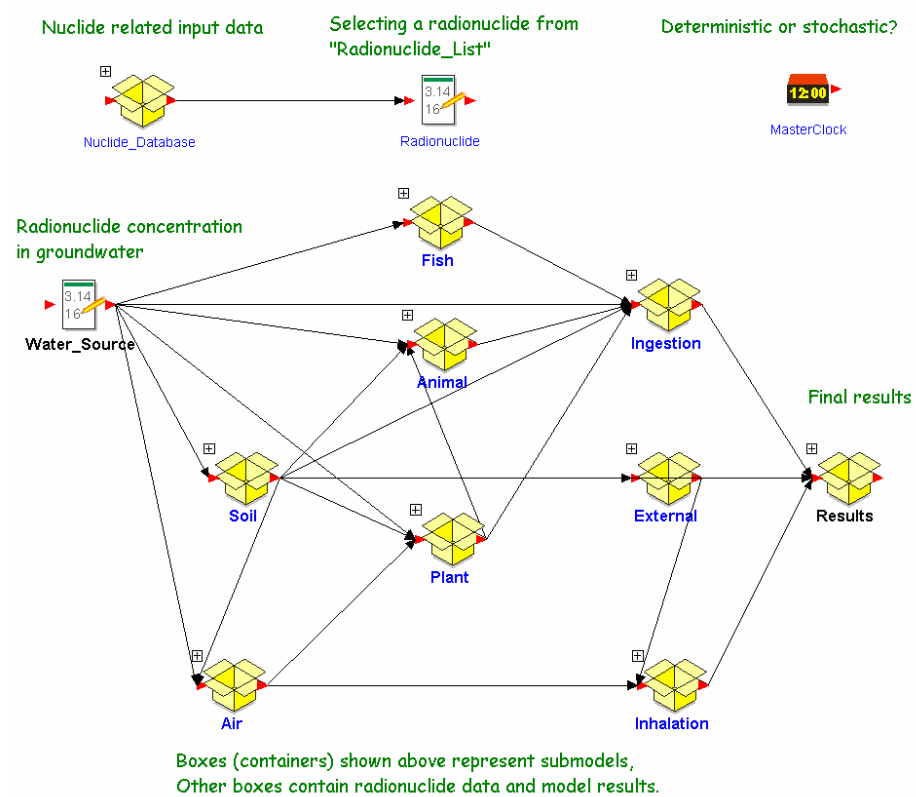


Figure 6.8-3. Graphical Representation of the Groundwater Scenario in GoldSim

Many calculations are performed using data vectors to reduce the number of elements. Twelve data array labels are used: primary radionuclides (31), total number of radionuclides (75), pathways (15), plant types (5), crop food types 4), animal product types (4), number of long-lived decay products (3), population groups (4), environments (5), air submodel pathway (4), crop uptake pathway (4), and animal uptake pathway (4). These data sets and submodel pathways are discussed in the mathematical model (Section 6.4).

6.8.1 Nuclide Database

The *Nuclide_Database* container (Figure 6.8-4) includes all radionuclide-related input parameters (under the *Nuclide_Data* container) and their selection in the model (under the *Data_Selection* container). Besides the two containers, there is one data element, *Radionuclide_List*, which includes 31 long-lived radionuclides shown in Table 6.1-1.

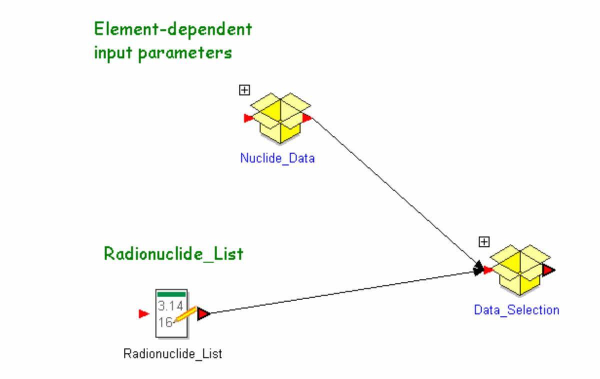


Figure 6.8-4. Content of *Nuclide_Database* Container

The *Nuclide_Data* container includes five subcontainers (element-specific partition coefficients, crop transfer factors, animal product transfer coefficients, fish bioaccumulation factors, and nuclear data). For example, the *Crop_Transfer* container (Figure 6.8-5) includes 80 distribution parameters for 16 elements and 5 plant types. The format of the other three containers (*Animal_Transfer*, *Fish_Transfer*, *Kd_Coefficients*) is similar. The *Nuclear_Data* container includes radionuclide half-lives, branching fractions, external dose coefficients for contaminated soil, and dose coefficients for inhalation and ingestion. All nuclear input data have fixed values and are in array form.

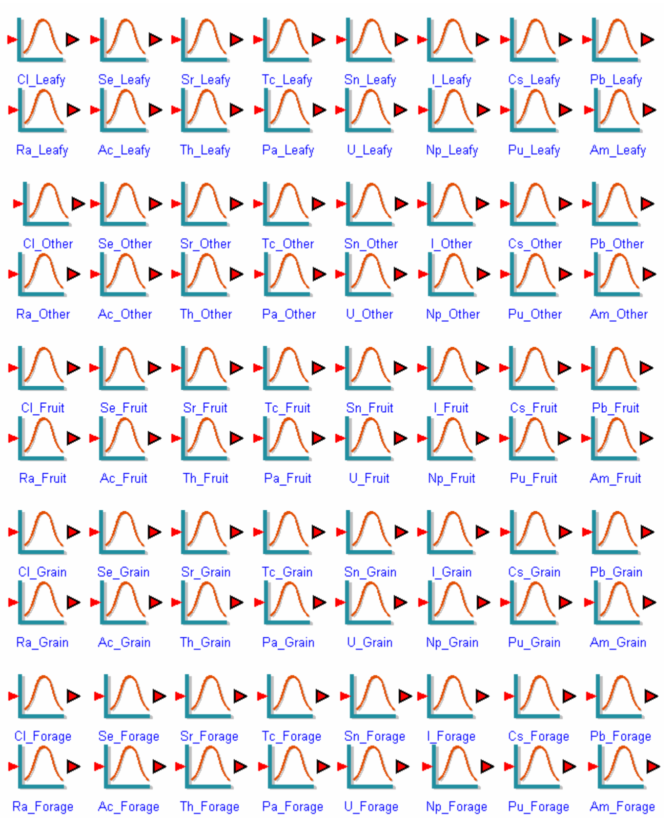


Figure 6.8-5. Input Parameters for Crop Transfer Factors

Within the *Data_Selection* container (Figure 6.8-6), dose coefficients for the short-lived decay products are added to the corresponding dose coefficient for the primary radionuclides. This is calculated in the *Effective_DCF* container (Figure 6.8-7). In the other three containers shown in Figure 6.8-6, 15 radionuclide-specific input parameters for the primary radionuclides, the first decay products, and the second decay products (if the primary radionuclide has decay products) are selected. After a radionuclide is selected for processing through the model, the radionuclide specific input parameters are determined using *Selector* elements. Figure 6.8-8 shows the selectors for the primary radionuclide; selectors in the first decay product and the second decay product containers are analogous. Parameter names, GoldSim element types, data sources, data types, related mathematical equation numbers, and notations for the *Nuclide_Database* container are shown in Table 6.8-1. Information for the decay product containers (*Decay1_Rn* and *Decay2_Rn*) is not tabulated, but it is similar to that shown for the primary radionuclides (Table 6.8-1). The selection of decay products is discussed in Section 6.4.1.2 and Table 6.4-3. After the radionuclide-related input parameters are selected, the values are passed to the appropriate submodels.

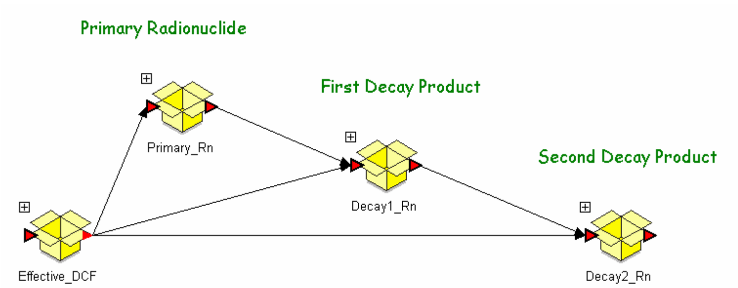


Figure 6.8-6. Radionuclide-Specific Input Parameter Selection

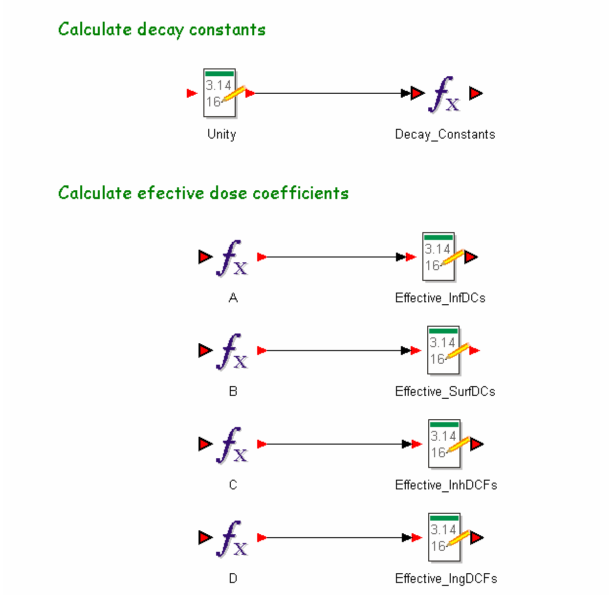


Figure 6.8-7. Calculation of Effective Dose Coefficients

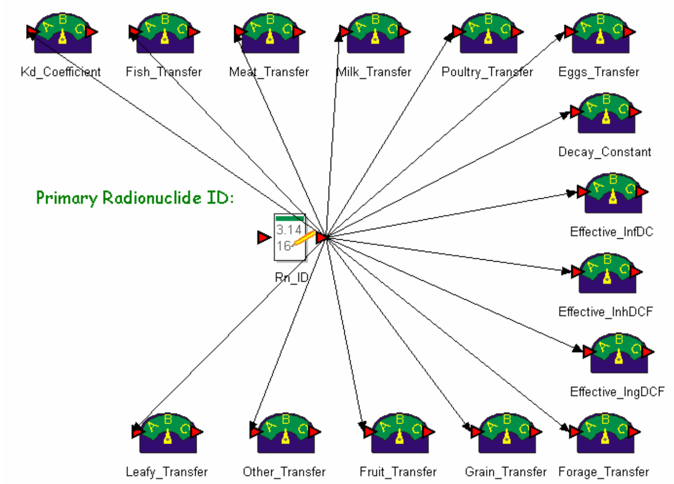


Figure 6.8-8. *Primary_Rn* Container and Selection of the Second Decay Product

Table 6.8-1. Radionuclide-Related Input Parameters in the *Nuclide_Database* Container

First Level Box Name	Second Level Box Name	Parameter or Container Name	Element Type [a]	Data Source [b]	Data Type [c]	Equation	Notation
Radionuclide_List			Data	Input	Vector(31)	6.4.1-1	*i*
Nuclide_ Data	*Kd_Coefficients*		Container	Not shown in detail			
	Crop_Transfers						
	Animal_Transfers						
	Fish_Transfers						
	Nuclear_Data						
Data_ Selection	*Effective_ DCF*	*Unity*	Data	—	Vector(31)	—	—
		Decay_Constants	Expression	Calculated	Vector(31)	6.4.1-1	$\lambda_{d\ i}$
		A	Expression	Calculated	Vector(31)	6.4.7-2	$DCi_{soil,i}$
		B	Expression	Calculated	Vector(31)	Not used	—
		C	Expression	Calculated	Vector(31)	6.4.8-8	$DCF_{inh,i}$
		D	Expression	Calculated	Vector(31)	6.4.9-7	$DCF_{ing,i}$
		Effective_InfDCs	Data	Calculated	Vector(31)	6.4.7-2	$EDCi_{soil,i}$
		Effective_SurDCs	Data	Calculated	Vector(31)	Not used	—
		Effective_InhDCFs	Data	Calculated	Vector(31)	6.4.8-8	$EDCF_{inh,i}$
		Effective_IngDCFs	Data	Calculated	Vector(31)	6.4.9-6	$EDCF_{ing,i}$

Table 6.8-1. Radionuclide-Related Input Parameters in the *Nuclide_Database* Container (Continued)

First Level Box Name	Second Level Box Name	Parameter or Container Name	Element Type [a]	Data Source [b]	Data Type [c]	Equation	Notation
Data_ Selection (Cont.)	*Primary_ Rn*	*Rn_ID*	Data	Dbase	Scalar	6.4.1-1	I
		Decay_Constant	Selector	Dbase	Scalar	6.4.1-1	$\lambda_{d\,I}$
		Effective_InfDC	Selector	Dbase	Scalar	6.4.7-1	$EDCi_{soil,i}$
		Effective_InhDCF	Selector	Dbase	Scalar	6.4.8-2	$EDCF_{inh,i}$
		Effective_IngDCF	Selector	Dbase	Scalar	6.4.9-2	$EDCF_{ing,i}$
		Kd_Coefficient	Selector	Dbase	Scalar	6.4.1-28	Kd_i
		Fish_Transfer	Selector	Dbase	Scalar	6.4.5-1	BF_i
		Beef_Transfer	Selector	Dbase	Scalar	6.4.4-2	$Fm_{i,1}$
		Poultry_Transfer	Selector	Dbase	Scalar	6.4.4-2	$Fm_{i,2}$
		Milk_Transfer	Selector	Dbase	Scalar	6.4.4-2	$Fm_{i,3}$
		Eggs_Transfer	Selector	Dbase	Scalar	6.4.4-2	$Fm_{i,4}$
		Leafy_Transfer	Selector	Dbase	Scalar	6.4.3-2	$F_{s\rightarrow p,i,1}$
		Other_Transfer	Selector	Dbase	Scalar	6.4.3-2	$F_{s\rightarrow p,i,2}$
		Fruit_Transfer	Selector	Dbase	Scalar	6.4.3-2	$F_{s\rightarrow p,i,3}$
		Grain_Transfer	Selector	Dbase	Scalar	6.4.3-2	$F_{s\rightarrow p,i,4}$
		Forage_Transfer	Selector	Dbase	Scalar	6.4.3-2	$F_{s\rightarrow p,i,5}$
	Decay1_Rn		Container	Not shown in detail in this table			
	Decay2_Rn		Container	Not shown in detail in this table			

NOTE: The following notes apply to all GoldSim tables in Section 6.8.

[a] Element type is the GoldSim element type used for inputs, calculations, and other manipulations.

[b] If the data source is "Input," the parameter values are entered in the GoldSim element. If the source is "Dbase," values are taken from a database, or calculated values. If the data source is "Calculated," it is a quantity calculated using other elements. If the source and the corresponding equation notation are dashes (–), the element is added for GoldSim array calculations.

[c] Data types are scalar (a single value) or array (a set of values). A one-dimensional array is called a vector, and a two-dimensional array is called a matrix. The number of values in the array is given in parenthesis.

6.8.2 Surface Soil Submodel

The mathematical equations for the surface soil submodel are discussed in Section 6.4.1. The contents of the submodel container are shown in Figure 6.8-9. All GoldSim elements in the surface soil submodel are listed in Table 6.8-2. The submodel includes five lower-level containers. The *SoilModel_Input* container includes all input parameters in the submodel (Figure 6.8-10), which are all distribution parameters. The *Soil_Conc* container includes calculations of the leaching factor for the surface soil and the resuspendable soil layer (critical soil thickness) (Equations 6.4.1-28 and 6.4.1-29) and the radionuclide concentration for primary radionuclides in these two soil layers (Equations 6.4.1-3 or 6.4.1-25 and Equation 6.4.1-4) (Figure 6.8-11). The *Soil_Conc_1* container includes calculations of the radionuclide buildup in soil for the first decay product (Equation 6.4.1-26) (Figure 6.8-12), while the *Soil_Conc_2* container includes calculations of the buildup of the second decay product (Equation 6.4.1-27) (Figure 6.8-13). The calculation of decay-product buildup uses radionuclide-specific input parameters. Although the special submodel for ^{14}C in the soil is discussed separately

(Section 6.4.6), the soil concentration of ^{14}C is included in the *C14_Soil* container in the surface soil submodel.

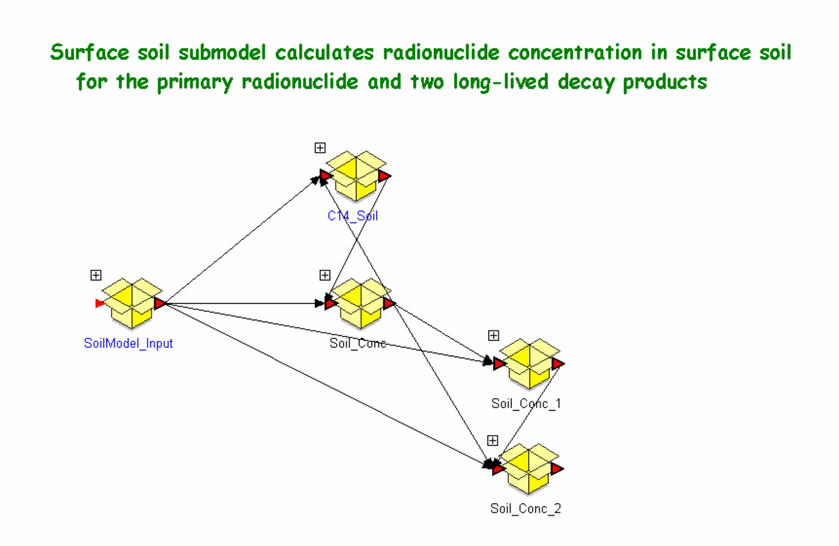


Figure 6.8-9. Soil Submodel Container

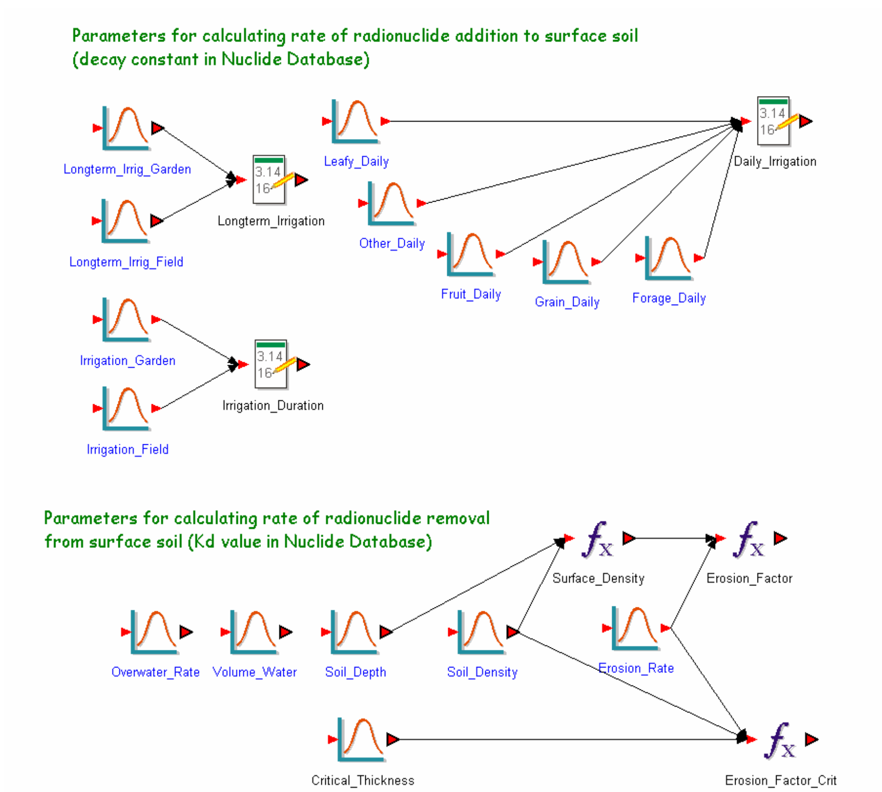


Figure 6.8-10. Input Parameter Container (*SoilModel_Input*) for the Soil Submodel

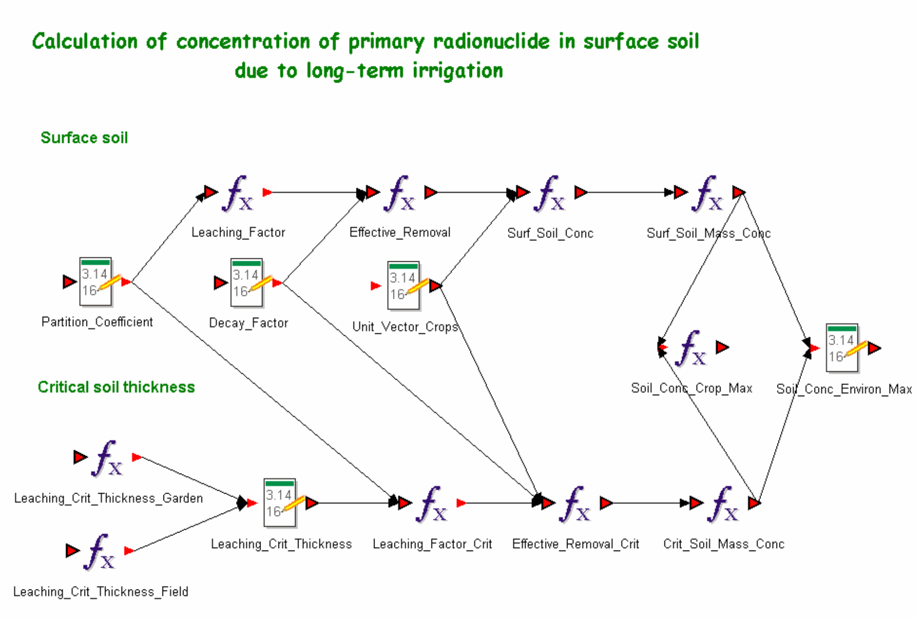


Figure 6.8-11. Soil Concentration Container for the Primary Radionuclide (*Soil_Conc*) for the Soil Submodel

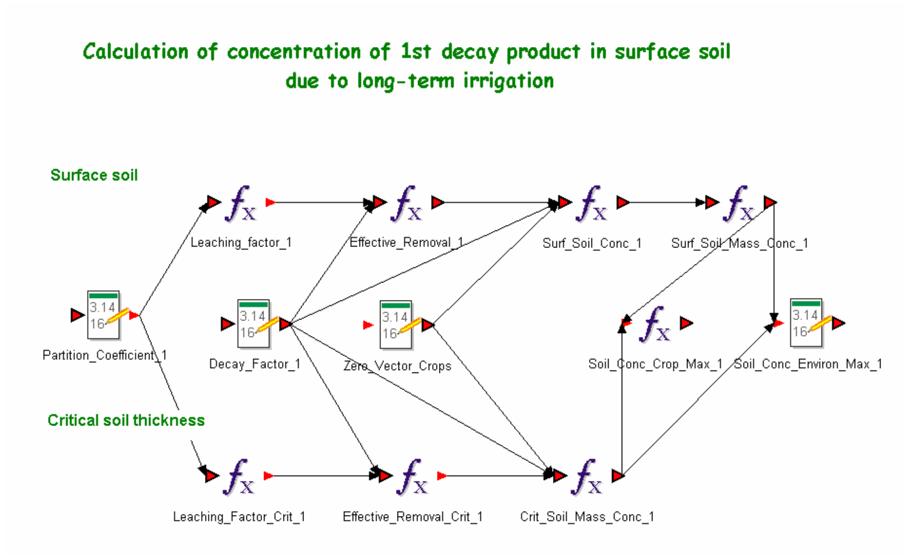


Figure 6.8-12. Soil Concentration Container for the First Decay Product (*Soil_Conc_1*) for the Soil Submodel

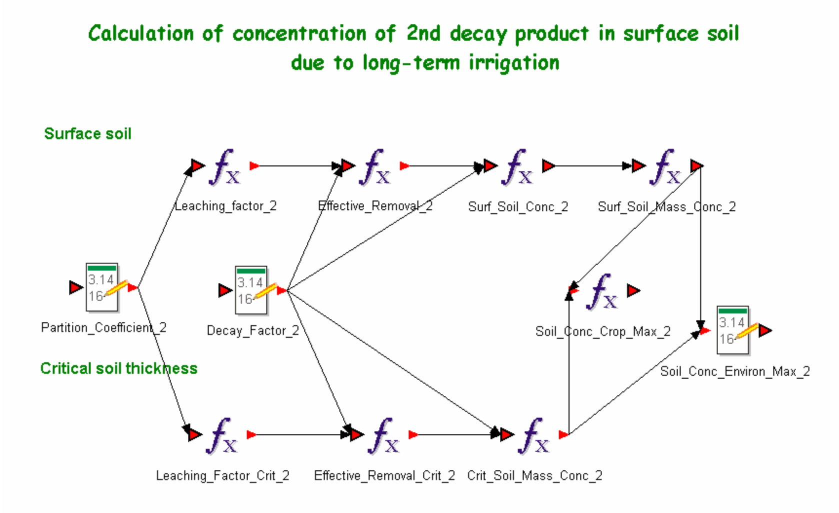


Figure 6.8-13. Soil Concentration Container for the Second Decay Product (*Soil_Conc_2*) for the Soil Submodel

Table 6.8-2. Parameters in the Surface Soil Submodel

Low Level Box Name	**Parameter Name**	**Element Type**	**Data Source**	**Data Type**	**Equation**	**Notation**
SoilModel_ Input	*Leafy_Daily*	Stochastic	Input	Scalar	6.4.3-4	IRD_1
	Other_Daily	Stochastic	Input	Scalar	6.4.3-4	IRD_2
	Fruit_Daily	Stochastic	Input	Scalar	6.4.3-4	IRD_3
	Grain_Daily	Stochastic	Input	Scalar	6.4.3-4	IRD_4
	Forage_Daily	Stochastic	Input	Scalar	6.4.3-4	IRD_5
	Daily_Irrigation	Data	Calculated	Vector(5)	6.4.3-4	IRD_j
	Longterm_Irrig_Garden	Stochastic	Input	Scalar	6.4.1-3 6.4.1-4	IR_j
	Longterm_Irrig_Field	Stochastic	Input	Scalar	6.4.1-3 6.4.1-4	IR_j
	Longterm_Irrigation	Data	Calculated	Vector(5)	6.4.1-3 6.4.1-4	IR_j
	Irrigation_Garden	Stochastic	Input	Scalar	6.4.1-3	$T_{irr,j}$
	Irrigation_Field	Stochastic	Input	Scalar	6.4.1-3	$T_{irr,j}$
	Irrigation_Duration	Data	Calculated	Vector(5)	6.4.1-3	$T_{irr,j}$
	Overwater_Rate	Stochastic	Input	Scalar	6.4.1-28	OW
	Volume_Water	Stochastic	Input	Scalar	6.4.1-28	θ
	Erosion_Rate	Stochastic	Input	Scalar	6.4.1-31	ER
	Erosion_Factor	Expression	Calculated	Scalar	6.4.1-31	λ_e
	Soil_Depth	Stochastic	Input	Scalar	6.4.1-6	d
	Soil_Density	Stochastic	Input	Scalar	6.4.1-6	ρ
	Surface_Density	Expression	Calculated	Scalar	6.4.1-5	ρ_s
	Critical_Thickness	Stochastic	Input	Scalar	6.4.1-6	d_c
	Erosion_Factor_Crit	Expression	Calculated	Scalar	6.4.1-32	λ_{ec}

Table 6.8-2. Parameters in the Surface Soil Submodel (Continued)

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
C14_Soil	*Emission_Factor*	Data	Input	Scalar	6.4.6-1	$\lambda_{a,C\text{-}14}$
	C14_Zero	Data	—	Vector(5)	—	—
	C14Conc_CropSoil	Expression	Calculated	Vector(5)	6.4.6-1	$Cs_{C\text{-}14,j}$
	C14Conc_InhSoil	Expression	Calculated	Vector(5)	6.4.6-1	$Cs_{C\text{-}14,j}$
	C14Conc_InhGas	Expression	Calculated	Vector(5)	6.4.6-1	$Cs_{c,C\text{-}14,j}$
Soil_Conc	*Partition_Coefficient*	Data	Dbase	Scalar	6.4.1-28	Kd_i
	Leaching_Factor	Expression	Calculated	Scalar	6.4.1-28	$\lambda_{l,i}$
	Decay_Factor	Data	Dbase	Scalar	6.4.1-1	$\lambda_{d,i}$
	Effective_Removal	Expression	Calculated	Scalar	6.4.1-3	$\lambda_{eff,i}$
	Surf_Soil_Conc	Expression	Calculated	Vector(5)	6.4.1-4	Cs_i
	Surf_Soil_Mass_Conc	Expression	Calculated	Vector(5)	6.4.1-5	$Cs_{m,i,j}$
	Unit_Vector_Crops	Data	—	Vector(5)	—	—
	Leaching_Crit_ Thickness_Garden	Expression	Calculated	Scalar	6.4.1—30	OW_c
	Leaching_Crit_ Thickness_Field	Expression	Calculated	Scalar	6.4.1-30	OW_c
	Leaching_Crit_ Thickness	Expression	Calculated	Vector(5)	6.4.1-30	OW_c
	Leaching_Factor_Crit	Expression	Calculated	Vector(5)	6.4.1-29	$\lambda_{lc,i}$
	Effective_Removal_Crit	Expression	Calculated	Vector(5)	6.4.1-33	$\lambda_{eff,c,i}$
	Crit_Soil_Mass_Conc	Expression	Calculated	Vector(5)	6.4.1-5	$Cs_{mc,i,j}$
	Soil_Conc_Crop_Max	Expression	Calculated	Vector(5)	—	$Cs_{m,i,j}$ *or* $Cs_{mc,i,j}$
	Soil_Conc_Environ_Max	Data	Calculated	Vector(5)	—	$Cs_{m,i,n}$ *or* $Cs_{mc,i,n}$
Soil_Conc_1	*Partition_ Coefficient_1*	Data	Dbase	Scalar	6.4.1-28	Kd_1
	Leaching_Factor_1	Expression	Calculated	Scalar	6.4.1-28	$\lambda_{l,1}$
	Decay_Factor_1	Data	Dbase	Scalar	6.4.1-1	$\lambda_{d,1}$
	Effective_Removal_1	Expression	Calculated	Scalar	6.4.1-3	$\lambda_{eff,1}$
	Surf_Soil_Conc_1	Expression	Calculated	Vector(5)	6.4.1-26	Cs_1
	Surf_Soil_Mass_Conc_1	Expression	Calculated	Vector(5)	6.4.1-5	$Cs_{m,1}$
	Zero_Vector_Crops	Data	—	Vector(5)	—	—
	Leaching_Factor_Crit_1	Expression	Calculated	Vector(5)	6.4.1-29	$\lambda_{lc,1}$
	Effective_Removal_Crit_ 1	Expression	Calculated	Vector(5)	6.4.1-33	$\lambda_{eff,c,1}$
	Crit_Soil_Mass_Conc_1	Expression	Calculated	Vector(5)	6.4.1-5	$Cs_{mc,1,j}$
	Soil_Conc_Crop_Max_1	Expression	Calculated	Vector(5)	—	$Cs_{m,1,j}$ *or* $Cs_{mc,1,j}$
	Soil_Conc_Environ_Max_ 1	Data	Calculated	Vector(5)	—	$Cs_{m,1,n}$ *or* $Cs_{mc,1,n}$

Table 6.8-2. Parameters in the Surface Soil Submodel (Continued)

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Soil_Conc_2	*Partition_ Coefficient_2*	Data	Dbase	Scalar	6.4.1-28	Kd_2
	Leaching_Factor_2	Expression	Calculated	Scalar	6.4.1-28	$\lambda_{l,2}$
	Decay_Factor_2	Data	Dbase	Scalar	6.4.1-1	$\lambda_{d,2}$
	Effective_Removal_2	Expression	Calculated	Scalar	6.4.1-3	$\lambda_{eff,2}$
	Surf_Soil_Conc_2	Expression	Calculated	Vector(5)	6.4.1-27	Cs_2
	Surf_Soil_Mass_Conc_2	Expression	Calculated	Vector(5)	6.4.1-5	$Cs_{m,2}$
	Leaching_Factor_Crit_2	Expression	Calculated	Vector(5)	6.4.1-29	$\lambda_{lc,2}$
	Effective_Removal_Crit_2	Expression	Calculated	Vector(5)	6.4.1-33	$\lambda_{eff,c,2}$
	Crit_Soil_Mass_Conc_2	Expression	Calculated	Vector(5)	6.4.1-5	$Cs_{mc,2,j}$
	Soil_Conc_Crop_Max_2	Expression	Calculated	Vector(5)	—	$Cs_{m,2,j}$ *or* $Cs_{mc,2,j}$
	Soil_Conc_Environ_Max_2	Data	Calculated	Vector(5)	—	$Cs_{m,2,n}$ *or* $Cs_{mc,2,n}$

NOTE: See notes for Table 6.8-1.

6.8.3 Air Submodel

The mathematical equations used for the air submodel are discussed in Section 6.4.2. All parameters in the air submodel are summarized in Table 6.8-3. This submodel includes five lower-level containers (Figure 6.8-14). The *AirModel_Input* container includes the following input parameters: mass loading for deposition of resuspended soil on crops, mass loading for inhalation of resuspended soil, and the enhancement factor (Figure 6.8-15). The *Dust_Air* container calculates airborne radionuclide concentrations due to resuspended particles for direct deposition on crops (Equation 6.4.2-1) and human inhalation (Equation 6.4.2-2). Resuspended particles originate from the surface soil and decay product accumulation in surface soil is considered in the soil container. The *Radon_Air* container includes calculations related to the release of radon gas from ^{226}Ra-contaminated soil (Figure 8.6-16). Radon-222 is a decay product of the primary radionuclide ^{226}Ra, which is a decay product of ^{230}Th. The special submodel for ^{14}C in the air (Section 6.4.6.2) is included in the *C14_Air* container of the air submodel (Figure 8.6-17). Calculations that are carried out in this container concern only gaseous releases of ^{14}C from surface soil to air. Resuspension of particulates containing ^{14}C is addressed in the *Dust_Air* container. Radionuclide concentrations in the air due to emission of aerosols from evaporative coolers are calculated in the *Evaporative_Air* container. Because aerosols are released directly from contaminated groundwater, a decay chain due to radionuclide buildup in the soil is not considered.

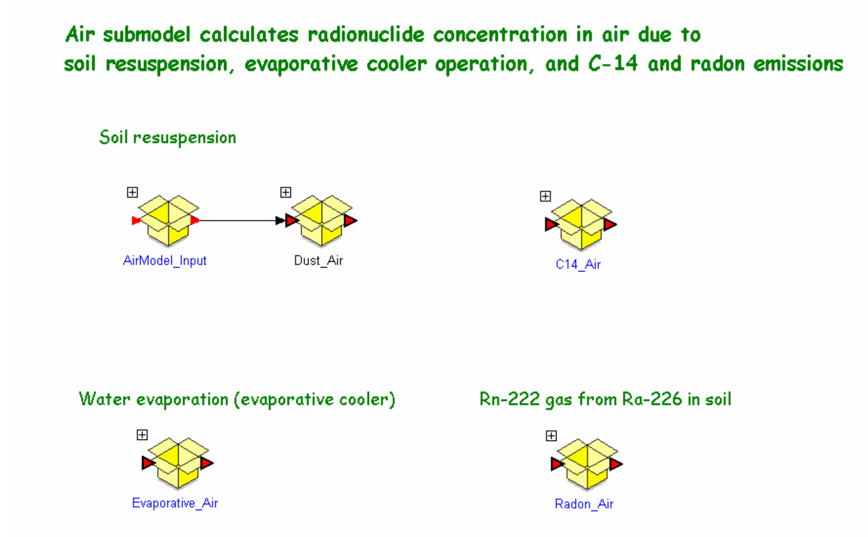


Figure 6.8-14. Air Submodel Container

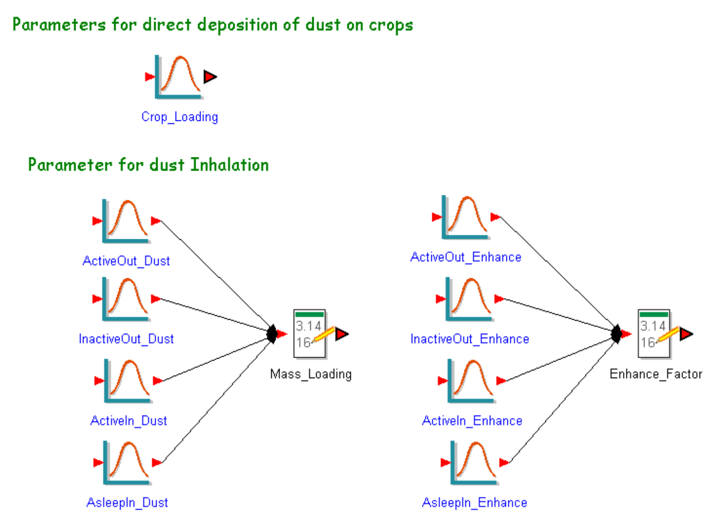


Figure 6.8-15. Input Parameter Container (*AirModel_Input*) for the Air Submodel

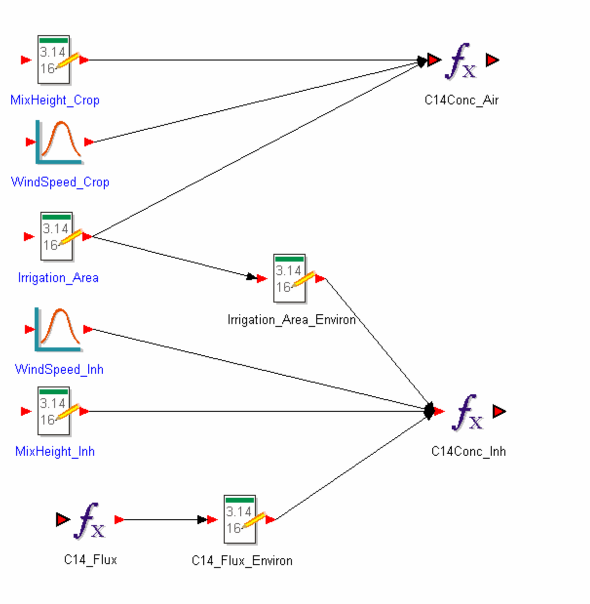


Figure 6.8-16. *Radon_Air* Container of the Air Submodel

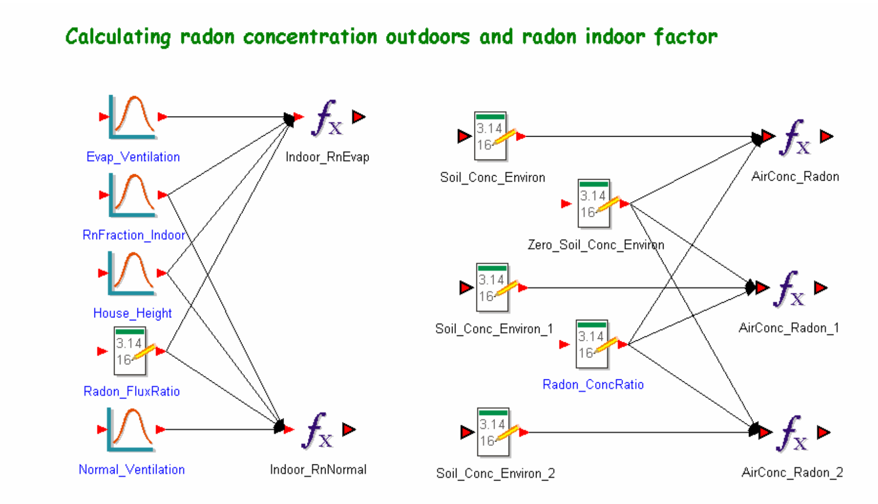


Figure 6.8-17. *C14_Air* Container of the Air Submodel

Table 6.8-3. Parameters in the Air Submodel

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
AirModel_Input	*Crop_Loading*	Stochastic	Input	Scalar	6.4.2-1	S
	ActiveOut_Dust	Stochastic	Input	Scalar	6.4.2-2	S_1
	InactiveOut_Dust	Stochastic	Input	Scalar	6.4.2-2	S_2
	ActiveIn_Dust	Stochastic	Input	Scalar	6.4.2-2	S_3
	AsleepIn_Dust	Stochastic	Input	Scalar	6.4.2-2	S_4
	Mass_Loading	Data	Calculated	Vector(5)	6.4.2-2	S_n
	ActiveOut_Enhance	Stochastic	Input	Scalar	6.4.2-2	$f_{enhance,1}$

Table 6.8-3. Parameters in the Air Submodel (Continued)

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
AirModel_Input (Continued)	*InactiveOut_Enhance*	Stochastic	Input	Scalar	6.4.2-2	$f_{enhance,2}$
	ActiveIn_Enhance	Stochastic	Input	Scalar	6.4.2-2	$f_{enhance,3}$
	AsleepIn_Enhance	Stochastic	Input	Scalar	6.4.2-2	$f_{enhance,4}$
	Enhance_Factor	Data	Calculated	Vector(5)	6.4.2-2	$f_{enhance,n}$
Dust_Air	*AirConc_Crop*	Expression	Calculated	Scalar	6.4.2-1	$Ca_{p,\ i}$
	AirConc_Crop_1	Expression	Calculated	Scalar	6.4.2-1	$Ca_{p,\ 1}$
	AirConc_Crop_2	Expression	Calculated	Scalar	6.4.2-1	$Ca_{p,\ 2}$
	AirConc_Inh	Expression	Calculated	Vector(5)	6.4.2-2	$Ca_{h,\ i,n}$
	AirConc_Inh_1	Expression	Calculated	Vector(5)	6.4.2-2	$Ca_{h,\ 1,n}$
	AirConc_Inh_2	Expression	Calculated	Vector(5)	6.4.2-2	$Ca_{h,\ 2,n}$
C14_Air	*Mixing_Height_Crop*	Data	Input	Scalar	6.4.6-3	H_{mix}
	Wind_Speed_Crop	Stochastic	Input	Scalar	6.4.6-3	U
	Irrigation_Area	Data	Input	Vector(5)	6.4.6-3	A_j
	Wind_Speed_Inh	Stochastic	Input	Scalar	6.4.6-3	U
	Mixing_Height_Inh	Data	Input	Scalar	6.4.6-3	H_{mix}
	Irrigation_Area_ Environment	Data	Input	Vector(5)	6.4.6-3	A_n
	C14Conc_Air	Expression	Calculated	Vector(5)	6.4.6-3	$Ca_{g,C\text{-}14,}$
	C14_Flux	Expression	Calculated	Vector(5)	6.4.6-2	$EVSN_j$
	C14_Flux_Environ	Expression	Calculated	Vector(5)	6.4.6-3	$EVSN_n$
	C14Conc_Inh	Expression	Calculated	Vector(5)	6.4.6-3	$Ca_{g,C\text{-}14,n}$
Evaporative_Air	*Evap_Fraction*	Stochastic	Input	Scalar	6.4.2-3	f_{evap}
	Water_Usage	Stochastic	Input	Scalar	6.4.2-3	M_{water}
	Airflow_Rate	Stochastic	Input	Scalar	6.4.2-3	F_{air}
	AirConc_Evap	Expression	Calculated	Scalar	6.4.2-3	$Ca_{e,i}$
Radon_Air	*Radon_ConcRatio*	Stochastic	Input	Scalar	6.4.2-4	$f_{m,\ Rn\text{-}222}$
	Soil_Conc_Environ	Data	Calculated	Vector(5)	6.4.2-2	$Cs_{m,i,n}$
	Soil_Conc_Environ_1	Data	Calculated	Vector(5)	6.4.2-2	$Cs_{m,1,n}$
	Soil_Conc_Environ_2	Data	Calculated	Vector(5)	6.4.2-2	$Cs_{m,2,n}$
	AirConc_Radon	Expression	Calculated	Vector(5)	6.4.2-4	$Ca_{g,Rn\text{-}222}$
	AirConc_Radon_1	Expression	Calculated	Vector(5)	6.4.2-4	$Ca_{g,Rn\text{-}222}$
	AirConc_Radon_2	Expression	Calculated	Vector(5)	6.4.2-4	$Ca_{g,Rn\text{-}222}$
	Evap_Ventilation	Stochastic	Input	Scalar	6.4.2-5	v_e
	RnFraction_Indoor	Stochastic	Input	Scalar	6.4.2-6	f_{house}
	House_Height	Stochastic	Input	Scalar	6.4.2-5	H
	Radon_FluxRatio	Data	Input	Scalar	6.4.2-7	$CF_{Rn\text{-}222}$
	Normal_Ventilation	Stochastic	Input	Scalar	6.4.2-5	v_n
	Indoor_RnEvap	Expression	Calculated	Scalar	6.4.2-8	$IF_{e,Rn\text{-}222}$
	Indoor_RnNormal	Expression	Calculated	Scalar	6.4.2-7	$IF_{n,Rn\text{-}222}$

NOTE: See notes for Table 6.8-1.

6.8.4 Plant Submodel

Mathematical equations for the plant submodel are discussed in Section 6.4.3. All parameters in the submodel are listed in Table 6.8-4. The contents of the submodel container (Figure 6.8-18) include five lower-level containers. The *PlantModel_Input* container includes many input parameters related to agriculture (Figure 6.8-19). There is also another container under the *PlantModel_Input* container, which contains input parameters related to irrigation. Each mechanism of radionuclide transfer into crops is considered separately in the plant submodel. The *Water_Uptake* container includes calculations of radionuclide concentrations in crops (Equations 6.4.3-3, 6.4.3-4, and 6.4.3-5) due to foliar interception of contaminated groundwater (Figure 6.8-20). One element in that container, the *Intercept_Factor*, combines the interception fractions for the various crops into a vector and checks to determine if the sum exceeds 1.0 (this parameter cannot exceed 1.0; Section 6.4.3.2). The *Root_Uptake* container includes calculations of the radionuclide concentrations in crops (Equation 6.4.3-2) due to root uptake of radionuclides. The *Dust_Uptake* container includes calculations of the radionuclide concentrations in crops (Equations 6.4.3-6, 6.4.3-7, and 6.4.3-8) due to the deposition of resuspended contaminated soil. The *C14_Crop* container includes the calculations of transfer of ^{14}C into plants (Section 6.4.6.3).

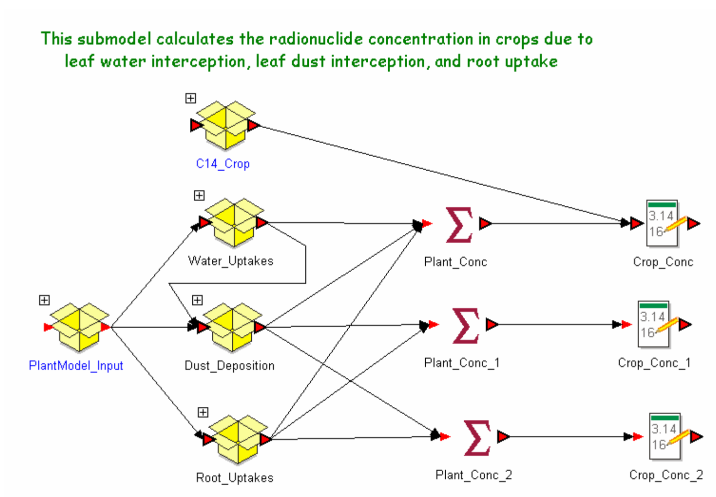


Figure 6.8-18. Plant Submodel Container

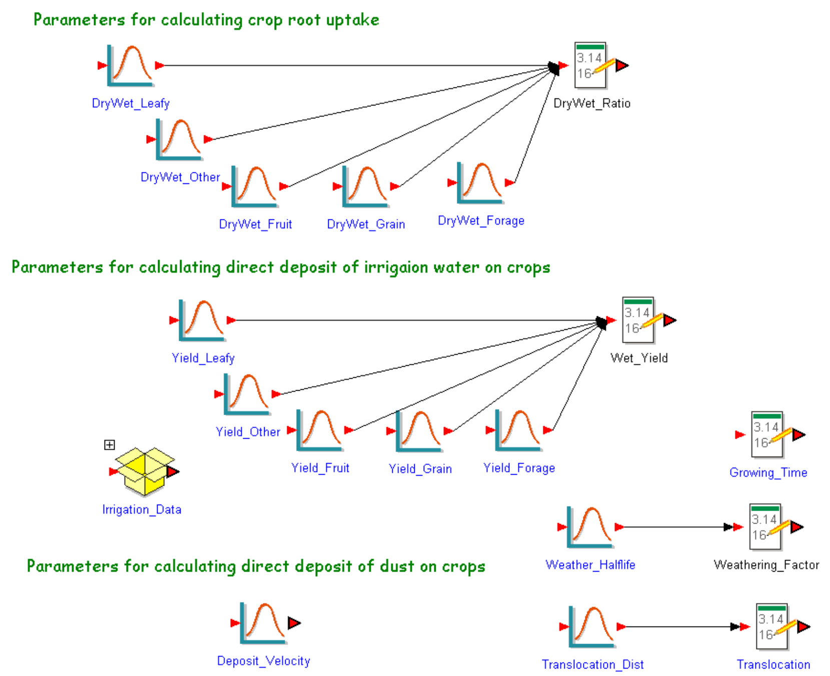


Figure 6.8-19. Input Parameter Container (*PlantModel_Input*) for the Plant Submodel

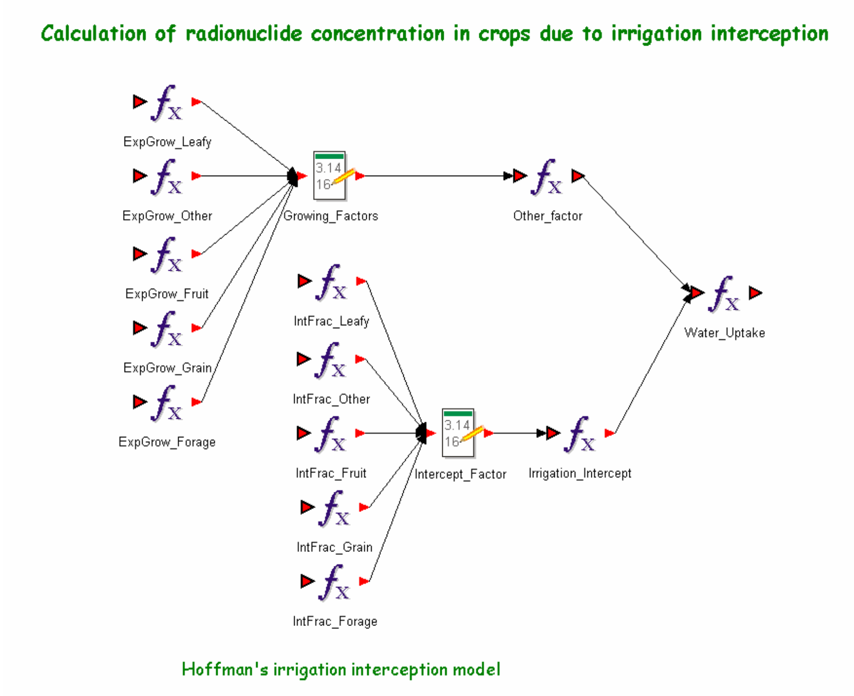


Figure 6.8-20. *Water_Uptake* Container of the Plant Submodel

Table 6.8-4. Parameters in the Plant Submodel

First Level Name	Second Level Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Plant Model_ Input	*DryWet_Leafy*		Stochastic	Input	Scalar	6.4.3-2	DW_1
	DryWet_Other		Stochastic	Input	Scalar	6.4.3-2	DW_2
	DryWet_Fruit		Stochastic	Input	Scalar	6.4.3-2	DW_3
	DryWet_Grain		Stochastic	Input	Scalar	6.4.3-2	DW_4
	DryWet_Forage		Stochastic	Input	Scalar	6.4.3-2	DW_5
	DryWet_Ratio		Data	Calculated	Vector(5)	6.4.3-2	DW_j
	Yield_Leafy		Stochastic	Input	Scalar	6.4.3-3	Y_1
	Yield_Other		Stochastic	Input	Scalar	6.4.3-3	Y_2
	Yield_Fruit		Stochastic	Input	Scalar	6.4.3-3	Y_3
	Yield_Grain		Stochastic	Input	Scalar	6.4.3-3	Y_4
	Yield_Forage		Stochastic	Input	Scalar	6.4.3-3	Y_5
	Wet_Yield		Data	Calculated	Vector(5)	6.4.3-3	Y_j
	Growing_Time		Data	Input	Vector(5)	6.4.3-3	$t_{g,\,j}$
	Weather_Halflife		Stochastic	input	Scalar	6.4.3-3	T_w
	Weathering_Factor		Data	Calculated	Scalar	6.4.3-3	λ_w
	Translocation_Dist		Stochastic	Input	Scalar	6.4.3-3	T_j
	Translocation		Data	Input	Vector(5)	6.4.3-3	T_j
	Deposit_Velocity		Stochastic	Input	Scalar	6.4.3-7	V_d
	Irrigation _Data	*DryBiom_Leafy*	Stochastic	Input	Scalar	6.4.3-5	DB_1
		DryBiom_Other	Stochastic	Input	Scalar	6.4.3-5	DB_2
		DryBiom_Fruit	Stochastic	Input	Scalar	6.4.3-5	DB_3
		DryBiom_Grain	Stochastic	Input	Scalar	6.4.3-5	DB_4
		DryBiom_Forage	Stochastic	Input	Scalar	6.4.3-5	DB_5
		IrriAmt_Leafy	Stochastic	Input	Scalar	6.4.3-5	IA_1
		IrriAmt_Other	Stochastic	Input	Scalar	6.4.3-5	IA_2
		IrriAmt_Fruit	Stochastic	Input	Scalar	6.4.3-5	IA_3
		IrriAmt_Grain	Stochastic	Input	Scalar	6.4.3-5	IA_4
		IrriAmt_Forage	Stochastic	Input	Scalar	6.4.3-5	IA_5
		Irrigation_Intensity	Stochastic	Input	Scalar	6.4.3-5	I
		Overhead_Leafy	Stochastic	Input	Scalar	6.4.3-3	$f_{o,1}$
		Overhead_Other	Stochastic	Input	Scalar	6.4.3-3	$f_{o,2}$
		Overhead_Fruit	Stochastic	Input	Scalar	6.4.3-3	$f_{o,3}$
		Overhead_Grain	Stochastic	Input	Scalar	6.4.3-3	$f_{o,4}$
		Overhead_Forage	Stochastic	Input	Scalar	6.4.3-3	$f_{o,5}$
		Overhead_Factor	Data	Calculated	Vector(5)	6.4.3-3	$f_{o,j}$

Table 6.8-4. Parameters in the Plant Submodel (Continued)

First Level Name	Second Level Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Water_ Uptakes	*ExpGrow_Leafy*		Expression	Calculated	Scalar	6.4.3-3	$e^{-\lambda w\ tg,1}$
	ExpGrow_Other		Expression	Calculated	Scalar	6.4.3-3	$e^{-\lambda w\ tg,2}$
	ExpGrow_Fruit		Expression	Calculated	Scalar	6.4.3-3	$e^{-\lambda w\ tg,3}$
	ExpGrow_Grain		Expression	Calculated	Scalar	6.4.3-3	$e^{-\lambda w\ tg,4}$
	ExpGrow_Forage		Expression	Calculated	Scalar	6.4.3-3	$e^{-\lambda w\ tg,5}$
	Growing_Factors		Data	Calculated	Vector(5)	6.4.3-3	$1-e^{-\lambda w\ tg,j}$
	Other_Factor		Expression	Calculated	Vector(5)	6.4.3-3	$T_j /(Y_j \lambda_w)(1-e^{-\lambda w\ tg,j})$
	IntFrac_Leafy		Expression	Calculated	Scalar	6.4.3-3	Rw_1
	IntFrac_Other		Expression	Calculated	Scalar	6.4.3-3	Rw_2
	IntFrac_Fruit		Expression	Calculated	Scalar	6.4.3-3	Rw_3
	IntFrac_Grain		Expression	Calculated	Scalar	6.4.3-3	Rw_4
	IntFrac_Forage		Expression	Calculated	Scalar	6.4.3-3	Rw_5
	Intercept_Factor		Data	Calculated	Vector(5)	6.4.3-3	Rw_j
	Irrigation_Intercept		Expression	Calculated	Vector(5)	6.4.3-3	$Dw_{i,j}\ Rw$
	Water_Uptake		Expression	Calculated	Vector(5)	6.4.3-3	$Cp_{water\ i,j}$
Root_ Uptakes	*Transfer_Factor*		Data	Dbase	Vector(5)	6.4.3-2	$F_{s\rightarrow p,\ i,j}$
	Transfer_Factor_1		Data	Dbase	Vector(5)	6.4.3-2	$F_{s\rightarrow p,\ 1,j}$
	Transfer_Factor_2		Data	Dbase	Vector(5)	6.4.3-2	$F_{s\rightarrow p,\ 2,j}$
	Root_Uptake		Expression	Calculated	Vector(5)	6.4.3-2	$Cp_{root,\ i,j}$
	Root_Uptake_1		Expression	Calculated	Vector(5)	6.4.3-2	$Cp_{root,\ 1,j}$
	Root_Uptake_2		Expression	Calculated	Vector(5)	6.4.3-2	$Cp_{root,\ 2,j}$
Dust_ Uptakes	*Dust_Factor*		Data	Input	Vector(5)	6.4.3-8	a_j
	ExpDust_Leafy		Expression	Calculated	Scalar	6.4.3-8	$e^{-a_1 DB_1}$
	ExpDust_Other		Expression	Calculated	Scalar	6.4.3-8	$e^{-a_2 DB_2}$
	ExpDust_Fruit		Expression	Calculated	Scalar	6.4.3-8	$e^{-a_3 DB_3}$
	ExpDust_Grain		Expression	Calculated	Scalar	6.4.3-8	$e^{-a_4 DB_4}$
	ExpDust_Forage		Expression	Calculated	Scalar	6.4.3-8	$e^{-a_5 DB_5}$
	Dust_Intercept		Data	Calculated	Vector(5)	6.4.3-8	Ra_j
	Air_Interception		Expression	Calculated	Vector(5)	6.4.3-6	$Da_{i,j}\ Ra_j$
	Air_Interception_1		Expression	Calculated	Vector(5)	6.4.3-6	$Da_{1,j}\ Ra_j$
	Air_Interception_2		Expression	Calculated	Vector(5)	6.4.3-6	$Da_{2,j}\ Ra_j$
	Dust_Uptake		Expression	Calculated	Vector(5)	6.4.3-6	$Cp_{dust,\ i,j}$
	Dust_Uptake_1		Expression	Calculated	Vector(5)	6.4.3-6	$Cp_{dust,\ 1,j}$
	Dust_Uptake_2		Expression	Calculated	Vector(5)	6.4.3-6	$Cp_{dust,\ 2,j}$
C14_ Crop	*Crop_Carbon*		Data	Input	Vector(5)	6.4.6-6	$fc_{plant,j}$
	Air_Carbon		Data	Input	Scalar	6.4.6-5	fc_{air}
	Soil_Carbon		Data	Input	Scalar	6.4.6-4	fc_{soil}
	Cair_Uptake		Data	Input	Scalar	6.4.6-6	Fa
	Csoil_Uptake		Data	Input	Scalar	6.4.6-6	Fs
	C14Crop_Air		Expression	Calculated	Vector(5)	6.4.6-6	$Fa\ Ca_{C\text{-}14} / fc_{air}$

Table 6.8-4. Parameters in the Plant Submodel (Continued)

First Level Name	Second Level Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
C14_ Crop (Continued)	*C14Crop_Soil*		Expression	Calculated	Vector(5)	6.4.6-6	$Fs\ Cs_{C-14} / (fc_{soil}\ \rho_s)$
	C14Conc_Crop		Expression	Calculated	Vector(5)	6.4.6-6	$Cp_{C-14,j}$
Plant_Conc			Sum	Calculated	Vector(5)	6.4.3-1	$Cp_{i,j}$
Plant_Conc_1			Sum	Calculated	Vector(5)	6.4.3-1	$Cp_{1,j}$
Plant_Conc_2			Sum	Calculated	Vector(5)	6.4.3-1	$Cp_{2,j}$
Crop_Conc			Data	Calculated	Vector(4)	6.4.3-1	$Cp_{i,j}$
Crop_Conc_1			Data	Calculated	Vector(4)	6.4.3-1	$Cp_{1,j}$
Crop_Conc_2			Data	Calculated	Vector(4)	6.4.3-1	$Cp_{2,j}$

NOTE: See notes for Table 6.8-1.

6.8.5 Animal Submodel

The mathematical equations for the animal submodel are discussed in Section 6.4.4. All parameters in the submodel are listed in Table 6.8-5. The contents of the animal submodel container (Figure 6.8-21) include three lower level containers. The *AnimalModel_Input* container includes all animal consumption rates for feed, water, and soil (Figure 6.8-22). The *Animal_Ingestions* container includes three containers for calculating animal uptake from the consumption of contaminated animal feed (Equation 6.4.4-2), contaminated water (Equation 6.4.4-3), and contaminated soil (Equation 6.4.4-4) for four types of animal products. The *C14_Animal* container includes the calculation of ^{14}C transfer to animal products (Section 6.4.6.4).

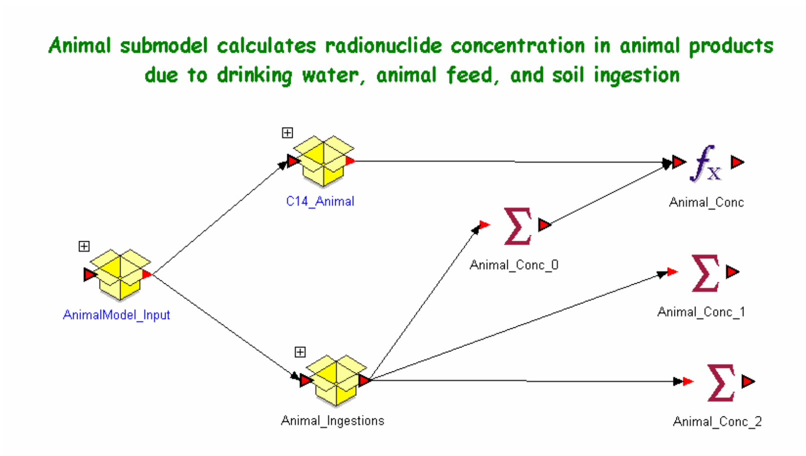


Figure 6.8-21. Animal Submodel Container

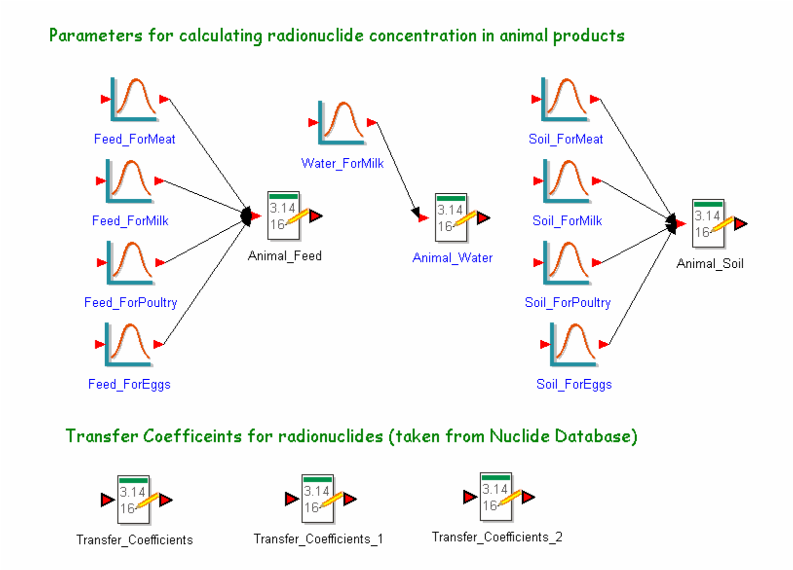


Figure 6.8-22. Input Parameter Container (*AnimalModel_Input*) for the Animal Submodel

Table 6.8-5. Parameters in the Animal Submodel

Low Level Name	**Parameter Name**	**Element Type**	**Data Source**	**Data Type**	**Equation**	**Notation**
Animal Model_ Input	*Water_ForMilk*	Stochastic	Input	Scalar	6.4.4-3	Qw_2
	Animal_Water	Data	Input	Vector(4)	6.4.4-3	Qw_k
	Feed_ForMeat	Stochastic	Input	Scalar	6.4.4-2	Qf_1
	Feed_ForMilk	Stochastic	Input	Scalar	6.4.4-2	Qf_2
	Feed_ForPoultry	Stochastic	Input	Scalar	6.4.4-2	Qf_3
	Feed_ForEggs	Stochastic	Input	Scalar	6.4.4-2	Qf_4
	Animal_Feed	Data	Calculated	Vector(4)	6.4.4-2	Qf_k
	Soil_ForMeat	Stochastic	Input	Scalar	6.4.4-4	Qs_1
	Soil_ForMilk	Stochastic	Input	Scalar	6.4.4-4	Qs_2
	Soil_ForPoultry	Stochastic	Input	Scalar	6.4.4-4	Qs_3
	Soil_ForEggs	Stochastic	Input	Scalar	6.4.4-4	Qs_4
	Animal_Soil	Data	Calculated	Vector(4)	6.4.4-4	Qs_k
	Transfer_Coefficients	Data	Dbase	Vector(4)	6.4.4-2	$Fm_{i,k}$
	Transfer_Coefficients_1	Data	Dbase	Vector(4)	6.4.4-2	$Fm_{1,k}$
	Transfer_Coefficients_2	Data	Dbase	Vector(4)	6.4.4-2	$Fm_{2,k}$
Animal_ Ingestion	*Water_Contribution*	Expression	Calculated	Vector(4)	6.4.4-3	$Cd_{water\ i,k}$
	Feed_Conc	Data	Calculated	Vector(4)	6.4.3-1	$Cp_{i,j}$
	Feed_Conc_1	Data	Calculated	Vector(4)	6.4.3-1	$Cp_{1,j}$
	Feed_Conc_2	Data	Calculated	Vector(4)	6.4.3-1	$Cp_{2,j}$
	Feed_Contribution	Expression	Calculated	Vector(4)	6.4.4-2	$Cd_{feed\ i,k}$
	Feed_Contribution_1	Expression	Calculated	Vector(4)	6.4.4-2	$Cd_{feed\ 1,k}$
	Feed_Contribution_2	Expression	Calculated	Vector(4)	6.4.4-2	$Cd_{feed\ 2,k}$

Table 6.8-5. Parameters in the Animal Submodel (Continued)

Low Level Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Animal_ Ingestion (Continued)	*Soil_Mass_Conc_Animal*	Data	Calculated	Vector(4)	6.4.4-4	$Cs_{m,i,k}$
	Soil_Mass_Conc_ Animal_1	Data	Calculated	Vector(4)	6.4.4-4	$Cs_{m,1,k}$
	Soil_Mass_Conc_ Animal_2	Data	Calculated	Vector(4)	6.4.4-4	$Cs_{m,2,k}$
	Soil_Contribution	Expression	Calculated	Vector(4)	6.4.4-4	$Cd_{soil\ I,k}$
	Soil_Contribution_1	Expression	Calculated	Vector(4)	6.4.4-4	$Cd_{soil\ 1,k}$
	Soil_Contribution_2	Expression	Calculated	Vector(4)	6.4.4-4	$Cd_{soil\ 2,k}$
C14_ Animal	*Animal_Carbon*	Data	Input	Vector(4)	6.4.6-7	$fc_{anim,k}$
	C14Conc_Feed	Data	Calculated	Vector(4)	6.4.6-6	$Cp_{C\text{-}14,j}$
	C14From_Feed	Expression	Calculated	Vector(4)	6.4.6-7	$Cp_{C\text{-}14,j}\ Qf_k$
	C14From_Water	Expression	Calculated	Vector(4)	6.4.6-7	$Cw_{C\text{-}14}\ Qw_k$
	C14Conc_Soil	Data	Calculated	Vector(4)	6.4.1-5	$Cs_{m,i,k}$ *or* $Cs_{mc,i,k}$
	C14From_Soil	Expression	Calculated	Vector(4)	6.4.6-7	$Cs_{C\text{-}14}\ Qs_k$
	Feed_Carbon	Data	Input	Vector(4)	6.4.6-6	$fc_{plant,j}$
	CFrom_Feed	Expression	Calculated	Vector(4)	6.4.6-7	$fc_{plant,j}\ Qf_k$
	Water_Carbon	Data	Input	Scalar	6.4.6-7	fc_{water}
	Cfrom_Water	Expression	Calculated	Vector(4)	6.4.6-7	$fc_{water}\ Qw_k$
	Cfrom_Soil	Expression	Calculated	Vector(4)	6.4.6-7	$fc_{soil}\ Qs_k$
	C14Conc_Animal	Expression	Calculated	Vector(4)	6.4.6-7	$Cd_{C\text{-}14,k}$
Animal_Conc		Expression	Calculated	Vector(4)	6.4.4-1	$Cd_{i,k}$
Animal_Conc_0		Sum	Calculated	Vector(4)	6.4.4-1	$Cd_{i,k}$
Animal_Conc_1		Sum	Calculated	Vector(4)	6.4.4-1	$Cd_{1,k}$
Animal_Conc_2		Sum	Calculated	Vector(4)	6.4.4-1	$Cd_{2,k}$

NOTE: See notes for Table 6.8-1.

6.8.6 Fish Submodel

The fish submodel (Figure 6.8-23) is described in Section 6.4.5. The fish submodel container includes calculations of activity concentration in the fish. Because ^{14}C transport to fish is the same as that for other radionuclides, the ^{14}C special submodel is not considered separately. All parameters in the submodel are listed in Table 6.8-6.

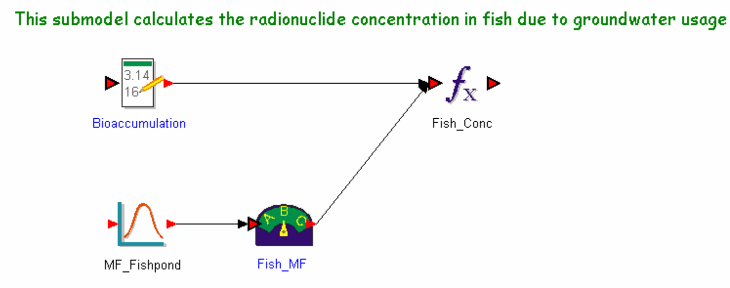


Figure 6.8-23. Fish Submodel Container

Table 6.8-6. Parameters in the Fish Submodel

Submodel Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Fish	*Bioaccumulation*	Data	Dbase	Scalar	6.4.5-1	BF_i
	MF_Fishpond	Stochastic	Input	Scalar	6.4.5-2	MF_i
	Fish_MF	Selector	Input	Scalar	6.4.5-2	MF_i
	Fish_Conc	Expression	Calculated	Scalar	6.4.5-2	Cf_i

NOTE: See notes for Table 6.8-1.

6.8.7 External Exposure Submodel

The external exposure submodel is discussed in Section 6.4.7. All parameters in the submodel are listed in Table 6.8-7. This submodel includes two lower level containers (Figure 6.8-24). The *External_Input* container (Figure 6.8-25) contains all of the external exposure related input parameters for this submodel plus the input data for the population groups and associated time budgets. Model calculations are included in the *External_Model* container (Figure 6.8-26). Decay products that build up in the soil as a result of the decay of primary radionuclides are considered in the calculation of external exposure to soil.

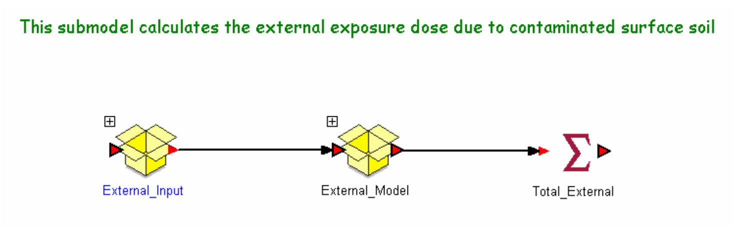


Figure 6.8-24. External Exposure Submodel Container

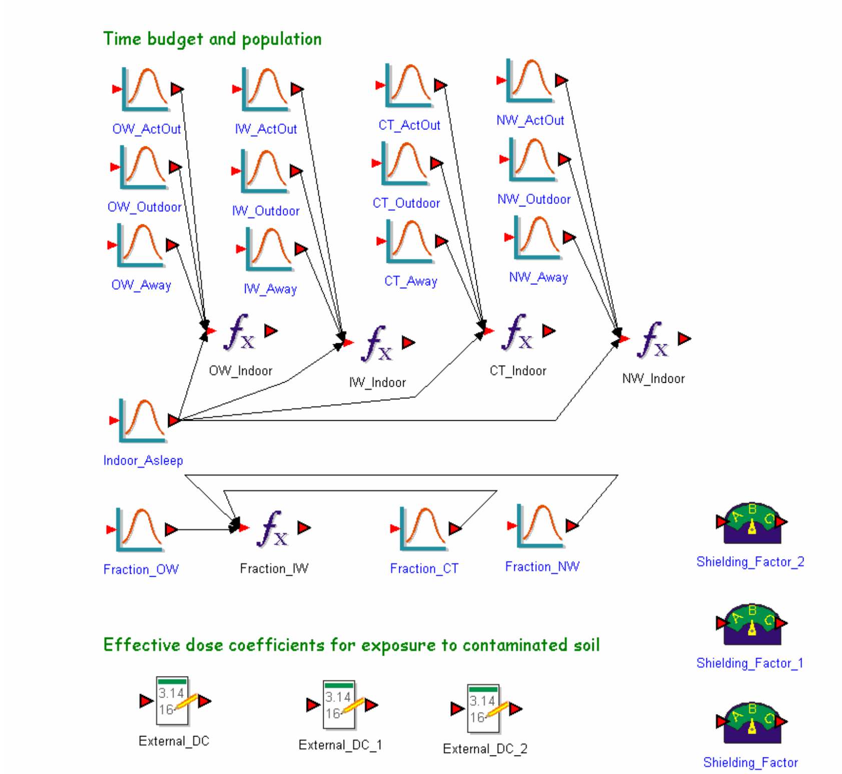


Figure 6.8-25. Input Parameter Container (*External_Input*) of the External Exposure Submodel

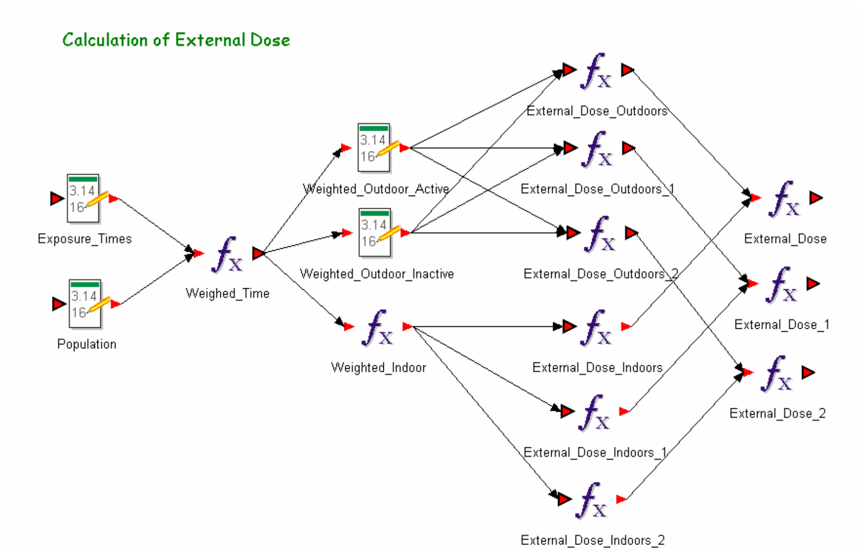


Figure 6.8-26. *External_Model* Container of the External Exposure Submodel

Table 6.8-7. Parameters in the External Exposure Submodel

Low Level Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
External_ Input	*OW_ActOut*	Stochastic	Input	Scalar	6.4.7-1	$t_{1,1}$
	IW_ActOut	Stochastic	Input	Scalar	6.4.7-1	$t_{1,2}$
	CT_ActOut	Stochastic	Input	Scalar	6.4.7-1	$t_{1,3}$
	NW_ActOut	Stochastic	Input	Scalar	6.4.7-1	$t_{1,4}$
	OW_Outdoor	Stochastic	Input	Scalar	6.4.7-1	$t_{2,1}$
	IW_Outdoor	Stochastic	Input	Scalar	6.4.7-1	$t_{2,2}$
	CT_Outdoor	Stochastic	Input	Scalar	6.4.7-1	$t_{2,3}$
	NW_Outdoor	Stochastic	Input	Scalar	6.4.7-1	$t_{2,4}$
	OW_Away	Stochastic	Input	Scalar	6.4.7-1	$t_{5,1}$
	IW_Away	Stochastic	Input	Scalar	6.4.7-1	$t_{5,2}$
	CT_Away	Stochastic	Input	Scalar	6.4.7-1	$t_{5,3}$
	NW_Away	Stochastic	Input	Scalar	6.4.7-1	$t_{5,4}$
	Indoor_Asleep	Stochastic	Input	Scalar	6.4.7-1	$t_{4,m}$
	OW_Indoor	Expression	Calculated	Scalar	6.4.7-1	$t_{3,1}$
	IW_Indoor	Expression	Calculated	Scalar	6.4.7-1	$t_{3,2}$
	CT_Indoor	Expression	Calculated	Scalar	6.4.7-1	$t_{3,3}$
	NW_Indoor	Expression	Calculated	Scalar	6.4.7-1	$t_{3,4}$
	Fraction_OW	Stochastic	Calculated	Scalar	6.4.7-1	PP_1
	Fraction_IW	Expression	Calculated	Scalar	6.4.7-1	PP_2
	Fraction_CT	Stochastic	Input	Scalar	6.4.7-1	PP_3
	Fraction_NW	Stochastic	Input	Scalar	6.4.7-1	PP_4
	Shielding_Factor	Selector	Input	Scalar	6.4.7-1	$f_{ext,i,3}$ and $f_{ext,i,4}$
	Shielding_Factor_1	Selector	Input	Scalar	6.4.7-1	$f_{ext,1,3}$ and $f_{ext,1,4}$
	Shielding_Factor_2	Selector	Input	Scalar	6.4.7-1	$f_{ext,2,3}$ and $f_{ext,2,4}$
	External_DC	Data	Dbase	Scalar	6.4.7-1	$EDCi_{soil,0}$
	External_DC_1	Data	Dbase	Scalar	6.4.7-1	$EDCi_{soil,1}$
	External_DC_2	Data	Dbase	Scalar	6.4.7-1	$EDCi_{soil,2}$
External_ Model	*Exposure_times*	Data	Calculated	Matrix (5,4)	6.4.7-1	$t_{n,m}$
	Population	Data	Calculated	Vector(4)	6.4.7-1	PP_m
	Weighted_Time	Expression	Calculated	Vector(5)	6.4.7-1	$PP_m\ t_{n,m}$
	Weighted_Outdoor	Expression	Calculated	Scalar	6.4.7-1	$PP_m\ t_{1,m} + PP_m\ t_{2,m}$
	Weighted_Indoor	Expression	Calculated	Scalar	6.4.7-1	$PP_m\ t_{3,m} + PP_m\ t_{4,m}$
	External_Time	Expression	Calculated	Scalar	6.4.7-1	$\sum f_{ext,i,n}(\sum PP_m\ t_{n,m})$
	External_Time_1	Expression	Calculated	Scalar	6.4.7-1	$\sum f_{ext,1,n}(\sum PP_m\ t_{n,m})$
	External_Time_2	Expression	Calculated	Scalar	6.4.7-1	$\sum f_{ext,2,n}(\sum PP_m\ t_{n,m})$
	External_Dose	Expression	Calculated	Scalar	6.4.7-1	$D_{ext\ 0}$
	External_Dose_1	Expression	Calculated	Scalar	6.4.7-1	$D_{ext\ 1}$
	External_Dose_2	Expression	Calculated	Scalar	6.4.7-1	$D_{ext\ 2}$
Total_External		Expression	Calculated	Scalar	6.4.7-1	$D_{ext\ i}$

NOTE: See notes for Table 6.8-1.

6.8.8 Inhalation Submodel

The mathematical equations for the inhalation submodel are discussed in Section 6.4.8. All parameters in the submodel are listed in Table 6.8-8. The contents of this submodel container include three lower level containers (Figure 6.8-27). The *Inhalation_Input* container includes all inhalation related input parameters used in this submodel (Figure 6.8-28). The time budget for the receptor is calculated in the *External_Input* container of the external exposure submodel. The *Dust_Inhalation* container includes the calculations of human inhalation of contaminated resuspended particles. Decay products are considered for resuspended particles in the air as the consequence of radionuclide buildup in soil. This container also includes calculations for $^{14}CO_2$ inhalation. The *Radon_Inhalation* container includes calculations of the inhalation dose from radon decay products that are produced following exhalation of radon gas from ^{226}Ra-contaminated soil. The dose from inhalation of contaminated aerosols generated from evaporative coolers is calculated in the expression element *Cooler_Inhalation*.

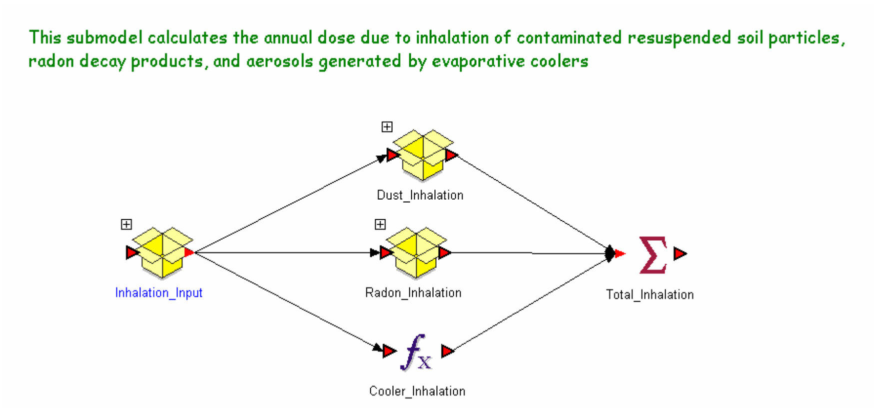


Figure 6.8-27. Inhalation Submodel Container

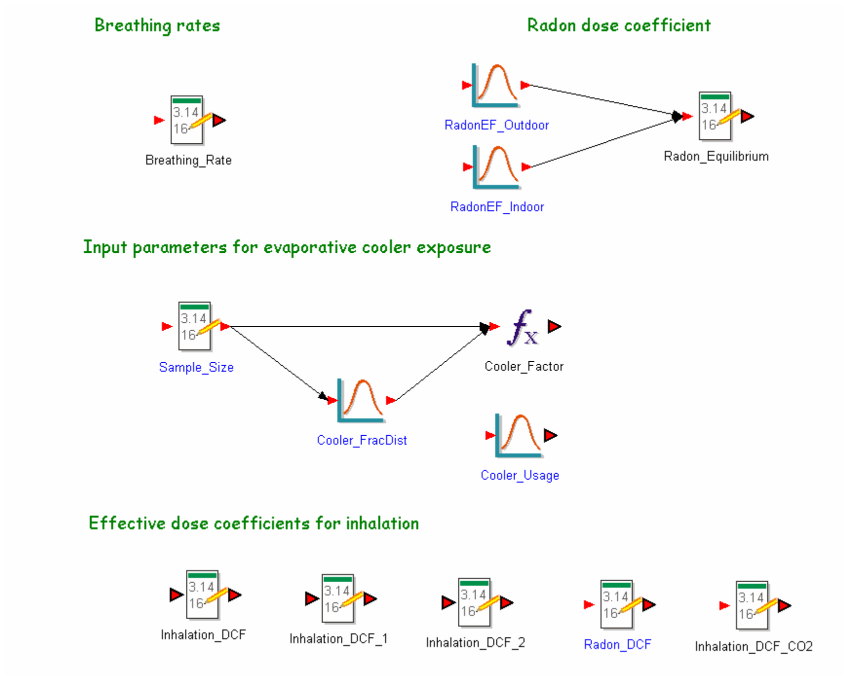


Figure 6.8-28. Input Parameter Container (*Inhalation_Input*) for the Inhalation Submodel

Table 6.8-8. Parameters in the Inhalation Submodel

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Inhalation_ Input	*Breathing_Rate*	Data	Input	Vector(5)	6.4.8-2	$BR_{n,}$
	Sample_Size	Data	Input	Scalar	6.4.8-3	f_{cooler}
	Cooler_FacDist	Stochastic	Input	Scalar	6.4.8-3	f_{cooler}
	Cooler_Factor	Expression	Calculated	Scalar	6.4.8-3	f_{cooler}
	Cooler_Usage	Stochastic	Input	Scalar	6.4.8-3	f_{use}
	RadonEF_Outdoor	Stochastic	Input	Scalar	6.4.8-6	$EF_{Rn\text{-}222,1\&2}$
	RadonEF_Indoor	Stochastic	Input	Scalar	6.4.8-6	$EF_{Rn\text{-}222,3\&4}$
	Radon_Equilibrium	Data	Calculated	Vector(5)	6.4.8-6	$EF_{Rn\text{-}222,n}$
	Radon_DCF	Data	Input	Scalar	6.4.8-6	$DCF_{inh,Rn\text{-}222}$
	Inhalation_DCF	Data	Dbase	Scalar	6.4.8-2	$EDCF_{inh,I}$
	Inhalation_DCF_1	Data	Dbase	Scalar	6.4.8-2	$EDCF_{inh,1}$
	Inhalation_DCF_2	Data	Dbase	Scalar	6.4.8-2	$EDCF_{inh,2}$
Dust_ Inhalation	*C14Gas_Inhalation*	Expression	Calculated	Vector(5)	6.4.8-4	$D_{inh,g,C\text{-}14,n}$
	Total_C14	Sum	Calculated	Scalar	6.4.8-4	$D_{inh,g,C\text{-}14}$
	Activity_Inhalation	Expression	Calculated	Vector(5)	6.4.8-2	$D_{inh,p,0,n}$
	Activity_Inhalation_1	Expression	Calculated	Vector(5)	6.4.8-2	$D_{inh,p\ 1,n}$
	Activity_Inhalation_2	Expression	Calculated	Vector(5)	6.4.8-2	$D_{inh,p\ 2,n}$
	Inhalation_Dose_0	Sum	Calculated	Scalar	6.4.8-2	$D_{inh,p,0}$
	Inhalation_Dose	Expression	Calculated	Scalar	6.4.8-2	$D_{inh,p,0}$
	Inhalation_Dose_1	Sum	Calculated	Scalar	6.4.8-2	$D_{inh,p,1}$
	Inhalation_Dose_2	Sum	Calculated	Scalar	6.4.8-2	$D_{inh,p,2}$
	Total_Dust	Sum	Calculated	Scalar	6.4.8-2	$D_{inh,p,i}$

Table 6.8-8. Parameters in the Inhalation Submodel (Continued)

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Radon_ Inhalation	*Radon_Correction*	Data	Calculated	Vector(5)	6.4.8-7 6.4.2-7 6.4.2-8	*1* for *n=1&2* $(1- f_{cooler}\, f_{use})\, IF_n + f_{cooler}\, f_{use}\, IF_e$ for *n=3&4* *0 for n=5*
	Rn_Inhalation	Expression	Calculated	Vector(5)	6.4.8-7	$D_{inh,g,Rn\text{-}222,n}$
	Rn_Inhalation_1	Expression	Calculated	Vector(5)	6.4.8-7	$D_{inh,g,Rn\text{-}222,n}$
	Rn_Inhalation_2	Expression	Calculated	Vector(5)	6.4.8-7	$D_{inh,g,Rn\text{-}222,n}$
	Radon_Dose	Sum	Calculated	Scalar	6.4.8-7	$D_{inh,g,Rn\text{-}222}$
	Radon_Dose_1	Sum	Calculated	Scalar	6.4.8-7	$D_{inh,g,Rn\text{-}222}$
	Radon_Dose_2	Sum	Calculated	Scalar	6.4.8-7	$D_{inh,g,Rn\text{-}222}$
	Total_Radon	Sum	Calculated	Scalar	6.4.8-7	$D_{inh,g,Rn\text{-}222}$
Cooler_Inhalation		Expression	Calculated	Scalar	6.4.8-3	$D_{inh,e,i}$
Total_Inhalation		Sum	Calculated	Scalar	6.4.8-1	$D_{inh,i}$

NOTE: See notes for Table 6.8-1.

6.8.9 Ingestion Submodel

The human ingestion pathways include 11 individual pathways (Section 6.4.9). All parameters in the submodel are listed in Table 6.8-9. This submodel includes two lower level containers (Figure 6.8-29). The *Ingestion_Input* container includes various human foodstuff consumption rates (Figure 6.8-30). The *Ingestion_Model* container (Figure 6.8-31) includes calculations of the ingestion dose from each foodstuff for primary radionuclides. Contributions from long-lived decay products that accumulate in the soil are calculated if applicable. To provide the results of exposure pathway analysis, ingestion dose is presented for individual pathways and radionuclides.

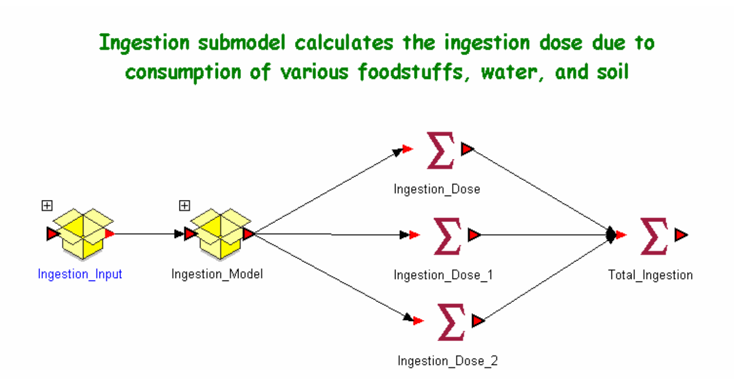


Figure 6.8-29. Ingestion Submodel Container

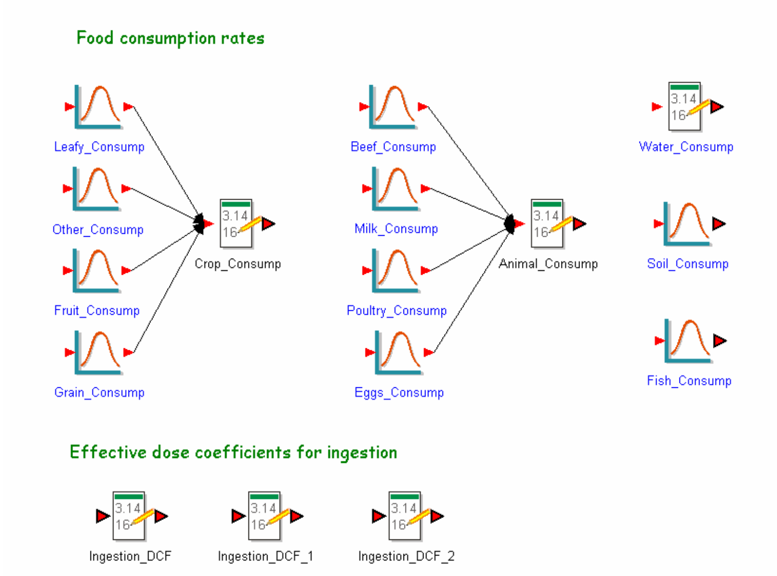


Figure 6.8-30. Input Parameter Container (*Ingestion_Input*) for the Ingestion Submodel

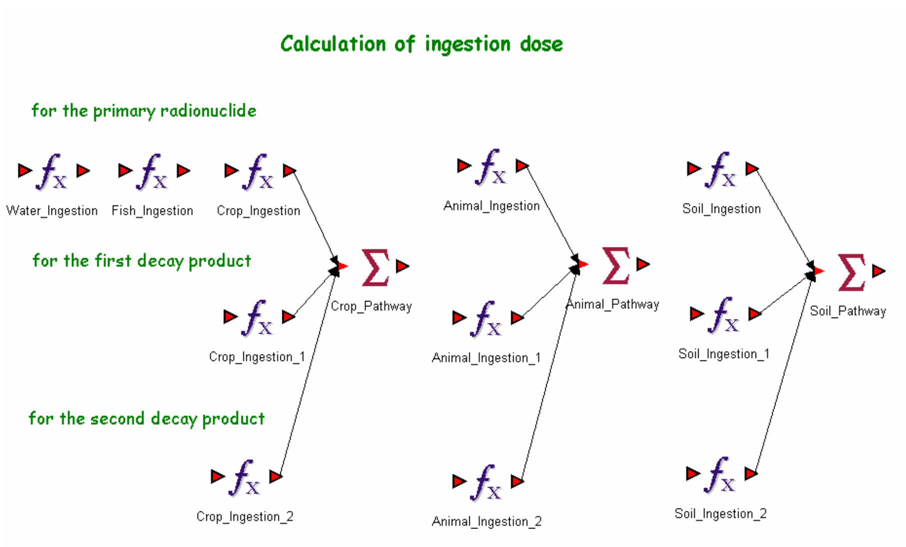


Figure 6.8-31. *Ingestion_Model* Container of the Ingestion Submodel

Table 6.8-9. Parameters in the Ingestion Submodel

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Ingestion_ Input	*Leafy_Consump*	Stochastic	Input	Scalar	6.4.9-3	Up_1
	Other_Consump	Stochastic	Input	Scalar	6.4.9-3	Up_2
	Fruit_Consump	Stochastic	Input	Scalar	6.4.9-3	Up_3
	Grain_Consump	Stochastic	Input	Scalar	6.4.9-3	Up_4
	Crop_Consump	Data	Calculated	Vector(4)	6.4.9-3	Up_j
	Beef_Consump	Stochastic	Input	Scalar	6.4.9-4	Ud_1
	Poultry_Consump	Stochastic	Input	Scalar	6.4.9-4	Ud_2

Table 6.8-9. Parameters in the Ingestion Submodel (Continued)

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Ingestion_ Input (Continued)	*Milk_Consump*	Stochastic	Input	Scalar	6.4.9-4	Ud_3
	Eggs_Consump	Stochastic	Input	Scalar	6.4.9-4	Ud_4
	Animal_Consump	Data	Calculated	Vector(4)	6.4.9-4	Ud_k
	Water_Consump	Data	Input	Scalar	6.4.9-2	Uw
	Fish_Consump	Stochastic	Input	Scalar	6.4.9-5	Uf
	Soil_Consump	Stochastic	Input	Scalar	6.4.9-6	Us
	Ingestion_DCF	Data	Dbase	Scalar	6.4.9-2	$EDCF_{ing,\,0}$
	Ingestion_DCF_1	Data	Dbase	Scalar	6.4.9-2	$EDCF_{ing,\,1}$
	Ingestion_DCF_2	Data	Dbase	Scalar	6.4.9-2	$EDCF_{ing,\,2}$
Ingestion_ Model	*Water_Ingestion*	Expression	Calculated	Scalar	6.4.9-2	$D_{ing,w,i}$
	Fish_Ingestion	Expression	Calculated	Scalar	6.4.9-5	$D_{ing,f,i}$
	Crop_Ingestion	Expression	Calculated	Vector(4)	6.4.9-3	$D_{ing,p,0}$
	Crop_Ingestion_1	Expression	Calculated	Vector(4)	6.4.9-3	$D_{ing,p,1}$
	Crop_Ingestion_2	Expression	Calculated	Vector(4)	6.4.9-3	$D_{ing,p,2}$
	Crop_Pathway	Sum	Calculated	Vector(4)	6.4.9-3	$D_{ing,p,i}$
	Animal_Ingestion	Expression	Calculated	Vector(4)	6.4.9-4	$D_{ing,d,0}$
	Animal_Ingestion_1	Expression	Calculated	Vector(4)	6.4.9-4	$D_{ing,d,1}$
	Animal_Ingestion_2	Expression	Calculated	Vector(4)	6.4.9-4	$D_{ing,d,2}$
	Animal_Pathway	Sum	Calculated	Vector(4)	6.4.9-4	$D_{ing,d,i}$
	Soil_Ingestion	Expression	Calculated	Scalar	6.4.9-6	$D_{ing,s,0}$
	Soil_Ingestion_1	Expression	Calculated	Scalar	6.4.9-6	$D_{ing,s,1}$
	Soil_Ingestion_2	Expression	Calculated	Scalar	6.4.9-6	$D_{ing,s,2}$
	Soil_Pathway	Sum	Calculated	Scalar	6.4.9-6	$D_{ing,s,i}$
Ingestion_Dose		Sum	Calculated	Scalar	6.4.9-1	$D_{ing,0}$
Ingestion_Dose_1		Sum	Calculated	Scalar	6.4.9-1	$D_{ing,1}$
Ingestion_Dose_2		Sum	Calculated	Scalar	6.4.9-1	$D_{ing,2}$
Total_ingestion		Sum	Calculated	Scalar	6.4.9-1	$D_{ing,i}$

NOTE: See notes for Table 6.8-1.

6.8.10 BDCF Results

The calculation of annual doses and BDCFs for individual radionuclides is discussed in Section 6.4.10. All parameters in the submodel are listed in Table 6.8-10. The ERMYN GoldSim model calculates the total dose from a radionuclide, the dose from each exposure pathway, the dose from primary radionuclide and the decay products, and the activity concentration of the radionuclide in the environmental media (Figure 6.8-32).

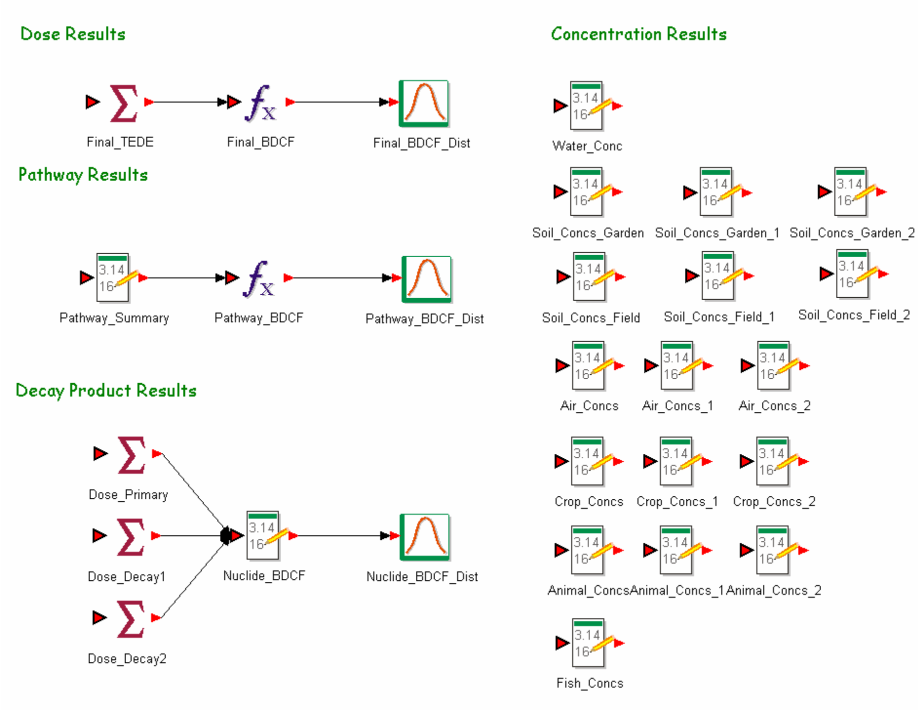


Figure 6.8-32. Final BDCF Result Container

Table 6.8-10. Parameters in the Final BDCF Results

Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Final_TEDE	Sum	Calculated	Scalar	6.4.10-1	$D_{all,i}$
Final_BDCF	Expression	Calculated	Scalar	6.4.10-2	$BDCF_i$
Pathway_Summary	Data	Calculated	Vector(15)	6.4.10-3	$D_{p,i}$
Pathway_BDCF	Expression	Calculated	Vector(15)	6.4.10-4	$BDCF_{p,i}$
Dose_Primary	Sum	Calculated	Scalar	—	—
Dose_Decay1	Sum	Calculated	Scalar	—	—
Dose_Decay2	Sum	Calculated	Scalar	—	—
Nuclide_BDCF	Data	Calculated	Vector(3)	—	—
Final_BDCF_Dist	Result	Calculated	Scalar	—	—
Pathway_BDCF_Dist	Result	Calculated	Vector(15)	—	—
Nuclide_BDCF_Dist	Result	Calculated	Vector(3)	—	—
Water_Conc	Data	Calculated	Scalar	6.4.1-1	Cw
Soil_Concs_Garden	Data	Calculated	Scalar	6.4.1-5	$Cs_{m,i,j=1}$
Soil_Concs_Garden_1	Data	Calculated	Scalar	6.4.1-5	$Cs_{m,1,j=1}$
Soil_Concs_Garden_2	Data	Calculated	Scalar	6.4.1-5	$Cs_{m,2,j=1}$
Soil_Concs_Field	Data	Calculated	Scalar	6.4.1-5	$Cs_{m,i,j=5}$
Soil_Concs_ Field_1	Data	Calculated	Scalar	6.4.1-5	$Cs_{m,1,j=5}$
Soil_Concs_ Field_2	Data	Calculated	Scalar	6.4.1-5	$Cs_{m,2,j=5}$
Air_Concs	Data	Calculated	Matrix(4,5)	6.4.2-1	Ca_i

Table 6.8-10. Parameters in the Final BDCF Results (Continued)

Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Air_Concs_1	Data	Calculated	Matrix(4,5)	6.4.2-1	Ca_1
Air_Concs_2	Data	Calculated	Matrix(4,5)	6.4.2-1	Ca_2
Crop_Concs	Data	Calculated	Matrix(5,4)	6.4.3-1	Cp_i
Crop_Concs_1	Data	Calculated	Matrix(5,4)	6.4.3-1	Cp_1
Crop_Concs_2	Data	Calculated	Matrix(5,4)	6.4.3-1	Cp_2
Animal_Concs	Data	Calculated	Matrix(4,4)	6.4.4-1	Cd_i
Animal_Concs_1	Data	Calculated	Matrix(4,4)	6.4.4-1	Cd_1
Animal_Concs_2	Data	Calculated	Matrix(4,4)	6.4.4-1	Cd_2
Fish_Concs	Data	Calculated	Scalar	6.4.5-1	*Cf*

NOTE: See notes for Table 6.8-1.

6.9 NUMERICAL MODEL (GOLDSIM IMPLEMENTATION) OF THE BIOSPHERE MODEL FOR THE VOLCANIC ASH EXPOSURE SCENARIO

This section describes the ERMYN model for the volcanic ash scenario (*ERMYN_VA*) and shows the overall model algorithm, submodel structures, input parameters, and calculated results. Many parts of the GoldSim model for the volcanic ash scenario are similar to, and in some cases the same as, those used in the groundwater model (*ERMYN_GW*; Section 6.8). The GoldSim file, *ERMYN_VA_Rev01.gsm*, is part of the output, which is listed in Appendix A. Similar to the mathematical model (Section 6.5), the *ERMYN_VA* is structured as a series of submodels. For each submodel, the linkage of the GoldSim elements to input parameters is tabulated in this section. The description of the *ERMYN_VA* design is simplified because many parts are the same as those used in the groundwater model, *ERMYN_GW_Rev01*. As with the *ERMYN_GW_Rev01* model, there is one container box (*Biosphere_Model*) on the cover page of the *ERMYN_VA* model (Figure 6.9-1).

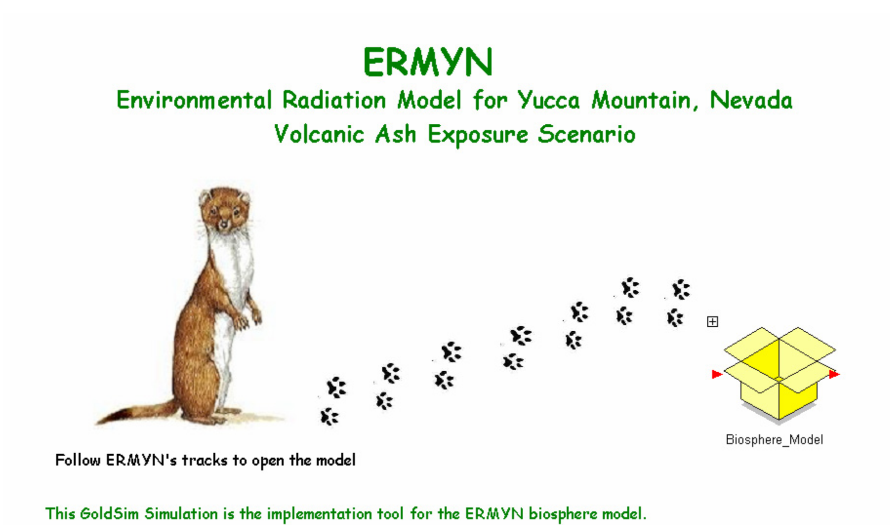


Figure 6.9-1. Cover Page for the *ERMYN_VA Model Rev 01* in GoldSim

The *Biosphere_Model* container holds the submodel containers and the radionuclide data (Figure 6.9-2). The overall model structure looks much like the block diagram of the conceptual model for the volcanic ash scenario shown in Figure 6.3-4, and each container in the GoldSim simulation corresponds to a submodel.

Nine containers, including seven submodels, one results box, and one radionuclide database box, are shown in Figure 6.9-2. The fish and ^{14}C special submodels are excluded from the volcanic ash scenario. Each box is discussed in detail in the following sections. Only three input parameters can be changed at this level: *Radionuclide* and *Ash_Source_Areal* and *Ash_Source_Mass*. The *Radionuclide* parameter can only be selected from the data element of *Radionuclide_List* that is built into the *Nuclide_Database* container. *Ash_Source_Areal* and *Ash_Source_Mass* represent the source terms for the model. They are expressed in terms of the radionuclide concentration in surface soil per unit area (Cs_i) and radionuclide concentration per unit mass of resuspendable soil layer ($Cs_{mc,i}$) and have default values of 1 Bq/m^2 and 1 Bq/kg, respectively. GoldSim can be run in deterministic and stochastic modes by adjusting settings in the *MasterClock*. If the stochastic mode is chosen, the number of realizations, the sampling method (Monte Carlo or Latin Hypercube), and the random seed number need to be selected. Because the BDCF is not a function of time, the time option is disabled.

Similar to the *ERMYN_GW_Rev01* model, many calculations are performed using the data array to reduce the number of GoldSim elements used in the ERMYN. Thirteen data arrays are used with the following labels: primary radionuclides (31), total number of radionuclides (75), pathways (15), plant types (5), crop food types (4), animal product types (4), number of decay products (3), population groups (4), environments (5), soil conditions (2), air submodel pathway (4), crop uptake pathway (4), and animal uptake pathway (4). These data sets and submodel pathways are discussed in Section 6.5.

6.9.1 Nuclide Database

The nuclide database for the volcanic ash scenario is similar to the one used for the groundwater scenario, except that there are no radioactive decay products accumulating in the soil. Thirty-one primary radionuclides are included in the *ERMYN_VA* (Section 6.8.1). The *Nuclide_Database* container is the same as that used for the *ERMYN_GW* (Figure 6.8-4) even though fewer radionuclides are considered in this scenario. The *Nuclide_Data* container does not include the *Fish_Transfer* container with the bioaccumulation factors because these data are only used in the groundwater scenario. Only two lower-level containers are in the *Data_Selection* container. Thirteen radionuclide-specific input parameters are selected using the *Selector* elements (Figure 6.9-3).

All GoldSim elements in the *Nuclide_Database* container are presented in Table 6.9-1. This table lists input parameters for each lower level container and their characteristics, including parameter name, GoldSim element type, data source, data types, equation number where the equation is originally defined, and symbol notation.

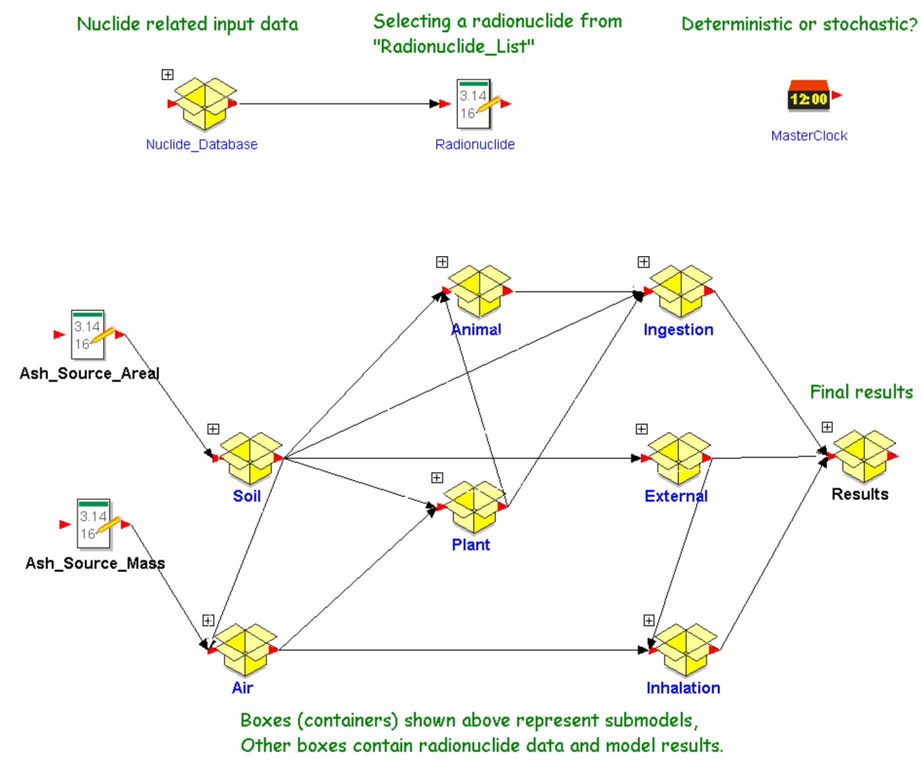


Figure 6.9-2. Biosphere Model for the Volcanic Ash Scenario

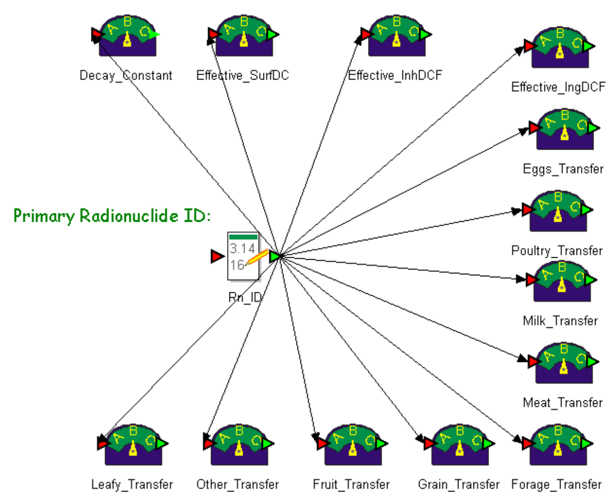


Figure 6.9-3. *Nuclide_Database* Container, Data Selection

Table 6.9-1. Radionuclide Related Input Parameters

First Level Box Name	Second Level Box Name	Parameter or Container Name	Element Type [a]	Data Source [b]	Data Type [c]	Equation	Notation
Radionuclide_List			Data	Input	Vector(31)	6.5.1-1	i
Nuclide_ Data	*Kd_Coefficients*		Container	Not shown in detail			
	Crop_Transfers						
	Animal_Transfers						
	Nuclear_Data						
Data_ Selection	*Effective_ DCF*	*Unity*	Data	-	Vector(31)	-	-
		Decay_Constants	Expression	Calculated	Vector(31)	6.4.1-1	$\lambda_{d\ i}$
		A	Expression	Calculated	Vector(31)	Not used	-
		B	Expression	Calculated	Vector(31)	6.5.5-2	$EDCs_{soil,i}$
		C	Expression	Calculated	Vector(31)	6.4.8-8	$EDCF_{inh,i}$
		D	Expression	Calculated	Vector(31)	6.4.9-7	$EDCF_{ing,i}$
		Effective_InfDCs	Data	Calculated	Vector(31)	Not used	-
		Effective_SurDCs	Data	Calculated	Vector(31)	6.5.5-2	$EDCs_{soil,i}$
		Effective_InhDCFs	Data	Calculated	Vector(31)	6.4.8-8	$EDCF_{inh,i}$
		Effective_IngDCFs	Data	Calculated	Vector(31)	6.4.9-7	$EDCF_{ing,i}$
	Primary_ Rn	*Rn_ID*	Data	Dbase	Scalar	6.4.1-1	i
		Decay_Constant	Selector	Dbase	Scalar	6.4.1-1	$\lambda_{d\ i}$
		Effective_SurDC	Selector	Dbase	Scalar	6.5.5-1	$EDCs_{soil,i}$
		Effective_InhDCF	Selector	Dbase	Scalar	6.5.6-2	$EDCF_{inh,i}$
		Effective_IngDCF	Selector	Dbase	Scalar	6.5.7-2	$EDCF_{ing,i}$
		Beef_Transfer	Selector	Dbase	Scalar	6.5.4-2	$Fm_{i,1}$
		Poultry_Transfer	Selector	Dbase	Scalar	6.5.4-2	$Fm_{i,2}$
		Milk_Transfer	Selector	Dbase	Scalar	6.5.4-2	$Fm_{i,3}$
		Eggs_Transfer	Selector	Dbase	Scalar	6.5.4-2	$Fm_{i,4}$
		Leafy_Transfer	Selector	Dbase	Scalar	6.5.3-2	$F_{s\rightarrow p,i,1}$
		Other_Transfer	Selector	Dbase	Scalar	6.5.3-2	$F_{s\rightarrow p,i,2}$
		Fruit_Transfer	Selector	Dbase	Scalar	6.5.3-2	$F_{s\rightarrow p,i,3}$
		Grain_Transfer	Selector	Dbase	Scalar	6.5.3-2	$F_{s\rightarrow p,i,4}$
		Forage_Transfer	Selector	Dbase	Scalar	6.5.3-2	$F_{s\rightarrow p,i,5}$

NOTE: The following notes apply to all GoldSim tables in Section 6.9.

[a] Element type is the GoldSim element type used for inputs, calculations, and other manipulations.

[b] If the data source is "Input," the parameter values are entered in the GoldSim element. If the source is "Dbase," values are taken from a database, or calculated values. If the data source is "Calculated" it is a quantity calculated in the model from the other data. If the source and the corresponding equation notation are dashes (–), the element is added for GoldSim array calculations.

[c] Data types are scalar (a single value) or array (a set of values). A one-dimensional array is called a vector, and a two-dimensional array is called a matrix. The number of values in the array is given in parentheses.

6.9.2 Surface Soil Submodel

The mathematical equations for the surface soil submodel are discussed in Section 6.5.1. All parameters used in this submodel are listed in Table 6.9-2. The contents of the submodel container are shown in Figure 6.9-4. Only a few GoldSim elements are used in this container to calculate the mass radionuclide concentration in the surface soil (Equation 6.5.1-2).

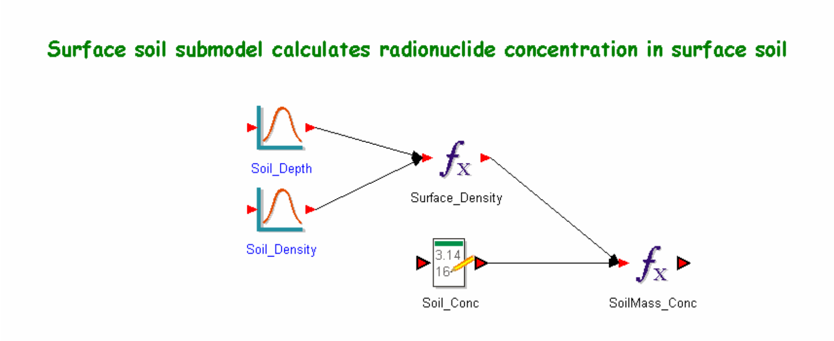


Figure 6.9-4. Surface Soil Submodel Container

Table 6.9-2. Parameters in the Surface Soil Submodel

Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Soil_Conc	Data	Input	Scalar	6.5.1-1	Cs_i
Soil_Depth	Stochastic	Input	Scalar	6.5.1-2	d
Soil_Density	Stochastic	Input	Scalar	6.5.1-2	ρ
Surface_Density	Expression	Calculated	Scalar	6.5.1-2	ρ_s
SoilMass_Conc	Expression	Calculated	Scalar	6.5.1-2	$Cs_{m,i}$

NOTE: See notes for Table 6.9-1.

6.9.3 Air Submodel

The mathematical equations used for the air submodel are discussed in Section 6.5.2. All parameters used in this submodel are listed in Table 6.9-3. The contents of the submodel container are shown in Figure 6.9-5. One lower level container is included in the submodel. The *AirModel_Input* container calculates the mass loading and enhancement factors that are used for calculating the radionuclide concentration in the air due to resuspended particles. The air submodel calculates radionuclide concentrations in the air for crop deposition (Equation 6.5.2-1) and human inhalation (Equation 6.5.2-2). Airborne concentrations of radon gas released from ^{226}Ra-contaminated soils are calculated using Equation 6.5.2-8.

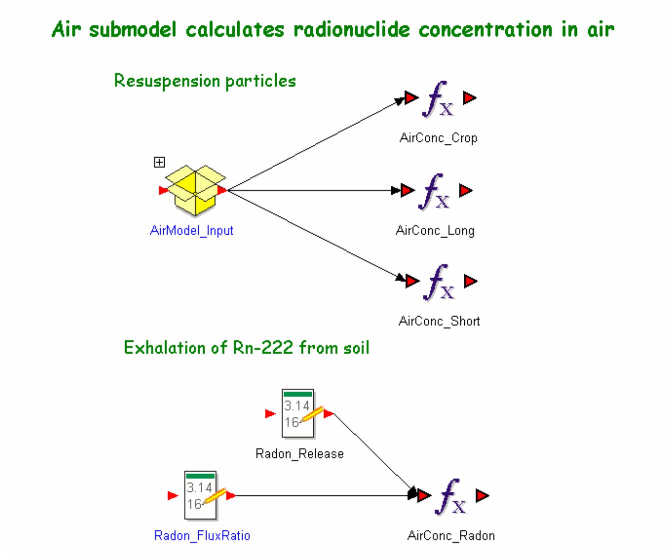


Figure 6.9-5. Air Submodel Container

Table 6.9-3. Parameters in the Air Submodel

Low Layer Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
AirModel_ Input	*Crop_Loading*	Stochastic	Input	Scalar	6.5.2-1	S
	ActiveOut_Dust	Stochastic	Input	Scalar	6.5.2-3	S_1
	InactiveOut_Dust	Stochastic	Input	Scalar	6.5.2-3	S_2
	ActiveIn_Dust	Stochastic	Input	Scalar	6.5.2-3	S_3
	AsleepIn_Dust	Stochastic	Input	Scalar	6.5.2-3	S_4
	Mass_Loading	Data	Calculated	Vector(5)	6.5.2-3	S_n
	ActiveOut_Ash	Stochastic	Input	Scalar	6.5.2-3	$S_{v,1}$
	InactiveOut_Ash	Stochastic	Input	Scalar	6.5.2-3	$S_{v,2}$
	ActiveIn_Ash	Stochastic	Input	Scalar	6.5.2-3	$S_{v,3}$
	AsleepIn_Ash	Stochastic	Input	Scalar	6.5.2-3	$S_{v,4}$
	Ash_Loading	Data	Calculated	Vector(5)	6.5.2-3	$S_{v,n}$
	ActiveOut_Enhance	Stochastic	Input	Scalar	6.5.2-2	$f_{enhance,1}$
	InactiveOut_Enhance	Stochastic	Input	Scalar	6.5.2-2	$f_{enhance,2}$
	ActiveIn_Enhance	Stochastic	Input	Scalar	6.5.2-2	$f_{enhance,3}$
	AsleepIn_Enhance	Stochastic	Input	Scalar	6.5.2-2	$f_{enhance,4}$
	Enhance_Factor	Data	Calculated	Vector(5)	6.5.2-2	$f_{enhance,n}$
AirConc_Crop		Expression	Calculated	Scalar	6.5.2-1	$Ca_{p,i}$
AirConc_Short		Expression	Calculated	Vector(5)	6.5.2-4	$Ca_{h,i,n}$
AirConc_Long		Expression	Calculated	Vector(5)	6.5.2-4	$Ca_{v,i,n}$
Radon_Release		Data	Input	Scalar	6.5.2-6	$FD_{Rn\text{-}222}$
RnFlux_Ratio		Data	Input	Scalar	6.5.2-7	$CF_{Rn\text{-}222}$
AirConc_Radon		Expression	Calculated	Scalar	6.5.2-8	$Ca_{g,Rn\text{-}222}$

NOTE: See notes for Table 6.9-1.

6.9.4 Plant Submodel

Mathematical equations for the plant submodel are discussed in Section 6.5.3. All parameters used in this submodel are listed in Table 6.9-4. The contents of the submodel container are shown in Figure 6.9-6. This submodel includes two lower level containers. The *Root_Uptake* container (Equation 6.5.3-2) calculates radionuclide concentrations in crops due to contaminated soil. The *Dust_Deposition* container (Equation 6.5.3-3) calculates radionuclide concentrations in crops due to direct deposition of resuspended soil from cultivated lands.

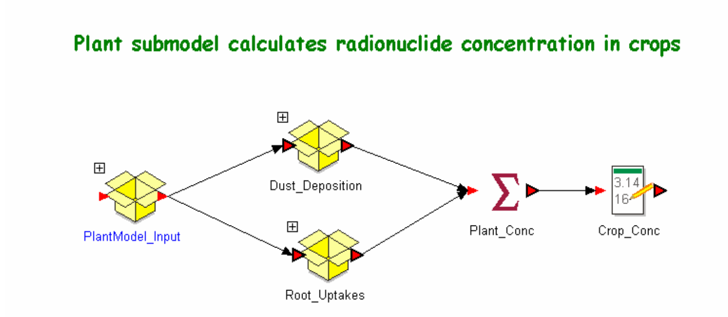


Figure 6.9-6. Plant Submodel Container

Table 6.9-4. Parameters in the Plant Submodel

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
PlantModel_ Input	*DryWet_Leafy*	Stochastic	Input	Scalar	6.5.3-2	DW_1
	DryWet_Other	Stochastic	Input	Scalar	6.5.3-2	DW_2
	DryWet_Fruit	Stochastic	Input	Scalar	6.5.3-2	DW_3
	DryWet_Grain	Stochastic	Input	Scalar	6.5.3-2	DW_4
	DryWet_Forage	Stochastic	Input	Scalar	6.5.3-2	DW_5
	DryWet_Ratio	Data	Calculated	Vector(5)	6.5.3-2	DW_j
	Yield_Leafy	Stochastic	Input	Scalar	6.5.3-3	Y_1
	Yield_Other	Stochastic	Input	Scalar	6.5.3-3	Y_2
	Yield_Fruit	Stochastic	Input	Scalar	6.5.3-3	Y_3
	Yield_Grain	Stochastic	Input	Scalar	6.5.3-3	Y_4
	Yield_Forage	Stochastic	Input	Scalar	6.5.3-3	Y_5
	Wet_Yield	Data	Calculated	Vector(5)	6.5.3-3	Y_j
	DryBiom_Leafy	Stochastic	Input	Scalar	6.5.3-5	DB_1
	DryBiom_Other	Stochastic	Input	Scalar	6.5.3-5	DB_2
	DryBiom_Fruit	Stochastic	Input	Scalar	6.5.3-5	DB_3
	DryBiom_Grain	Stochastic	Input	Scalar	6.5.3-5	DB_4
	DryBiom_Forage	Stochastic	Input	Scalar	6.5.3-5	DB_5
	Deposit_Velocity	Stochastic	Input	Scalar	6.5.3-4	V_d
	Weather_Halflife	Stochastic	input	Scalar	6.5.3-3	T_w
	Weathering_Factor	Data	Calculated	Scalar	6.5.3-3	λ_w
	Translocation_Dist	Stochastic	Input	Scalar	6.5.3-3	T_j
	Translocation	Data	Input	Vector(5)	6.5.3-3	T_j
	Growing_Time	Data	Input	Vector(5)	6.5.3-3	$t_{g,j}$

Table 6.9-4. Parameters in the Plant Submodel (Continued)

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Dust_ Deposition	*Dust_Factor*	Data	Input	Vector(5)	6.5.3-5	a_j
	ExpDust_Leafy	Expression	Calculated	Scalar	6.5.3-5	$e^{-a_1 DB_1}$
	ExpDust_Other	Expression	Calculated	Scalar	6.5.3-5	$e^{-a_2 DB_2}$
	ExpDust_Fruit	Expression	Calculated	Scalar	6.5.3-5	$e^{-a_3 DB_3}$
	ExpDust_Grain	Expression	Calculated	Scalar	6.5.3-5	$e^{-a_4 DB_4}$
	ExpDust_Forage	Expression	Calculated	Scalar	6.5.3-5	$e^{-a_5 DB_5}$
	Dust_Intercept	Data	Calculated	Vector(5)	6.5.3-5	Ra_j
	ExpGrow_Leafy	Expression	Calculated	Scalar	6.5.3-3	$e^{-\lambda w\, tg,1}$
	ExpGrow_Other	Expression	Calculated	Scalar	6.5.3-3	$e^{-\lambda w\, tg,2}$
	ExpGrow_Fruit	Expression	Calculated	Scalar	6.5.3-3	$e^{-\lambda w\, tg,3}$
	ExpGrow_Grain	Expression	Calculated	Scalar	6.5.3-3	$e^{-\lambda w\, tg,4}$
	ExpGrow_Forage	Expression	Calculated	Scalar	6.5.3-3	$e^{-\lambda w\, tg,5}$
	Growing_Factors	Data	Calculated	Vector(5)	6.5.3-3	$1-e^{-\lambda w\, tg,j}$
	Other_Factor	Expression	Calculated	Vector(5)	6.5.3-3	$T_j/(Y_j\lambda_w)\,(1-e^{-\lambda w\, tg,j})$
	Air_Interception	Expression	Calculated	Vector(5)	6.5.3-3	Ra_j
	Dust_Uptake	Expression	Calculated	Vector(5)	6.5.3-3	$Cp_{dust\ i,j}$
Root_ Uptakes	*Transfer_Factor*	Data	Dbase	Vector(5)	6.5.3-2	$F_{s\rightarrow p\ i,j}$
	Root_Uptake	Expression	Calculated	Vector(5)	6.5.3-2	$Cp_{root\ i,j}$
Plant_Conc		Sum	Calculated	Vector(5)	6.5.3-1	$Cp_{\ i,j}$
Crop_Conc		Data	Calculated	Vector(4)	6.5.3-1	$Cp_{\ i,j}$

NOTE: See notes for Table 6.9-1.

6.9.5 Animal Submodel

Mathematical equations for the animal submodel are discussed in Section 6.5.4. All parameters used in this submodel are listed in Table 6.9-5. The animal submodel container includes two lower level containers (Figure 6.9-7). The *AnimalModel_Input* container includes input parameters for the animal submodel. The *Animal_Ingestion* container calculates radionuclide concentrations in animal products due to the ingestion of contaminated feed (Equation 6.5.4-2) and contaminated soil (Equation 6.5.4-3).

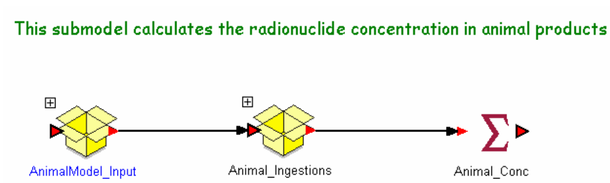


Figure 6.9-7. Animal Submodel Container

Table 6.9-5. Parameters in the Animal Submodel

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Animal Model_ Input	*Feed_ForMeat*	Stochastic	Input	Scalar	6.5.4-2	Qf_1
	Feed_ForMilk	Stochastic	Input	Scalar	6.5.4-2	Qf_2
	Feed_ForPoultry	Stochastic	Input	Scalar	6.5.4-2	Qf_3
	Feed_ForEggs	Stochastic	Input	Scalar	6.5.4-2	Qf_4
	Animal_Feed	Data	Calculated	Vector(4)	6.5.4-2	Qf_k
	Soil_ForMeat	Stochastic	Input	Scalar	6.5.4-3	Qs_1
	Soil_ForMilk	Stochastic	Input	Scalar	6.5.4-3	Qs_2
	Soil_ForPoultry	Stochastic	Input	Scalar	6.5.4-3	Qs_3
	Soil_ForEggs	Stochastic	Input	Scalar	6.5.4-3	Qs_4
	Animal_Soil	Data	Calculated	Vector(4)	6.5.4-3	Qs_k
	Transfer_Coefficients	Data	Dbase	Vector(4)	6.5.4-2	$Fm_{i,k}$
Animal_ Ingestions	*Feed_Conc*	Data	Calculated	Vector(4)	6.5.3-1	$Cp_{i,j}$
	Feed_Contribution	Expression	Calculated	Vector(4)	6.5.4-2	$Cd_{feed,i,k}$
	Soil_Contribution	Expression	Calculated	Vector(4)	6.5.4-3	$Cd_{soil,i,k}$
Animal_Conc		Sum	Calculated	Vector(4)	6.5.4-1	$Cd_{i,k}$

NOTE: See notes for Table 6.9-1.

6.9.6 External Exposure Submodel

Mathematical equations for the external exposure submodel are discussed in Section 6.5.5. All parameters used in this submodel are listed in Table 6.9-6. The external exposure submodel container includes two lower level containers (Figure 6.9-8). The *External_Input* container is used for input data for the population groups and the associated time budgets, and the *External_Model* container calculates the effective external exposure time and the human external radiation dose (Equation 6.5.5-1).

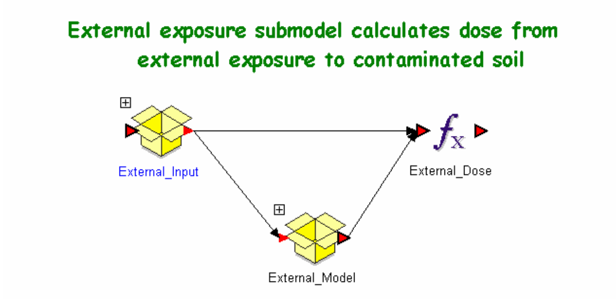


Figure 6.9-8. External Exposure Submodel Container

Table 6.9-6. Parameters in the External Exposure Submodel

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
External_ Input	*OW_ActOut*	Stochastic	Input	Scalar	6.5.5-1	$t_{1,1}$
	IW_ActOut	Stochastic	Input	Scalar	6.5.5-1	$t_{1,2}$
	CT_ActOut	Stochastic	Input	Scalar	6.5.5-1	$t_{1,3}$
	NW_ActOut	Stochastic	Input	Scalar	6.5.5-1	$t_{1,4}$
	OW_Outdoor	Stochastic	Input	Scalar	6.5.5-1	$t_{2,1}$
	IW_Outdoor	Stochastic	Input	Scalar	6.5.5-1	$t_{2,2}$
	CT_Outdoor	Stochastic	Input	Scalar	6.5.5-1	$t_{2,3}$
	NW_Outdoor	Stochastic	Input	Scalar	6.5.5-1	$t_{2,4}$
	OW_Away	Stochastic	Input	Scalar	6.5.5-1	$t_{5,1}$
	IW_Away	Stochastic	Input	Scalar	6.5.5-1	$t_{5,2}$
	CT_Away	Stochastic	Input	Scalar	6.5.5-1	$t_{5,3}$
	NW_Away	Stochastic	Input	Scalar	6.5.5-1	$t_{5,4}$
	Indoor_Asleep	Stochastic	Input	Scalar	6.5.5-1	$t_{4,m}$
	OW_Indoor	Expression	Calculated	Scalar	6.5.5-1	$t_{3,1}$
	IW_Indoor	Expression	Calculated	Scalar	6.5.5-1	$t_{3,2}$
	CT_Indoor	Expression	Calculated	Scalar	6.5.5-1	$t_{3,3}$
	NW_Indoor	Expression	Calculated	Scalar	6.5.5-1	$t_{3,4}$
	Fraction_OW	Stochastic	Input	Scalar	6.5.5-1	PP_1
	Fraction_IW	Expression	Calculated	Scalar	6.5.5-1	PP_2
	Fraction_CT	Stochastic	Input	Scalar	6.5.5-1	PP_3
	Fraction_NW	Stochastic	Input	Scalar	6.5.5-1	PP_4
	Shielding_Factor	Data	Input	Scalar	6.5.5-1	$f_{ext,i,3}$ and $f_{ext,i,4}$
	External_DC	Data	Dbase	Scalar	6.5.5-1	$EDCs_{soil,i}$
External_ Model	*Exposure_times*	Data	Calculated	Matrix (5,4)	6.5.5-1	$t_{n,m}$
	Population	Data	Calculated	Vector(4)	6.5.5-1	PP_m
	Weighted_Time	Expression	Calculated	Vector(5)	6.5.5-1	$PP_m\ t_{n,m}$
	Weighted_Outdoor	Expression	Calculated	Scalar	6.5.5-1	$PP_m\ t_{1,m} + PP_m\ t_{2,m}$
	Weighted_Indoor	Expression	Calculated	Scalar	6.5.5-1	$PP_m\ t_{3,m} + PP_m\ t_{4,m}$
	External_Time	Expression	Calculated	Scalar	6.5.5-1	$\sum f_{ext,i,n}(\sum PP_m\ t_{n,m})$
External_Dose		Expression	Calculated	Scalar	6.5.5-1	$D_{ext,i}$

NOTE: See notes for Table 6.9-1.

6.9.7 Inhalation Submodel

Mathematical equations for the inhalation submodel are discussed in Section 6.5.6. All parameters used in this submodel are listed in Table 6.9-7. The contents of the inhalation submodel container include one lower level container (Figure 6.9-9). The *Inhalation_Input* container includes inhalation-related input parameters (e.g., breathing rates and radon data). The time budgets for the receptor are calculated in the *External* model container. Inhalation doses are calculated under normal and post-volcanic conditions (Equation 6.5.6-2). The radon inhalation dose due to exhalation of radon gas from ^{226}Ra in volcanic ash on the ground is also included in this submodel (Equation 6.5.6-4).

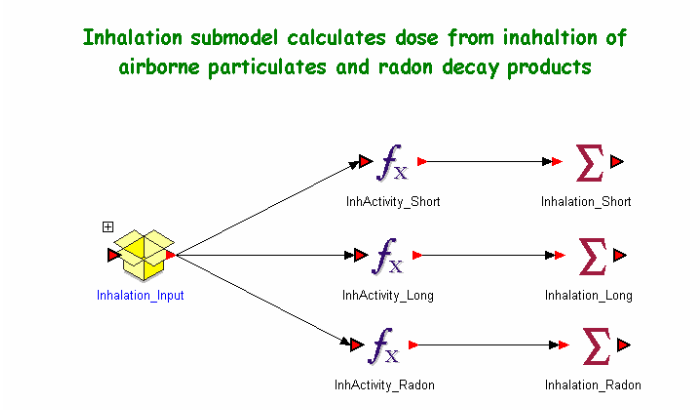


Figure 6.9-9. Inhalation Submodel Container

Table 6.9-7. Parameters in the Inhalation Submodel

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Inhalation_ Input	*Breathing_Rate*	Data	Input	Vector(5)	6.5.6-2	BR_n
	RadonEF_Outdoor	Stochastic	Input	Scalar	6.5.6-3	$EF_{Rn\text{-}222,1\&2}$
	RadonET_Indoor	Stochastic	Input	Scalar	6.5.6-3	$EF_{Rn\text{-}222,3\&4}$
	Radon_Equilibrium	Data	Calculated	Vector(5)	6.5.6-3	$EF_{Rn\text{-}222,n}$
	Radon_DCF	Data	Input	Scalar	6.5.6-3	$DCF_{inh,Rn\text{-}222}$
	Inhalation_DCF	Data	Dbase	Scalar	6.5.6-2	$EDCF_{inh,i}$
InhActivity_Short		Expression	Calculated	Vector(5)	6.5.6-2	$D_{inh,v,i}$
InhActivity_Long		Expression	Calculated	Vector(5)	6.5.6-2	$D_{inh,p,i}$
InhActivity_Radon		Expression	Calculated	Vector(5)	6.5.6-3	$D_{inh,g,Rn\text{-}222,n}$
Inhalation_Short		Sum	Calculated	Scalar	6.5.6-4	$D_{inh,v,i}$
Inhalation_Long		Sum	Calculated	Scalar	6.5.6-4	$D_{inh,p,i}$
Inhalation_Radon		Sum	Calculated	Scalar	6.5.6-3	$D_{inh,g,Rn\text{-}222}$

NOTE: See notes for Table 6.9-1.

6.9.8 Ingestion Submodel

Mathematical equations for the human ingestion submodel, which includes nine pathways, are discussed in Section 6.5.7. All parameters used in this submodel are listed in Table 6.9-8. The GoldSim ingestion submodel container includes one lower level container (Figure 6.9-10). The *Ingestion_Input* container includes food consumption rates. To provide the results of pathway analysis, the ingestion dose is calculated for individual pathways and for total ingestion.

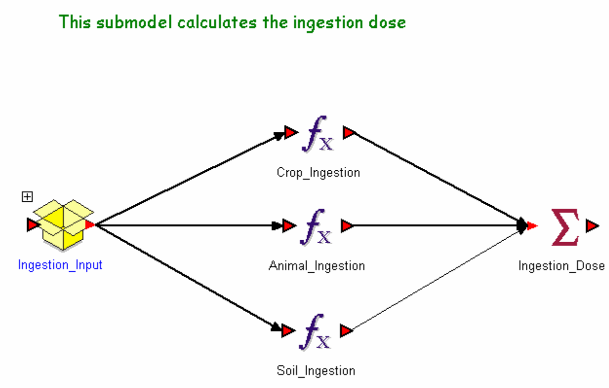


Figure 6.9-10. Ingestion Submodel Container

Table 6.9-8. Parameters in the Ingestion Submodel

Low Level Box Name	Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
Ingestion_ Input	*Leafy_Consump*	Stochastic	Input	Scalar	6.5.7-2	Up_1
	Other_Consump	Stochastic	Input	Scalar	6.5.7-2	Up_2
	Fruit_Consump	Stochastic	Input	Scalar	6.5.7-2	Up_3
	Grain_Consump	Stochastic	Input	Scalar	6.5.7-2	Up_4
	Crop_Consump	Data	Calculated	Vector(4)	6.5.7-2	Up_j
	Beef_Consump	Stochastic	Input	Scalar	6.5.7-3	Ud_1
	Poultry_Consump	Stochastic	Input	Scalar	6.5.7-3	Ud_2
	Milk_Consump	Stochastic	Input	Scalar	6.5.7-3	Ud_3
	Eggs_Consump	Stochastic	Input	Scalar	6.5.7-3	Ud_4
	Animal_Consump	Data	Calculated	Vector(4)	6.5.7-3	Ud_k
	Soil_Consump	Stochastic	Input	Scalar	6.5.7-4	Us
	Ingestion_DCF	Data	Dbase	Scalar	6.5.7-2	$EDCF_{ing,i}$
Crop_Ingestion		Expression	Calculated	Vector(4)	6.5.7-2	$D_{ing,p,i}$
Animal_Ingestion		Expression	Calculated	Vector(4)	6.5.7-3	$D_{ing,d,i}$
Soil_Ingestion		Expression	Calculated	Scalar	6.5.7-4	$D_{ing,s,i}$
Ingestion_Dose		Sum	Calculated	Scalar	6.5.7-1	$D_{ing,0}$

NOTE: See notes for Table 6.9-1.

6.9.9 BDCF Results

The committed effective dose and BDCF for each radionuclide are discussed in Section 6.5.8. All parameters used in this submodel are listed in Table 6.9-9. The BDCF for volcanic ash deposition has three parts. The first part includes external exposure, radon inhalation, and ingestion pathways; the second part includes inhalation of resuspended particles at post-volcanic levels; and the third part includes inhalation of resuspended particles at normal levels. In GoldSim, the pathway results are also calculated (Figure 6.9-11).

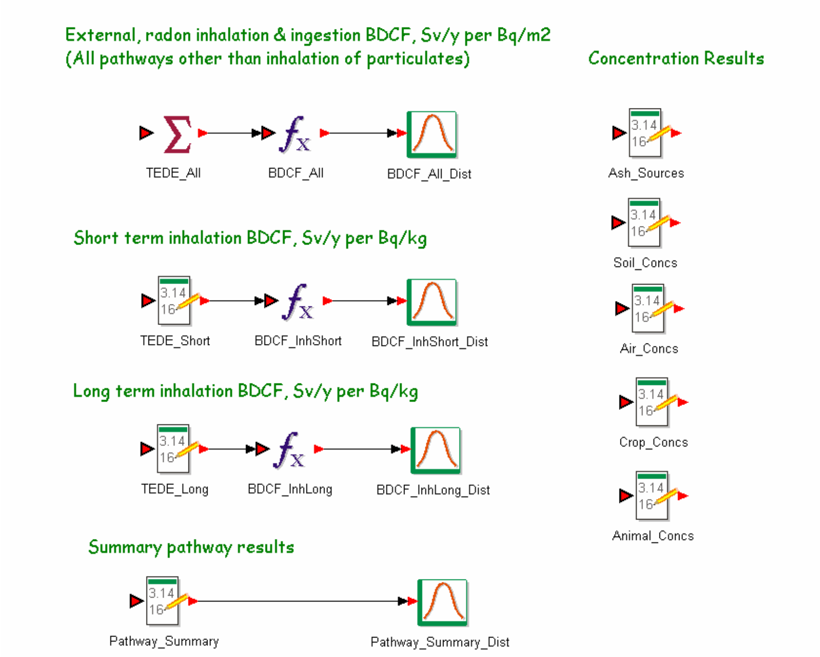


Figure 6.9-11. Final BDCF Result Container

Table 6.9-9. Parameters in the Final BDCF Results

Parameter Name	Element Type	Data Source	Data Type	Equation	Notation
TEDE_All	Sum	Calculated	Scalar	6.5.8-1	$D_{all,i}$
BDCF_All	Expression	Calculated	Scalar	6.5.8-2	$BDCF_{ext,ing,Rn,i}$
TEDE_Short	Data	Calculated	Scalar	6.5.8-1	$D_{inh,v,i}$
BDCF_InhShort	Expression	Calculated	Scalar	6.5.8-2	$BDCF_{inh,v,i}$
TEDE_Long	Data	Calculated	Scalar	6.5.8-1	$D_{inh,p,i}$
BDCF_InhLong	Expression	Calculated	Scalar	6.5.8-2	$BDCF_{inh,p,i}$
Pathway_Summary	Data	Calculated	Vector(12)	6.4.10-3	$D_{p,i}$
Pathway_BDCF	Expression	Calculated	Vector(12)	6.4.10-4	$BDCF_{p,i}$
BDCF_All_Dist	Result	Calculated	Scalar	—	—
BDCF_InhShort_Dist	Result	Calculated	Scalar	—	—
BDCF_InhLong_Dist	Result	Calculated	Scalar	—	—
BDCF_Pathway_Dist	Result	Calculated	Vector(12)	—	—

NOTE: See notes for Table 6.9-1.

6.10 VERIFICATION OF THE BIOSPHERE MODEL IMPLEMENTATION IN GOLDSIM

Verification of the ERMYN in GoldSim is carried out by executing the model and comparing the results with results of hand calculations based on the equations described in Sections 6.4 and 6.5. Several test cases are performed to ensure that the *ERMYN_GW* and *ERMYN_VA* models are correctly implemented. The test cases are carried out as deterministic runs because stochastic runs are simply sets of many deterministic runs, and the correctness of the stochastic simulation is a property of the GoldSim software.

In addition to verifying the deterministic realization with hand calculations, tests of the stochastic calculations are carried out in which the results of stochastic realizations are compared with the results of the deterministic realization. This was done to gain confidence that the stochastic results include the deterministic result, which has been verified with hand calculations. Because the sample means of input parameter distributions from some recommended distributions do not match the verification values of the input parameters, the mean of the output from the stochastic realizations is not expected to exactly match the results of the deterministic run. However, the deterministic results are expected to be within the range of the output distributions from the stochastic results. In addition, a test was performed of the stability of the mean BDCF value with respect to sampling of parameter distributions.

As implemented in GoldSim, the ERMYN calculates BDCFs for individual radionuclides one at a time. The BDCFs are correlated because for a given model realization number, all sampled radionuclide-independent parameters are the same regardless of a radionuclide.

6.10.1 Verification of the Model Implementation for the Groundwater Scenario

6.10.1.1 Verification of Deterministic Calculations

Input parameters for verifying the model implementation for the groundwater scenario are taken from the Mean-Mode-Average column in Table 6.6-3. Four radionuclides, ^{239}Pu, ^{14}C, ^{226}Ra, and ^{232}Th are tested under the groundwater scenario for the present-day climate conditions. For the base case, ^{239}Pu is selected as a representative radionuclide (Table 6.10-1). ^{239}Pu does not have any long-lived decay products that would be included in the chain of this radionuclide decay in the soil. ^{14}C is selected for the ^{14}C special submodel (Table 6.10-2). ^{226}Ra has one long lived decay product, ^{210}Pb, and the gaseous decay product, ^{222}Rn (Table 6.10-3). ^{232}Th is representative of those radionuclides whose decay chain in the surface soil include two long-lived decay products (Table 6.10-4). In the tables, the hand calculation equations are listed so that the calculations can be reproduced using inputs from Table 6.6-3. In addition, the results from GoldSim are presented with the corresponding GoldSim element names. The results from both methods are the same, indicating that the GoldSim implementation of the ERMYN (groundwater scenario; Section 6.4) is correct. The GoldSim files described in this section are listed in Appendix A.

The verification results for ^{239}Pu (case 1) are presented in Table 6.10-1. In this table, the verification steps (i.e., the sequential quantities calculated in the model) are presented in the order of each submodel discussed in Section 6.4. The hand-calculated results from the important biosphere model equations are presented in the table for comparison with the GoldSim results.

Verification results for ^{14}C (case 2) are presented in Table 6.10-2. Because ^{14}C is a special radionuclide, the model for ^{14}C (Section 6.4.6) transport and accumulation in the environmental media differs from the model for the other radionuclides. Therefore, the content of this table is different from Table 6.10-1.

Another special radionuclide is ^{226}Ra (case 3). Verification results for this radionuclide are presented in Table 6.10-3. Radium-226 has one long-lived decay product that is considered for the decay of this radionuclide in the surface soil (Table 6.4-3) and produces radon gas, which eventually decays to a long-lived decay product (^{210}Pb) that would accumulate in irrigated soils. Furthermore, consideration of different radon concentrations indoors and outdoors, the circumstances involving the operation of evaporative coolers, and normal ventilation conditions, made the calculation more complicated. For verification of exposures related to the accumulation of long-lived decay products of a primary radionuclide in surface soils, ^{232}Th and its long-lived decay products, ^{228}Th and ^{228}Ra, are considered (case 4) (Table 6.10-4).

Table 6.10-1. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 1, ^{239}Pu)

Submodel	Parameter in Mathematical Model					Parameter in GoldSim		Notes [c]
	Parameter Name	Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
Soil	Leaching removal rate constant, surf. soil	$\lambda_{l,Pu\text{-}239}$	6.4.1-28	1/yr	1.76E–04	*Leaching_Factor*	1.76E–04	Same
	Leaching removal rate constant, critical thickness, gardens	$\lambda_{lc,Pu\text{-}239,1}$	6.4.1-29	1/yr	2.51E–01	*Leaching_Factor_Crit*	2.51E–01	Same
	Leaching removal rate constant, critical thickness, fields	$\lambda_{lc,Pu\text{-}239,5}$	6.4.1-29	1/yr	4.91E–01	*Leaching_Factor_Crit*	4.91E–01	Same
	Erosion removal rate constant, surface soil	λ_{e}	6.4.1-31	1/yr	5.33E–04	*Erosion_Factor*	5.33E–04	Same
	Erosion removal rate constant, critical thickness	λ_{ec}	6.4.1-32	1/yr	6.67E–02	*Erosion_Factor_Crit*	6.67E–02	Same
	Effective removal rate constant, surf. soil	$\lambda_{eff,Pu\text{-}239}$	6.4.1-3	1/yr	7.38E–04	*Effective_Removal*	7.38E–04	Same
	Effective removal rate constant, critical thickness, gardens	$\lambda_{eff,c,Pu\text{-}239,1}$	6.4.1-33	1/yr	3.18E–01	*Effective_Removal_Crit*	3.18E–01	Same
	Effective removal rate constant, critical thickness, fields	$\lambda_{eff,c,Pu\text{-}239,5}$	6.4.1-33	1/yr	5.57E–01	*Effective_Removal_Crit*	5.57E–01	Same
	Concentration in surface soil, gardens	$Cs_{Pu\text{-}239,1}$	6.4.1-3	Bq/m^2	87.7	*Surf_Soil_Conc*	87.7	Same
	Concentration in soil mass, gardens	$Cs_{m,Pu\text{-}239,1}$	6.4.1-5	Bq/kg	0.23	*Surf_Soil_Mass_Conc*	0.23	Same
	Concentration in surface soil, fields	$Cs_{Pu\text{-}239,5}$	6.4.1-3	Bq/m^2	616.6	*Surf_Soil_Conc*	616.6	Same
	Concentration in soil mass, fields	$Cs_{m,Pu\text{-}239,5}$	6.4.1-5	Bq/kg	1.64	*Surf_Soil_Mass_Conc*	1.64	Same
	Concentration in critical thickness, mass, gardens	$Cs_{mc,Pu\text{-}239,1}$	6.4.1-5	Bq/kg	0.96	*Crit_Soil_Mass_Conc*	0.96	Same
	Concentration in critical thickness, mass, fields	$Cs_{mc,Pu\text{-}239,5}$	6.4.1-5	Bq/kg	1.06	*Crit_Soil_Mass_Conc*	1.06	Same
Air	Concentration in air, garden crops	$Ca_{p,Pu\text{-}239,1}$	6.4.2-1	Bq/m^3	1.15E–07	*AirConc_Crop*	1.15E–07	
	Concentration in air, field crops	$Ca_{p,Pu\text{-}239,5}$			1.97E–07	*AirConc_Crop*	1.97E–07	Same
	Concentration in air for inhalation: Active outdoors	$Ca_{h,Pu\text{-}239,1}$	6.4.2-2	Bq/m^3	4.93E–06	*AirConc_Inh*	4.93E–06	Same
	Inactive outdoors	$Ca_{h,Pu\text{-}239,2}$			2.29E–07		2.29E–07	Same
	Active indoors	$Ca_{h,Pu\text{-}239,3}$			3.82E–07		3.82E–07	Same
	Asleep indoors	$Ca_{h,Pu\text{-}239,4}$			1.15E–07		1.15E–07	Same
	Away	$Ca_{h,Pu\text{-}239,5}$			0.00E+00		0.00E+00	Same

Table 6.10-1. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 1, ^{239}Pu) (Continued)

Submodel	Parameter in Mathematical Model: Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Parameter in GoldSim: Element Name	ERMYN_GW Result [b]	Notes [c]
Air (Continued)	Concentration in air from evaporative cooler		$Ca_{e,Pu\text{-}239}$	6.4.2-3	Bq/m^3	1.02E–06	*AirConc_Evap*	1.02E–06	Same
Plant	Concentration due to root uptake	Leafy vegetables	$Cp_{root,Pu\text{-}239,1}$	6.4.3-2	Bq/kg	4.75E–06	*Root_Uptake*	4.75E–06	Same
		Other vegetables	$Cp_{root,Pu\text{-}239,2}$			4.58E–06		4.58E–06	Same
		Fruit	$Cp_{root,Pu\text{-}239,3}$			5.05E–06		5.05E–06	Same
		Grain	$Cp_{root,Pu\text{-}239,4}$			2.82E–05		2.82E–05	Same
		Forage	$Cp_{root,Pu\text{-}239,5}$			3.62E–04		3.62E–04	Same
	Irrigation interception fraction	Leafy vegetables	Rw_1	6.4.3-5	-	0.216	*Intercept_Factor*	0.216	Same
		Other vegetables	Rw_2			0.301		0.301	Same
		Fruit	Rw_3			0.360		0.360	Same
		Grain	Rw_4			0.470		0.470	Same
		Forage	Rw_5			0.258		0.258	Same
	Concentration due to water interception	Leafy vegetables	$Cp_{water,Pu\text{-}239,1}$	6.4.3-3	Bq/kg	5.23E–03	*Water_Uptake*	5.23E–03	Same
		Other vegetables	$Cp_{water,Pu\text{-}239,2}$			8.35E–04		8.35E–04	Same
		Fruit	$Cp_{water,Pu\text{-}239,3}$			9.78E–04		9.78E–04	Same
		Grain	$Cp_{water,Pu\text{-}239,4}$			6.72E–03		6.72E–03	Same
		Forage	$Cp_{water,Pu\text{-}239,5}$			1.40E–02		1.40E–02	Same
	Dust interception fraction	Leafy vegetables	Ra_1	6.4.3-8	-	0.456	*Dust_Intercept*	0.456	Same
		Other vegetables	Ra_2			0.787		0.787	Same
		Fruit	Ra_3			0.893		0.893	Same
		Grain	Ra_4			0.962		0.962	Same
		Forage	Ra_5			0.751		0.751	Same
	Concentration due to dust interception	Leafy vegetables	$Cp_{dust,Pu\text{-}239,1}$	6.4.3-6	Bq/kg	2.16E–04	*Dust_Uptake*	2.16E–04	Same
		Other vegetables	$Cp_{dust,Pu\text{-}239,2}$			2.99E–05		2.99E–05	Same
		Fruit	$Cp_{dust,Pu\text{-}239,3}$			5.19E–05		5.19E–05	Same
		Grain	$Cp_{dust,Pu\text{-}239,4}$			4.49E–04		4.49E–04	Same
		Forage	$Cp_{dust,Pu\text{-}239,5}$			9.44E–04		9.44E–04	Same

Table 6.10-1. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 1, ^{239}Pu) (Continued)

Submodel	Parameter in Mathematical Model: Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Parameter in GoldSim: Element Name	ERMYN_GW Result [b]	Notes [c]
Plant (Continued)	Concentration in crops	Leafy vegetables	$Cp_{Pu\text{-}239,1}$	6.4.3-1	Bq/kg	5.45E–03	*Plant_Conc*	5.45E–03	Same
		Other vegetables	$Cp_{Pu\text{-}239,2}$			8.70E–04		8.70E–04	Same
		Fruit	$Cp_{Pu\text{-}239,3}$			1.04E–03		1.04E–03	Same
		Grain	$Cp_{Pu\text{-}239,4}$			7.20E–03		7.20E–03	Same
		Forage	$Cp_{Pu\text{-}239,5}$			1.53E–02		1.53E–02	Same
Animal	Concentration due to feed	Meat	$Cd_{feed,Pu\text{-}239,1}$	6.4.4-2	Bq/kg or Bq/L	9.65E–06	*Feed_Contribution*	9.65E–06	Same
		Milk	$Cd_{feed,Pu\text{-}239,2}$			2.16E–07		2.16E–07	Same
		Poultry	$Cd_{feed,Pu\text{-}239,3}$			2.25E–06		2.25E–06	Same
		Eggs	$Cd_{feed,Pu\text{-}239,4}$			3.18E–06		3.18E–06	Same
	Concentration due to water	Meat	$Cd_{water,Pu\text{-}239,1}$	6.4.4-3	Bq/kg or Bq/L	7.80E–07	*Water_ Contribution*	7.80E–07	Same
		Milk	$Cd_{water,Pu\text{-}239,2}$			1.84E–08		1.84E–08	Same
		Poultry	$Cd_{water,Pu\text{-}239,3}$			6.00E–07		6.00E–07	Same
		Eggs	$Cd_{water,Pu\text{-}239,4}$			8.50E–07		8.50E–07	Same
	Concentration due to soil	Meat	$Cd_{soil,Pu\text{-}239,1}$	6.4.4-4	Bq/kg or Bq/L	1.50E–05	*Soil_Contribution*	1.50E–05	Same
		Milk	$Cd_{soil,Pu\text{-}239,2}$			3.59E–07		3.59E–07	Same
		Poultry	$Cd_{soil,Pu\text{-}239,3}$			2.29E–05		2.29E–05	Same
		Eggs	$Cd_{soil,Pu\text{-}239,4}$			3.25E–05		3.25E–05	Same
	Concentration in animal products	Meat	$Cd_{Pu\text{-}239,1}$	6.4.4-1	Bq/kg or Bq/L	2.54E–05	*Animal_Conc*	2.54E–05	Same
		Milk	$Cd_{Pu\text{-}239,2}$			5.94E–07		5.94E–07	Same
		Poultry	$Cd_{Pu\text{-}239,3}$			2.58E–05		2.58E–05	Same
		Eggs	$Cd_{Pu\text{-}239,4}$			3.65E–05		3.65E–05	Same
Fish	Concentration in Fish		$Cf_{Pu\text{-}239}$	6.4.5-2	Bq/kg	0.170	*Fish_Conc*	0.170	Same
External	Environment-specific exposure time	Active outdoors	$\sum(PP_m\, t_{1,m})$	6.4.7-1	h/d	0.45	*Weighted_Time*	0.45	Same
		Inactive outdoors	$\sum(PP_m\, t_{2,m})$			1.45		1.45	Same
		Active indoors	$\sum(PP_m\, t_{3,m})$			9.45		9.45	Same
		Asleep indoors	$\sum(PP_m\, t_{4,m})$			8.30		8.30	Same
		Away	$\sum(PP_m\, t_{5,m})$			4.35		4.35	Same
	External dose		$D_{ext,Pu\text{-}239}$	6.4.7-1	Sv/yr	6.48E–12	*Total _External*	6.48E–12	Same

Table 6.10-1. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 1, ^{239}Pu) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
Inhalation	Inhalation dose, soil particles		$D_{inh,p,Pu\text{-}239}$	6.4.8-2	Sv/yr	3.54E–07	*Total_Dust*	3.54E–07	Same
	Inhalation dose, evaporative cooler		$D_{inh,e,Pu\text{-}239}$	6.4.8-3	Sv/yr	1.72E–07	*Cooler_Inhalation*	1.72E–07	Same
	Inhalation dose		$D_{inh,Pu\text{-}239}$	6.4.8-1	Sv/yr	5.26E–07	*Total_Inhalation*	5.26E–07	Same
Ingestion	Ingestion dose for water		$D_{ing,w,Pu\text{-}239}$	6.4.9-2	Sv/yr	1.83E–07	*Water_Ingestion*	1.83E–07	Same
	Ingestion dose for crops	Leafy vegetables	$D_{ing,p,Pu\text{-}239,1}$	6.4.9-3	Sv/yr	5.17E–09	*Crop_Ingestion*	5.17E–09	Same
		Other vegetables	$D_{ing,p,Pu\text{-}239,2}$		Sv/yr	1.03E–09		1.03E–09	Same
		Fruit	$D_{ing,p,Pu\text{-}239,3}$		Sv/yr	3.29E–09		3.29E–09	Same
		Grain	$D_{ing,p,Pu\text{-}239,4}$		Sv/yr	4.16E–10		4.16E–10	Same
	Ingestion dose for animal products	Meat	$D_{ing,d,Pu\text{-}239,1}$	6.4.9-4	Sv/yr	1.82E–11	*Animal_Ingestion*	1.82E–11	Same
		Milk	$D_{ing,d,Pu\text{-}239,2}$		Sv/yr	6.95E–13		6.95E–13	Same
		Poultry	$D_{ing,d,Pu\text{-}239,3}$		Sv/yr	2.72E–12		2.72E–12	Same
		Eggs	$D_{ing,d,Pu\text{-}239,4}$		Sv/yr	4.86E–11		4.86E–11	Same
	Ingestion dose for fish		$D_{ing,f,Pu\text{-}239}$	6.4.9-5	Sv/yr	9.82E–09	*Fish_Ingestion*	9.82E–09	Same
	Ingestion dose for soil		$D_{ing,s,Pu\text{-}239}$	6.4.9-6	Sv/yr	8.76E–09	*Soil_Ingestion*	8.76E–09	Same
	Ingestion dose		$D_{ing,Pu\text{-}239}$	6.4.9-1	Sv/yr	2.12E–07	*Total_Ingestion*	2.12E–07	Same
All Pathway	All-pathway dose		$D_{all,Pu\text{-}239}$	6.4.10-1	Sv/yr	7.38E–07	*Final_TEDE*	7.38E–07	Same
	BDCF		$BDCF_{Pu\text{-}239}$	6.4.10-2	(Sv/yr)/(Bq/m^3)	7.38E–07	*Final_BDCF*	7.38E–07	Same

[a] Input data for this verification taken from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN Verification.xls*, which contains this calculation in worksheet *GWPu239*, is listed in Appendix A.

[b] The ERMYN is realized in GoldSim using the deterministic mode and data from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN_GW _Rev01_Pu239verf.gsm*, for this run is provided in Appendix A.

[c] Comparison of results from Calculated Value (Column 6) and *ERMYN_GW* Result (Column 8).

Surf. Soil = surface soil.

Table 6.10-2. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 2, ^{14}C)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		**Notation in Equation**	**Equation Number**	**Units**	**Calculated Value [a]**	**Element Name**	***ERMYN_GW* Result [b]**	
^{14}C/Soil	Leaching removal rate constant, surf. soil		$\lambda_{l,C\text{-}14}$	6.4.1-28	1/yr	1.16E–02	*Leaching_Factor*	1.16E–02	Same
	Leaching removal rate constant, critical thickness, gardens		$\lambda_{lc,C\text{-}14,1}$	6.4.1-29	1/yr	1.66E+01	*Leaching_Factor_Crit*	1.66E+01	Same
	Leaching removal rate constant, critical thickness, fields		$\lambda_{lc,C\text{-}14,5}$	6.4.1-29	1/yr	3.25E+01	*Leaching_Factor_Crit*	3.25E+01	Same
	Erosion removal rate constant, surface soil		λ_e	6.4.1-31	1/yr	5.33E–04	*Erosion_Factor*	5.33E–04	Same
	Erosion removal rate constant, critical thickness		λ_{ec}	6.4.1-32	1/yr	6.67E–02	*Erosion_Factor_Crit*	6.67E–02	Same
	Effective removal rate constant, surf. soil		$\lambda_{eff,C\text{-}14}$	6.4.1-3	1/yr	1.23E–02	*Effective_Removal*	1.23E–02	Same
	Effective removal rate constant, critical thickness, gardens		$\lambda_{eff,c,C\text{-}14,1}$	6.4.6-1 [d]	1/yr	1.67E+01	*Effective_Removal_Crit*	1.67E+01	Same
	Effective removal rate constant, critical thickness, fields		$\lambda_{eff,c,C\text{-}14,5}$	6.4.6-1 [d]	1/yr	3.25E+01	*Effective_Removal_Crit*	3.25E+01	Same
	Concentration in surface soil, gardens		$Cs_{C\text{-}14,1}$	6.4.6-1	Bq/m^2	4.13E–02	*C14Conc_InhGas*	4.13E–02	Same
	Concentration in soil mass, gardens		$Cs_{m,C\text{-}14,1}$	6.4.1-5	Bq/kg	1.10E–04	*Surf_Soil_Mass_Conc*	1.10E–04	Same
	Concentration in surface soil, fields		$Cs_{C\text{-}14,5}$	6.4.6-1	Bq/m^2	8.09E–02	*C14Conc_InhGas*	8.09E–02	Same
	Concentration in soil mass, fields		$Cs_{m,C\text{-}14,5}$	6.4.1-5	Bq/kg	2.16E–04	*Surf_Soil_Mass_Conc*	2.16E–04	Same
	Concentration in critical thickness, mass, gardens		$Cs_{mc,C\text{-}14,1}$	6.4.6-1 6.4.1-5	Bq/kg	7.84E–03	*Crit_Soil_Mass_Conc*	7.84E–03	Same
	Concentration in critical thickness, mass, fields		$Cs_{mc,C\text{-}14,5}$	6.4.6-1 6.4.1-5	Bq/kg	1.09E–02	*Crit_Soil_Mass_Conc*	1.09E–02	Same
	Concentration in crop land	Leafy vegetables	$Cs_{C\text{-}14,1}$	6.4.6-1	Bq/m^2	8.98E–02	*C14Conc_CropSoil*	8.98E–02	Same
		Other vegetables	$Cs_{C\text{-}14,2}$			1.28E–01		1.28E–01	
		Fruit	$Cs_{C\text{-}14,3}$			1.23E–01		1.23E–01	
		Grain	$Cs_{C\text{-}14,4}$			7.70E–02		7.70E–02	
		Forage	$Cs_{C\text{-}14,5}$			1.09E–01		1.09E–01	

Table 6.10-2. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 2, ^{14}C) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
^{14}C/Air	Concentration in air for inhalation, gas, active outdoors		$Ca_{g,C\text{-}14,1}$	6.4.6-3	Bq/m^3	1.74E–05	*C14Conc_Inh*	1.74E–05	Same
	Concentration in air for inhalation, gas, other environments		$Ca_{g,C\text{-}14,4}$	6.4.6-3	Bq/m^3	2.63E–07	*C14Conc_Inh*	2.63E–07	Same
	Concentration in air for inhalation (particulates)	Active outdoors	$Ca_{h,C\text{-}14,1}$	6.4.2.2	Bq/m^3	3.26E–08	*AirConc_Inh*	3.26E–08	Same
		Inactive outdoors	$Ca_{h\ C\text{-}14,2}$			1.88E–09		1.88E–09	Same
		Active indoors	$Ca_{h,C\text{-}14,3}$			3.14E–09		3.14E–09	Same
		Asleep indoors	$Ca_{h,C\text{-}14,4}$			9.41E–10		9.41E–10	Same
		Away	$Ca_{h,C\text{-}14,5}$			0.00E+00		0.00E+00	Same
	Concentration in air for crop uptake ($^{14}CO_2$)	Leafy vegetables	$Ca_{g,C\text{-}14,1}$	6.4.6-3	Bq/m^3	1.47E–06	*C14Conc_Air*	1.47E–06	Same
		Other vegetables	$Ca_{g,C\text{-}14,2}$			2.10E–06		2.10E–06	Same
		Fruit	$Ca_{g,C\text{-}14,3}$			2.02E–06		2.02E–06	Same
		Grain	$Ca_{g,C\text{-}14,4}$			4.28E–05		4.28E–05	Same
		Forage	$Ca_{g,C\text{-}14,5}$			6.05E–05		6.05E–05	Same
	Concentration in air from evaporative cooler		$Ca_{e,C\text{-}14}$	6.4.2-3	Bq/m^3	1.02E–6	*AirConc_Evap*	1.02E–06	Same
^{14}C/Plant	Concentration in crops	Leafy vegetables	$Cp_{C\text{-}14,1}$	6.4.6-6	Bq/kg	7.36E–04	*C14Conc_Crop*	7.36E–04	Same
		Other vegetables	$Cp_{C\text{-}14,2}$			1.05E–03		1.05E–03	Same
		Fruit	$Cp_{C\text{-}14,3}$			1.01E–03		1.01E–03	Same
		Grain	$Cp_{C\text{-}14,4}$			9.34E–02		9.34E–02	Same
		Forage	$Cp_{C\text{-}14,5}$			2.97E–02		2.97E–02	Same
^{14}C/ Animal	Concentration in animal product	Meat	$Cd_{C\text{-}14,1}$	6.4.6-7	Bq/kg	8.24E–02	*C14Conc_Animal*	8.24E–02	Same
		Milk	$Cd_{C\text{-}14,2}$			2.41E–02		2.41E–02	Same
		Poultry	$Cd_{C\text{-}14,3}$			4.77E–02		4.77E–02	Same
		Eggs	$Cd_{C\text{-}14,4}$			3.57E–02		3.57E–02	Same
Fish	Concentration in Fish		$Cf_{C\text{-}14}$	6.4.5-2	Bq/kg	4.6	*Fish_Conc*	4.6	Same
Inhalation	Inhalation dose, ^{14}C gas		$D_{inh,g,C\text{-}14}$	6.4.8-4	Sv/yr	3.73E–14	*Total_C14*	3.73E–14	Same
	Inhalation dose, evaporative cooler		$D_{inh,e,C\text{-}14}$	6.4.8-3	Sv/yr	8.29E–12	*Cooler_Inhalation*	8.29E–12	Same
	Inhalation dose, soil particles		$D_{inh,p,C\text{-}14}$	6.4.8-2	Sv/yr	1.28E–13	*Total_Dust*	1.28E–13	Same
	Inhalation dose		$D_{inh,C\text{-}14}$	6.4.8-1	Sv/yr	8.46E–12	*Total_Inhalation*	8.46E–12	Same

Table 6.10-2. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 2, ^{14}C) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
External	Environment-specific exposure time	Active outdoors	$\sum(PP_m\, t_{1,m})$	6.4.7-1	h/d	0.45	*Weighted_Time*	0.45	Same
		Inactive outdoors	$\sum(PP_m\, t_{2,m})$			1.45		1.45	Same
		Active indoors	$\sum(PP_m\, t_{3,m})$			9.45		9.45	Same
		Asleep indoors	$\sum(PP_m\, t_{4,m})$			8.30		8.30	Same
		Away	$\sum(PP_m\, t_{5,m})$			4.35		4.35	Same
	External dose		$D_{ext,C\text{-}14}$	6.4.7-1	Sv/yr	7.55E–17	*Total _External*	7.55E–17	Same
Ingestion	Ingestion dose for water		$D_{ing,w,C\text{-}14}$	6.4.9-2	Sv/yr	4.24E–10	*Water_Ingestion*	4.24E–10	Same
	Ingestion dose for crops	Leafy vegetables	$D_{ing,p,C\text{-}14,1}$	6.4.9-3	Sv/yr	1.62E–12	*Crop_Ingestion*	1.62E–12	Same
		Other vegetables	$D_{ing,p,C\text{-}14,2}$		Sv/yr	2.88E–12		2.88E–12	Same
		Fruit	$D_{ing,p,C\text{-}14,3}$		Sv/yr	7.43E–12		7.43E–12	Same
		Grain	$D_{ing,p,C\text{-}14,4}$		Sv/yr	1.25E–11		1.25E–11	Same
	Ingestion dose for animal products	Meat	$D_{ing,d,C\text{-}14,1}$	6.4.9-4	Sv/yr	1.36E–10	*Animal_Ingestion*	1.36E–10	Same
		Milk	$D_{ing,d,C\text{-}14,2}$		Sv/yr	6.52E–11		6.52E–11	Same
		Poultry	$D_{ing,d,C\text{-}14,3}$		Sv/yr	1.16E–11		1.16E–11	Same
		Eggs	$D_{ing,d,C\text{-}14,4}$		Sv/yr	1.10E–10		1.10E–10	Same
	Ingestion dose for fish		$D_{ing,f,C\text{-}14}$	6.4.9-5	Sv/yr	6.15E–10	*Fish_Ingestion*	6.15E–10	Same
	Ingestion dose for soil		$D_{ing,s,C\text{-}14}$	6.4.9-6	Sv/yr	1.66E–13	*Soil_Ingestion*	1.66E–13	Same
	Ingestion dose		$D_{ing,C\text{-}14}$	6.4.9-1	Sv/yr	1.39E–09	*Total_Ingestion*	1.39E–09	Same
All Pathway	All-pathway dose		$D_{all,C\text{-}14}$	6.4.10-1	Sv/yr	1.40E–09	*Final_TEDE*	1.40E–09	Same
	BDCF		$BDCF_{C\text{-}14}$	6.4.10-2	(Sv/yr)/(Bq/m^3)	1.40E–09	*Final_BDCF*	1.40E–09	Same

[a] Input data for this verification taken from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN Verification.xls,* which contains this calculation in worksheet *GWC14*, is listed in Appendix A.

[b] The ERMYN is realized in GoldSim using the deterministic mode and data from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN_GW _Rev01_C14verf.gsm*, for this run is listed in Appendix A.

[c] Comparison of results from Calculated Value (Column 6) and *ERMYN_GW* Result (Column 8).

[d] The sum of the removal rate constants given in the cited equation.

Surf. Soil = surface soil

Table 6.10-3. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 3, ^{226}Ra)

Submodel	Parameter in Mathematical Model					Parameter in GoldSim		Notes [c]
	Parameter Name	Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
Soil	Leaching removal rate constant, surface soil, ^{226}Ra	$\lambda_{l,Ra\text{-}226}$	6.4.1-28	1/yr	5.85E–06	*Leaching_Factor*	5.85E–06	Same
	Leaching removal rate constant, critical thickness, gardens, ^{226}Ra	$\lambda_{lc,Ra\text{-}226,1}$	6.4.1-29	1/yr	8.36E–03	*Leaching_Factor_Crit*	8.36E–03	Same
	Leaching removal rate constant, critical thickness, fields, ^{226}Ra	$\lambda_{lc,Ra\text{-}226,5}$	6.4.1-29	1/yr	1.64E–02	*Leaching_Factor_Crit*	1.64E–02	Same
	Erosion removal rate constant, surface soil	λ_{e}	6.4.1-31	1/yr	5.33E–04	*Erosion_Factor*	5.33E–04	Same
	Erosion removal rate constant, critical thickness	λ_{ec}	6.4.1-32	1/yr	6.67E–02	*Erosion_Factor_Crit*	6.67E–02	Same
	Effective removal rate constant, surface soil, ^{226}Ra	$\lambda_{eff,Ra\text{-}226}$	6.4.1-3	1/yr	9.72E–04	*Effective_Removal*	9.72E–04	Same
	Effective removal rate constant, critical thickness, gardens, ^{226}Ra	$\lambda_{eff,c,Ra\text{-}226,1}$	6.4.1-33	1/yr	7.55E–02	*Effective_Removal_Crit*	7.55E–02	Same
	Effective removal rate constant, critical thickness, fields, ^{226}Ra	$\lambda_{eff,c,Ra\text{-}226,5}$	6.4.1-33	1/yr	8.35E–02	*Effective_Removal_Crit*	8.35E–02	Same
	Concentration in surface soil, gardens, ^{226}Ra	$Cs_{Ra\text{-}226,1}$	6.4.1-3	Bq/m^2	8.67E+01	*Surf_Soil_Conc*	8.67E+01	Same
	Concentration in soil mass, gardens, ^{226}Ra	$Cs_{m,Ra\text{-}226,1}$	6.4.1-5	Bq/kg	2.31E–01	*Surf_Soil_Mass_Conc*	2.31E–01	Same
	Concentration in surface soil, fields, ^{226}Ra	$Cs_{Ra\text{-}226,5}$	6.4.1-3	Bq/m^2	5.90E+02	*Surf_Soil_Conc*	5.90E+02	Same
	Concentration in soil mass, fields, ^{226}Ra	$Cs_{m,Ra\text{-}226,5}$	6.4.1-5	Bq/kg	1.57E+00	*Surf_Soil_Mass_Conc*	1.57E+00	Same
	Concentration in critical thickness, mass, gardens, ^{226}Ra	$Cs_{mc,Ra\text{-}226,1}$	6.4.1-5	Bq/kg	4.02E+00	*Crit_Soil_Mass_Conc*	4.02E+00	Same
	Concentration in critical thickness, mass, fields, ^{226}Ra	$Cs_{mc,Ra\text{-}226,5}$	6.4.1-5	Bq/kg	7.11E+00	*Crit_Soil_Mass_Conc*	7.11E+00	Same
	Leaching removal rate constant, surface soil, ^{210}Pb	$\lambda_{l,Pb\text{-}210}$	6.4.1-28	1/yr	1.32E–05	*Leaching_Factor_1*	1.32E–05	Same
	Leaching removal rate constant, critical thickness, gardens, ^{210}Pb	$\lambda_{lc,Pb\text{-}210,1}$	6.4.1-29	1/yr	1.88E–02	*Leaching_Factor_Crit_1*	1.88E–02	Same
	Leaching removal rate constant, critical thickness, fields, ^{210}Pb	$\lambda_{lc,Pb\text{-}210,5}$	6.4.1-29	1/yr	3.68E–02	*Leaching_Factor_Crit_1*	3.68E–02	Same

Table 6.10-3. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 3, ^{226}Ra) (Continued)

	Parameter in Mathematical Model					Parameter in GoldSim		
Submodel	**Parameter Name**	**Notation in Equation**	**Equation Number**	**Units**	**Calculated Value [a]**	**Element Name**	***ERMYN_GW* Result [b]**	**Notes [c]**
Soil (Continued)	Effective removal rate constant, surface soil, ^{210}Pb	$\lambda_{eff,Pb\text{-}210}$	6.4.1-3	1/yr	3.16E–02	*Effective_Removal_1*	3.16E–02	Same
	Effective removal rate constant, critical thickness, gardens, ^{210}Pb	$\lambda_{eff,c,Pb\text{-}210,1}$	6.4.1-33	1/yr	1.17E–01	*Effective_Removal_Crit_1*	1.17E–01	Same
	Effective removal rate constant, critical thickness, fields, ^{210}Pb	$\lambda_{eff,c,Pb\text{-}210,5}$	6.4.1-33	1/yr	1.35E–01	*Effective_Removal_Crit_1*	1.35E–01	Same
	Concentration in surface soil, gardens, ^{210}Pb	$Cs_{Pb\text{-}210,1}$	6.4.1-26	Bq/m^2	6.00E+01	*Surf_Soil_Conc_1*	6.00E+01	Same
	Concentration in soil mass, gardens, ^{210}Pb	$Cs_{m,Pb\text{-}210,1}$	6.4.1-5	Bq/kg	1.60E–01	*Surf_Soil_Mass_Conc_1*	1.60E–01	Same
	Concentration in surface soil, fields, ^{210}Pb	$Cs_{Pb\text{-}210,5}$	6.4.1-26	Bq/m^2	5.41E+02	*Surf_Soil_Conc_1*	5.41E+02	Same
	Concentration in soil mass, fields, ^{210}Pb	$Cs_{m,Pb\text{-}210,5}$	6.4.1-5	Bq/kg	1.44E+00	*Surf_Soil_Mass_Conc_1*	1.44E+00	Same
	Concentration in critical thickness, mass, gardens, ^{210}Pb	$Cs_{mc,Pb\text{-}210,1}$	6.4.1-5	Bq/kg	1.07E+00	*Crit_Soil_Mass_Conc_1*	1.07E+00	Same
	Concentration in critical thickness, mass, fields, ^{210}Pb	$Cs_{mc,Pb\text{-}210,5}$	6.4.1-5	Bq/kg	1.64E+00	*Crit_Soil_Mass_Conc_1*	1.64E+00	Same
Air	Concentration in air, garden crops, ^{226}Ra	$Ca_{p,Ra\text{-}226,1}$	6.4.2-1	Bq/m^3	4.82E–07	*AirConc_Crop*	4.82E–07	Same
	Concentration in air, garden crops, ^{226}Ra	$Ca_{p,Ra\text{-}226,5}$			8.53E–07		8.53E–07	Same
	Concentration in air for inhalation of ^{226}Ra: Active outdoors	$Ca_{h,Ra\text{-}226,1}$	6.4.2-2	Bq/m^3	2.13E–05	*AirConc_Inh*	2.13E–05	Same
	Inactive outdoors	$Ca_{h,Ra\text{-}226,2}$			9.65E–07		9.65E–07	Same
	Active indoors	$Ca_{h,Ra\text{-}226,3}$			1.61E–06		1.61E–06	Same
	Asleep indoors	$Ca_{h,Ra\text{-}226,4}$			4.82E–07		4.82E–07	Same
	Away	$Ca_{h,Ra\text{-}226,5}$			0.00E+00		0.00E+00	Same
	Concentration in air from evaporative cooler, ^{226}Ra	$Ca_{e,Ra\text{-}226}$	6.4.2-3	Bq/m^3	1.02E–06	*AirConc_Evap*	1.02E–06	Same
	Radon concentration in outdoor air, gardens (environments other than active outdoors)	$Ca_{g,Rn\text{-}222,2}$	6.4.2-4	Bq/m^3	5.78E–02	*AirConc_Radon*	5.78E–02	
	Radon concentration in outdoor air, field (active outdoors)	$Ca_{g,Rn\text{-}222,1}$	6.4.2-4	Bq/m^3	3.93E–01	*AirConc_Radon*	3.93E–01	Same
	Radon indoor factor for normal condition	$IF_{n,Rn\text{-}222}$	6.4.2-7	-	1.913	*Indoor_RnNormal*	1.913	Same

Table 6.10-3. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 3, ^{226}Ra) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
Air (Continued)	Indoor radon increase factor for evaporative cooler operation		$IF_{e,Rn\text{-}222}$	6.4.2-8	-	1.059	*Indoor_RnEvap*	1.059	Same
	Concentration in air, garden crops, ^{210}Pb		$Ca_{p,Pb\text{-}210,1}$	6.4.2-1	Bq/m^3	1.29E–07	*AirConc_Crop_1*	1.29E–07	Same
	Concentration in air, garden crops, ^{210}Pb		$Ca_{p,Pb\text{-}210,5}$			1.97E–07		1.97E–07	Same
	Concentration in air for inhalation of ^{210}Pb	Active outdoors	$Ca_{h,Pb\text{-}210,1}$	6.4.2-2	Bq/m^3	4.93E–06	*AirConc_Inh_1*	4.93E–06	Same
		Inactive outdoors	$Ca_{h,Pb\text{-}210,2}$			2.57E–07		2.57E–07	Same
		Active indoors	$Ca_{h,Pb\text{-}210,3}$			4.29E–07		4.29E–07	Same
		Asleep indoors	$Ca_{h,Pb\text{-}210,4}$			1.29E–07		1.29E–07	Same
		Away	$Ca_{h,Pb\text{-}210,5}$			0.00E+00		0.00E+00	Same
Plant	Concentration due to root uptake, ^{226}Ra	Leafy vegetables	$Cp_{root,Ra\text{-}226,1}$	6.4.3-2	Bq/kg	1.10E–03	*Root_Uptake*	1.10E–03	Same
		Other vegetables	$Cp_{root,Ra\text{-}226,2}$			2.86E–04		2.86E–04	Same
		Fruit	$Cp_{root,Ra\text{-}226,3}$			2.03E–04		2.03E–04	Same
		Grain	$Cp_{root,Ra\text{-}226,4}$			4.40E–03		4.40E–03	Same
		Forage	$Cp_{root,Ra\text{-}226,5}$			2.84E–02		2.84E–02	Same
	Irrigation interception fraction	Leafy vegetables	Rw_1	6.4.3-5	-	0.216	*Intercept_Factor*	0.216	Same
		Other vegetables	Rw_2			0.301		0.301	Same
		Fruit	Rw_3			0.360		0.360	Same
		Grain	Rw_4			0.470		0.470	Same
		Forage	Rw_5			0.258		0.258	Same
	Concentration due to water interception, ^{226}Ra	Leafy vegetables	$Cp_{water,Ra\text{-}226,1}$	6.4.3-3	Bq/kg	5.23E–03	*Water_Uptake*	5.23E–03	Same
		Other vegetables	$Cp_{water,Ra\text{-}226,2}$			8.35E–04		8.35E–04	Same
		Fruit	$Cp_{water,Ra\text{-}226,3}$			9.78E–04		9.78E–04	Same
		Grain	$Cp_{water,Ra\text{-}226,4}$			6.72E–03		6.72E–03	Same
		Forage	$Cp_{water,Ra\text{-}226,5}$			1.40E–02		1.40E–02	Same
	Dust interception fraction	Leafy vegetables	Ra_1	6.4.3-8	-	0.456	*Dust_Intercept*	0.456	Same
		Other vegetables	Ra_2			0.787		0.787	Same
		Fruit	Ra_3			0.893		0.893	Same
		Grain	Ra_4			0.962		0.962	Same
		Forage	Ra_5			0.751		0.751	Same

Table 6.10-3. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 3, ^{226}Ra) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	Notes [c]
Plant (Continued)	Concentration due to dust interception, ^{226}Ra	Leafy vegetables	$Cp_{dust,Ra\text{-}226,1}$	6.4.3-6	Bq/kg	9.08E–04	*Dust_Uptake*	9.08E–04	Same
		Other vegetables	$Cp_{dust,Ra\text{-}226,2}$			1.26E–04		1.26E–04	Same
		Fruit	$Cp_{dust,Ra\text{-}226,3}$			2.19E–04		2.19E–04	Same
		Grain	$Cp_{dust,Ra\text{-}226,4}$			1.94E–03		1.94E–03	Same
		Forage	$Cp_{dust,Ra\text{-}226,5}$			4.08E–03		4.08E–03	Same
	Concentration in crops, ^{226}Ra	Leafy vegetables	$Cp_{Ra\text{-}226,1}$	6.4.3-1	Bq/kg	7.24E–03	*Plant_Conc*	7.24E–03	Same
		Other vegetables	$Cp_{Ra\text{-}226,2}$			1.25E–03		1.25E–03	Same
		Fruit	$Cp_{Ra\text{-}226,3}$			1.40E–03		1.40E–03	Same
		Grain	$Cp_{Ra\text{-}226,4}$			1.31E–02		1.31E–02	Same
		Forage	$Cp_{Ra\text{-}226,5}$			4.65E–02		4.65E–02	Same
	Concentration due to root uptake, ^{210}Pb	Leafy vegetables	$Cp_{root,Pb\text{-}210,1}$	6.4.3-2	Bq/kg	1.68E–04	*Root_Uptake_1*	1.68E–04	Same
		Other vegetables	$Cp_{root,Pb\text{-}210,2}$			1.48E–04		1.48E–04	Same
		Fruit	$Cp_{root,Pb\text{-}210,3}$			2.30E–04		2.30E–04	Same
		Grain	$Cp_{root,Pb\text{-}210,4}$			7.17E–03		7.17E–03	Same
		Forage	$Cp_{root,Pb\text{-}210,5}$			5.71E–03		5.71E–03	Same
	Concentration due to dust interception, ^{210}Pb	Leafy vegetables	$Cp_{dust,Pb\text{-}210,1}$	6.4.3-6	Bq/kg	2.42E–04	*Dust_Uptake_1*	2.42E–04	Same
		Other vegetables	$Cp_{dust,Pb\text{-}210,2}$			3.36E–05		3.36E–05	Same
		Fruit	$Cp_{dust,Pb\text{-}210,3}$			5.83E–05		5.83E–05	Same
		Grain	$Cp_{dust,Pb\text{-}210,4}$			4.49E–04		4.49E–04	Same
		Forage	$Cp_{dust,Pb\text{-}210,5}$			9.43E–04		9.43E–04	Same
	Concentration in crops, ^{210}Pb	Leafy vegetables	$Cp_{Pb\text{-}210,1}$	6.4.3-1	Bq/kg	4.10E–04	*Plant_Conc_1*	4.10E–04	Same
		Other vegetables	$Cp_{Pb\text{-}210,2}$			1.82E–04		1.82E–04	Same
		Fruit	$Cp_{Pb\text{-}210,3}$			2.89E–04		2.89E–04	Same
		Grain	$Cp_{Pb\text{-}210,4}$			7.61E–03		7.61E–03	Same
		Forage	$Cp_{Pb\text{-}210,5}$			6.66E–03		6.66E–03	Same

Table 6.10-3. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 3, ^{226}Ra) (Continued)

	Parameter in Mathematical Model						Parameter in GoldSim		
Submodel	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	Notes [c]
Animal	Concentration due to feed, ^{226}Ra	Meat	$Cd_{feed,Ra\text{-}226,1}$	6.4.4-2	Bq/kg	1.82E–03	*Feed_Contribution*	1.82E–03	Same
		Milk	$Cd_{feed,Ra\text{-}226,2}$			1.66E–03		1.66E–03	Same
		Poultry	$Cd_{feed,Ra\text{-}226,3}$			5.77E–05		5.77E–05	Same
		Eggs	$Cd_{feed,Ra\text{-}226,4}$			1.32E–06		1.32E–06	Same
	Concentration due to water, ^{226}Ra	Meat	$Cd_{water,Ra\text{-}226,1}$	6.4.4-3	Bq/kg	4.86E–05	*Water_Contribution*	4.86E–05	Same
		Milk	$Cd_{water,Ra\text{-}226,2}$			4.64E–05		4.64E–05	Same
		Poultry	$Cd_{water,Ra\text{-}226,3}$			8.50E–06		8.50E–06	Same
		Eggs	$Cd_{water,Ra\text{-}226,4}$			1.95E–07		1.95E–07	Same
	Concentration due to soil, ^{226}Ra	Meat	$Cd_{soil,Ra\text{-}226,1}$	6.4.4-4	Bq/kg	4.03E–03	*Soil_Contribution*	4.03E–03	Same
		Milk	$Cd_{soil,Ra\text{-}226,2}$			3.92E–03		3.92E–03	Same
		Poultry	$Cd_{soil,Ra\text{-}226,3}$			1.37E–03		1.37E–03	Same
		Eggs	$Cd_{soil,Ra\text{-}226,4}$			3.14E–05		3.14E–05	Same
	Concentration in animal products, ^{226}Ra	Meat	$Cd_{Ra\text{-}226,1}$	6.4.4-1	Bq/kg	5.90E–03	*Animal_Conc*	5.90E–03	Same
		Milk	$Cd_{Ra\text{-}226,2}$			5.62E–03		5.62E–03	Same
		Poultry	$Cd_{Ra\text{-}226,3}$			1.43E–03		1.43E–03	Same
		Eggs	$Cd_{Ra\text{-}226,4}$			3.29E–05		3.29E–05	Same
	Concentration due to feed, ^{210}Pb	Meat	$Cd_{feed,Pb\text{-}210,1}$	6.4.4-2	Bq/kg	2.03E–04	*Feed_ Contribution_1*	2.03E–04	Same
		Milk	$Cd_{feed,Pb\text{-}210,2}$			6.96E–05		6.96E–05	Same
		Poultry	$Cd_{feed,Pb\text{-}210,3}$			4.95E–05		4.95E–05	Same
		Eggs	$Cd_{feed,Pb\text{-}210,4}$			1.11E–04		1.11E–04	Same
	Concentration due to soil, ^{210}Pb	Meat	$Cd_{soil,Pb\text{-}210,1}$	6.4.4-4	Bq/kg	7.24E–04	*Soil_Contribution_1*	7.24E–04	Same
		Milk	$Cd_{soil,Pb\text{-}210,2}$			2.65E–04		2.65E–04	Same
		Poultry	$Cd_{soil,Pb\text{-}210,3}$			5.36E–04		5.36E–04	Same
		Eggs	$Cd_{soil,Pb\text{-}210,4}$			1.20E–03		1.20E–03	Same
	Concentration in animal products, ^{210}Pb	Meat	$Cd_{Pb\text{-}210,1}$	6.4.4-1	Bq/kg	9.28E–04	*Animal_Conc_1*	9.28E–04	Same
		Milk	$Cd_{Pb\text{-}210,2}$			3.35E–04		3.35E–04	Same
		Poultry	$Cd_{Pb\text{-}210,3}$			5.85E–04		5.85E–04	Same
		Eggs	$Cd_{Pb\text{-}210,4}$			1.31E–03		1.31E–03	Same
Fish	Concentration in Fish		$Cf_{Ra\text{-}226}$	6.4.5-2	Bq/kg	0.278	*Fish_Conc*	0.278	Same

Table 6.10-3. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 3, ^{226}Ra) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
External	Environment-specific exposure time	Active outdoors	$\sum(PP_m\ t_{1,m})$	6.4.7-1	h/d	0.45	*Weighted_Time*	0.45	Same
		Inactive outdoors	$\sum(PP_m\ t_{2,m})$			1.45		1.45	Same
		Active indoors	$\sum(PP_m\ t_{3,m})$			9.45		9.45	Same
		Asleep indoors	$\sum(PP_m\ t_{4,m})$			8.30		8.30	Same
		Away	$\sum(PP_m\ t_{5,m})$			4.35		4.35	Same
	External dose, ^{226}Ra		-	6.4.7-1	Sv/yr	3.01E–07	*External_Dose*	3.01E–07	Same
	External dose, ^{210}Pb		-	6.4.7-1	Sv/yr	1.60E–10	*External_Dose_1*	1.60E–10	Same
	Total external dose		$D_{ext,Ra\text{-}226}$	6.4.7-1	Sv/yr	3.01E–07	*Total _External*	3.01E–07	Same
Inhalation	Inhalation dose, soil particles, ^{226}Ra		$D_{inh,p,Ra\text{-}226}$	6.4.8-2	Sv/yr	1.21E–07	*Inhalation_Dose*	1.21E–07	Same
	Inhalation dose, evaporative cooler, ^{226}Ra		$D_{inh,e,Ra\text{-}226}$	6.4.8-3	Sv/yr	1.38E–08	*Cooler_Inhalation*	1.38E–08	Same
	Inhalation dose, radon		$D_{inh,g,Rn\text{-}222}$	6.4.8-7	Sv/yr	1.79E–06	*Total_Radon*	1.79E–06	Same
	Inhalation dose, soil particles, ^{210}Pb		-	6.4.8-2	Sv/yr	3.18E–08	*Inhalation_Dose_1*	3.18E–08	Same
	Total Inhalation dose		$D_{inh,Ra\text{-}226}$	6.4.8-1	Sv/yr	1.96E–06	*Total_Inhalation*	1.96E–06	Same
Ingestion	Ingestion dose for water, ^{226}Ra		$D_{ing,w,Ra\text{-}226}$	6.4.9-2	Sv/yr	2.05E–07	*Water_Ingestion*	2.05E–07	Same
	Ingestion dose for crops, ^{226}Ra	Leafy vegetables	$D_{ing,p,Ra\text{-}226,1}$	6.4.9-3	Sv/yr	7.67E–09	*Crop_Ingestion*	7.67E–09	Same
		Other vegetables	$D_{ing,p,Ra\text{-}226,2}$			1.65E–09		1.65E–09	Same
		Fruit	$D_{ing,p,Ra\text{-}226,3}$			4.97E–09		4.97E–09	Same
		Grain	$D_{ing,p,Ra\text{-}226,4}$			8.42E–10		8.42E–10	Same
	Ingestion dose for animal products, ^{226}Ra	Meat	$D_{ing,d,Ra\text{-}226,1}$	6.4.9-4	Sv/yr	4.72E–09	*Animal_Ingestion*	4.72E–09	Same
		Milk	$D_{ing,d,Ra\text{-}226,2}$			7.34E–09		7.34E–09	Same
		Poultry	$D_{ing,d,Ra\text{-}226,3}$			1.69E–10		1.69E–10	Same
		Eggs	$D_{ing,d,Ra\text{-}226,4}$			4.88E–11		4.88E–11	Same
	Ingestion dose for fish, ^{226}Ra		$D_{ing,f,Ra\text{-}226}$	6.4.9-5	Sv/yr	1.79E–08	*Fish_Ingestion*	1.79E–08	Same
	Ingestion dose for soil, ^{226}Ra		$D_{ing,s,Ra\text{-}226}$	6.4.9-6	Sv/yr	4.11E–08	*Soil_Ingestion*	4.11E–08	Same
	Ingestion dose, ^{226}Ra		-	6.4.9-1	Sv/yr	2.91E–07	*Ingestion_Dose*	2.91E–07	Same
	Ingestion dose for crops, ^{210}Pb	Leafy vegetables	$D_{ing,p,Pb\text{-}210,1}$	6.4.9-3	Sv/yr	2.96E–09	*Crop_Ingestion_1*	2.96E–09	Same
		Other vegetables	$D_{ing,p,Pb\text{-}210,2}$			1.64E–09		1.64E–09	Same
		Fruit	$D_{ing,p,Pb\text{-}210,3}$			6.98E–09		6.98E–09	Same
		Grain	$D_{ing,p,Pb\text{-}210,4}$			3.34E–09		3.34E–09	Same

Table 6.10-3. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 3, ^{226}Ra) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
Ingestion (cont.)	Ingestion dose for animal products, ^{210}Pb	Meat	$D_{ing,d,Pb\text{-}210,1}$	6.4.9-4	Sv/yr	5.04E–09	*Animal_Ingestion_1*	5.04E–09	Same
		Milk	$D_{ing,d,Pb\text{-}210,2}$			2.98E–09		2.98E–09	Same
		Poultry	$D_{ing,d,Pb\text{-}210,3}$			4.69E–10		4.69E–10	Same
		Eggs	$D_{ing,d,Pb\text{-}210,4}$			1.33E–08		1.33E–08	Same
	Ingestion dose for soil, ^{210}Pb		$D_{ing,s,Pb\text{-}210}$	6.4.9-6	Sv/yr	7.47E–08	*Soil_Ingestion_1*	7.47E–08	Same
	Ingestion dose, ^{210}Pb		-	6.4.9-1	Sv/yr	1.11E–07	*Ingestion_Dose_1*	1.11E–07	Same
	Total ingestion dose		$D_{ing,Ra\text{-}226}$	6.4.9-1	Sv/yr	4.03E–07	*Total_Ingestion*	4.03E–07	Same
All Pathway	All-pathway dose		$D_{all,Ra\text{-}226}$	6.4.10-1	Sv/yr	2.66E–06	*Final_TEDE*	2.66E–06	Same
	BDCF		$BDCF_{Ra\text{-}226}$	6.4.10-2	(Sv/yr)/(Bq/m^3)	2.66E–06	*Final_BDCF*	2.66E–06	Same

[a] Input data for this verification taken from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN Verification.xls,* which contains this calculation in worksheet *GWRa226*, is listed in Appendix A.

[b] The ERMYN is realized in GoldSim using the deterministic mode and data from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN_GW _Rev01_Ra226verf.gsm*, for this run is listed in Appendix A.

[c] Comparison of results from Calculated Value (Column 6) and *ERMYN_GW* Result (Column 8).

Table 6.10-4. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 4, ^{232}Th)

Submodel	Parameter in Mathematical Model					Parameter in GoldSim		Notes [c]
	Parameter Name	**Notation in Equation**	**Equation Number**	**Units**	**Calculated Value [a]**	**Element Name**	***ERMYN_GW* Result [b]**	
Soil	Leaching removal rate constant, surface soil, ^{232}Th	$\lambda_{l,Th\text{-}232}$	6.4.1-28	1/yr	7.02E–05	*Leaching_Factor*	7.02E–05	Same
	Leaching removal rate constant, critical thickness, gardens, ^{232}Th	$\lambda_{lc,Th\text{-}232,1}$	6.4.1-29	1/yr	1.00E–01	*Leaching_Factor_Crit*	1.00E–01	Same
	Leaching removal rate constant, critical thickness, fields, ^{232}Th	$\lambda_{lc,Th\text{-}232,5}$	6.4.1-29	1/yr	1.96E–01	*Leaching_Factor_Crit*	1.96E–01	Same
	Erosion removal rate constant, surface soil	λ_e	6.4.1-31	1/yr	5.33E–04	*Erosion_Factor*	5.33E–04	Same
	Erosion removal rate constant, critical thickness	λ_{ec}	6.4.1-32	1/yr	6.67E–02	*Erosion_Factor_Crit*	6.67E–02	Same
	Effective removal rate constant, surface soil, ^{232}Th	$\lambda_{eff,Th\text{-}232}$	6.4.1-3	1/yr	6.04E–04	*Effective_Removal*	6.04E–04	Same
	Effective removal rate constant, critical thickness, gardens, ^{232}Th	$\lambda_{eff,c,Th\text{-}232,1}$	6.4.1-33	1/yr	1.67E–01	*Effective_Removal_Crit*	1.67E–01	Same
	Effective removal rate constant, critical thickness, fields, ^{232}Th	$\lambda_{eff,c,Th\text{-}232,5}$	6.4.1-33	1/yr	2.63E–01	*Effective_Removal_Crit*	2.63E–01	Same
	Concentration in surface soil, gardens, ^{232}Th	$Cs_{Th\text{-}232,1}$	6.4.1-3	Bq/m^2	8.83E+01	*Surf_Soil_Conc*	8.83E+01	Same
	Concentration in soil mass, gardens, ^{232}Th	$Cs_{m,Th\text{-}232,1}$	6.4.1-5	Bq/kg	2.35E–01	*Surf_Soil_Mass_Conc*	2.35E–01	Same
	Concentration in surface soil, fields, ^{232}Th	$Cs_{Th\text{-}232,5}$	6.4.1-3	Bq/m^2	6.33E+02	*Surf_Soil_Conc*	6.33E+02	Same
	Concentration in soil mass, fields, ^{232}Th	$Cs_{m,Th\text{-}232,5}$	6.4.1-5	Bq/kg	1.69E+00	*Surf_Soil_Mass_Conc*	1.69E+00	Same
	Concentration in critical thickness, mass, gardens, ^{232}Th	$Cs_{mc,Th\text{-}232,1}$	6.4.1-5	Bq/kg	1.82E+00	*Crit_Soil_Mass_Conc*	1.82E+00	Same
	Concentration in critical thickness, mass, fields, ^{232}Th	$Cs_{mc,Th\text{-}232,5}$	6.4.1-5	Bq/kg	2.26E+00	*Crit_Soil_Mass_Conc*	2.26E+00	Same
	Leaching removal rate constant, surface soil, ^{228}Ra	$\lambda_{l,Ra\text{-}228}$	6.4.1-28	1/yr	5.85E–06	*Leaching_Factor_1*	5.85E–06	Same
	Leaching removal rate constant, critical thickness, gardens, ^{228}Ra	$\lambda_{lc,Ra\text{-}228,1}$	6.4.1-29	1/yr	8.36E–03	*Leaching_Factor_Crit_1*	8.36E–03	Same
	Leaching removal rate constant, critical thickness, fields, ^{228}Ra	$\lambda_{lc,Ra\text{-}228,5}$	6.4.1-29	1/yr	1.64E–02	*Leaching_Factor_Crit_1*	1.64E–02	Same

Table 6.10-4. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 4, ^{232}Th) (Continued)

Submodel	Parameter in Mathematical Model					Parameter in GoldSim		Notes [c]
	Parameter Name	Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
Soil (Continued)	Effective removal rate constant, surface soil, ^{228}Ra	$\lambda_{eff,Ra\text{-}228}$	6.4.1-3	1/yr	1.21E–01	*Effective_Removal_1*	1.21E–01	Same
	Effective removal rate constant, critical thickness, gardens, ^{228}Ra	$\lambda_{eff,c,Ra\text{-}228,1}$	6.4.1-33	1/yr	1.96E–01	*Effective_Removal_Crit_1*	1.96E–01	Same
	Effective removal rate constant, critical thickness, fields, ^{228}Ra	$\lambda_{eff,c,Ra\text{-}228,5}$	6.4.1-33	1/yr	2.04E–01	*Effective_Removal_Crit_1*	2.04E–01	Same
	Concentration in surface soil, gardens, ^{228}Ra	$Cs_{Ra\text{-}228,1}$	6.4.1-26	Bq/m^2	8.08E+01	*Surf_Soil_Conc_1*	8.08E+01	Same
	Concentration in soil mass, gardens, ^{228}Ra	$Cs_{m,Ra\text{-}228,1}$	6.4.1-5	Bq/kg	2.16E–01	*Surf_Soil_Mass_Conc_1*	2.16E–01	Same
	Concentration in surface soil, fields, ^{228}Ra	$Cs_{Ra\text{-}228,5}$	6.4.1-26	Bq/m^2	6.18E+02	*Surf_Soil_Conc_1*	6.18E+02	Same
	Concentration in soil mass, fields, ^{228}Ra	$Cs_{m,Ra\text{-}228,5}$	6.4.1-5	Bq/kg	1.65E+00	*Surf_Soil_Mass_Conc_1*	1.65E+00	Same
	Concentration in critical thickness, mass, gardens, ^{228}Ra	$Cs_{mc,Ra\text{-}228,1}$	6.4.1-5	Bq/kg	1.12E+00	*Crit_Soil_Mass_Conc_1*	1.12E+00	Same
	Concentration in critical thickness, mass, fields, ^{228}Ra	$Cs_{mc,Ra\text{-}228,5}$	6.4.1-5	Bq/kg	1.34E+00	*Crit_Soil_Mass_Conc_1*	1.34E+00	Same
	Leaching removal rate constant, surface soil, ^{228}Th	$\lambda_{l,Th\text{-}228}$	6.4.1-28	1/yr	7.02E–05	*Leaching_Factor_2*	7.02E–05	Same
	Leaching removal rate constant, critical thickness, gardens, ^{228}Th	$\lambda_{lc,Th\text{-}228,1}$	6.4.1-29	1/yr	1.00E–01	*Leaching_Factor_Crit_2*	1.00E–01	Same
	Leaching removal rate constant, critical thickness, fields, ^{228}Th	$\lambda_{lc,Th\text{-}228,5}$	6.4.1-29	1/yr	1.96E–01	*Leaching_Factor_Crit_2*	1.96E–01	Same
	Effective removal rate constant, surface soil, ^{228}Th	$\lambda_{eff,Th\text{-}228}$	6.4.1-3	1/yr	3.63E–01	*Effective_Removal_2*	3.63E–01	Same
	Effective removal rate constant, critical thickness, gardens, ^{228}Th	$\lambda_{eff,c,Th\text{-}228,1}$	6.4.1-33	1/yr	5.29E–01	*Effective_Removal_Crit_2*	5.29E–01	Same
	Effective removal rate constant, critical thickness, fields, ^{228}Th	$\lambda_{eff,c,Th\text{-}228,5}$	6.4.1-33	1/yr	6.25E–01	*Effective_Removal_Crit_2*	6.25E–01	Same
	Concentration in surf. soil, gardens, ^{228}Th	$Cs_{Th\text{-}228,1}$	6.4.1-27	Bq/m^2	7.83E+01	*Surf_Soil_Conc_2*	7.83E+01	Same
	Concentration in soil mass, gardens, ^{228}Th	$Cs_{m,Th\text{-}228,1}$	6.4.1-5	Bq/kg	2.09E–01	*Surf_Soil_Mass_Conc_2*	2.09E–01	Same

Table 6.10-4. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 4, ^{232}Th) (Continued)

	Parameter in Mathematical Model						Parameter in GoldSim		
Submodel	**Parameter Name**		**Notation in Equation**	**Equation Number**	**Units**	**Calculated Value [a]**	**Element Name**	***ERMYN_GW* Result [b]**	**Notes [c]**
Soil (Continued)	Concentration in surface soil, fields, ^{228}Th		$Cs_{Th\text{-}228,5}$	6.4.1-27	Bq/m^2	6.13E+02	*Surf_Soil_Conc_2*	6.13E+02	Same
	Concentration in soil mass, fields, ^{228}Th		$Cs_{m,Th\text{-}228,5}$	6.4.1-5	Bq/kg	1.64E+00	*Surf_Soil_Mass_ Conc_2*	1.64E+00	Same
	Concentration in critical thickness, mass, gardens, ^{228}Th		$Cs_{mc,Th\text{-}228,1}$	6.4.1-5	Bq/kg	7.66E–01	*Crit_Soil_Mass_ Conc_2*	7.66E–01	Same
	Concentration in critical thickness, mass, fields, ^{228}Th		$Cs_{mc,Th\text{-}228,5}$	6.4.1-5	Bq/kg	7.74E–01	*Crit_Soil_Mass_ Conc_2*	7.74E–01	Same
Air	Concentration in air, garden crops, ^{232}Th		$Ca_{p,Th\text{-}232,1}$	6.4.2-1	Bq/m^3	2.18E–07	*AirConc_Crop*	2.18E–07	Same
	Concentration in air, field crops, ^{232}Th		$Ca_{p,Th\text{-}232,5}$			2.71E–07		2.71E–07	Same
	Concentration in air for inhalation of ^{232}Th	Active outdoors	$Ca_{h,Th\text{-}232,1}$	6.4.2-2	Bq/m^3	6.77E–06	*AirConc_Inh*	6.77E–06	Same
		Inactive outdoors	$Ca_{h,Th\text{-}232,2}$			4.36E–07		4.36E–07	Same
		Active indoors	$Ca_{h,Th\text{-}232,3}$			7.26E–07		7.26E–07	Same
		Asleep indoors	$Ca_{h,Th\text{-}232,4}$			2.18E–07		2.18E–07	Same
		Away	$Ca_{h,Th\text{-}232,5}$			0.00E+00		0.00E+00	Same
	Concentration in air from evaporative cooler, ^{232}Th		$Ca_{e,Th\text{-}232}$	6.4.2-3	Bq/m^3	1.02E–06	*AirConc_Evap*	1.02E–06	Same
	Concentration in air, garden crops, ^{228}Ra		$Ca_{p,Ra\text{-}228,1}$	6.4.2-1	Bq/m^3	1.34E–07	*AirConc_Crop_1*	1.34E–07	Same
	Concentration in air, field crops, ^{228}Ra		$Ca_{p,Ra\text{-}228,5}$			1.98E–07		1.98E–07	Same
	Concentration in air for inhalation of ^{228}Ra	Active outdoors	$Ca_{h,Ra\text{-}228,1}$	6.4.2-2	Bq/m^3	4.95E–06	*AirConc_Inh_1*	4.95E–06	Same
		Inactive outdoors	$Ca_{h,Ra\text{-}228,2}$			2.69E–07		2.69E–07	Same
		Active indoors	$Ca_{h,Ra\text{-}228,3}$			4.48E–07		4.48E–07	Same
		Asleep indoors	$Ca_{h,Ra\text{-}228,4}$			1.34E–07		1.34E–07	Same
		Away	$Ca_{h,Ra\text{-}228,5}$			0.00E+00		0.00E+00	Same
	Concentration in air, garden crops, ^{228}Th		$Ca_{p,Th\text{-}228,1}$	6.4.2-1	Bq/m^3	9.19E–08	*AirConc_Crop_2*	9.19E–08	Same
	Concentration in air, field crops, ^{228}Th		$Ca_{p,Th\text{-}228,5}$			1.96E–07		1.96E–07	Same
	Concentration in air for inhalation of ^{228}Th	Active outdoors	$Ca_{h,Th\text{-}228,1}$	6.4.2-2	Bq/m^3	4.91E–06	*AirConc_Inh_2*	4.91E–06	Same
		Inactive outdoors	$Ca_{h,Th\text{-}228,2}$			1.84E–07		1.84E–07	Same
		Active indoors	$Ca_{h,Th\text{-}228,3}$			3.06E–07		3.06E–07	Same
		Asleep indoors	$Ca_{h,Th\text{-}228,4}$			9.19E–08		9.19E–08	Same
		Away	$Ca_{h,Th\text{-}228,5}$			0.00E+00		0.00E+00	Same

Table 6.10-4. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 4, ^{232}Th) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
Plant	Concentration due to root uptake, ^{232}Th	Leafy vegetables	$Cp_{root,Th\text{-}232,1}$	6.4.3-2	Bq/kg	7.09E–05	*Root_Uptake*	7.09E–05	Same
		Other vegetables	$Cp_{root,Th\text{-}232,2}$			1.07E–05		1.07E–05	Same
		Fruit	$Cp_{root,Th\text{-}232,3}$			8.20E–06		8.20E–06	Same
		Grain	$Cp_{root,Th\text{-}232,4}$			2.59E–04		2.59E–04	Same
		Forage	$Cp_{root,Th\text{-}232,5}$			3.71E–03		3.71E–03	Same
	Irrigation interception fraction	Leafy vegetables	Rw_1	6.4.3-5	-	0.216	*Intercept_Factor*	0.216	Same
		Other vegetables	Rw_2			0.301		0.301	Same
		Fruit	Rw_3			0.360		0.360	Same
		Grain	Rw_4			0.470		0.470	Same
		Forage	Rw_5			0.258		0.258	Same
	Concentration due to water interception, ^{232}Th	Leafy vegetables	$Cp_{water,Th\text{-}232,1}$	6.4.3-3	Bq/kg	5.23E–03	*Water_Uptake*	5.23E–03	Same
		Other vegetables	$Cp_{water,Th\text{-}232,2}$			8.35E–04		8.35E–04	Same
		Fruit	$Cp_{water,Th\text{-}232,3}$			9.78E–04		9.78E–04	Same
		Grain	$Cp_{water,Th\text{-}232,4}$			6.72E–03		6.72E–03	Same
		Forage	$Cp_{water,Th\text{-}232,5}$			1.40E–02		1.40E–02	Same
	Dust interception fraction	Leafy vegetables	Ra_1	6.4.3-8	-	0.456	*Dust_Intercept*	0.456	Same
		Other vegetables	Ra_2			0.787		0.787	Same
		Fruit	Ra_3			0.893		0.893	Same
		Grain	Ra_4			0.962		0.962	Same
		Forage	Ra_5			0.751		0.751	Same
	Concentration due to dust interception, ^{232}Th	Leafy vegetables	$Cp_{dust,Th\text{-}232,1}$	6.4.3-6	Bq/kg	4.10E–04	*Dust_Uptake*	4.10E–04	Same
		Other vegetables	$Cp_{dust,Th\text{-}232,2}$			5.69E–05		5.69E–05	Same
		Fruit	$Cp_{dust,Th\text{-}232,3}$			9.87E–05		9.87E–05	Same
		Grain	$Cp_{dust,Th\text{-}232,4}$			6.17E–04		6.17E–04	Same
		Forage	$Cp_{dust,Th\text{-}232,5}$			1.30E–03		1.30E–03	Same

Table 6.10-4. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 4, ^{232}Th) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
Plant (cont.)	Concentration in crops, ^{232}Th	Leafy vegetables	$Cp_{Th\text{-}232,1}$	6.4.3-1	Bq/kg	5.71E–03	*Plant_Conc*	5.71E–03	Same
		Other vegetables	$Cp_{Th\text{-}232,2}$			9.03E–04		9.03E–04	Same
		Fruit	$Cp_{Th\text{-}232,3}$			1.09E–03		1.09E–03	Same
		Grain	$Cp_{Th\text{-}232,4}$			7.60E–03		7.60E–03	Same
		Forage	$Cp_{Th\text{-}232,5}$			1.90E–02		1.90E–02	Same
	Concentration due to root uptake, ^{228}Ra	Leafy vegetables	$Cp_{root,Ra\text{-}228,1}$	6.4.3-2	Bq/kg	1.03E–03	*Root_Uptake_1*	1.03E–03	Same
		Other vegetables	$Cp_{root,Ra\text{-}228,2}$			2.66E–04		2.66E–04	Same
		Fruit	$Cp_{root,Ra\text{-}228,3}$			1.89E–04		1.89E–04	Same
		Grain	$Cp_{root,Ra\text{-}228,4}$			4.61E–03		4.61E–03	Same
		Forage	$Cp_{root,Ra\text{-}228,5}$			2.97E–02		2.97E–02	Same
	Concentration due to dust interception, ^{228}Ra	Leafy vegetables	$Cp_{dust,Ra\text{-}228,1}$	6.4.3-6	Bq/kg	2.53E–04	*Dust_Uptake_1*	2.53E–04	Same
		Other vegetables	$Cp_{dust,Ra\text{-}228,2}$			3.51E–05		3.51E–05	Same
		Fruit	$Cp_{dust,Ra\text{-}228,3}$			6.08E–05		6.08E–05	Same
		Grain	$Cp_{dust,Ra\text{-}228,4}$			4.50E–04		4.50E–04	Same
		Forage	$Cp_{dust,Ra\text{-}228,5}$			9.46E–04		9.46E–04	Same
	Concentration in crops, ^{228}Ra	Leafy vegetables	$Cp_{Ra\text{-}228,1}$	6.4.3-1	Bq/kg	1.28E–03	*Plant_Conc_1*	1.28E–03	Same
		Other vegetables	$Cp_{Ra\text{-}228,2}$			3.02E–04		3.02E–04	Same
		Fruit	$Cp_{Ra\text{-}228,3}$			2.50E–04		2.50E–04	Same
		Grain	$Cp_{Ra\text{-}228,4}$			5.07E–03		5.07E–03	Same
		Forage	$Cp_{Ra\text{-}228,5}$			3.07E–02		3.07E–02	Same
	Concentration due to root uptake, ^{228}Th	Leafy vegetables	$Cp_{root,Th\text{-}228,1}$	6.4.3-2	Bq/kg	6.29E–05	*Root_Uptake_2*	6.29E–05	Same
		Other vegetables	$Cp_{root,Th\text{-}228,2}$			9.47E–06		9.47E–06	Same
		Fruit	$Cp_{root,Th\text{-}228,3}$			7.27E–06		7.27E–06	Same
		Grain	$Cp_{root,Th\text{-}228,4}$			2.51E–04		2.51E–04	Same
		Forage	$Cp_{root,Th\text{-}228,5}$			3.60E–03		3.60E–03	Same

Table 6.10-4. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 4, ^{232}Th) (Continued)

Submodel	Parameter in Mathematical Model: Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Parameter in GoldSim: Element Name	ERMYN_GW Result [b]	Notes [c]
Plant (Continued)	Concentration due to dust interception, ^{228}Th	Leafy vegetables	$Cp_{dust,Th\text{-}228,1}$	6.4.3-6	Bq/kg	1.73E–04	*Dust_Uptake_2*	1.73E–04	Same
		Other vegetables	$Cp_{dust,Th\text{-}228,2}$			2.40E–05		2.40E–05	Same
		Fruit	$Cp_{dust,Th\text{-}228,3}$			4.16E–05		4.16E–05	Same
		Grain	$Cp_{dust,Th\text{-}228,4}$			4.47E–04		4.47E–04	Same
		Forage	$Cp_{dust,Th\text{-}228,5}$			9.39E–04		9.39E–04	Same
	Concentration in crops, ^{228}Th	Leafy vegetables	$Cp_{Th\text{-}228,1}$	6.4.3-1	Bq/kg	2.36E–04	*Plant_Conc_2*	2.36E–04	Same
		Other vegetables	$Cp_{Th\text{-}228,2}$			3.35E–05		3.35E–05	Same
		Fruit	$Cp_{Th\text{-}228,3}$			4.89E–05		4.89E–05	Same
		Grain	$Cp_{Th\text{-}228,4}$			6.98E–04		6.98E–04	Same
		Forage	$Cp_{Th\text{-}228,5}$			4.54E–03		4.54E–03	Same
Animal	Concentration due to feed, ^{232}Th	Meat	$Cd_{feed,Th\text{-}232,1}$	6.4.4-2	Bq/kg	1.01E–04	*Feed_Contribution*	1.01E–04	Same
		Milk	$Cd_{feed,Th\text{-}232,2}$			5.14E–06		5.14E–06	Same
		Poultry	$Cd_{feed,Th\text{-}232,3}$			1.17E–05		1.17E–05	Same
		Eggs	$Cd_{feed,Th\text{-}232,4}$			6.91E–06		6.91E–06	Same
	Concentration due to water, ^{232}Th	Meat	$Cd_{water,\ Th\text{-}232,1}$	6.4.4-3	Bq/kg	6.60E–06	*Water_Contribution*	6.60E–06	Same
		Milk	$Cd_{water,\ Th\text{-}232,2}$			3.52E–07		3.52E–07	Same
		Poultry	$Cd_{water,\ Th\text{-}232,3}$			2.95E–06		2.95E–06	Same
		Eggs	$Cd_{water,\ Th\text{-}232,4}$			1.75E–06		1.75E–06	Same
	Concentration due to soil, ^{232}Th	Meat	$Cd_{soil,\ Th\text{-}232,1}$	6.4.4-4	Bq/kg	1.74E–04	*Soil_Contribution*	1.74E–04	Same
		Milk	$Cd_{soil,\ Th\text{-}232,2}$			9.43E–06		9.43E–06	Same
		Poultry	$Cd_{soil,\ Th\text{-}232,3}$			2.14E–04		2.14E–04	Same
		Eggs	$Cd_{soil,\ Th\text{-}232,4}$			1.27E–04		1.27E–04	Same
	Concentration in animal products, ^{232}Th	Meat	$Cd_{\ Th\text{-}232,1}$	6.4.4-1	Bq/kg	2.82E–04	*Animal_Conc*	2.82E–04	Same
		Milk	$Cd_{\ Th\text{-}232,2}$			1.49E–05		1.49E–05	Same
		Poultry	$Cd_{\ Th\text{-}232,3}$			2.29E–04		2.29E–04	Same
		Eggs	$Cd_{\ Th\text{-}232,4}$			1.36E–04		1.36E–04	Same

Table 6.10-4. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 4, ^{232}Th) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
Animal (Continued)	Concentration due to feed, ^{228}Ra	Meat	$Cd_{feed,Ra\text{-}228,1}$	6.4.4-2	Bq/kg	1.21E–03	*Feed_ Contribution_1*	1.21E–03	Same
		Milk	$Cd_{feed,Ra\text{-}228,2}$			1.09E–03		1.09E–03	Same
		Poultry	$Cd_{feed,Ra\text{-}228,3}$			2.24E–05		2.24E–05	Same
		Eggs	$Cd_{feed,Ra\text{-}228,4}$			5.14E–07		5.14E–07	Same
	Concentration due to soil, ^{228}Ra	Meat	$Cd_{soil,Ra\text{-}228,1}$	6.4.4-4	Bq/kg	9.35E–04	*Soil_Contribution_1*	9.35E–04	Same
		Milk	$Cd_{soil,Ra\text{-}228,2}$			9.08E–04		9.08E–04	Same
		Poultry	$Cd_{soil,Ra\text{-}228,3}$			3.81E–04		3.81E–04	Same
		Eggs	$Cd_{soil,Ra\text{-}228,4}$			8.73E–06		8.73E–06	Same
	Concentration in animal products, ^{228}Ra	Meat	$Cd_{Ra\text{-}228,1}$	6.4.4-1	Bq/kg	2.14E–03	*Animal_Conc_1*	2.14E–03	Same
		Milk	$Cd_{Ra\text{-}228,2}$			2.00E–03		2.00E–03	Same
		Poultry	$Cd_{Ra\text{-}228,3}$			4.03E–04		4.03E–04	Same
		Eggs	$Cd_{Ra\text{-}228,4}$			9.24E–06		9.24E–06	Same
	Concentration due to feed, ^{228}Th	Meat	$Cd_{feed,Th\text{-}228,1}$	6.4.4-2	Bq/kg	2.42E–05	*Feed_ Contribution_2*	2.42E–05	Same
		Milk	$Cd_{feed,Th\text{-}228,2}$			1.23E–06		1.23E–06	Same
		Poultry	$Cd_{feed,Th\text{-}228,3}$			1.07E–06		1.07E–06	Same
		Eggs	$Cd_{feed,Th\text{-}228,4}$			6.35E–07		6.35E–07	Same
	Concentration due to soil, ^{228}Th	Meat	$Cd_{soil,Th\text{-}228,1}$	6.4.4-4	Bq/kg	1.26E–04	*Soil_Contribution_2*	1.26E–04	Same
		Milk	$Cd_{soil,Th\text{-}228,2}$			6.84E–06		6.84E–06	Same
		Poultry	$Cd_{soil,Th\text{-}228,3}$			9.04E–05		9.04E–05	Same
		Eggs	$Cd_{soil,Th\text{-}228,4}$			5.36E–05		5.36E–05	Same
	Concentration in animal products, ^{228}Th	Meat	$Cd_{Th\text{-}228,1}$	6.4.4-1	Bq/kg	1.50E–04	*Animal_Conc_2*	1.50E–04	Same
		Milk	$Cd_{Th\text{-}228,2}$			8.06E–06		8.06E–06	Same
		Poultry	$Cd_{Th\text{-}228,3}$			9.15E–05		9.15E–05	Same
		Eggs	$Cd_{Th\text{-}228,4}$			5.43E–05		5.43E–05	Same
Fish	Concentration in Fish		$Cf_{Th\text{-}232}$	6.4.5-2	Bq/kg	4.57E–01	*Fish_Conc*	4.57E–01	Same

Table 6.10-4. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 4, ^{232}Th) (Continued)

Submodel	Parameter in Mathematical Model: Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Parameter in GoldSim: Element Name	*ERMYN_GW* Result [b]	Notes [c]
External	Environment-specific exposure time	Active outdoors	$\sum(PP_m\ t_{1,m})$	6.4.7-1	h/d	0.45	*Weighted_Time*	0.45	Same
		Inactive outdoors	$\sum(PP_m\ t_{2,m})$			1.45		1.45	Same
		Active indoors	$\sum(PP_m\ t_{3,m})$			9.45		9.45	Same
		Asleep indoors	$\sum(PP_m\ t_{4,m})$			8.30		8.30	Same
		Away	$\sum(PP_m\ t_{5,m})$			4.35		4.35	Same
	External dose, ^{232}Th		-	6.4.7-1	Sv/yr	9.35E–12	*External_Dose*	9.35E–12	Same
	External dose, ^{228}Ra		-	6.4.7-1	Sv/yr	1.55E–07	*External_Dose_1*	1.55E–07	Same
	External dose, ^{228}Th		-	6.4.7-1	Sv/yr	2.58E–07	*External_Dose_2*	2.58E–07	Same
	Total external dose		$D_{ext,Th\text{-}232}$	6.4.7-1	Sv/yr	4.13E–07	*Total _External*	4.13E–07	Same
Inhalation	Inhalation dose, soil particles, ^{232}Th		$D_{inh,p,Th\text{-}232}$	6.4.8-2	Sv/yr	5.47E–07	*Inhalation_Dose*	5.47E–07	Same
	Inhalation dose, evaporative cooler, ^{232}Th		$D_{inh,e,Th\text{-}232}$	6.4.8-3	Sv/yr	1.59E–07	*Cooler_Inhalation*	1.59E–07	Same
	Inhalation dose, soil particles, ^{228}Ra		-	6.4.8-2	Sv/yr	5.23E–08	*Inhalation_Dose_1*	5.23E–08	Same
	Inhalation dose, soil particles, ^{228}Th		-	6.4.8-2	Sv/yr	1.14E–07	*Inhalation_Dose_1*	1.14E–07	Same
	Total inhalation dose		$D_{inh,Th\text{-}232}$	6.4.8-1	Sv/yr	8.73E–07	*Total_Inhalation*	8.73E–07	Same
Ingestion	Ingestion dose for water, ^{232}Th		$D_{ing,w,Th\text{-}232}$	6.4.9-2	Sv/yr	1.69E–07	*Water_Ingestion*	1.69E–07	Same
	Ingestion dose for crops, ^{232}Th	Leafy vegetables	$D_{ing,p,Th\text{-}232,1}$	6.4.9-3	Sv/yr	4.99E–09	*Crop_Ingestion*	4.99E–09	Same
		Other vegetables	$D_{ing,p,Th\text{-}232,2}$			9.87E–10		9.87E–10	Same
		Fruit	$D_{ing,p,Th\text{-}232,3}$			3.18E–09		3.18E–09	Same
		Grain	$D_{ing,p,Th\text{-}232,4}$			4.04E–10		4.04E–10	Same
	Ingestion dose for animal products, ^{232}Th	Meat	$D_{ing,d,Th\text{-}232,1}$	6.4.9-4	Sv/yr	1.85E–10	*Animal_Ingestion*	1.85E–10	Same
		Milk	$D_{ing,d,Th\text{-}232,2}$			1.61E–11		1.61E–11	Same
		Poultry	$D_{ing,d,Th\text{-}232,3}$			2.22E–11		2.22E–11	Same
		Eggs	$D_{ing,d,Th\text{-}232,4}$			1.66E–10		1.66E–10	Same
	Ingestion dose for fish, ^{232}Th		$D_{ing,f,Th\text{-}232}$	6.4.9-5	Sv/yr	2.43E–08	*Fish_Ingestion*	2.43E–08	Same
	Ingestion dose for soil, ^{232}Th		$D_{ing,s,Th\text{-}232}$	6.4.9-6	Sv/yr	1.53E–08	*Soil_Ingestion*	1.53E–08	Same
	Ingestion dose, ^{232}Th		-	6.4.9-1	Sv/yr	2.18E–07	*Ingestion_Dose*	2.18E–07	Same

Table 6.10-4. Verification of ERMYN in GoldSim for the Groundwater Scenario (Case 4, ^{232}Th) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_GW* Result [b]	
Ingestion (Continued)	Ingestion dose for crops, ^{228}Ra	Leafy vegetables	$D_{ing,p,Ra\text{-}228,1}$	6.4.9-3	Sv/yr	3.37E–09	*Crop_Ingestion_1*	3.37E–09	Same
		Other vegetables	$D_{ing,p,Ra\text{-}228,2}$			9.95E–10		9.95E–10	Same
		Fruit	$D_{ing,p,Ra\text{-}228,3}$			2.21E–09		2.21E–09	Same
		Grain	$D_{ing,p,Ra\text{-}228,4}$			8.12E–10		8.12E–10	Same
	Ingestion dose for animal products, ^{228}Ra	Meat	$D_{ing,d,Ra\text{-}228,1}$	6.4.9-4	Sv/yr	4.25E–09	*Animal_Ingestion_1*	4.25E–09	Same
		Milk	$D_{ing,d,\ Ra\text{-}228,2}$			6.51E–09		6.51E–09	Same
		Poultry	$D_{ing,d,Ra\text{-}228,3}$			1.18E–10		1.18E–10	Same
		Eggs	$D_{ing,d,Ra\text{-}228,4}$			3.42E–11		3.42E–11	Same
	Ingestion dose for soil, ^{228}Ra		$D_{ing,s,Ra\text{-}228}$	6.4.9-6	Sv/yr	2.85E–08	*Soil_Ingestion_1*	2.85E–08	Same
	Ingestion dose, ^{228}Ra		-	6.4.9-1	Sv/yr	4.68E–08	*Ingestion_Dose_1*	4.68E–08	Same
	Ingestion dose for crops, ^{228}Th	Leafy vegetables	$D_{ing,p,Th\text{-}228,1}$	6.4.9-3	Sv/yr	1.27E–10	*Crop_Ingestion_2*	1.27E–10	Same
		Other vegetables	$D_{ing,p,Th\text{-}228,2}$			2.26E–11		2.26E–11	Same
		Fruit	$D_{ing,p,Th\text{-}228,3}$			8.85E–11		8.85E–11	Same
		Grain	$D_{ing,p,Th\text{-}228,4}$			2.29E–11		2.29E–11	Same
	Ingestion dose for animal products, ^{228}Th	Meat	$D_{ing,d,Th\text{-}228,1}$	6.4.9-4	Sv/yr	6.11E–11	*Animal_Ingestion_2*	6.11E–11	Same
		Milk	$D_{ing,d,Th\text{-}228,2}$			5.36E–12		5.36E–12	Same
		Poultry	$D_{ing,d,Th\text{-}228,3}$			5.48E–12		5.48E–12	Same
		Eggs	$D_{ing,d,Th\text{-}228,4}$			4.10E–11		4.10E–11	Same
	Ingestion dose for soil, ^{228}Th		$D_{ing,s,Th\text{-}228}$	6.4.9-6	Sv/yr	3.99E–09	*Soil_Ingestion_2*	3.99E–09	Same
	Ingestion dose, ^{228}Th		-	6.4.9-1	Sv/yr	4.37E–09	*Ingestion_Dose_2*	4.37E–09	Same
	Total ingestion dose		$D_{ing,Th\text{-}232}$	6.4.9-1	Sv/yr	2.69E–07	*Total_Ingestion*	2.69E–07	Same
All Pathway	All-pathway dose		$D_{all,Ra\text{-}226}$	6.4.10-1	Sv/yr	1.56E–06	*Final_TEDE*	1.56E–06	Same
	BDCF		$BDCF_{Ra\text{-}226}$	6.4.10-2	(Sv/yr)/(Bq/m^3)	1.56E–06	*Final_BDCF*	1.56E–06	Same

[a] Input data for this verification taken from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN Verification.xls,* which contains this calculation in worksheet *GWRa226*, is listed in Appendix A.

[b] The ERMYN is realized in GoldSim using the deterministic mode and data from the "mean, mode, or average" column in Table 6.6-3. The electronic file, *ERMYN_GW _Rev01_Th232verf.gsm*, for this run is listed in Appendix A.

[c] Comparison of results from Calculated Value (Column 6) and *ERMYN_GW* Result (Column 8).

6.10.1.2 Verification of Stochastic Calculations

To verify the stochastic calculations implemented in the ERMYN, results from deterministic and stochastic runs are compared for ^{239}Pu (Table 6.10-5). Differences between these runs are relatively small when compared to the standard deviation of the stochastic runs (i.e., about one standard deviation or less). The differences between the deterministic results and the mean values from the stochastic runs result primarily from the fact that the values that were used in the deterministic calculations were representative deterministic values that were not always equal to the means of the distribution ("Mean, Mode, or Average" column in Table 6.6-3). Because they propagate the expected parametric uncertainties to the results, the stochastic results are considered more realistic than the deterministic ones.

Table 6.10-5. Results from Deterministic and Stochastic Runs for the Groundwater Exposure Scenario

Radionuclide	Parameter	Deterministic Results	Stochastic Results (Mean ± Standard Deviation)
^{239}Pu	External exposure dose (Sv/yr)	6.48E–12	(8.78 ± 4.80)E–12
	Inhalation dose (Sv/yr)	5.26E–07	(7.17 ± 3.26)E–07
	Ingestion dose (Sv/yr)	2.12E–07	(2.38 ± 0.57)E–07
	BDCF (Sv/yr)/(Bq/m^3)	7.38E–07	(9.55 ± 3.37)E–07
^{14}C	External exposure dose (Sv/yr)	7.55E–17	(1.35 ± 0.76)E–16
	Inhalation dose (Sv/yr)	8.46E–12	(1.15 ±0.86)E–11
	Ingestion dose (Sv/yr)	1.39E–09	(1.92 ± 1.85)E–09
	BDCF (Sv/yr)/(Bq/m^3)	1.40E–09	(1.93 ± 1.85)E–09
^{226}Ra	External exposure dose (Sv/yr)	3.01E–07	(4.24 ±2.49)E–07
	Inhalation dose (Sv/yr)	1.96E–06	(2.90 ± 1.85)E–06
	Ingestion dose (Sv/yr)	4.03E–07	(4.53 ± 3.08)E–07
	BDCF (Sv/yr)/(Bq/m^3)	2.66E–06	(3.78 ± 2.16)E–06
^{232}Th	External exposure dose (Sv/yr)	4.13E–07	(5.57 ± 3.33)E–07
	Inhalation dose (Sv/yr)	8.73E–07	(9.89 ± 5.22)E–07
	Ingestion dose (Sv/yr)	2.69E–07	(3.06 ± 0.84)E–07
	BDCF (Sv/yr)/(Bq/m^3)	1.56E–06	(1.85 ± 0.73)E–06

NOTE: Deterministic calculations done using *ERMYN_GW_Rev 01_Pu239verf.gsm*; for stochastic calculations all 1,000 realizations were run in the same file; the file is listed in Appendix A. The pathway results of statistical calculations are in the Excel file, *GW BDCFs Pathway Analysis PDF.xls*, listed in Appendix A.

Figure 6.13-1 presented later in this report shows the ranges of BDCFs for all primary radionuclides, including their mean and median values, minima and maxima, as well as the 5th and 95th percentiles. The variance in the BDCF values is a result of the input parameter variability and uncertainty that is propagated into the model output. Some BDCF distributions have relatively long tails extending far beyond the 95th percentile point. For the distributions with long tails, a question arises of the stability of the mean BDCF value with respect to sampling of parameter distributions. The stability of the mean BDCF was investigated for the distribution of present-day climate BDCF for ^{99}Tc. For this radionuclide, the distribution extends past the 95th percentile by about an order of magnitude (Figure 6.13-1). The results of model runs performed using different random seed values are shown in Table 6.10-6. The results show that the variations in the mean value for ^{99}Tc caused by varying the random seed are small compared to the range of the BDCF distribution for this radionuclide.

Table 6.10-6. Mean BDCF for ^{99}Tc for the Present-Day Climate Obtained by Executing the Biosphere Model with Different Random Seed Values

Random Seed	BDCF (Sv/yr per Bq/m^3)			
	Mean	Standard Error	95 % Confidence Interval for the Mean	
			Lower Limit	Upper Limit
1	1.12E–09	3.99E–11	1.05E–09	1.20E–09
2	1.10E–09	3.22E–11	1.04E–09	1.16E–09
3	1.10E–09	2.57E–11	1.05E–09	1.15E–09
5	1.09E–09	2.73E–11	1.04E–09	1.15E–09
10	1.10E–09	2.66E–11	1.05E–09	1.15E–09
15	1.09E–09	2.66E–11	1.04E–09	1.15E–09
20	1.15E–09	3.71E–11	1.07E–09	1.22E–09

NOTES: The results were obtained by running the model in GoldSim using the file *ERMYN_GW_Rev01.gsm* file (Appendix A). Summary of the results and the related calculations can be found in the Excel file *Random Seed Variations.xls*.

The limits of the 95% confidence interval for the mean were calculated as 1.96 times the standard error of the mean.

6.10.2 Verification of the Model Implementation for the Volcanic Ash Scenario

6.10.2.1 Verification of Deterministic Calculations

Similar to the groundwater scenario, verification of the implementation of the model for the volcanic ash exposure scenario in GoldSim is performed using input values from Table 6.6-3. Two radionuclides, ^{239}Pu and ^{226}Ra, are tested for the present-day climate. For the base case, ^{239}Pu is selected; model runs for ^{226}Ra include calculation of doses from inhalation of decay products of ^{222}Rn. The GoldSim files described in this section are listed in Appendix A.

The verification results for ^{239}Pu are presented in Table 6.10-7, in which the comparison is presented in the order of each submodel discussed in Section 6.5. The hand-calculated results from the important equations in the biosphere model are presented in the table for comparison with the GoldSim results.

Verification results for ^{226}Ra are presented in Table 6.10-8. The only difference between ^{226}Ra and ^{239}Pu calculations is the radon inhalation calculation for ^{226}Ra. The long-lived decay products that build up in the soil as a result of long-term irrigation (^{210}Pb for ^{226}Ra; ^{228}Ra and ^{228}Th for ^{232}Th), that are considered in the groundwater scenario, are not included in the BDCF for the volcanic ash scenario because the process of radionuclide buildup in the soil is not relevant in this case. Radionuclide concentration in the soil is the source term for the volcanic scenario and is modeled outside the biosphere model. The results from both methods are the same, indicating that the implementation of the volcanic biosphere model in ERMYN (volcanic ash scenario; Section 6.5) is correct.

Table 6.10-7. Verification of ERMYN in GoldSim for the Volcanic Ash Scenario (Case 1, ^{239}Pu)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_VA* Result [b]	
Soil	Concentration in agricultural land		$Cs_{m,Pu\text{-}239}$	6.5.1-2	Bq/kg	2.67E–03	*SoilMass_Conc*	2.67E–03	Same
Air	Concentration in air for crop		$Ca_{p,Pu\text{-}239}$	6.5.2-1	Bq/m^3	6.40E–10	*AirConc_Crop*	6.40E–10	Same
	Concentration in air at nominal condition (long-term)	Active outdoors	$Ca_{nc,Pu\text{-}239,1}$	6.5.2-4	Bq/m^3	8.70E–06	*AirConc_Long*	8.70E–06	Same
		Inactive outdoors	$Ca_{nc,Pu\text{-}239,2}$			7.20E–08		7.20E–08	Same
		Active indoors	$Ca_{nc,Pu\text{-}239,3}$			1.20E–07		1.20E–07	Same
		Asleep indoors	$Ca_{nc,Pu\text{-}239,4}$			3.60E–08		3.60E–08	Same
		Away	$Ca_{nc,Pu\text{-}239,5}$			0.00E+00		0.00E+00	Same
	Concentration in air at post volcanic condition (short-term)	Active outdoors	$Ca_{v,Pu\text{-}239,1}$	6.5.2-4	Bq/m^3	8.70E–06	*AirConc_Short*	8.70E–06	Same
		Inactive outdoors	$Ca_{v,Pu\text{-}239,2}$			7.20E–08		7.20E–08	Same
		Active indoors	$Ca_{v,Pu\text{-}239,3}$			1.20E–07		1.20E–07	Same
		Asleep indoors	$Ca_{v,Pu\text{-}239,4}$			3.60E–08		3.60E–08	Same
		Away	$Ca_{v,Pu\text{-}239,5}$			0.00E+00		0.00E+00	Same
Plant	Concentration due to root uptake	Leafy vegetables	$Cp_{root,Pu\text{-}239,1}$	6.5.3-2	Bq/kg	5.41E–08	*Root_Uptake*	5.41E–08	Same
		Other vegetables	$Cp_{root,Pu\text{-}239,2}$			5.22E–08		5.22E–08	Same
		Fruit	$Cp_{root,Pu\text{-}239,3}$			5.76E–08		5.76E–08	Same
		Grain	$Cp_{root,Pu\text{-}239,4}$			4.58E–08		4.58E–08	Same
		Forage	$Cp_{root,Pu\text{-}239,5}$			5.87E–07		5.87E–07	Same
	Dust interception fraction	Leafy vegetables	Ra_1	6.5.3-5	-	0.456	*Dust_Intercept*	0.456	Same
		Other vegetables	Ra_2			0.787		0.787	Same
		Fruit	Ra_3			0.893		0.893	Same
		Grain	Ra_4			0.962		0.962	Same
		Forage	Ra_5			0.751		0.751	Same
	Concentration due to dust interception	Leafy vegetables	$Cp_{dust,Pu\text{-}239,1}$	6.5.3-3	Bq/kg	1.20E–06	*Dust_Uptake*	1.20E–06	Same
		Other vegetables	$Cp_{dust,Pu\text{-}239,2}$			1.67E–07		1.67E–07	Same
		Fruit	$Cp_{dust,Pu\text{-}239,3}$			2.90E–07		2.90E–07	Same
		Grain	$Cp_{dust,Pu\text{-}239,4}$			1.46E–06		1.46E–06	Same
		Forage	$Cp_{dust,Pu\text{-}239,5}$			3.06E–06		3.06E–06	Same

Table 6.10-7. Verification of ERMYN in GoldSim for the Volcanic Ash Scenario (Case 1, ^{239}Pu) (Continued)

Submodel	Parameter in Mathematical Model: Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Parameter in GoldSim: Element Name	*ERMYN_VA* Result [b]	Notes [c]
Plant (Continued)	Concentration in crops	Leafy vegetables	$Cp_{Pu\text{-}239,1}$	6.5.3-1	Bq/kg	1.26E–06	*Plant_Conc*	1.26E–06	Same
		Other vegetables	$Cp_{Pu\text{-}239,2}$			2.19E–07		2.19E–07	Same
		Fruit	$Cp_{Pu\text{-}239,3}$			3.48E–07		3.48E–07	Same
		Grain	$Cp_{Pu\text{-}239,4}$			1.50E–06		1.50E–06	Same
		Forage	$Cp_{Pu\text{-}239,5}$			3.65E–06		3.65E–06	Same
Animal	Concentration due to feed	Meat	$Cd_{feed,Pu\text{-}239,1}$	6.5.4-2	Bq/kg	2.30E–09	*Feed_Contribution*	2.30E–09	Same
		Milk	$Cd_{feed,Pu\text{-}239,2}$			5.16E–11		5.16E–11	Same
		Poultry	$Cd_{feed,Pu\text{-}239,3}$			4.69E–10		4.69E–10	Same
		Eggs	$Cd_{feed,Pu\text{-}239,4}$			6.64E–10		6.64E–10	Same
	Concentration due to soil	Meat	$Cd_{soil,Pu\text{-}239,1}$	6.5.4-3	Bq/kg	2.43E–08	*Soil_Contribution*	2.43E–08	Same
		Milk	$Cd_{soil,Pu\text{-}239,2}$			5.83E–10		5.83E–10	Same
		Poultry	$Cd_{soil,Pu\text{-}239,3}$			6.40E–08		6.40E–08	Same
		Eggs	$Cd_{soil,Pu\text{-}239,4}$			9.07E–08		9.07E–08	Same
	Concentration in animal products	Meat	$Cd_{Pu\text{-}239,1}$	6.5.4-1	Bq/kg	2.66E–08	*Animal_Conc*	2.66E–08	Same
		Milk	$Cd_{Pu\text{-}239,2}$			6.34E–10		6.34E–10	Same
		Poultry	$Cd_{Pu\text{-}239,3}$			6.45E–08		6.45E–08	Same
		Eggs	$Cd_{Pu\text{-}239,4}$			9.13E–08		9.13E–08	Same
External	Environment-specific exposure time	Active outdoors	$\sum(PP_m\, t_{1,m})$	6.5.5-1	h/d	0.45	*Weighted_Time*	0.45	Same
		Inactive outdoors	$\sum(PP_m\, t_{2,m})$			1.59		1.59	Same
		Active indoors	$\sum(PP_m\, t_{3,m})$			10.87		10.87	Same
		Asleep indoors	$\sum(PP_m\, t_{4,m})$			8.30		8.30	Same
		Away	$\sum(PP_m\, t_{5,m})$			2.79		2.79	Same
	Effective exposure time		$\sum[f_{ext,Pu\text{-}239,n}\, \sum(PP_m\, t_{n,m})]$	6.5.5-1	h/yr	2,848	*External_Time*	2,848	Same
	External dose		$D_{ext,Pu\text{-}239}$	6.5.5-1	Sv/yr	2.91E–12	*External_Dose*	2.91E–12	Same

Table 6.10-7. Verification of ERMYN in GoldSim for the Volcanic Ash Scenario (Case 1, ^{239}Pu) (Continued)

Submodel	Parameter in Mathematical Model: Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Parameter in GoldSim: Element Name	*ERMYN_VA* Result [b]	Notes [c]
Inhalation	Long-term inhalation dose (at nominal condition)		$D_{inh,p,Pu\text{-}239}$	6.5.6-2	Sv/yr	3.41E–07	*Inhalation_Long*	3.41E–07	Same
	Short-term inhalation dose (at post-volcanic condition)		$D_{inh,v,Pu\text{-}239}$	6.5.6-2	Sv/yr	3.41E–07	*Inhalation_Short*	3.41E–07	Same
Ingestion	Ingestion dose for crops	Leafy vegetables	$D_{ing,p,Pu\text{-}239,1}$	6.5.7-2	Sv/yr	1.19E–12	*Crop_Ingestion*	1.19E–12	Same
		Other vegetables	$D_{ing,p,Pu\text{-}239,2}$			2.60E–13		2.60E–13	Same
		Fruit	$D_{ing,p,Pu\text{-}239,3}$			1.11E–12		1.11E–12	Same
		Grain	$D_{ing,p,Pu\text{-}239,4}$			8.68E–14		8.68E–14	Same
	Ingestion dose for animal products	Meat	$D_{ing,d,Pu\text{-}239,1}$	6.5.7-3	Sv/yr	1.90E–14	*Animal_Ingestion*	1.90E–14	Same
		Milk	$D_{ing,d,Pu\text{-}239,2}$			7.42E–16		7.42E–16	Same
		Poultry	$D_{ing,d,Pu\text{-}239,3}$			6.80E–15		6.80E–15	Same
		Eggs	$D_{ing,d,Pu\text{-}239,4}$			1.21E–13		1.21E–13	Same
	Ingestion dose for soil		$D_{ing,s,Pu\text{-}239}$	6.5.7-4	Sv/yr	2.44E–11	*Soil_Ingestion*	2.44E–11	Same
	Ingestion dose		$D_{ing,Pu\text{-}239}$	6.5.7-1	Sv/yr	2.72E–11	*Ingestion_Dose*	2.72E–11	Same
All Pathway	Dose for external, radon, and ingestion		$D_{all,Pu\text{-}239}$	6.5.8-1	Sv/yr	3.02E–11	*TEDE_All*	3.02E–11	Same
	Inhalation dose, particulates, post-volcanic condition		$D_{inh,v,Pu\text{-}239}$	6.5.8-1	Sv/yr	3.41E–07	*TEDE_Short*	3.41E–07	Same
	Inhalation dose, particulates, nominal condition		$D_{inh,p,Pu\text{-}239}$	6.5.8-1	Sv/yr	3.41E–07	*TEDE_Long*	3.41E–07	Same
	BDCF for external, radon, and ingestion		$BDCF_{Pu\text{-}239}$	6.5.8-2	(Sv/yr)/(Bq/m^2)	3.02E–11	*BDCF_All*	3.02E–11	Same
	BDCF for inhalation at post-volcanic condition		$BDCF_{inh,v,Pu\text{-}239}$	6.5.8-2	(Sv/yr)/(Bq/kg)	3.41E–07	*BDCF_InhShort*	3.41E–07	Same
	BDCF for inhalation at nominal condition		$BDCF_{inh,p,Pu\text{-}239}$	6.5.8-2	(Sv/yr)/(Bq/kg)	3.41E–07	*BDCF_InhLong*	3.41E–07	Same

[a] Input data for this verification taken from the “mean, mode, or average” column in Table 6.6-3. The electronic file, *ERMYN Verification.xls*, which contains this calculation in worksheet *VAPu239*, is listed in Appendix A.

[b] The ERMYN is realized in GoldSim using the deterministic mode and data from the “mean, mode, or average” column in Table 6.6-3. The electronic file, *ERMYN_VA_Rev01_Pu239verf.gsm*, for this run is listed in Appendix A.

[c] Comparison of results from Calculated Value (Column 6) and *ERMYN_GW* Result (Column 8).

Table 6.10-8. Verification of ERMYN in GoldSim for the Volcanic Ash Scenario (Case 2, ^{226}Ra)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_VA* Result [b]	
Soil	Concentration in agricultural land		$Cs_{m,Ra\text{-}226}$	6.5.1-2	Bq/kg	2.67E–03	*SoilMass_Conc*	2.67E–03	Same
Air	Concentration in air for crop		$Ca_{p,Ra\text{-}226}$	6.5.2-1	Bq/m^3	6.40E–10	*AirConc_Crop*	6.40E–10	Same
	Concentration in air at nominal condition	Active outdoors	$Ca_{nc,Ra\text{-}226,1}$	6.5.2-4	Bq/m^3	8.70E–06	*AirConc_Long*	8.70E–06	Same
		Inactive outdoors	$Ca_{nc,Ra\text{-}226,2}$			7.20E–08		7.20E–08	Same
		Active indoors	$Ca_{nc,Ra\text{-}226,3}$			1.20E–07		1.20E–07	Same
		Asleep indoors	$Ca_{nc,Ra\text{-}226,4}$			3.60E–08		3.60E–08	Same
		Away	$Ca_{nc,Ra\text{-}226,5}$			0.00E+00		0.00E+00	Same
	Concentration in air at post volcanic condition	Active outdoors	$Ca_{v,Ra\text{-}226,1}$	6.5.2-4	Bq/m^3	8.70E–06	*AirConc_Short*	8.70E–06	Same
		Inactive outdoors	$Ca_{v,Ra\text{-}226,2}$			7.20E–08		7.20E–08	Same
		Active indoors	$Ca_{v,Ra\text{-}226,3}$			1.20E–07		1.20E–07	Same
		Asleep indoors	$Ca_{v,Ra\text{-}226,4}$			3.60E–08		3.60E–08	Same
		Away	$Ca_{v,Ra\text{-}226,5}$			0.00E+00		0.00E+00	Same
	Radon concentration in air		$Ca_{g,Rn\text{-}222}$	6.5.2-8	Bq/m^3	6.00E–04	*AirConc_Radon*	6.00E–04	Same
Plant	Concentration due to root uptake	Leafy vegetables	$Cp_{root,Ra\text{-}226,2}$	6.5.3-2	Bq/kg	1.27E–05	*Root_Uptake*	1.27E–05	Same
		Other vegetables	$Cp_{root,Ra\text{-}226,2}$			3.30E–06		3.30E–06	Same
		Fruit	$Cp_{root,Ra\text{-}226,3}$			2.34E–06		2.34E–06	Same
		Grain	$Cp_{root,Ra\text{-}226,4}$			7.46E–06		7.46E–06	Same
		Forage	$Cp_{root,Ra\text{-}226,5}$			4.81E–05		4.81E–05	Same
	Dust interception fraction	Leafy vegetables	Ra_1	6.5.3-5	-	0.456	*Dust_Intercept*	0.456	Same
		Other vegetables	Ra_2			0.787		0.787	Same
		Fruit	Ra_3			0.893		0.893	Same
		Grain	Ra_4			0.962		0.962	Same
		Forage	Ra_5			0.751		0.751	Same
	Concentration due to dust interception	Leafy vegetables	$Cp_{dust,Ra\text{-}226,1}$	6.5.3-3	Bq/kg	1.20E–06	*Dust_Uptake*	1.20E–06	Same
		Other vegetables	$Cp_{dust,Ra\text{-}226,2}$			1.67E–07		1.67E–07	Same
		Fruit	$Cp_{dust,Ra\text{-}226,3}$			2.90E–07		2.90E–07	Same
		Grain	$Cp_{dust,Ra\text{-}226,4}$			1.46E–06		1.46E–06	Same
		Forage	$Cp_{dust,Ra\text{-}226,5}$			3.06E–06		3.06E–06	Same

Table 6.10-8. Verification of ERMYN in GoldSim for the Volcanic Ash Scenario (Case 2, ^{226}Ra) (Continued)

Submodel	Parameter in Mathematical Model						Parameter in GoldSim		Notes [c]
	Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Element Name	*ERMYN_VA* Result [b]	
Plant (Continued)	Concentration in crops	Leafy vegetables	$Cp_{Ra\text{-}226,1}$	6.5.3-1	Bq/kg	1.39E–05	*Plant_Conc*	1.39E–05	Same
		Other vegetables	$Cp_{Ra\text{-}226,2}$			3.46E–06		3.46E–06	Same
		Fruit	$Cp_{Ra\text{-}226,3}$			2.63E–06		2.63E–06	Same
		Grain	$Cp_{Ra\text{-}226,4}$			8.92E–06		8.92E–06	Same
		Forage	$Cp_{Ra\text{-}226,5}$			5.12E–05		5.12E–05	Same
Animal	Concentration due to feed	Meat	$Cd_{feed,Ra\text{-}226,1}$	6.5.4-2	Bq/kg	2.01E–06	*Feed_ Contribution*	2.01E–06	Same
		Milk	$Cd_{feed,Ra\text{-}226,2}$			1.83E–06		1.83E–06	Same
		Poultry	$Cd_{feed,Ra\text{-}226,3}$			3.94E–08		3.94E–08	Same
		Eggs	$Cd_{feed,Ra\text{-}226,4}$			9.05E–10		9.05E–10	Same
	Concentration due to soil	Meat	$Cd_{soil,Ra\text{-}226,1}$	6.5.4-3	Bq/kg	1.51E–06	*Soil_Contribution*	1.51E–06	Same
		Milk	$Cd_{soil,Ra\text{-}226,2}$			1.47E–06		1.47E–06	Same
		Poultry	$Cd_{soil,Ra\text{-}226,3}$			9.07E–07		9.07E–07	Same
		Eggs	$Cd_{soil,Ra\text{-}226,4}$			2.08E–08		2.08E–08	Same
	Concentration in animal products	Meat	$Cd_{Ra\text{-}226,1}$	6.5.4-1	Bq/kg	3.52E–06	*Animal_Conc*	3.52E–06	Same
		Milk	$Cd_{Ra\text{-}226,2}$			3.29E–06		3.29E–06	Same
		Poultry	$Cd_{Ra\text{-}226,3}$			9.46E–07		9.46E–07	Same
		Eggs	$Cd_{Ra\text{-}226,4}$			2.17E–08		2.17E–08	Same
External	Environment-specific exposure time	Active outdoors	$\sum(PP_m\ t_{1,m})$	6.5.5-1	h/d	0.45	*Weighted_Time*	0.45	Same
		Inactive outdoors	$\sum(PP_m\ t_{2,m})$			1.59		1.59	Same
		Active indoors	$\sum(PP_m\ t_{3,m})$			10.87		10.87	Same
		Asleep indoors	$\sum(PP_m\ t_{4,m})$			8.30		8.30	Same
		Away	$\sum(PP_m\ t_{5,m})$			2.79		2.79	Same
	Effective exposure time		$\sum[f_{ext,Ra\text{-}226,n}\ \sum(PP_m\ t_{n,m})]$	6.5.5-1	h/yr	3,548	*External_Time*	3,548	Same
	External dose		$D_{ext,Ra\text{-}226}$	6.5.5-1	Sv/yr	2.15E–08	*External_Dose*	2.15E–08	Same

Table 6.10-8. Verification of ERMYN in GoldSim for the Volcanic Ash Scenario (Case 2, ^{226}Ra) (Continued)

Submodel	Parameter in Mathematical Model: Parameter Name		Notation in Equation	Equation Number	Units	Calculated Value [a]	Parameter in GoldSim: Element Name	ERMYN_VA Result [b]	Notes [c]
Inhalation	Long-term inhalation dose, particulates, nominal condition		$D_{inh,p,Ra\text{-}226}$	6.5.6-2	Sv/yr	2.74E–08	*Inhalation_Long*	2.74E–08	Same
	Short-term inhalation dose, particulates, post-volcanic condition		$D_{inh,v,Ra\text{-}226}$	6.5.6-2	Sv/yr	2.74E–08	*Inhalation_Short*	2.74E–08	Same
	Inhalation dose from radon		$D_{inh,Rn\text{-}222}$	6.5.6-3	Sv/yr	1.08E–08	*Inhalation_Radon*	1.08E–08	
Ingestion	Ingestion dose for crops	Leafy vegetables	$D_{ing,p,Ra\text{-}226,1}$	6.5.7-2	Sv/yr	1.47E–11	*Crop_Ingestion*	1.47E–11	Same
		Other vegetables	$D_{ing,p,Ra\text{-}226,2}$			4.59E–12		4.59E–12	Same
		Fruit	$D_{ing,p,Ra\text{-}226,3}$			9.33E–12		9.33E–12	Same
		Grain	$D_{ing,p,Ra\text{-}226,4}$			5.75E–13		5.75E–13	Same
	Ingestion dose for animal products	Meat	$D_{ing,d,Ra\text{-}226,1}$	6.5.7-3	Sv/yr	2.81E–12	*Animal_Ingestion*	2.81E–12	Same
		Milk	$D_{ing,d,Ra\text{-}226,2}$			4.30E–12		4.30E–12	Same
		Poultry	$D_{ing,d,Ra\text{-}226,3}$			1.11E–13		1.11E–13	Same
		Eggs	$D_{ing,d,Ra\text{-}226,4}$			3.22E–14		3.22E–14	Same
	Ingestion dose for soil		$D_{ing,s,Ra\text{-}226}$	6.5.7-4	Sv/yr	2.73E–11	*Soil_Ingestion*	2.73E–11	Same
	Ingestion dose		$D_{ing,Ra\text{-}226}$	6.5.7-1	Sv/yr	6.38E–11	*Ingestion_Dose*	6.38E–11	Same
All Pathway	Dose for external, radon, and ingestion		$D_{all,Ra\text{-}226}$	6.5.8-1	Sv/yr	3.24E–08	*TEDE_All*	3.24E–08	Same
	Inhalation dose, particulates, post-volcanic condition		$D_{inh,v,Ra\text{-}226}$	6.5.8-1	Sv/yr	2.74E–08	*TEDE_Short*	2.74E–08	Same
	Inhalation dose, particulates, nominal condition		$D_{inh,p,Ra\text{-}226}$	6.5.8-1	Sv/yr	2.74E–08	TEDE_Long	2.74E–08	Same

Table 6.10-8. Verification of ERMYN in GoldSim for the Volcanic Ash Scenario (Case 2, ^{226}Ra) (Continued)

	Parameter in Mathematical Model					Parameter in GoldSim		
Submodel	**Parameter Name**	**Notation in Equation**	**Equation Number**	**Units**	**Calculated Value** [a]	**Element Name**	***ERMYN_VA* Result** [b]	**Notes** [c]
All Pathway	BDCF for external, radon, and ingestion	$BDCF_{Ra\text{-}226}$	6.5.8-2	(Sv/yr)/(Bq/m^2)	3.24E–08	*BDCF_All*	3.24E–08	Same
	BDCF for inhalation at post-volcanic condition	$BDCF_{inh,v,Ra\text{-}226}$	6.5.8-2	(Sv/yr)/(Bq/kg)	2.74E–08	*BDCF_InhShort*	2.74E–08	Same
	BDCF for inhalation at nominal condition	$BDCF_{inh,p,Ra\text{-}226}$	6.5.8-2	(Sv/yr)/(Bq/kg)	2.74E–08	*BDCF_InhLong*	2.74E–08	Same

[a] Input data for this verification taken from the “mean, mode, or average” column in Table 6.6-3. The electronic file, *ERMYN Verification.xls*, which contains this calculation in worksheet *VARa226*, is listed in Appendix A.

[b] The ERMYN is realized in GoldSim using the deterministic mode and data from the “mean, mode, or average” column in Table 6.6-3. The electronic file, *ERMYN_VA_Rev01_Ra226verf.gsm*, for this run is listed in Appendix A.

[c] Comparison of results from Calculated Value (Column 6) and *ERMYN_GW* Result (Column 8).

6.10.2.2 Verification of Stochastic Calculations

Similar to the groundwater exposure scenario, deterministic and stochastic runs for ^{239}Pu were performed using input parameters from Table 6.6-3. The results (Table 6.10-9) reveal small differences between the deterministic and stochastic runs, except for the ingestion dose and BDCF for combined external and ingestion pathways. In the groundwater scenario, radionuclide concentrations in surface soil depend on several stochastic parameters, such as the partition coefficient, and are thus calculated as stochastic variables. Unlike the groundwater scenario, radionuclide concentrations in ash deposited in the ground, which is the source of radionuclides for the volcanic ash scenario, are equal to the unit areal activity concentration. This results in a relatively small difference between the deterministic and stochastic calculations. For the ingestion pathway, sample means and reasonable estimates for some parameters, such as soil depth and transfer coefficients, are different. As before, differences between the BDCFs calculated using the two methods are not significant because the deterministic results are within the one standard deviation of the stochastic mean values.

Table 6.10-9. Results from the Deterministic and Stochastic Runs for the Volcanic Ash Scenario

Radionuclide	Parameter	Deterministic Results	Stochastic Results (Mean ± Standard Deviation)
^{239}Pu	External dose (Sv/yr)	2.91E–12	(2.94 ± 0.06)E–12
	Long-term inhalation dose, particulates, nominal condition (Sv/yr)	3.41E–07	(6.12 ± 3.91)E–07
	Short-term inhalation dose, particulates, post-volcanic condition (Sv/yr)	3.41E–07	(3.98 ± 2.26)E–07
	Ingestion dose (Sv/yr)	2.72E–11	(8.20 ± 8.50)E–11
	BDCF for external exposure and ingestion (Sv/yr)/(Bq/m^2)	3.02E–11	(8.49 ± 8.50)E–11
	BDCF for inhalation of particulates; post-volcanic conditions (Sv/yr)/(Bq/kg)	3.41E–07	(3.98 ± 2.26)E–07
	BDCF for inhalation of particulates; nominal conditions (Sv/yr)/(Bq/kg)	3.41E–07	(6.12 ± 3.91)E–07
^{226}Ra	External dose (Sv/yr)	2.15E–08	(2.17 ± 0.04)E–08
	Long-term inhalation dose, particulates, nominal condition (Sv/yr)	2.74E–08	(4.91 ± 3.14)E–08
	Short-term inhalation dose, particulates, post-volcanic condition (Sv/yr)	2.74E–08	(3.19 ± 1.81)E–08
	Inhalation dose, radon decay products (Sv/yr)	1.08E–08	(1.09 ± 0.13)E–08
	Ingestion dose (Sv/yr)	6.38E–11	(2.31 ± 2.89)E–10
	BDCF for external exposure, ingestion, and inhalation of radon decay products (Sv/yr)/(Bq/m^2)	3.24E–08	(3.29 ± 0.14)E–08
	BDCF for inhalation of particulates; post-volcanic conditions (Sv/yr)/(Bq/kg)	2.74E–08	(3.19 ± 1.81)E–08
	BDCF for inhalation of particulates; nominal conditions (Sv/yr)/(Bq/kg)	2.74E–08	(4.91 ± 3.14)E–08

NOTE: Deterministic calculations done using *ERMYN_GW_Pu239verf.gsm*; for stochastic calculations all 1,000 realizations were run in the same file; the file is listed in Appendix A.

6.11 BIOSPHERE DOSE CONVERSION FACTORS FOR THE GROUNDWATER EXPOSURE SCENARIO

BDCFs for the groundwater exposure scenario are used in calculation of annual dose to the RMEI from radionuclides released from the geosphere to the biosphere in groundwater. A radionuclide-specific groundwater BDCF is numerically equal to the all-pathway annual dose that the RMEI would receive if the hypothetical community that includes the RMEI used the groundwater containing a unit activity concentration of a given radionuclide for irrigation or domestic purposes.

BDCFs for the groundwater exposure scenario apply to the TSPA scenarios and cases that result in the release of radionuclides to groundwater. Because BDCFs are developed for a unit radionuclide concentration in groundwater, they are independent of the actual processes that resulted in radionuclide release to the groundwater.

Biosphere exposure scenarios should not be confused with TSPA scenario classes. The biosphere exposure scenario is a well-defined, connected sequence of FEPs that describe characteristics of the biosphere, where radionuclide transport and human exposure occurs. The biosphere model exposure scenario is constructed to evaluate radiological consequences of radionuclide releases to the reference biosphere in a given medium, such as the groundwater, irrespective of the cause of contamination in the groundwater.

The BDCFs for the groundwater exposure scenario were calculated using probabilistic analysis in GoldSim V.8.02.500 (2005 [DIRS 174650]), in a series of simulations for each of the 31 primary radionuclides (Section 6.1.3). Each simulation resulted in 1,000 model realizations. A model realization is one of the possible model outcomes obtained as a result of a single round of sampling of the model input parameters. This section describes the format and the summary of the results of biosphere modeling for the groundwater exposure scenario, as well as their use in the TSPA model.

6.11.1 Modeling Methods

6.11.1.1 Treatment of Uncertainty

The probabilistic approach was chosen to develop BDCFs. This approach allows statistical sampling of parameter values defined by their probability distribution functions. This method, called Monte Carlo analysis, provides a quantitative evaluation of the parameter uncertainties and their impacts on the modeling outcome. Uncertainty in the model outcome is represented by the probability distribution of the BDCFs. Input parameter values were sampled using the Latin Hypercube sampling method for consistency with the sampling technique to be used in TSPA. With Latin Hypercube sampling, the probability distribution is divided into intervals of equal probability. The code then randomly samples a value within each interval, which results in a more even and consistent sampling over each variable compared with the conventional Monte Carlo random sampling scheme. The value of the random seed in GoldSim was set to 1.

6.11.1.2 Incorporation of Climate Change

The biosphere model was constructed for a biosphere having an arid or semi-arid climate. There are several climate states that meet such conditions. The implementation of the climate in the biosphere is discussed in this section.

6.11.1.2.1 Regulatory Basis of the Climate Treatment in the Reference Biosphere

To take into account the changes that will occur during the period of geologic stability (ending at one million years after disposal) in the TSPA, it is required that the "DOE should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology. In all analyses done to demonstrate compliance with this part, DOE must assume that all of those factors remain constant as they are at the time of license application submission to NRC" (10 CFR 63.305(b) [DIRS 173273]). In contrast to the direction not to project changes in society, the biosphere, human biology, or human knowledge or technology, 10 CFR 63.305(c) (70 FR 53313 [DIRS 178394]) directs the DOE to vary factors related to climate.

Human exposure pathways and associated parameters are elements of the reference biosphere (63.102 [DIRS 173273]) and they depend on the dietary and lifestyle activities. Many aspects of human activity are determined by the climate; specifically, changes in irrigation rates are climate-induced. One thus has to address a question of whether the change in irrigation rates is best viewed as a result of human activity, a factor which section 10 CFR 63.305(c) (70 FR 53313 [DIRS 178394]) directs the DOE not to vary in its performance assessments, or as a result of climate change, a factor which 10 CFR 63.305(c) (70 FR 53313 [DIRS 178394]) directs the DOE to vary over the period of geologic stability (i.e., one million years).

In the preamble to the individual protection standards issued in 2001, the EPA addressed the question of whether "it is reasonable to consider, select, and hold constant today's known and assumed attributes of the biosphere for use in projecting radiation-related effects upon the public of releases from the Yucca Mountain disposal system." (66 FR 32074 [DIRS 155216], p. 32,122). The EPA noted that comments received were generally supportive of holding present biosphere conditions constant for the purpose of making performance projections for the disposal system. EPA pointed out that the National Academy of Sciences (NAS) in *Technical Bases for Yucca Mountain Standards* (National Research Council 1995 [DIRS 100018]) had cautioned against making unreasonably speculative assumptions about the future in its recommendations for a reference biosphere, and concluded that "[t]he DOE will perform the dose calculation to estimate exposure resulting from releases from the waste into the accessible environment based upon the assumption of present-day conditions in the vicinity of Yucca Mountain" (66 FR 32047 [DIRS 155216], p. 32,090).

Although this discussion and others in the EPA and NRC preambles that accompanied the final rules issued in 2001 (66 FR 55732 [DIRS 156671]; 66 FR 55732 [DIRS 156671]) consistently emphasize that biosphere conditions should not be varied over time, the specific question of how climate-induced changes in irrigation usage should be addressed was not raised. However, in the preamble to the proposed rule (70 FR 49014 [DIRS 177357]), EPA discussed at length why it was not proposing to alter the characteristics of the RMEI in light of the extension of the compliance period beyond 10,000 years. EPA noted (70 FR 49014 [DIRS 177357], p. 49,023):

> "Some commenters might question whether it is important to have internal consistency between climate/biosphere characteristics and RMEI lifestyle and characteristics. We believe that it would be highly speculative to select RMEI characteristics to correspond to some future climate state. We require that DOE consider climate change within 10,000 years, and are proposing today also to require consideration of climate change for much longer times…. As noted above, we believe the present-day RMEI represents a conservative choice if, as seems likely, future climate in the Yucca Mountain region tends to be cooler and wetter. Under wetter conditions, agricultural activities around the site area would rely less on irrigation using well water. With less use of contaminated ground water for irrigation, the contribution to the RMEI dose from contaminated food would presumably be lowered or perhaps eliminated… We believe that the RMEI, as presently defined for present-day conditions, is a reasonably conservative approach for the dose assessments, and is appropriate for wetter climate conditions. Assumptions regarding the possible uses of ground water are quite speculative and have been avoided to the extent possible in the setting of the standard (66 FR 32111). Therefore we are not redefining the RMEI characteristics in any attempt to correlate them with climatic variations, primarily due to speculation regarding the uses of ground water by man. As noted above, this approach is consistent with the NAS conclusion that there is no exact correlation between potential climate changes and shifts in the distribution and activities of human populations."

In its determination not to redefine the RMEI characteristics "in any attempt to correlate them with climatic variations, primarily due to speculation regarding the uses of ground water by man," the 2005 preamble specifically recognized that, "[u]nder wetter conditions, agricultural activities around the site area would rely less on irrigation using well water." Notwithstanding this recognition, the EPA determined that "the RMEI, as presently defined for present-day conditions, is a reasonably conservative approach for the dose assessments, and is appropriate for wetter climate conditions" (70 FR 49014 [DIRS 177357], p. 49,023).

In the following section, the methods of incorporating climate change into the biosphere model are developed, the effect of the climate change on the BDCFs is investigated, and the climate-dependent model parameters are evaluated to determine which of those parameters can be classified as those resulting from human activity.

6.11.1.2.2 Evaluation of Climate Change Effects on the BDCFs

To investigate the effect of the climate change on the BDCFs, the biosphere model was constructed for a biosphere with a range of climates from arid to semi-arid. During the first 10,000 years after the closure of the repository, the climate is projected to change from the present-day (interglacial) climate, initially evolving through a monsoon climate, to a glacial transition climate. Although the monsoon climate generally is wetter, and the glacial transition climate is wetter and cooler than the present-day climate, the biosphere would continue to be arid to semi-arid and radionuclide environmental transport pathways as well as the human exposure pathways would be expected to remain essentially unchanged. The modeling of the climate change is addressed through model input parameters. Selected model inputs have climate-dependent values; the conceptual and mathematical structures of the biosphere model remain the same for the arid to semi-arid climatic conditions.

Climate refers to the meteorological conditions that characteristically prevail in a particular region. The climate model for the Yucca Mountain region was formulated using paleoclimate and paleoenvironmental reconstructions based on microfossil evaluations in Owens Lake, California, and cores and calcite isotope records from Devils Hole, Death Valley National Park, Nevada. The sequence and duration of past climate periods are identified and applied to the Yucca Mountain site, which has a similar climate setting to project the future climate (BSC 2004 [DIRS 170002], Section 1).

Some of the forecasted future climates at Yucca Mountain were represented using the present-day analogues. Specifically, temperature and precipitation records from present-day meteorological stations located at colder and wetter sites were selected to represent future climate states (BSC 2004 [DIRS 170002], Section 6.6.1). The forecasted future climate states for the first 10,000 years postclosure, their durations, and future climate analogue locations are summarized in Table 6.11-1. BDCFs were developed for the three climate states.

Table 6.11-1. Predicted Future Climates and the Future Climate Analogue Locations for the First 10,000 Years Postclosure

Climate State	Duration	Representative Meteorological Stations
Present-day interglacial climate	400 to 600 years	Yucca Mountain region
Monsoon climate	900 to 1,400 years	Average lower bound: Yucca Mountain region Average upper bound: Nogales, Arizona Hobbs, New Mexico
Glacial transition climate	8,000 to 8,700 years	Average lower bound: Beowawe, Nevada Delta, Utah Average upper bound: Spokane, Washington Rosalia, Washington St. John, Washington

Source: BSC 2004 [DIRS 170002], Table 6-1.

To calculate BDCFs for the three climate states within the arid to semi-arid range, i.e., for the present-day, monsoon, and glacial transition climates, detailed biosphere model input sets were developed for the present-day climate and the upper bound of the glacial transition climate. These climatic conditions represent a range of arid to semi-arid conditions with respect to temperature and precipitation. For the upper bound of the glacial transition climate, climate-dependent model input parameters were based on future climate analogue sites represented by meteorological conditions in east central Washington state. BDCFs were calculated for these two climates using the same samples of input vectors to retain correlations between the runs and a proportionality function was then developed representing the dependence of the BDCFs on climate, which was used to interpolate the BDCF values for the intermediate climates between the present-day and the upper bound of the glacial transition climatic conditions. To determine the dependence of BDCFs on climate, the range of each climate-dependent biosphere model input value was determined. The range for each parameter spanned from the average value for the present-day climate to the average value for the upper bound of the glacial transition climate. The biosphere model was then executed using these parameter ranges as inputs for the climate-dependent parameters; the climate-independent parameters were not changed. Correlation coefficients were then calculated for the climate-dependent model-input parameters and the model output (i.e., the BDCFs). Correlation coefficients were found to be highest for the long-term average annual irrigation rate and the BDCFs for representative radionuclides were proportional to the value of the annual average irrigation rate. Using this proportionality, BDCFs for the monsoon climate and the glacial transition climate for each radionuclide were calculated by interpolation between the values for the present-day climate and the upper bound of the glacial transition climate. The details of these calculations are presented below.

In the first step, BDCFs were calculated for the present-day and the upper bound of glacial transition climates. The discussion and the statistics for these results are presented in Section 6.11.2. The mean values of the BDCFs for these two climate states, and the ratio of the two, are shown in Table 6.11-2.

Table 6.11-2. Mean Groundwater BDCFs for the Present-Day and Upper Bound of Glacial Transition Climates and their Ratios

Radionuclide	Mean BDCF, Sv/yr per Bq/m^3		BDCF Ratio (Glacial Transition to Present-Day Climate)
	Present-Day Climate	Glacial Transition Climate–Upper Bound	
^{14}C	1.93E–09	1.81E–09	0.94
^{36}Cl	8.09E–09	5.36E–09	0.66
^{79}Se	2.42E–08	1.37E–08	0.57
^{90}Sr	3.43E–08	2.89E–08	0.84
^{99}Tc	1.12E–09	8.87E–10	0.79
^{126}Sn	4.33E–07	2.21E–07	0.51
^{129}I	1.29E–07	1.10E–07	0.86
^{135}Cs	1.45E–08	8.79E–09	0.60
^{137}Cs	1.30E–07	7.61E–08	0.58
^{210}Pb	2.74E–06	2.16E–06	0.79
^{226}Ra	3.78E–06	2.12E–06	0.56
^{228}Ra	9.05E–07	7.17E–07	0.79
^{227}Ac	1.30E–06	7.85E–07	0.60
^{228}Th	3.15E–07	1.92E–07	0.61
^{229}Th	2.58E–06	1.46E–06	0.57
^{230}Th	1.08E–06	5.94E–07	0.55
^{232}Th	1.85E–06	9.81E–07	0.53
^{231}Pa	2.44E–06	1.33E–06	0.54
^{232}U	6.04E–07	4.24E–07	0.70
^{233}U	8.97E–08	6.03E–08	0.67
^{234}U	8.19E–08	5.59E–08	0.68

Table 6.11-2. Mean Groundwater BDCFs for the Present-Day and Upper Bound of Glacial Transition Climates and their Ratios (Continued)

Radionuclide	Mean BDCF, Sv/yr per Bq/m^3		BDCF Ratio (Glacial Transition to Present-Day Climate)
	Present-Day Climate	Glacial Transition Climate–Upper Bound	
^{235}U	9.41E–08	6.17E–08	0.66
^{236}U	7.67E–08	5.26E–08	0.69
^{238}U	7.87E–08	5.43E–08	0.69
^{237}Np	2.74E–07	1.52E–07	0.56
^{238}Pu	7.61E–07	4.60E–07	0.60
^{239}Pu	9.55E–07	5.46E–07	0.57
^{240}Pu	9.51E–07	5.45E–07	0.57
^{242}Pu	9.07E–07	5.18E–07	0.57
^{241}Am	8.34E–07	4.63E–07	0.56
^{243}Am	8.88E–07	4.87E–07	0.55

NOTE: The mean BDCF values and their ratios were calculated using Excel (file name = *GW BDCF Present-Day and Future Climates.xls*, worksheet name = *Comparison_Climates*; Appendix A).

The data in Table 6.11-2 indicate that BDCF values for the upper bound of the glacial transition climate are consistently lower than the corresponding values for the present-day climate. The differences between the BDCFs are within a factor of two. The ratios of the BDCFs for the upper bound glacial transition and the present-day climates ranged from 0.51 to 0.94, depending on a radionuclide.

Inspection of the BDCF distributions for the present-day climate presented in Section 6.11.2 (Table 6.11-8) indicates that the BDCF variability, as measured by the 95th to the 5th percentile point, is at least a factor of about 6.2 for ^{14}C, 4.0 for ^{99}Tc, 2.0 for ^{129}I, 3.2 for ^{237}Np, and 3.1 for ^{239}Pu. Variability in the BDCF values due to normal parametric uncertainty dominates the change in expected mean BDCF values caused by extreme climate change. It was therefore appropriate to use interpolation between the two extreme climate states, for which detailed information was available, to generate BDCFs for the expected distribution of climates in the future.

To evaluate this approach, the influence of climate change on the BDCF values was investigated. For the input parameters that are affected by climate change (Table 6.11-3), uniform distributions of parameter values were constructed ranging between the parameter averages for the extreme climates (i.e., the present-day and the upper bound of the glacial transition climates). The uniform distribution was selected because it is the simplest distribution that captures the range of parameter values. The value for the annual average irrigation rate was taked to be in the rage from 0.50 to 0.95 m/yr. These values correspond to the averages for the present-day and the upper bound glacial transition climates for all representative crops (MO0403SPAAEIBM.002 [DIRS 169392]). The model parameter that was this distribution was used for was the annual average garden irrigation rate.

Table 6.11-3. Climate-Dependent Input Parameters and Their Average Values for the Present-Day Climate and the Upper Bound of the Glacial Transition Climate

Parameter	Present-Day Climate	Glacial Transition Climate (Upper Bound)
Growing time, other vegetables	80 d	100 d
Growing time, fruits	160 d	105 d
Growing time, grains	200 d	185 d
Growing time, cattle forage	75 d	90 d
Irrigation application, leafy vegetables	14.7 mm	14.6 mm
Irrigation application, other vegetables	26.0 mm	25.0 mm
Irrigation application, fruits	33.9 mm	34.2 mm
Irrigation application, grains	56.7 mm	51.3 mm
Irrigation application, cattle forage	57.8 mm	53.5 mm
Average annual irrigation rate	0.95 m/yr	0.50 m/yr
Daily average irrigation rate, leafy vegetables	5.41 mm/d	3.81 mm/d
Daily average irrigation rate, other vegetables	7.71 mm/d	3.84 mm/d
Daily average irrigation rate, fruits	7.41 mm/d	3.90 mm/d
Daily average irrigation rate, grains	4.64 mm/d	3.36 mm/d
Daily average irrigation rate, cattle forage	6.55 mm/d	4.14 mm/d
Overwatering rate	0.079 m/yr	0.067 m/yr
Water concentration modifying factor (for fisheries)	4.15 [a]	2.4 [a]
Evaporative cooler use factor	0.39	0.085

Source: MO0403SPAAEIBM.002 [DIRS 169392]; MO0407SPACRBSM.002 [DIRS 170677]; MO0406SPAETPBM.002 [DIRS 170150].

[a] All radionuclides except ^{14}C, for which 1 was used.

The model was then executed using these distributions for the climate-dependent parameters, one value of the annual average irrigation rate, and the other input parameter distributions and values left unchanged. The irrigation rate was the average for all representative crops (BSC 2004 [DIRS 169673], Section 6.5); the separate values for the field and garden crops were not used. BDCF values for 1,000 model realizations were calculated for each primary radionuclide. The influence of climate-dependent input parameters on the model output was determined by calculating raw (value) correlation coefficients for the BDCFs and climate-dependent input parameters, which are listed in Table 6.11-4. The calculations were carried out using Excel spreadsheet *Correlations for Climate Dependent Parameter.xls* in Appendix A.

Table 6.11-4. Correlations (Raw Correlation Coefficients) for Groundwater BDCFs and Climate-Dependent Input Parameters

Radionuclide	Growing time				Irrigation Application				
	Other Vegetables	Fruits	Grains	Cattle Forage	Leafy Vegetables	Other Vegetables	Fruits	Grains	Cattle Forage
^{14}C	0	0	0	0	0	0	0	0	0
^{36}Cl	0	0	0	0	0	0	0	0	0
^{79}Se	0	0	0	0	0	0	0	0	0
^{90}Sr	0	0.0824	0	0	0	0	0.1001	0	0
^{99}Tc	0	0	0	0	0	0	0	0	0
^{126}Sn	0	0	0	0	0	0	0	0	0
^{129}I	0	0	0	0	0	0	0	0	0
^{135}Cs	0	0	0	0	0	0	0	0	0
^{137}Cs	0	0	0	0	0	0	0	0	0
^{210}Pb	0	0	0	0	0	0	0	0	0
^{226}Ra	0	0	0	0	0	0	0	0	0
^{228}Ra	0	0	0	0	0	0	0	0	0
^{227}Ac	0	0	0	0	0	0	0	0	0
^{228}Th	0	0	0	0	0	0	0	0	0
^{229}Th	0	0	0	0	0	0	0	0	0
^{230}Th	0	0	0	0	0	0	0	0	0
^{232}Th	0	0	0	0	0	0	0	0	0
^{231}Pa	0	0	0	0	0	0	0	0	0
^{232}U	0	0	0	0	0	0	0	0	0
^{233}U	0	0	0	0	0	0	0	0	0
^{234}U	0	0	0	0	0	0	0	0	0
^{235}U	0	0	0	0	0	0	0	0	0
^{236}U	0	0	0	0	0	0	0	0	0
^{238}U	0	0	0	0	0	0	0	0	0
^{237}Np	0	0	0	0	0	0	0	0	0
^{238}Pu	0	0	0	0	0	0	0	0	0
^{239}Pu	0	0	0	0	0	0	0	0	0
^{240}Pu	0	0	0	0	0	0	0	0	0
^{242}Pu	0	0	0	0	0	0	0	0	0
^{241}Am	0	0	0	0	0	0	0	0	0
^{243}Am	0	0	0	0	0	0	0	0	0

Table 6.11-4. Correlations (Raw Correlation Coefficients) for Groundwater BDCFs and Climate-Dependent Input Parameters (Continued)

Radionuclide	Average Annual Irrigation Rate	Daily Average Irrigation Rate					Overwatering Rate	Water concentration modifying factor	Evaporative Cooler Use Factor
		Leafy Vegetables	Other Vegetables	Fruits	Grains	Cattle Forage			
^{14}C	0	0	0	0	0	0	0	0	0
^{36}Cl	0.1648	0	0.0901	0	0	0	0	0	0
^{79}Se	0	0	0	0	0	0	0	0	0
^{90}Sr	0.2596	0	0	0	0	0	0	0	0
^{99}Tc	0.1321	0.0826	0	0	0	0	0	0	0
^{126}Sn	0.2777	0	0	0	0	0	0	0	0
^{129}I	0	0.0826	0	0	0	0.0954	0	0	0
^{135}Cs	0	0	0	0	0	0	0	0.1223	0
^{137}Cs	0.1200	0	0	0	0	0	0	0.1131	0
^{210}Pb	0	0	0	0	0	0	0	0.1094	0
^{226}Ra	0.2722	0	0	0	0	0	0	0	0
^{228}Ra	0.3125	0	0	0	0	0	0	0	0
^{227}Ac	0.1616	0	0	0	0	0	0	0	0.2073
^{228}Th	0.1612	0	0.0943	0	0	0	0	0	0.3107
^{229}Th	0.1897	0	0	0	0	0	0	0	0.1414
^{230}Th	0.2144	0	0	0	0	0	0	0	0.1311
^{232}Th	0.2867	0	0	0	0	0	0	0	0.0942
^{231}Pa	0.2267	0	0	0	0	0	0	0	0.1818
^{232}U	0.1925	0	0	0	0	0	0	0	0.1165
^{233}U	0.1267	0	0	0	0	0	0	0	0.2067
^{234}U	0.1153	0	0	0	0	0	0	0	0.2286
^{235}U	0.1763	0	0	0	0	0	0	0	0.1639
^{236}U	0.1147	0	0	0	0	0	0	0	0.2290
^{238}U	0.1352	0	0	0	0	0	0	0	0.2108
^{237}Np	0.1383	0	0.0940	0	0	0	0	0	0.3358
^{238}Pu	0	0	0.0997	0	0	0	0	0	0.2363
^{239}Pu	0.1120	0	0.1109	0	0	0	0	0	0.2335
^{240}Pu	0.1109	0	0.1106	0	0	0	0	0	0.2338
^{242}Pu	0.1124	0	0.1109	0	0	0	0	0	0.2334
^{241}Am	0.1656	0	0	0	0	0	0	0	0.1540
^{243}Am	0.1846	0	0	0	0	0	0	0	0.1547

NOTE: Values were calculated using Excel *Correlations for Climate Dependent Parameters.xls*; Appendix A. Non-zero values are provided for only those correlation coefficients that differ significantly from zero at the 99% confidence level.

In Table 6.11-4, only the correlation coefficients with values that differ from zero at the 99% confidence level are shown as non-zero numbers. The lack of correlation was determined by performing a statistical test on the correlation coefficients. The null hypothesis was that the (true) population correlation coefficient is zero. If the calculated value of the correlation coefficient for the sampling distribution is *r*, values of *t* can be calculated as:

$$t = \frac{r}{\sqrt{\frac{(1-r^2)}{n-2}}} \qquad \text{(Eq. 6.11-1)}$$

where *n* is the number of data points in the sampling distribution (i.e., 1,000). The *t*-values then can be compared with Student's *t*-values for $n-2$ degrees of freedom (Steel and Torrie 1980 [DIRS 150857], pp. 278 to 279). Values of *t* calculated for different values of *r* are listed in Table 6.11-5. The null hypothesis that the population correlation coefficient is equal to zero (no correlation) can be rejected at the 99% confidence level if the value of *t* is less than 2.576 (Steel and Torrie 1980 [DIRS 150857], Table A.3) because the one-tail area under the probability distribution function for *t* is equal to 0.995 for $t = 2.576$. This corresponds to the value of *r* equal to, or less than, 0.0813 (from Equation 6.11-1). The distribution of *t* approaches a normal distribution when the degrees of freedom are large, which is the case here. Thus, for correlation coefficients less than 0.0813, the value is set to zero in Table 6.11-4.

Table 6.11-5. Calculated Values of Correlation Coefficient and Variable *t*

Calculated Correlation Coefficient, r	*t*	Calculated Correlation Coefficient, r	*t*
0.0000	0.000	0.0790	2.504
0.0100	0.316	0.0800	2.535
0.0200	0.632	0.0810	2.567
0.0300	0.948	0.0812	2.574
0.0400	1.265	0.0813	2.577
0.0500	1.582	0.0820	2.599
0.0600	1.899	0.1000	3.175
0.0610	1.931	0.1200	3.819
0.0620	1.962	0.1400	4.467
0.0630	1.994	0.1600	5.121
0.0700	2.217	0.1800	5.781
0.0780	2.472	0.2000	6.449

NOTE: See Excel file *Correlations for GW BDCFs PDC.xls* in Appendix A for details of calculations.

Over 80% of BDCF sets (of 1,000 model realizations) are positively correlated with the average annual irrigation rate (Table 6.11-4). The BDCFs for 61% of the radionuclides are also positively correlated with the evaporative cooler use factor. BDCFs for a few radionuclides also show a positive correlation with the water concentration modifying factor and the daily average irrigation rates. However, there exists a positive correlation between all of these parameters because they all have higher values in hotter climates so these parameters are in fact correlated, although these correlations are not explicitly expressed in the biosphere model.

There is practically no correlation of the BDCFs with the crop growing times. The crop growing times are the only parameters that can be considered independent of human activities. All the remaining climate-dependent model parameters involve human actions and are related to the amount of water usage for irrigation and for evaporative cooling. This finding is important because of the requirement to vary in the performance assessment the factors that are related to climate but keep the factors related to the society constant, as they are at the time of license application, i.e., at the present-day level (10 CFR 63.305(b) [DIRS 173273] and 10 CFR 63.305(c) (70 FR 53313 [DIRS 178394])). As the effect of growing time on the BDCFs is negligible, the present-day climate BDCFs adequately represent the other aspects of the climate change in the biosphere.

This conclusion notwithstanding, it is prudent to evaluate the magnitude of the effect the climate change would have on the BDCFs. To accomplish this, a method was developed that would allow calculation of the BDCFs for all the climate states projected for the 10,000 years following the closure of the repository. The annual average irrigation rate was used as a surrogate parameter to represent the dependence of the BDCFs on all parameters that change with the ambient temperature. This parameter was selected because it had positive correlation with the BDCFs for the greatest number of radionuclides and the correlation coefficients for this parameter were relatively high, comparable with the correlation coefficients for the other climate-dependent parameters. Only the correlation coefficients for the evaporative cooler use factor were comparable in terms of the value but the development of the annual average irrigation rate involved a much larger degree of objectivity and was therefore determined to be more suitable (BSC 2004 [DIRS 169673], Section 6.5; BSC 2005 [DIRS 172827], Section 6.3.4.2). The dependence of the BDCFs on the average annual irrigation rate was further evaluated.

To evaluate the dependence of BDCFs on the annual average irrigation rate, the data from 1,000 individual model realizations were used. If the raw individual realization data are plotted, the stochastic variability among BDCFs from the multiple random inputs results in plots that show little discernable trend. To generate graphs illustrating the trend, averaging over realizations to minimize the impact of other variables was required. The results of 1,000 model realizations were sorted by annual irrigation rate, and the irrigation rate and the corresponding BDCFs were averaged in blocks of 100 values. These averages for five representative radionuclides, ^{14}C, ^{99}Tc, ^{129}I, ^{237}Np, and ^{239}Pu are shown in Table 6.11-6. Based on these results, the graphs were constructed for ^{99}Tc, ^{129}I, ^{237}Np, and ^{239}Pu, reproduced in Figure 6.11-6, which show that the BDCFs for these representative radionuclides increase with the increasing annual average irrigation rate. BDCFs for ^{14}C show a weak reverse trend and don't correlate well with any of the climate-dependent parameters (Table 6.11-4). Modeling of the ^{14}C transport in the biosphere uses a different approach than that for the other radionuclides (Section 6.4.6) and does not show the same climate dependence. The graphs were generated in Excel file *Dependence of BDCFs on Irrigation Rate.xls*; Appendix A.

Table 6.11-6. Dependence of BDCFs for ^{14}C, ^{99}Tc, ^{129}I, ^{237}Np, and ^{239}Pu on Annual Average Irrigation Rate

Realization Number [a]	Irrigation Rate [b]	Biosphere Dose Conversion Factor (Sv/yr per Bq/m^3) [c]				
		^{14}C	^{99}Tc	^{129}I	^{237}Np	^{239}Pu
1 to 100	5.22E–01	1.96E–09	6.99E–10	1.09E–07	1.85E–07	6.59E–07
101 to 200	5.67E–01	1.97E–09	7.04E–10	1.09E–07	1.90E–07	6.42E–07
201 to 300	6.13E–01	2.07E–09	7.20E–10	1.14E–07	1.84E–07	6.37E–07
301 to 400	6.58E–01	1.94E–09	7.66E–10	1.08E–07	1.87E–07	6.50E–07
401 to 500	7.03E–01	2.24E–09	7.47E–10	1.13E–07	1.97E–07	6.86E–07
501 to 600	7.47E–01	1.65E–09	7.81E–10	1.14E–07	1.88E–07	7.06E–07
601 to 700	7.93E–01	1.56E–09	7.73E–10	1.14E–07	2.04E–07	7.36E–07
701 to 800	8.38E–01	1.83E–09	8.02E–10	1.12E–07	2.03E–07	6.73E–07
801 to 900	8.83E–01	1.72E–09	7.87E–10	1.11E–07	2.04E–07	6.89E–07
901 to 1000	9.28E–01	1.81E–09	7.97E–10	1.16E–07	2.12E–07	7.35E–07

NOTE: Values were calculated using Excel (*Dependence of BDCFs on Irrigation Rate*; Appendix A).

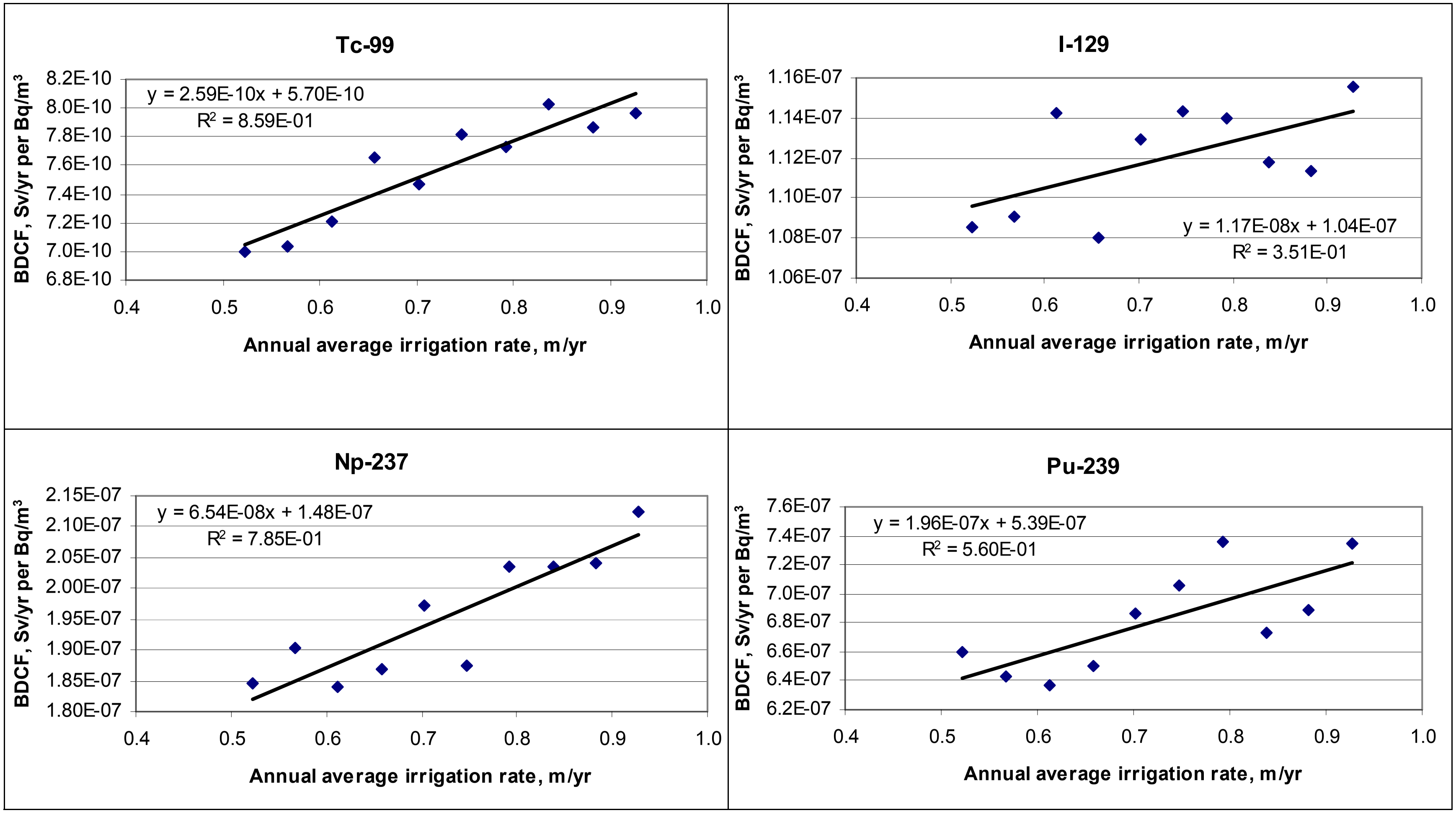
[a] Realization number after sorting by annual average irrigation rate.

[b] Average of the long-term irrigation rate (annual average irrigation rate) for the range of realizations.

[c] Average of the BDCFs for the range of realizations.

Given that the BDCFs can be shown to increase linearly with the value of a climate-dependent parameter, the annual average irrigation rate (Figure 6.11-1), the BDCFs for the average upper bound of the monsoon and the average lower bound of the glacial transition climates were calculated by interpolation between the BDCF values for the present-day and the upper bound of the glacial transition climates. The strength of the observed dependencies shows that BDCFs can be scaled with the average annual irrigation rate. Based on the future climate analogue sites, values of the average annual irrigation rates are (DTN: MO0403SPAAEIBM.002 [DIRS 169392]):

- 0.95 m/yr for the present-day climate and the lower bound of the monsoon climate
- 0.88 m/yr for the lower bound of the glacial transition climate (based on Delta, Utah)
- 0.52 m/yr for the upper bound of the monsoon climate (based on Nogales, Arizona)
- 0.50 m/yr for the upper bound of the glacial transition climate (based on Spokane and other locations in east central Washington).



Source: Table 6.11-6

Figure 6.11-1. Graphical Representation of Dependence BDCFs for ^{99}Tc, ^{129}I, ^{237}Np, and ^{239}Pu on Annual Average Irrigation Rate

Because differences between the irrigation rates for the upper bound of the monsoon (0.52 m/yr) and the upper bound of the glacial transition climates (0.50 m/yr) are small, one value of 0.50 m/yr is used. The relationship between the average annual irrigation rates and the BDCFs for the climate states under consideration is shown in Figure 6.11-2.

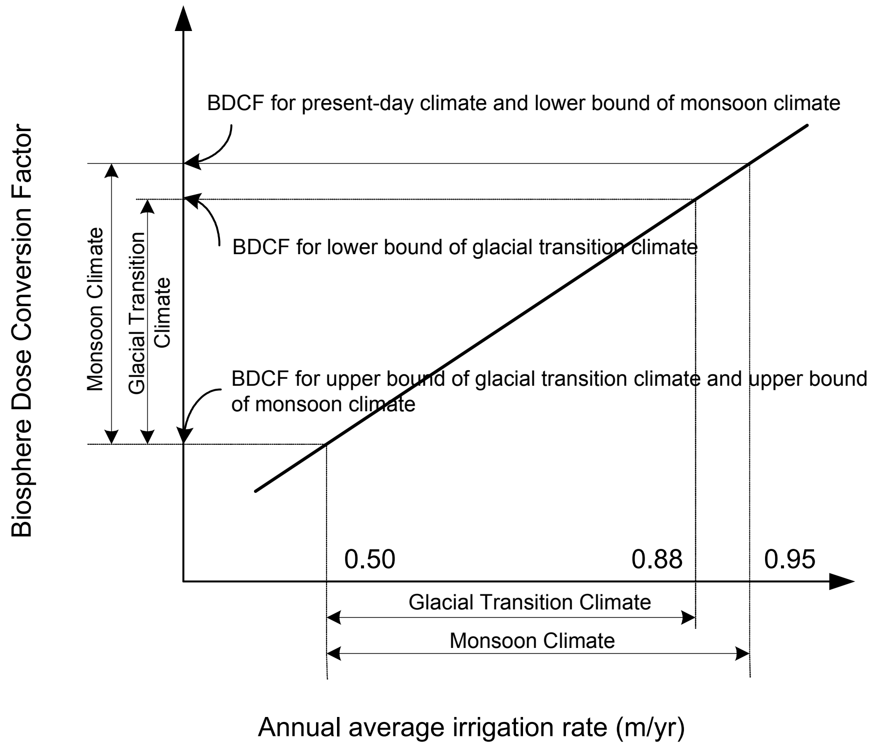


Figure 6.11-2. Scaling of the Groundwater Biosphere Dose Conversion Factors with Climate

BDCF values for the lower bound of the glacial transition climate can be calculated as:

$$BDCF_{LBGT} = BDCF_{UBGT} + \frac{0.88 - 0.50}{0.95 - 0.50}(BDCF_{IC} - BDCF_{UBGT}) \qquad \text{(Eq. 6.11-2)}$$

where

$BDCF_{LBGT}$	=	BDCF for the lower bound of glacial transition climate
$BDCF_{UBGT}$	=	BDCF for the upper bound of glacial transition climate
$BDCF_{IC}$	=	BDCF for the present-day climate (interglacial)
$\frac{0.88-0.50}{0.95-0.50}$	=	Scaling factor equal to the difference in average annual irrigation rates between the lower and upper bounds of the glacial transition climate divided by the difference in average annual irrigation rates between the present-day climate and the upper bound of the glacial transition climate.

BDCF values for individual realizations for the monsoon and the glacial transition climates were then calculated by randomly sampling over the range of BDCF values for these climates. For the monsoon climate, the sampling was over the entire range between the two extreme BDCF values for an individual realization (i.e., the values for the present-day climate and the upper bound of the glacial transition climate), and was calculated as:

$$BDCF_{MC} = BDCF_{UBGT} + (BDCF_{IC} - BDCF_{UBGT})\ RAND \qquad \text{(Eq. 6.11-3)}$$

where

$BDCF_{MC}$ = BDCF for the monsoon climate

$RAND$ = random number greater than or equal to 0 and less than 1.

For the glacial transition climate, the sampling was between the value for the lower and upper bounds of the glacial transition climate and was calculated as:

$$BDCF_{GTC} = BDCF_{UBGT} + \frac{0.88 - 0.50}{0.95 - 0.50}(BDCF_{IC} - BDCF_{UBGT})\ RAND \qquad \text{(Eq. 6.11-4)}$$

where

$BDCF_{GTC}$ = BDCF for the glacial transition climate.

These calculations were performed using Excel (*GW BDCFs Present-Day and Future Climates.xls*; Appendix A).

6.11.1.3 Incorporation of Decay Products for the Primary Radionuclides

Some BDCFs include contributions from their short-lived decay products. The primary radionuclides (radionuclides tracked in the TSPA) and the decay products, whose contributions were included in the BDCF for a primary radionuclide, are shown in Table 6.11-7.

^{232}Th is accompanied in the groundwater by ^{228}Ra and ^{228}Th (and their short-lived decay products). These radionuclides are its relatively long-lived progeny from the perspective of biosphere transport but not so for the geosphere transport. ^{228}Ra and ^{228}Th may not be tracked in the TSPA because of their half-lives, which are only 5.75 and 1.91 yr, respectively. However, the dose contribution of ^{228}Ra and ^{228}Th must be taken into account. This can be accomplished by combining BDCFs for ^{228}Ra and ^{228}Th with that of ^{232}Th, under the assumption of localized secular equilibrium between these radionuclides.

^{232}U is accompanied in the groundwater by its relatively long-lived decay product, ^{228}Th, and its short-lived decay products. The dose contribution from ^{228}Th in equilibrium with ^{232}U could be included by adding their BDCFs.

In a similar fashion, if the concentration of ^{210}Pb in groundwater is not calculated and if equilibrium could be assumed to exist between the concentrations ^{226}Ra and ^{210}Pb in the groundwater, their BDCFs should be combined to account for the ^{210}Pb dose contribution as a decay product of ^{226}Ra.

Table 6.11-7. Primary Radionuclides and their Decay Products Included in the Groundwater BDCFs

Primary Radionuclide	Decay Products Included in BDCF
^{14}C	
^{36}Cl	
^{79}Se	
^{90}Sr	^{90}Y
^{99}Tc	
^{126}Sn	
^{129}I	
^{135}Cs	
^{137}Cs	^{137m}Ba
^{210}Pb	^{210}Bi, ^{210}Po
^{226}Ra	^{222}Rn, ^{218}Po, ^{214}Pb, ^{218}At, ^{214}Bi, ^{214}Po, ^{210}Tl
^{228}Ra	^{228}Ra, ^{228}Ac
^{227}Ac	^{227}Th, ^{223}Fr, ^{223}Ra, ^{219}Rn, ^{215}Po, ^{211}Pb, ^{211}Bi, ^{207}Tl, ^{211}Po
^{228}Th	^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po, ^{208}Tl
^{229}Th	^{225}Ra, ^{225}Ac, ^{221}Fr, ^{223}At, ^{213}Bi, ^{213}Po, ^{209}Tl, ^{209}Pb
^{230}Th	
^{232}Th	
^{231}Pa	
^{232}U	
^{233}U	
^{234}U	
^{235}U	
^{236}U	
^{238}U	^{234}Th, ^{234m}Pa, ^{234}Pa
^{237}Np	^{233}Pa
^{238}Pu	
^{239}Pu	
^{240}Pu	
^{242}Pu	
^{241}Am	
^{243}Am	^{239}Np

6.11.2 Modeling Results: Groundwater Biosphere Dose Conversion Factors

BDCFs for the present-day climate, upper bound of the glacial transition climate, monsoon climate, and glacial transition climate were calculated as described in the previous section. The BDCFs for a specific climate state consist of a set of 1,000 row vectors, with vector elements representing BDCFs for different radionuclides and a row (vector) number corresponding to a model realization. These three sets of BDCF vectors for the three climate states are given in the Excel file *GW BDCFs Present-Day and Future Climates.xls* (Appendix A). Summary statistics for the BDCFs are presented in Tables 6.11-8 to 6.11-11 for the present-day climate, upper bound of the glacial transition climate, monsoon climate, and glacial transition climate, respectively. The statistics include the mean, standard deviation (STD), minimum, maximum, and percentiles of cumulative distribution in increments of 5%. The values listed in Tables 6.11-8 to 6.11-11 are presented to the third digit although only two digits are significant. This is to avoid round-off errors in the TSPA calculation of the annual dose. The BDCFs can be considered as intermediate results and, as such, should be given with an additional significant digit.

In addition, BDCF sums were produced for the three primary radionuclides, ^{226}Ra, ^{232}Th, and ^{232}U, to include the contribution from their long-lived decay products in the case the concentrations of these decay products were not calculated in the TSPA model. The statistics for these BDCF sums are also shown in Tables 6.11-8 to 6.11-11. BDCFs sums include the following radionuclides: ^{226}Ra + ^{210}Pb; ^{232}Th + ^{228}Ra + ^{228}Th; and ^{232}U + ^{228}Th, assuming radioactive equilibrium with a parent radionuclide.

Table 6.11-8. Statistics for the Groundwater BDCFs for the Present-Day Climate, Sv/yr per Bq/m^3

	^{14}C	^{36}Cl	^{79}Se	^{90}Sr	^{99}Tc	^{126}Sn	^{129}I	^{135}Cs	^{137}Cs	^{210}Pb	^{226}Ra	^{226}Ra + ^{210}Pb
Mean	1.93E–09	8.09E–09	2.42E–08	3.43E–08	1.12E–09	4.33E–07	1.29E–07	1.45E–08	1.30E–07	2.74E–06	3.78E–06	6.52E–06
STD	1.85E–09	1.41E–08	7.48E–08	6.59E–09	1.26E–09	2.39E–07	5.28E–08	1.02E–08	6.33E–08	1.13E–06	2.16E–06	2.58E–06
Minimum	7.18E–10	1.28E–09	3.62E–09	2.51E–08	5.28E–10	8.92E–08	8.59E–08	3.10E–09	3.87E–08	1.63E–06	8.79E–07	2.90E–06
5%	8.30E–10	1.88E–09	5.02E–09	2.75E–08	6.01E–10	1.57E–07	9.37E–08	4.97E–09	6.18E–08	1.82E–06	1.46E–06	3.63E–06
10%	8.78E–10	2.14E–09	5.68E–09	2.86E–08	6.29E–10	1.89E–07	9.69E–08	5.80E–09	6.97E–08	1.90E–06	1.67E–06	3.95E–06
15%	9.33E–10	2.41E–09	6.19E–09	2.93E–08	6.53E–10	2.15E–07	1.00E–07	6.68E–09	7.52E–08	1.95E–06	1.85E–06	4.20E–06
20%	9.96E–10	2.65E–09	6.64E–09	2.98E–08	6.77E–10	2.35E–07	1.02E–07	7.38E–09	8.16E–08	2.00E–06	2.08E–06	4.44E–06
25%	1.04E–09	2.96E–09	7.14E–09	3.03E–08	6.99E–10	2.58E–07	1.04E–07	7.99E–09	8.76E–08	2.06E–06	2.23E–06	4.68E–06
30%	1.09E–09	3.22E–09	7.65E–09	3.09E–08	7.26E–10	2.75E–07	1.07E–07	8.72E–09	9.32E–08	2.12E–06	2.41E–06	4.91E–06
35%	1.16E–09	3.61E–09	8.31E–09	3.13E–08	7.57E–10	2.93E–07	1.09E–07	9.35E–09	9.90E–08	2.17E–06	2.59E–06	5.16E–06
40%	1.22E–09	4.03E–09	8.89E–09	3.17E–08	7.82E–10	3.17E–07	1.11E–07	1.02E–08	1.03E–07	2.23E–06	2.76E–06	5.39E–06
45%	1.28E–09	4.42E–09	9.66E–09	3.23E–08	8.15E–10	3.44E–07	1.14E–07	1.10E–08	1.08E–07	2.29E–06	2.98E–06	5.69E–06
50%	1.36E–09	4.86E–09	1.02E–08	3.27E–08	8.51E–10	3.74E–07	1.17E–07	1.17E–08	1.14E–07	2.38E–06	3.21E–06	5.96E–06
55%	1.44E–09	5.72E–09	1.12E–08	3.34E–08	8.85E–10	4.07E–07	1.20E–07	1.26E–08	1.20E–07	2.49E–06	3.46E–06	6.23E–06
60%	1.54E–09	6.31E–09	1.24E–08	3.40E–08	9.29E–10	4.36E–07	1.24E–07	1.36E–08	1.28E–07	2.56E–06	3.74E–06	6.60E–06
65%	1.68E–09	6.99E–09	1.37E–08	3.46E–08	9.82E–10	4.70E–07	1.28E–07	1.45E–08	1.36E–07	2.67E–06	4.02E–06	6.87E–06
70%	1.86E–09	7.74E–09	1.58E–08	3.54E–08	1.05E–09	5.08E–07	1.33E–07	1.58E–08	1.46E–07	2.82E–06	4.35E–06	7.20E–06
75%	2.04E–09	8.63E–09	1.89E–08	3.63E–08	1.13E–09	5.50E–07	1.37E–07	1.73E–08	1.56E–07	2.99E–06	4.75E–06	7.70E–06
80%	2.36E–09	1.02E–08	2.27E–08	3.76E–08	1.24E–09	6.20E–07	1.43E–07	1.93E–08	1.66E–07	3.16E–06	5.23E–06	8.34E–06
85%	2.71E–09	1.19E–08	2.92E–08	3.90E–08	1.42E–09	6.84E–07	1.53E–07	2.24E–08	1.85E–07	3.46E–06	5.85E–06	8.89E–06
90%	3.28E–09	1.54E–08	4.11E–08	4.11E–08	1.79E–09	7.61E–07	1.66E–07	2.69E–08	2.06E–07	4.01E–06	6.57E–06	9.73E–06
95%	5.11E–09	2.29E–08	6.75E–08	4.63E–08	2.41E–09	8.76E–07	1.90E–07	3.46E–08	2.59E–07	5.22E–06	7.64E–06	1.11E–05
Maximum	2.56E–08	3.00E–07	1.51E–06	8.60E–08	2.85E–08	1.68E–06	1.13E–06	8.48E–08	4.56E–07	1.30E–05	1.75E–05	2.82E–05

Table 6.11-8. Statistics for the Groundwater BDCFs for the Present-Day Climate, Sv/yr per Bq/m^3 (Continued)

	^{228}Ra	^{227}Ac	^{228}Th	^{229}Th	^{230}Th	^{232}Th	^{232}Th + ^{228}Ra + ^{228}Th	^{231}Pa	^{232}U	^{232}U + ^{228}Th	^{233}U
Mean	9.05E–07	1.30E–06	3.15E–07	2.58E–06	1.08E–06	1.85E–06	3.07E–06	2.44E–06	6.04E–07	9.18E–07	8.97E–08
STD	1.40E–07	5.28E–07	8.58E–08	1.03E–06	4.34E–07	7.33E–07	8.70E–07	1.02E–06	2.17E–07	2.54E–07	3.35E–08
Minimum	6.14E–07	4.08E–07	1.38E–07	7.43E–07	2.74E–07	5.05E–07	1.35E–06	6.58E–07	2.87E–07	4.67E–07	4.13E–08
5%	7.12E–07	6.23E–07	1.95E–07	1.32E–06	5.30E–07	8.97E–07	1.88E–06	1.20E–06	3.49E–07	5.91E–07	5.14E–08
10%	7.43E–07	7.07E–07	2.16E–07	1.49E–06	6.13E–07	1.05E–06	2.10E–06	1.38E–06	3.76E–07	6.41E–07	5.58E–08
15%	7.66E–07	7.93E–07	2.33E–07	1.64E–06	6.76E–07	1.16E–06	2.23E–06	1.50E–06	4.04E–07	6.84E–07	6.00E–08
20%	7.83E–07	8.59E–07	2.44E–07	1.75E–06	7.33E–07	1.24E–06	2.33E–06	1.63E–06	4.30E–07	7.15E–07	6.41E–08
25%	8.01E–07	9.27E–07	2.55E–07	1.88E–06	7.88E–07	1.31E–06	2.44E–06	1.73E–06	4.50E–07	7.43E–07	6.68E–08
30%	8.23E–07	9.78E–07	2.64E–07	2.00E–06	8.29E–07	1.39E–06	2.53E–06	1.85E–06	4.70E–07	7.65E–07	6.97E–08
35%	8.38E–07	1.03E–06	2.75E–07	2.09E–06	8.70E–07	1.48E–06	2.64E–06	1.96E–06	4.88E–07	7.84E–07	7.23E–08
40%	8.53E–07	1.09E–06	2.87E–07	2.19E–06	9.20E–07	1.56E–06	2.74E–06	2.04E–06	5.13E–07	8.15E–07	7.50E–08
45%	8.67E–07	1.15E–06	2.96E–07	2.28E–06	9.62E–07	1.64E–06	2.83E–06	2.14E–06	5.38E–07	8.43E–07	7.79E–08
50%	8.80E–07	1.21E–06	3.06E–07	2.37E–06	1.01E–06	1.73E–06	2.96E–06	2.26E–06	5.60E–07	8.72E–07	8.09E–08
55%	9.02E–07	1.27E–06	3.19E–07	2.48E–06	1.04E–06	1.84E–06	3.06E–06	2.36E–06	5.82E–07	9.03E–07	8.46E–08
60%	9.24E–07	1.32E–06	3.27E–07	2.61E–06	1.10E–06	1.92E–06	3.20E–06	2.45E–06	5.99E–07	9.38E–07	8.87E–08
65%	9.42E–07	1.40E–06	3.39E–07	2.73E–06	1.15E–06	2.02E–06	3.29E–06	2.58E–06	6.29E–07	9.68E–07	9.31E–08
70%	9.60E–07	1.47E–06	3.50E–07	2.89E–06	1.23E–06	2.12E–06	3.39E–06	2.71E–06	6.61E–07	1.00E–06	9.87E–08
75%	9.86E–07	1.57E–06	3.63E–07	3.05E–06	1.30E–06	2.24E–06	3.55E–06	2.88E–06	7.06E–07	1.05E–06	1.05E–07
80%	1.01E–06	1.68E–06	3.80E–07	3.28E–06	1.38E–06	2.41E–06	3.73E–06	3.09E–06	7.50E–07	1.10E–06	1.12E–07
85%	1.05E–06	1.82E–06	3.94E–07	3.52E–06	1.50E–06	2.62E–06	3.96E–06	3.35E–06	8.15E–07	1.16E–06	1.21E–07
90%	1.09E–06	2.07E–06	4.15E–07	3.94E–06	1.64E–06	2.83E–06	4.18E–06	3.78E–06	8.98E–07	1.24E–06	1.33E–07
95%	1.16E–06	2.30E–06	4.70E–07	4.58E–06	1.91E–06	3.22E–06	4.72E–06	4.44E–06	1.01E–06	1.38E–06	1.52E–07
Maximum	1.53E–06	4.32E–06	8.02E–07	8.05E–06	3.27E–06	5.26E–06	6.65E–06	8.56E–06	1.86E–06	2.21E–06	3.13E–07

Table 6.11-8. Statistics for the Groundwater BDCFs for the Present-Day Climate, Sv/yr per Bq/m^3 (Continued)

	^{234}U	^{235}U	^{236}U	^{238}U	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu	^{241}Am	^{243}Am
Mean	8.19E–08	9.41E–08	7.67E–08	7.87E–08	2.74E–07	7.61E–07	9.55E–07	9.51E–07	9.07E–07	8.34E–07	8.88E–07
STD	2.81E–08	3.67E–08	2.60E–08	2.62E–08	9.70E–08	2.78E–07	3.37E–07	3.35E–07	3.20E–07	4.03E–07	4.12E–07
Minimum	3.96E–08	3.91E–08	3.75E–08	3.85E–08	1.06E–07	2.61E–07	3.49E–07	3.47E–07	3.31E–07	2.16E–07	2.21E–07
5%	4.90E–08	4.93E–08	4.61E–08	4.70E–08	1.43E–07	4.00E–07	5.20E–07	5.19E–07	4.94E–07	3.78E–07	4.07E–07
10%	5.30E–08	5.44E–08	5.00E–08	5.11E–08	1.66E–07	4.53E–07	5.85E–07	5.84E–07	5.56E–07	4.37E–07	4.76E–07
15%	5.66E–08	6.01E–08	5.33E–08	5.49E–08	1.81E–07	4.92E–07	6.35E–07	6.35E–07	6.03E–07	4.70E–07	5.14E–07
20%	6.02E–08	6.40E–08	5.66E–08	5.82E–08	1.92E–07	5.27E–07	6.70E–07	6.69E–07	6.36E–07	5.06E–07	5.55E–07
25%	6.27E–08	6.67E–08	5.88E–08	6.04E–08	2.05E–07	5.64E–07	7.06E–07	7.05E–07	6.71E–07	5.40E–07	5.89E–07
30%	6.57E–08	7.03E–08	6.17E–08	6.26E–08	2.17E–07	5.89E–07	7.43E–07	7.41E–07	7.06E–07	5.83E–07	6.27E–07
35%	6.77E–08	7.47E–08	6.35E–08	6.51E–08	2.26E–07	6.23E–07	7.82E–07	7.81E–07	7.43E–07	6.16E–07	6.67E–07
40%	7.03E–08	7.78E–08	6.60E–08	6.75E–08	2.37E–07	6.58E–07	8.29E–07	8.25E–07	7.88E–07	6.51E–07	7.12E–07
45%	7.26E–08	8.16E–08	6.81E–08	6.99E–08	2.49E–07	6.90E–07	8.62E–07	8.61E–07	8.18E–07	6.95E–07	7.60E–07
50%	7.45E–08	8.53E–08	7.00E–08	7.24E–08	2.58E–07	7.15E–07	9.01E–07	8.99E–07	8.57E–07	7.47E–07	7.96E–07
55%	7.79E–08	8.93E–08	7.31E–08	7.50E–08	2.69E–07	7.52E–07	9.38E–07	9.34E–07	8.92E–07	7.85E–07	8.45E–07
60%	8.21E–08	9.41E–08	7.68E–08	7.85E–08	2.80E–07	7.75E–07	9.75E–07	9.72E–07	9.26E–07	8.32E–07	8.97E–07
65%	8.55E–08	9.98E–08	8.01E–08	8.21E–08	2.93E–07	8.17E–07	1.02E–06	1.02E–06	9.69E–07	8.76E–07	9.39E–07
70%	8.93E–08	1.06E–07	8.36E–08	8.71E–08	3.06E–07	8.58E–07	1.08E–06	1.07E–06	1.03E–06	9.40E–07	9.89E–07
75%	9.52E–08	1.15E–07	8.89E–08	9.14E–08	3.22E–07	8.97E–07	1.14E–06	1.14E–06	1.08E–06	1.01E–06	1.07E–06
80%	1.01E–07	1.22E–07	9.39E–08	9.73E–08	3.43E–07	9.61E–07	1.19E–06	1.19E–06	1.13E–06	1.13E–06	1.19E–06
85%	1.08E–07	1.32E–07	1.01E–07	1.04E–07	3.73E–07	1.03E–06	1.27E–06	1.27E–06	1.21E–06	1.23E–06	1.30E–06
90%	1.17E–07	1.43E–07	1.09E–07	1.11E–07	4.07E–07	1.13E–06	1.38E–06	1.38E–06	1.31E–06	1.37E–06	1.42E–06
95%	1.35E–07	1.65E–07	1.25E–07	1.29E–07	4.52E–07	1.28E–06	1.61E–06	1.61E–06	1.53E–06	1.60E–06	1.67E–06
Maximum	2.20E–07	2.97E–07	2.02E–07	2.07E–07	8.05E–07	2.09E–06	2.93E–06	2.90E–06	2.79E–06	3.30E–06	3.37E–06

Sources: DTNs: MO0605SPAINEXI.003 [DIRS 177172]; MO0609SPASRPBM.004 [DIRS 179988]; MO0403SPAAEIBM.002 [DIRS 169392]; MO0407SPACRBSM.002 [DIRS 170677]; MO0406SPAETPBM.002 [DIRS 170150]; MO0503SPADCESR.000 [DIRS 172896].

NOTE: See Excel file *GW BDCFs Present-Day and Future Climates.xls* in Appendix A for details of calculations.

STD = standard deviation.

Table 6.11-9. Statistics for the Groundwater BDCFs for the Upper Bound of Glacial Transition Climate, Sv/yr per Bq/m^3

	^{14}C	^{36}Cl	^{79}Se	^{90}Sr	^{99}Tc	^{126}Sn	^{129}I	^{135}Cs	^{137}Cs	^{210}Pb	^{226}Ra	^{226}Ra + ^{210}Pb
Mean	1.81E–09	5.36E–09	1.37E–08	2.89E–08	8.87E–10	2.21E–07	1.10E–07	8.79E–09	7.61E–08	2.16E–06	2.12E–06	4.28E–06
STD	1.85E–09	1.08E–08	3.49E–08	3.54E–09	9.09E–10	1.21E–07	3.47E–08	5.58E–09	3.55E–08	6.40E–07	1.20E–06	1.44E–06
Minimum	6.27E–10	1.02E–09	3.11E–09	2.39E–08	5.06E–10	4.91E–08	8.29E–08	2.39E–09	2.48E–08	1.52E–06	5.45E–07	2.25E–06
5%	7.25E–10	1.37E–09	3.81E–09	2.53E–08	5.46E–10	8.28E–08	8.79E–08	3.45E–09	3.77E–08	1.64E–06	8.42E–07	2.68E–06
10%	7.78E–10	1.54E–09	4.22E–09	2.58E–08	5.60E–10	9.83E–08	9.00E–08	3.96E–09	4.27E–08	1.68E–06	9.65E–07	2.84E–06
15%	8.13E–10	1.67E–09	4.55E–09	2.62E–08	5.76E–10	1.10E–07	9.17E–08	4.40E–09	4.59E–08	1.70E–06	1.07E–06	3.00E–06
20%	8.65E–10	1.81E–09	4.80E–09	2.65E–08	5.88E–10	1.21E–07	9.32E–08	4.81E–09	4.94E–08	1.73E–06	1.16E–06	3.13E–06
25%	9.21E–10	1.95E–09	5.06E–09	2.67E–08	6.02E–10	1.32E–07	9.48E–08	5.23E–09	5.25E–08	1.77E–06	1.28E–06	3.26E–06
30%	9.66E–10	2.10E–09	5.33E–09	2.70E–08	6.16E–10	1.43E–07	9.64E–08	5.56E–09	5.57E–08	1.80E–06	1.37E–06	3.37E–06
35%	1.03E–09	2.25E–09	5.61E–09	2.73E–08	6.34E–10	1.52E–07	9.75E–08	5.94E–09	5.88E–08	1.83E–06	1.46E–06	3.52E–06
40%	1.10E–09	2.54E–09	5.98E–09	2.75E–08	6.49E–10	1.64E–07	9.90E–08	6.40E–09	6.08E–08	1.87E–06	1.56E–06	3.67E–06
45%	1.16E–09	2.71E–09	6.30E–09	2.78E–08	6.65E–10	1.77E–07	1.01E–07	6.85E–09	6.36E–08	1.91E–06	1.68E–06	3.82E–06
50%	1.23E–09	2.97E–09	6.70E–09	2.81E–08	6.90E–10	1.93E–07	1.03E–07	7.25E–09	6.67E–08	1.96E–06	1.81E–06	3.97E–06
55%	1.31E–09	3.40E–09	7.27E–09	2.84E–08	7.10E–10	2.09E–07	1.05E–07	7.72E–09	7.04E–08	2.02E–06	1.96E–06	4.11E–06
60%	1.42E–09	3.79E–09	8.06E–09	2.86E–08	7.36E–10	2.22E–07	1.06E–07	8.30E–09	7.46E–08	2.06E–06	2.07E–06	4.26E–06
65%	1.57E–09	4.22E–09	8.75E–09	2.90E–08	7.63E–10	2.39E–07	1.09E–07	8.83E–09	7.83E–08	2.12E–06	2.24E–06	4.47E–06
70%	1.74E–09	4.87E–09	9.79E–09	2.94E–08	8.19E–10	2.59E–07	1.12E–07	9.46E–09	8.45E–08	2.20E–06	2.41E–06	4.67E–06
75%	1.91E–09	5.49E–09	1.13E–08	2.99E–08	8.82E–10	2.83E–07	1.15E–07	1.02E–08	9.07E–08	2.30E–06	2.65E–06	4.93E–06
80%	2.25E–09	6.31E–09	1.35E–08	3.06E–08	9.69E–10	3.13E–07	1.20E–07	1.14E–08	9.65E–08	2.42E–06	2.90E–06	5.29E–06
85%	2.56E–09	7.87E–09	1.69E–08	3.14E–08	1.08E–09	3.53E–07	1.25E–07	1.31E–08	1.05E–07	2.56E–06	3.27E–06	5.58E–06
90%	3.17E–09	1.03E–08	2.39E–08	3.26E–08	1.31E–09	3.85E–07	1.34E–07	1.55E–08	1.18E–07	2.85E–06	3.63E–06	6.07E–06
95%	4.93E–09	1.48E–08	3.63E–08	3.53E–08	1.75E–09	4.44E–07	1.51E–07	1.97E–08	1.50E–07	3.49E–06	4.28E–06	6.77E–06
Maximum	2.55E–08	2.51E–07	6.55E–07	5.92E–08	1.88E–08	8.62E–07	7.50E–07	4.48E–08	2.69E–07	8.45E–06	1.03E–05	1.66E–05

Table 6.11-9. Statistics for the Groundwater BDCFs for the Upper Bound of Glacial Transition Climate, Sv/yr per Bq/m^3 (Continued)

	^{228}Ra	^{227}Ac	^{228}Th	^{229}Th	^{230}Th	^{232}Th	^{232}Th + ^{228}Ra + ^{228}Th	^{231}Pa	^{232}U	^{232}U + ^{228}Th	^{233}U
Mean	7.17E–07	7.85E–07	1.92E–07	1.46E–06	5.94E–07	9.81E–07	1.89E–06	1.33E–06	4.24E–07	6.16E–07	6.03E–08
STD	7.28E–08	2.50E–07	3.19E–08	5.03E–07	2.12E–07	3.61E–07	4.25E–07	5.03E–07	1.20E–07	1.30E–07	1.70E–08
Minimum	5.63E–07	3.68E–07	1.25E–07	6.28E–07	2.26E–07	3.17E–07	1.04E–06	5.07E–07	2.64E–07	4.06E–07	3.98E–08
5%	6.21E–07	4.68E–07	1.47E–07	8.44E–07	3.25E–07	5.00E–07	1.32E–06	7.41E–07	2.91E–07	4.67E–07	4.33E–08
10%	6.36E–07	5.04E–07	1.57E–07	9.36E–07	3.70E–07	5.81E–07	1.41E–06	8.14E–07	3.06E–07	4.84E–07	4.50E–08
15%	6.46E–07	5.38E–07	1.62E–07	1.00E–06	3.97E–07	6.39E–07	1.49E–06	8.76E–07	3.16E–07	5.00E–07	4.64E–08
20%	6.55E–07	5.71E–07	1.66E–07	1.05E–06	4.18E–07	6.81E–07	1.53E–06	9.29E–07	3.27E–07	5.11E–07	4.75E–08
25%	6.65E–07	6.03E–07	1.69E–07	1.10E–06	4.48E–07	7.13E–07	1.59E–06	9.79E–07	3.38E–07	5.24E–07	4.89E–08
30%	6.73E–07	6.30E–07	1.73E–07	1.15E–06	4.73E–07	7.50E–07	1.63E–06	1.04E–06	3.47E–07	5.34E–07	4.98E–08
35%	6.83E–07	6.55E–07	1.77E–07	1.21E–06	4.93E–07	7.91E–07	1.68E–06	1.08E–06	3.59E–07	5.46E–07	5.08E–08
40%	6.89E–07	6.88E–07	1.80E–07	1.26E–06	5.13E–07	8.40E–07	1.72E–06	1.11E–06	3.70E–07	5.62E–07	5.19E–08
45%	6.96E–07	7.13E–07	1.84E–07	1.31E–06	5.30E–07	8.79E–07	1.77E–06	1.16E–06	3.84E–07	5.72E–07	5.38E–08
50%	7.05E–07	7.41E–07	1.88E–07	1.35E–06	5.47E–07	9.24E–07	1.83E–06	1.21E–06	3.95E–07	5.84E–07	5.48E–08
55%	7.16E–07	7.72E–07	1.91E–07	1.41E–06	5.73E–07	9.71E–07	1.87E–06	1.27E–06	4.06E–07	5.99E–07	5.68E–08
60%	7.25E–07	7.98E–07	1.96E–07	1.46E–06	5.97E–07	1.01E–06	1.93E–06	1.33E–06	4.21E–07	6.14E–07	5.92E–08
65%	7.35E–07	8.32E–07	2.00E–07	1.52E–06	6.25E–07	1.06E–06	1.98E–06	1.39E–06	4.33E–07	6.28E–07	6.13E–08
70%	7.44E–07	8.69E–07	2.05E–07	1.59E–06	6.62E–07	1.11E–06	2.05E–06	1.46E–06	4.51E–07	6.49E–07	6.38E–08
75%	7.58E–07	9.16E–07	2.09E–07	1.70E–06	6.95E–07	1.17E–06	2.13E–06	1.55E–06	4.76E–07	6.80E–07	6.74E–08
80%	7.71E–07	9.67E–07	2.15E–07	1.80E–06	7.46E–07	1.25E–06	2.23E–06	1.68E–06	5.05E–07	7.09E–07	7.14E–08
85%	7.87E–07	1.04E–06	2.23E–07	1.96E–06	7.98E–07	1.35E–06	2.33E–06	1.80E–06	5.49E–07	7.52E–07	7.49E–08
90%	8.12E–07	1.13E–06	2.31E–07	2.14E–06	8.79E–07	1.47E–06	2.46E–06	1.97E–06	5.87E–07	7.86E–07	8.30E–08
95%	8.56E–07	1.26E–06	2.50E–07	2.44E–06	1.00E–06	1.64E–06	2.69E–06	2.36E–06	6.47E–07	8.46E–07	9.25E–08
Maximum	1.04E–06	1.97E–06	3.36E–07	4.11E–06	1.67E–06	2.59E–06	3.58E–06	4.10E–06	1.11E–06	1.33E–06	1.78E–07

Table 6.11-9. Statistics for the Groundwater BDCFs for the Upper Bound of Glacial Transition Climate, Sv/yr per Bq/m^3 (Continued)

	^{234}U	^{235}U	^{236}U	^{238}U	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu	^{241}Am	^{243}Am
Mean	5.59E–08	6.17E–08	5.26E–08	5.43E–08	1.52E–07	4.60E–07	5.46E–07	5.45E–07	5.18E–07	4.63E–07	4.87E–07
STD	1.44E–08	1.88E–08	1.34E–08	1.36E–08	3.71E–08	1.46E–07	1.70E–07	1.69E–07	1.62E–07	1.97E–07	2.00E–07
Minimum	3.83E–08	3.69E–08	3.62E–08	3.72E–08	9.20E–08	2.27E–07	2.69E–07	2.69E–07	2.56E–07	1.74E–07	1.77E–07
5%	4.14E–08	4.06E–08	3.92E–08	4.03E–08	1.05E–07	2.80E–07	3.44E–07	3.43E–07	3.26E–07	2.44E–07	2.60E–07
10%	4.29E–08	4.28E–08	4.05E–08	4.16E–08	1.11E–07	3.01E–07	3.66E–07	3.66E–07	3.48E–07	2.69E–07	2.88E–07
15%	4.42E–08	4.44E–08	4.18E–08	4.29E–08	1.19E–07	3.23E–07	3.87E–07	3.87E–07	3.68E–07	2.83E–07	3.03E–07
20%	4.52E–08	4.62E–08	4.27E–08	4.41E–08	1.23E–07	3.39E–07	4.07E–07	4.07E–07	3.87E–07	3.03E–07	3.25E–07
25%	4.62E–08	4.78E–08	4.37E–08	4.51E–08	1.27E–07	3.56E–07	4.22E–07	4.21E–07	4.00E–07	3.24E–07	3.44E–07
30%	4.72E–08	4.92E–08	4.45E–08	4.59E–08	1.31E–07	3.71E–07	4.42E–07	4.41E–07	4.20E–07	3.40E–07	3.60E–07
35%	4.81E–08	5.09E–08	4.54E–08	4.68E–08	1.35E–07	3.85E–07	4.61E–07	4.59E–07	4.37E–07	3.54E–07	3.79E–07
40%	4.90E–08	5.29E–08	4.62E–08	4.78E–08	1.38E–07	4.00E–07	4.75E–07	4.74E–07	4.51E–07	3.75E–07	3.98E–07
45%	5.04E–08	5.47E–08	4.74E–08	4.91E–08	1.41E–07	4.15E–07	4.91E–07	4.91E–07	4.66E–07	3.92E–07	4.18E–07
50%	5.16E–08	5.67E–08	4.87E–08	5.04E–08	1.45E–07	4.30E–07	5.09E–07	5.08E–07	4.83E–07	4.14E–07	4.43E–07
55%	5.28E–08	5.93E–08	4.96E–08	5.19E–08	1.48E–07	4.44E–07	5.29E–07	5.28E–07	5.02E–07	4.38E–07	4.63E–07
60%	5.45E–08	6.14E–08	5.13E–08	5.34E–08	1.52E–07	4.65E–07	5.45E–07	5.44E–07	5.18E–07	4.58E–07	4.83E–07
65%	5.66E–08	6.41E–08	5.33E–08	5.55E–08	1.58E–07	4.81E–07	5.70E–07	5.70E–07	5.42E–07	4.87E–07	5.15E–07
70%	5.90E–08	6.77E–08	5.54E–08	5.75E–08	1.63E–07	5.07E–07	5.97E–07	5.96E–07	5.67E–07	5.17E–07	5.42E–07
75%	6.14E–08	7.15E–08	5.77E–08	6.04E–08	1.70E–07	5.32E–07	6.22E–07	6.21E–07	5.91E–07	5.53E–07	5.73E–07
80%	6.43E–08	7.64E–08	6.03E–08	6.28E–08	1.78E–07	5.62E–07	6.67E–07	6.66E–07	6.34E–07	5.98E–07	6.20E–07
85%	6.81E–08	8.04E–08	6.39E–08	6.64E–08	1.89E–07	6.00E–07	7.00E–07	7.00E–07	6.65E–07	6.57E–07	6.87E–07
90%	7.49E–08	8.72E–08	7.01E–08	7.21E–08	2.03E–07	6.46E–07	7.77E–07	7.77E–07	7.38E–07	7.41E–07	7.60E–07
95%	8.44E–08	9.61E–08	7.90E–08	8.13E–08	2.24E–07	7.43E–07	8.80E–07	8.77E–07	8.37E–07	8.60E–07	8.79E–07
Maximum	1.39E–07	1.72E–07	1.31E–07	1.31E–07	3.64E–07	1.15E–06	1.39E–06	1.37E–06	1.32E–06	1.65E–06	1.69E–06

Sources: DTNs: MO0605SPAINEXI.003 [DIRS 177172]; MO0609SPASRPBM.004 [DIRS 179988]; MO0403SPAAEIBM.002 [DIRS 169392]; MO0407SPACRBSM.002 [DIRS 170677]; MO0406SPAETPBM.002 [DIRS 170150]; MO0503SPADCESR.000 [DIRS 172896].

NOTE: See Excel file *GW BDCFs Present-Day and Future Climates.xls* in Appendix A for details of calculations.

STD = standard deviation.

Table 6.11-10. Statistics for the Groundwater BDCFs for the Monsoon Climate, Sv/yr per Bq/m^3

	^{14}C	^{36}Cl	^{79}Se	^{90}Sr	^{99}Tc	^{126}Sn	^{129}I	^{135}Cs	^{137}Cs	^{210}Pb	^{226}Ra	^{226}Ra + ^{210}Pb
Mean	1.87E–09	6.65E–09	1.91E–08	3.16E–08	1.00E–09	3.24E–07	1.19E–07	1.16E–08	1.03E–07	2.45E–06	2.92E–06	5.37E–06
STD	1.85E–09	1.18E–08	5.95E–08	5.55E–09	1.01E–09	1.89E–07	4.15E–08	8.10E–09	5.22E–08	9.16E–07	1.72E–06	2.08E–06
Minimum	6.68E–10	1.07E–09	3.15E–09	2.43E–08	5.08E–10	6.44E–08	8.46E–08	2.52E–09	2.72E–08	1.55E–06	7.24E–07	2.36E–06
5%	7.81E–10	1.58E–09	4.35E–09	2.61E–08	5.69E–10	1.12E–07	8.98E–08	4.05E–09	4.80E–08	1.70E–06	1.07E–06	3.02E–06
10%	8.20E–10	1.77E–09	4.86E–09	2.68E–08	5.91E–10	1.31E–07	9.27E–08	4.69E–09	5.29E–08	1.76E–06	1.27E–06	3.28E–06
15%	8.72E–10	1.97E–09	5.25E–09	2.73E–08	6.12E–10	1.54E–07	9.54E–08	5.46E–09	5.71E–08	1.81E–06	1.42E–06	3.49E–06
20%	9.31E–10	2.22E–09	5.60E–09	2.78E–08	6.30E–10	1.71E–07	9.73E–08	5.91E–09	6.21E–08	1.84E–06	1.54E–06	3.67E–06
25%	9.91E–10	2.42E–09	6.02E–09	2.82E–08	6.48E–10	1.84E–07	9.96E–08	6.29E–09	6.70E–08	1.90E–06	1.69E–06	3.84E–06
30%	1.04E–09	2.65E–09	6.42E–09	2.87E–08	6.63E–10	1.98E–07	1.01E–07	6.94E–09	7.05E–08	1.95E–06	1.80E–06	4.05E–06
35%	1.10E–09	2.90E–09	6.80E–09	2.92E–08	6.86E–10	2.19E–07	1.03E–07	7.52E–09	7.62E–08	2.00E–06	1.99E–06	4.25E–06
40%	1.15E–09	3.22E–09	7.29E–09	2.96E–08	7.06E–10	2.39E–07	1.05E–07	8.04E–09	8.18E–08	2.05E–06	2.18E–06	4.46E–06
45%	1.22E–09	3.56E–09	7.83E–09	2.99E–08	7.37E–10	2.55E–07	1.07E–07	8.79E–09	8.62E–08	2.11E–06	2.30E–06	4.63E–06
50%	1.29E–09	3.96E–09	8.45E–09	3.03E–08	7.66E–10	2.75E–07	1.09E–07	9.38E–09	9.05E–08	2.16E–06	2.45E–06	4.87E–06
55%	1.38E–09	4.40E–09	9.26E–09	3.07E–08	8.00E–10	2.96E–07	1.12E–07	1.01E–08	9.54E–08	2.22E–06	2.65E–06	5.15E–06
60%	1.48E–09	5.06E–09	1.01E–08	3.11E–08	8.35E–10	3.22E–07	1.16E–07	1.10E–08	1.03E–07	2.28E–06	2.88E–06	5.40E–06
65%	1.61E–09	5.67E–09	1.12E–08	3.17E–08	8.79E–10	3.49E–07	1.19E–07	1.17E–08	1.08E–07	2.39E–06	3.12E–06	5.69E–06
70%	1.79E–09	6.41E–09	1.28E–08	3.23E–08	9.40E–10	3.81E–07	1.22E–07	1.26E–08	1.14E–07	2.49E–06	3.41E–06	6.03E–06
75%	1.97E–09	7.10E–09	1.49E–08	3.33E–08	1.02E–09	4.20E–07	1.27E–07	1.37E–08	1.21E–07	2.63E–06	3.70E–06	6.37E–06
80%	2.29E–09	8.46E–09	1.77E–08	3.42E–08	1.11E–09	4.67E–07	1.32E–07	1.48E–08	1.31E–07	2.79E–06	4.07E–06	6.82E–06
85%	2.64E–09	9.61E–09	2.30E–08	3.57E–08	1.27E–09	5.17E–07	1.38E–07	1.74E–08	1.43E–07	3.06E–06	4.53E–06	7.33E–06
90%	3.24E–09	1.27E–08	3.29E–08	3.76E–08	1.54E–09	5.82E–07	1.50E–07	2.15E–08	1.68E–07	3.47E–06	5.12E–06	7.97E–06
95%	4.96E–09	1.92E–08	5.12E–08	4.17E–08	2.06E–09	6.70E–07	1.75E–07	2.77E–08	2.06E–07	4.36E–06	6.09E–06	9.09E–06
Maximum	2.55E–08	2.61E–07	1.34E–06	8.44E–08	2.01E–08	1.63E–06	8.00E–07	7.30E–08	4.05E–07	9.29E–06	1.15E–05	1.87E–05

Table 6.11-10. Statistics for the Groundwater BDCFs for the Monsoon Climate, Sv/yr per Bq/m^3 (Continued)

	^{228}Ra	^{227}Ac	^{228}Th	^{229}Th	^{230}Th	^{232}Th	^{232}Th + ^{228}Ra + ^{228}Th	^{231}Pa	^{232}U	^{232}U + ^{228}Th	^{233}U
Mean	8.09E–07	1.04E–06	2.52E–07	2.01E–06	8.33E–07	1.41E–06	2.47E–06	1.88E–06	5.12E–07	7.64E–07	7.48E–08
STD	1.21E–07	4.25E–07	7.01E–08	8.41E–07	3.55E–07	6.03E–07	7.35E–07	8.39E–07	1.77E–07	2.11E–07	2.70E–08
Minimum	5.93E–07	3.86E–07	1.30E–07	6.88E–07	2.51E–07	4.06E–07	1.20E–06	6.01E–07	2.77E–07	4.34E–07	4.03E–08
5%	6.50E–07	5.34E–07	1.64E–07	9.96E–07	3.94E–07	6.58E–07	1.51E–06	8.98E–07	3.13E–07	5.17E–07	4.67E–08
10%	6.76E–07	5.89E–07	1.74E–07	1.15E–06	4.62E–07	7.67E–07	1.68E–06	1.04E–06	3.35E–07	5.42E–07	4.92E–08
15%	6.95E–07	6.46E–07	1.85E–07	1.25E–06	5.14E–07	8.34E–07	1.77E–06	1.12E–06	3.54E–07	5.70E–07	5.16E–08
20%	7.08E–07	6.90E–07	1.94E–07	1.35E–06	5.48E–07	9.10E–07	1.87E–06	1.20E–06	3.72E–07	5.92E–07	5.39E–08
25%	7.23E–07	7.31E–07	2.01E–07	1.41E–06	5.83E–07	9.70E–07	1.93E–06	1.28E–06	3.84E–07	6.14E–07	5.60E–08
30%	7.36E–07	7.77E–07	2.10E–07	1.49E–06	6.18E–07	1.02E–06	2.00E–06	1.36E–06	4.03E–07	6.34E–07	5.81E–08
35%	7.46E–07	8.21E–07	2.16E–07	1.57E–06	6.53E–07	1.08E–06	2.07E–06	1.44E–06	4.18E–07	6.54E–07	6.06E–08
40%	7.57E–07	8.58E–07	2.24E–07	1.65E–06	6.88E–07	1.14E–06	2.13E–06	1.51E–06	4.37E–07	6.75E–07	6.31E–08
45%	7.67E–07	9.07E–07	2.34E–07	1.74E–06	7.28E–07	1.21E–06	2.23E–06	1.61E–06	4.51E–07	6.95E–07	6.53E–08
50%	7.83E–07	9.54E–07	2.42E–07	1.84E–06	7.66E–07	1.28E–06	2.33E–06	1.71E–06	4.67E–07	7.16E–07	6.81E–08
55%	7.99E–07	9.96E–07	2.49E–07	1.93E–06	8.05E–07	1.37E–06	2.41E–06	1.80E–06	4.88E–07	7.43E–07	7.13E–08
60%	8.18E–07	1.05E–06	2.58E–07	2.02E–06	8.43E–07	1.44E–06	2.55E–06	1.89E–06	5.06E–07	7.69E–07	7.40E–08
65%	8.35E–07	1.12E–06	2.66E–07	2.13E–06	8.97E–07	1.53E–06	2.64E–06	1.99E–06	5.32E–07	7.99E–07	7.72E–08
70%	8.59E–07	1.19E–06	2.78E–07	2.27E–06	9.37E–07	1.62E–06	2.75E–06	2.09E–06	5.60E–07	8.28E–07	8.15E–08
75%	8.79E–07	1.25E–06	2.92E–07	2.38E–06	9.93E–07	1.73E–06	2.90E–06	2.26E–06	5.89E–07	8.71E–07	8.60E–08
80%	9.08E–07	1.33E–06	3.06E–07	2.54E–06	1.07E–06	1.85E–06	3.05E–06	2.43E–06	6.27E–07	9.21E–07	9.11E–08
85%	9.37E–07	1.44E–06	3.19E–07	2.76E–06	1.17E–06	1.99E–06	3.18E–06	2.66E–06	6.81E–07	9.69E–07	9.68E–08
90%	9.76E–07	1.58E–06	3.45E–07	3.11E–06	1.28E–06	2.16E–06	3.39E–06	2.95E–06	7.43E–07	1.04E–06	1.09E–07
95%	1.04E–06	1.87E–06	3.73E–07	3.60E–06	1.52E–06	2.56E–06	3.88E–06	3.49E–06	8.53E–07	1.16E–06	1.25E–07
Maximum	1.44E–06	3.69E–06	5.92E–07	6.71E–06	2.67E–06	4.03E–06	5.38E–06	5.98E–06	1.48E–06	1.80E–06	2.39E–07

Table 6.11-10. Statistics for the Groundwater BDCFs for the Monsoon Climate, Sv/yr per Bq/m^3 (Continued)

	^{234}U	^{235}U	^{236}U	^{238}U	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu	^{241}Am	^{243}Am
Mean	6.87E–08	7.76E–08	6.45E–08	6.63E–08	2.12E–07	6.10E–07	7.48E–07	7.46E–07	7.11E–07	6.47E–07	6.86E–07
STD	2.28E–08	2.96E–08	2.11E–08	2.13E–08	7.73E–08	2.35E–07	2.87E–07	2.85E–07	2.73E–07	3.27E–07	3.35E–07
Minimum	3.87E–08	3.79E–08	3.66E–08	3.76E–08	9.21E–08	2.36E–07	2.92E–07	2.91E–07	2.77E–07	2.00E–07	2.05E–07
5%	4.44E–08	4.41E–08	4.20E–08	4.30E–08	1.21E–07	3.27E–07	4.10E–07	4.10E–07	3.90E–07	2.92E–07	3.15E–07
10%	4.68E–08	4.72E–08	4.42E–08	4.54E–08	1.33E–07	3.67E–07	4.52E–07	4.51E–07	4.30E–07	3.26E–07	3.56E–07
15%	4.89E–08	5.08E–08	4.61E–08	4.75E–08	1.41E–07	3.95E–07	4.85E–07	4.84E–07	4.61E–07	3.52E–07	3.88E–07
20%	5.10E–08	5.37E–08	4.81E–08	4.97E–08	1.49E–07	4.17E–07	5.11E–07	5.10E–07	4.85E–07	3.89E–07	4.18E–07
25%	5.26E–08	5.64E–08	4.95E–08	5.13E–08	1.56E–07	4.40E–07	5.34E–07	5.34E–07	5.08E–07	4.20E–07	4.49E–07
30%	5.47E–08	5.87E–08	5.15E–08	5.32E–08	1.64E–07	4.58E–07	5.67E–07	5.66E–07	5.39E–07	4.44E–07	4.77E–07
35%	5.68E–08	6.15E–08	5.35E–08	5.48E–08	1.72E–07	4.84E–07	5.96E–07	5.93E–07	5.67E–07	4.73E–07	5.05E–07
40%	5.89E–08	6.40E–08	5.54E–08	5.70E–08	1.78E–07	5.11E–07	6.27E–07	6.26E–07	5.96E–07	5.01E–07	5.34E–07
45%	6.12E–08	6.66E–08	5.75E–08	5.91E–08	1.87E–07	5.34E–07	6.55E–07	6.52E–07	6.22E–07	5.28E–07	5.68E–07
50%	6.36E–08	7.04E–08	5.97E–08	6.12E–08	1.94E–07	5.57E–07	6.85E–07	6.83E–07	6.50E–07	5.62E–07	6.06E–07
55%	6.57E–08	7.39E–08	6.17E–08	6.36E–08	2.05E–07	5.87E–07	7.19E–07	7.16E–07	6.83E–07	6.02E–07	6.43E–07
60%	6.83E–08	7.86E–08	6.38E–08	6.61E–08	2.16E–07	6.17E–07	7.55E–07	7.52E–07	7.17E–07	6.39E–07	6.78E–07
65%	7.14E–08	8.26E–08	6.70E–08	6.88E–08	2.27E–07	6.50E–07	7.96E–07	7.92E–07	7.56E–07	6.76E–07	7.20E–07
70%	7.37E–08	8.63E–08	6.92E–08	7.19E–08	2.39E–07	6.81E–07	8.39E–07	8.38E–07	7.96E–07	7.26E–07	7.71E–07
75%	7.79E–08	9.13E–08	7.30E–08	7.57E–08	2.50E–07	7.26E–07	8.81E–07	8.78E–07	8.37E–07	7.86E–07	8.40E–07
80%	8.31E–08	9.88E–08	7.76E–08	8.04E–08	2.64E–07	7.69E–07	9.37E–07	9.34E–07	8.92E–07	8.55E–07	9.03E–07
85%	8.83E–08	1.05E–07	8.27E–08	8.60E–08	2.83E–07	8.25E–07	1.02E–06	1.02E–06	9.73E–07	9.42E–07	9.83E–07
90%	9.67E–08	1.17E–07	9.00E–08	9.34E–08	3.08E–07	9.13E–07	1.13E–06	1.13E–06	1.08E–06	1.09E–06	1.15E–06
95%	1.11E–07	1.33E–07	1.04E–07	1.08E–07	3.59E–07	1.08E–06	1.30E–06	1.30E–06	1.24E–06	1.29E–06	1.38E–06
Maximum	2.03E–07	2.40E–07	1.89E–07	1.89E–07	6.13E–07	1.84E–06	2.09E–06	2.09E–06	1.99E–06	2.56E–06	2.62E–06

Sources: DTNs: MO0605SPAINEXI.003 [DIRS 177172]; MO0609SPASRPBM.004 [DIRS 179988]; MO0403SPAAEIBM.002 [DIRS 169392]; MO0407SPACRBSM.002 [DIRS 170677]; MO0406SPAETPBM.002 [DIRS 170150]; MO0503SPADCESR.000 [DIRS 172896].

NOTE: See Excel file *GW BDCFs Present-Day and Future Climates.xls* in Appendix A for details of calculations.

STD = standard deviation.

Table 6.11-11. Statistics for the Groundwater BDCFs for the Glacial Transition Climate, Sv/yr per Bq/m^3

	^{14}C	^{36}Cl	^{79}Se	^{90}Sr	^{99}Tc	^{126}Sn	^{129}I	^{135}Cs	^{137}Cs	^{210}Pb	^{226}Ra	^{226}Ra + ^{210}Pb
Mean	1.86E–09	6.52E–09	1.79E–08	3.13E–08	9.94E–10	3.14E–07	1.18E–07	1.14E–08	9.99E–08	2.41E–06	2.84E–06	5.25E–06
STD	1.85E–09	1.18E–08	5.13E–08	5.14E–09	1.10E–09	1.83E–07	4.26E–08	8.00E–09	5.06E–08	8.49E–07	1.68E–06	2.00E–06
Minimum	6.59E–10	1.09E–09	3.22E–09	2.40E–08	5.12E–10	5.38E–08	8.31E–08	2.78E–09	2.81E–08	1.53E–06	7.07E–07	2.30E–06
5%	7.67E–10	1.53E–09	4.21E–09	2.61E–08	5.61E–10	1.06E–07	9.02E–08	3.98E–09	4.57E–08	1.70E–06	1.02E–06	3.02E–06
10%	8.20E–10	1.79E–09	4.77E–09	2.67E–08	5.86E–10	1.29E–07	9.29E–08	4.67E–09	5.18E–08	1.76E–06	1.24E–06	3.26E–06
15%	8.70E–10	1.96E–09	5.21E–09	2.71E–08	6.06E–10	1.49E–07	9.49E–08	5.22E–09	5.81E–08	1.80E–06	1.38E–06	3.44E–06
20%	9.20E–10	2.14E–09	5.59E–09	2.77E–08	6.22E–10	1.65E–07	9.71E–08	5.71E–09	6.19E–08	1.85E–06	1.52E–06	3.66E–06
25%	9.72E–10	2.31E–09	5.94E–09	2.81E–08	6.42E–10	1.81E–07	9.88E–08	6.30E–09	6.54E–08	1.89E–06	1.66E–06	3.86E–06
30%	1.02E–09	2.57E–09	6.32E–09	2.84E–08	6.66E–10	1.96E–07	1.00E–07	6.79E–09	6.91E–08	1.93E–06	1.79E–06	4.05E–06
35%	1.08E–09	2.90E–09	6.78E–09	2.89E–08	6.85E–10	2.12E–07	1.02E–07	7.35E–09	7.35E–08	1.98E–06	1.92E–06	4.21E–06
40%	1.15E–09	3.15E–09	7.15E–09	2.93E–08	7.05E–10	2.28E–07	1.05E–07	7.94E–09	7.68E–08	2.03E–06	2.11E–06	4.37E–06
45%	1.21E–09	3.45E–09	7.71E–09	2.97E–08	7.31E–10	2.47E–07	1.07E–07	8.56E–09	8.15E–08	2.08E–06	2.26E–06	4.62E–06
50%	1.28E–09	3.78E–09	8.23E–09	3.00E–08	7.52E–10	2.67E–07	1.09E–07	9.08E–09	8.75E–08	2.14E–06	2.40E–06	4.77E–06
55%	1.36E–09	4.30E–09	9.04E–09	3.06E–08	7.88E–10	2.89E–07	1.12E–07	9.57E–09	9.25E–08	2.20E–06	2.56E–06	4.97E–06
60%	1.46E–09	4.86E–09	9.78E–09	3.11E–08	8.24E–10	3.09E–07	1.14E–07	1.04E–08	9.78E–08	2.29E–06	2.76E–06	5.23E–06
65%	1.62E–09	5.54E–09	1.09E–08	3.16E–08	8.78E–10	3.39E–07	1.17E–07	1.13E–08	1.04E–07	2.38E–06	3.01E–06	5.49E–06
70%	1.80E–09	6.17E–09	1.26E–08	3.21E–08	9.32E–10	3.71E–07	1.21E–07	1.22E–08	1.11E–07	2.48E–06	3.22E–06	5.78E–06
75%	1.98E–09	7.07E–09	1.47E–08	3.29E–08	9.96E–10	3.94E–07	1.25E–07	1.33E–08	1.19E–07	2.60E–06	3.53E–06	6.16E–06
80%	2.29E–09	8.21E–09	1.74E–08	3.38E–08	1.09E–09	4.42E–07	1.29E–07	1.50E–08	1.29E–07	2.76E–06	3.93E–06	6.60E–06
85%	2.64E–09	9.79E–09	2.24E–08	3.49E–08	1.24E–09	4.84E–07	1.37E–07	1.74E–08	1.45E–07	2.92E–06	4.44E–06	7.17E–06
90%	3.21E–09	1.25E–08	3.20E–08	3.68E–08	1.47E–09	5.67E–07	1.47E–07	2.09E–08	1.63E–07	3.30E–06	5.09E–06	7.73E–06
95%	5.05E–09	1.87E–08	4.99E–08	4.03E–08	2.02E–09	6.75E–07	1.70E–07	2.67E–08	2.00E–07	4.28E–06	5.98E–06	8.97E–06
Maximum	2.55E–08	2.54E–07	1.20E–06	6.71E–08	2.49E–08	1.40E–06	9.30E–07	7.21E–08	3.91E–07	9.32E–06	1.37E–05	1.88E–05

Table 6.11-11. Statistics for the Groundwater BDCFs for the Glacial Transition Climate, Sv/yr per Bq/m^3 (Continued)

	^{228}Ra	^{227}Ac	^{228}Th	^{229}Th	^{230}Th	^{232}Th	^{232}Th + ^{228}Ra + ^{228}Th	^{231}Pa	^{232}U	^{232}U + ^{228}Th	^{233}U
Mean	8.00E–07	1.02E–06	2.46E–07	1.95E–06	8.07E–07	1.36E–06	2.41E–06	1.81E–06	5.03E–07	7.49E–07	7.33E–08
STD	1.15E–07	4.04E–07	6.43E–08	7.78E–07	3.32E–07	5.69E–07	6.91E–07	7.82E–07	1.71E–07	2.01E–07	2.58E–08
Minimum	5.77E–07	3.98E–07	1.26E–07	6.60E–07	2.38E–07	3.38E–07	1.08E–06	6.24E–07	2.65E–07	4.21E–07	3.99E–08
5%	6.53E–07	5.22E–07	1.61E–07	9.98E–07	3.99E–07	6.28E–07	1.52E–06	8.79E–07	3.14E–07	5.03E–07	4.58E–08
10%	6.70E–07	5.83E–07	1.75E–07	1.13E–06	4.60E–07	7.48E–07	1.63E–06	1.03E–06	3.29E–07	5.41E–07	4.88E–08
15%	6.87E–07	6.25E–07	1.84E–07	1.23E–06	4.97E–07	8.09E–07	1.73E–06	1.12E–06	3.49E–07	5.59E–07	5.14E–08
20%	7.01E–07	6.80E–07	1.95E–07	1.31E–06	5.36E–07	8.64E–07	1.82E–06	1.19E–06	3.65E–07	5.84E–07	5.35E–08
25%	7.15E–07	7.28E–07	2.01E–07	1.40E–06	5.74E–07	9.51E–07	1.90E–06	1.26E–06	3.79E–07	6.05E–07	5.54E–08
30%	7.28E–07	7.70E–07	2.08E–07	1.47E–06	6.07E–07	1.03E–06	1.99E–06	1.35E–06	3.97E–07	6.31E–07	5.74E–08
35%	7.40E–07	8.15E–07	2.14E–07	1.54E–06	6.33E–07	1.07E–06	2.06E–06	1.42E–06	4.11E–07	6.49E–07	5.97E–08
40%	7.55E–07	8.50E–07	2.20E–07	1.61E–06	6.65E–07	1.13E–06	2.14E–06	1.49E–06	4.27E–07	6.65E–07	6.18E–08
45%	7.69E–07	8.91E–07	2.28E–07	1.70E–06	7.04E–07	1.19E–06	2.21E–06	1.56E–06	4.47E–07	6.88E–07	6.43E–08
50%	7.85E–07	9.34E–07	2.36E–07	1.79E–06	7.44E–07	1.26E–06	2.28E–06	1.63E–06	4.62E–07	7.09E–07	6.64E–08
55%	7.96E–07	9.84E–07	2.42E–07	1.87E–06	7.85E–07	1.33E–06	2.36E–06	1.73E–06	4.78E–07	7.24E–07	6.97E–08
60%	8.11E–07	1.04E–06	2.51E–07	1.98E–06	8.27E–07	1.39E–06	2.45E–06	1.81E–06	5.01E–07	7.48E–07	7.22E–08
65%	8.28E–07	1.08E–06	2.60E–07	2.10E–06	8.79E–07	1.48E–06	2.57E–06	1.91E–06	5.22E–07	7.77E–07	7.51E–08
70%	8.43E–07	1.13E–06	2.69E–07	2.20E–06	9.14E–07	1.57E–06	2.70E–06	2.04E–06	5.46E–07	8.08E–07	7.87E–08
75%	8.64E–07	1.19E–06	2.81E–07	2.32E–06	9.75E–07	1.66E–06	2.80E–06	2.18E–06	5.77E–07	8.48E–07	8.30E–08
80%	8.88E–07	1.28E–06	2.91E–07	2.45E–06	1.04E–06	1.78E–06	2.94E–06	2.31E–06	6.16E–07	8.86E–07	8.90E–08
85%	9.09E–07	1.41E–06	3.06E–07	2.68E–06	1.11E–06	1.92E–06	3.09E–06	2.52E–06	6.69E–07	9.38E–07	9.69E–08
90%	9.48E–07	1.58E–06	3.26E–07	3.01E–06	1.22E–06	2.13E–06	3.32E–06	2.80E–06	7.34E–07	1.02E–06	1.06E–07
95%	1.02E–06	1.79E–06	3.61E–07	3.49E–06	1.45E–06	2.40E–06	3.66E–06	3.26E–06	8.37E–07	1.15E–06	1.23E–07
Maximum	1.34E–06	3.34E–06	5.63E–07	6.05E–06	2.61E–06	4.29E–06	5.64E–06	7.10E–06	1.51E–06	1.79E–06	2.48E–07

Table 6.11-11. Statistics for the Groundwater BDCFs for the Glacial Transition Climate, Sv/yr per Bq/m^3 (Continued)

	^{234}U	^{235}U	^{236}U	^{238}U	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu	^{241}Am	^{243}Am
Mean	6.74E–08	7.60E–08	6.33E–08	6.51E–08	2.05E–07	5.91E–07	7.24E–07	7.22E–07	6.88E–07	6.23E–07	6.61E–07
STD	2.17E–08	2.83E–08	2.01E–08	2.03E–08	7.07E–08	2.15E–07	2.62E–07	2.61E–07	2.49E–07	2.99E–07	3.08E–07
Minimum	3.83E–08	3.73E–08	3.63E–08	3.72E–08	9.43E–08	2.41E–07	2.97E–07	2.97E–07	2.82E–07	2.03E–07	2.07E–07
5%	4.39E–08	4.38E–08	4.15E–08	4.24E–08	1.18E–07	3.26E–07	4.08E–07	4.08E–07	3.88E–07	2.91E–07	3.14E–07
10%	4.65E–08	4.74E–08	4.39E–08	4.51E–08	1.29E–07	3.57E–07	4.49E–07	4.48E–07	4.26E–07	3.25E–07	3.45E–07
15%	4.87E–08	5.01E–08	4.58E–08	4.73E–08	1.39E–07	3.91E–07	4.79E–07	4.79E–07	4.55E–07	3.58E–07	3.88E–07
20%	5.03E–08	5.25E–08	4.75E–08	4.90E–08	1.47E–07	4.18E–07	5.06E–07	5.05E–07	4.81E–07	3.86E–07	4.17E–07
25%	5.21E–08	5.52E–08	4.91E–08	5.05E–08	1.56E–07	4.36E–07	5.37E–07	5.36E–07	5.10E–07	4.10E–07	4.41E–07
30%	5.40E–08	5.75E–08	5.08E–08	5.25E–08	1.62E–07	4.58E–07	5.64E–07	5.62E–07	5.35E–07	4.31E–07	4.69E–07
35%	5.58E–08	6.01E–08	5.26E–08	5.43E–08	1.70E–07	4.85E–07	5.86E–07	5.85E–07	5.57E–07	4.58E–07	4.93E–07
40%	5.79E–08	6.33E–08	5.44E–08	5.61E–08	1.77E–07	5.06E–07	6.12E–07	6.12E–07	5.82E–07	4.84E–07	5.22E–07
45%	6.02E–08	6.61E–08	5.66E–08	5.81E–08	1.84E–07	5.26E–07	6.38E–07	6.37E–07	6.05E–07	5.15E–07	5.51E–07
50%	6.21E–08	6.89E–08	5.84E–08	6.01E–08	1.92E–07	5.53E–07	6.66E–07	6.65E–07	6.33E–07	5.42E–07	5.85E–07
55%	6.42E–08	7.21E–08	6.03E–08	6.24E–08	1.99E–07	5.75E–07	6.97E–07	6.96E–07	6.62E–07	5.86E–07	6.22E–07
60%	6.69E–08	7.65E–08	6.26E–08	6.48E–08	2.10E–07	6.01E–07	7.39E–07	7.38E–07	7.02E–07	6.16E–07	6.53E–07
65%	6.90E–08	7.99E–08	6.48E–08	6.74E–08	2.19E–07	6.31E–07	7.71E–07	7.70E–07	7.33E–07	6.53E–07	6.95E–07
70%	7.16E–08	8.42E–08	6.72E–08	6.97E–08	2.27E–07	6.59E–07	8.11E–07	8.10E–07	7.71E–07	7.05E–07	7.46E–07
75%	7.53E–08	8.99E–08	7.07E–08	7.34E–08	2.35E–07	6.88E–07	8.57E–07	8.55E–07	8.14E–07	7.67E–07	8.07E–07
80%	8.05E–08	9.62E–08	7.55E–08	7.81E–08	2.53E–07	7.30E–07	9.13E–07	9.07E–07	8.69E–07	8.24E–07	8.69E–07
85%	8.74E–08	1.04E–07	8.16E–08	8.41E–08	2.76E–07	7.85E–07	9.69E–07	9.66E–07	9.20E–07	9.08E–07	9.62E–07
90%	9.59E–08	1.15E–07	8.99E–08	9.22E–08	2.99E–07	8.70E–07	1.07E–06	1.07E–06	1.02E–06	1.04E–06	1.09E–06
95%	1.07E–07	1.30E–07	1.00E–07	1.03E–07	3.43E–07	1.02E–06	1.24E–06	1.23E–06	1.17E–06	1.21E–06	1.26E–06
Maximum	1.83E–07	2.37E–07	1.71E–07	1.72E–07	5.92E–07	1.59E–06	2.21E–06	2.18E–06	2.10E–06	2.48E–06	2.53E–06

Sources: DTNs: MO0605SPAINEXI.003 [DIRS 177172]; MO0609SPASRPBM.004 [DIRS 179988]; MO0403SPAAEIBM.002 [DIRS 169392]; MO0407SPACRBSM.002 [DIRS 170677]; MO0406SPAETPBM.002 [DIRS 170150]; MO0503SPADCESR.000 [DIRS 172896].

NOTE: See Excel file *GW BDCFs Present-Day and Future Climates.xls* in Appendix A for details of calculations.

STD = standard deviation.

The mean BDCFs for the present-day (Table 6.11-8), monsoon (Table 6.11-10) and glacial transition (Table 6.11-11) climates are compared in Table 6.11-12. The BDCFs for the future climates states are lower than the present-day BDCFs by up to about 25%. Therefore using the present-day BDCFs for the TSPA for the entire period of geologic stability does not underestimate the doses to the RMEI.

Table 6.11-12. Comparison of Mean BDCFs for the Present-Day, Monsoon, and Glacial Transition Climates

Radionuclide	Groundwater BDCF, Sv/yr per Bq/m^3			BDCF Ratio	
	Present-Day Climate	Monsoon Climate	Glacial Transition Climate	Monsoon to Present-Day	Glacial Transition to Present Day
^{14}C	1.93E–09	1.87E–09	1.86E–09	0.97	0.96
^{36}Cl	8.09E–09	6.65E–09	6.52E–09	0.82	0.81
^{79}Se	2.42E–08	1.91E–08	1.79E–08	0.79	0.74
^{90}Sr	3.43E–08	3.16E–08	3.13E–08	0.92	0.91
^{99}Tc	1.12E–09	1.00E–09	9.94E–10	0.89	0.89
^{126}Sn	4.33E–07	3.24E–07	3.14E–07	0.75	0.73
^{129}I	1.29E–07	1.19E–07	1.18E–07	0.92	0.91
^{135}Cs	1.45E–08	1.16E–08	1.14E–08	0.80	0.79
^{137}Cs	1.30E–07	1.03E–07	9.99E–08	0.79	0.77
^{210}Pb	2.74E–06	2.45E–06	2.41E–06	0.89	0.88
^{226}Ra	3.78E–06	2.92E–06	2.84E–06	0.77	0.75
^{228}Ra	9.05E–07	8.09E–07	8.00E–07	0.89	0.88
^{227}Ac	1.30E–06	1.04E–06	1.02E–06	0.80	0.78
^{228}Th	3.15E–07	2.52E–07	2.46E–07	0.80	0.78
^{229}Th	2.58E–06	2.01E–06	1.95E–06	0.78	0.76
^{230}Th	1.08E–06	8.33E–07	8.07E–07	0.77	0.75
^{232}Th	1.85E–06	1.41E–06	1.36E–06	0.76	0.74
^{231}Pa	2.44E–06	1.88E–06	1.81E–06	0.77	0.74
^{232}U	6.04E–07	5.12E–07	5.03E–07	0.85	0.83
^{233}U	8.97E–08	7.48E–08	7.33E–08	0.83	0.82
^{234}U	8.19E–08	6.87E–08	6.74E–08	0.84	0.82
^{235}U	9.41E–08	7.76E–08	7.60E–08	0.82	0.81
^{236}U	7.67E–08	6.45E–08	6.33E–08	0.84	0.83
^{238}U	7.87E–08	6.63E–08	6.51E–08	0.84	0.83
^{237}Np	2.74E–07	2.12E–07	2.05E–07	0.77	0.75
^{238}Pu	7.61E–07	6.10E–07	5.91E–07	0.80	0.78
^{239}Pu	9.55E–07	7.48E–07	7.24E–07	0.78	0.76
^{240}Pu	9.51E–07	7.46E–07	7.22E–07	0.78	0.76
^{242}Pu	9.07E–07	7.11E–07	6.88E–07	0.78	0.76
^{241}Am	8.34E–07	6.47E–07	6.23E–07	0.78	0.75
^{243}Am	8.88E–07	6.86E–07	6.61E–07	0.77	0.74

Source: Excel file *GW BDCFs Present-Day and Future Climates.xls* (Appendix A).

6.11.3 TSPA Use of Groundwater Biosphere Dose Conversion Factors

The assessment of annual doses is carried out in the TSPA model, which uses BDCFs as input parameters. The TSPA model calculates annual fluxes of individual radionuclides at a specified distance from the repository, which, when divided by the annual water demand, yield annual average radionuclide concentrations in the groundwater used by the receptor. The total annual dose is the sum of the annual doses from individual primary radionuclides tracked in the TSPA model. The total annual dose is calculated as:

$$D_{total}(t) = \sum_i BDCF_i \times Cw_i(t) \qquad \text{(Eq. 6.11-5)}$$

where

$D_{total}(t)$ = time-dependent total annual dose to a defined receptor (RMEI) resulting from the release of radionuclides from the repository; includes contributions from all radionuclides considered in the TSPA (Sv/yr)

$BDCF_i$ = biosphere dose conversion factor for radionuclide *i* (Sv/yr per Bq/m^3)

$Cw_i(t)$ = time-dependent activity concentration of radionuclide *i* in the groundwater (Bq/m^3) calculated by TSPA.

Equation 6.11-5 is based on a linear relationship between groundwater concentrations and dose.

The annual dose at time *t* is calculated using the activity concentration in water at time *t*, *Cw(t)*. The product of the radionuclide concentration in groundwater and the BDCF represents the dose that would prevail if the concentration of radionuclide *i* in water, $Cw_i(t)$, persisted prior to time *t* for the assumed stochastically sampled irrigation duration used in the biosphere model. In the event that groundwater concentration of a particular radionuclide is increasing, this assumption will result in overestimating the dose for that radionuclide (Section 6.3.1.4). If radionuclide concentrations in groundwater are decreasing, the dose may be underestimated (Section 6.3.1.4).

The effect of climate change on the BDCFs for the groundwater exposure scenario was evaluated from the perspective of the factors that are related to human activity, such as the groundwater use for irrigation, which section 10 CFR 63.305(b) [DIRS 173273] directs not to vary in the performance assessments, and the factors that are independent of human activities, which 10 CFR 63.305(c) requires to vary (70 FR 53313 [DIRS 178394]) (Section 6.11.1.2). A conclusion was reached that the climate-related factors that have the largest effect on the BDCFs depend on human activities and that the BDCFs are relatively insensitive to the effects of climate change on the other factors. Furthermore, the BDCFs for the future climate, which is predicted to be cooler and wetter than the present-day climate, are lower than the corresponding present-day climate BDCFs and would result in lower doses to the RMEI. Therefore, using the present-day climate BDCFs represents a conservative choice, meets the regulatory requirements and should be used for the assessment of doses to the RMEI for the entire period of the geologic stability.

The groundwater BDCFs are correlated because for a given biosphere model realization number, all sampled radionuclide-independent parameters are the same regardless of a radionuclide. The raw correlation coefficients for the sets of 1,000 BDCFs were calculated in the Excel file *Correlations for GW BDCFs PD.xls* (Appendix A). These correlations between the BDCFs are captured in the TSPA model through sampling of the BDCF sets (rows in the two-dimensional array provided to TSPA), where for a given realization, the TSPA model samples BDCFs from one, randomly selected realization of the biosphere model.

The correlations between the BDCFs for different radionuclides are generally the highest for the radionuclides with the atomic number of 88 and higher. These radionuclides have similar exposure pathways, similar energies, and types of radiation and their BDCFs depend strongly on radionuclide concentration in surface soil. This latter dependence also causes higher correlations between the BDCFs for radionuclides with the atomic number equal to or greater than 88 and the BDCFs for radionuclides that have a significant BDCF contribution from the external exposure pathway (^{126}Sn and ^{137}Cs).

6.12 BIOSPHERE DOSE CONVERSION FACTORS FOR THE VOLCANIC ASH EXPOSURE SCENARIO

Volcanic BDCFs are used in the calculation of the annual dose conditional on a volcanic eruption through the repository. Specifically, volcanic BDCFs are used to predict, in a stochastic manner to allow for parametric uncertainty, the annual dose (Sv/yr) to the RMEI for a unit activity mass concentration (Bq/kg) in a resuspendable layer of soil and a unit activity areal concentration (1 Bq/m^2) in the surface soil. The surface soil, as previously noted, is defined as a topsoil layer with a thickness equal to the tillage depth. The volcanic BDCFs are used in the volcanic eruption modeling case of the igneous scenario class because this is the only modeling case that results in radionuclide release to the biosphere as a result of a volcanic eruption. The BDCFs are calculated for each radionuclide considered by TSPA for the volcanic eruption modeling case. Volcanic BDCFs were caluclated using GoldSim V.8.02.500 (2005 [DIRS 174650]).

For the volcanic ash exposure scenario, the only source of radionuclides in the biosphere is contaminated volcanic ash deposited on the ground surface as the result of a volcanic eruption and redistributed to the location of the hypothetical community. After radionuclides enter the biosphere, radionuclide migration through the biosphere occurs due to a number of transport processes that lead to contamination and accumulation in the environmental media (e.g., soil, air, flora, and fauna). Human exposure to radionuclides in the environment arises when people come in contact with contaminated environmental media. Direct inhalation of ash during volcanic eruption is treated separately (Section 6.15.2). Unlike the groundwater BDCFs, only one set of volcanic BDCFs represents all climates within the range of biosphere model applicability. This is because most of the climate-dependent biosphere model input parameters are related to irrigation and those parameters are not used in the model for the volcanic exposure scenario because the origin of contamination for this scenario is not the groundwater. This makes the volcanic biosphere model practically insensitive to climate changes, as described in Section 6.12.1.2.

6.12.1 Modeling Methods

6.12.1.1 Treatment of Uncertainty

Analogous to the groundwater BDCFs, volcanic BDCFs were developed using the probabilistic approach to propagate the uncertainty in input parameters, defined by their probability distribution functions, into the results of the model. The uncertainty in the model outcome is represented by 1,000 different biosphere model realizations using different sets of uncertain model input parameters. The input parameter distributions were sampled using Latin Hypercube sampling. For this analysis, the value of the random seed in GoldSim was set to 1.

6.12.1.2 Incorporation of Climate Change

Annual doses arising from volcanic eruption are calculated by combining the biosphere model input to the TSPA model (i.e., BDCFs) with the source term. BDCFs are independent of the source term. The discussion of climate change presented here concerns only the BDCFs, not the source term, which is calculated in the TSPA model.

The only climate-dependent input parameter affecting the BDCFs for the volcanic ash scenario is the crop type-dependent growing time of crops for the human and animal consumption, which potentially may affect the ingestion exposure pathway. This input parameter was determined to be independent of the receptor characteristics and, as such, needs to be evaluated for its effect on the BDCF values (see discussion in Section 6.12.1.2 of the climate-dependent model parameters and their inclusion in the biosphere model). Other climate-dependent processes may exist, such as the enhanced diffusion of the contaminants through the soil column due to irrigation or under the conditions of higher precipitation. The biosphere model conservatively does consider the decrease of radionuclide concentration in the soil due to these processes. The volcanic BDCFs were calculated for the two climates: the present-day and the upper bound of the glacial transition climate. Since the climate change only affects the ingestion pathway, it may only have an effect on the BDCF component that accounts for the ingestion, inhalation of radon decay products, and external exposure. The comparison of the BDCF components for these pathways showed the difference of much less than a percent between the BDCF components for ingestion, inhalation of radon decay products, and external exposure for the two climates (Excel file *VA BDCF Present-Day and Future Climates.xls*, worksheet *BDCF Climate Comparison* in Appendix A).

Because climate change has negligible effect on BDCFs it is recommended that one set of BDCFs, those developed for the present-day climate, be used for the entire period of geologic stability.

6.12.1.3 Incorporation of Decay Products

Some BDCFs include contributions from the short-lived decay products of a primary radionuclide. The primary radionuclides (radionuclides tracked in the TSPA) and the decay products, whose contributions were included in the BDCF for a primary radionuclide, are shown in Table 6.12-1.

^{232}Th is accompanied in the contaminated volcanic ash and soil by ^{228}Ra and ^{228}Th (and their short-lived decay products) whose half-lives are relatively long with respect to biosphere transport processes. Although ^{228}Ra and ^{228}Th may not be tracked in TSPA because of their short half-lives, which are only 5.75 year and 1.91 year, respectively, their dose contribution must be taken into account. This can be accomplished by combining volcanic BDCF components for ^{228}Ra and ^{228}Th with that of ^{232}Th, under the assumption of radioactive equilibrium between these radionuclides.

^{232}U is accompanied in the ash fall by its relatively long-lived decay product, ^{228}Th and its short-lived decay products. The dose contribution from ^{228}Th in equilibrium with ^{232}U could be included by adding their volcanic BDCF components.

Table 6.12-1. Primary Radionuclides and their Decay Products Included in the Volcanic BDCFs

Primary Radionuclide	Decay Products Included in BDCF
^{90}Sr	^{90}Y
^{99}Tc	
^{126}Sn	
^{129}I	
^{137}Cs	^{137m}Ba
^{210}Pb	^{210}Bi, ^{210}Po
^{226}Ra	^{222}Rn, ^{218}Po, ^{214}Pb, ^{218}At, ^{214}Bi, ^{214}Po, ^{210}Tl
^{228}Ra	^{228}Ra, ^{228}Ac
^{227}Ac	^{227}Th, ^{223}Fr, ^{223}Ra, ^{219}Rn, ^{215}Po, ^{211}Pb, ^{211}Bi, ^{207}Tl, ^{211}Po
^{228}Th	^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po, ^{208}Tl
^{229}Th	^{225}Ra, ^{225}Ac, ^{221}Fr, ^{223}At, ^{213}Bi, ^{213}Po, ^{209}Tl, ^{209}Pb
^{230}Th	
^{232}Th	
^{231}Pa	
^{232}U	
^{233}U	
^{234}U	
^{235}U	
^{236}U	
^{238}U	^{234}Th, ^{234m}Pa, ^{234}Pa
^{237}Np	^{233}Pa
^{238}Pu	
^{239}Pu	
^{240}Pu	
^{242}Pu	
^{241}Am	
^{243}Am	^{239}Np

Source: Table 6.3-7.

In a similar fashion, if the concentration of ^{210}Pb in the ash is not calculated and if equilibrium could be assumed to exist between the concentrations ^{226}Ra and ^{210}Pb in the soil, their volcanic

BDCF components should be combined to account for the ^{210}Pb dose contribution as a decay product of ^{226}Ra.

6.12.2 Modeling Results: Volcanic Biosphere Dose Conversion Factors

As described in Section 6.5.8.2, two source terms are required to calculate annual dose for a volcanic event. These source terms are calculated in the TSPA model using ASHPLUME and FAR outputs (SNL 2007 [DIRS 179347]) for the areas classified as the channels and the interchannel divides. The two source terms are the radionuclide concentration in the resuspendable layer of soil in units of mass activity concentration (e.g., Bq/kg) and depth-integrated (areal) radionuclide concentration in surface soil units of surface activity concentration (e.g., Bq/m^2). Radionuclide concentration in the resuspendable layer of soil is used to calculate inhalation dose from exposure to suspended particulates. Areal radionuclide concentration is used in estimates of doses from the remaining exposure pathways included in the model, i.e., ingestion, inhalation of radon decay products, and external exposure.

Consistent with this format, volcanic BDCFs consist of three BDCF components for each primary radionuclide. The first component, $BDCF_{ext,ing,Rn,i}$, accounts for exposure to sources external to the body, ingestion, and inhalation of radon decay products. This component is numerically equal to the annual dose to the RMEI from these exposure pathways per unit of areal radionuclide concentration in the soil (Sv/yr per Bq/m^2). The second and third BDCF components, called the short-term and the long-term inhalation BDCF components, account for inhaling airborne particulates. The short-term inhalation component, $BDCF_{inh,v,i}$, is numerically equal to the early-time increase in inhalation dose (over and above the long-term inhalation dose described by the long-term inhalation BDCF component) during the first year following a volcanic eruption per unit of radionuclide concentration in the soil layer that can become resuspended (Sv/yr per Bq/kg). This term is used together with the time function, representing the decrease of the airborne particulate concentration with time, to calculate short-term increase in inhalation exposure due to elevated levels of airborne particulate matter after a volcanic eruption, relative to the conditions existing before and long after an eruption. With time, mass loading returns to the pre-eruption level. These exposure conditions are described by the long-term inhalation BDCF, $BDCF_{inh,p,i}$, which accounts for inhalation of resuspended particulates under nominal conditions, i.e., when the mass loading is not elevated as the result of volcanic eruption. This component is numerically equal to the annual dose to the RMEI from inhaling particulates at the nominal concentration in the air, per unit of radionuclide concentration in the soil that can be resuspended (Sv/yr per Bq/kg).

A set of volcanic BDCFs consists of 1,000 row vectors. A vector can be regarded as a one-dimensional array containing the results of a single realization of the biosphere model for all primary radionuclides. Technically, the model is executed separately for individual primary radionuclides. The vectors are then produced by compiling the BDCFs for a given realization number. Such an approach is valid because for a given model realization number all sampled radionuclide-independent parameters are the same regardless of a radionuclide.

The elements in a row vector correspond to the volcanic BDCF components (three per radionuclide) for individual radionuclides of interest for a given model realization; the rows represent individual model realizations. The BDCFs were calculated for 27 primary radionuclides listed in Table 6.1-1. In addition, sums of BDCF components were produced for the three primary radionuclides, ^{226}Ra, ^{232}Th and ^{232}U, to include the contribution from their long-lived decay products, which themselves are primary radionuclides, in the case the concentrations of these decay products were not calculated in the TSPA model. BDCF sums included the following radionuclides: ^{226}Ra + ^{210}Pb; ^{232}Th + ^{228}Ra + ^{228}Th; and ^{232}U + ^{228}Th, assuming radioactive equilibrium with a parent radionuclide.

A row vector in the set of volcanic BDCFs thus consists of 90 numeric elements (30 radionuclides × 3 BDCF components). The number of radionuclides includes 27 primary radionuclides plus 3 primary radionuclides in equilibrium with other shorter-lived primary radionuclides. Because the set consists of 1,000 row vectors, the entire BDCF data set has 90,000 values (30 radionuclides × 3 BDCF components × 1,000 model realizations), which are listed in Excel file *VA BDCFs Present-Day and Future Climates.xls* (Appendix A).

Summary statistics for the volcanic BDCF components are presented in Tables 6.12-2 to 6.12-4 for the short-term particulate inhalation component; long-term particulate inhalation component; and the ingestion, radon decay product inhalation, and external exposure component; respectively. The statistics include the mean, standard deviation (STD), minimum, maximum, and percentiles of the cumulative distribution in increments of 5%. Included in Tables 6.12-2 to 6.12-4 are the BDCF components of 27 primary radionuclides and the BDCF component sums for ^{226}Ra, ^{232}Th and ^{232}U, to include the contribution from their long-lived decay products. The BDCF sums include the following radionuclides: ^{226}Ra + ^{210}Pb; ^{232}Th + ^{228}Ra + ^{228}Th; and ^{232}U + ^{228}Th, assuming radioactive equilibrium with a parent radionuclide. The values listed in Tables 6.12-2 to 6.12-4 are presented with three digits although only two digits are significant. This is to avoid round-off errors in the TSPA calculation of the annual dose. The BDCFs can be considered as intermediate results and, as such, should be given with an additional significant digit.

Table 6.12-2. Statistics for the Volcanic BDCF Component for the Short-Term Inhalation of Particulates, Sv/yr per Bq/kg

	^{90}Sr	^{99}Tc	^{126}Sn	^{129}I	^{137}Cs	^{210}Pb	^{226}Ra	^{226}Ra + ^{210}Pb	^{228}Ra	^{227}Ac
Mean	5.30E–10	4.45E–11	5.20E–10	1.20E–10	1.31E–10	3.35E–08	3.19E–08	6.54E–08	5.36E–08	5.85E–07
STD	3.01E–10	2.52E–11	2.95E–10	6.81E–11	7.44E–11	1.90E–08	1.81E–08	3.71E–08	3.04E–08	3.32E–07
Minimum	7.68E–11	6.44E–12	7.53E–11	1.74E–11	1.90E–11	4.85E–09	4.62E–09	9.47E–09	7.76E–09	8.47E–08
5%	1.79E–10	1.50E–11	1.76E–10	4.06E–11	4.43E–11	1.13E–08	1.08E–08	2.21E–08	1.81E–08	1.98E–07
10%	2.19E–10	1.83E–11	2.14E–10	4.95E–11	5.41E–11	1.38E–08	1.32E–08	2.70E–08	2.21E–08	2.41E–07
15%	2.55E–10	2.14E–11	2.50E–10	5.78E–11	6.31E–11	1.61E–08	1.53E–08	3.15E–08	2.58E–08	2.81E–07
20%	2.87E–10	2.41E–11	2.82E–10	6.50E–11	7.10E–11	1.81E–08	1.73E–08	3.54E–08	2.90E–08	3.17E–07
25%	3.16E–10	2.65E–11	3.10E–10	7.16E–11	7.82E–11	2.00E–08	1.90E–08	3.90E–08	3.19E–08	3.49E–07
30%	3.44E–10	2.88E–11	3.37E–10	7.79E–11	8.50E–11	2.17E–08	2.07E–08	4.24E–08	3.47E–08	3.79E–07
35%	3.69E–10	3.10E–11	3.62E–10	8.36E–11	9.13E–11	2.33E–08	2.22E–08	4.55E–08	3.73E–08	4.07E–07
40%	3.95E–10	3.31E–11	3.87E–10	8.95E–11	9.77E–11	2.50E–08	2.38E–08	4.87E–08	3.99E–08	4.36E–07
45%	4.31E–10	3.62E–11	4.23E–10	9.76E–11	1.07E–10	2.72E–08	2.59E–08	5.32E–08	4.35E–08	4.76E–07
50%	4.64E–10	3.90E–11	4.55E–10	1.05E–10	1.15E–10	2.93E–08	2.79E–08	5.73E–08	4.69E–08	5.12E–07
55%	4.95E–10	4.15E–11	4.86E–10	1.12E–10	1.22E–10	3.13E–08	2.98E–08	6.11E–08	5.00E–08	5.46E–07
60%	5.33E–10	4.47E–11	5.22E–10	1.21E–10	1.32E–10	3.36E–08	3.21E–08	6.57E–08	5.38E–08	5.88E–07
65%	5.67E–10	4.76E–11	5.56E–10	1.28E–10	1.40E–10	3.58E–08	3.41E–08	7.00E–08	5.73E–08	6.26E–07
70%	6.11E–10	5.12E–11	5.99E–10	1.38E–10	1.51E–10	3.86E–08	3.67E–08	7.53E–08	6.17E–08	6.74E–07
75%	6.63E–10	5.57E–11	6.51E–10	1.50E–10	1.64E–10	4.19E–08	3.99E–08	8.18E–08	6.70E–08	7.32E–07
80%	7.31E–10	6.13E–11	7.17E–10	1.66E–10	1.81E–10	4.62E–08	4.40E–08	9.02E–08	7.38E–08	8.07E–07
85%	8.33E–10	6.99E–11	8.17E–10	1.89E–10	2.06E–10	5.26E–08	5.01E–08	1.03E–07	8.42E–08	9.20E–07
90%	9.50E–10	7.97E–11	9.32E–10	2.15E–10	2.35E–10	6.00E–08	5.72E–08	1.17E–07	9.60E–08	1.05E–06
95%	1.14E–09	9.60E–11	1.12E–09	2.59E–10	2.83E–10	7.23E–08	6.89E–08	1.41E–07	1.16E–07	1.26E–06
Maximum	1.94E–09	1.63E–10	1.90E–09	4.39E–10	4.80E–10	1.23E–07	1.17E–07	2.39E–07	1.96E–07	2.14E–06

Table 6.12-2. Statistics for the Volcanic BDCF Component for the Short-Term Inhalation of Particulates, Sv/yr per Bq/kg (Continued)

	^{228}Th	^{229}Th	^{230}Th	^{232}Th	^{232}Th + ^{228}Ra + ^{228}Th	^{231}Pa	^{232}U	^{232}U + ^{228}Th	^{233}U	^{234}U
Mean	1.45E–07	8.54E–07	3.41E–07	3.68E–07	5.66E–07	7.70E–07	1.24E–07	2.69E–07	3.21E–08	3.15E–08
STD	8.21E–08	4.84E–07	1.94E–07	2.09E–07	3.21E–07	4.37E–07	7.02E–08	1.52E–07	1.82E–08	1.78E–08
Minimum	2.10E–08	1.24E–07	4.94E–08	5.33E–08	8.20E–08	1.11E–07	1.79E–08	3.89E–08	4.65E–09	4.55E–09
5%	4.90E–08	2.89E–07	1.15E–07	1.24E–07	1.92E–07	2.60E–07	4.19E–08	9.08E–08	1.08E–08	1.06E–08
10%	5.97E–08	3.52E–07	1.41E–07	1.52E–07	2.33E–07	3.17E–07	5.10E–08	1.11E–07	1.32E–08	1.30E–08
15%	6.96E–08	4.11E–07	1.64E–07	1.77E–07	2.72E–07	3.70E–07	5.95E–08	1.29E–07	1.54E–08	1.51E–08
20%	7.84E–08	4.63E–07	1.85E–07	1.99E–07	3.07E–07	4.17E–07	6.70E–08	1.45E–07	1.74E–08	1.70E–08
25%	8.63E–08	5.09E–07	2.03E–07	2.19E–07	3.38E–07	4.59E–07	7.38E–08	1.60E–07	1.91E–08	1.87E–08
30%	9.39E–08	5.54E–07	2.21E–07	2.39E–07	3.67E–07	4.99E–07	8.02E–08	1.74E–07	2.08E–08	2.04E–08
35%	1.01E–07	5.94E–07	2.38E–07	2.56E–07	3.94E–07	5.36E–07	8.62E–08	1.87E–07	2.23E–08	2.19E–08
40%	1.08E–07	6.36E–07	2.54E–07	2.74E–07	4.22E–07	5.73E–07	9.22E–08	2.00E–07	2.39E–08	2.34E–08
45%	1.18E–07	6.94E–07	2.77E–07	2.99E–07	4.60E–07	6.25E–07	1.01E–07	2.18E–07	2.61E–08	2.56E–08
50%	1.27E–07	7.48E–07	2.99E–07	3.22E–07	4.96E–07	6.74E–07	1.08E–07	2.35E–07	2.81E–08	2.75E–08
55%	1.35E–07	7.97E–07	3.19E–07	3.44E–07	5.29E–07	7.18E–07	1.16E–07	2.51E–07	2.99E–08	2.94E–08
60%	1.45E–07	8.58E–07	3.43E–07	3.70E–07	5.69E–07	7.73E–07	1.24E–07	2.70E–07	3.22E–08	3.16E–08
65%	1.55E–07	9.13E–07	3.65E–07	3.94E–07	6.06E–07	8.23E–07	1.32E–07	2.87E–07	3.43E–08	3.36E–08
70%	1.67E–07	9.83E–07	3.93E–07	4.24E–07	6.52E–07	8.86E–07	1.43E–07	3.09E–07	3.69E–08	3.62E–08
75%	1.81E–07	1.07E–06	4.27E–07	4.60E–07	7.09E–07	9.63E–07	1.55E–07	3.36E–07	4.01E–08	3.93E–08
80%	2.00E–07	1.18E–06	4.70E–07	5.07E–07	7.81E–07	1.06E–06	1.71E–07	3.70E–07	4.42E–08	4.33E–08
85%	2.28E–07	1.34E–06	5.36E–07	5.78E–07	8.90E–07	1.21E–06	1.94E–07	4.22E–07	5.04E–08	4.94E–08
90%	2.59E–07	1.53E–06	6.11E–07	6.59E–07	1.01E–06	1.38E–06	2.22E–07	4.81E–07	5.75E–08	5.63E–08
95%	3.12E–07	1.84E–06	7.36E–07	7.94E–07	1.22E–06	1.66E–06	2.67E–07	5.80E–07	6.92E–08	6.79E–08
Maximum	5.30E–07	3.12E–06	1.25E–06	1.35E–06	2.07E–06	2.82E–06	4.53E–07	9.83E–07	1.17E–07	1.15E–07

Table 6.12-2. Statistics for the Volcanic BDCF Component for the Short-Term Inhalation of Particulates, Sv/yr per Bq/kg (Continued)

	^{235}U	^{236}U	^{238}U	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu	^{241}Am	^{243}Am
Mean	2.83E–08	2.92E–08	2.69E–08	1.66E–07	3.61E–07	3.98E–07	3.98E–07	3.78E–07	3.23E–07	3.20E–07
STD	1.61E–08	1.66E–08	1.53E–08	9.43E–08	2.05E–07	2.26E–07	2.26E–07	2.14E–07	1.83E–07	1.82E–07
Minimum	4.10E–09	4.23E–09	3.90E–09	2.41E–08	5.23E–08	5.76E–08	5.76E–08	5.47E–08	4.67E–08	4.64E–08
5%	9.58E–09	9.89E–09	9.10E–09	5.62E–08	1.22E–07	1.35E–07	1.35E–07	1.28E–07	1.09E–07	1.08E–07
10%	1.17E–08	1.21E–08	1.11E–08	6.85E–08	1.49E–07	1.64E–07	1.64E–07	1.56E–07	1.33E–07	1.32E–07
15%	1.36E–08	1.41E–08	1.29E–08	8.00E–08	1.74E–07	1.91E–07	1.91E–07	1.82E–07	1.55E–07	1.54E–07
20%	1.53E–08	1.58E–08	1.46E–08	9.01E–08	1.96E–07	2.16E–07	2.16E–07	2.05E–07	1.75E–07	1.73E–07
25%	1.69E–08	1.74E–08	1.61E–08	9.91E–08	2.15E–07	2.37E–07	2.37E–07	2.25E–07	1.92E–07	1.91E–07
30%	1.84E–08	1.90E–08	1.75E–08	1.08E–07	2.34E–07	2.58E–07	2.58E–07	2.45E–07	2.09E–07	2.08E–07
35%	1.97E–08	2.04E–08	1.87E–08	1.16E–07	2.52E–07	2.77E–07	2.77E–07	2.63E–07	2.24E–07	2.23E–07
40%	2.11E–08	2.18E–08	2.01E–08	1.24E–07	2.69E–07	2.97E–07	2.97E–07	2.82E–07	2.40E–07	2.39E–07
45%	2.30E–08	2.38E–08	2.19E–08	1.35E–07	2.94E–07	3.24E–07	3.24E–07	3.07E–07	2.62E–07	2.60E–07
50%	2.48E–08	2.56E–08	2.36E–08	1.46E–07	3.16E–07	3.49E–07	3.49E–07	3.31E–07	2.82E–07	2.80E–07
55%	2.65E–08	2.73E–08	2.51E–08	1.55E–07	3.37E–07	3.72E–07	3.72E–07	3.53E–07	3.01E–07	2.99E–07
60%	2.85E–08	2.94E–08	2.70E–08	1.67E–07	3.63E–07	4.00E–07	4.00E–07	3.80E–07	3.24E–07	3.22E–07
65%	3.03E–08	3.13E–08	2.88E–08	1.78E–07	3.87E–07	4.26E–07	4.26E–07	4.04E–07	3.45E–07	3.42E–07
70%	3.26E–08	3.37E–08	3.10E–08	1.91E–07	4.16E–07	4.58E–07	4.58E–07	4.35E–07	3.71E–07	3.69E–07
75%	3.55E–08	3.66E–08	3.37E–08	2.08E–07	4.52E–07	4.98E–07	4.98E–07	4.73E–07	4.03E–07	4.01E–07
80%	3.91E–08	4.03E–08	3.71E–08	2.29E–07	4.98E–07	5.49E–07	5.49E–07	5.21E–07	4.45E–07	4.41E–07
85%	4.45E–08	4.59E–08	4.23E–08	2.61E–07	5.68E–07	6.26E–07	6.26E–07	5.94E–07	5.07E–07	5.03E–07
90%	5.08E–08	5.24E–08	4.82E–08	2.98E–07	6.47E–07	7.13E–07	7.13E–07	6.77E–07	5.78E–07	5.74E–07
95%	6.11E–08	6.31E–08	5.81E–08	3.59E–07	7.80E–07	8.59E–07	8.59E–07	8.16E–07	6.96E–07	6.91E–07
Maximum	1.04E–07	1.07E–07	9.85E–08	6.08E–07	1.32E–06	1.46E–06	1.46E–06	1.38E–06	1.18E–06	1.17E–06

Sources: DTNs: MO0605SPAINEXI.003 [DIRS 177172]; MO0609SPASRPBM.004 [DIRS 179988]; MO0403SPAAEIBM.002 [DIRS 169392]; MO0407SPACRBSM.002 [DIRS 170677]; MO0406SPAETPBM.002 [DIRS 170150]; MO0503SPADCESR.000 [DIRS 172896].

NOTE: See Excel file *VA BDCFs Present-Day and Future Climates.xls* in Appendix A for details of calculations.

STD = standard deviation.

Table 6.12-3. Statistics for the Volcanic BDCF Component for the Long-Term Inhalation of Particulates, Sv/yr per Bq/kg

	^{90}Sr	^{99}Tc	^{126}Sn	^{129}I	^{137}Cs	^{210}Pb	^{226}Ra	^{226}Ra + ^{210}Pb	^{228}Ra	^{227}Ac
Mean	8.16E–10	6.84E–11	8.00E–10	1.85E–10	2.02E–10	5.15E–08	4.91E–08	1.01E–07	8.24E–08	9.00E–07
STD	5.21E–10	4.37E–11	5.11E–10	1.18E–10	1.29E–10	3.29E–08	3.14E–08	6.43E–08	5.27E–08	5.75E–07
Minimum	1.39E–10	1.17E–11	1.36E–10	3.14E–11	3.43E–11	8.77E–09	8.36E–09	1.71E–08	1.40E–08	1.53E–07
5%	2.76E–10	2.32E–11	2.71E–10	6.26E–11	6.83E–11	1.74E–08	1.66E–08	3.41E–08	2.79E–08	3.05E–07
10%	3.32E–10	2.78E–11	3.25E–10	7.52E–11	8.21E–11	2.10E–08	2.00E–08	4.09E–08	3.35E–08	3.66E–07
15%	3.78E–10	3.17E–11	3.70E–10	8.55E–11	9.34E–11	2.39E–08	2.27E–08	4.66E–08	3.82E–08	4.17E–07
20%	4.14E–10	3.47E–11	4.06E–10	9.38E–11	1.02E–10	2.62E–08	2.49E–08	5.11E–08	4.18E–08	4.57E–07
25%	4.58E–10	3.84E–11	4.49E–10	1.04E–10	1.13E–10	2.89E–08	2.76E–08	5.65E–08	4.63E–08	5.06E–07
30%	4.96E–10	4.17E–11	4.87E–10	1.12E–10	1.23E–10	3.14E–08	2.99E–08	6.12E–08	5.02E–08	5.48E–07
35%	5.28E–10	4.43E–11	5.18E–10	1.20E–10	1.31E–10	3.34E–08	3.18E–08	6.52E–08	5.34E–08	5.83E–07
40%	5.71E–10	4.79E–11	5.60E–10	1.29E–10	1.41E–10	3.61E–08	3.44E–08	7.05E–08	5.77E–08	6.31E–07
45%	6.26E–10	5.26E–11	6.14E–10	1.42E–10	1.55E–10	3.96E–08	3.77E–08	7.73E–08	6.33E–08	6.91E–07
50%	6.83E–10	5.74E–11	6.70E–10	1.55E–10	1.69E–10	4.32E–08	4.11E–08	8.43E–08	6.91E–08	7.54E–07
55%	7.24E–10	6.07E–11	7.10E–10	1.64E–10	1.79E–10	4.57E–08	4.36E–08	8.93E–08	7.31E–08	7.99E–07
60%	7.85E–10	6.59E–11	7.70E–10	1.78E–10	1.94E–10	4.96E–08	4.72E–08	9.68E–08	7.93E–08	8.66E–07
65%	8.49E–10	7.12E–11	8.32E–10	1.92E–10	2.10E–10	5.36E–08	5.11E–08	1.05E–07	8.57E–08	9.37E–07
70%	9.11E–10	7.64E–11	8.93E–10	2.06E–10	2.25E–10	5.75E–08	5.48E–08	1.12E–07	9.20E–08	1.01E–06
75%	1.03E–09	8.62E–11	1.01E–09	2.33E–10	2.54E–10	6.49E–08	6.18E–08	1.27E–07	1.04E–07	1.13E–06
80%	1.14E–09	9.59E–11	1.12E–09	2.59E–10	2.83E–10	7.22E–08	6.88E–08	1.41E–07	1.15E–07	1.26E–06
85%	1.26E–09	1.05E–10	1.23E–09	2.84E–10	3.11E–10	7.93E–08	7.56E–08	1.55E–07	1.27E–07	1.39E–06
90%	1.47E–09	1.23E–10	1.44E–09	3.33E–10	3.64E–10	9.29E–08	8.85E–08	1.81E–07	1.49E–07	1.62E–06
95%	1.84E–09	1.55E–10	1.81E–09	4.17E–10	4.56E–10	1.16E–07	1.11E–07	2.27E–07	1.86E–07	2.03E–06
Maximum	4.08E–09	3.42E–10	4.00E–09	9.23E–10	1.01E–09	2.58E–07	2.45E–07	5.03E–07	4.12E–07	4.50E–06

Table 6.12-3. Statistics for the Volcanic BDCF Component for the Long-Term Inhalation of Particulates, Sv/yr per Bq/kg (Continued)

	^{228}Th	^{229}Th	^{230}Th	^{232}Th	^{232}Th + ^{228}Ra + ^{228}Th	^{231}Pa	^{232}U	^{232}U + ^{228}Th	^{233}U	^{234}U
Mean	2.23E–07	1.31E–06	5.25E–07	5.66E–07	8.71E–07	1.18E–06	1.90E–07	4.13E–07	4.94E–08	4.84E–08
STD	1.42E–07	8.39E–07	3.35E–07	3.62E–07	5.57E–07	7.56E–07	1.22E–07	2.64E–07	3.15E–08	3.09E–08
Minimum	3.79E–08	2.24E–07	8.94E–08	9.64E–08	1.48E–07	2.01E–07	3.24E–08	7.03E–08	8.40E–09	8.23E–09
5%	7.54E–08	4.45E–07	1.78E–07	1.92E–07	2.95E–07	4.01E–07	6.45E–08	1.40E–07	1.67E–08	1.64E–08
10%	9.06E–08	5.34E–07	2.14E–07	2.30E–07	3.54E–07	4.81E–07	7.75E–08	1.68E–07	2.01E–08	1.97E–08
15%	1.03E–07	6.08E–07	2.43E–07	2.62E–07	4.03E–07	5.48E–07	8.82E–08	1.91E–07	2.29E–08	2.24E–08
20%	1.13E–07	6.67E–07	2.67E–07	2.87E–07	4.42E–07	6.01E–07	9.67E–08	2.10E–07	2.51E–08	2.46E–08
25%	1.25E–07	7.38E–07	2.95E–07	3.18E–07	4.89E–07	6.65E–07	1.07E–07	2.32E–07	2.77E–08	2.72E–08
30%	1.36E–07	7.99E–07	3.19E–07	3.45E–07	5.30E–07	7.20E–07	1.16E–07	2.51E–07	3.00E–08	2.94E–08
35%	1.44E–07	8.51E–07	3.40E–07	3.67E–07	5.64E–07	7.67E–07	1.23E–07	2.68E–07	3.20E–08	3.13E–08
40%	1.56E–07	9.20E–07	3.68E–07	3.96E–07	6.10E–07	8.29E–07	1.33E–07	2.89E–07	3.46E–08	3.39E–08
45%	1.71E–07	1.01E–06	4.03E–07	4.35E–07	6.69E–07	9.09E–07	1.46E–07	3.17E–07	3.79E–08	3.71E–08
50%	1.87E–07	1.10E–06	4.40E–07	4.74E–07	7.30E–07	9.92E–07	1.60E–07	3.46E–07	4.14E–08	4.05E–08
55%	1.98E–07	1.17E–06	4.66E–07	5.02E–07	7.73E–07	1.05E–06	1.69E–07	3.67E–07	4.38E–08	4.29E–08
60%	2.14E–07	1.26E–06	5.05E–07	5.45E–07	8.38E–07	1.14E–06	1.83E–07	3.98E–07	4.75E–08	4.66E–08
65%	2.32E–07	1.37E–06	5.46E–07	5.89E–07	9.06E–07	1.23E–06	1.98E–07	4.30E–07	5.13E–08	5.03E–08
70%	2.49E–07	1.47E–06	5.86E–07	6.32E–07	9.73E–07	1.32E–06	2.13E–07	4.61E–07	5.51E–08	5.40E–08
75%	2.81E–07	1.65E–06	6.61E–07	7.13E–07	1.10E–06	1.49E–06	2.40E–07	5.20E–07	6.22E–08	6.09E–08
80%	3.12E–07	1.84E–06	7.35E–07	7.93E–07	1.22E–06	1.66E–06	2.67E–07	5.79E–07	6.91E–08	6.77E–08
85%	3.43E–07	2.02E–06	8.08E–07	8.72E–07	1.34E–06	1.82E–06	2.93E–07	6.36E–07	7.60E–08	7.45E–08
90%	4.02E–07	2.37E–06	9.46E–07	1.02E–06	1.57E–06	2.13E–06	3.43E–07	7.45E–07	8.90E–08	8.72E–08
95%	5.03E–07	2.97E–06	1.19E–06	1.28E–06	1.97E–06	2.67E–06	4.30E–07	9.33E–07	1.12E–07	1.09E–07
Maximum	1.11E–06	6.57E–06	2.62E–06	2.83E–06	4.35E–06	5.92E–06	9.52E–07	2.06E–06	2.47E–07	2.42E–07

Table 6.12-3. Statistics for the Volcanic BDCF Component for the Long-Term Inhalation of Particulates, Sv/yr per Bq/kg (Continued)

	^{235}U	^{236}U	^{238}U	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu	^{241}Am	^{243}Am
Mean	4.36E–08	4.50E–08	4.14E–08	2.56E–07	5.56E–07	6.12E–07	6.12E–07	5.82E–07	4.96E–07	4.93E–07
STD	2.78E–08	2.87E–08	2.65E–08	1.63E–07	3.55E–07	3.91E–07	3.91E–07	3.72E–07	3.17E–07	3.15E–07
Minimum	7.42E–09	7.66E–09	7.05E–09	4.35E–08	9.46E–08	1.04E–07	1.04E–07	9.90E–08	8.44E–08	8.38E–08
5%	1.48E–08	1.52E–08	1.40E–08	8.66E–08	1.88E–07	2.07E–07	2.07E–07	1.97E–07	1.68E–07	1.67E–07
10%	1.77E–08	1.83E–08	1.68E–08	1.04E–07	2.26E–07	2.49E–07	2.49E–07	2.37E–07	2.02E–07	2.00E–07
15%	2.02E–08	2.08E–08	1.92E–08	1.18E–07	2.57E–07	2.84E–07	2.84E–07	2.69E–07	2.30E–07	2.28E–07
20%	2.21E–08	2.28E–08	2.10E–08	1.30E–07	2.82E–07	3.11E–07	3.11E–07	2.95E–07	2.52E–07	2.50E–07
25%	2.45E–08	2.53E–08	2.33E–08	1.44E–07	3.12E–07	3.44E–07	3.44E–07	3.27E–07	2.79E–07	2.77E–07
30%	2.65E–08	2.74E–08	2.52E–08	1.56E–07	3.38E–07	3.73E–07	3.73E–07	3.54E–07	3.02E–07	3.00E–07
35%	2.82E–08	2.91E–08	2.68E–08	1.66E–07	3.60E–07	3.97E–07	3.97E–07	3.77E–07	3.21E–07	3.19E–07
40%	3.05E–08	3.15E–08	2.90E–08	1.79E–07	3.89E–07	4.29E–07	4.29E–07	4.07E–07	3.47E–07	3.45E–07
45%	3.35E–08	3.45E–08	3.18E–08	1.96E–07	4.27E–07	4.70E–07	4.70E–07	4.47E–07	3.81E–07	3.78E–07
50%	3.65E–08	3.77E–08	3.47E–08	2.14E–07	4.66E–07	5.13E–07	5.13E–07	4.87E–07	4.16E–07	4.13E–07
55%	3.87E–08	3.99E–08	3.67E–08	2.27E–07	4.93E–07	5.43E–07	5.43E–07	5.16E–07	4.40E–07	4.37E–07
60%	4.20E–08	4.33E–08	3.99E–08	2.46E–07	5.35E–07	5.89E–07	5.89E–07	5.60E–07	4.77E–07	4.74E–07
65%	4.54E–08	4.68E–08	4.31E–08	2.66E–07	5.78E–07	6.37E–07	6.37E–07	6.05E–07	5.16E–07	5.12E–07
70%	4.87E–08	5.02E–08	4.62E–08	2.86E–07	6.21E–07	6.84E–07	6.84E–07	6.49E–07	5.54E–07	5.50E–07
75%	5.49E–08	5.66E–08	5.22E–08	3.22E–07	7.00E–07	7.71E–07	7.71E–07	7.32E–07	6.25E–07	6.20E–07
80%	6.10E–08	6.30E–08	5.80E–08	3.58E–07	7.78E–07	8.58E–07	8.58E–07	8.14E–07	6.95E–07	6.90E–07
85%	6.71E–08	6.92E–08	6.38E–08	3.94E–07	8.56E–07	9.43E–07	9.43E–07	8.95E–07	7.64E–07	7.58E–07
90%	7.86E–08	8.11E–08	7.47E–08	4.61E–07	1.00E–06	1.10E–06	1.10E–06	1.05E–06	8.94E–07	8.88E–07
95%	9.85E–08	1.02E–07	9.36E–08	5.78E–07	1.26E–06	1.38E–06	1.38E–06	1.31E–06	1.12E–06	1.11E–06
Maximum	2.18E–07	2.25E–07	2.07E–07	1.28E–06	2.78E–06	3.06E–06	3.06E–06	2.91E–06	2.48E–06	2.46E–06

Sources: DTNs: MO0605SPAINEXI.003 [DIRS 177172]; MO0609SPASRPBM.004 [DIRS 179988]; MO0403SPAAEIBM.002 [DIRS 169392]; MO0407SPACRBSM.002 [DIRS 170677]; MO0406SPAETPBM.002 [DIRS 170150]; MO0503SPADCESR.000 [DIRS 172896].

NOTE: See Excel file *VA BDCFs Present-Day and Future Climates.xls* in Appendix A for details of calculations.

STD = standard deviation.

Table 6.12-4. Statistics for the Volcanic BDCF Component for the Ingestion, Inhalation of Radon Decay Products, and External Exposure, Sv/yr per Bq/m^2

	^{90}Sr	^{99}Tc	^{126}Sn	^{129}I	^{137}Cs	^{210}Pb	^{226}Ra	^{226}Ra +^{210}Pb	^{228}Ra	^{227}Ac
Mean	1.81E–09	2.72E–10	2.54E–08	1.26E–09	7.17E–09	2.29E–09	3.29E–08	3.52E–08	1.27E–08	6.16E–09
STD	3.67E–10	5.16E–10	4.41E–10	2.59E–09	1.55E–10	3.06E–09	1.44E–09	3.45E–09	7.44E–10	1.80E–10
Minimum	1.44E–09	5.08E–12	2.38E–08	1.39E–10	6.75E–09	6.35E–10	2.97E–08	3.07E–08	1.17E–08	5.78E–09
5%	1.50E–09	2.04E–11	2.47E–08	2.22E–10	6.95E–09	8.08E–10	3.05E–08	3.20E–08	1.20E–08	5.94E–09
10%	1.53E–09	2.86E–11	2.48E–08	2.51E–10	7.00E–09	8.88E–10	3.11E–08	3.25E–08	1.21E–08	5.99E–09
15%	1.56E–09	3.51E–11	2.50E–08	2.77E–10	7.02E–09	9.53E–10	3.13E–08	3.28E–08	1.22E–08	6.01E–09
20%	1.57E–09	4.38E–11	2.51E–08	3.08E–10	7.05E–09	1.02E–09	3.15E–08	3.32E–08	1.23E–08	6.04E–09
25%	1.59E–09	5.65E–11	2.51E–08	3.36E–10	7.07E–09	1.08E–09	3.18E–08	3.34E–08	1.23E–08	6.06E–09
30%	1.61E–09	7.01E–11	2.52E–08	3.66E–10	7.09E–09	1.15E–09	3.20E–08	3.37E–08	1.23E–08	6.07E–09
35%	1.63E–09	8.16E–11	2.52E–08	3.99E–10	7.11E–09	1.24E–09	3.22E–08	3.39E–08	1.24E–08	6.09E–09
40%	1.65E–09	9.04E–11	2.53E–08	4.41E–10	7.13E–09	1.33E–09	3.24E–08	3.41E–08	1.24E–08	6.11E–09
45%	1.67E–09	1.09E–10	2.53E–08	4.97E–10	7.14E–09	1.44E–09	3.26E–08	3.44E–08	1.25E–08	6.12E–09
50%	1.70E–09	1.27E–10	2.54E–08	5.45E–10	7.16E–09	1.55E–09	3.28E–08	3.47E–08	1.25E–08	6.14E–09
55%	1.73E–09	1.51E–10	2.54E–08	6.12E–10	7.17E–09	1.70E–09	3.30E–08	3.50E–08	1.26E–08	6.15E–09
60%	1.77E–09	1.79E–10	2.55E–08	6.74E–10	7.19E–09	1.82E–09	3.32E–08	3.52E–08	1.26E–08	6.17E–09
65%	1.80E–09	2.11E–10	2.55E–08	7.50E–10	7.21E–09	1.97E–09	3.35E–08	3.55E–08	1.27E–08	6.18E–09
70%	1.84E–09	2.49E–10	2.56E–08	8.55E–10	7.22E–09	2.15E–09	3.37E–08	3.58E–08	1.27E–08	6.21E–09
75%	1.89E–09	2.92E–10	2.57E–08	1.01E–09	7.24E–09	2.43E–09	3.40E–08	3.61E–08	1.28E–08	6.23E–09
80%	1.98E–09	3.48E–10	2.57E–08	1.17E–09	7.26E–09	2.77E–09	3.43E–08	3.65E–08	1.29E–08	6.26E–09
85%	2.06E–09	4.44E–10	2.58E–08	1.58E–09	7.30E–09	3.26E–09	3.45E–08	3.70E–08	1.31E–08	6.30E–09
90%	2.22E–09	5.90E–10	2.59E–08	2.28E–09	7.34E–09	3.83E–09	3.48E–08	3.77E–08	1.33E–08	6.35E–09
95%	2.46E–09	9.56E–10	2.61E–08	4.84E–09	7.42E–09	5.67E–09	3.52E–08	3.95E–08	1.38E–08	6.47E–09
Maximum	6.10E–09	8.95E–09	2.79E–08	2.86E–08	8.48E–09	6.11E–08	3.95E–08	9.43E–08	2.62E–08	7.76E–09

Table 6.12-4. Statistics for the Volcanic BDCF Component for the Ingestion, Inhalation of Radon Decay Products, and External Exposure, Sv/yr per Bq/m^2 (Continued)

	^{228}Th	^{229}Th	^{230}Th	^{232}Th	^{232}Th + ^{228}Ra + ^{228}Th	^{231}Pa	^{232}U	^{232}U + ^{228}Th	^{233}U	^{234}U
Mean	1.86E–08	4.69E–09	8.51E–11	8.83E–11	3.13E–08	7.12E–10	3.82E–10	1.90E–08	6.48E–11	5.96E–11
STD	3.01E–10	2.40E–10	7.82E–11	8.44E–11	9.35E–10	2.92E–10	4.01E–10	5.16E–10	6.12E–11	5.90E–11
Minimum	1.75E–08	4.33E–09	1.92E–11	1.72E–11	2.94E–08	5.02E–10	4.34E–11	1.79E–08	1.31E–11	9.60E–12
5%	1.81E–08	4.46E–09	2.59E–11	2.43E–11	3.02E–08	5.30E–10	9.76E–11	1.83E–08	2.14E–11	1.77E–11
10%	1.82E–08	4.49E–09	3.01E–11	2.89E–11	3.05E–08	5.42E–10	1.17E–10	1.84E–08	2.44E–11	2.07E–11
15%	1.83E–08	4.52E–09	3.33E–11	3.25E–11	3.06E–08	5.52E–10	1.35E–10	1.85E–08	2.70E–11	2.31E–11
20%	1.83E–08	4.54E–09	3.72E–11	3.66E–11	3.07E–08	5.62E–10	1.50E–10	1.86E–08	2.94E–11	2.55E–11
25%	1.84E–08	4.55E–09	4.02E–11	3.98E–11	3.08E–08	5.69E–10	1.66E–10	1.87E–08	3.18E–11	2.78E–11
30%	1.84E–08	4.57E–09	4.37E–11	4.36E–11	3.09E–08	5.79E–10	1.82E–10	1.87E–08	3.42E–11	3.01E–11
35%	1.85E–08	4.59E–09	4.71E–11	4.73E–11	3.10E–08	5.88E–10	2.01E–10	1.88E–08	3.71E–11	3.30E–11
40%	1.85E–08	4.60E–09	5.09E–11	5.14E–11	3.10E–08	5.97E–10	2.21E–10	1.88E–08	4.02E–11	3.59E–11
45%	1.86E–08	4.62E–09	5.54E–11	5.63E–11	3.11E–08	6.09E–10	2.42E–10	1.89E–08	4.34E–11	3.90E–11
50%	1.86E–08	4.63E–09	6.00E–11	6.12E–11	3.12E–08	6.23E–10	2.69E–10	1.89E–08	4.74E–11	4.29E–11
55%	1.86E–08	4.65E–09	6.52E–11	6.68E–11	3.13E–08	6.36E–10	2.92E–10	1.90E–08	5.11E–11	4.64E–11
60%	1.87E–08	4.67E–09	7.03E–11	7.23E–11	3.14E–08	6.56E–10	3.25E–10	1.90E–08	5.61E–11	5.12E–11
65%	1.87E–08	4.69E–09	7.92E–11	8.19E–11	3.15E–08	6.80E–10	3.68E–10	1.91E–08	6.26E–11	5.76E–11
70%	1.87E–08	4.71E–09	8.65E–11	8.99E–11	3.16E–08	7.08E–10	4.04E–10	1.91E–08	6.82E–11	6.30E–11
75%	1.88E–08	4.74E–09	9.62E–11	1.00E–10	3.17E–08	7.49E–10	4.54E–10	1.92E–08	7.56E–11	7.01E–11
80%	1.88E–08	4.78E–09	1.15E–10	1.20E–10	3.18E–08	8.01E–10	5.17E–10	1.93E–08	8.54E–11	7.96E–11
85%	1.89E–08	4.85E–09	1.38E–10	1.45E–10	3.20E–08	8.58E–10	5.93E–10	1.94E–08	9.70E–11	9.08E–11
90%	1.90E–08	4.95E–09	1.69E–10	1.79E–10	3.22E–08	9.32E–10	7.53E–10	1.95E–08	1.21E–10	1.14E–10
95%	1.91E–08	5.14E–09	2.28E–10	2.43E–10	3.27E–08	1.12E–09	1.02E–09	1.97E–08	1.63E–10	1.54E–10
Maximum	1.95E–08	7.02E–09	8.68E–10	9.34E–10	4.53E–08	4.56E–09	5.88E–09	2.47E–08	9.04E–10	8.70E–10

Table 6.12-4. Statistics for the Volcanic BDCF Component for the Ingestion, Inhalation of Radon Decay Products, and External Exposure, Sv/yr per Bq/m^2 (Continued)

	^{235}U	^{236}U	^{238}U	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu	^{241}Am	^{243}Am
Mean	2.06E–09	5.48E–11	1.62E–09	2.98E–09	7.78E–11	8.49E–11	8.52E–11	8.04E–11	2.51E–10	2.67E–09
STD	6.37E–11	5.59E–11	6.16E–11	6.36E–10	7.72E–11	8.50E–11	8.50E–11	8.06E–11	7.00E–11	8.02E–11
Minimum	1.94E–09	7.38E–12	1.52E–09	2.62E–09	1.33E–11	1.40E–11	1.42E–11	1.31E–11	1.86E–10	2.51E–09
5%	1.98E–09	1.51E–11	1.55E–09	2.71E–09	2.13E–11	2.27E–11	2.30E–11	2.14E–11	1.99E–10	2.57E–09
10%	2.00E–09	1.79E–11	1.57E–09	2.73E–09	2.52E–11	2.71E–11	2.73E–11	2.55E–11	2.02E–10	2.59E–09
15%	2.01E–09	2.02E–11	1.57E–09	2.74E–09	2.83E–11	3.05E–11	3.07E–11	2.88E–11	2.06E–10	2.60E–09
20%	2.01E–09	2.24E–11	1.58E–09	2.76E–09	3.19E–11	3.43E–11	3.46E–11	3.24E–11	2.09E–10	2.62E–09
25%	2.02E–09	2.47E–11	1.59E–09	2.77E–09	3.52E–11	3.80E–11	3.83E–11	3.59E–11	2.12E–10	2.62E–09
30%	2.03E–09	2.68E–11	1.59E–09	2.78E–09	3.84E–11	4.15E–11	4.18E–11	3.92E–11	2.15E–10	2.63E–09
35%	2.03E–09	2.96E–11	1.60E–09	2.79E–09	4.17E–11	4.52E–11	4.54E–11	4.27E–11	2.18E–10	2.64E–09
40%	2.04E–09	3.24E–11	1.60E–09	2.80E–09	4.52E–11	4.91E–11	4.93E–11	4.63E–11	2.21E–10	2.64E–09
45%	2.04E–09	3.52E–11	1.61E–09	2.81E–09	4.92E–11	5.34E–11	5.37E–11	5.05E–11	2.24E–10	2.65E–09
50%	2.05E–09	3.90E–11	1.61E–09	2.82E–09	5.34E–11	5.80E–11	5.83E–11	5.49E–11	2.29E–10	2.66E–09
55%	2.05E–09	4.23E–11	1.61E–09	2.83E–09	5.92E–11	6.45E–11	6.47E–11	6.10E–11	2.33E–10	2.67E–09
60%	2.06E–09	4.69E–11	1.62E–09	2.85E–09	6.37E–11	6.94E–11	6.97E–11	6.57E–11	2.39E–10	2.67E–09
65%	2.07E–09	5.29E–11	1.63E–09	2.87E–09	7.16E–11	7.80E–11	7.83E–11	7.38E–11	2.45E–10	2.68E–09
70%	2.07E–09	5.80E–11	1.63E–09	2.89E–09	7.93E–11	8.67E–11	8.69E–11	8.20E–11	2.53E–10	2.69E–09
75%	2.08E–09	6.48E–11	1.64E–09	2.92E–09	8.79E–11	9.60E–11	9.62E–11	9.09E–11	2.61E–10	2.70E–09
80%	2.09E–09	7.37E–11	1.65E–09	2.97E–09	1.04E–10	1.14E–10	1.14E–10	1.07E–10	2.74E–10	2.71E–09
85%	2.10E–09	8.43E–11	1.66E–09	3.10E–09	1.23E–10	1.34E–10	1.34E–10	1.27E–10	2.93E–10	2.73E–09
90%	2.12E–09	1.07E–10	1.68E–09	3.26E–09	1.59E–10	1.75E–10	1.75E–10	1.65E–10	3.27E–10	2.76E–09
95%	2.15E–09	1.44E–10	1.71E–09	3.75E–09	2.07E–10	2.28E–10	2.28E–10	2.16E–10	3.77E–10	2.80E–09
Maximum	2.83E–09	8.23E–10	2.41E–09	1.20E–08	9.18E–10	1.01E–09	1.01E–09	9.57E–10	1.00E–09	3.42E–09

Sources: DTNs: MO0605SPAINEXI.003 [DIRS 177172]; MO0609SPASRPBM.004 [DIRS 179988]; MO0403SPAAEIBM.002 [DIRS 169392]; MO0407SPACRBSM.002 [DIRS 170677]; MO0406SPAETPBM.002 [DIRS 170150]; MO0503SPADCESR.000 [DIRS 172896].

NOTE: See Excel file *VA BDCFs Present-Day and Future Climates.xls* in Appendix A for details of calculations.

STD = standard deviation.

6.12.3 TSPA Integration and Use of Volcanic Biosphere Dose Conversion Factors

The radionuclide concentration in volcanic ash initially deposited on the ground at the location of the RMEI or redistributed to that location is the only source of radionuclide contamination in the biosphere for the volcanic ash exposure scenario. As noted before, direct inhalation of ash during volcanic eruption is treated separately (Section 6.15.2).

The format of the source term (radionuclide concentration in the environmental medium that is the source of contamination in the biosphere) is an important aspect of integration of the BDCFs with the source term in the biosphere model component of the TSPA model. The source term for evaluation of RMEI exposure to radionuclides released from the repository during a volcanic eruption is calculated using two models, ASHPLUME and FAR. ASHPLUME atmospheric ash dispersal model and the associated computer code calculate ash and radioactive waste concentrations initially deposited in the Yucca Mountain region, including the area occupied by the community that includes the RMEI. FAR model and supporting software evaluate the redistribution of that initially deposited volcanic ash and associated radioactive waste within the Fortymile Wash drainage area and calculates contaminant transport within the soil. FAR segregates the Fortymile Wash alluvial fan into distributary channels and interchannel divides. On interchannel divides, radioactive waste is considered to be deposited only from primary ash fall. Radionuclides within this fallout are initially concentrated at the surface but then diffuse within the soil profile. In channels, the initial radionuclide concentration includes the primary fallout as well as the radionuclides redistributed from the upper basin by fluvial processes. Both of these components will be mixed with channel sediments by fluvial scour and redeposition (SNL 2007 [DIRS 179347], Section 6.2). Radionuclides in the distributary channel are also subject to diffusion within the soil.

The following expression that combines the source terms (calculated in the TSPA model) and the BDCFs (provided by the biosphere model) is used to calculate the annual dose to the RMEI for the volcanic ash exposure scenario, conditional upon an eruption:

$$D_{all\ pathway,i}(t,T) = BDCF_{ext,ing,Rn,i}\ Cs_i(t) + \left(BDCF_{inh,v,i}\,f(t-T) + BDCF_{inh,p,i}\right)Cs_{mc,i}(t)$$

(Eq. 6.12-1)

where

$D_{all\ pathway,\ i}(t,T)$ = all-pathway annual dose for primary radionuclide i at time t (yr) after the repository closure, conditional on a volcanic eruption at time T (yr) (Sv/yr)

$BDCF_{ext,ing,Rn,i}$ = BDCF component for external exposure, ingestion, and inhalation of radon decay products for primary radionuclide i (Sv/yr per Bq/m^2)

$Cs_i(t)$ = areal radionuclide concentration in a specified depth of surface soil at time t (yr) after the repository closure (Bq/m^2) calculated in TSPA model

$BDCF_{inh,v,i}$ = BDCF component representing average inhalation exposure in the first year after a volcanic eruption; used in calculation of short-term inhalation exposure at post-eruption level of mass loading in excess of nominal mass loading for primary radionuclide *i* (Sv/yr per Bq/kg)

$BDCF_{inh,p,i}$ = BDCF component for long-term inhalation at nominal level of mass loading for primary radionuclide *i* (Sv/yr per Bq/kg)

$f(t\text{-}T)$ = decay function describing reduction of the annual average mass loading with time at time $t\text{-}T$ following a volcanic eruption

$Cs_{mc,i}(t)$ = activity concentration of radionuclide *i* per unit mass of soil in the resuspendable layer of surface soil (critical thickness) at time *t* (yr) after the repository closure calculated in TSPA model from the Fortymile-wash Ash Redistribution model (FAR) waste concentrations (Bq/kg).

The time-dependent areal radionuclide concentration in surface soil, $Cs_i(t)$, represents radionuclide activity integrated over the tillage depth. The tillage depth is a biosphere model parameter (Section 6.6) that is also provided as input to the TSPA model (included in the output DTN) to allow calculation of soil depth-integrated radionuclide concentration per unit surface area of the soil.

The time-dependent radionuclide activity concentration per unit mass, $Cs_{mc,i}(t)$, is calculated by averaging mass radionuclide concentration over the depth of the resuspendable layer of soil (critical thickness). The critical depth, i.e., the depth of surface soil layer that is available for resuspension, is represented by the uniform distribution with a minimum of 0.001 m (1 mm) and a maximum of 0.003 m (3 mm) and is included in the output DTN of this model report (DTN: MO0702PAVBPDCF.000). This parameter is not used directly in the biosphere model.

Both source terms used in the calculation of doses (Equation 6.12-1), i.e., the areal radionuclide concentration in surface soil, $Cs_i(t)$, and the mass radionuclide concentration in the resuspendable soil layer, $Cs_{mc,i}(t)$, are calculated in TSPA by weighting the appropriate radionuclide concentrations by the respective expected areas of the distributary channels and the interchannel divides at the location of the RMEI. The radioactive waste mass concentration in the resuspendable layer of soil, $Cs_{mc,i}(t)$, is determined from the results of the ASHPLUME and FAR models. These models produce the results in terms of contaminant concentration per unit volume. The concentration per unit volume can be converted to concentration per unit mass by dividing it by the density of the resuspendable layer, ρ_c. In the interchannel divides, the density of the resuspendable layer, ρ_c, can be calculated from the known ash thickness, d_a, density, ρ_a, and surface soil density, ρ_s, as:

$$\rho_c = \frac{d_a\ \rho_a + (d_c - d_a)\ \rho_s}{d_c} \quad \text{when } d_a < d_c \text{ and}$$

$$\rho_c = \rho_a \quad \text{when } d_a \geq d_c \qquad \text{(Eq. 6.12-2)}$$

where

ρ_c = bulk density of resuspendable layer of surface soil, including volcanic ash (kg/m^3)

d_c = thickness of resuspendable soil layer, i.e., the critical thickness (m)

d_a = thickness of initial ash layer (m)

ρ_a = bulk density of volcanic ash (kg/m^3)

ρ_s = bulk density of the surface soil (without ash) (kg/m^3).

The sampling results of bulk density of the surface soil for individual biosphere model realizations are included in the output DTN: MO0702PAVBPDCF.000. In the channels, where the ash is mixed with soil and diluted, the density of resuspendable layer, ρ_c, can be approximated by the density of soil, ρ_s.

Because of the anticipated decrease in airborne particulate concentration over time, the dose from inhalation of airborne particulates is a function of time after a volcanic eruption. This is accomplished by multiplying the BDCF component representing the first year dose from inhalation of particulates, $BDCF_{inh,v,i}$, by the mass loading time decrease function. As noted before, $BDCF_{inh,v,i}$ represents inhalation exposure in excess of the nominal, steady-state (i.e., at pre-eruption mass loading levels) inhalation exposure. The function of time, *f(t-T)* in Equation 6.12-1, thus accounts for the reduction of mass loading in the years immediately following volcanic eruption (occurring at time T). Mass loading decreases exponentially with time after the eruption ($t > T$) (based on BSC 2006 [DIRS 177101], Section 7.1; DTN: MO0605SPAINEXI.003 [DIRS 177172]) as:

$$f(t-T) = e^{-\lambda(t-T)} \quad \text{(Eq. 6.12-3)}$$

where

λ = mass loading decrease rate constant (1/yr)

T = time of a volcanic eruption (yr); t-T = 0 represents the first year after a volcanic eruption.

The mass loading decrease constant (λ in Equation 6.12-3) depends on the ash thickness. For a contaminated layer depth of less than 10 mm, it is represented by a triangular probability distribution function with a mode of 0.33/yr, a minimum of 0.2/yr, and a maximum of 2.0/yr (DTN: MO0605SPAINEXI.003 [DIRS 177172]). For a contaminated layer depth of 10 mm or more, the mass loading decrease constant is represented by a triangular distribution with a mode of 0.20/yr, a minimum of 0.125/yr, and a maximum of 1.0/yr (DTN: MO0605SPAINEXI.003 [DIRS 177172]). This latter distribution is used in TSPA for reasons discussed below.

As noted previously, the ash redistribution model considers the interchannel divides separately from the distributary channels that carry redistributed ash (SNL 2007 [DIRS 179347], Section 6.2). These areas can have a different thickness of ash or ash mixed with soil, and thus different mass loading decrease rate constants. To account for these differences, it is recommended that the mass loading decrease rate constant used in the TSPA model is that for the greater of the contaminated soil thickness in the distributary channels and interchannel divides. Because the thickness of the redistributed ash in the channels is likely to be greater than the threshold depth of 10 mm, it is reasonable to always use the mass loading decrease rate constant for the thicker contaminated layer.

In the TSPA model, calculations of dose are carried out in a series of time steps. The mass loading decrease function is thus calculated for every time step. It is recommended that the value of the mass loading function representative of a time step is that for the time beginning that time step to ensure that the annual dose for the first year is not systematically underestimated. For example, in the case of the first time step after an eruption, $t\text{-}T = 0$ would be used to calculate $f(t\text{-}T)$ (Equation 6.12-3) for the first time step, irrespective of the length of the TSPA time step.

The total annual conditional dose at time $t\text{-}T$ after a volcanic eruption, and time t after repository closure, is the sum of all-pathway doses for individual primary radionuclides included in the TSPA (primary radionuclides), including their decay products:

$$D_{total}(t,T) = \sum_i D_{all\ pathway,i}(t,T) \qquad \text{(Eq. 6.12-4)}$$

where

$D_{total}(t,T)$	=	total annual dose from all radionuclides at time $t\text{-}T$ after a volcanic release of radionuclides from the repository at time t after repository closure (Sv/yr)
$D_{all\ pathway,i}(t,T)$	=	all-pathway annual dose for primary radionuclide i at time $t\text{-}T$ after a volcanic release of radionuclides from the repository and time t after repository closure (Sv/yr).

Because climate change has a negligible effect on BDCFs it is recommended that one set of BDCFs, those developed for the present-day climate, be used for the entire period of geologic stability.

The volcanic BDCF components are correlated because for a given biosphere model realization number, all sampled radionuclide-independent parameters are the same regardless of a radionuclide. These correlations between the BDCF components are captured in the TSPA model through sampling of the row vectors, where for a given realization, the TSPA model samples BDCFs from one, randomly selected, realization of the biosphere model.

6.13 UNCERTAINTY AND SENSITIVITY ANALYSIS FOR GROUNDWATER BIOSPHERE DOSE CONVERSION FACTORS

6.13.1 Distributions of Biosphere Dose Conversion Factors

This section evaluates the distributions of all BDCFs and examines the trends in their values and their causes. Each run of the biosphere model for the groundwater exposure scenario for a given radionuclide produced 1,000 model realizations, that is, 1,000 BDCF values, each for a different set of input parameter values. BDCFs were calculated for three climate states, as described in Section 6.11.

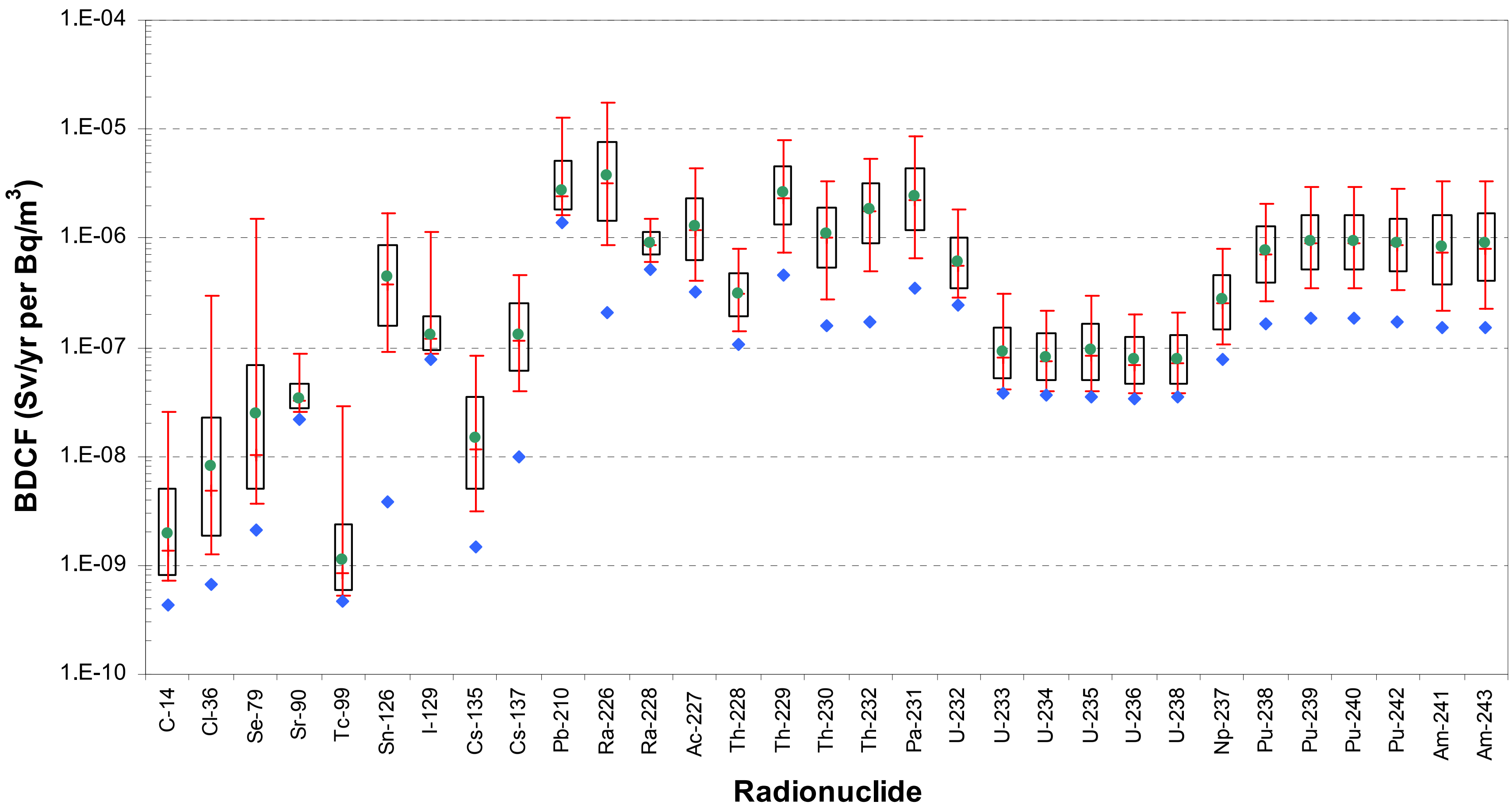
Figure 6.13-1 shows the ranges of BDCFs for all primary radionuclides, including their mean and median values, minima and maxima, as well as the 5th and 95th percentiles. The variance in the BDCF values is a result of the input parameter variability and uncertainty that is propagated into the model output. A number of trends can be observed in the BDCF values. First, the mean BDCF values for non-actinides generally increase with increasing mass of a radionuclide. The mean BDCF values for the actinides are generally higher than those for the lighter radionuclides and are roughly within an order of magnitude of each other, with the values for ^{226}Ra being the highest.

To better show the span of the BDCF values and identify radionuclides that have the lowest and the highest BDCF values, the BDCFs were sorted in ascending order by the value of the means (Figure 6.13-2). The BDCF values are the highest for the radionuclides with relatively high atomic numbers and generally tend to decrease with decreasing atomic number. The lowest BDCF value is for ^{99}Tc; the highest is for ^{210}Pb and ^{226}Ra. The high value for ^{226}Ra is due to the contribution from inhalation of radon decay products. The difference between the highest and the lowest BDCFs is almost 5 orders of magnitude.

Figures 6.13-1 and 6.13-2 show that the degree of variance in the BDCF values differs greatly among the radionuclides. The minimum-to-maximum range is much wider than the 5th to 95th percentile range of the BDCF values. The BDCF for ^{79}Se has the widest minimum-to-maximum range of BDCF values, extending over about 2.6 orders of magnitude (a factor of 417); the range for ^{228}Ra is only 0.4 orders of magnitude (a factor of about 2.6). The 5th to 95th percentile range is much narrower, spanning from a factor of 1.6 for ^{228}Ra up to a factor of 13.4 for ^{79}Se.

For calculations, see Excel file *GW BDCF Variability Plot.xls* (Appendix A); for discussion of pathway contributions see Sections 6.13.2.

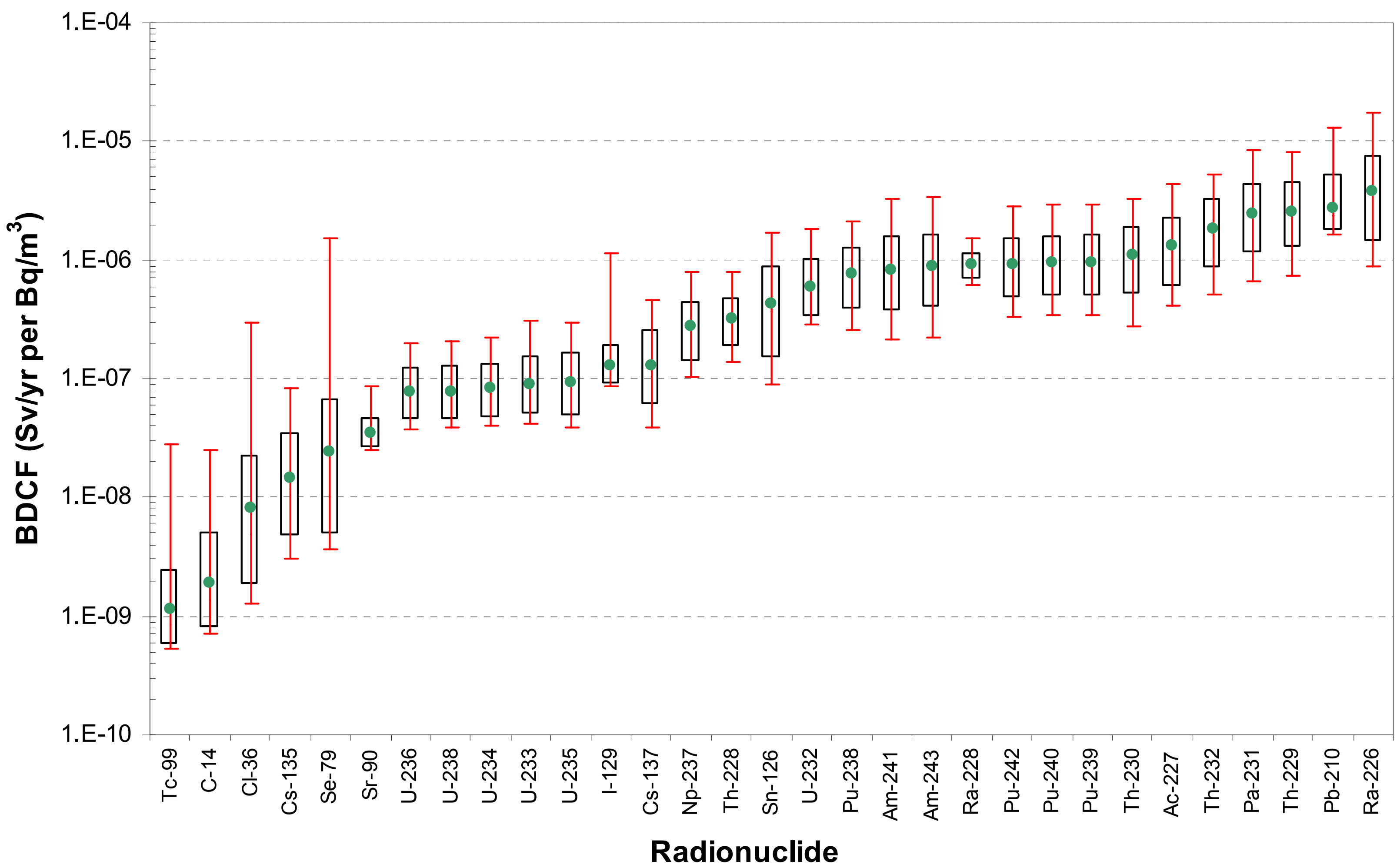
The mean values of BDCF distributions (represented by dots in Figure 6.13-1) are greater than the median (50th percentile) values (represented by tick marks on vertical solid lines in Figure 6.13-1). This indicates that the distributions are not symmetrical but instead approach lognormal distributions, as expected from the Central Limit Theorem (lognormal distributions arise from multiplication of randomly distributed parameters, a tendency that is reinforced by the fact that many stochastic input parameters are themselves lognormal).



Source: Excel file *GW BDCF Variability Plots.xls* (Appendix A).

NOTE: Boxes represent 5th to 95th percentile range. The vertical solid lines represent the range and the tick mark on the line is the median. Diamonds represent BDCF contribution from drinking water; dots represent the mean BDCF.

Figure 6.13-1. Distributions of BDCFs for the Groundwater Exposure Scenario and the Present-Day Climate



Source: Excel file *GW BDCF Variability Plots.xls* (Appendix A).

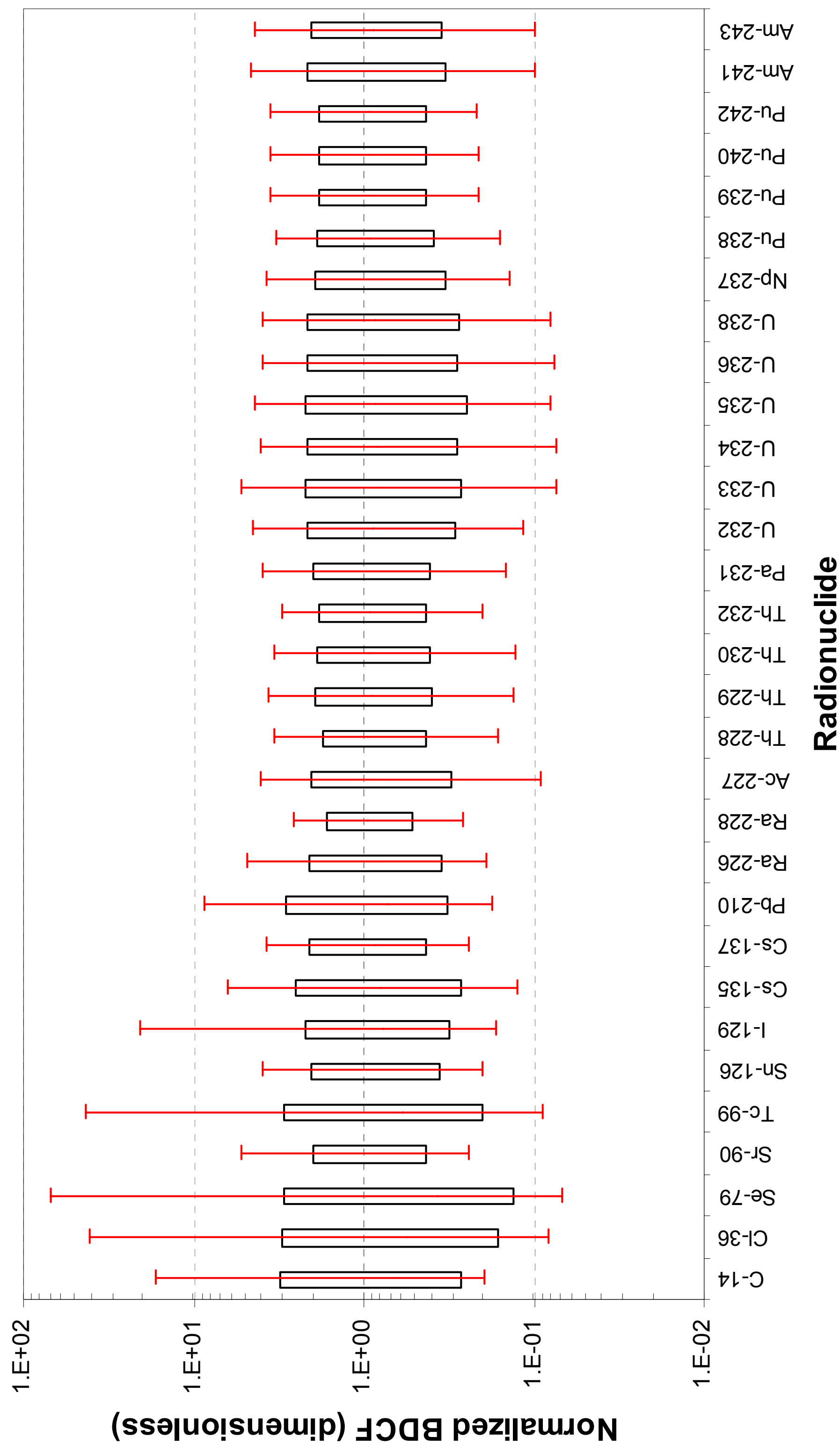
NOTE: Boxes represent 5th to 95th percentile range. The vertical solid lines represent the range. Dots represent the mean BDCF.

Figure 6.13-2. Distributions of BDCFs for the Groundwater Exposure Scenario and the Present-Day Climate Sorted by the Mean BDCF Value

It can be seen in Figure 6.13-1 that the tails of the BDCF distributions (i.e., the distribution beyond the 5th and 95th percentiles) differ among the radionuclides. For some radionuclides, such as ^{99}Tc, the minimum-to-maximum range is much wider than the 5th to 95th percentile range. The tails of BDCF distributions are primarily caused by sampling of parameters that are represented by the lognormal distributions, such as the partition coefficients (K_ds), soil-to-plant transfer factors, and transfer coefficients for animal products. Both high K_ds and high transfer factors can result in a high value of BDCF and, conversely, low K_ds and low transfer factors can result in a low value of BDCF. However, usually when a high value is sampled from the K_d distribution, a low value is sampled from the transfer factor distribution because K_ds are negatively correlated with the transfer factors with a rank correlation coefficient of –0.8. High values of K_ds and transfer factors produce high radionuclide concentrations in crops thus influencing the dose from consumption of crops and animal products (because of animal consumption of forage crops), such as for ^{99}Tc and ^{36}Cl. As a result, BDCF distributions for radionuclides that have a high percentage of BDCF contribution from the ingestion pathway (see Table 6.13-1 and the discussion of pathway analysis in Section 6.13.2) tend to have relatively long tails. Low K_ds also influence the distribution tails. Distributions of BDCFs for most of the actinides that have non-ingestion pathways as dominant pathways have relatively short tails.

The range in the BDCF values for a radionuclide can be better evaluated when the BDCFs are normalized to their mean value, as shown in Figure 6.13-3. This figure shows the distribution of BDCF values about the mean. The 5th percentile values are within a factor of 0.2 to 0.8 of the mean BDCF, depending on a radionuclide. The 95th percentiles are within a factor of 1.3 to 2.8 of the mean (for calculations see Excel file *GW BDCF Variability Plots.xls*, worksheet *BDCF Normalized to Mean*). The minimum values are from 0.2 (^{126}Sn and ^{226}Ra) to 0.7 (^{90}Sr) of the mean, and maximum values are from 2.5 (^{90}Sr) to about 63 (^{79}Se) times greater than the mean.

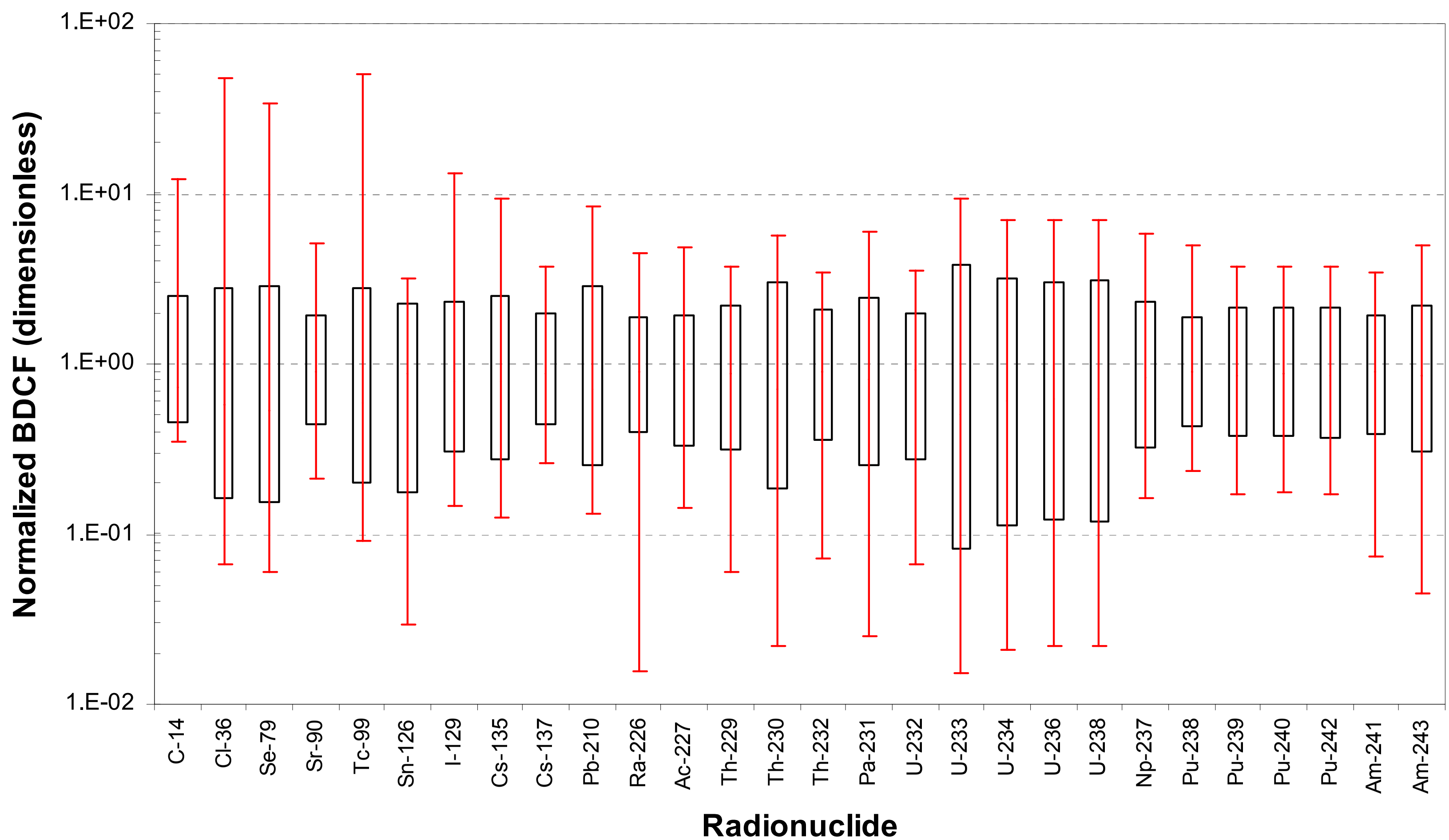
Per 10 CFR 63.312(d) [DIRS 173273], the drinking water component in the biosphere model is fixed; therefore, the distribution of BDCFs results from variability and uncertainty in the contributions from all other pathways. As a result, the distribution of BDCFs tends to be narrow if drinking water is an important pathway (e.g., ^{90}Sr and ^{129}I) and wider if the contribution of drinking water is less important. To show this effect, the drinking water contribution for individual radionuclides was subtracted from their BDCF statistics and the remainder normalized to its mean value (Figure 6.13-4). The variability (as measured by the 5th to 95th percentile levels) between normalized BDCF distributions, once the fixed drinking water component is removed, is more consistent among radionuclides than for the total normalized values.



Source: Excel file *GW BDCF Variability Plots.xls* (Appendix A).

NOTE: Boxes represent 5th to 95th percentile range. The vertical solid lines represent the range.

Figure 6.13-3. Distributions of BDCFs for Groundwater Exposure Scenario, Present-Day Climate, Normalized to the Mean Value



Source: Excel file *GW BDCF Variability Plots.xls* (Appendix A).

NOTE: Boxes represent 5th to 95th percentile range. The vertical solid lines represent the range.

Figure 6.13-4. Distributions of BDCFs (exclusive of the drinking water component) for Groundwater Exposure Scenario, Present-Day Climate, Normalized to the Mean Value

6.13.2 Summary of Pathway Analysis Results

The aim of the pathway analysis is to identify those pathways that are important contributors to the BDCFs, so further analyses can focus on their contributing environmental transport and exposure pathways and the corresponding input parameters. The biosphere model for the groundwater exposure scenario includes 15 exposure pathways. Pathway analysis was conducted, using the mean values of the BDCFs, to determine the relative importance of individual exposure pathways in terms of their contributions to BDCFs for various radionuclides.

The pathway contributions to the mean BDCFs for the groundwater exposure scenario are reproduced in Tables 6.13-1 and 6.13-2. Pathway contributions differ among radionuclides, but the RMEI ingestion of water is an important pathway for most radionuclides. Ingestion of locally produced food is important for most radionuclides with atomic numbers less than about 88. Inhalation of particulate matter tends to dominate doses for radionuclides with atomic numbers greater than 88 (e.g., isotopes of actinium, thorium, uranium, plutonium, and americium). Inhalation of radioactive aerosols generated by evaporative coolers also is an important inhalation exposure pathway for some of these radionuclides. Other pathways are only important for a few radionuclides. For instance, external exposure is a dominant pathway for ^{126}Sn and ^{137}Cs; inhalation of radon decay products is important for ^{226}Ra and ^{230}Th; and fish consumption is important for ^{14}C, cesium isotopes, and ^{210}Pb (Table 6.13-1).

For the upper bound of the glacial transition climate, the importance of the evaporative cooler pathway is greatly reduced, as is the importance of the pathways that are related to radionuclide concentration in the surface soil (the equilibrium activity concentration in the surface soil is less because of the decreased irrigation rate) (Table 6.13-2). This increases the relative importance of the water ingestion pathway, which is a dominant pathway for many radionuclides. Inhalation of particulate matter remains an important pathway for the radionuclides with the atomic number greater than 88 (Table 6.13-2).

To visualize the results of the pathway analysis described above and to show the patterns in pathway importance for various radionuclides, Figures 6.13-5 and 6.13-6 show percent pathway contributions to the mean BDCF for several selected radionuclides for the present-day and upper bound glacial transition climates, respectively. The selected radionuclides include those radionuclides that were identified as important in previous performance assessments. The results of the TSPA for the supplemental science and performance analysis indicated that ^{14}C, ^{99}Tc, and ^{129}I were the most important dose contributors for nominal performance during the first 20,000 years postclosure. Radionuclides important in the initial period are those that are relatively mobile in the environment. Radionuclides with the mass number greater than 88 tend to move more slowly in the environment because of their high sorption onto the solids. Three radionuclides, ^{234}U, ^{237}Np, and ^{239}Pu were selected to represent this group.

Figures 6.13-5 and 6.13-6 show that ingestion of water and inhalation of particulate matter are the dominant pathways for all selected radionuclides. The figures also show how the relative contributions of these pathways change when the irrigation with contaminated water is reduced for the future climate represented by the upper bound of the glacial transition climate. Consumption of water becomes a more important pathway although its absolute contribution to the BDCF is unaffected.

Table 6.13-1. Exposure Pathway Contributions (%) for the Groundwater BDCFs for the Present-Day Climate

Radionuclide	External Exposure	Inhalation			Ingestion										
		Particulate Matter	Evaporative Cooler Aerosols	Radon	Water	Leafy Vegetables	Other Vegetables	Fruit	Grain	Meat	Milk	Poultry	Eggs	Fish	Soil
^{14}C	0.0	0.0	0.6	0.0	22.0	0.1	0.2	0.4	0.6	7.2	3.4	0.6	5.6	59.4	0.0
^{36}Cl	0.0	0.0	0.9	0.0	8.4	2.1	3.1	10.3	3.5	29.0	22.5	0.1	11.1	9.0	0.0
^{79}Se	0.0	0.1	0.1	0.0	8.7	0.4	0.2	0.7	0.1	70.0	3.5	1.0	11.7	3.2	0.2
^{90}Sr	1.0	0.2	0.9	0.0	64.7	5.9	3.3	5.5	0.8	4.7	5.7	0.1	2.1	4.9	0.4
^{99}Tc	0.0	0.1	2.3	0.0	41.7	8.8	1.7	6.2	0.7	6.0	18.3	0.2	12.6	1.4	0.0
^{126}Sn	93.4	0.1	0.1	0.0	0.9	0.0	0.0	0.0	0.0	1.6	0.1	0.0	0.1	3.6	0.0
^{129}I	0.0	0.0	0.1	0.0	60.1	2.6	0.7	2.5	0.5	5.8	8.5	0.2	13.2	5.4	0.3
^{135}Cs	0.0	0.3	0.1	0.0	10.1	0.7	0.3	1.2	0.2	11.1	6.3	6.0	4.4	58.6	0.8
^{137}Cs	35.2	0.1	0.1	0.0	7.6	0.4	0.1	0.5	0.1	3.7	2.1	2.9	2.2	44.4	0.5
^{210}Pb	0.0	2.2	0.7	0.0	50.8	2.7	0.6	2.4	0.3	0.6	0.4	0.2	6.6	28.0	4.2
^{226}Ra	11.2	2.6	0.5	73.7	5.4	0.6	0.2	0.9	0.2	0.5	0.5	0.1	1.6	0.6	1.3
^{228}Ra	5.9	16.6	3.5	0.0	56.3	2.8	0.6	2.3	0.3	0.6	0.9	0.1	0.0	6.5	3.4
^{227}Ac	1.6	42.3	26.4	0.0	24.5	1.1	0.3	0.9	0.1	0.1	0.0	0.0	0.0	1.6	1.1
^{228}Th	3.6	25.0	27.0	0.0	33.1	1.4	0.3	1.2	0.2	0.2	0.0	0.0	0.1	7.1	0.8
^{229}Th	2.3	52.8	19.5	0.0	18.1	0.9	0.2	0.7	0.1	0.2	0.0	0.0	0.1	3.9	1.2
^{230}Th	1.4	50.8	18.5	8.4	14.4	0.7	0.2	0.6	0.1	0.3	0.1	0.0	0.2	3.1	1.0
^{232}Th	30.1	41.7	11.7	0.0	9.1	1.0	0.4	0.9	0.2	0.6	0.7	0.0	0.1	1.9	1.6
^{231}Pa	2.5	61.3	18.6	0.0	14.3	0.7	0.2	0.7	0.1	0.2	0.0	0.0	0.0	0.3	1.0
^{232}U	23.0	14.4	12.1	0.0	40.7	1.8	0.4	1.5	0.2	0.2	0.3	0.5	2.8	1.2	0.9
^{233}U	0.3	26.2	21.0	0.0	41.8	1.8	0.4	1.6	0.2	0.3	0.4	0.6	3.3	1.3	0.9
^{234}U	0.0	22.0	22.6	0.1	44.1	1.9	0.5	1.7	0.2	0.3	0.4	0.6	3.4	1.3	0.9
^{235}U	17.5	18.9	17.7	0.0	36.5	1.6	0.4	1.4	0.2	0.2	0.4	0.5	2.8	1.1	0.7
^{236}U	0.0	21.6	22.4	0.0	44.7	1.9	0.5	1.7	0.2	0.3	0.5	0.6	3.5	1.3	0.9
^{238}U	4.7	19.4	20.1	0.0	44.5	1.9	0.5	1.7	0.2	0.3	0.5	0.6	3.5	1.3	0.9
^{237}Np	7.4	21.1	35.7	0.0	28.8	1.4	0.5	2.0	0.2	0.7	0.0	0.0	0.0	1.9	0.3

Table 6.13-1. Exposure Pathway Contributions (%) for the Groundwater BDCFs for the Present-Day Climate (Continued)

Radionuclide	External Exposure	Inhalation			Ingestion										
		Particulate Matter	Evaporative Cooler Aerosols	Radon	Water	Leafy Vegetables	Other Vegetables	Fruit	Grain	Meat	Milk	Poultry	Eggs	Fish	Soil
^{238}Pu	0.0	43.8	27.9	0.0	21.9	1.0	0.2	0.8	0.1	0.0	0.0	0.0	0.0	3.2	1.0
^{239}Pu	0.0	50.5	24.5	0.0	19.2	0.9	0.2	0.7	0.1	0.0	0.0	0.0	0.0	2.8	0.9
^{240}Pu	0.0	50.4	24.6	0.0	19.3	0.9	0.2	0.7	0.1	0.0	0.0	0.0	0.0	2.8	0.9
^{242}Pu	0.0	50.6	24.5	0.0	19.2	0.9	0.2	0.7	0.1	0.0	0.0	0.0	0.0	2.8	0.9
^{241}Am	0.1	54.6	22.7	0.0	17.9	0.9	0.2	0.7	0.1	0.1	0.0	0.0	0.0	1.7	1.1
^{243}Am	3.5	54.1	21.2	0.0	16.8	0.8	0.2	0.7	0.1	0.1	0.0	0.0	0.0	1.6	1.0

Source: Excel file *GW BDCFs Pathway Analysis PDC.xls*; Appendix A

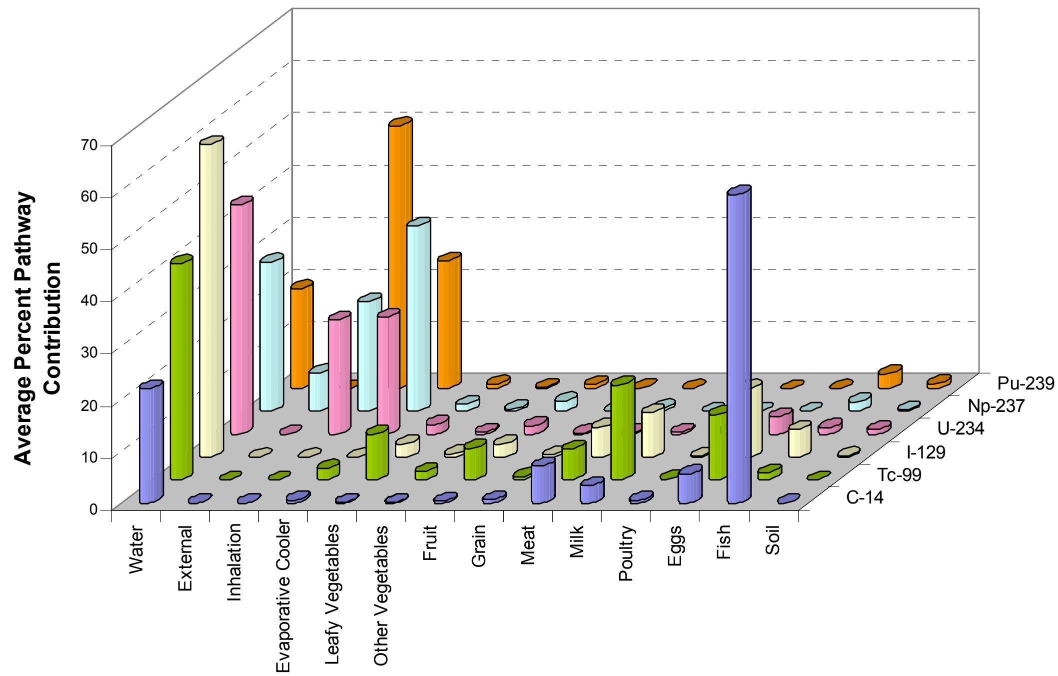
Table 6.13-2. Exposure Pathway Contributions (%) for the Groundwater BDCFs for the Upper Bound of Glacial Transition Climate

Radionuclide	External Exposure	Inhalation			Ingestion										
		Particulate Matter	Evaporative Cooler Aerosols	Radon	Water	Leafy Vegetables	Other Vegetables	Fruit	Grain	Meat	Milk	Poultry	Eggs	Fish	Soil
^{14}C	0.0	0.0	0.1	0.0	23.4	0.1	0.1	0.2	0.5	4.8	2.3	0.5	4.6	63.4	0.0
^{36}Cl	0.0	0.0	0.3	0.0	12.7	2.2	3.1	10.6	3.2	27.2	21.1	0.1	11.6	7.8	0.0
^{79}Se	0.0	0.1	0.0	0.0	15.4	0.5	0.2	0.7	0.1	62.7	3.2	1.1	12.5	3.3	0.2
^{90}Sr	0.6	0.1	0.2	0.0	76.9	4.4	2.1	3.5	0.6	2.9	3.6	0.0	1.5	3.3	0.3
^{99}Tc	0.0	0.1	0.6	0.0	52.8	7.7	1.4	5.1	0.6	4.8	14.8	0.2	10.8	1.0	0.0
^{126}Sn	92.1	0.1	0.0	0.0	1.7	0.1	0.0	0.0	0.0	1.6	0.1	0.0	0.1	4.0	0.0
^{129}I	0.0	0.0	0.0	0.0	70.3	2.1	0.4	1.6	0.4	4.3	6.3	0.1	10.5	3.6	0.2
^{135}Cs	0.0	0.3	0.0	0.0	16.6	0.7	0.2	1.0	0.2	9.1	5.2	5.6	4.1	56.1	0.8
^{137}Cs	30.1	0.1	0.0	0.0	13.1	0.5	0.1	0.5	0.1	3.6	2.1	3.1	2.3	44.1	0.5
^{210}Pb	0.0	1.5	0.2	0.0	64.6	2.3	0.4	1.6	0.3	0.5	0.3	0.2	4.8	20.6	2.9
^{226}Ra	9.9	2.3	0.2	71.8	9.7	0.7	0.2	0.8	0.2	0.4	0.4	0.1	1.5	0.6	1.3
^{228}Ra	3.7	11.5	1.0	0.0	71.0	2.4	0.4	1.5	0.3	0.4	0.6	0.1	0.0	4.8	2.3
^{227}Ac	1.3	43.3	9.5	0.0	40.6	1.3	0.2	0.8	0.1	0.1	0.0	0.0	0.0	1.5	1.2
^{228}Th	3.0	22.3	9.6	0.0	54.3	1.6	0.3	1.0	0.2	0.2	0.0	0.0	0.1	6.7	0.8
^{229}Th	2.0	50.9	7.5	0.0	32.0	1.1	0.2	0.7	0.1	0.2	0.0	0.0	0.1	3.9	1.3
^{230}Th	1.2	50.3	7.3	8.0	26.3	0.9	0.2	0.6	0.2	0.3	0.1	0.0	0.2	3.2	1.1
^{232}Th	28.2	42.1	4.8	0.0	17.2	1.1	0.4	0.9	0.2	0.6	0.6	0.1	0.1	2.1	1.8
^{231}Pa	2.3	60.4	7.4	0.0	26.4	0.9	0.2	0.7	0.1	0.2	0.0	0.0	0.0	0.3	1.1
^{232}U	17.0	12.3	3.7	0.0	57.9	1.8	0.3	1.1	0.2	0.2	0.3	0.5	2.8	1.0	0.8
^{233}U	0.3	20.8	6.8	0.0	62.1	1.9	0.3	1.2	0.2	0.3	0.4	0.5	3.3	1.1	0.8
^{234}U	0.0	17.7	7.2	0.0	64.7	2.0	0.4	1.3	0.2	0.2	0.4	0.6	3.4	1.1	0.8
^{235}U	13.8	15.7	5.9	0.0	55.7	1.7	0.3	1.1	0.2	0.2	0.3	0.5	2.9	1.0	0.7
^{236}U	0.0	17.3	7.1	0.0	65.1	2.0	0.4	1.3	0.2	0.2	0.4	0.6	3.4	1.1	0.8
^{238}U	3.5	15.4	6.3	0.0	64.4	2.0	0.3	1.3	0.2	0.2	0.4	0.6	3.4	1.1	0.8
^{237}Np	7.2	19.7	14.0	0.0	51.7	1.7	0.5	2.0	0.2	0.7	0.0	0.0	0.0	1.9	0.3

Table 6.13-2. Exposure Pathway Contributions (%) for the Groundwater BDCFs for the Upper Bound of Glacial Transition Climate (Continued)

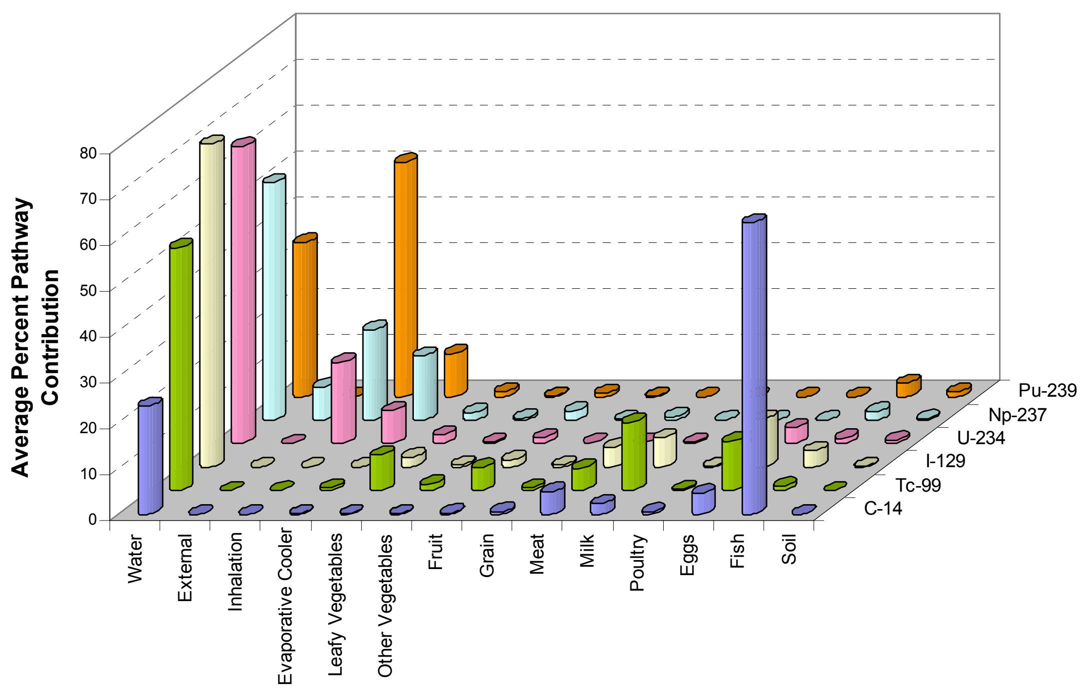
Radionuclide	External Exposure	Inhalation			Ingestion										
		Particulate Matter	Evaporative Cooler Aerosols	Radon	Water	Leafy Vegetables	Other Vegetables	Fruit	Grain	Meat	Milk	Poultry	Eggs	Fish	Soil
^{238}Pu	0.0	47.3	10.0	0.0	36.2	1.2	0.2	0.7	0.1	0.0	0.0	0.0	0.0	3.1	1.1
^{239}Pu	0.0	51.0	9.3	0.0	33.6	1.1	0.2	0.7	0.1	0.0	0.0	0.0	0.0	2.9	1.1
^{240}Pu	0.0	50.9	9.3	0.0	33.7	1.1	0.2	0.7	0.1	0.0	0.0	0.0	0.0	2.9	1.1
^{242}Pu	0.0	51.1	9.3	0.0	33.5	1.1	0.2	0.7	0.1	0.0	0.0	0.0	0.0	2.9	1.1
^{241}Am	0.1	53.8	8.9	0.0	32.2	1.1	0.2	0.7	0.1	0.1	0.0	0.0	0.0	1.7	1.2
^{243}Am	3.2	53.0	8.4	0.0	30.6	1.0	0.2	0.6	0.1	0.1	0.0	0.0	0.0	1.7	1.1

Source: Excel file *GW BDCFs Pathway Analysis FC.xls*; Appendix A



Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

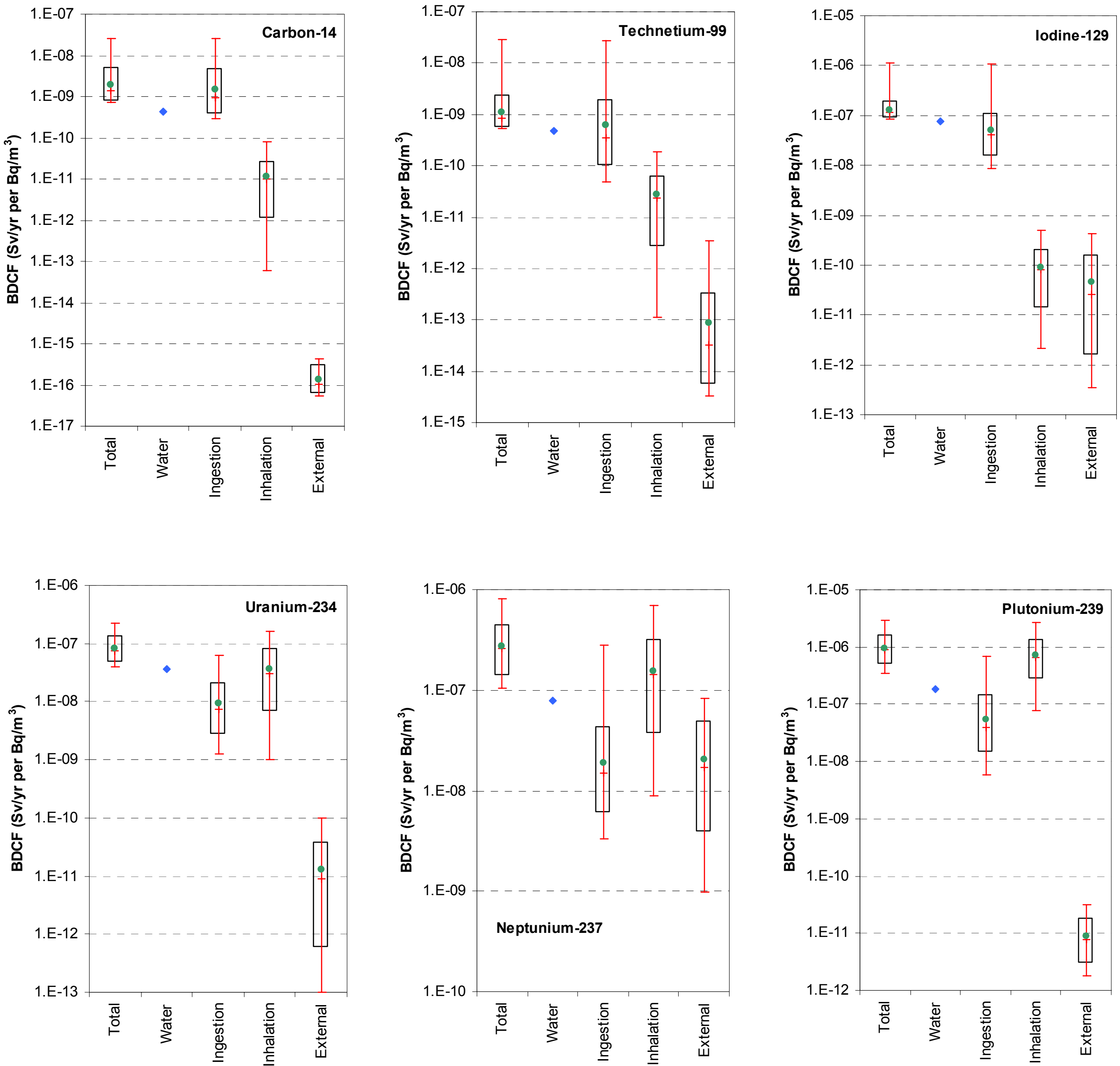
Figure 6.13-5. Groundwater BDCF Pathway Contributions for the Present-Day Climate



Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

Figure 6.13-6. Groundwater BDCF Pathway Contributions for the Upper Bound of the Glacial Transition Climate

The variation associated with the major exposure pathways for the present-day climate for the radionuclides shown in Figure 6.13-5 is illustrated in Figure 6.13-7.



Source: Excel file *GW BDCF Variability Plots.xls* (Appendix A).

NOTE: Boxes represent 5th to 95th percentile range for the groundwater exposure scenario BDCFs for the present-day climate. Vertical solid line represents the range and the tick mark on the line is the median. Diamonds represent BDCF contributions from drinking water; dots represent the mean values.

Figure 6.13-7. Uncertainty Associated with the Major Exposure Pathway BDCFs for Selected Radionuclides, Present-Day Climate

6.13.3 Sources of Uncertainty in the Biosphere Dose Conversion Factors

The source of variance in the BDCF values is the uncertainty and variability in the values of the input parameters for the biosphere model. The pathway importance and uncertainty contributions from the input parameters are not necessarily related. Frequently, the parameters that have a large influence on the value of the BDCF do not contribute to an appreciable degree, or even at all, to the variance in the BDCF. The obvious examples are parameters that are fixed, such as consumption of drinking water and the dose coefficients.

This section discusses the degree to which individual input parameters influence the BDCFs. This was quantified by calculation of correlation coefficients. A correlation coefficient is a number between -1 and 1 that measures the degree to which the observed values of two variables appear to be linearly related. Two values of the correlation coefficient were calculated: the raw (value) (Pearson) correlation coefficient and the rank (Spearman) correlation coefficient. The rank correlation coefficient supplements the value correlation coefficient by eliminating the influence of the possible aberrant or extreme input-result pairs on the correlation coefficient value. The rank correlation coefficient is computed using the same formula as that of the value correlation coefficient with the ranks of the data value being used rather than the actual values (GoldSim Technology Group 2003 [DIRS 166226], pp. 330 to 331). The rank correlation coefficient is also used when the two variables being evaluated have different distributions and are unlikely to be related linearly. In such a case, a correlation can be determined using the rank correlation coefficient even for variables with different distributions.

Correlation coefficients for the stochastic model input parameters and BDCFs for the groundwater exposure scenario were calculated for the selected radionuclides (^{14}C, ^{99}Tc, ^{129}I, ^{234}U, ^{237}Np, and ^{239}Pu) (Excel file *GW PDC Correlations.xls* in Appendix A). The results are presented in Table 6.13-3 for the present-day climate. Only those correlations that are non-zero at the 99% confidence interval (absolute value of the raw (value) correlation coefficient equal or greater than 0.0812) are shown in the table. The list includes the "false" correlations that are above the threshold value, as explained later in this section.

Table 6.13-3. Correlation Coefficients for the Input Parameters and BDCFs for the Groundwater Exposure Scenario and the Present-Day Climate

Radionuclide	Parameter Name	Correlation Coefficient	
		Value (Pearson)	Rank (Spearman)
^{14}C	Carbon bioaccumulation factor for fish	0.867	0.921
	Fish consumption rate	0.316	0.320
	Actinium transfer factor for other vegetables	0.106	
	Thorium transfer coefficient for poultry	0.100	
	Actinium transfer factor for forage	0.099	
	Soil intake rate for cattle	0.090	
	Yield of leafy vegetables	0.082	
	Milk consumption rate		0.091
	Beef consumption rate		0.085
	Protactinium partition coefficient (K_d)		-0.085

Table 6.13-3. Correlation Coefficients for the Input Parameters and BDCFs for the Groundwater Exposure Scenario and the Present-Day Climate (Continued)

Radionuclide	Parameter Name	Correlation Coefficient Value (Pearson)	Correlation Coefficient Rank (Spearman)
^{99}Tc	Technetium transfer coefficient for milk	0.373	0.302
	Overwatering rate	-0.251	-0.630
	Technetium partition coefficient (K_d)	0.240	-0.139
	Technetium transfer factor for forage	0.152	0.173
	Technetium transfer coefficient for meat	0.151	0.197
	Technetium transfer factor for grain	0.137	0.176
	Iodine transfer factor for forage	0.129	
	Iodine transfer factor grain	0.112	
	Chlorine transfer factor for fruit	0.111	
	Technetium transfer factor for leafy vegetables	0.111	0.193
	Technetium transfer factor for other vegetables	0.098	0.139
	Strontium transfer factor for forage	0.088	
	Protactinium bioaccumulation factor for fish	0.086	
	Technetium transfer factor for fruit	0.086	0.174
	Technetium transfer coefficient for eggs		0.172
	Dry-to-wet weight ratio for fruit		0.128
	Irrigation amount, forage		-0.106
	Weathering half-life		0.100
	Uranium bioaccumulation factor for fish		-0.099
	Uranium transfer coefficient for eggs		-0.094
	Translocation factor for other vegetables, fruits and grains		0.083
^{129}I	Iodine transfer coefficient for meat	0.223	0.201
	Iodine transfer factor for grain	0.218	
	Overwatering rate	-0.185	-0.266
	Iodine transfer coefficient for milk	0.180	0.204
	Iodine transfer factor for cattle forage	0.176	
	Iodine transfer coefficient for eggs	0.171	0.275
	Translocation factor for other vegetables, fruits and grains	0.160	0.199
	Iodine bioaccumulation factor for fish	0.125	0.225
	Weathering half-life	0.122	0.320
	Neptunium transfer factor for leafy vegetables	0.113	
	Milk consumption rate	0.108	0.089
	Dry biomass, forage	0.105	0.142
	Yield, forage	-0.101	-0.192
	Feed consumption rate, laying hen	0.097	
	Irrigation duration, fields	0.094	0.090
	Technetium transfer coefficient for poultry	0.087	
	Irrigation intensity		-0.173
	Iodine partition coefficient (K_d)		0.110
	Fish consumption rate		0.103
	Egg consumption rate		0.102

Table 6.13-3. Correlation Coefficients for the Input Parameters and BDCFs for the Groundwater Exposure Scenario and the Present-Day Climate (Continued)

Radionuclide	Parameter Name	Correlation Coefficient Value (Pearson)	Correlation Coefficient Rank (Spearman)
^{129}I (Continued)	Iodine transfer factor for fruit		-0.097
	Mass loading for inactive outdoor environment		0.094
^{234}U	Uranium partition coefficient (K_d)	0.555	0.647
	Evaporative cooler water transfer fraction	0.380	0.448
	Uranium transfer factor for leafy vegetables	-0.374	-0.480
	Uranium transfer factor for fruit	-0.346	-0.510
	Uranium transfer factor for other vegetables	-0.328	-0.485
	Uranium transfer factor for grain	-0.285	-0.504
	Uranium transfer factor for cattle forage	-0.207	-0.507
	Enhancement factor for active outdoor environment	0.161	0.138
	Mass loading for active outdoor environment	0.151	0.118
	Uranium transfer coefficient for eggs	0.121	0.083
	Erosion rate	-0.112	-0.087
	Overwatering rate	-0.106	-0.157
	Water usage rate for evaporative cooler	0.102	0.095
	Neptunium transfer factor for other vegetables	0.099	
	Time spent active outdoors by non-workers	0.085	
	Translocation factor for other vegetables, fruits and grains	0.084	0.088
	Irrigation duration, gardens		0.098
	Deposition velocity		0.096
	Poultry consumption rate		-0.086
^{237}Np	Evaporative cooler water transfer fraction	0.563	0.605
	Overwatering rate	-0.297	-0.351
	Neptunium partition coefficient (K_d)	0.258	0.291
	Water usage rate in evaporative coolers	0.179	0.147
	Mass loading for active outdoor environment	0.157	0.146
	Neptunium transfer factor for leafy vegetables	-0.147	-0.234
	Irrigation duration, gardens	0.128	0.155
	Neptunium transfer factor for other vegetables	-0.127	-0.247
	Surface soil depth	-0.120	-0.107
	Poultry consumption rate	-0.113	-0.119
	Neptunium transfer coefficient for eggs	0.105	
	Enhancement factor for active outdoor environment	0.104	0.120
	Neptunium transfer factor for grain	-0.100	-0.234
	Daily irrigation, other vegetables	0.095	0.086
	Time spent active outdoors by non-workers	0.090	0.118
	Evaporative cooler usage factor	0.089	0.083
	Neptunium bioaccumulation factor for fish	0.085	
	Tin transfer factor for fruit	0.085	
	Airflow rate for evaporative coolers	-0.084	
	Neptunium transfer factor for forage		-0.242

Table 6.13-3. Correlation Coefficients for the Input Parameters and BDCFs for the Groundwater Exposure Scenario and the Present-Day Climate (Continued)

Radionuclide	Parameter Name	Correlation Coefficient Value (Pearson)	Correlation Coefficient Rank (Spearman)
^{237}Np (Continued)	Neptunium transfer factor for fruit		-0.166
	Tin partition coefficient (K_d)		-0.085
	Deposition velocity		0.084
^{239}Pu	Plutonium partition coefficient (K_d)	0.384	0.454
	Evaporative cooler water transfer fraction	0.382	0.426
	Mass loading for active outdoor environment	0.367	0.351
	Plutonium transfer factor for other vegetables	-0.283	-0.348
	Plutonium transfer factor for leafy vegetables	-0.279	-0.357
	Soil erosion rate	-0.274	-0.267
	Plutonium transfer factor for fruit	-0.251	-0.373
	Enhancement factor for active outdoor environment	0.195	0.190
	Irrigation duration, fields	0.191	0.185
	Plutonium transfer factor for grain	-0.183	-0.334
	Enhancement factor for active indoor environment	0.170	0.170
	Plutonium bioaccumulation factor for fish	0.165	0.117
	Plutonium transfer factor for cattle forage	-0.142	-0.354
	Surface soil depth	-0.127	-0.123
	Daily irrigation, other vegetables	0.121	0.103
	Water usage rate in evaporative coolers	0.110	0.101
	Radium partition coefficient (K_d)	0.109	
	Time spent active outdoors by non-workers	0.104	0.104
	Uranium transfer factor for other vegetables	0.096	
	Mass loading for active indoor environment	0.091	0.090
	Time spent active outdoors by commuters		0.088

Source: Excel file *GW PDC Correlations.xls* (Appendix A).
NOTE: Shaded cells contain false correlations.

For ^{14}C, the highest correlations are with the bioaccumulation factor in fish and the consumption rate of fish. Fish consumption is also the most important pathway (Table 6.13-1).

For ^{99}Tc, the greatest correlation is with the transfer coefficient for milk and the overwatering rate (negative correlation). For ^{99}Tc, milk consumption is the second most important pathway (after consumption of water with constant contribution to dose). Overwatering rate is used to calculate the leaching removal rate constant (Section 6.4.1.3), which, in turn, affects the activity concentration in the soil and thus root uptake. The BDCFs for ^{99}Tc are also correlated with the partition coefficient (K_d), animal transfer coefficients and soil-to-plant transfer factors. It needs to be recognized that the input variables of partition coefficients and soil-to-plant transfer factors (Table 6.6-3) are correlated so if one of these variables shows a correlation with the BDCFs, it is reasonable to expect the other to also be identified as important.

Parameters that influence the BDCF for ^{129}I are related to radionuclide transport to animal products and fish. These parameters are primarily the transfer factors and transfer coefficients. The weathering half-life and the translocation factor that control the amount of activity externally deposited on a plant remaining in an edible product have higher correlation coefficients than those for ^{99}Tc, indicating that this transport mechanism is more important for ^{129}I than it is for ^{99}Tc. Overwatering rate is also an important parameter, as it is for the BDCF for ^{99}Tc.

The variance in the BDCF for ^{234}U has its source primarily in the partition coefficient value followed by evaporative cooler transfer factor and the transfer factors for crops. Other parameters that influence the level of radionuclides in the soil, such as the overwatering rate and erosion rate, are also important. In addition, some parameters used in the calculation of the inhalation dose from airborne particulate matter contribute to a lesser degree to variance in the BDCF.

For ^{237}Np and ^{239}Pu, partition coefficients are important because they control the accumulation of these radionuclides in the soil. Soil-to-plant transfer factors have high correlation coefficients for these radionuclides because of the negative correlation between partition coefficients and transfer factors built into the biosphere model (Table 6.6-3). Also important are the parameters that are used in evaluation of the particulate inhalation pathway, including the inhalation of aerosols generated by evaporative coolers (e.g., the fraction of contaminant in the water that is transferred by a cooler to the airstream) and resuspended soil particles (e.g., mass loading, enhancement factor, and inhalation exposure time for the active outdoor environment).

The correlation coefficients presented in Table 6.13-3 were generated using the GoldSim code, which is the implementing software for the biosphere model. GoldSim provides the user with the capability to calculate correlation coefficients between any two or more distributions of outputs and input parameters. As noted before, the correlation coefficients presented in Table 6.13-3 include some correlations, with the low absolute correlation coefficient values, that are false. For the BDCFs for ^{129}I, the parameters with the absolute value of the raw correlation coefficient greater than or equal to 0.125 are provided in Table 6.13-4.

Table 6.13-4. Raw Correlation Coefficients for BDCF Values for ^{129}I and Input Parameters with Absolute Values Greater than 0.125

GoldSim Input Parameter	Correlation Coefficient
Iodine transfer coefficient for meat	0.223
Iodine transfer factor for grain	0.218
Overwatering rate	-0.185
Iodine transfer coefficient for milk	0.180
Iodine transfer factor for cattle forage	0.176
Iodine transfer coefficient for eggs	0.171
Translocation factor for other vegetables, fruits and grains	0.160
Iodine bioaccumulation factor for fish	0.125

Source: Excel file *GW PDC Correlations.xls* (Appendix A).

There are about 290 stochastic input parameters for the groundwater exposure scenario that are sampled for any model realization. However, only about 120 variable parameters are used to calculate a BDCF for a primary radionuclide with no long-lived decay products. It is thus of interest to determine a value for the correlation coefficient below which there is no statistical significance, in order to identify those parameters that are inconsequential with respect to the BDCF variance. The details of such an approach are presented in the text by Steel and Torrie (1980 [DIRS 150857], p. 279) (also explained in Section 6.11.1.2.2). To test the null hypothesis of the true correlation coefficient being zero, the measured correlation coefficient (r) is used to calculate t from Equation 6.11-1, which for convenience is reproduced below as Equation 6.13-1. The value of t is then compared with Student's t for n–2 degrees of freedom (n = the number of data points used to derive r) for the required confidence interval.

$$t = \frac{r}{\sqrt{\dfrac{1-r^2}{n-2}}} \qquad \text{(Eq. 6.13-1)}$$

For generating the BDCFs, the number of realizations (n) was 1,000. For a large number of degrees of freedom, the Student's t distribution is closely approximated by the normal distribution, so the 99% confidence interval for the absolute value of t is 2.576 (Steel and Torrie 1980 [DIRS 150857], Table A.3). Substituting these values into Equation 6.13-1 results in an absolute value of r, below which the null hypothesis would not be rejected, as 0.062. The corresponding absolute value of the correlation coefficient at the 99% confidence level (t = 2.576) for rejecting the null hypothesis is 0.0812. In other words the correlation coefficients equal to or less then 0.0812 are not significant at the 99% confidence level.

When setting up GoldSim to conduct correlation coefficient calculations, the user selects the parameter against which the correlation will be made. In this case, the parameter is the output BDCF array. The user either can select, on a one-by-one basis, the input parameter distributions to use for the correlation or nominate to do the correlation matrix for all stochastic parameters. Without any prior sensitivity analysis, there is no basis to select any particular set of parameters for the correlation analysis; the normal default is to use all stochastic inputs to generate the matrix. In following this path, GoldSim automatically includes the radionuclide specific parameters for all radionuclides and not just the set for the radionuclide under consideration. In the case of ^{99}Tc, some of these additional parameters are determined to be potentially significant, i.e., greater than 0.0812, as shown in Table 6.13-5.

Table 6.13-5. Observed Raw Correlation Coefficients for ^{129}I BDCF Values and Input Parameters with Absolute Values Greater Than 0.0812 and Less Than 0.125

GoldSim Input Parameter	Correlation Coefficient
Weathering half-life	0.122
Neptunium transfer factor for leafy vegetables	0.113
Milk consumption rate	0.108
Dry biomass, forage	0.105
Yield, forage	-0.101
Feed consumption rate, laying hen	0.097
Irrigation duration, fields	0.094
Technetium transfer coefficient for poultry	0.087

Source: Excel file *GW PDC Correlations.xls* (Appendix A).

From the previous discussion on the significance of the parametric correlation, Table 6.13-5 appears to indicate some unexpected parameter correlations being generated by GoldSim. Further investigation illustrates that the results in Table 6.13-5 are predictable.

In the ^{129}I example, there are 167 stochastic parameters included in the biosphere model that are not associated with ^{129}I but are associated with all the other radionuclides included in the model. GoldSim, once set up for a scenario, keeps track of all parameters whether or not they are radionuclide specific. Thus, by selecting to generate the correlation matrix for all stochastic parameters, these (redundant) 167 parameters are automatically included. The alternative, but tedious and error prone, approach is to individually select, one by one, the 100+ parameters that are used for the radionuclide being evaluated.

When the statistical approach is used to test the null hypothesis that the actual correlation is not significantly different from zero, it is necessary to establish a confidence interval for accepting/rejecting the hypothesis. For the 95% confidence interval, a value is established for the measured correlation coefficient; if the correlation coefficient is less than this value, it is postulated that there are no underlying correlation between variables. If random tests (i.e., the GoldSim model run with a new random number seed) were performed a large number of times, in only 5% of cases would the observed value of the correlation lead to the rejection of the null hypothesis (i.e., exceed the cut-off value).

In the reported case, although GoldSim was run only once, the random test applies to each of the 167 parameters for which there is no ^{129}I dependency. The analysis of calculating the measured and expected number of "significant" non-zero correlation values is relatively simple and is reported in Table 6.13-6 for the 167 independent (i.e., not correlated) parameters. The data in Excel file *GW PDC Correlations.xls* (Appendix A) show that the observed number of false correlation events is in line with the expected number. Because some parameters in the biosphere model are correlated with each other, the actual number of false correlations may be greater than the number predicted from the number of variable parameters and the confidence level. For example, for ^{99}Tc, four out of five parameters that appear in Table 6.13-3 as falsely correlated with the BDCF for ^{99}Tc are in fact correlated with each other. Consequently, GoldSim is behaving in a logical and consistent manner.

Table 6.13-6. The Number of Expected and Observed False Correlation Values for Independent Input Parameters as a Function of Confidence Level

Confidence Level	*t* [a]	Correlation Coefficient [b]	Expected Number [c]	Observed Number [d]
5.0%	1.96	0.062	8.4	7
2.0%	2.33	0.074	3.3	4
1.0%	2.58	0.081	1.7	2
0.2%	3.10	0.098	0.3	1

[a] Value of *t* (Equation 6.13-1) corresponding to the confidence level shown in the first column (from Steel and Torrie 1980 [DIRS 150857], Table A.3)

[b] Correlation coefficient corresponding to the value of *t* (Excel file *GW PDC Correlations.xls* (Appendix A)

[c] Calculated as a product of the confidence level (first column) and 167 parameters.

[d] From Excel file *GW PDC Correlations.xls* (Appendix A).

6.13.4 Analysis of the Environmental Transport Pathways and Radionuclide Accumulation in the Environmental Media

The dose to the receptor from radionuclides in well water arises from the transport of radionuclides from water to environmental media (environmental transport pathways) and from human exposure to these media (receptor exposure pathways).

For many radionuclides, especially non-actinides, consumption of locally produced food is an important contributor to BDCFs. The doses from consumption of locally produced food depend on the radionuclide concentration in these foods and on their respective consumption rates. The relative importance of transport processes that contribute to radionuclide concentration in locally produced foods is discussed in this section.

Environmental transport pathways lead to radionuclide accumulation in the environmental media. The environmental media included in the biosphere model for the groundwater exposure scenario include well water (groundwater), surface soil, air, plants, animals, and fish. For the groundwater exposure scenario, water is the source of contamination in the biosphere. Surface soil becomes contaminated when well water is used for irrigation. Airborne contamination is a result of resuspension of contaminated soil and operation of evaporative coolers. Radionuclide accumulation in plants occurs as a result of transport from water, soil, and air. The source of radionuclide intake by animals is water, fodder crops, and soil.

6.13.4.1 Radionuclide Accumulation in Surface Soil

In the groundwater exposure scenario, surface soil is an environmental medium that can be considered a secondary source of contamination for many environmental transport and receptor exposure pathways (groundwater is a primary source). These pathways include resuspension of soil particles with the subsequent deposition on crops or inhalation by humans, external exposure, radionuclide uptake by crops through their roots, emission of radioactive gases and their transport to crops and humans, and soil ingestion by humans and animals. In fact, there are only a few transport processes and pathways in the biosphere model that do not originate in the soil, namely the deposition of contaminated water on crop surfaces, water ingestion by humans and animals, radionuclide bioaccumulation in fish, and inhalation of aerosols generated by evaporative coolers. For the remaining pathways, activity concentration in soil has a direct effect on the outcome of the relevant submodels.

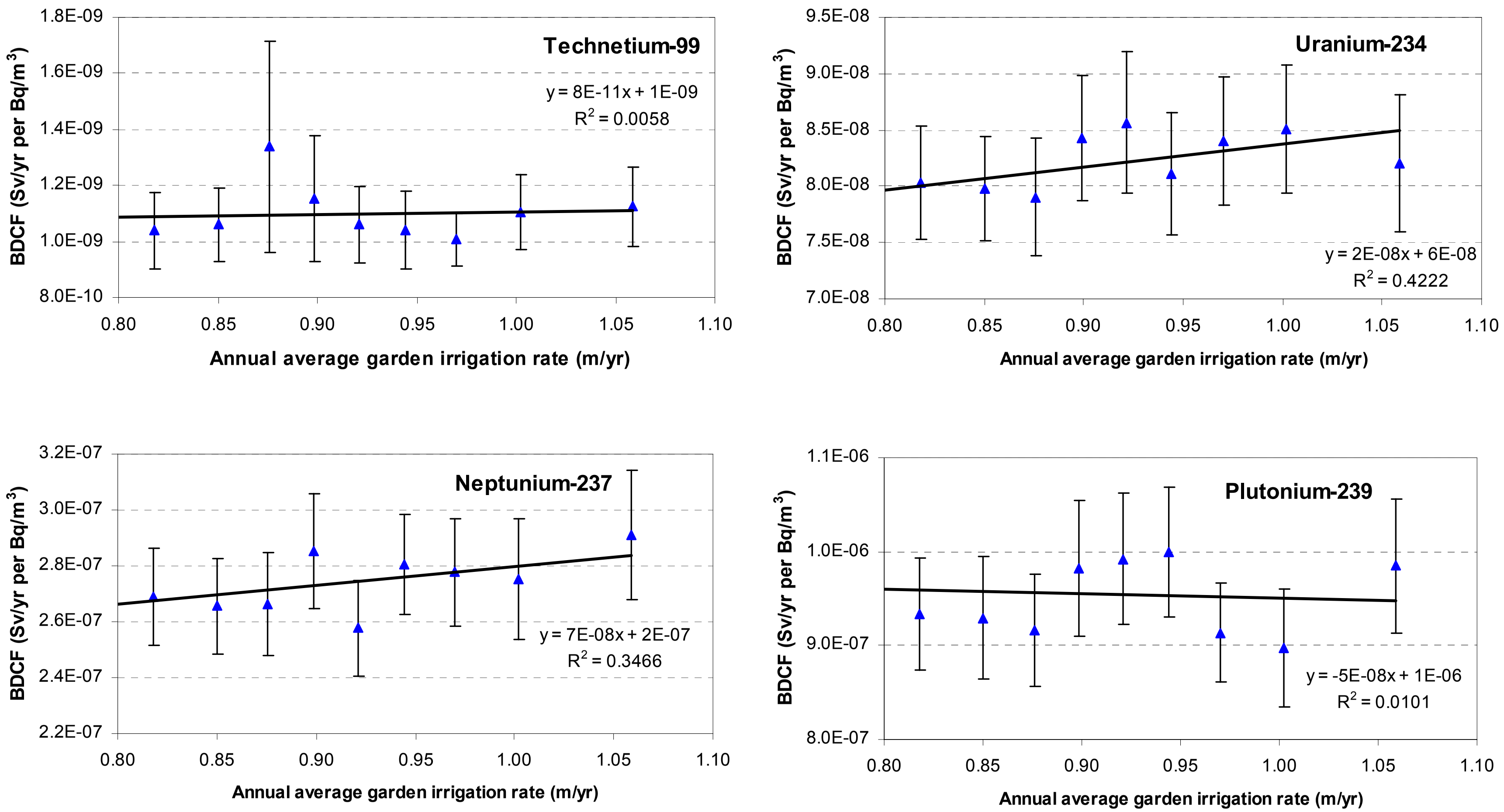
The source of radionuclides in the surface soil is from groundwater used for irrigation. The buildup of radionuclides in soil from this input is offset by the processes that remove radionuclides from the soil. Removal processes include leaching, surface soil erosion and radioactive decay (a removal mechanism for the parent radionuclide, but a source for the decay product). Radionuclide concentrations in soil are calculated separately for garden and field crops. In addition, two soil layers are considered: the entire surface soil layer and a thin part of that layer at the surface that can become resuspended. Generally, the change in radionuclide concentration in soil is equal to the rate of radionuclide input (irrigation), minus the rate of radionuclide loss. For equilibrium conditions, the rate of radionuclide addition is equal to the rate of radionuclide removal, with concentrations in the soil remaining constant. The biosphere model calculates equilibrium radionuclide concentrations in the resuspendable surface soil layer and the radionuclide concentration in the surface soil layer that includes buildup as a result of long-term irrigation. These quantities are used for predicting root uptake of activity, for calculating radionuclide concentration in the atmosphere from resuspension of soil particles (for inhalation and attachment to foliage), and for inadvertent soil ingestion. In either case, radionuclide concentration in the soil is proportional to the irrigation rate (Section 6.4.1.1)

For the present-day climate, the range of annual average irrigation rates for garden crops is from 0.69 to 1.13 m/yr; the annual average irrigation rate for the field crops is in the range from 1.41 to 2.14 m/yr (Table 6.6-3). The average irrigation rate depends on the climate and thus could be a function of time. However, because stochastic BDCFs are defined for a given climate, the average irrigation rate for a given climate is not a function of time. Annual average irrigation rates were developed using Food and Agriculture Organization methods based on determination of crop water requirements, which are calculated from evapotranspiration of a grass reference surface and adjusted with a crop-specific coefficient (BSC 2004 [DIRS 169673], Section 6.5.2). Parameter inputs were growing season lengths, average monthly weather data for the climate states under consideration, as well as salinity of irrigation water. These parameters are site-specific. The dependence of the BDCFs on the values of annual average irrigation rates for the garden and field crops is shown in Figures 6.13-8 and 6.13-9, respectively, for a few selected radionuclides (Excel file *Dependence of GW BDCFs on Inputs_Part 1.xls*, Appendix A).

The graphs were plotted using averaged values of the independent and dependent variables. If the unsorted data for individual realizations are plotted, the stochastic variability among BDCFs from the multiple random inputs results in plots that show little discernable trend. To generate a graph illustrating the effects of an input parameter on BDCFs, averaging over realizations was required to minimize the impact of other variables. The results of model realizations were sorted by the value of the independent variable (here the annual average irrigation rates). Then the irrigation rates and the corresponding BDCFs were averaged in blocks of 100 values. The calculations were performed and the graph generated in an Excel spreadsheet (*Dependence of GW BDCFs on Inputs_Part 1.xls*, included in Appendix A). The triangle symbols in the graph represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The standard error was calculated as standard deviation of the BDCF values in a block of 100 values divided by a square root of the number of results in a block, that is, $\sqrt{100} = 10$.

There is one data point in the ^{99}Tc graphs that is an outlier with a high BDCF value. If included in the plots, this outlier results in large error bars for the point that includes this value in the corresponding bin with 100 BDCF values. This outlier was caused by a high sampled value of K_d, low sampled value of overwatering rate that together produced a low leaching rate and consequently high radionuclide concentration in the field soil, which had the strongest effect on the root uptake and radionuclide concentration in crops for animal consumption and, consequently, on radionuclide concentration in milk. The BDCF calculated in that realization was over 25 times greater than the average. To better show the relationship between the input parameter and the BDCFs, this point was removed from the graphs for ^{99}Tc presented further in this analysis report.

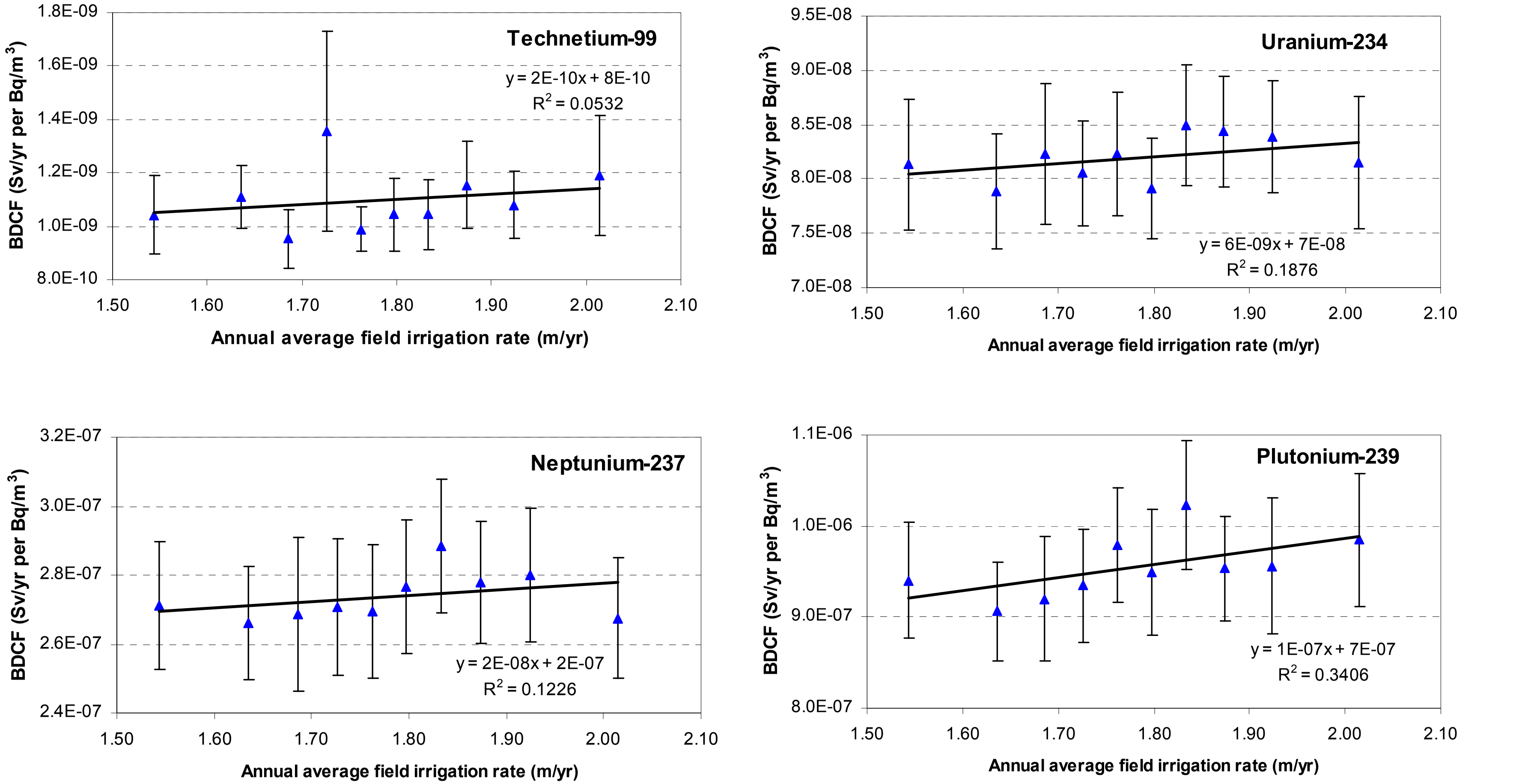
The graphs in Figures 6.13-8 and 6.13-9 show that there is a positive relationship between BDCFs and irrigation rate for both the garden and field irrigation rates. This dependence is not statistically significant for ^{99}Tc, which is the radionuclide that does not strongly adsorb to soil particles (i.e., has a low K_d value). The graph for ^{239}Pu garden irrigation rate shows a negative correlation between the BDCFs and the irrigation rate; however this dependence is not statistically significant.



Source: Excel file Dependence of *GW BDCFs on Inputs_Part 1.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of the irrigation rate.

Figure 6.13-8. Dependence of BDCF for the Groundwater Exposure Scenario and Present-Day Climate on Annual Average Garden Irrigation Rate



Source: Excel file *Dependence of GW BDCFs on Inputs_Part 1.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of the irrigation rate.

Figure 6.13-9. Dependence of BDCF for the Groundwater Exposure Scenario and Present-Day Climate on Annual Average Field Irrigation Rate

The deterministic analysis (deterministic runs of the model) was conducted for ^{237}Np and ^{239}Pu to determine the difference between the BDCF values calculated using the minimum, average and the maximum of the irrigation rate ranges. The input parameter values used in the model were the same as those used for the model verification (Section 6.11). For the stochastic model parameters, these values are either the distribution means or the values that best represent a distribution, such as the mode. The results of these analyses are summarized in Table 6.13-7.

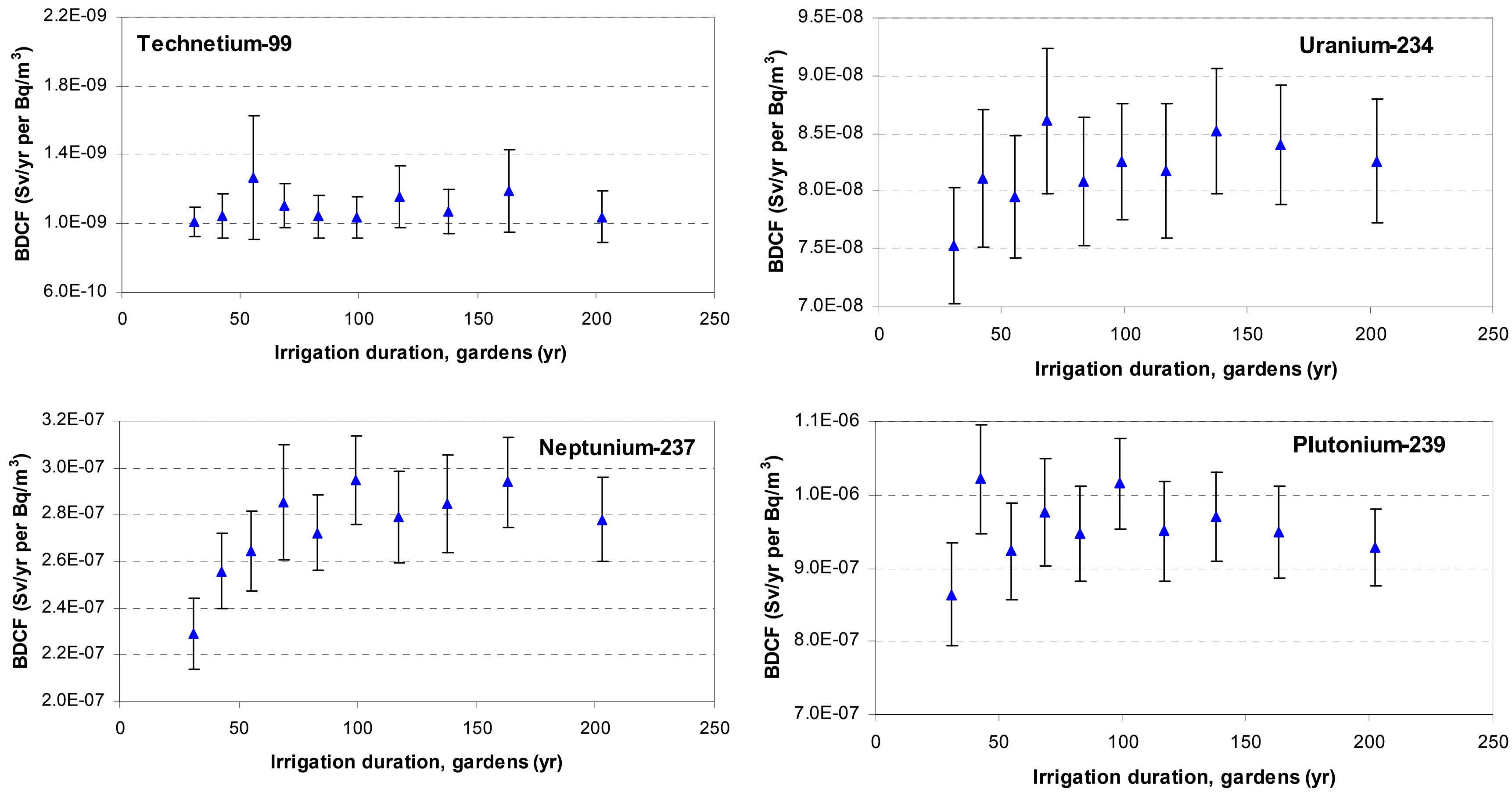
This deterministic analysis is one of several included in this report. Deterministic analyses are performed to evaluate the relative effect on the modeling results. These analyses are not intended to precisely quantify the change in BDCF resulting from a change in an input parameter. If the model parameters were sampled, as it is done in the stochastic runs, the corresponding changes may be somewhat different. However, the relative effect is represented well by the change in the results of deterministic runs.

Table 6.13-7. BDCF and Percent Change from Average for Different Levels of Annual Average Irrigation Rate

Irrigation Conditions	Irrigation Rate, m/yr	^{237}Np		^{239}Pu	
		BDCF, Sv/yr per Bq/m^3	**% Change from Average**	**BDCF, Sv/yr per Bq/m^3**	**% Change from Average**
Garden Irrigation					
Average	0.91	2.12E–07	0.0	7.38E–07	0.0
Minimum	0.69	2.04E–07	-3.5	7.25E–07	-1.8
Maximum	1.13	2.19E–07	3.5	7.47E–07	1.2
Field Irrigation					
Average	1.78	2.12E–07	0.0	7.38E–07	0.0
Minimum	1.41	2.07E–07	-2.2	7.06E–07	-4.3
Maximum	2.14	2.16E–07	2.2	7.69E–07	4.2

Source: BDCFs were calculated in deterministic runs of *ERMYN_GW_Rev01_Base_Det.gsm* by changing the radionuclide selection and the value of annual average irrigation rate. The percent change for the BDCFs was calculated in the Excel spreadsheet *Dependence of GW BDCFs on Inputs_Part 1.xls* (Appendix A).

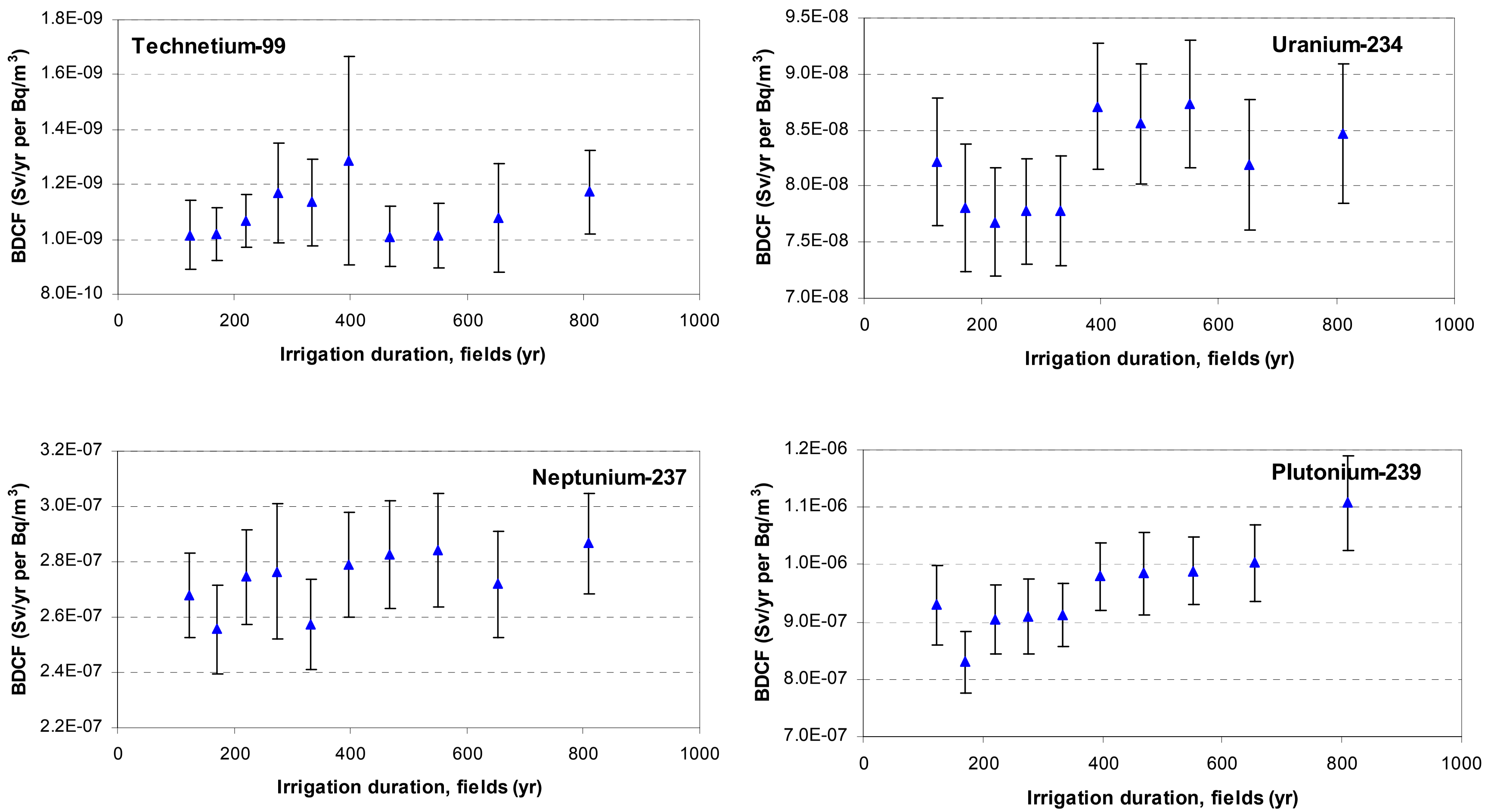
The results of the BDCF calculations using different irrigation rates indicate that the BDCFs for ^{237}Np and ^{239}Pu are relatively insensitive to the value of the annual average irrigation rate and that the value varies by only a few percent over the variability range of this parameter. This is in part because the range of the garden and field irrigation rates is relatively narrow and although the irrigation rates affect the value of the BDCF, they do not have a strong effect on its variability. Another parameter that influences radionuclide concentration in the soil is the irrigation duration. The dependence of the BDCFs on the values of irrigation duration for the garden and field crops is shown in Figures 6.13-10 and 6.13-11, respectively, for the same radionuclides as used in the previous graphs (Excel file *Dependence of GW BDCFs on Inputs_Part 1.xls*, Appendix A).



Source: Excel file *Dependence of GW BDCFs on Inputs_Part 1.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of the irrigation rate.

Figure 6.13-10. Dependence of BDCF for the Groundwater Exposure Scenario and Present-Day Climate on Garden Irrigation Duration



Source: Excel file Dependence of *GW BDCFs on Inputs_Part 1.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of the irrigation rate.

Figure 6.13-11. Dependence of BDCF for the Groundwater Exposure Scenario and Present-Day Climate on Field Irrigation Duration

The graphs in Figures 6.13-10 and 6.13-11 show a positive relationship between BDCFs and irrigation duration for both the garden and field irrigation rates for all radionuclides except ^{99}Tc. The deterministic analysis (deterministic runs of the model) was conducted for ^{237}Np and ^{239}Pu to determine the difference between the BDCF values calculated using the minimum, maximum and high value (10,000 years) of the irrigation duration. Other input parameter values used in the model were the same as those used for the model verification (Section 6.11). The results of these analyses are summarized in Table 6.13-8.

Table 6.13-8. BDCF and Percent BDCF Change for Different Levels of Annual Average Irrigation Duration

Irrigation Conditions	Irrigation Duration, yr	^{237}Np		^{239}Pu	
		BDCF, Sv/yr per Bq/m^3	% Change from Average	BDCF, Sv/yr per Bq/m^3	% Change from Average
Garden Irrigation					
Minimum and Mode	25	2.12E–07	0.0	7.38E–07	0.0
Maximum	250	2.27E–07	7.5	7.38E–07	0.0
High value	10,000	2.33E–07	10.1	1.25E–06	69.6
Field Irrigation					
Minimum and Mode	100	2.12E–07	0.0	7.38E–07	0.0
Maximum	1000	2.12E–07	0.3	8.97E–07	21.6
High value	10,000	2.12E–07	0.3	1.18E–06	60.3
Field and Garden Irrigation					
High value	10,000	2.34E–07	10.5	1.70E–06	129.9

Source: BDCFs were calculated in deterministic runs of *ERMYN_GW_Rev01_Base_Det.gsm* by changing the radionuclide selection and the value of annual average irrigation rate. The percent change for the BDCFs was calculated in the Excel file *Dependence of GW BDCFs on Inputs_Part 1.xls* (Appendix A).

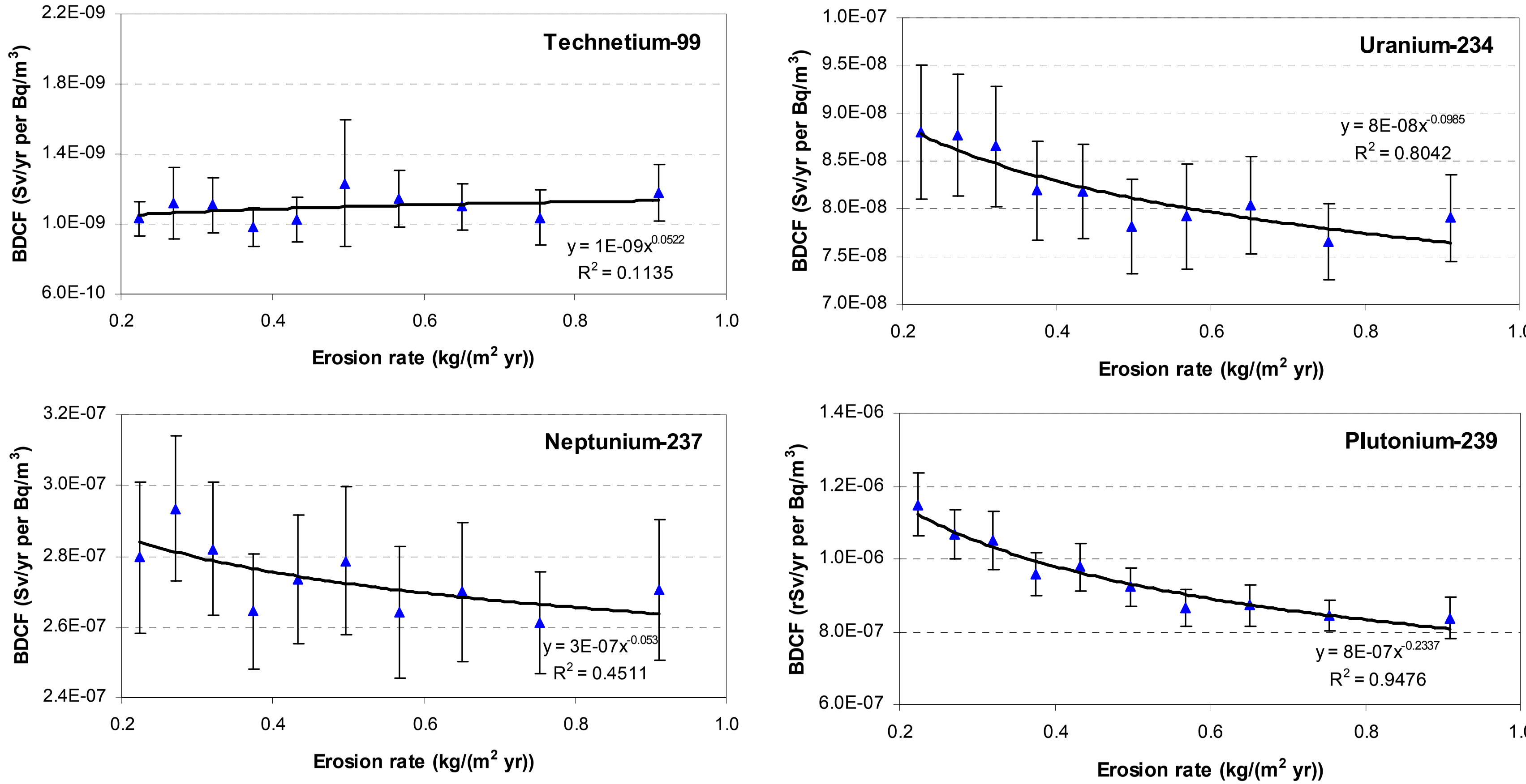
The results of the BDCF calculations using different irrigation durations indicate that the BDCFs for ^{237}Np are relatively insensitive to the value of the irrigation duration for the fields and gardens, even if very high irrigation duration is used. Because of a large partition coefficient, ^{239}Pu accumulates in the soil slowly, until the equilibrium concentration is approached. The equilibrium concentration of ^{239}Pu in the soil would be effectively reached much sooner than 10,000 years (the value used in this analysis) because the soil erosion would limit radionuclide accumulation in the soil.

Offsetting radionuclide addition from irrigation are the processes that remove radionuclides from surface soil. These processes are collectively represented in the model by the effective removal rate constant appearing in several equations in Sections 6.4.1.1 and 6.4.1.2. The biosphere model includes removal of radionuclides from surface soil by radioactive decay, leaching to the deep soil, and soil erosion.

The surface soil erosion removal rate constant, λ_e, represents the rate of radionuclide loss from the surface soil due to wind (dominant for the present-day climate) as well as surface erosion from occasional heavy precipitation (an important contributor to erosion in the wetter climates). This parameter is calculated in the biosphere model using the annual average erosion rate for the surface soil, representing the removal of soil mass per unit area per unit time, and the surface soil depth and density (Section 6.4.1.4). The value of annual average erosion rate is a radionuclide-independent parameter that is strongly site-specific and depends on environmental characteristics and land use. The range of the soil erosion rate is from 0.20 to 1.1 kg/(m^2 yr), which, when divided by the density of surface soil (65 to 510 kg/m^2), gives the erosion removal rate constant range from about 0.0004 to about 0.017 per year (from the modeling results included in the Excel file *Dependence of GW BDCFs on Inputs_Part 2.xls*, Appendix A). The soil erosion rate was developed from the information include in the USDA Natural Resources Conservation Service database and from other literature sources. The values were selected such that they are representative of the types of soils, climate, and land use conditions in Amargosa Valley (SNL 2007 [DIRS 179993], Section 6.4).

Graphs were produced that show the BDCF dependence on the value of erosion rate used in the biosphere model for ^{99}Tc, ^{234}U, ^{237}Np, and ^{239}Pu. The graphs were plotted using averaged values of the independent and dependent variables in blocks of 100 data pairs, as described above, and are shown in Figure 6.13-12 (Excel file *Dependence of GW BDCFs on Inputs_Part 2.xls*, Appendix A).

A few observations can be made based on Figure 6.13-12. First, the BDCFs for ^{99}Tc do not appear to depend on erosion rate. This is because technetium is an element that has a relatively low K_d and thus leaching is a much more important radionuclide removal mechanism than soil erosion. Second, soil erosion is important for those radionuclides that have a moderate (^{234}U and ^{237}Np) and high value of K_d (^{239}Pu). For these radionuclides, a distinct dependence on the erosion rate can be observed, especially in the lower region of the parameter range. In this region of the parameter range, the effectiveness of soil erosion as a mechanism of radionuclide removal from surface soil is diminished and radionuclides build up in surface soil. For the higher erosion rate, the BDCFs for these radionuclides seem to asymptotically converge to a constant BDCF value, which is consistent with the dependence of the equilibrium activity concentration in the soil on the erosion removal rate constant. In this region, the removal processes effectively reduce the activity concentration in the soil and the BDCF is controlled by other pathways that are not related to radionuclide concentration in the surface soil, such as consumption of water, or ingestion of crops contaminated by deposition of water on the foliage. In fact, for the highly sorbing radionuclides, their uptake by crops from soil is a less important mechanism than the radionuclide deposition on plant surfaces from irrigation as discussed in Section 6.13.4.3.



Source: Excel file *Dependence of GW BDCFs on Inputs_Part2.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of the erosion rate.

Figure 6.13-12. Dependence of BDCF for the Groundwater Exposure Scenario and Present-Day Climate on Soil Erosion Rate

Another process that results in radionuclide removal from surface soil is leaching. The process of leaching radionuclides from the surface soil is evaluated using element-specific leaching removal rate constants (Section 6.4.1.3). The leaching removal rate constant for each radionuclide (λ_l) is calculated using a relationship shown in Section 6.4.1.3 as Equation 6.4.1-28, which is reproduced below:

$$\lambda_l = \frac{OW}{d \times \theta \left(1 + \frac{\rho}{\theta} K_d\right)} \qquad \text{(Eq. 6.13-2)}$$

where

OW = crop overwatering rate (m/yr)

d = depth of surface soil (m)

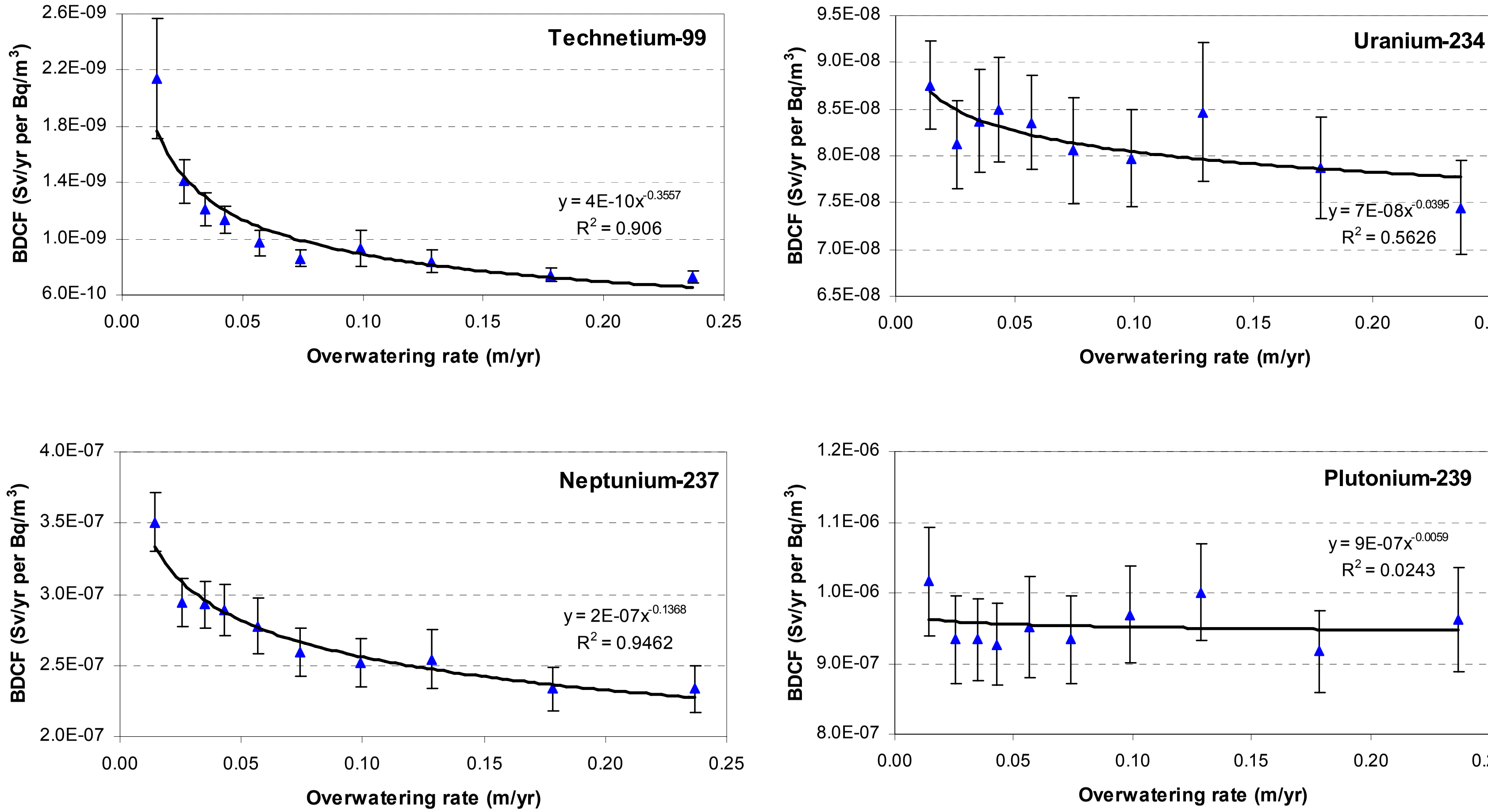
ρ = bulk density of surface soil (kg/m^3)

θ = volumetric water content of soil (dimensionless)

K_d = solid-liquid partition coefficient for the radionuclide in surface soil (Bq/kg $_{solid}$)/(Bq/m^3 $_{liquid}$) = (m^3 $_{liquid}$ /kg $_{solid}$)

The value of the leaching removal rate constant is influenced by the overwatering rate (OW), solid–liquid partition coefficient (K_d), and other parameters that characterize soil properties. Soil-specific parameters were taken from the USDA Natural Resources Conservation Service database and from other literature sources. The values were selected such that they are representative of the types of soils, climate, and land use conditions in Amargosa Valley (SNL 2007 [DIRS 179993], Section 4.1). The volumetric water content of soil is defined as the fraction of the soil volume representing water-filled porosity. The value of this parameter depends on soil texture and ranges from less than 0.1 (dry soils) to between 0.4 and 0.5 (water-saturated soils) for the soil types in Amargosa Valley, with typical values of about 0.2 to 0.3.

The value of the overwatering rate was developed for representative crops based on the crop leaching fraction (the amount of water applied in addition to crop water requirements to remove excess salts from the root zone) or the deep percolation of precipitation below the crop root zone. As shown in Table 6.13-3, the overwatering rate has a high correlation coefficient with BDCFs for most radionuclides. In arid regions, the overwatering rate usually is determined by calculating the amount of water required to transport accumulated salts introduced by the irrigation water out of the surface soil to maintain productivity. The value of this parameter is on the order of 10 cm/yr (BSC 2004 [DIRS 169673], Section 6.9). The dependence of BDCFs for selected radionuclides on the value of the overwatering rate is shown in Figure 6.13-13 (Excel file *Dependence of GW BDCFs on Inputs_Part 1.xls*, Appendix A).



Source: Excel file Dependence of *GW BDCFs on Inputs_Part 1.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of the overwatering rate.

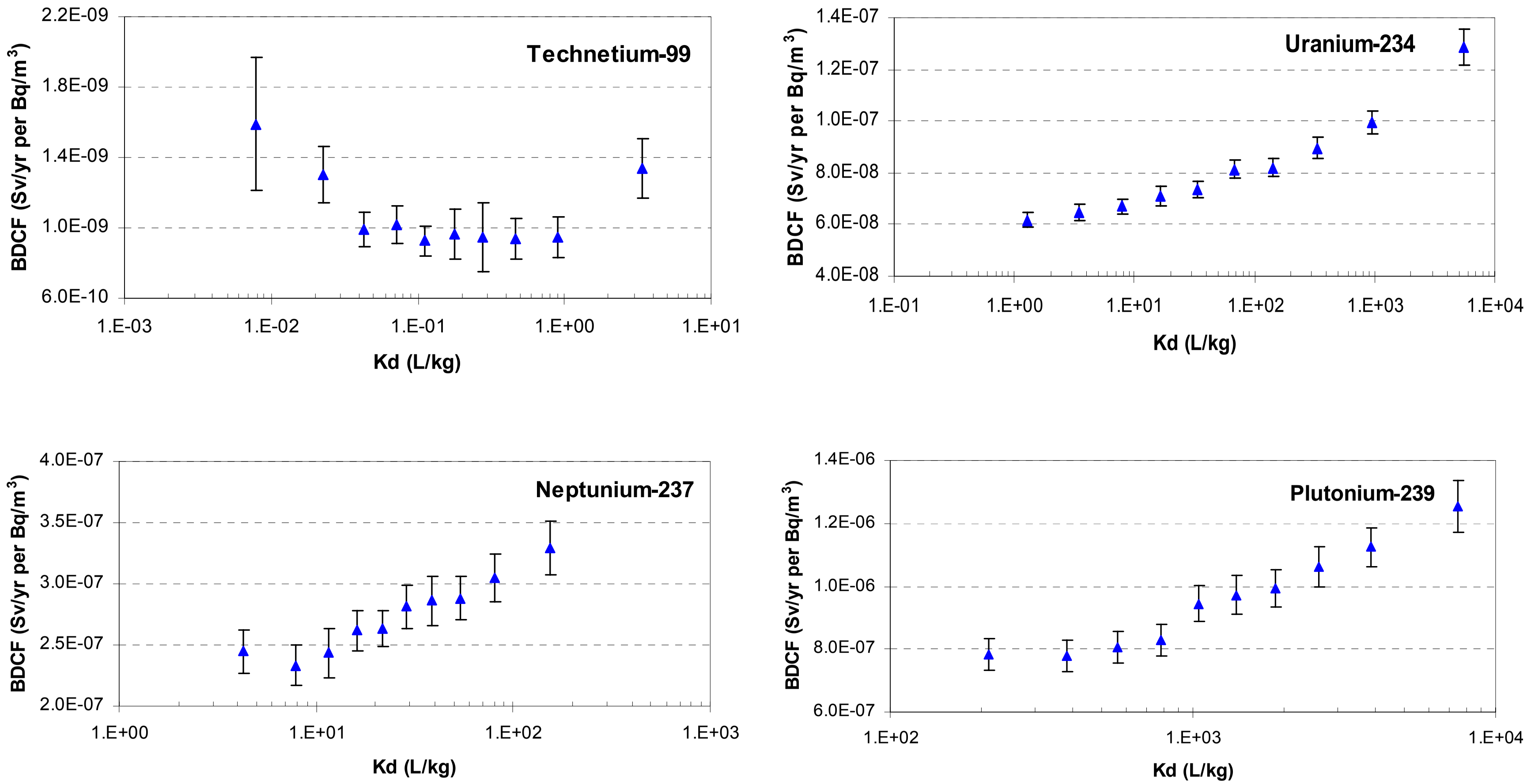
Figure 6.13-13. Dependence of BDCF for the Groundwater Exposure Scenario and Present-Day Climate on Overwatering Rate

From Figure 13-3, it can be seen that the BDCFs decrease as overwatering increases for most radionuclides. This is because overwatering causes leaching of radionuclides out of the surface soil thus decreasing the level of radionuclide concentration in the soil. Decreased activity concentration in the soil results in less activity available for plant root uptake and leads to a reduced ingestion dose, as well as reduced inhalation and external exposures. The degree of the correlation with the overwatering rate can be seen by the range of the error bars for the radionuclides shown in Figure 6.13-13. ^{239}Pu removal, and thus, concentration in the soil depends more on soil erosion than on leaching; in addition, the dominant exposure pathway for this radionuclide is inhalation of resuspended soil particles, which originate in the upper layer of the soil. For ^{239}Pu, the concentration in that layer is greater than the concentration in the surface soil, and this quantity does not depend strongly on the overwatering rate but rather on the irrigation rate (Equation 6.4.1-30), hence the weak dependence of the BDCFs for this radionuclide on overwatering.

The leaching removal rate constant also depends on the value of partition coefficient, K_d. The K_ds, in turn, depend on soil characteristics, with values spanning several orders of magnitude (with geometric means from 0.14 L/kg for technetium to 3.6×10^4 L/kg for radium) (SNL 2007 [DIRS 179993], Section 6.3). The overall uncertainty in the K_d values spans several orders of magnitude. To illustrate the overall effect of the uncertainty in the K_d values on the biosphere modeling results, plots were generated that show the dependence of BDCFs on K_d values (Figure 6.13-14). The plots were constructed for the same four radionuclides as for the preceding plots (Excel files *Dependence of GW BDCFs on Inputs_Part 1.xls*, Appendix A). These radionuclides represent distributions with high (^{239}Pu), moderate (^{237}Np and ^{234}U), and low (^{99}Tc) mean values of K_ds.

Figure 6.13-14 shows that although the range of K_d values covers several orders of magnitude, the impact of these large changes in K_d values on BDCF values is less than a factor of 2 about the mean value for most radionuclides. For ^{237}Np and ^{234}U, elements with a moderate value of K_d, there is little change in BDCF values for K_d values at the low end of the range. In this region, leaching is efficient and little buildup is expected. At higher K_d values, the BDCFs increase due to radionuclide retention in the soil. BDCF values for a radionuclide with a high K_d (^{239}Pu) gradually increase as K_d increases (due to low leaching and thus greater buildup in soil), but should converge to a fixed value at high K_d values. In this region of high K_d values, BDCFs no longer increase as K_ds increase because the equilibrium radionuclide concentration in surface soil is controlled by soil erosion.

Technetium has the lowest mean K_d of elements considered for TSPA (a geometric mean of 0.14 L/kg compared to the next lowest of 4.5 L/kg for iodine). The BDCFs for ^{99}Tc show the effect of increased plant uptake at low K_d values resulting from the inverse correlation between the soil-to-plant transfer factor and K_d. For a low K_d, leaching is an efficient radionuclide removal mechanism keeping the equilibrium concentration of this element in surface soil at a relatively low level, but, for such low K_d values, increased plant uptake due to availability of the radionuclide in the solution drives the BDCF to higher values. As the K_d increases, the BDCF passes through a minimum and, for the K_ds in the upper region of their range, increases as leaching becomes less efficient as a removal mechanism. This causes increased radionuclide buildup in surface soil and, consequently, causes an increase in the BDCF components that depend on radionuclide concentration in the soil.

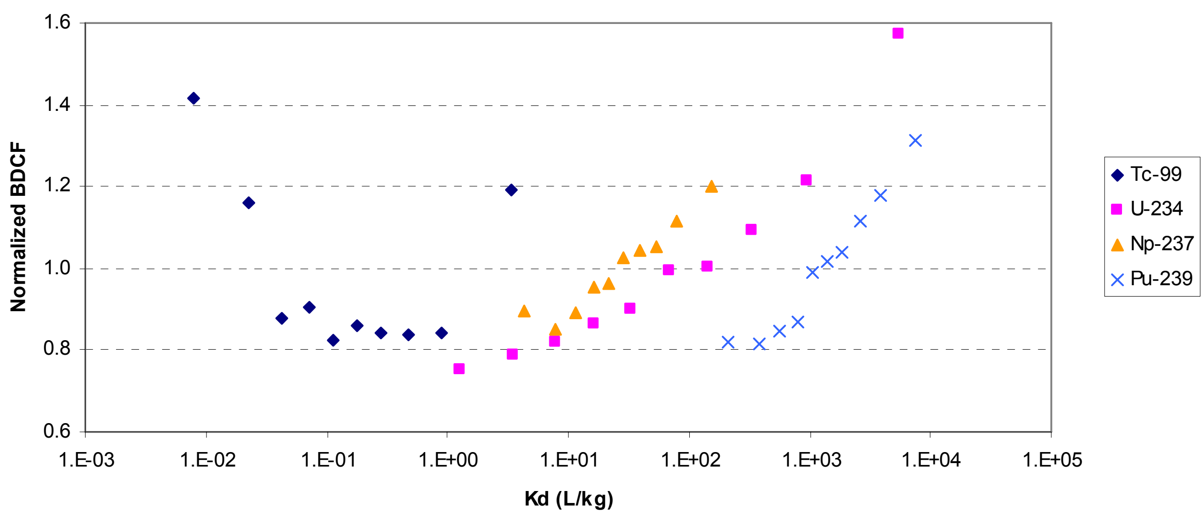


Source: Excel file *Dependence of GW BDCFs on Inputs_Part 1.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of the K_d.

Figure 6.13-14. Dependence of BDCF for the Groundwater Exposure Scenario and Present-Day Climate on K_ds

To illustrate how the BDCFs are affected by the K_ds over the range of K_d values, the plots shown in Figure 6.13-14 were combined, as shown in Figure 6.13-15. In the combined plot, the BDCFs for individual radionuclides shown in Figure 6.13-14 were normalized to the average BDCF value (from 1,000 model realizations) so they could be compared side-by-side. The resulting figure has the "U" shape with the high BDCF resulting from either very low or very high K_ds, as explained previously. The position of the plots for the individual radionuclides in the combined graph reflects their sorptive characteristics. The graph also shows the relative insensitivity of the BDCF values to order-of-magnitude changes in the K_d values. This adds confidence that the selection of the K_d values for the biosphere model is justified, and that additional data on K_d values in Amargosa Valley would not invalidate biosphere modeling results or affect the sensitivity of those results to the parameter values.



Source: Excel file *Dependence of GW BDCFs on Inputs_Part 1.xls* (Appendix A). This plot is a complilation of graphs shown in Figure 6.13-14.

Figure 6.13-15. Combined Representation of Dependence of Normalized BDCF for the Groundwater Exposure Scenario and Present-Day Climate on K_ds

6.13.4.2 Radionuclide Transport to Air

Radionuclides transported to the atmosphere originate in two environmental media: water and soil. Radionuclide transport from water to air is only considered in the case of aerosols generated by operation of evaporative coolers. Radionuclide transport from soil to air occurs via resuspension of surface soil and exhalation of gases from the soil.

6.13.4.2.1 Operation of Evaporative Coolers

Inhalation of particulate matter and inhalation of aerosols generated by evaporative coolers are important pathways for actinides (Tables 6.13-1 and 6.13-2), the latter depending on climate conditions. Inhalation of aerosols generated by evaporative cooler contributes on average from 0% to 36% to the present-day climate BDCFs and from 0% to about 14% to the upper bound of the glacial transition climate BDCFs for the groundwater exposure scenario, depending on a radionuclide. As expected, the importance of the evaporative cooler pathway decreases for the climates that are cooler and wetter than the present-day climate because of the decreased need to use air cooling.

Radionuclide concentration in indoor air when evaporative coolers are in operation is calculated in the biosphere model as (Equation 6.4.2-3):

$$Ca_{e,i} = f_{evap} \frac{M_{water}}{F_{air}} Cw_i \tag{Eq. 6.13-3}$$

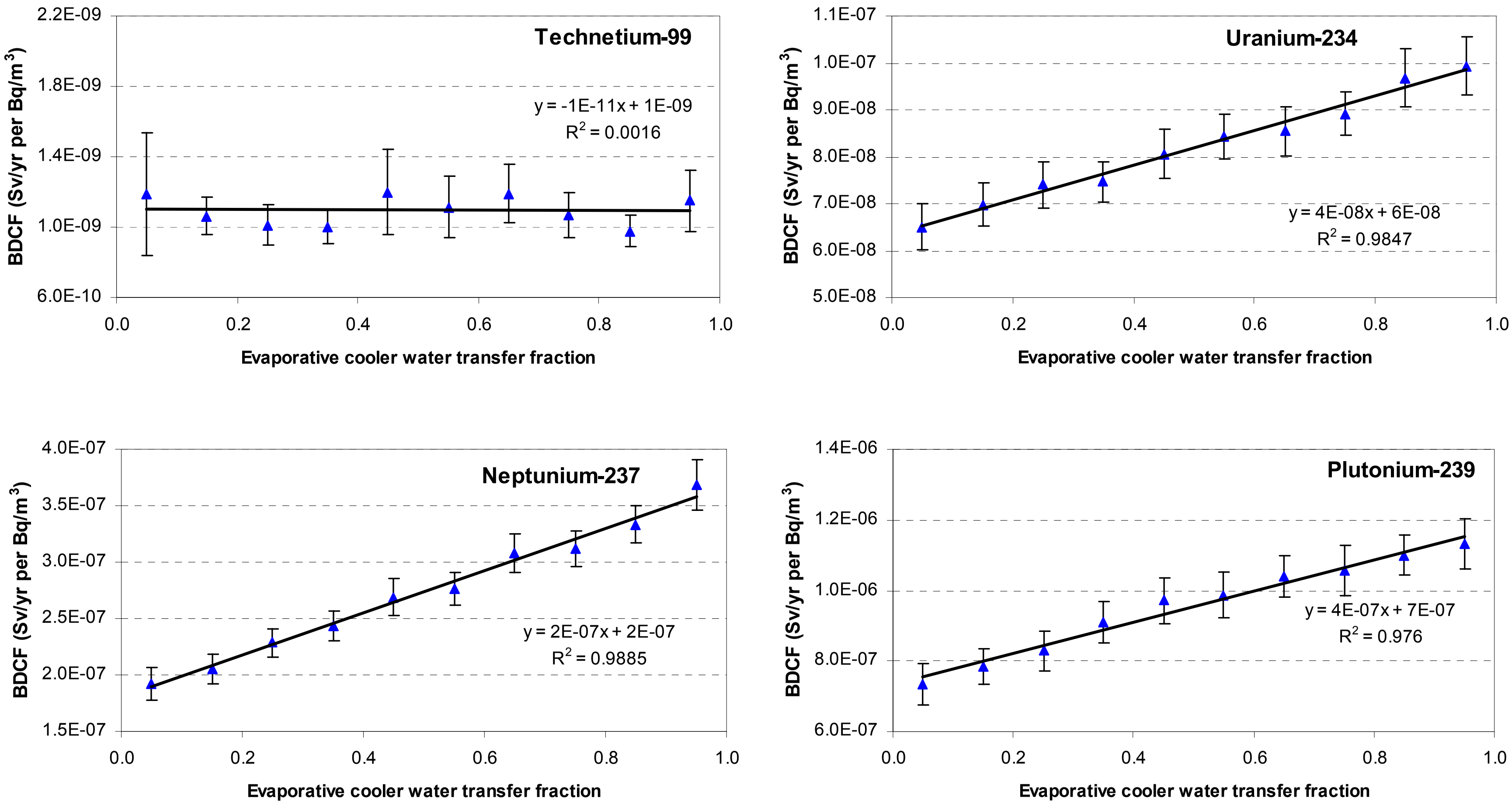
where

$Ca_{e,i}$	=	activity concentration of radionuclide *i* in the air resulting from the operation of an evaporative cooler (Bq/m^3)
f_{evap}	=	fraction of radionuclides in water transferred to indoor air (dimensionless)
M_{water}	=	water evaporation rate (water use) for an evaporative cooler (m^3/h)
F_{air}	=	air flow rate for an evaporative cooler (m^3/h)
Cw_i	=	activity concentration of radionuclide *i* in the groundwater (Bq/m^3).

The parameters in Equation 6.13-3 that are related to evaporative cooler operation, such as the water use rate and the air flow rate, were developed based on the technical specifications of evaporative coolers that would be suitable for the type of houses in Amargosa Valley. A search of the scientific literature did not find environmental assessments that considered the transport of contaminants through the evaporative cooler, so there is a lack of experimental measurements of the transfer of radionuclides from water to air. Therefore, a range from zero to unity was used in the model. This was done to evaluate the importance of this parameter in the biosphere model and to determine if a further investigation leading to a more accurate value was warranted.

The dependence of BDCFs on the value of the water transfer fraction for evaporative coolers is shown in Figures 6.13-16 for the present-day climate for ^{99}Tc, ^{234}U, ^{237}Np, and ^{239}Pu (Excel file *Dependence of GW BDCFs on Inputs_Part 3.xls*, Appendix A). As can be seen, this parameter does not affect the BDCF values for ^{99}Tc but influences BDCFs for ^{234}U, ^{237}Np, and ^{239}Pu values, with the strongest dependence on BDCFs for ^{237}Np.

The influence of the water transfer fraction (and thus activity concentration in air) on BDCFs for five radionuclides was estimated in a series of deterministic model runs. The difference between the mean BDCF value obtained in a deterministic run and the mean of the BDCF distribution from a stochastic realization of the model results from the selection of representative (fixed) input parameter values for the deterministic runs. Some of these representative values are not the mean of the distribution used in the stochastic realizations.



Source: Excel file Dependence of *GW BDCFs on Inputs_Part 3.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of the evaporative cooler water transfer fraction.

Figure 6.13-16. Dependence of BDCF for the Groundwater Exposure Scenario and the Present-Day Climate on the Water Transfer Fraction for Evaporative Coolers

The calculations were done for the average value of the water transfer fraction and for the maximum value. The results are presented in Table 6.13-9. It needs to be noted that the activity concentration in air shown in Table 6.13-9, like all intermediate results calculated in the biosphere model, is based on a unit activity concentration in groundwater (1 Bq/m^3). Changing the water transfer fraction from a mean of 0.5 to a maximum of one causes an increase from less than 1% for the ^{129}I BDCF, up to 34% for the ^{237}Np BDCF for the present-day climate.

Table 6.13-9. ^{237}Np BDCF and Percent Change for Different Values of Water Transfer Fraction for Evaporative Coolers for the Present-Day Climate

Radionuclide	Water Transfer Fraction	Activity Concentration in Air, Bq/m3	BDCF, Sv/yr per Bq/m^3	% Change
^{99}Tc	0.5 (average)	1.024E–06	6.31E–10	
	1 (maximum)	2.048E–06	6.51E–10	3.0
^{129}I	0.5 (average)	1.024E–06	1.00E–07	
	1 (maximum)	2.048E–06	1.00E–07	0.1
^{234}U	0.5 (average)	1.024E–06	6.19E–08	
	1 (maximum)	2.048E–06	7.55E–08	22.0
^{237}Np	0.5 (average)	1.024E–06	2.12E–07	
	1 (maximum)	2.048E–06	2.83E–07	34.0
^{239}Pu	0.5 (average)	1.024E–06	7.38E–07	
	1 (maximum)	2.048E–06	9.10E–07	23.3

NOTE: BDCFs were calculated in deterministic runs of *ERMYN_GW_Rev01_Base_Det.gsm* and by changing the radionuclide selection and the value of water transfer fraction for evaporative coolers. The percent change for the BDCFs was calculated in the Excel spreadsheet *Dependence of GW BDCFs on Inputs_Part 3.xls* (Appendix A).

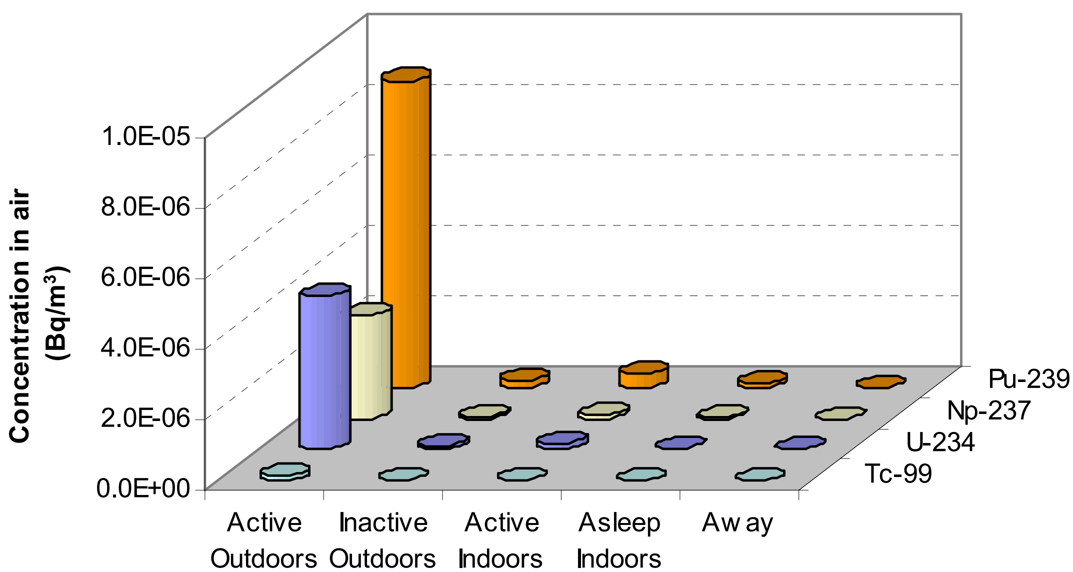
The model for evaluation of activity of aerosols generated by evaporative coolers uses a very conservative assumption that the fraction of radionuclides in the water transferred to the cooling airflow is, on average, 50% (Table 6.6-3). In a properly operated and maintained cooler, the dissolved radioactive species would precipitate out inside the unit during water evaporation and the water vapor introduced into the indoor air would be essentially mineral free. The subsequent contamination of the cooler air could occur when the air flowing through the cooler pads liberates small particles of the solids left behind after evaporation, especially if a cooler is poorly maintained (BSC 2004 [DIRS 169672], Section 6.5). Alternatively, the indoor air could become contaminated if water carry-over occurred through the gaps between the cooler pad fibers or through the thin spots, with the subsequent water evaporation outside the cooler (BSC 2004 [DIRS 169672], Section 6.5). However, since this effect results in a loss in cooler performance, the coolers are designed to prevent the water carry-over.

6.13.4.2.2 Resuspension of Surface Soil

Radionuclide concentrations in the air from the resuspension of contaminated surface soil are calculated as expressed by Equation 6.4.2-2. Radionuclide concentration in the air depends on the radionuclide concentration in the surface soil and the enhancement factor that quantifies the difference between the radionuclide concentrations per unit mass in the airborne soil particles relative to those on the ground. These quantities also depend on the receptor environment.

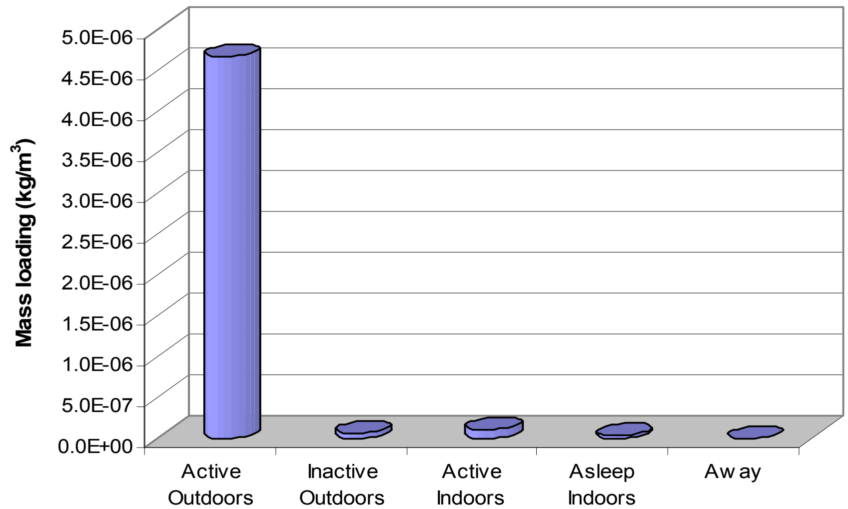
Five receptor environments associated with different human activities are considered in the biosphere model, four in the contaminated area: active outdoors ($n = 1$), inactive outdoors ($n = 2$), active indoors ($n = 3$), asleep indoors ($n = 4$), and one outside of the contaminated area ($n = 5$) (see BSC 2005 [DIRS 172827], Section 6.2 for detailed discussion of receptor environments). These mutually exclusive environments represent behavioral and environmental combinations for which the receptor would receive a substantially different rate of exposure via inhalation or external exposure. Activity concentration in the air outside the contaminated area is zero.

The average radionuclide concentrations in air in the five environments for ^{99}Tc, ^{234}U, ^{237}Np, and ^{239}Pu are shown in Figure 6.13-17. The activity concentration in soil for ^{99}Tc is much lower than that for the remaining three radionuclides because ^{99}Tc does not build up in surface soil as much as the actinides do. This is due to a higher leaching removal rate constant for this element. It can also be seen that the radionuclide concentration in air for the active outdoor environment is much higher than that in any of the remaining environments. From Equation 6.4.2-2, the radionuclide concentration in air depends on the radionuclide concentration in surface soil (discussed in Section 6.13.4.1), atmospheric mass loading, and the enhancement factor. The radionuclide concentration in the outdoor active environment is high because both atmospheric mass loading is high for this environment, compared to the other environments, as shown in Figure 6.13-18.



Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

Figure 6.13-17. Average Radionuclide Concentration in Air from Resuspension of Soil by Radionuclide and Environment per Unit Radionuclide Concentration in Groundwater

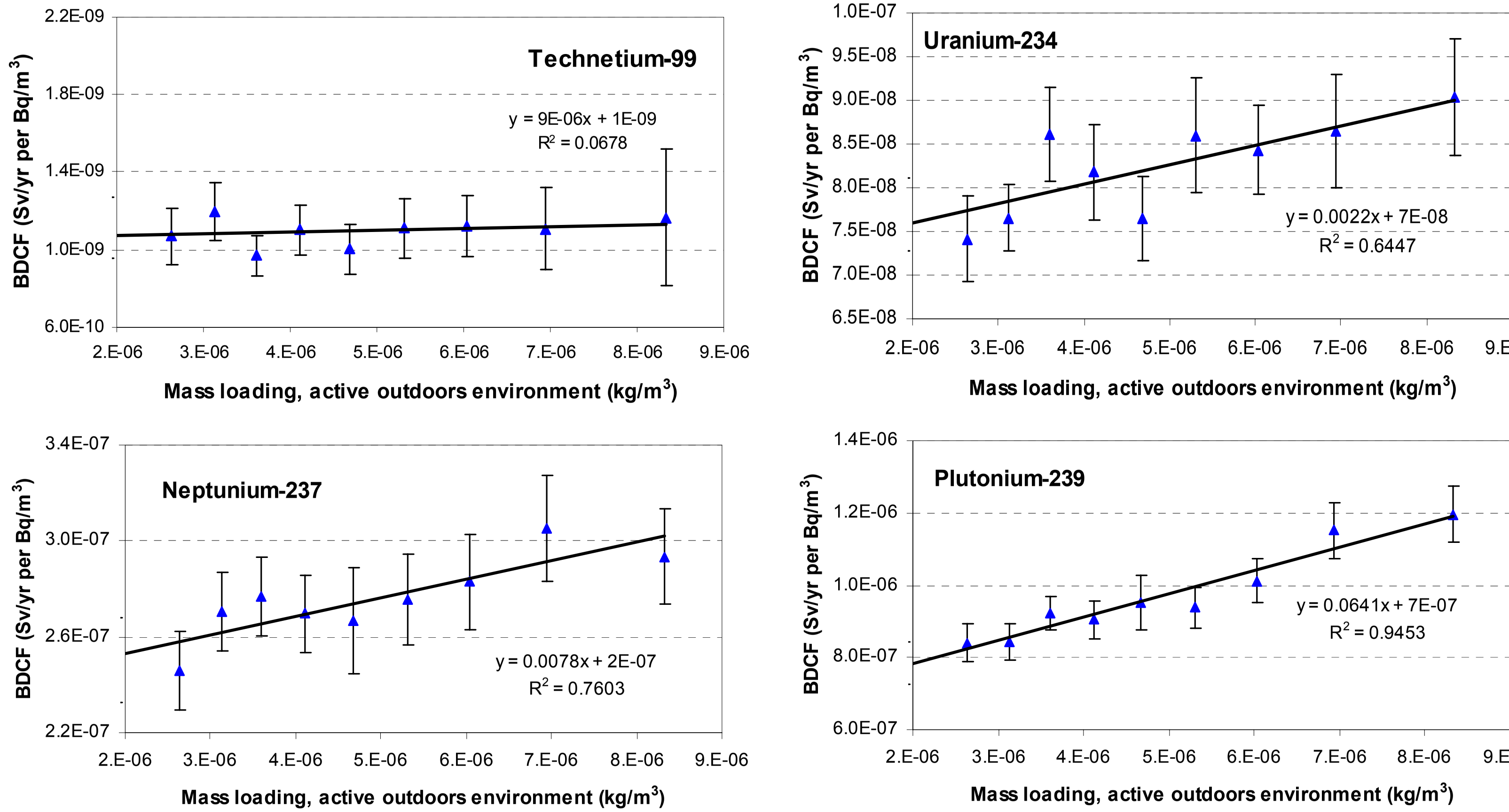


Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

Figure 6.13-18. Average Particulate Concentration in Air (Mass Loading) in the Receptor Environments

Because inhalation of airborne particulates from soil resuspension is an important exposure pathway (Table 6.13-1) and mass loading is an important parameter, graphs were produced that show the dependence of the BDCFs on this parameter. These graphs show the dependence of BDCFs for ^{99}Tc, ^{234}U, ^{237}Np, and ^{239}Pu on mass loading in the active outdoor environment (Figure 6.13-19), inactive outdoor environment (Figure 6.13-20), and active indoor environment (Figure 6.13-21).

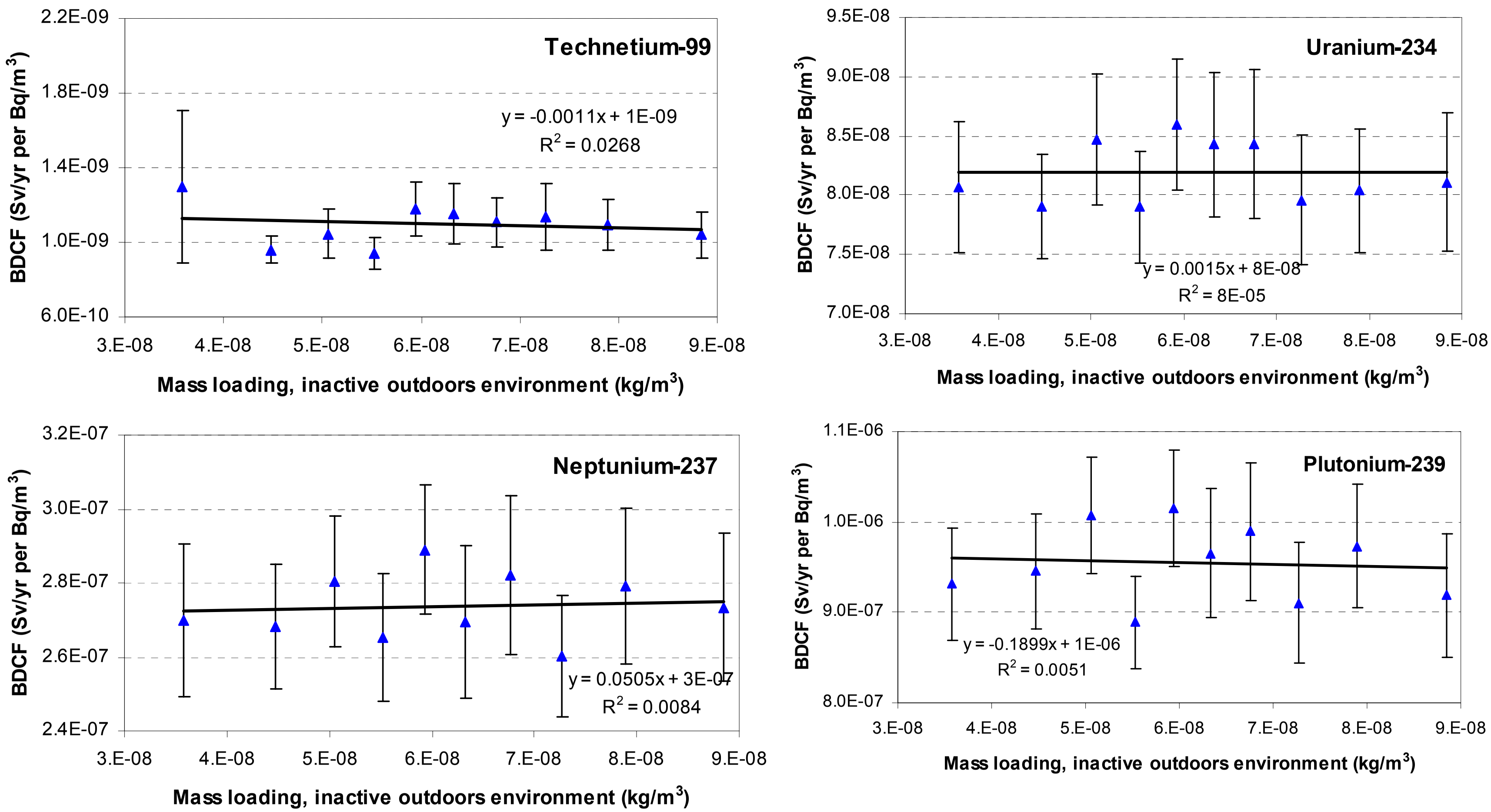
The BDCFs for all radionuclides are unaffected by the mass loading in the inactive outdoor environment. The BDCFs for ^{99}Tc are, as expected, unaffected by mass loading in either of the environments. The BDCFs for the remaining radionuclides show dependence on the mass loading in the active outdoors and active indoor environments.



Source: Excel file *Dependence of GW BDCFs on Inputs_Part 3.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of the mass loading.

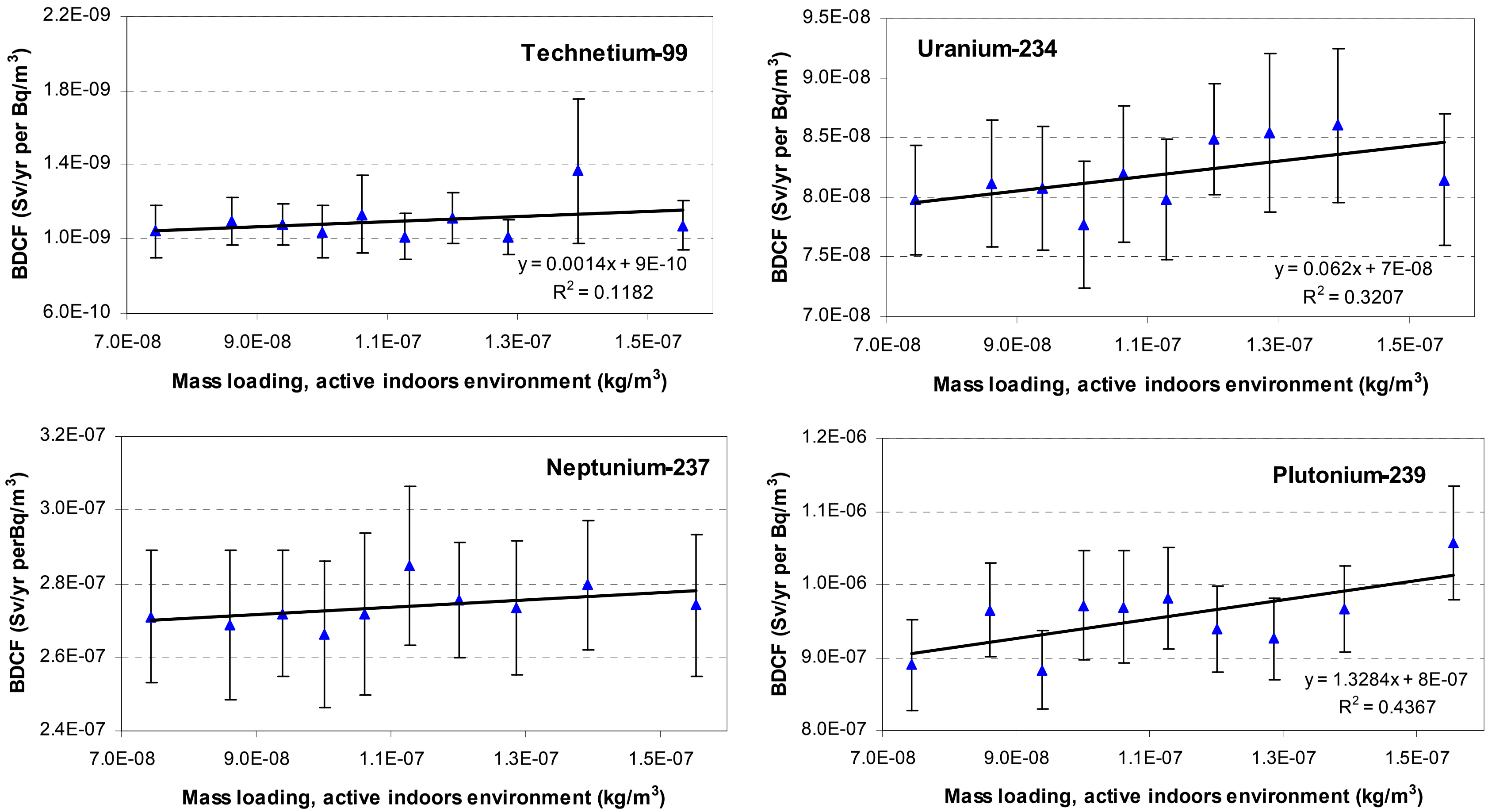
Figure 6.13-19. Dependence of BDCFs for the Groundwater Exposure Scenario and the Present-Day Climate on the Atmospheric Mass Loading for the Active Outdoor Environment



Source: Excel file *Dependence of GW BDCFs on Inputs_Part 3.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of the mass loading.

Figure 6.13-20. Dependence of BDCFs for the Groundwater Exposure Scenario and the Present-Day Climate on the Atmospheric Mass Loading for the Inactive Outdoor Environment



Source: Excel file *Dependence of GW BDCFs on Inputs_Part 3.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of the mass loading.

Figure 6.13-21. Dependence of BDCFs for the Groundwater Exposure Scenario and the Present-Day Climate on the Atmospheric Mass Loading for the Active Indoor Environment

The influence of mass loading in the active outdoor, inactive outdoor, and active indoor environments on the BDCFs for ^{237}Np and ^{239}Pu was estimated in a series of deterministic model runs. The mass loading parameters used in the runs and the corresponding BDCF values are presented in Table 6.13-10.

Table 6.13-10. BDCFs for ^{237}Np and ^{239}Pu and Percent Change for Different Levels of Mass Loading in the Receptor Environments

			^{237}Np		^{239}Pu	
Environment	**Statistic**	**Mass Loading, kg/m^3**	**BDCF Sv/yr per Bq/m^3**	**% Change**	**BDCF Sv/yr per Bq/m^3**	**% Change**
Active Outdoors	Mode	3.0E–06	2.12E–07	0.0	7.38E–07	0.0
	Minimum	1.0E–06	1.98E–07	-6.3	6.36E–07	-13.8
	Maximum	10.0E–06	2.58E–07	22.2	1.09E–06	48.3
Inactive Outdoors	Mode	0.06E–06	2.12E–07	0.0	7.38E–07	0.0
	Maximum	0.1E–06	2.12E–07	0.3	7.48E–07	1.4
	3 x Mode	0.18E–06	2.14E–07	1.0	7.69E–07	4.2
Active Indoors	Mode	0.1E–06	2.12E–07	0.0	7.38E–07	0.0
	Minimum	0.06E–06	2.07E–07	-2.2	6.70E–07	-9.2
	Maximum	0.175E–06	2.20E–07	4.2	8.65E–07	17.2

NOTE: BDCFs were calculated in deterministic runs of *ERMYN_GW_Rev01_Base_Det.gsm* by changing the radionuclide selection and the value of value of mass loading. The percent change for the BDCFs was calculated in the Excel spreadsheet *Dependence of GW BDCFs on Inputs_Part 3.xls* (Appendix A).

The results of the BDCF calculations using different values of mass loading indicate that the BDCFs for ^{237}Np are less sensitive to the value of the mass loading than the BDCFs for ^{239}Pu. This is because the inhalation of particulate matter is a more important pathway for ^{239}Pu than it is for ^{237}Np. The mass loading in the active outdoor environment has the greatest influence on the variance in the BDCF values. Variations of mass loading in the inactive outdoor environment have an insignificant effect on the BDCFs, even for the value equal to the tripled modal value.

6.13.4.3 Radionuclide Transport to Crops

Environmental transport pathways considered in the biosphere model for the groundwater exposure scenario that result in radionuclide transport to crops are:

- Deposition of contaminated water on crop surfaces
- Deposition of resuspended contaminated soil in crop surfaces
- Root uptakes of radionuclides present in surface soil.

The relative contributions of these pathways to the overall activity concentration in a crop type are pathway and crop-type dependent. Table 6.13-11 summarizes the fractions of radionuclide concentration in the crop types used in the biosphere model contributed by transport process considered in the model for a few selected radionuclides. The fractions for the present-day climate were calculated in the Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

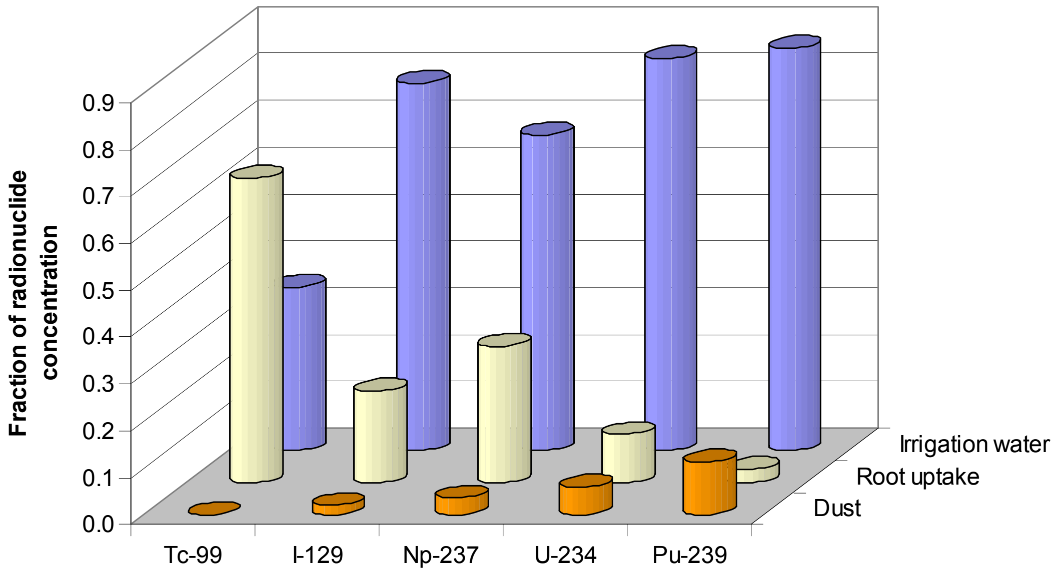
Because there is a trend regarding the importance of environmental transport pathways for each radionuclide, regardless of crop type, the fractions of radionuclide concentrations for a radionuclide were also averaged over all crop types included in the analysis. The results are shown in Table 6.13-11 and Figure 6.13-22 (Excel file *Detailed Pathway Analysis GW_PDC.xls* in Appendix A). This averaging was justified because the differences among the crop types were usually less than the differences between the mechanisms of radionuclide transport to a crop.

Figure 6.13-22 shows that radionuclide deposition on plant surfaces from irrigation water is the dominant mechanism of activity transport to crops for all radionuclides except ^{99}Tc. Root uptake is dominant for ^{99}Tc and a significant contributor for ^{129}I and ^{237}Np. Root uptake is relatively insignificant for ^{239}Pu because of its low uptake from the liquid phase, which is due to the high sorption properties of this element (it is preferably present in the solid phase). Particulate deposition is relatively unimportant, regardless of radionuclide, although it is greater for transuranics, which tend to accumulate in the soil to a greater degree than poorly sorbing elements such as technetium.

Table 6.13-11. Fractions of Activity in Crop Types from Considered Environmental Transport Pathways for Groundwater Exposure Scenario for Present-Day Climate

Radionuclide	Transport Process	Crop Type					Average
		Leafy Vegetables	Other Vegetables	Fruits	Grains	Forage	
^{99}Tc	Irrigation water deposition	0.322	0.380	0.390	0.395	0.259	0.349
	Dust deposition	0.000	0.000	0.001	0.001	0.000	0.001
	Root uptake	0.678	0.619	0.609	0.603	0.741	0.650
^{129}I	Irrigation water deposition	0.933	0.806	0.723	0.640	0.815	0.784
	Dust deposition	0.015	0.012	0.014	0.029	0.032	0.021
	Root uptake	0.051	0.182	0.262	0.331	0.153	0.196
^{234}U	Irrigation water deposition	0.927	0.859	0.832	0.818	0.748	0.837
	Dust deposition	0.042	0.037	0.049	0.090	0.078	0.059
	Root uptake	0.031	0.104	0.119	0.092	0.174	0.104
^{237}Np	Irrigation water deposition	0.820	0.641	0.606	0.686	0.614	0.673
	Dust deposition	0.025	0.018	0.025	0.062	0.050	0.036
	Root uptake	0.156	0.341	0.369	0.253	0.336	0.291
^{239}Pu	Irrigation water deposition	0.910	0.909	0.879	0.832	0.761	0.858
	Dust deposition	0.087	0.081	0.105	0.158	0.135	0.113
	Root uptake	0.002	0.010	0.016	0.010	0.104	0.028

Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).



Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

Figure 6.13-22. Environmental Transport Pathway Contributions for Groundwater Exposure Scenario and Present-Day Climate Averaged for All Crop Types

Not shown in Figure 6.13-22 is the relative importance of the environmental transport pathways leading to accumulation of ^{14}C in the plants. This is because the environmental transport of ^{14}C in the environment is evaluated in the biosphere model using a special submodel (Section 6.4.6), which is different than the plant submodel used for the other radionuclides (Section 6.4.3). This special submodel includes different mechanisms of carbon migration though the environment. Concentration of ^{14}C in crops and animal products is calculated based on the ratios of ^{14}C to stable carbon in the media that are the source of carbon for plants (air and soil) and for animals (feed, water, and soil), on the fraction of total carbon in plants or animal products that originates from these media, and on the carbon content of these media. The concentration of ^{14}C in crops and animal products thus reflects the relative abundance of ^{14}C and stable carbon in the environment. Pathway contributions for crops and animal products correspond to the consumption of these foodstuffs. In the case of ^{14}C transport to plants, almost 100% of ^{14}C in crops is from the air (carbon absorption during photosynthesis). The fraction of ^{14}C concentration in crops from root uptake is negligible (Excel file *Detailed Pathway Analysis GW_PDC.xls* in Appendix A).

Irrigation with contaminated water is an important environmental transport pathway for all radionuclides. Radionuclide concentrations in crops due to leaf uptake from contaminated irrigation water sprayed on plants is expressed as (Equation 6.4.3-3):

$$Cp_{water,i,j} = \frac{Dw_{i,j}\, f_{o,j}\, Rw_j\, T_j}{\lambda_w\, Y_j}\left(1 - e^{-\lambda_w\, t_{g,j}}\right) \qquad \text{(Eq. 6.13-4)}$$

where

$Dw_{i,j}$ = deposition rate of radionuclide i due to application of irrigation water on crop type j (Bq/(m^2 d))

$f_{o,j}$ = fraction of irrigation applied using overhead methods for plant type j (dimensionless)

Rw_j = interception fraction of irrigation water for crop type j (dimensionless)

T_j = translocation factor for crop type j (dimensionless)

λ_w = weathering constant (1/d), which can be calculated from weathering half-life (T_w in units of d) by $\lambda_w = \ln(2) / T_w$

$t_{g,j}$ = crop growing time for crop type j (d)

Y_j = crop yield or wet biomass for crop type j (kg$_{\text{wet weight}}$/m^2).

For overhead irrigation (i.e., sprinkler or spray), the rate of radionuclide deposition onto crops, Dw_j, is the product of the irrigation rate and radionuclide concentration in water. In this submodel, the radionuclide deposition rate from irrigation water is estimated as (Equation 6.4.3-4):

$$Dw_{i,j} = Cw_i \; IRD_j \qquad \text{(Eq. 6.13-5)}$$

where

IRD_j = daily average irrigation rate for crop type j during the growing season (m/d)

and the other parameter is defined in Equation 6.4.1-1.

The result calculated using Equation 6.13-4 is relatively insensitive to the value of the term in the parentheses, containing an exponential function. This is because the weathering time is much shorter than the crop growing time (the weathering rate constant is relatively large), so the exponential term approaches values that are close to zero. The uncertainty in the weathering half-life influences the uncertainty in some BDCF values, especially for those radionuclides that have a significant fraction of their BDCF due to ingestion of locally produced food, as can be seen in Table 6.13-3.

For the remaining parameters, the radionuclide concentration in crops is directly proportional to the deposition rate, fraction of irrigation applied using overhead methods, interception fraction, and translocation, and inversely proportional to the weathering constant and crop yield. These parameters influence the radionuclide concentration in crops from irrigation, making this environmental transport pathway the most important transport mechanisms for contamination of crops, but they do not contribute to an appreciable degree to the uncertainty in the all-pathway BDCF (Table 6.13-3). One reason is that many agricultural parameters that are used for this pathway were developed based on representative crops and with consideration of site-specific conditions and, as the result, the level of uncertainty associated with these parameters is relatively low.

A parameter that received some attention in the past was the interception fraction for irrigation water. This parameter quantifies the amount of contaminated water intercepted by crop surfaces. The histograms of water interception fraction for all crop types used in the biosphere model are shown in Figure 6.13-23. The biosphere model is relatively insensitive to the value of this parameter, as illustrated in Figure 6.13-24 for ^{99}Tc, a radionuclide that has a high BDCF contribution from the ingestion of locally produced food.

The water interception pathway is more important as a transport pathway for elements that are poorly taken up from the soil through their roots, as indicated in Figure 6.13-22. However, for these elements, ingestion of locally produced food is, overall, not a very important pathway, so the influence of the water interception fraction on the BDCFs for these radionuclides is expected to be even less.

The influence of irrigation interception fraction on BDCFs for five radionuclides was estimated in a series of deterministic model runs. The calculations were done for the average and twice the average irrigation interception fractions for all crops. The irrigation interception values used in the calculations are listed in Table 6.13-12 and the results are presented in Table 6.13-13.

Table 6.13-12. Irrigation Interception Fractions Used in Calculations

Irrigation Interception Fraction	Leafy Vegetables	Other Vegetables	Fruit	Grain	Forage
Average for all crops	0.216	0.301	0.360	0.470	0.258
2 x Average for all crops	0.432	0.602	0.719	0.940	0.516

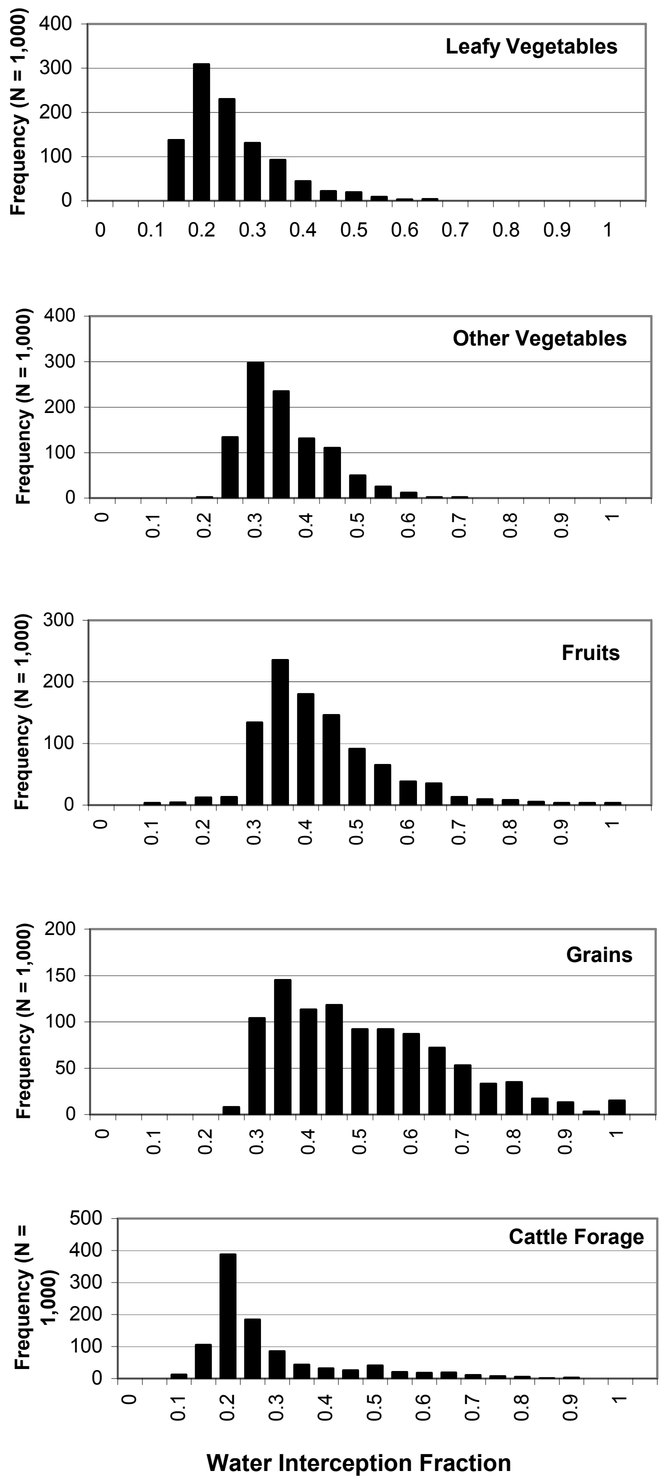
Source: Excel spreadsheet *Dependence of GW BDCFs on Inputs_Part 2*.xls (Appendix A).

Table 6.13-13. BDCFs and Percent Change for Different Irrigation Interception Fractions

Radionuclide	Irrigation Interception Fraction	BDCF Sv/yr per Bq/m^3	% Change Relative to Average
^{99}Tc	Average for all crops	6.31E–10	
	2 x Average for all crops	6.77E–10	7.2
^{129}I	Average for all crops	1.00E–07	
	2 x Average for all crops	1.13E–07	12.4
^{234}U	Average for all crops	6.19E–08	
	2 x Average for all crops	6.42E–08	3.7
^{237}Np	Average for all crops	2.12E–07	
	2 x Average for all crops	2.16E–07	2.0
^{239}Pu	Average for all crops	7.38E–07	
	2 x Average for all crops	7.47E–07	1.3

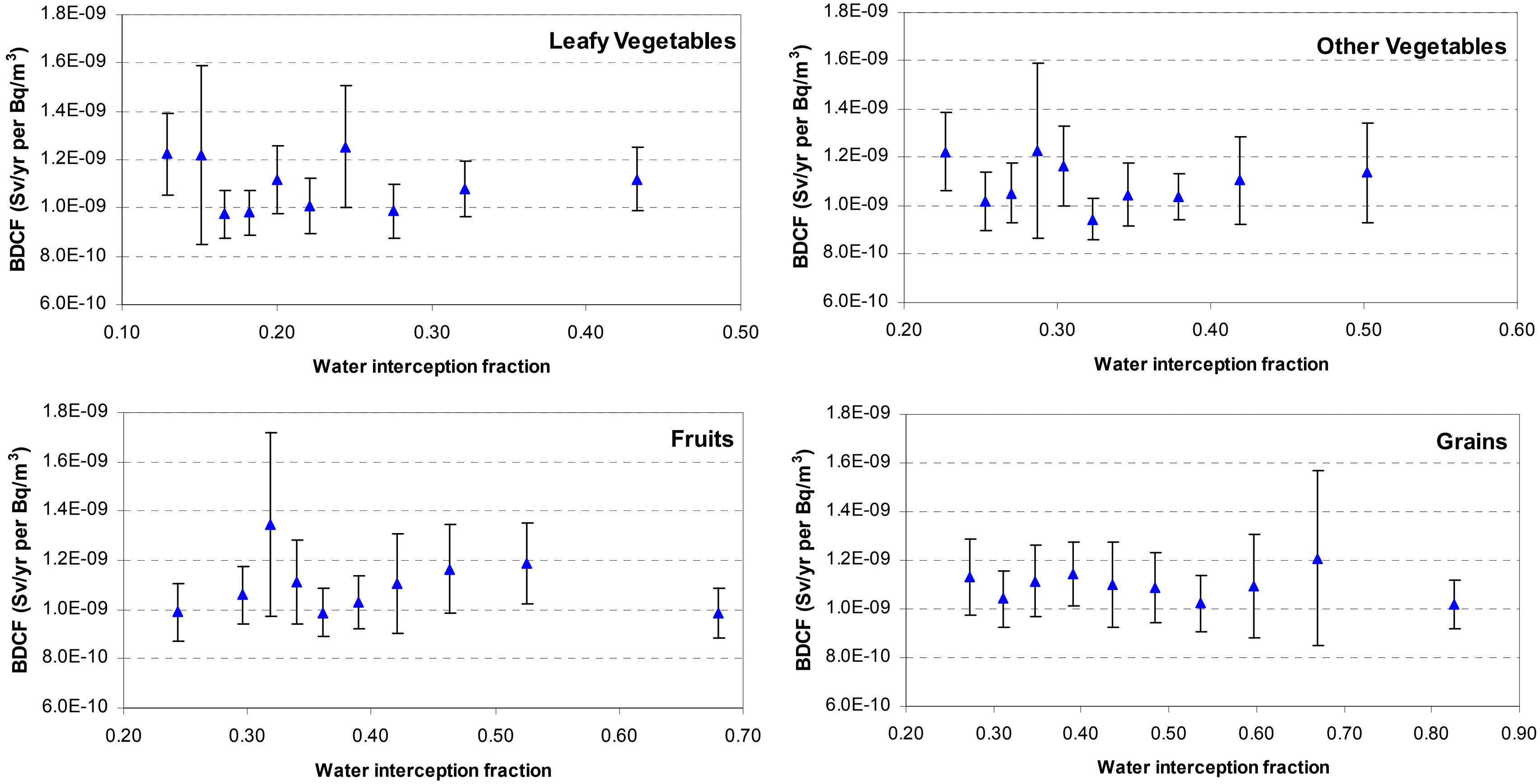
NOTE: BDCFs were calculated in deterministic runs of *ERMYN_GW_Rev01_Base_Det.gsm* by changing the radionuclide selection and the value of mass loading. The percent change for the BDCFs was calculated in the Excel spreadsheet *Dependence of GW BDCFs on Inputs_Part 2*.xls (Appendix A).

Doubling the irrigation interception fraction results, on average, in an increase in the BDCF from about 1 to 2% for ^{237}Np and ^{239}Pu to about 12% for ^{129}I.



Source: Excel file *Water Interception Fraction.xls* (Appendix A).

Figure 6.13-23. Water Interception Fraction Histograms by Crop Type Resulting from 1,000 Realizations of the Biosphere Model



Source: Excel file *Dependence of GW BDCFs on Inputs_Part 2.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of water interception fraction.

Figure 6.13-24. Dependence of ^{99}Tc BDCF for the Groundwater Exposure Scenario and Present-Day Climate on Water Interception Fraction by Type of Crops for Human Consumption

Root uptake is the second most important environmental transport pathway that gives rise to radionuclide concentration in crops (Figure 6.13-22 and Table 6.13-11). The activity concentration of radionuclides in crops from root uptake is estimated as (Equation 6.4.3-2):

$$Cp_{root,i,j} = Cs_{m,i}\ F_{s\rightarrow p,i,j}\ DW_j \qquad \text{(Eq. 6. 13-6)}$$

where

$Cs_{m,i,j}$ = crop type-dependent activity concentration of radionuclide i in surface soil (Bq/kg $_{\text{dry soil}}$)

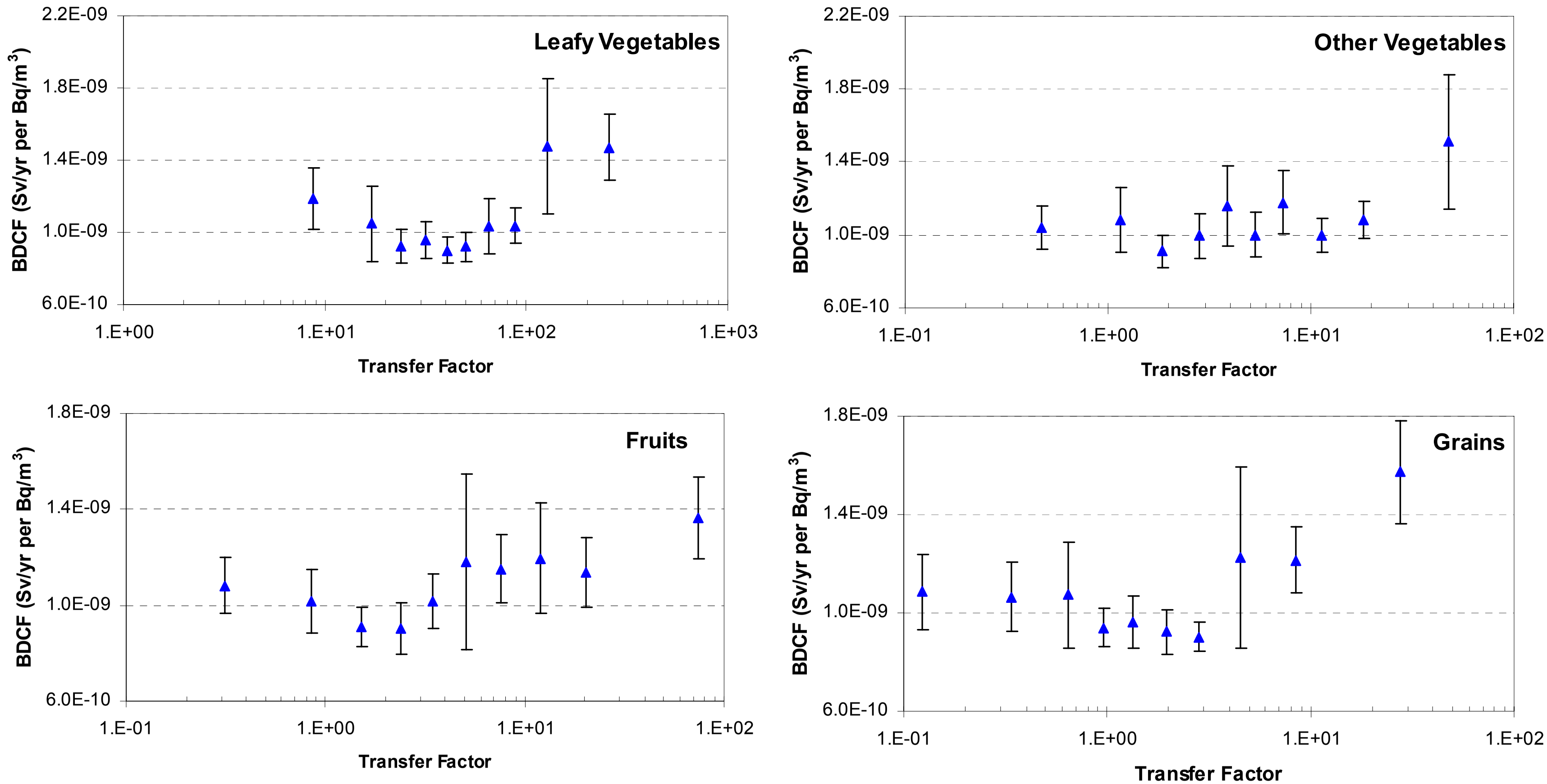
$F_{s\rightarrow p,i,j}$ = soil-to-plant transfer factor for radionuclide i and crop type j (Bq/kg $_{\text{dry plant}}$ per Bq/kg $_{\text{dry soil}}$)

DW_j = dry-to-wet weight ratio for edible parts of crop type j (kg $_{\text{dry plant}}$ /kg $_{\text{wet plant}}$).

The dry-to-wet weight ratio was developed from measurements of reference crops and has a low degree of uncertainty. The soil-to-plant transfer factor, in contrast, was developed based on literature data for many elements and crop types and has a relatively wide distribution. This uncertainty is transferred to the biosphere model results, as indicated by the results of the correlation analysis, which point to the soil-to-plant transfer factors as statistically significant contributors to the overall BDCF variance (Table 6.13-3).

Of the radionuclides shown in Figure 6.13-22 and in Table 6.13-11, ^{99}Tc and ^{237}Np have the highest fraction of activity in crops that is attributable to the root uptake. The dependence of the BDCFs for these two radionuclides on the transfer factors for the crop types considered in the biosphere model is presented in Figures 6.13-25 and 6.13-26, for ^{99}Tc and ^{237}Np, respectively (*Dependence of GW BDCFs on Inputs_Part 2.xls* in Appendix A).

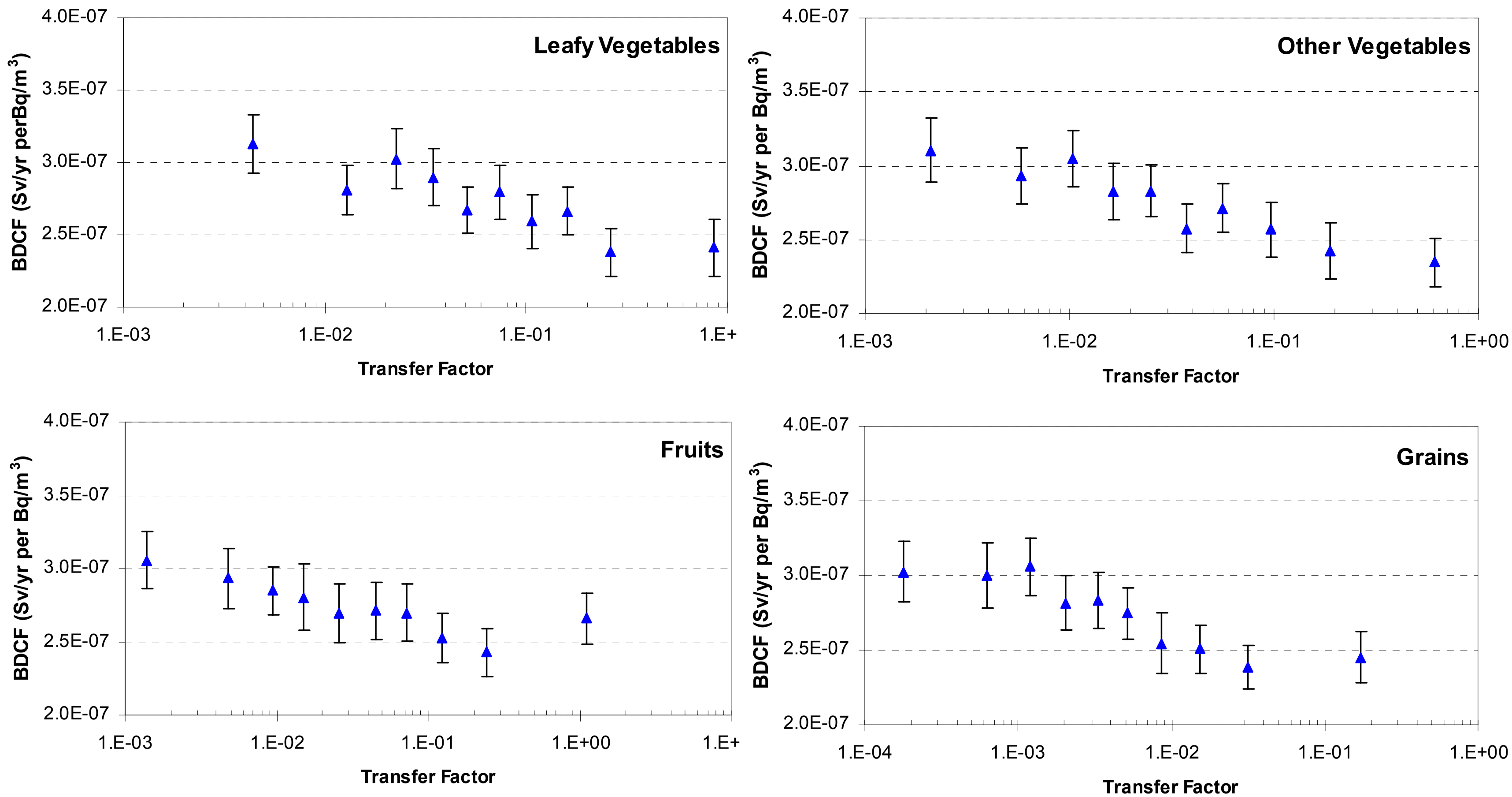
The dependence of the BDCF for ^{99}Tc and ^{237}Np on the soil-to-plant transfer factor corresponds to the BDCF dependence on the partition coefficients for these radionuclides (Figure 6.13-14) because these two parameters are correlated in the model. The correlation is negative because a high K_d reduces the amount of an element present in solution and thus its availability for root uptake. This results in low transfer factors for high values of K_ds. Thus, the trends for ^{237}Np shown in Figure 6.13-26 for transfer factors are opposite of the trend for ^{237}Np shown in Figure 6.13-14 for the K_ds. Graphs in Figure 6.13-25 for ^{99}Tc show the U-shape dependence of the BDCFs on transfer factors. For the low transfer factor values, the BDCFs are relatively high because of the corresponding high K_d values and the resulting increased radionuclide accumulation in surface soil. At the high end of the transfer factor value range, the root uptake is an important transport pathway and although radionuclides do not accumulate in the soil (K_ds are low) they are effectively taken up by plants through their roots.



Source: Excel file Dependence of *GW BDCFs on Inputs_Part 2.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of transfer factor.

Figure 6.13-25. Dependence of BDCFs for ^{99}Tc for the Groundwater Exposure Scenario and the Present-Day Climate on Transfer Factors by Crop Type



Source: Excel file *Dependence of GW BDCFs on Inputs_Part 2.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of transfer factor.

Figure 6.13-26. Dependence of BDCFs for ^{237}Np for the Groundwater Exposure Scenario and the Present-Day Climate on Transfer Factors by Crop Type

6.13.4.4 Radionuclide Transport to Animal Products

Environmental transport pathways considered in the biosphere model that result in radionuclide transport to animal products are animal consumption of feed; water; and soil; and, indirectly, environmental transport pathways leading to radionuclide accumulation in forage plants and in the surface soil.

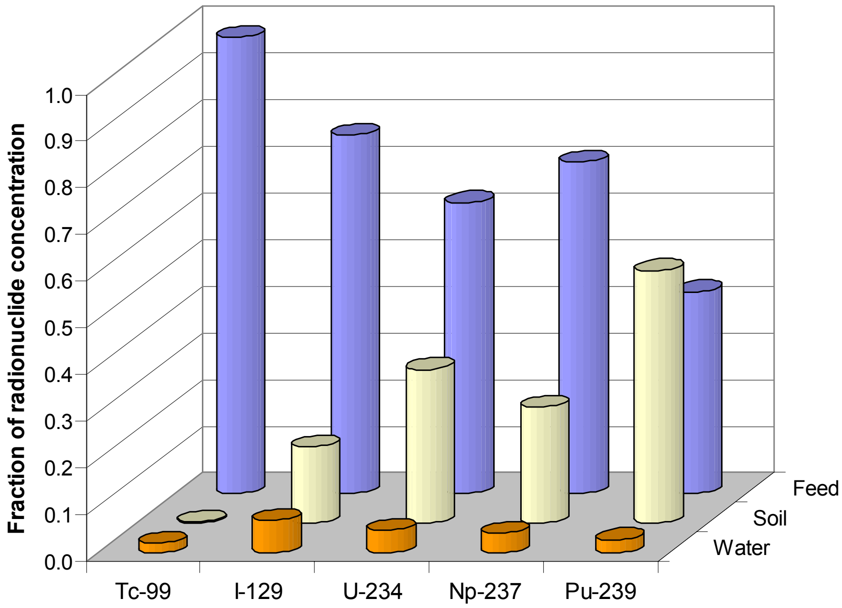
The relative contributions of these pathways to the overall activity concentration in an animal product is pathway and animal-product dependent. Table 6.13-14 summarizes the fractions of radionuclide concentration in the animal products considered in the biosphere model by transport process for selected radionuclides. The fractions for the present-day climate were calculated in the Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

Table 6.13-14. Fractions of Activity in Animal Products from Environmental Transport Pathways for Groundwater Exposure Scenario for Present-Day Climate

Radionuclide	Transport Process	Animal Product				Average Meat and Milk	Average Poultry and Eggs
		Meat	Milk	Poultry	Eggs		
^{99}Tc	Feed Consumption	0.976	0.976	0.886	0.885	0.976	0.886
	Water Consumption	0.021	0.021	0.086	0.086	0.021	0.086
	Soil Consumption	0.003	0.003	0.028	0.029	0.003	0.028
^{129}I	Feed Consumption	0.771	0.765	0.643	0.643	0.768	0.643
	Water Consumption	0.068	0.069	0.101	0.100	0.068	0.100
	Soil Consumption	0.161	0.166	0.256	0.257	0.164	0.257
^{234}U	Feed Consumption	0.628	0.618	0.401	0.404	0.623	0.402
	Water Consumption	0.048	0.048	0.084	0.083	0.048	0.084
	Soil Consumption	0.324	0.334	0.514	0.513	0.329	0.514
^{237}Np	Feed Consumption	0.715	0.705	0.487	0.488	0.710	0.488
	Water Consumption	0.042	0.042	0.077	0.077	0.042	0.077
	Soil Consumption	0.243	0.253	0.436	0.436	0.248	0.436
^{239}Pu	Feed Consumption	0.439	0.424	0.199	0.199	0.432	0.199
	Water Consumption	0.028	0.028	0.032	0.032	0.028	0.032
	Soil Consumption	0.533	0.548	0.770	0.770	0.540	0.770

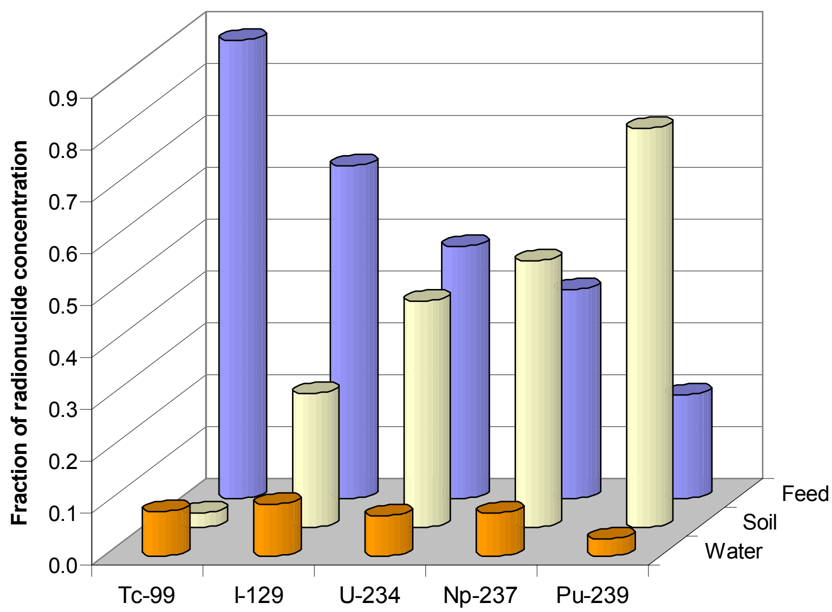
Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

To show trends regarding the importance of environmental transport processes for a given radionuclide, the fractions of radionuclide concentrations for a radionuclide were averaged over animal products of bovine origin (meat and milk) and poultry origin (poultry and eggs) included in the analysis. The results are shown in Table 6.13-14, and Figures 6.13-27 and 6.13-28, for meat and milk and for poultry and eggs, respectively. This averaging was justified because the differences between individual animal products (milk and meat as well as poultry and eggs) were usually much less than the differences between the mechanisms of radionuclide transport to these products. This is because the source of contaminated food is the same for cattle and milk cows as well as for chicken and laying hens.



Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

Figure 6.13-27. Average Contributions of Environmental Transport Pathways to Radionuclide Transport to Meat and Milk



Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

Figure 6.13-28. Average Contributions of Environmental Transport Pathways to Radionuclide Transport to Poultry and Eggs

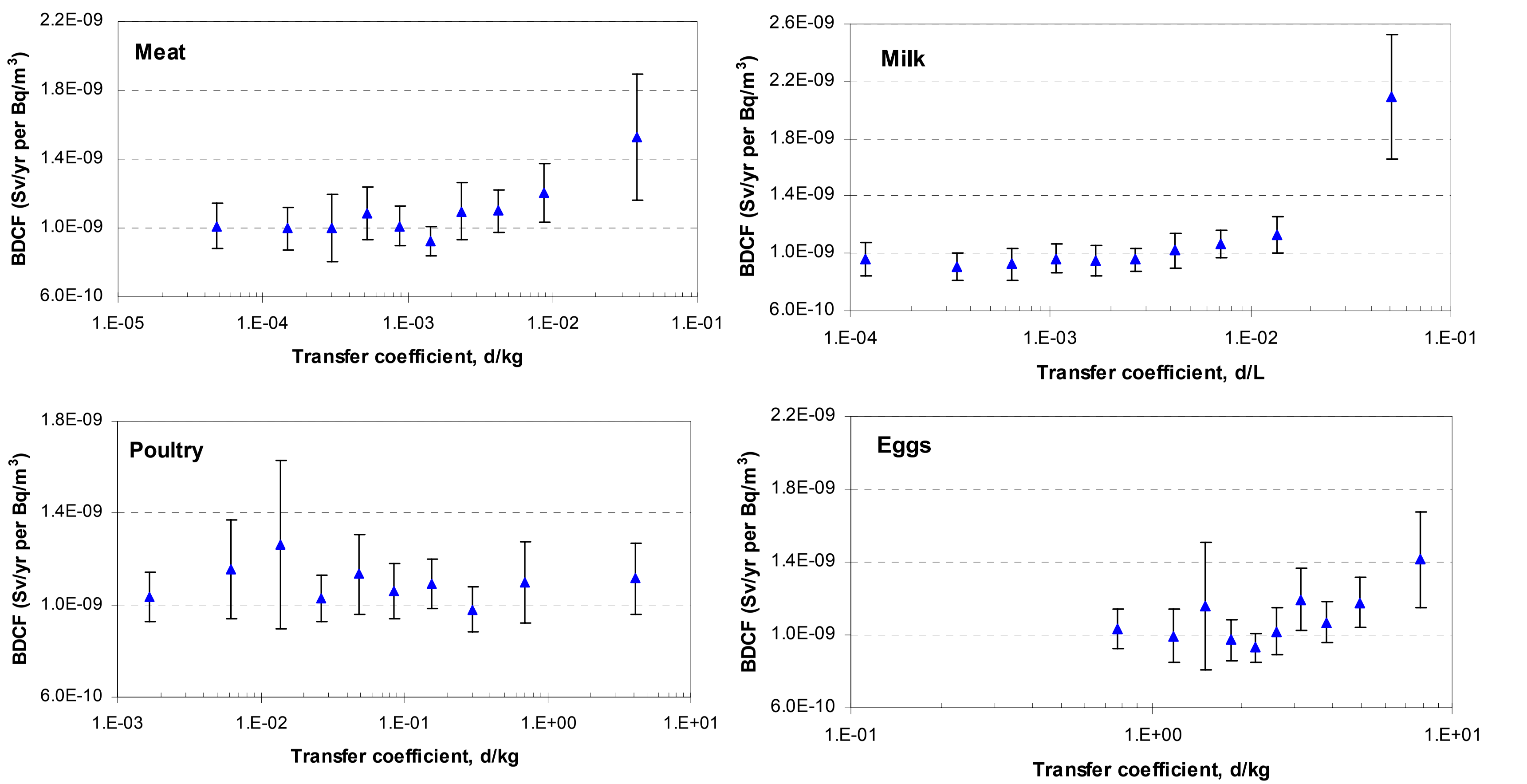
Figures 6.13-27 and 6.13-28 show that for meat and milk, the contribution from animal feed is dominant for all radionuclides except ^{239}Pu; for poultry and eggs, animal feed contributes the most for ^{99}Tc and ^{129}I. The contribution from ingestion of soil generally increases with atomic number and especially dominates for ^{239}Pu. This is due to the buildup of these radionuclides in surface soil that is irrigated with contaminated water over a long period of time and to the relatively high soil intake by chickens. Ingestion of water is relatively unimportant regardless of the radionuclide and the animal product.

Not shown is the relative importance of the environmental transport pathways leading to accumulation of ^{14}C in animal products. This is because the environmental transport of ^{14}C in the environment is evaluated in the biosphere model using a special submodel (Section 6.4.6), which is different than the animal submodel used for the other radionuclides (Section 6.4.4). This special submodel includes different mechanisms of carbon migration though the environment. In the case of ^{14}C transport to animal products, the fraction of ^{14}C intake from feed is 97-98%, 2-3% from water, and less than 0.02% from soil (Excel file *Detailed Pathway Analysis GW_PDC.xls*, Appendix A).

^{99}Tc and ^{129}I are examples of radionuclides that have a higher proportion of BDCFs that are due to consumption of locally produced animal products than most other radionuclides. For most radionuclides, especially actinides, ingestion of animal products is not an important exposure pathway (Tables 6.13-1 and 6.13-2).

The concentration of a radionuclide in a specific animal product (Cd_k) (Section 6.4.4) is calculated in the biosphere model as the product of the animal intake of a radionuclide and the animal intake-to-animal product transfer coefficient. Animal intake, in turn, is a product of a radionuclide concentration in the ingested media (feed, water, and soil) and the animal consumption rate of these media. The environmental transport pathways for the soil and animal feed are described in Sections 6.13.4.1 and 6.13.4.3, respectively. As noted previously, only the intake of feed and soil are significant contributors to radionuclide concentrations in animal products.

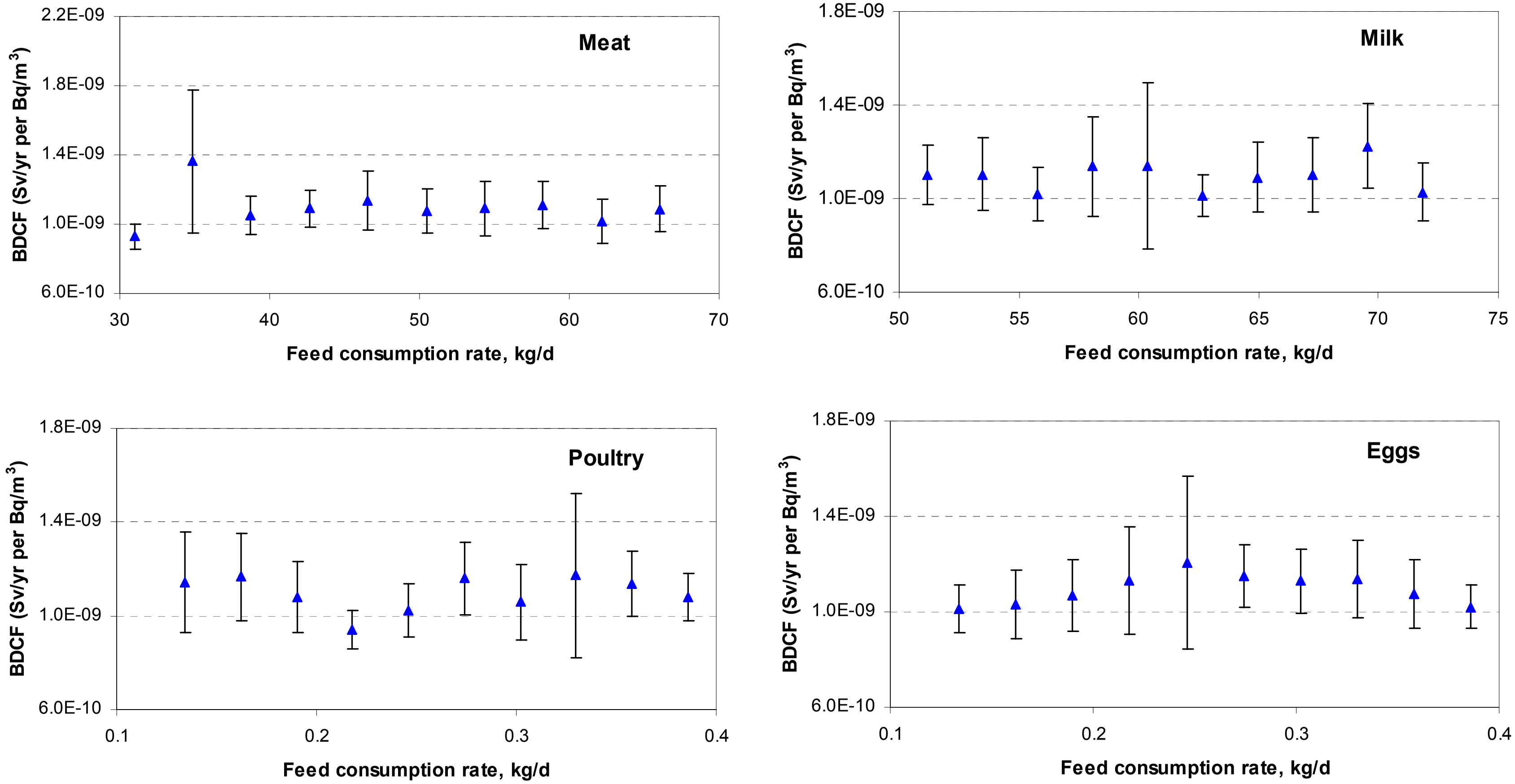
The dependence of BDCFs for ^{99}Tc on the value of the transfer coefficient for animal products is shown in Figure 6.13-29. This radionuclide was chosen because it has a relatively high BDCF contribution from the consumption of locally produced animal products. The BDCFs tend to increase as the transfer coefficients for meat, milk and eggs increase but only in the upper region of the range of transfer coefficients. The variability in the BDCF does not depend strongly on the variability in animal consumption rates as shown in Figure 6.13-30 for ^{99}Tc and also in Table 6.13-3. This is because these parameters tend to have relatively narrow distributions.



Source: Excel file *Dependence of GW BDCFs on Inputs_Part 2.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of transfer coefficient.

Figure 6.13-29. Dependence of BDCF for ^{99}Tc for the Groundwater Exposure Scenario and the Present-Day Climate on Transfer Coefficients by Animal Product



Source: Excel file *Dependence of GW BDCFs on Inputs_Part 2.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of feed consumption rates.

Figure 6.13-30. Dependence of BDCF for ^{99}Tc for the Groundwater Exposure Scenario and the Present-Day Climate on Animal Feed Consumption Rates by Animal Product

6.13.4.5 Radionuclide Transport to Aquatic Food

The activity concentration in fish is calculated as a product of activity concentration in the well water, water concentration modifying factor (the product of these two factors gives the concentration in the pond water) and the bioaccumulation factor (Equation 6.4.5-2). The water concentration modifying factor accounts for radionuclide concentration in the water caused by water evaporation from fish ponds and is developed using site-specific conditions. It has a small range of uncertainty relative to the distribution of the bioaccumulation factor, which was developed from a literature review. The bioaccumulation of radionuclides in fish is element specific and the fish consumption pathway is important for only a few radionuclides that have high values of the bioaccumulation factor (carbon, cesium, and lead). The bioaccumulation of these elements in fish is overestimated, especially for carbon, because farmed fish in Amargosa Valley received uncontaminated commercially produced feed (BSC 2004 [DIRS 169672], Sections 6.4.2 and 6.4.3). Bioaccumulation factors reported in literature and used in the biosphere model were measured in natural systems, in which all components of the system are contaminated and in equilibrium.

6.13.5 Analysis of the Receptor Exposure Pathways

The dose to the receptor is influenced by radionuclide levels in the environmental media (Section 6.13.4). It is also influenced by the factors that control the intake of these media by ingestion and inhalation and by the duration of exposure to radionuclides in media that are external to the receptor. These factors are discussed in this section.

6.13.5.1 Ingestion

The ingestion dose to the receptor arises from consumption of contaminated water and locally produced food. The dose from consumption of a given food type is calculated in the biosphere model as the product of radionuclide concentrations in the foodstuff, the consumption rate, and the dose coefficient converting radionuclide intake by ingestion to dose.

Ingestion of contaminated water is an important pathway for almost all radionuclides, as shown in Tables 6.13-1 and 6.13-2. This component of the annual dose to the receptor is defined by the rule in 10 CFR 63.312(d) [DIRS 173273], which requires that the RMEI consumption of water is 2 L/d. Because the water consumption rate is a fixed value and radionuclide concentration in the water is assumed to be constant, there is no uncertainty associated with this pathway in the biosphere model.

The pathway contributions from consumption of locally produced food (Tables 6.13-1 and 6.13-2) are directly proportional to consumption rates of these foods. The consumption rates of locally produced food were developed based on the dietary characteristics of Amargosa Valley residents. Because food consumption rates are represented in the model by the distribution of their averages, as required by 10 CFR 63.312(b) [DIRS 173273], the variance in their values is relatively small.

To evaluate the sensitivity of BDCFs to consumption rates, deterministic model runs using the mean or best estimate input parameter values were performed for selected radionuclides at different levels of consumption rates. First, the "baseline" BDCF levels were established by using the mean values of the current consumption rates for the RMEI. The dietary characteristics of the RMEI reflect averages for the adult Amargosa Valley population. Then, BDCFs for the same radionuclides were calculated using doubled consumption rates of locally produced food. The consumption rates of locally produced food used in these calculations are provided in Table 6.13-15.

Table 6.13-15. Annual Consumption Rates of Locally Produced Food Used in the Evaluation

Receptor	Consumption Rate by Food Type (kg/yr)									
	Water	Leafy Vegetables	Other Vegetables	Fruit	Grain	Meat	Milk	Poultry	Eggs	Fish
RMEI	730.5	3.78	4.73	12.68	0.23	2.85	4.66	0.42	5.3	0.23
2 × RMEI consumption	730.5	7.56	9.46	25.36	0.46	5.7	9.32	0.84	10.6	0.46

Source: DTN: MO0407SPACRBSM.002 [DIRS 170677].

The BDCFs for the present-day climate calculated using the consumption rates shown in Table 6.13-15 are summarized in Table 6.13-16. Table 6.13-16 also includes the percent change in the BDCF for a given consumption rate relative to the BDCF for the RMEI.

Table 6.13-16. BDCFs for Different Levels of Consumption of Locally Produced Food

Radionuclide	RMEI	Double RMEI Consumption	
	BDCF Sv/y per Bq/m^3	BDCF Sv/y per Bq/m^3	% Change Relative to the RMEI
^{14}C	1.40E–09	2.36E–09	69.0
^{99}Tc	6.31E–10	7.74E–10	22.6
^{129}I	1.00E–07	1.23E–07	22.4
^{234}U	6.19E–08	6.59E–08	6.4
^{237}Np	2.12E–07	2.20E–07	4.2
^{239}Pu	7.38E–07	7.58E–07	2.7

NOTE: BDCFs were calculated in deterministic runs of *ERMYN_GW_Rev01_Base_Det.gsm* by changing the radionuclide selection and the values of food consumption rates. The percent change for the BDCFs was calculated in the Excel spreadsheet *Dependence of GW BDCFs on Inputs_Part 2.xls* (Appendix A).

The values in Table 6.13-16 indicate that the BDCFs for actinides are relatively unaffected by changes in the consumption rates of locally produced food. The BDCFs for these radionuclides increase no more than about 7%. The BDCF for ^{99}Tc increases by about 23% when food consumption is doubled. The greatest difference is for ^{14}C because of the large proportion of the BDCF arising from consumption of food, especially fish. However, as noted in Section 6.13.4.5, the dose from the fish consumption is overestimated for ^{14}C because of the use of uncontaminated feed in the fishery (fish get their carbon primarily from their food, not from the water).

6.13.5.2 Inhalation

The following components of the inhalation pathway are included in the biosphere model:

- Inhalation of particulate matter
- Inhalation of aerosols generated by an evaporative cooler
- Inhalation of radon decay products
- Inhalation of $^{14}CO_2$ and inhalation of ^{14}C in particulate matter.

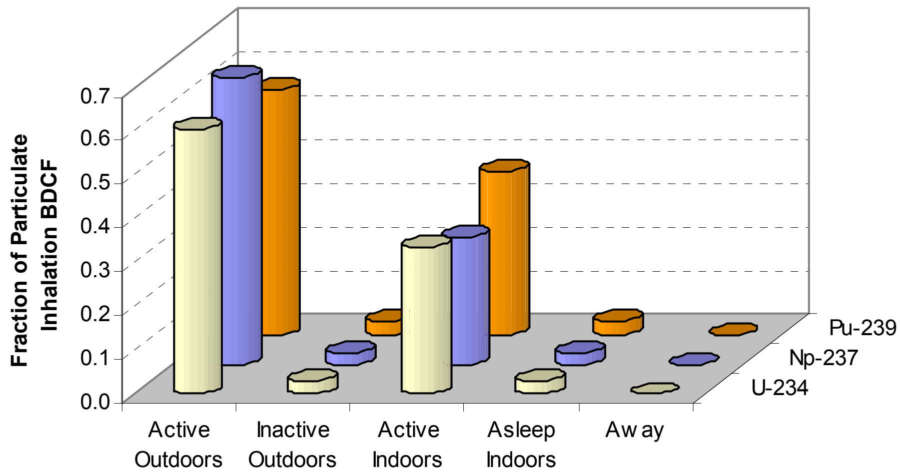
Inhalation of radon decay products is the most important pathway for ^{226}Ra and it is also a significant pathway for ^{230}Th, because these radionuclides include ^{222}Rn in their decay chains. The dose from inhalation of radon decay products depends on the level of radon gas in the air, degree of equilibrium with its decay products and the breathing rate. Inhalation of ^{14}C is a negligible contributor to the BDCF for this radionuclide. Inhalation of particulate matter and aerosols generated by evaporative coolers is further discussed in this section.

6.13.5.2.1 Inhalation of Particulate Matter

Inhalation exposure is calculated in the biosphere model by using a time-budget method, where a receptor's time is spent in several mutually exclusive environments. Inhalation of particulate matter arising from resuspension of contaminated soil occurs in all receptor environments except when away from the contaminated area. A short summary of the environments and their characteristics with regard to the receptor follows:

- Active outdoors – receptor is outdoors conducting dust generating activities
- Inactive outdoors – receptor is outdoors conducting activities that do not resuspend soil
- Active indoors – receptor is awake indoors
- Asleep indoors – receptor is sleeping indoors
- Away – receptor is away from contaminated area.

Figure 6.13-31 shows the fractional contributions from these environments to the BDCF component resulting from inhalation of airborne particulates. Inhalation exposure accrued in the active outdoor environment is by far a dominant contributor (the Excel file *Detailed Pathway Analysis GW_PDC.xls* is the source of this and other figures in this section).



Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

Figure 6.13-31. Average Fraction of Dose from Particulate Inhalation by Radionuclide and Environment

To explain the reasons behind the high inhalation exposure in the active outdoor environment and a relatively high inhalation exposure in the active indoor environment and discuss the sources of uncertainty, the mathematical representation of the particulate inhalation submodel is described below. The inhalation dose from airborne particulates is calculated as (Equation 6.4.8-2):

$$D_{inh,p,i} = \sum_{l} D_{inh,p,l} = \sum_{l} EDCF_{inh,l} \left[\sum_{n} Ca_{h,l,n} \, BR_n \sum_{m} \left(PP_m \, t_{n,m} \right) \right] \qquad \text{(Eq. 6.13-7)}$$

where

$D_{inh,p,i}$ = annual dose from inhalation exposure to primary radionuclide i in resuspended particles (Sv/yr)

$D_{inh,p,l}$ = annual dose from inhalation exposure to long-lived radionuclide l in a decay chain of primary radionuclide i in resuspended particles (Sv/yr)

l = radionuclide index for a decay chain, $l = 0$ for primary radionuclide, 1 for the first long-lived decay product, 2 for the second long-lived decay product

$EDCF_{inh,l}$ = effective dose coefficient for inhalation of long-lived radionuclide l in a decay chain of primary radionuclide i (Sv/Bq). Calculation of effective dose coefficients is discussed in Section 6.4.8.5.

n = environment index; $n = 1$ for active outdoors, 2 for inactive outdoors, 3 for active indoors, 4 for asleep indoors, and 5 for away from the contaminated area

$Ca_{h,l,n}$ = activity concentration of radionuclide l in a decay chain of primary radionuclide i in air for environment n (Bq/m^3)

BR_n = breathing rate for environment n (m^3/h)

m = population group index; m = 1 for local outdoor workers, 2 for local indoor workers, 3 for commuters, and 4 for nonworkers

PP_m = fraction of the total population in population group m (population proportion) (dimensionless)

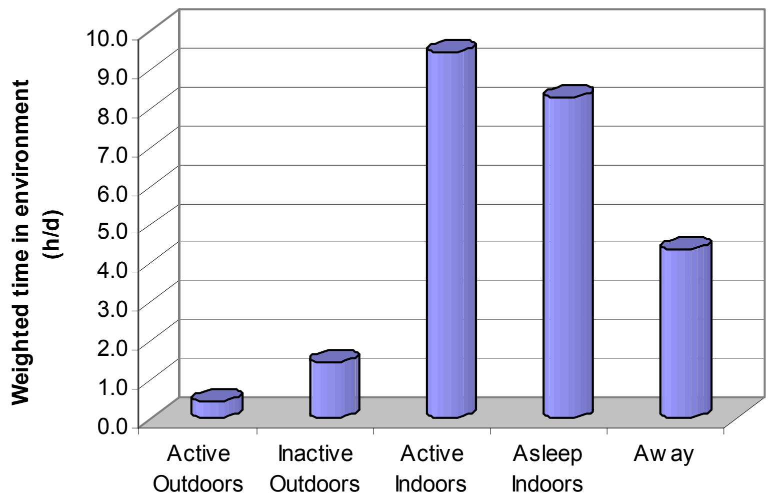
$t_{n,m}$ = annual amount of time that population group m spends in environment n (exposure time) (h/yr).

The dose from inhalation of particulate matter in a given receptor environment is calculated as a product of radionuclide concentration in air, breathing rate, and time spent in that environment.

The activity concentration in air, $Ca_{h,l,n}$, is an environment-specific quantity that depends on the level of soil-disturbing and dust-generating activities that are conducted in an environment and on the level of increase of mass activity concentration of resuspended material relative to the mass activity concentration of the surface soil. These parameters were discussed in Section 6.13.4.2. Mass loading was developed based on measurements of resuspended particulate concentrations in environments or conditions analogous to those considered in the biosphere model (BSC 2006 [DIRS 177101], Section 6.2). The active outdoor environment is characterized by the highest mass loading levels of all receptor environments. However, the enhancement factor, the parameter that quantifies a ratio of mass activity concentration of resuspended material relative to the mass activity concentration of the surface soil, is the lowest in the active outdoor environment. The mass loading in the active indoor environment is the second highest and the enhancement factor is higher than that for the active outdoor environment, which causes a relatively high inhalation dose for this environment (Excel file *Detailed Pathway Analysis GW_PDC.xls*, Appendix A).

Inhalation exposure for an environment depends on the time spent in this environment by the receptor. Since the receptor for the biosphere model is a hypothetical individual representative of different population groups living in Amargosa Valley, the time spent in an environment is weighted by the population proportions for individual population group. Population groups are mutually exclusive fractions of the Amargosa Valley population that constitute the hypothetical receptor and are described in detail in *Characteristics of the Receptor for the Biosphere Model* (BSC 2005 [DIRS 172827], Section 6.3.1). In Equation 6.13-7, the weighted time spent in an environment is represented by the product of PP_m and $t_{n,m}$. Population proportions, PP_m, were developed from 2000 census data (BSC 2005 [DIRS 172827], Section 6.3.1). Time spent in an environment by a population group, $t_{n,m}$, was calculated based on 2000 census data for the residents of Amargosa Valley (BSC 2005 [DIRS 172827], Section 6.3.2).

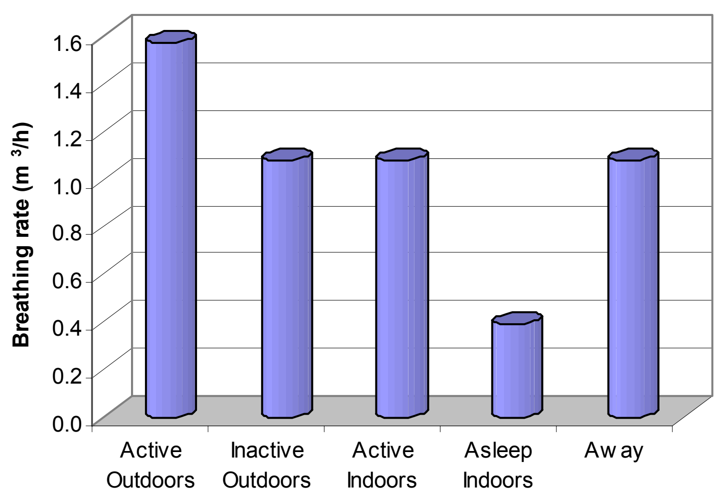
Figure 6.13-32 shows the population-weighted time for all receptor environments. The receptor spends relatively few hours per day active outdoors (0.45 h) and inactive outdoors (1.45 h) and most time indoors (9.45 h active and 8.3 h asleep). Despite this receptor behavior pattern, inhalation exposure in the active outdoor environment is dominant because of the high level of airborne particulates in that environment.



Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

Figure 6.13-32. Average Weighted Time Spent in the Receptor Environments for the Groundwater Exposure Scenario

Another factor affecting radionuclide intake by inhalation, and thus inhalation dose, is the breathing rate. Breathing rate in the biosphere model is also environment-dependent and is highest in the active outdoor environment, as illustrated in Figure 6.13-33.

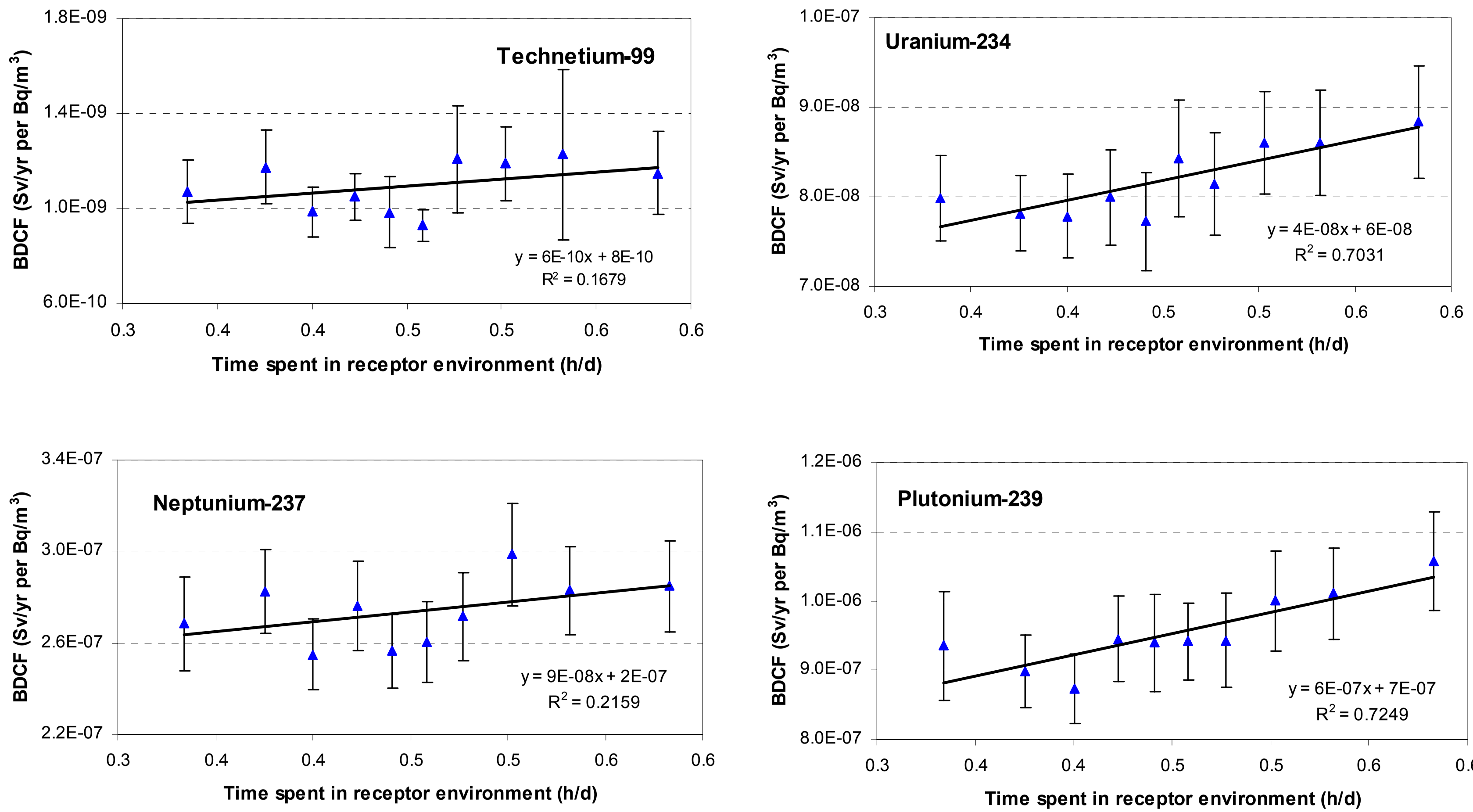


Source: Excel file *Detailed Pathway Analysis GW_PDC.xls* (Appendix A).

Figure 6.13-33. Breathing Rates in the Receptor Environments

Breathing rates for the receptor environments correspond to the activities and exercise levels expected in an environment and were adopted from the reference values reported in International Commission on Radiological Protection Publication 66 (ICRP 1994 [DIRS 153705]), as described in *Characteristics of the Receptor for the Biosphere Model* (BSC 2005 [DIRS 172827], Section 6.3.3).

The correlation statistics presented in Table 6.13-3 indicate that there are only a few receptor related parameters used in the calculation of the inhalation dose that affect the variance in BDCFs. One of these parameters is the time spent in the active outdoor environment by non-workers and commuters. These two groups are by far the most common among Amargosa Valley residents, accounting, on average, for over 78% of the population (Excel files *Detailed Pathway Analysis GW_PDC.xls*, Appendix A). The times spent outdoors by these two groups are included in the calculation of the weighted time ($PP_m \times t_{n,m}$ in Equation 6.13-7) and significantly influence its value. The dependence of the BDCFs for selected radionuclides on the value of the weighted time in the active outdoor environment is graphically shown in Figure 6.13-34. The BDCFs for ^{234}U, ^{237}Np, and ^{239}Pu, used here as examples, depend relatively strongly on the value of this parameter, especially ^{239}Pu. The dependence of the BDCF for the same radionuclide on the time spent in the other environments is weaker than that for the active outdoor environment. The environment that has the second strongest dependence of the BDCFs on the exposure time is the active indoor environment (Excel file *Dependence of GW BDCFs on Inputs_Part 3.xls*, Appendix A).



Source: Excel file *Dependence of GW BDCFs on Inputs_Part 3.xls* (Appendix A).

NOTE: The triangles represent the mean of 100 values. The error bars represent the uncertainty range for the mean at the 95% uncertainty interval, calculated as 1.96 times the standard error of the mean. The outlier point with a high BDCF value for ^{99}Tc was removed to better show the trend in the BDCFs for this radionuclide as a function of time spent in an environment.

Figure 6.13-34. Dependence of the BDCFs for Selected Radionuclides on the Population Weighted Time Spent in the Active Outdoor Environment

6.13.5.2.2 Inhalation of Aerosols Generated by Evaporative Coolers

Inhalation of aerosols generated by evaporative coolers is another pathway leading to inhalation exposure. This type of inhalation exposure occurs only in the indoor environments, that is, when the RMEI is active indoors and asleep, and only while evaporative coolers are being used. The importance of this pathway is greatly reduced for the cooler climates (Tables 6.13-1 and 6.13-2).

The inhalation dose from airborne aerosols generated by evaporative coolers is calculated as (Equation 6.4.8-3):

$$D_{inh,e,i} = EDCF_{inh,i}\ Ca_{e,i}\ f_{cooler}\ f_{use} \sum_{n=3}^{4} BR_n \left(\sum_{m} PP_m\ t_{n,m} \right) \qquad \text{(Eq. 6.13-8)}$$

where

$D_{inh,e,i}$ = annual dose from inhalation of primary radionuclide i from evaporative cooler operation (Sv/yr)

$EDCF_{inh,i}$ = effective dose coefficient for inhalation of radionuclide i (Sv/Bq)

$Ca_{e,i}$ = activity concentration of radionuclide i in indoor air attributable to the evaporative cooler operation (Bq/m^3)

n = environment index (n = 3 or n = 4 denotes an indoor environment)

f_{cooler} = fraction of houses with evaporative coolers (dimensionless)

f_{use} = annual evaporative cooler use factor (dimensionless)

and the other parameters are defined in Equation 6.4.8-2.

The fraction of houses with evaporative coolers is a site-specific parameter that was developed from the results of a survey of Amargosa Valley residents. The value of the annual evaporative cooler use factor was based on local temperatures. The distributions of these parameters represent realistic, site-specific conditions (BSC 2005 [DIRS 172827], Section 6.3.4).

The parameters used to calculate the inhalation dose from aerosols generated by evaporative coolers contribute to the variance in the BDCFs for some radionuclides, particularly actinides. The parameter that accounts for the largest fraction of the BDCF variance is the evaporative cooler water transfer fraction, which was discussed in Section 6.13.4.2.1. Parameters that depend on the receptor behaviors, such as time spent indoors where exposure occurs, are not significant contributors to the BDCF variance (Table 6.13-3).

6.13.5.3 External Exposure

External exposure is an important pathway for only a few radionuclides having a BDCF contribution greater than 20% only for ^{126}Sn, ^{137}Cs, ^{232}Th, and ^{232}U (Tables 6.13-1 and 6.13-2). The dose from external exposure depends on radionuclide concentrations in the soil (discussed in

Section 6.13.4.1) and the duration of receptor exposure to the soil, modified by the building shielding factor, while indoors (Equation 6.4.7-1). There is little variability in this component because the receptor is assumed to be exposed to contaminated soil at all times, except for the time spent away by commuters (an average of 8 h/d), and an annual average of 2 h/d spent away by the other population groups.

6.14 UNCERTAINTY AND SENSITIVITY ANALYSIS FOR VOLCANIC BIOSPHERE DOSE CONVERSION FACTORS

6.14.1 Distributions of Biosphere Dose Conversion Factors

This section evaluates the distributions of the BDCF components for the volcanic ash exposure scenario for radionuclides included in the biosphere model for this scenario, examines trends in the BDCFs, and evaluates the causes of these trends. Each run of the biosphere model for the volcanic ash exposure scenario for a given radionuclide produced 1,000 model realizations, with the realization results in the form of three BDCF components.

The following expression that combines the source terms (calculated in the TSPA model) and the BDCF components (provided by the biosphere model) is used to calculate the annual dose to the RMEI for the volcanic ash exposure scenario, conditional upon an eruption (Equation 6.12-1):

$$D_{all\ pathway,i}(t,T) = BDCF_{ext,ing,Rn,i}\ Cs_i(t) + \left(BDCF_{inh,v,i}\, f(t-T) + BDCF_{inh,p,i}\right) Cs_{mc,i}(t)$$

(Eq. 6.14-1)

where

$D_{all\ pathway,\ i}(t,T)$ = all-pathway annual dose for primary radionuclide *i* at time *t* (yr) after the repository closure, conditional on a volcanic eruption at time *T* (yr), where $t > T$ (Sv/yr)

$BDCF_{ext,ing,Rn,i}$ = BDCF component for external exposure, ingestion, and inhalation of radon decay products for primary radionuclide *i* (Sv/yr per Bq/m^2)

$Cs_i(t)$ = areal radionuclide concentration in a specified depth of surface soil at time *t* (yr) after the repository closure (Bq/m^2) calculated in TSPA model

$BDCF_{inh,v,i}$ = BDCF component representing annual inhalation exposure in the first year after a volcanic eruption; used in calculation of short-term inhalation exposure at post-eruption level of mass loading in excess of nominal mass loading for primary radionuclide *i* (Sv/yr per Bq/kg)

$BDCF_{inh,p,i}$ = BDCF component for long-term inhalation at nominal level of mass loading for primary radionuclide *i* (Sv/yr per Bq/kg)

$f(t\text{-}T)$ = decay function describing reduction of the annual average mass loading with time at time $t\text{-}T$ following a volcanic eruption

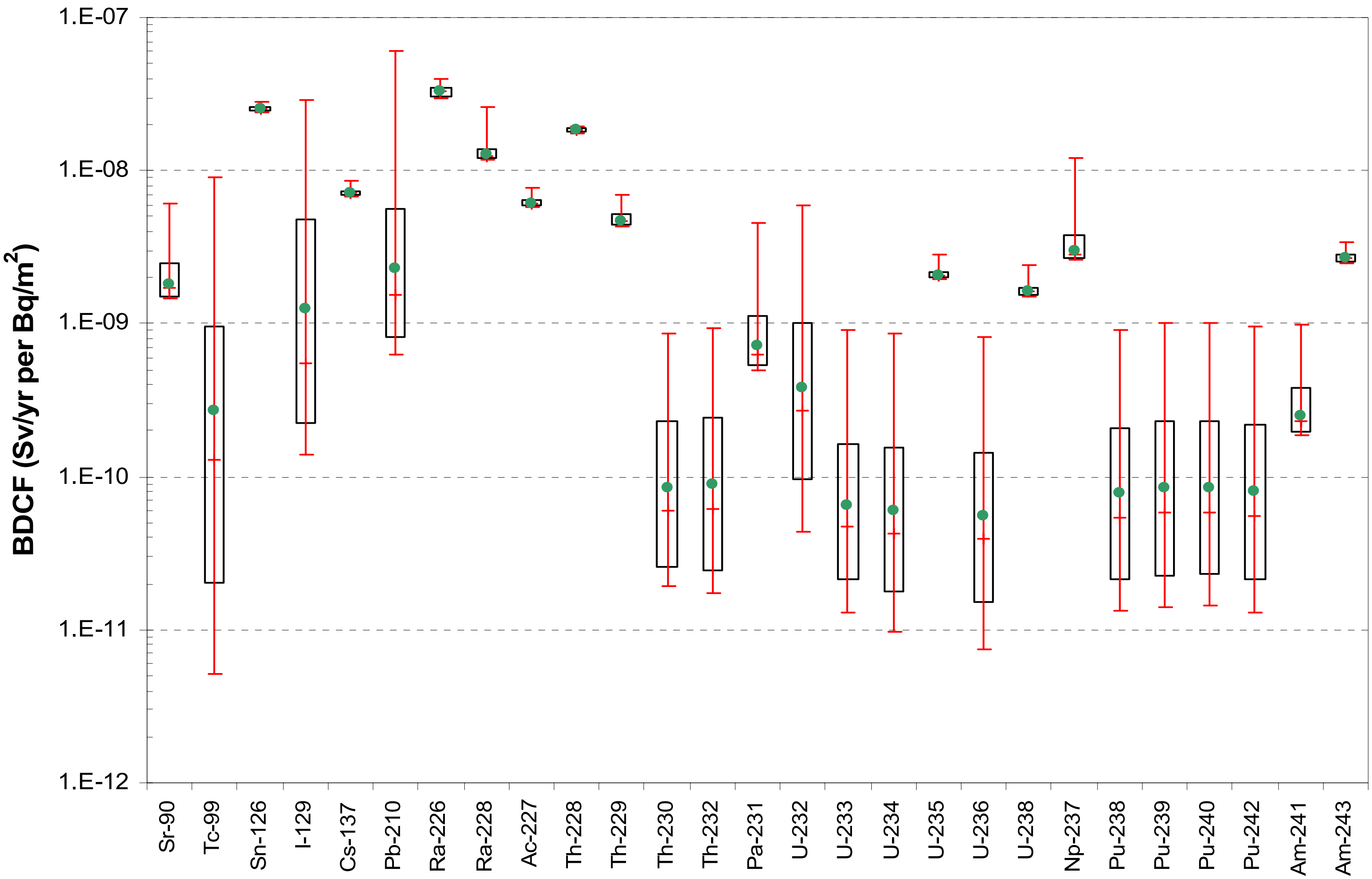
$Cs_{mc,i}(t)$ = activity concentration of radionuclide i per unit mass of soil in the resuspendable layer of surface soil (critical thickness) at time t (yr) after the repository closure calculated in TSPA model from the Fortymile-wash Ash Redistribution model (FAR) waste concentrations (Bq/kg).

The first component, $BDCF_{ext,ing,Rn,i}$, accounts for exposure to sources external to the body, ingestion, and inhalation of radon decay products. The second and third BDCF components account for inhaling airborne particulates. The term $BDCF_{inh,v,i}$ is numerically equal to the inhalation exposure, in excess of the long-term steady-state inhalation exposure, during the first year following a volcanic eruption. This term is used together with the time function (Equation 6.14-1) to calculate the short-term increase in inhalation exposure, due to elevated levels of airborne particulate matter, after a volcanic eruption, relative to the conditions existing before and long after an eruption. With time, mass loading returns to the pre-eruption level, as prescribed by the decay function $f(t\text{-}T)$. These steady-state conditions are described by the term $BDCF_{inh,p,i}$, which represents long-term inhalation of resuspended particulates under nominal conditions, i.e., when the mass loading is not elevated as the result of volcanic eruption.

Figures 6.14-1 to 6.14-3 show the ranges of the three BDCF components for all primary radionuclides included in the biosphere model for the volcanic ash scenario, including their mean and median values, minima and maxima, and the 5th and 95th percentiles. The figures were generated in the Excel workbook *VA BDCF Variability Plots.xls* (Appendix A). The variance in the BDCFs is a result of the input parameter variability and uncertainty that is propagated into the model output.

A number of trends can be observed in the BDCF values. The variability in the ingestion-radon-external exposure BDCF component differs greatly among radionuclides. The 95th to 5th percentile ratio varies from 1.1 to 46.8 (the highest value is for ^{99}Tc; the second highest value of 21.8 is for ^{129}I). The maximum values are higher than the minima by less than two orders of magnitude for most radionuclides. The highest maximum to minimum ratio is for ^{99}Tc (equal to 1,762); the second highest is or ^{129}I (equal to 205). There are a few radionuclides that have a very narrow distribution for the ingestion-radon-external exposure BDCF component. These are the radionuclides, such as ^{126}Sn and ^{137}Cs that have a large fraction of this BDCF component attributable to the external exposure pathway.

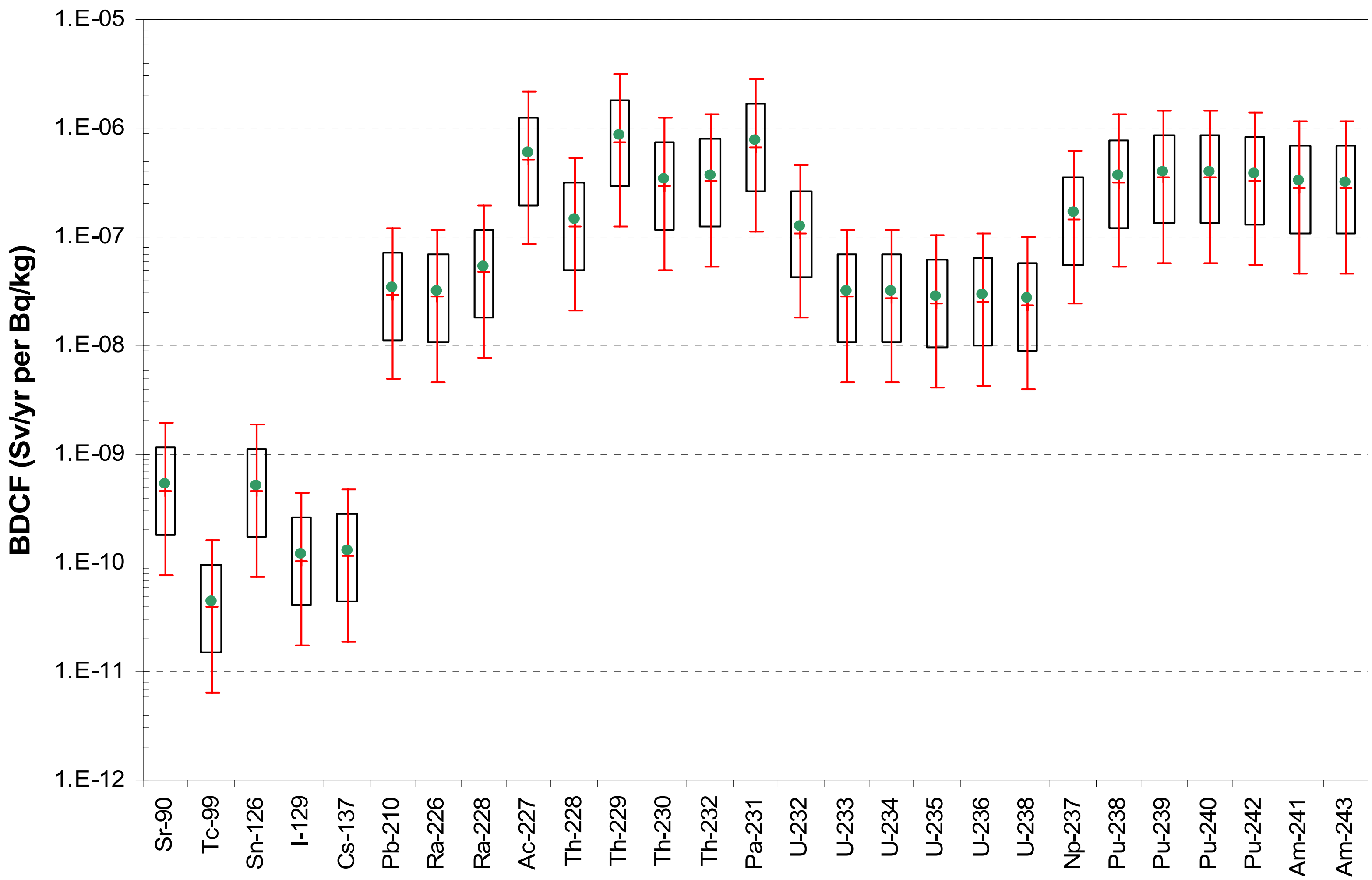
Input parameters used to calculate BDCF distributions for the short-term and long-term inhalation components differ among radionuclides only by the value of the inhalation dose coefficient, which is a fixed parameter. Thus, this parameter is a scaling factor and the range and variation of these BDCFs are the same for all radionuclides. For all short-term BDCF components, the ratio of the 95th to 5th percentile is 6.4 and the maximum to minimum ratio is 25.3. The corresponding values for the long-term inhalation component are 6.7 and 29.4, respectively.



Source: Excel file *VA BDCF Variability Plots.xls* (Appendix A).

NOTE: Boxes represent 5th to 95th percentile range. The vertical solid lines represent the range and the tick mark on the line is the median. Dots represent the mean BDCF.

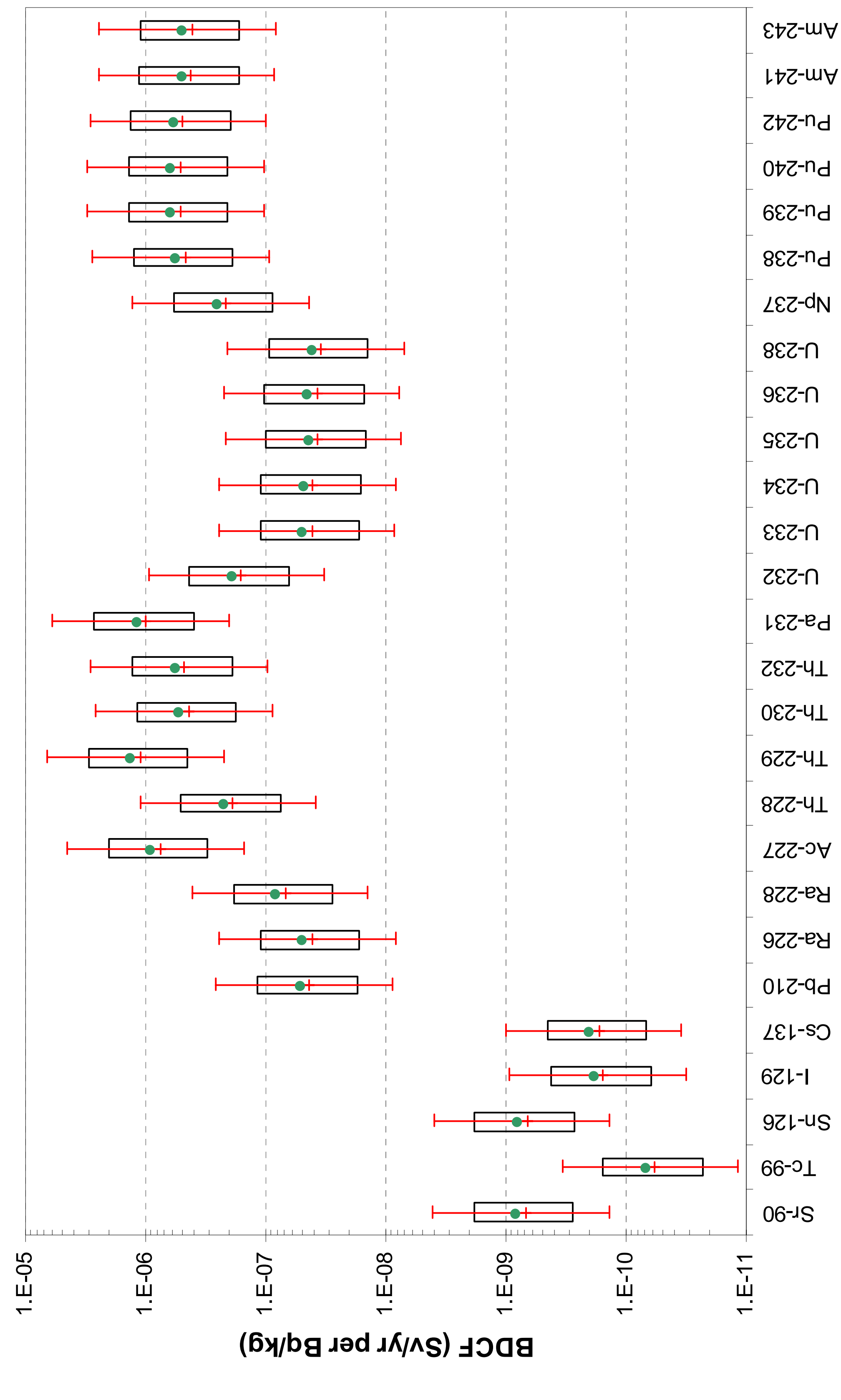
Figure 6.14-1. Distributions of the Ingestion-Radon-External Exposure Component of the BDCFs for the Volcanic Ash Exposure Scenario



Source: Excel file *VA BDCF Variability Plots.xls* (Appendix A).

NOTE: Boxes represent 5th to 95th percentile range. The vertical solid lines represent the range and the tick mark on the line is the median. Dots represent the mean BDCF.

Figure 6.14-2. Distributions of the Short-Term Inhalation Component of the BDCFs for the Volcanic Ash Exposure Scenario



Source: Excel file *VA BDCF Variability Plots.xls* described in Appendix A.

NOTE: Boxes represent 5th to 95th percentile range. The vertical solid lines represent the range and the tick mark on the line is the median. Dots represent the mean BDCF.

Figure 6.14-3. Distributions of the Long-Term Inhalation Component of the BDCFs for the Volcanic Ash Exposure Scenario

6.14.2 Summary of Pathway Analysis

The pathway analysis identifies those pathways that are important contributors to the BDCF components. The biosphere model for the volcanic ash exposure scenario includes 12 exposure pathways. The pathways related to groundwater contamination—such as water consumption, consumption of aquatic food, and inhalation of aerosols from evaporative coolers—are not included because contamination of water is modeled in the groundwater exposure scenario. Pathway analysis was conducted, using the mean values of the BDCFs, to determine the relative importance of individual exposure pathways in terms of their contributions to BDCFs for various radionuclides.

To calculate the annual dose, the BDCF components are combined in the TSPA model with the time dependent source terms and the mass loading decay function (Equation 6.14-1). Because the source terms and the corresponding BDCF components for the particulate inhalation and for the remaining pathways are calculated independently, the pathway contributions for all exposure pathways cannot be combined. Therefore, the remainder of this section addresses only the BDCF component that includes external exposure, ingestion, and inhalation of radon decay products although it is expected that particulate inhalation would be a dominant pathway for the radionuclide with the mass number greater than 88, as was the case for the groundwater exposure scenario. This pathway is represented by the separate BDCF components.

The pathway contributions to the mean BDCF component for external exposure, ingestion, and inhalation of radon decay products are shown Table 6.14-1. The differences between the volcanic ash scenario BDCFs for the present-day and future climates are insignificant (Section 6.12.1.2).

Because the particulate inhalation BDCF components (long-term and short-term inhalation) are calculated using a different source term (1 Bq/kg) from that used to generate the BDCF component accounting for external exposure, ingestion, and inhalation of radon decay products (1 Bq/m^2), it is not possible to combine these exposure pathways without making an assumption about the depth distribution of radionuclides in the soil. To combine the pathway analyses and to put into perspective their relative significance, an assumption was made that the radionuclide concentration in the surface soil is uniformly distributed. Under such conditions, radionuclide concentration in the soil used in the model for calculation of inhalation exposure would be the same as the radionuclide concentration in the soil used for the root uptake by crops. For the uniform distribution of 1 Bq/m^2, the radionuclide concentration per unit mass is 4.80×10^{-3} Bq/kg (average value from GoldSim runs of the model for the volcanic ash exposure scenario). The percent pathway contributions under such conditions are listed in Table 6.14-2. The results indicate that inhalation of particulates is an important pathway for most actinides. Pathway contributions for the other radionuclides are more diverse.

Table 6.14-1. Exposure Pathway Contributions (%) for the Mean BDCF Components for External Exposure, Ingestion, and Inhalation of Radon Decay Products for the Volcanic Ash Exposure Scenario for the Present-Day Climate

Radionuclide	Radon	Leafy Vegetables	Other Vegetables	Fruit	Grain	Meat	Milk	Poultry	Eggs	Soil	External
^{90}Sr	0.0	5.0	3.7	5.0	0.4	2.2	2.8	0.0	1.1	0.3	79.5
^{99}Tc	0.0	23.0	5.0	19.0	1.2	9.7	22.2	0.3	19.4	0.0	0.2
^{126}Sn	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	99.8
^{129}I	0.0	3.0	1.8	6.1	2.1	9.6	14.2	0.9	52.4	1.7	8.2
^{137}Cs	0.0	0.0	0.0	0.1	0.0	0.3	0.2	0.2	0.2	0.0	98.8
^{210}Pb	0.0	9.3	4.1	17.5	1.0	2.0	1.3	0.8	26.6	16.4	21.0
^{226}Ra	33.2	0.2	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.2	66.1
^{228}Ra	0.0	1.1	0.6	1.1	0.1	0.2	0.3	0.0	0.0	1.1	95.5
^{227}Ac	0.0	0.4	0.1	0.4	0.0	0.1	0.0	0.0	0.0	1.4	97.5
^{228}Th	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	99.7
^{229}Th	0.0	0.9	0.2	0.8	0.1	0.2	0.0	0.0	0.1	2.7	95.0
^{230}Th	0.0	16.2	3.8	14.2	1.5	4.0	0.1	0.4	2.5	49.6	7.8
^{232}Th	0.0	16.8	4.0	14.8	1.6	4.1	0.1	0.4	2.6	51.6	4.0
^{231}Pa	0.0	4.5	2.5	9.4	0.8	1.1	0.0	0.0	0.1	13.3	68.4
^{232}U	0.0	6.3	2.9	11.5	0.7	2.0	2.7	9.6	44.7	17.3	2.2
^{233}U	0.0	5.7	2.7	10.3	0.6	1.8	2.4	8.6	40.3	15.6	11.9
^{234}U	0.0	6.0	2.8	10.8	0.6	1.9	2.6	9.1	42.2	16.4	7.7
^{235}U	0.0	0.2	0.1	0.3	0.0	0.1	0.1	0.2	1.2	0.5	97.5
^{236}U	0.0	6.2	2.9	11.2	0.6	1.9	2.6	9.3	43.5	16.9	4.9
^{238}U	0.0	0.2	0.1	0.4	0.0	0.1	0.1	0.3	1.5	0.6	96.7
^{237}Np	0.0	1.0	0.8	5.6	0.1	0.5	0.0	0.0	0.0	0.7	91.2
^{238}Pu	0.0	15.9	3.4	15.2	1.6	0.5	0.0	0.1	1.3	57.8	4.3
^{239}Pu	0.0	16.1	3.4	15.3	1.6	0.5	0.0	0.1	1.3	58.3	3.5
^{240}Pu	0.0	16.0	3.4	15.2	1.6	0.5	0.0	0.1	1.3	58.1	3.7
^{242}Pu	0.0	16.1	3.4	15.3	1.6	0.5	0.0	0.1	1.3	58.4	3.3
^{241}Am	0.0	4.6	1.0	4.5	0.4	0.4	0.0	0.1	0.3	16.0	72.8
^{243}Am	0.0	0.4	0.1	0.4	0.0	0.0	0.0	0.0	0.0	1.5	97.4

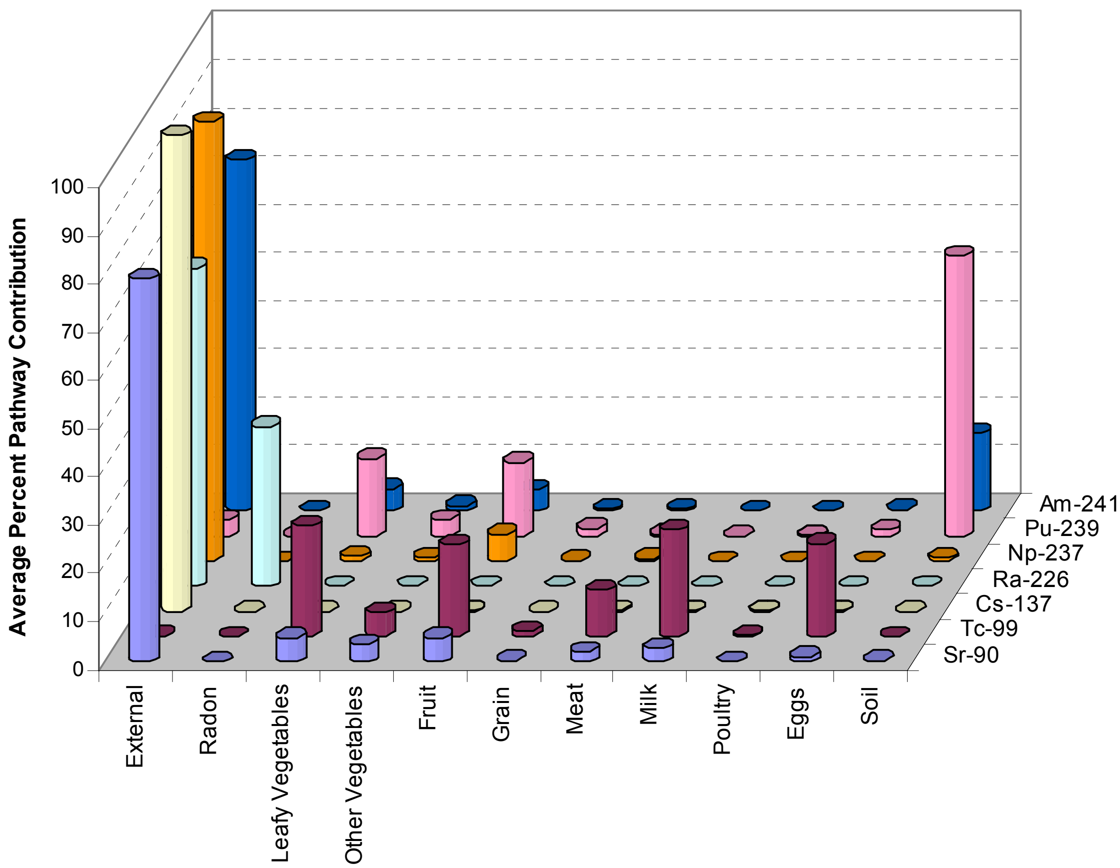
Source: Excel file *VA BDCF Pathway Analysis.xls* (Appendix A)

Table 6.14-2. Exposure Pathway Contributions (%) for the Mean BDCFs for the Volcanic Ash Exposure Scenario for the Present-Day Climate Assuming Uniform Radionuclide Concentration in Surface Soil

Radio-nuclide	External	Inhalation			Ingestion								
					Vegetables								
		Short	Long	Radon	Leafy	Other	Fruit	Grain	Meat	Milk	Poultry	Eggs	Soil
^{90}Sr	79.2	0.1	0.2	0.0	4.9	3.7	5.0	0.4	2.2	2.8	0.0	1.1	0.3
^{99}Tc	0.2	0.1	0.1	0.0	22.9	5.0	19.0	1.2	9.6	22.2	0.3	19.4	0.0
^{126}Sn	99.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
^{129}I	8.2	0.0	0.1	0.0	3.0	1.8	6.1	2.1	9.6	14.2	0.9	52.3	1.7
^{137}Cs	98.8	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.3	0.2	0.2	0.2	0.0
^{210}Pb	17.8	6.0	9.2	0.0	7.9	3.5	14.9	0.9	1.7	1.1	0.6	22.6	13.9
^{226}Ra	65.3	0.5	0.7	32.8	0.2	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.2
^{228}Ra	90.8	1.9	3.0	0.0	1.0	0.6	1.1	0.1	0.2	0.3	0.0	0.0	1.0
^{227}Ac	45.2	21.1	32.5	0.0	0.2	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.6
^{228}Th	91.1	3.4	5.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
^{229}Th	29.6	27.1	41.7	0.0	0.3	0.1	0.2	0.0	0.1	0.0	0.0	0.0	0.8
^{230}Th	0.2	38.6	59.4	0.0	0.3	0.1	0.3	0.0	0.1	0.0	0.0	0.1	1.0
^{232}Th	0.1	38.6	59.4	0.0	0.3	0.1	0.3	0.0	0.1	0.0	0.0	0.1	1.0
^{231}Pa	4.8	36.6	56.3	0.0	0.3	0.2	0.7	0.1	0.1	0.0	0.0	0.0	0.9
^{232}U	0.4	31.4	48.3	0.0	1.3	0.6	2.3	0.1	0.4	0.5	1.9	9.1	3.5
^{233}U	1.7	33.8	52.0	0.0	0.8	0.4	1.5	0.1	0.3	0.3	1.2	5.7	2.2
^{234}U	1.0	34.1	52.4	0.0	0.8	0.4	1.5	0.1	0.3	0.3	1.2	5.7	2.2
^{235}U	83.5	5.7	8.7	0.0	0.1	0.1	0.3	0.0	0.0	0.1	0.2	1.0	0.4
^{236}U	0.6	34.1	52.5	0.0	0.8	0.4	1.5	0.1	0.3	0.4	1.2	5.8	2.3
^{238}U	80.5	6.6	10.2	0.0	0.2	0.1	0.3	0.0	0.1	0.1	0.3	1.3	0.5
^{237}Np	54.4	15.9	24.5	0.0	0.6	0.5	3.4	0.1	0.3	0.0	0.0	0.0	0.4
^{238}Pu	0.1	38.7	59.5	0.0	0.3	0.1	0.3	0.0	0.0	0.0	0.0	0.0	1.0
^{239}Pu	0.1	38.7	59.6	0.0	0.3	0.1	0.3	0.0	0.0	0.0	0.0	0.0	1.0
^{240}Pu	0.1	38.7	59.6	0.0	0.3	0.1	0.3	0.0	0.0	0.0	0.0	0.0	1.0
^{242}Pu	0.1	38.7	59.6	0.0	0.3	0.1	0.3	0.0	0.0	0.0	0.0	0.0	1.0
^{241}Am	4.4	37.0	57.0	0.0	0.3	0.1	0.3	0.0	0.0	0.0	0.0	0.0	1.0
^{243}Am	39.7	23.4	35.9	0.0	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.6

Source: Excel file *VA BDCF Pathway Analysis.xls* (Appendix A)

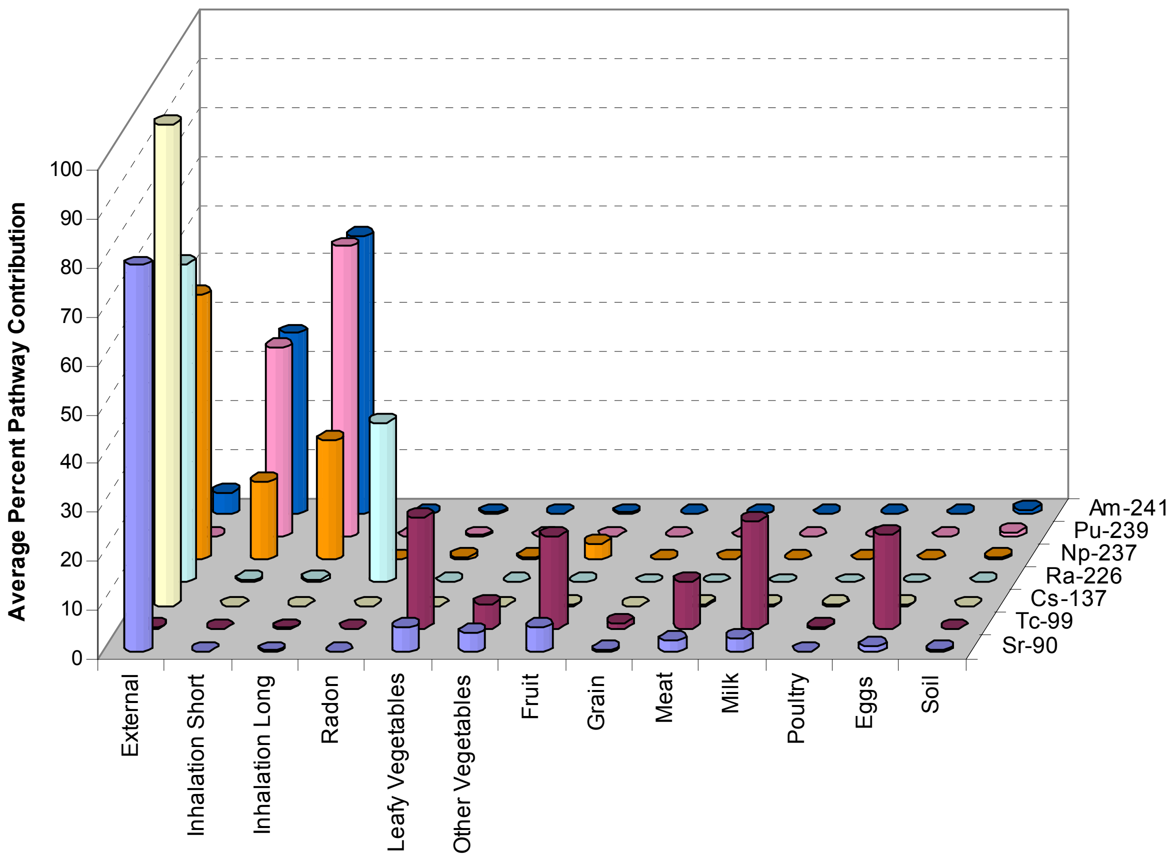
Figure 6.14-4 shows the average pathway contributions for the external exposure-ingestion-inhalation of radon decay products BDCF component (from Table 6.14-1) for several selected radionuclides (Excel file *Detailed Pathway Analysis VA.xls* in Appendix A). The selection includes the radionuclides that were identified as important in previous TSPA efforts, such as ^{90}Sr, ^{137}Cs, ^{237}Np, ^{239}Pu, and ^{241}Am. Technetium-99 and ^{226}Ra were added to the list as an example of a radionuclide with a notably different composition of pathway contributions. For most radionuclides, external exposure is the dominant pathway for that BDCF component with a contribution of more than 50% in 11 of the 27 cases. This is caused, in part, by assuming that radionuclides released from the repository during a volcanic eruption remain on the soil surface (Assumption 16 in Section 6.3.2.4) and thus their radiations are not attenuated. The contributions of the remaining pathways for ^{90}Sr and ^{99}Tc are quite diverse, and there is no dominant contributor. For ^{137}Cs, external exposure accounts for 99% of the dose. The BDCF for ^{226}Ra includes a large contribution from exposure to radon decay products (33%). Ingestion is an unimportant exposure pathway for most radionuclides.



Source: Excel file *Detailed Pathway Analysis VA.xls* (Appendix A).

Figure 6.14-4. Average Percent Pathway Contributions to Volcanic Ash Scenario BDCF Components for External Exposure, Ingestion, and Inhalation of Radon Decay Products

Figure 6.14-5 shows a graph of BDCF pathway contributions assuming uniform radionuclide concentration in the surface soil for selected radionuclides. For ^{90}Sr and ^{137}Cs, external exposure is the most important pathway. Inhalation of particulate matter dominates for ^{239}Pu and ^{241}Am as well as for ^{226}Ra. The latter has a significant contribution from inhalation of radon decay products. Neither of these pathways is important for ^{99}Tc, whose dose is dominated by the ingestion pathways.



Source: Excel file *Detailed Pathway Analysis VA.xls* (Appendix A).

Figure 6.14-5. Average Percent Pathway Contributions to Volcanic Ash Scenario BDCF Pathway Components Assuming Uniform Radionuclide Concentration in Surface Soil

6.14.3 Sources of Uncertainty in the Biosphere Dose Conversion Factors

The source of variance in the BDCF components (Figures 6.14-1 to 6.14-3) is the uncertainty and variability in the values of the input parameters for the biosphere model. This section discusses the degree to which selected input parameters influence the BDCFs. This was quantified by calculating correlation coefficients. A correlation coefficient is a number between -1 and 1 that measures the degree to which two variables are linearly related.

Correlation coefficients for the stochastic model input parameters and BDCF components for the volcanic ash exposure scenario were calculated for the selected radionuclides (Excel file *VA Correlations.xls*, Appendix A). Of the radionuclides considered in the biosphere model, ^{90}Sr, ^{99}Tc, ^{137}Cs, and ^{241}Am were selected as examples of radionuclides with the diversified pathway contributions (Tables 6.14-1 and 6.14-2). The correlation coefficients for the BDCF component for external exposure, ingestion, and inhalation of radon decay products were calculated for these radionuclides and are presented in Table 6.14-3 (Excel file *VA Correlations.xls*, Appendix A). Only those correlations that are non-zero at the 99% confidence interval (absolute value of the correlation coefficient equal or greater than 0.0812) are shown in the table. The list includes the "false" correlations that were above the threshold value (shaded cells), as explained in Section 6.13.3.

Table 6.14-3. Correlation Coefficients for Input Parameters and the BDCF Component for External Exposure, Ingestion, and Inhalation of Radon Decay Products

Radionuclide	Parameter	Correlation Coefficient	
		Value (Pearson)	Rank (Spearman)
^{90}Sr	Strontium transfer factor for fruit	0.543	0.616
	Strontium transfer factor for leafy vegetables	0.521	0.652
	Strontium transfer factor for other vegetables	0.490	0.603
	Surface soil depth	-0.488	-0.539
	Strontium transfer factor for forage	0.455	0.632
	Strontium transfer factor for grain	0.443	0.547
	Strontium partition coefficient (K_d)	-0.321	-0.682
	Strontium transfer coefficient for meat	0.162	0.113
	Soil density	-0.114	-0.116
	Dry-to-wet weight ratio for fruit	0.111	0.096
	Actinium transfer factor for other vegetables	0.099	
	Enhancement factor for active indoor environment	-0.086	
	Time spent inactive outdoors, commuters	-0.085	
	Consumption rate for leafy vegetables	0.084	
	Uranium transfer coefficient for eggs	0.082	
	Dry-to-wet weight ratio for leafy vegetables		0.099
	Time spent away by indoor workers		-0.087
	Tin transfer coefficient for eggs		-0.084
	Cesium transfer factor for cattle forage		-0.083

Table 6.14-3. Correlation Coefficients for Input Parameters and the BDCF Component for External Exposure, Ingestion, and Inhalation of Radon Decay Products (Continued)

Radionuclide	Parameter	Correlation Coefficient Value (Pearson)	Correlation Coefficient Rank (Spearman)
^{99}Tc	Technetium transfer factor for grain	0.447	0.676
	Technetium transfer factor for forage	0.394	0.677
	Technetium transfer factor for leafy vegetables	0.360	0.700
	Technetium transfer factor for fruit	0.348	0.678
	Soil depth	-0.279	-0.350
	Technetium transfer factor for other vegetables	0.272	0.607
	Technetium transfer coefficient for milk	0.235	0.199
	Technetium partition coefficient (K_d)	-0.175	-0.759
	Technetium transfer coefficient for meat	0.170	0.097
	Protactinium transfer factor for leafy vegetables	0.112	
	Americium transfer factor for fruit	0.107	
	Radium transfer factor for other vegetables	0.094	
	Protactinium transfer coefficient for milk	0.094	
	Consumption rate for eggs	0.093	
	Soil density	-0.093	
^{137}Cs	Cesium transfer coefficient for poultry	0.377	0.160
	Population fraction, outdoor workers	0.338	0.375
	Time spent away, indoor workers	-0.300	-0.342
	Time spent away, non-workers	-0.288	-0.324
	Population fraction, commuters	-0.276	-0.312
	Time spent inactive outdoors, indoor workers	0.256	0.288
	Cesium transfer factor for forage	0.250	0.207
	Soil depth	-0.219	-0.192
	Cesium transfer coefficient for eggs	0.197	0.093
	Cesium transfer factor for grain	0.197	0.199
	Time spent inactive outdoors, non-workers	0.185	0.218
	Cesium transfer factor for fruit	0.169	0.183
	Cesium transfer factor for other vegetables	0.146	0.162
	Time spent active outdoors, indoor workers	0.136	0.155
	Cesium transfer factor for leafy vegetables	0.131	0.179
	Cesium partition coefficient (K_d)	-0.117	-0.217
	Time spent active outdoors, non-workers	0.112	0.150
	Cesium transfer coefficient for meat	0.099	
	Time spent away, commuters	-0.097	-0.102
	Technetium transfer coefficient for milk	-0.091	
	Deposition velocity		0.100
	Protactinium partition coefficient (K_d)		-0.096
	Protactinium transfer factor for cattle forage		0.092

Table 6.14-3. Correlation Coefficients for Input Parameters and the BDCF Component for External Exposure, Ingestion, and Inhalation of Radon Decay Products (Continued)

Radionuclide	Parameter	Correlation Coefficient	
		Value (Pearson)	Rank (Spearman)
^{137}Cs (Continued)	Animal feed intake, meat		0.090
	Protactinium transfer factor for other vegetables		0.083
	Enhancement factor for inactive outdoor environment		-0.083
	Protactinium transfer coefficient for milk		-0.082
	Cesium transfer coefficient for milk		0.082
^{241}Am	Deposition velocity	0.605	0.429
	Soil depth	-0.463	-0.660
	Soil consumption rate	0.187	0.382
	Mass loading for crops	0.121	0.094
	Selenium transfer coefficient for poultry	0.109	
	Weathering half-life	0.098	
	Radium transfer factor fro other vegetables	0.090	
	Translocation factor for other vegetables, fruits and grains	0.088	
	Consumption rate for other vegetables	0.085	
	Time spent away, nonworkers		-0.104
	Neptunium transfer coefficient for poultry		0.100

Source: Excel file *VA Correlations.xls* (Appendix A).

NOTE: Shaded cells contain false correlations.

For ^{90}Sr and ^{99}Tc, the highest correlations for the external exposure, ingestion, and inhalation of radon decay product BDCF component are with the parameters that control transfer of radioactivity to crops and radionuclide concentration in the surface soil. For these radionuclides, there is a strong positive correlation of BDCFs with the soil-to-pant transfer factors and a negative correlation with K_ds, soil depth and soil density. Correlation with the K_d is an artifact of having K_ds and transfer factors negatively correlated in the model because leaching is not a radionuclide removal mechanism that is included in the model for the volcanic ash exposure scenario, and thus K_d is not used.

The variance in the ingestion-radon-external exposure BDCF component for ^{137}Cs is influenced primarily by the weighted time spent in the receptor environments, which depends on the population proportions and time spent in the receptor environments by the population groups. A small fraction of the BDCF variance for ^{137}Cs is due to the parameters related to the ingestion pathways. Although consumption of crops is an unimportant pathway for ^{137}Cs, soil-to-plant transfer factors, soil depth, and the partition coefficient were correlated with the BDCF component for ingestion, inhalation of radon decay products, and external exposure. This is because the variation in those input parameters is large relative to variation in the input parameters used to calculate external exposure.

The correlation coefficients for both inhalation components for all radionuclides are presented in Table 6.14-4. Only those correlations that are non-zero at the 99% confidence interval (absolute value of the correlation coefficient equal or greater than 0.0812) are shown in the table. The correlation coefficients are the same for all radionuclides because the stochastic parameters that are used to calculate these BDCF components are radionuclide–independent.

Table 6.14-4. Correlation Coefficients for the Input Parameters and Inhalation Components of BDCFs

BDCF Component	Parameter	Correlation Coefficient	
		Value (Pearson)	Rank (Spearman)
Short-term Inhalation	Enhancement factor, active outdoor environment	0.734	0.712
	Ash mass loading, active outdoor environment	0.527	0.562
	Enhancement factor, active indoor environment	0.256	0.276
	Population proportion, outdoor workers	0.217	0.222
	Time spent active outdoors, indoor workers	0.159	0.143
	Time spent active outdoors, non-workers	0.148	0.159
	Time spent inactive outdoors, outdoor workers	-0.082	
	Ash mass loading, active indoor environment		0.097
	Dry biomass, other vegetables		0.085
	Technetium transfer coefficient for eggs		0.081
Long-term inhalation	Enhancement factor, active outdoor environment	0.701	0.702
	Mass loading, active outdoor environment	0.537	0.555
	Population proportion, outdoor workers	0.215	0.241
	Time spent active outdoors, indoor workers	0.187	0.162
	Enhancement factor, active indoor environment	0.143	0.179
	Time spent active outdoors, non-workers	0.133	0.173

Source: Excel file *VA Correlations.xls* (Appendix A).

For both inhalation components, air mass loading for the active outdoor environment and the enhancement factor for the same environment are among the input parameters with large contributions to the uncertainty in the BDCF values. Also important are the parameters that control inhalation exposure time, such as the population proportions and time spent in the receptor environments.

The results of previous TSPA assessments indicate that, except for the initial few hundred years postclosure, the expected dose from a volcanic eruption is primarily due to the transuranics. The majority of the following analysis concentrates on the processes that are important for these radionuclides.

6.14.4 Analysis of the Environmental Transport Pathways and Radionuclide Accumulation in the Environmental Media

The dose to the receptor from deposition of contaminated volcanic ash on the soil surface arises from the intake of and exposure to contaminated soil and other environmental media that become contaminated as a result of environmental transport of radionuclides from the soil (soil is the source medium in the biosphere model for the volcanic ash exposure scenario). The environmental media included in the biosphere model for that exposure scenario include surface soil, air, plants, and animals. For the volcanic ash exposure scenario, water is assumed uncontaminated. Surface soil becomes contaminated from the deposition and redistribution of volcanic ash. Airborne contamination is a result of resuspension of contaminated soil. Radionuclide accumulation in plants occurs as a result of transport from soil and air. Feed and soil are sources of radionuclide intake by animals. This section discusses calculation of radionuclide concentrations in the environmental media.

6.14.4.1 Radionuclide Accumulation in Surface Soil

In the volcanic exposure scenario, surface soil is a primary source of contamination for all environmental transport and receptor exposure pathways. These pathways include resuspension of soil particles, with the subsequent deposition on crops and inhalation by humans; external exposure; radionuclide uptake by crops through their roots; emission of radon and inhalation of radon decay products by humans; and soil ingestion by humans and animals.

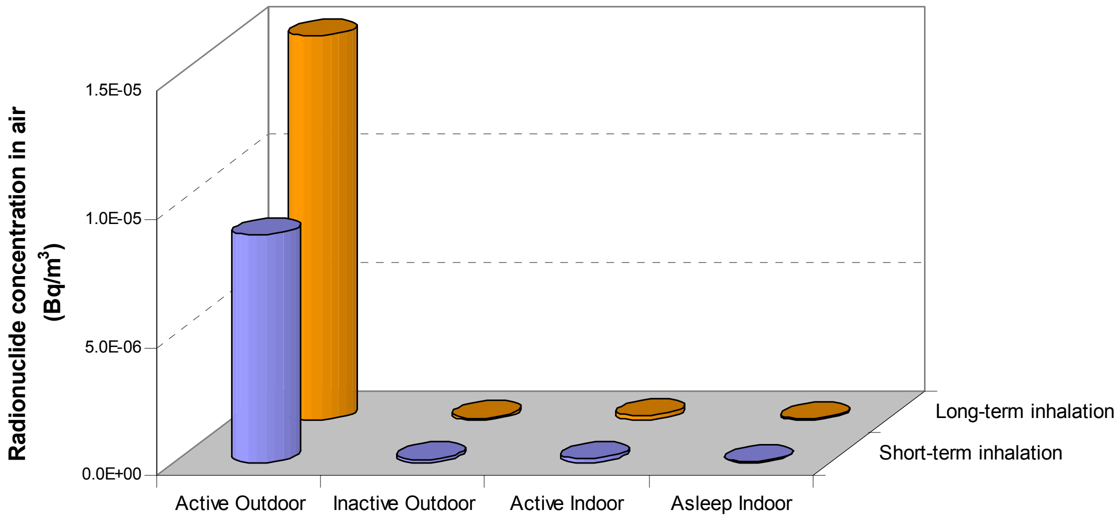
The biosphere model for the volcanic ash exposure scenario uses two source radionuclide concentrations in the soil: aerial radionuclide concentration in the surface soil (down to the tilling depth) and mass radionuclide concentrations in the resuspendable layer of surface soil. Unlike the biosphere model for the groundwater scenario, the biosphere model for the volcanic ash scenario does not account for any subsequent addition or removal of radionuclides to the soil. This calculation of the required radionuclide concentrations in the soil is carried out in the TSPA model.

To calculate radionuclide concentrations in the cultivated surface soil, the available activity of a radionuclide per unit area is mixed within the tilling depth of the soil, thus making the radionuclide concentrations inversely proportional to the soil depth. This relationship results in a negative correlation of the ingestion pathways with the soil depth, as shown in Table 6.14-3.

6.14.4.2 Radionuclide Transport to Air

Radionuclide transport from soil to air occurs via resuspension of surface soil and exhalation of radon from the soil. Resuspension of soil results in particulate matter becoming airborne.

The radionuclide concentration in air is calculated in the biosphere model for the volcanic ash exposure scenario using the same method as that used in the groundwater exposure scenario, as the product of radionuclide concentration in soil, atmospheric mass loading, and the enhancement factor (Section 6.4.2.1). Figure 6.14-6 shows the average radionuclide concentrations in air in the four contaminated receptor environments used in the calculation of the short-term and long-term inhalation BDCF components. The graph shows that the level of radionuclide concentration in air for the active outdoor environment is much higher than that in any of the remaining environments. Radionuclide concentration in air in Figure 6.14-6 is based on a unit activity concentration in surface soil and is the same for all radionuclides.

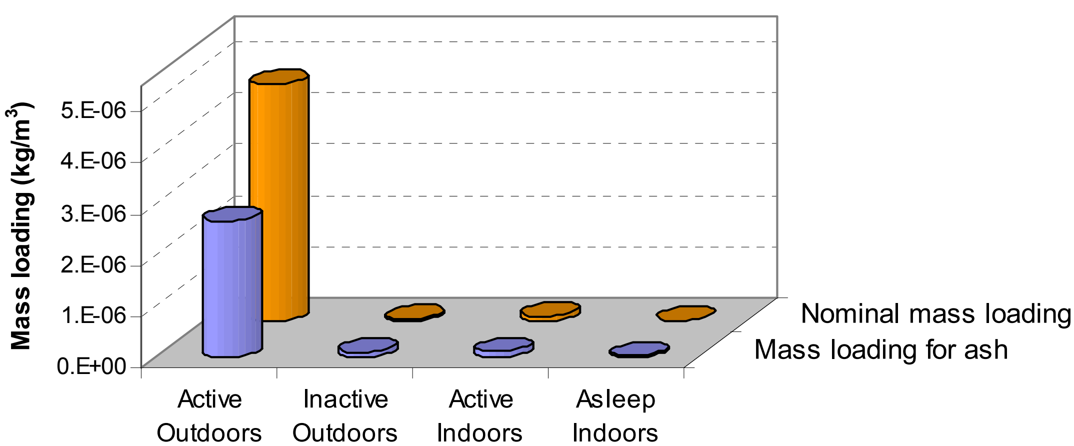


Source: Excel file *Detailed Pathway Analysis VA.xls* (Appendix A).

NOTE: Radionuclide concentration in air is based on unit activity concentration in the resuspendable soil layer.

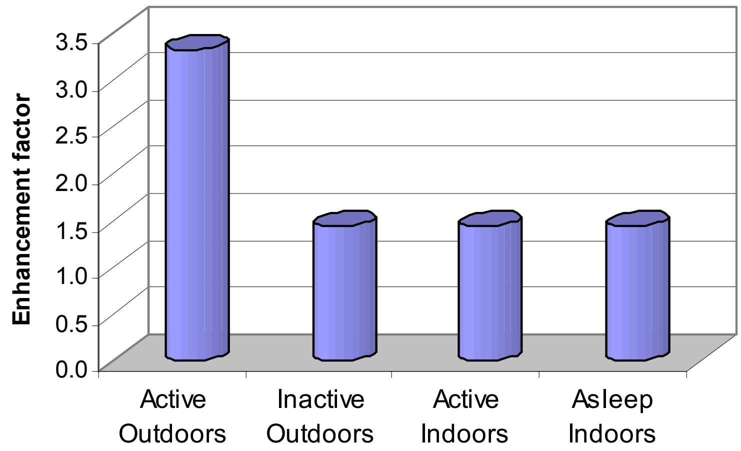
Figure 6.14-6. Average Radionuclide Concentration in Air by Receptor Environment Used in Calculation of Short-Term and Long-Term Inhalation BDCF Component

The radionuclide concentration in the active outdoor environment is high because both atmospheric mass loading and the enhancement factor are high for this environment, as shown in Figures 6.14-7 and 6.14-8, respectively. The mass loading for ash shown in Figure 6.14-7 is used to calculate the increase in mass loading following an eruption for the short-term inhalation BDCF component. The nominal mass loading is used in the calculation of the long-term inhalation BDCF component.



Source: Excel file *Detailed Pathway Analysis VA.xls* (Appendix A).

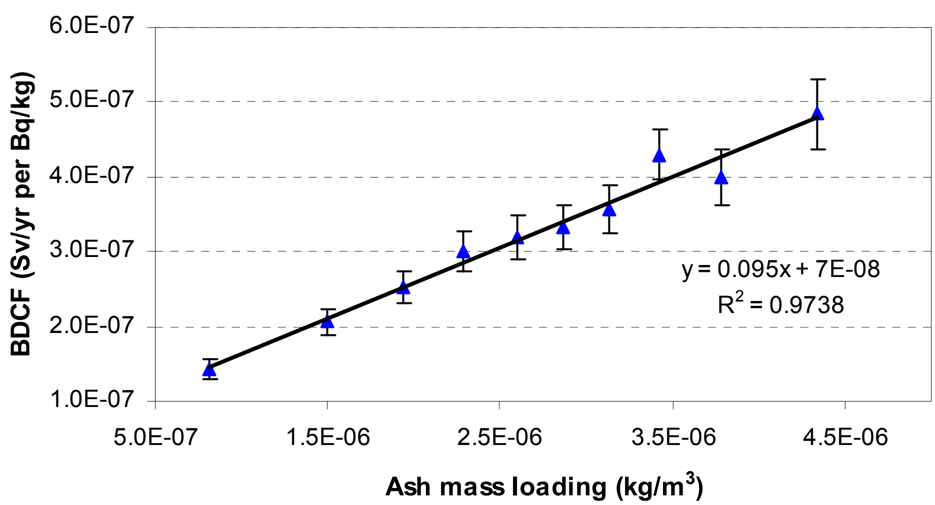
Figure 6.14-7. Average Atmospheric Mass Loading by Receptor Environment Used in Calculation of Short-Term (Mass Loading for Ash) and Long-Term (Nominal Mass Loading) Inhalation BDCF Component



Source: Excel file *Detailed Pathway Analysis VA.xls* (Appendix A).

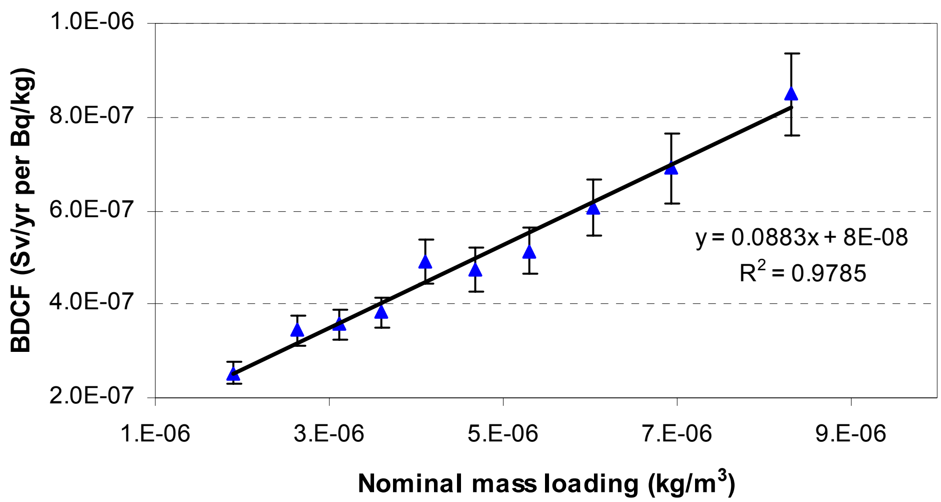
Figure 6.14-8. Average Enhancement Factor by Receptor Environment Used in Calculation of the Short-Term and Long-Term Inhalation BDCF Component

A dependence of both inhalation BDCF components for ^{241}Am on mass loading in the active outdoor environment is shown in Figures 6.14-9 and 6.4-10 for the averaged values of the variables. The graphs show that the inhalation BDCF components are strongly affected by mass loading in the active outdoor environment. This parameter alone accounts for almost 30% of the variance in the short-term and long-term inhalation BDCF components, as measured by the square of the correlation coefficient (Table 6.14-4).



Source: Excel file *Dependence of VA BDCFs on Inputs.xls* (Appendix A).

Figure 6.14-9. Dependence of Short-Term Inhalation BDCF Component for ^{241}Am on Ash Mass Loading in the Active Outdoor Environment



Source: Excel file *Dependence of VA BDCFs on Inputs.xls* (Appendix A).

Figure 6.14-10. Dependence of Long-Term Inhalation BDCF Component for ^{241}Am on Nominal Mass Loading in the Active Outdoor Environment

The dependence of inhalation BDCFs for the other radionuclides on particulate concentration in air would look similar to that shown in Figures 6.14-9 and 6.14-10 with the only difference resulting from the inhalation dose coefficient.

The influence of mass loading on the inhalation BDCF components was investigated in a series of deterministic model runs using ^{241}Am as a representative radionuclide. Table 6.14-5 contains the summary of the results including the values of mass loading in the active outdoor, inactive outdoor, and active indoor environments, the corresponding values of the short-term and long-term inhalation BDCF components, and the percent change relative to the average value. The mass loading levels used in the deterministic runs correspond to the mode of the distribution, the maximum and twice the maximum value.

The inhalation BDCF components change practically in proportion to the ash mass loading and nominal mass loading in the active outdoor environment (Figures 6.14-9 and 6.14-10). The other environments have a much smaller influence on the inhalation BDCF components. The second most important environment is the active indoor environment. The results presented in Table 6.14-5 show that even when mass loading in the inactive outdoor environment is twice the maximum value used in the model, the change in BDCF for ^{241}Am is less than 10%. Inhalation components for the other radionuclides show the same dependence on particulate concentrations in air.

Table 6.14-5. Inhalation BDCF Components for ^{241}Am and Percent Change for Different Levels of Mass Loading in the Active Outdoor Environment

Mass Loading Conditions	Short-term Inhalation			Long-term Inhalation		
	Ash Mass Loading mg/m^3	BDCF Sv/yr per Bq/kg	% BDCF Change	Nominal Mass Loading mg/m^3	BDCF Sv/yr per Bq/kg	% BDCF Change
Active Outdoors						
Mode	3.0	2.76E–07	0.0	3.0	2.76E–07	0.0
Maximum	5.0	4.22E–07	52.7	10.0	7.86E–07	184.3
2 × Maximum	10.0	7.86E–07	184.3	20.0	1.51E–06	447.7
Inactive Outdoors						
Mode	0.06	2.76E–07	0.0	0.06	2.76E–07	0.0
Maximum	0.20	2.87E–07	3.7	0.10	2.79E–07	1.1
2 × Maximum	0.40	3.01E–07	8.9	0.20	2.87E–07	3.7
Active Indoors						
Mode	0.100	2.76E–07	0.0	0.100	2.76E–07	0.0
Maximum	0.175	3.14E–07	13.5	0.175	3.14E–07	13.5
2 × Maximum	0.350	4.00E–07	44.8	0.350	4.00E–07	44.8

Sources: BDCFs were calculated in deterministic runs of *ERMYN_VA_Rev01_Base_Det.gsm* by changing the values of mass loading. The percent change for the BDCFs was calculated in the Excel spreadsheet *Dependence of VA BDCFs on Inputs.xls* (Appendix A).

The mass loading values used in the deterministic runs correspond to the mode of the distribution, maximum and twice the maximum. The last value is outside the range of expected conditions. This value was included to evaluate the consequences of unquantified uncertainties associated with using analog data to develop mass loading parameter ranges associated with the receptor environments. This value may also be representative of conditions that may occur in some circumstances, especially for short-term exposures, but were judged to be unlikely to occur as annual averages in the site-specific context.

6.14.4.3 Radionuclide Transport to Crops

Environmental transport pathways considered in the biosphere model for the volcanic ash exposure scenario that result in radionuclide transport to crops are:

- Deposition of resuspended contaminated soil in crop surfaces
- Root uptake of radionuclides present in surface soil.

The fractions of radionuclide concentration in the crop types contributed by transport process considered in the biosphere model for ^{90}Sr, ^{99}Tc, and ^{241}Am are summarized in Table 6.14-6; see Excel file *Detailed Pathway Analysis VA.xls* in Appendix A for calculation details. Radionuclides ^{90}Sr and ^{99}Tc were selected to show pathway contributions leading to contamination of crops for radionuclides whose BDCFs have a significant ingestion component. Americium-241, also included in Table 6.14-6, is a radionuclide that was identified as an important expected dose contributor in the other assessments (EPRI 2004 [DIRS 171915]).

Table 6.14-6. Fractions of Activity in Crops from Environmental Transport Processes for the Volcanic Ash Exposure Scenario

Radionuclide	Transport Process	Crop Type				
		Leafy Vegetables	Other Vegetables	Fruits	Grains	Cattle Forage
^{90}Sr	Dust deposition	0.026	0.009	0.028	0.028	0.017
	Root uptake	0.974	0.991	0.972	0.972	0.983
^{99}Tc	Dust deposition	0.001	0.002	0.005	0.007	0.002
	Root uptake	0.999	0.998	0.995	0.993	0.998
^{241}Am	Dust deposition	0.756	0.619	0.630	0.805	0.626
	Root uptake	0.244	0.381	0.370	0.195	0.374

Source: Excel file *Detailed Pathway Analysis VA.xls* (Appendix A).

For ^{90}Sr and ^{99}Tc, root uptake is a dominant mechanism of radionuclide transport to crops. Deposition of resuspended soil contributes only up to 3% of the activity concentration in plants for these radionuclides. Americium is an element that is taken up by plant roots relatively poorly, so the ^{241}Am concentration in plants is much less than that for ^{90}Sr and ^{99}Tc. The radionuclide concentrations on the plant surfaces from dust deposition are the same for all radionuclides because the parameters used to model these pathways are not element- or radionuclide-dependent. Therefore, deposition of resuspended soil on plant surfaces is the dominant mechanism of ^{241}Am transport to plants.

6.14.4.4 Radionuclide Transport to Animal Products

Environmental transport pathways considered in the biosphere model for the volcanic ash exposure scenario that result in radionuclide transport to animal products are animal consumption of feed and animal consumption of surface soil as well as, indirectly, environmental transport pathways leading to radionuclide accumulation in forage plants and in the surface soil.

The fractions of radionuclide concentration in animal products resulting from feed and soil consumption are summarized in Table 6.14-7.

Table 6.14-7. Fractions of Activity in Animal Products from Environmental Transport Processes for the Volcanic Ash Exposure Scenario

Radionuclide	Transport Process	Animal Product			
		Meat	Milk	Poultry	Eggs
^{90}Sr	Feed Consumption	0.960	0.959	0.652	0.652
	Soil Consumption	0.040	0.041	0.348	0.348
^{99}Tc	Feed Consumption	0.996	0.996	0.898	0.899
	Soil Consumption	0.004	0.004	0.102	0.101
^{241}Am	Feed Consumption	0.270	0.257	0.050	0.050
	Soil Consumption	0.730	0.743	0.950	0.950

Source: Excel file *Detailed Pathway Analysis VA.xls* (Appendix A).

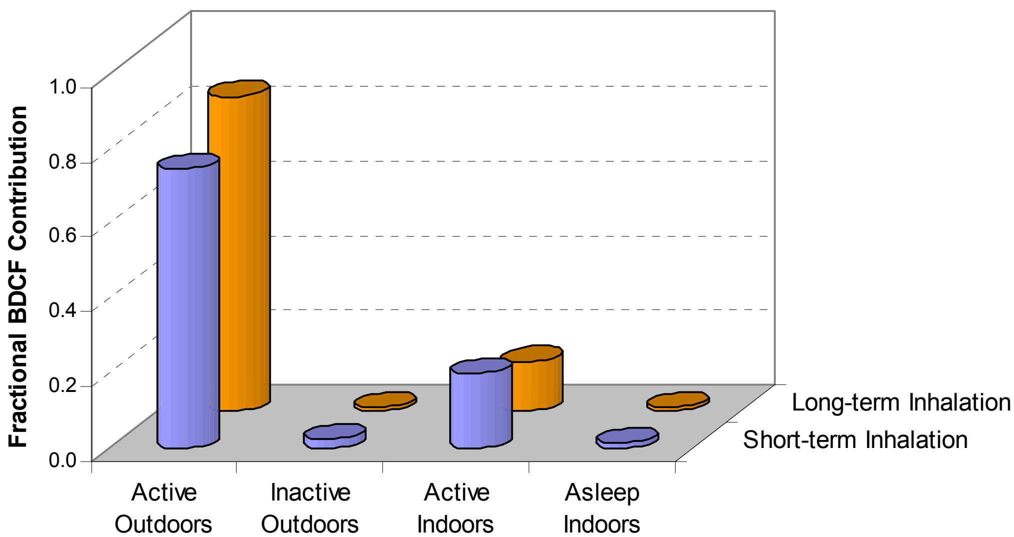
For ^{90}Sr and ^{99}Tc, feed consumption is the dominant mechanism of radionuclide transport to animal products, contributing 96% to nearly 100% of radionuclide concentration in meat and milk and 65% to 90% for poultry and eggs.

The environmental pathway contributions for ^{241}Am differ markedly from those for ^{90}Sr. This is because americium is poorly taken up from the soil by cattle forage, so its overall activity concentration in forage is less than that for ^{90}Sr. Thus, soil consumption becomes more important, in relative terms, because the activity intake for soil ingestion by an animal is the same for all radionuclides.

6.14.5 Receptor Exposure Pathways

6.14.5.1 Inhalation Pathway

The inhalation dose for the volcanic ash exposure scenario is calculated in the biosphere model using a time-budget method, analogous to that used in the biosphere model for the groundwater exposure scenario (Section 6.5.6). Inhalation of particulate matter arising from resuspension of contaminated soil occurs in all receptor environments except away from contaminated area. Figure 6.14-11 illustrates the fractional contributions from these environments to the BDCF components that results from inhalation of airborne particulates.

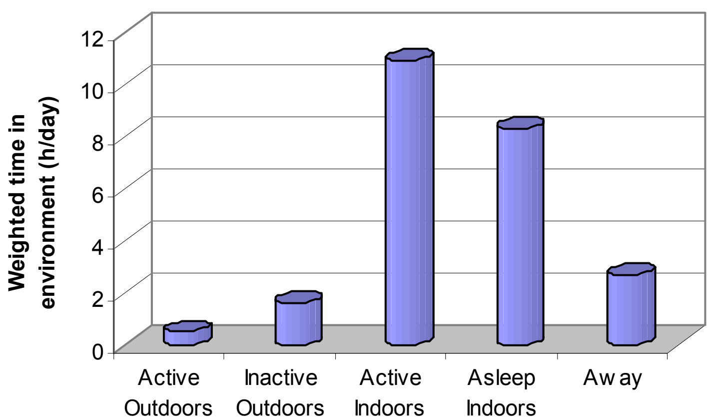


Source: Excel file *Detailed Pathway Analysis VA.xls* (Appendix A).

Figure 6.14-11. Fractional Contributions of the Receptor Environments to the Short-Term and Long-Term Inhalation BDCF Components

The inhalation dose accrued in an active outdoor environment is a dominant contributor to both inhalation BDCF components. Inhalation intake for an environment depends on the time spent in this environment by the receptor, the activity concentration in the air, and the receptor breathing rate. The activity concentration in air is an environment-specific quantity that depends on the level of soil-disturbing and dust-generating activities that are conducted in an environment and on the increase in mass activity concentration of resuspended material relative to the mass activity concentration of the surface soil, i.e., the enhancement factor. This parameter was discussed in Section 6.14.4.2. The activity concentration in air is highest in the active outdoor environment for the nominal conditions (used for calculation of the long-term inhalation BDCF component) and the post volcanic conditions of increased dustiness in air (used for calculation of the short-term BDCF component) as shown in Figure 6.14-6.

Inhalation exposure for an environment also depends on the time spent in this environment by the receptor. Figure 6.14-12 shows the weighted time for all receptor environments. There are small differences between this figure and Figure 6.13-32 showing weighted time spent in receptor environments for the groundwater exposure scenario. The differences result from the larger aerial extent of the contaminated area for the volcanic ash scenario, compared with the groundwater scenario. Consequently, some work locations are inside the contaminated area for the volcanic ash scenario and outside for the groundwater scenario. Still, the receptor spends relatively few hours per day active outdoors (0.49 h) and inactive outdoors (1.62 h) and most of his time indoors (10.92 h active and 8.30 h asleep). Time spent away from the contaminated area decreases form 4.35 h for the groundwater exposure scenario to 2.67 h for the volcanic ash exposure scenario.



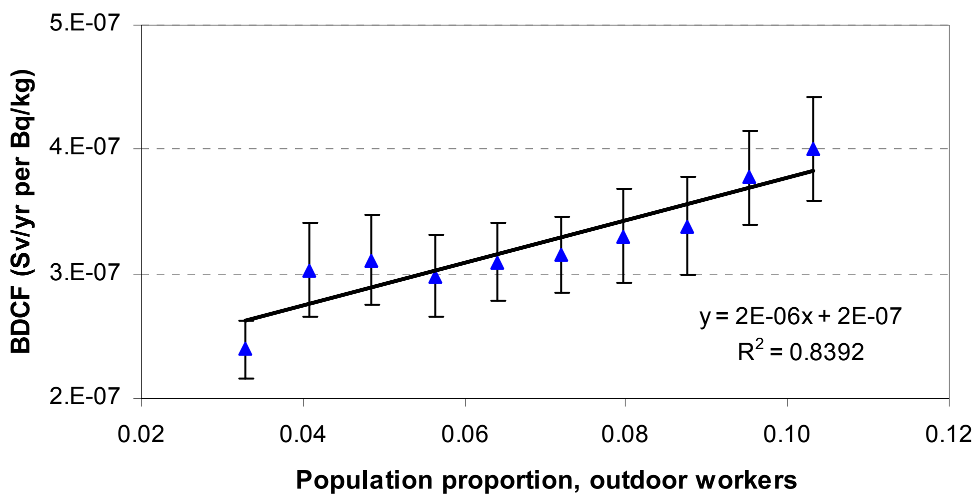
Source: Excel file *Detailed Pathway Analysis VA.xls* (Appendix A).

Figure 6.14-12. Weighted Time Spent in the Receptor Environments for Volcanic Ash Exposure Scenario

Another factor affecting radionuclide intake by inhalation is the breathing rate. The breathing rate in the biosphere model is environment-dependent and is the highest in the active outdoor environment. Breathing rates for various environments were shown in Figure 6.13-33. The same breathing rates were used for both exposure scenarios.

The correlation statistics presented in Table 6.14-4 indicate that there are only a few receptor-related parameters used in the calculation of the inhalation BDCF components that affect their variance. These parameters are the proportion of outdoor workers and the times spent by non-workers and indoor workers (the largest population fractions) in the active outdoor environment. Time spent in the inactive outdoor environment by outdoor workers is another receptor-related parameter listed in Table 6.14-4 as having a small correlation with the short-term inhalation BDCF component. However, this correlation is negative. This is probably due to the fact that the time spent active indoors is calculated as a balance of time not spent in the other environments. The negative correlation would then indicate that the time spent inactive outdoors reduces the time spent active indoors where the dose rate would be higher and, effectively, reduces the inhalation dose.

Because the majority of the inhalation exposure occurs in the active outdoor environment, which is associated with the highest levels of airborne particulate matter, the modeling results for the inhalation pathway are sensitive to the proportion of outdoor workers, who spend about half of their time outdoors in the active outdoor environment, and on the time spent in this environment by the other population groups. The dependence of the short-term inhalation BDCF component on the fraction of outdoor workers is shown in Figure 6.14-13; there is a direct correlation between these two variables.



Source: Excel file *Dependence of VA BDCFs on Inputs.xls* (Appendix A).

Figure 6.14-13. Dependence of Short-Term Inhalation BDCF Component for ^{241}Am on Proportion of Outdoor Workers

To investigate the influence of the time spent in the active outdoor environment by the outdoor workers, the biosphere model was run in the deterministic mode for two cases. The first case considered average conditions where the outdoor worker was assumed to spend 50% of their work time in the active outdoor environment. For the second case, the outdoor workers would spend 75% of their work time, a 50% increase over average conditions, in the active outdoor environment. The parameter values and the model results are summarized in Table 6.14-8. If the time in the active outdoor environment is increased from 50% to 75% of the work time (an increase of about 1.4 h in a total of 5.5 h/d worked), the long-term BDCF component increases by about 13%.

The members of all population groups that constitute the RMEI spend some time away from the contaminated area. Outdoor workers, indoor workers, and non-workers spend on average 2 h/d away; commuters spend, on average, 8 h/d away, including their work time. To evaluate the sensitivity of the inhalation BDCF component to the time away, 2 h/d of away time were subtracted for each of the population groups. This time was proportionally added to the times spent in other environments except for time asleep, which was kept fixed at 8.3 h/d. The resulting times are shown in Table 6.14-9.

Table 6.14-8. Effect of a Change in the Daily Exposure Time in the Active Outdoor Environment for Outdoor Workers on the Long-Term Inhalation BDCF Component for ^{241}Am

Conditions	Time in Environment, hr/d					BDCF Sv/yr per Bq/kg	% BDCF change
	Active Outdoors	Inactive Outdoors	Active Indoors	Asleep Indoors	Away		
Average (50% time active outdoors)	3.1	4.2	6.4	8.3	2.0	2.76E–07	0.0
75% time active outdoors	4.5	2.8	6.4	8.3	2.0	3.13E–07	13.3

Sources: BDCFs were calculated in deterministic runs of *ERMYN_VA_Rev01_Base_Det.gsm* by changing the exposure time in the receptor environments. The percent change for the BDCFs was calculated in the Excel spreadsheet *Dependence of VA BDCFs on Inputs.xls* (Appendix A).

Table 6.14-9. Base Case and Modified Times Spent in Receptor Environments by Population Groups

Environment	Commuters		Non-workers		Outdoor workers		Indoor workers	
	Base Case	Modified	Base Case	Modified	Base Case	Modified	Base Case	Modified
Active outdoors	0.3	0.4	0.3	0.3	3.1	3.6	0.3	0.3
Inactive outdoors	2.0	2.5	1.2	1.4	4.2	4.8	1.5	1.7
Active indoors	5.1	6.5	12.2	14.0	6.4	7.3	11.9	13.7
Asleep indoors	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Away	8.3	6.3	2.0	0.0	2.0	0.0	2.0	0.0

Source: Excel file *Dependence of VA BDCFs on Inputs.xls* (Appendix A).

The long-term inhalation BDCF component for ^{241}Am increased by 10% from 2.76×10^{-7} Sv/yr per Bq/kg to 3.04×10^{-7} Sv/yr per Bq/kg.

6.14.5.2 Ingestion

The ingestion dose is expected to be an insignificant contributor to the receptor exposure from a volcanic eruption, because most of the expected dose likely will be due to inhalation of transuranics. There are only a few radionuclides, such as ^{90}Sr and ^{99}Tc that are likely to have a higher dose contribution from the consumption of contaminated food. The dose from consumption of a given food type is calculated in the biosphere model as the product of radionuclide concentration in the food products, consumption rate, and the dose coefficient converting radionuclide intake by ingestion to dose. The consumption rates of locally produced food were discussed in Section 6.13.5.1, while the pathways and parameters affecting radionuclide transport to crops and animal products were discussed in Sections 6.13.4.3 and 6.13.4.4, respectively.

6.14.5.3 External Exposure

For many radionuclides, external exposure is an important contributor to the BDCF component for the external exposure, ingestion and inhalation of radon decay products (Table 6.14-1). As discussed previously, this is in part because of the assumption that the radionuclides remain on the ground surface and their radiations emitted in the direction of soil-atmosphere interface are not attenuated and/or absorbed by the soil. The dose coefficients used in this calculation, discussed in Section 6.5.5.2, were obtained from the FGR 13 (EPA 2002 [DIRS 175544]). These dose coefficients already include the additional component of radiation that was initially directed away from the soil-atmosphere interface but was scattered back out of the soil. The only additional attenuation considered in the model is the shielding provided by dwellings. External exposure depends on the level of contamination in the soil and the amount of time the receptor is exposed to radionuclides in the soil. The inhalation and external exposure time in the model is population-weighted (Section 6.14.5.1). Therefore, population proportions and time spent in the receptor environments are parameters that influence the variance in the BDCF contribution from external exposure (Table 6.14-3).

6.15 OTHER BIOSPHERE TSPA INPUTS

6.15.1 Dose Factors for Groundwater Protection Standards

The groundwater protection standards (10 CFR 63.331 [DIRS 173273]) prohibit releasing radionuclides from the repository to the accessible environment in excess of the values in Table 6.15-1, calculated based on radionuclide concentrations in 3,000-acre feet of water (representative volume) (10 CFR 63.332 [DIRS 173273]).

Table 6.15-1. Limits on Radionuclides in the Representative Volume

Radionuclide or type of radiation emitted	Limit	Is Natural Background Included?
Combined Radium-226 and Radium-228	5 picocuries per liter	Yes
Gross alpha activity (including Radium-226 but excluding radon and uranium)	15 picocuries per liter	Yes
Combined beta and photon emitting radionuclides	0.04 mSv (4 mrem) per year to the whole body or any organ, based on drinking 2 L/d of water from the representative volume	No

Source: 10 CFR 63.331 [DIRS 173273].

This section describes the development of two separate sets of conversion factors that are used in the calculation of (1) gross alpha activity concentration in groundwater, and (2) annual beta-photon dose from daily consumption of 2 liters of water. The quantities calculated using the radionuclide concentrations in groundwater and the conversion factors are then compared against the limits included in the groundwater protection standards of 10 CFR Part 63 [DIRS 173273]. Table 6.15-2 lists primary radionuclides, short-lived decay products, radionuclide emissions, and applicable gross alpha and/or beta-photon limits from the groundwater protection standards.

Table 6.15-2. Primary Radionuclides, Decay Products, and Applicable Groundwater Protection Limits

Primary Radionuclide and Mode of Decay		Short-Lived Decay Product and Mode of Decay		BF	Type and Energy of Radiation MeV per Nuclear Transformation			Half-life	Applicable Limit
					Alpha	Electron	Photon		
^{14}C	β–			1	—	0.049	—	5,730 yr	Beta and photon dose
^{36}Cl	ECβ+ β–			1	—	0.274	<	3.01E+05 yr	Beta and photon dose
^{79}Se	β–			1	—	0.056	—	1.13E+06 yr	Beta and photon dose
^{90}Sr	β–			1	—	0.196	—	29.12 yr	Beta and photon dose
		^{90}Y	β–	1	—	0.935	<	64.0 h	Beta and photon dose
^{99}Tc	β–			1	—	0.101	—	2.13E+05 yr	Beta and photon dose
^{126}Sn	β–			1	—	0.172	0.057	1.0E+05 yr	Beta and photon dose
		^{126m}Sb	IT β–	1	—	0.591	1.548	19.0 min	Beta and photon dose
		^{126}Sb	β–	0.14	—	0.283	2.834	12.4 d	Beta and photon dose
^{129}I	β–			1	—	0.064	0.025	1.57E+07 yr	Beta and photon dose
^{135}Cs	β–			1	—	0.067	—	2.3E+06 yr	Beta and photon dose
^{137}Cs	β–			1	—	0.187	—	30.0 yr	Beta and photon dose
		^{137m}Ba	IT	0.946	—	0.065	0.597	2.552 min	Beta and photon dose
Thorium Series (4n)									
^{240}Pu	SF α			1	5.156	0.011	0.002	6,537 yr	α concentration
^{236}U	α			1	4.505	0.011	0.002	2.3415E+07 yr	Excluded
^{232}Th	α			1	3.996	0.012	0.001	1.405E+10 yr	α concentration
^{228}Ra	β–			1	—	0.017	<	5.75 yr	5 pCi/L of ^{226}Ra + ^{228}Ra Beta and photon dose
		^{228}Ac	β–	1	—	0.475	0.971	6.13 h	Beta and photon dose
^{232}U	α			1	5.302	0.017	0.002	72 yr	Excluded
^{228}Th	α			1	5.400	0.021	0.003	1.9131 yr	α concentration
		^{224}Ra	α	1	5.674	0.002	0.010	3.66 d	α concentration
		^{220}Rn	α	1	6.288	<	<	55.6 s	Excluded
		^{216}Po	α	1	6.779	<	<	0.15 s	α concentration
		^{212}Pb	β–	1	—	0.176	0.148	10.64 h	Beta and photon dose
		^{212}Bi	β– α	1	2.174	0.472	0.186	60.55 min	α concentration Beta and photon dose

Table 6.15-2. Primary Radionuclides, Decay Products, and Applicable Groundwater Protection Limits (Continued)

Primary Radionuclide and Mode of Decay		Short-Lived Decay Product and Mode of Decay		BF	Type and Energy of Radiation MeV per Nuclear Transformation			Half-life	Applicable Limit
					Alpha	Electron	Photon		
		^{212}Po	α	0.6407	8.785	—	—	3.05E–07 s	α concentration
		^{208}Tl	β–	0.3593	—	0.598	3.375	3.07 min	Beta and photon dose
Neptunium Series (4n + 1)									
^{241}Am	α			1	5.479	0.052	0.033	432.2 yr	α concentration
^{237}Np	α			1	4.769	0.070	0.035	2.14E+06 yr	α concentration
		^{233}Pa	β–	1	—	0.196	0.204	27.0 d	Beta and photon dose
^{233}U	α			1	4.817	0.006	0.001	1.585E+05 yr	Excluded
^{229}Th	α			1	4.873	0.116	0.096	7340 yr	α concentration
		^{225}Ra	β–	1	—	0.107	0.014	14.8 d	Beta and photon dose
		^{225}Ac	α	1	5.787	0.022	0.018	10.0 d	α concentration
		^{221}Fr	α	1	6.304	0.010	0.031	4.8 min	α concentration
		^{217}At	α	1	7.067	<	<	3.23E–02 s	α concentration
		^{213}Bi	β– α	1	0.126	0.442	0.133	45.65 min	α concentration Beta and photon dose
		^{213}Po	α	0.9784	8.376	—	—	4.2E–06 s	α concentration
		^{209}Tl	β–	0.0216	—	0.688	2.032	2.20 min	Beta and photon dose
		^{209}Pb	β–	—	—	0.198	—	3.253 h	Beta and photon dose
Uranium Series (4n + 2)									
^{242}Pu	SF α			1	4.891	0.009	0.001	3.763E+05 yr	α concentration
^{238}U	SF α			1	4.187	0.010	0.001	4.468E+09 yr	Excluded
		^{234}Th	β–	1	—	0.060	0.009	24.10 d	Beta and photon dose
		^{234m}Pa	β– IT	0.998	—	0.822	0.012	1.17 min	Beta and photon dose
		^{234}Pa	β–	0.0033	—	0.494	1.919	6.70 h	Beta and photon dose
^{238}Pu	SF α			1	5.487	0.011	0.002	87.74 yr	α concentration
^{234}U	α			1	4.758	0.013	0.002	2.445E+05 yr	Excluded
^{230}Th	α			1	4.671	0.015	0.002	7.7E+04 yr	α concentration

Table 6.15-2. Primary Radionuclides, Decay Products, and Applicable Groundwater Protection Limits (Continued)

Primary Radionuclide and Mode of Decay		Short-Lived Decay Product and Mode of Decay		BF	Type and Energy of Radiation MeV per Nuclear Transformation			Half-life	Applicable Limit
					Alpha	Electron	Photon		
^{226}Ra	α			1	4.774	0.004	0.007	1,600 yr	5 pCi/L of ^{26}Ra + ^{228}Ra α concentration
		^{222}Rn	α	1	5.489	<	<	3.8235 d	Excluded
		^{218}Po	α	1	6.001	<	<	3.05 min	α concentration
		^{214}Pb	β–	0.9998	—	0.293	0.250	26.8 min	Beta and photon dose
		^{218}At	α	0.0002	6.697	0.040	0.007	2 s	α concentration
		^{214}Bi	β–	1	—	0.659	1.508	19.9 min	α concentration Beta and photon dose
		^{214}Po	α	0.9998	7.687	<	<	1.643E–04 s	α concentration
		^{210}Tl	β–	0.0002	—			1.3 min	Beta and photon dose
^{210}Pb	β–			1	—	0.038	0.005	22.3 yr	Beta and photon dose
		^{210}Bi	β–	1	—	0.389	—	5.012 d	Beta and photon dose
		^{210}Po	α	1	5.297	<	<	138.38 d	α concentration
Actinium Series (4n + 3)									
^{243}Am	α			1	5.270	0.022	0.056	7,380 yr	α concentration
		^{239}Np	β–	1	—	0.260	0.173	2.355 d	Beta and photon dose
^{239}Pu	α			1	5.148	0.007	<	2.4065E+04 yr	α concentration
^{235}U	α			1	4.396	0.049	0.156	7.038E+08 yr	Excluded
		^{231}Th	β–	1	—	0.165	0.026	25.52 h	Beta and photon dose
^{231}Pa	α			1	4.969	0.065	0.048	3.276E+04 yr	α concentration
^{227}Ac	β– α			1	0.068	0.016	<	21.773 yr	α concentration Beta and photon dose
		^{227}Th	α	0.9862	5.884	0.053	0.110	18.718 d	α concentration
		^{223}Fr	β–	0.0138	—	0.400	0.059	21.8 min	Beta and photon dose
		^{223}Ra	α	1	5.667	0.076	0.134	11.434 d	α concentration
		^{219}Rn	α	1	6.757	0.006	0.056	3.96 s	Excluded
		^{215}Po	α	1	7.386	<	<	1.78E–3 s	α concentration
		^{211}Pb	β–	1	—	0.456	0.051	36.1 min	Beta and photon dose

Table 6.15-2. Primary Radionuclides, Decay Products, and Applicable Groundwater Protection Limits (Continued)

Primary Radionuclide and Mode of Decay	Short-Lived Decay Product and Mode of Decay		BF	Type and Energy of Radiation MeV per Nuclear Transformation			Half-life	Applicable Limit
				Alpha	Electron	Photon		
	^{211}Bi	α β–	1	6.550	0.010	0.047	2.14 min	α concentration
	^{207}Tl	β–	0.9972	—	0.493	0.002	4.77 min	Beta and photon dose
	^{211}Po	α	0.0028	7.442	<	0.008	0.516 s	α concentration

Sources: Eckerman and Ryman 1993 [DIRS 107684], Table A.1.
Lide and Frederikse 1997 [DIRS 103178], p. 11-125 was used for ^{210}Tl.
Firestone et al. 1998 [DIRS 178201] was used for ^{79}Se half-life.

NOTES: Short-lived decay products of primary radionuclides are modeled to be in secular equilibrium with their parents.
BF = branching fraction; EC = electron capture; SF = spontaneous fission; IT = isomeric transformation.

For evaluation of compliance with the limit for ^{226}Ra and ^{228}Ra, the combined activity concentration of ^{226}Ra and ^{228}Ra in the groundwater is calculated based on the annual mass flux of these radionuclides at the controlled area boundary and the representative volume. The natural background concentrations of ^{226}Ra and ^{228}Ra in groundwater must be included with the calculated activity (10 CFR 63.331 [DIRS 173273]) for comparison to the limit of 5 pCi/L.

6.15.1.1 Gross Alpha Activity Conversion Factors

Gross alpha particle activity means the total radioactivity due to alpha particle emission as inferred from measurements on a dry sample (40 CFR 141.2 [DIRS 173245]). For this analysis, evaluation of gross alpha activity for consideration in TSPA is based on calculation, rather than measurement, of total alpha emissions from the primary radionuclides and their decay products (Sections 6.1.3 and 6.3.5). The calculation of radionuclide concentrations in water is based on the representative volume, which contains 3,000 acre-feet of water (about 3,714,450,000 liters) (10 CFR 63.332 [DIRS 173273]).

For compliance evaluation, gross alpha particle activity concentration has to include both the natural background concentration and that from the repository. The groundwater alpha activity concentration from the repository is the calculated alpha emissions from all primary radionuclides included in the TSPA model and their decay products, excluding radon and uranium.

For determining alpha activity concentration (excluding radon and uranium) for comparison with the limit for gross alpha activity of 15 pCi/L, the activity concentration of primary radionuclides in groundwater is calculated based on the annual mass flux of these radionuclides and the representative volume. Alpha particle activity is calculated as the total of alpha emissions from all primary radionuclides and decay products included in the model (Sections 6.1.3 and 6.3.5). Consistent with the approach used in the biosphere model (Section 6.3.1.4), short-lived decay products of a primary radionuclide are modeled to be in secular equilibrium with the primary radionuclide. After the activity concentration of a primary radionuclide in the groundwater is calculated, the value is multiplied by the number of alpha particles included in the decay chain to determine the total number of alpha particles associated with the decay of the primary radionuclide. The number of alpha particles is shown in Table 6.15-3. For example, if the calculated activity concentration of ^{229}Th in groundwater is 2 pCi/L, the alpha activity associated with the decay of ^{229}Th is 2 pCi/L $\times$ 5 alpha particles per decay = 10 pCi/L. The natural background concentrations of alpha emitters in groundwater (including ^{226}Ra but excluding radon and uranium) (10 CFR 63.331 [DIRS 173273]) must be then added to calculate the gross alpha activity concentration that is compared with the appropriate groundwater protection standard.

The alpha particle activity concentration in water is calculated as:

$$C_\alpha = \sum_i Cw_i \ N_{\alpha,i} \qquad \text{(Eq. 6.15-1)}$$

where

C_α = total alpha particle activity concentration in groundwater (Bq/m^3 or pCi/L)

Cw_i = activity concentration of a primary radionuclide i in groundwater (Bq/m^3 or pCi/L)

$N_{\alpha,\,i}$ = number of alpha particles attributed to one decay of a primary radionuclide i (from Table 6.15-3).

Table 6.15-3. Number of Alpha Particles Emitted per One Decay of a Primary Radionuclide Considered in the Gross Alpha Activity Limit of the Groundwater Protection Standards

Primary Radionuclide and % of Alpha Particles Emitted per Decay		**Short-lived Decay Products and % of Alpha Particles Emitted per Decay**		**Number of Alpha Particles** [a]
Thorium Series (4n)				
^{240}Pu	100			1
^{236}U [a]	100 [a]			0 [a]
^{232}Th [b]	100			1
^{232}U [a, c]	100 [a]			0 [a]
^{228}Th [b, c]	100			4 [a]
		^{224}Ra	100	
		^{220}Rn [a]	100 [a]	
		^{216}Po	100	
		^{212}Bi	35.93	
		^{212}Po	64.07	
Neptunium Series (4n + 1)				
^{241}Am	100			1
^{237}Np	100			1
^{233}U [b]	100 [a]			0 [a]
^{229}Th	100			5
		^{225}Ac	100	
		^{221}Fr	100	
		^{217}At	100	
		^{213}Bi	2.16	
		^{213}Po	97.84	
Uranium Series (4n + 2)				
^{242}Pu	100			1
^{238}U [b]	100 [a]			0 [a]
^{238}Pu	100			1
^{234}U [b]	100 [a]			0 [a]
^{230}Th	100			1
^{226}Ra	100			3 [a]
		^{222}Rn [b]	100 [b]	
		^{218}Po	99.98	
		^{218}At	0.02	
		^{214}Bi	0.02	
		^{214}Po	99.98	
^{210}Pb				1 [d]
		^{210}Po	100	

Table 6.15-3. Number of Alpha Particles Emitted per One Decay of a Primary Radionuclide Considered in the Gross Alpha Activity Limit of the Groundwater Protection Standards (Continued)

Primary Radionuclide and % of Alpha Particles Emitted per Decay		Short-lived Decay Products and % of Alpha Particles Emitted per Decay		Number of Alpha Particles
Actinium Series (4n + 3)				
^{243}Am	100			1
^{239}Pu	100			1
^{235}U [a]	100 [a]			0 [a]
^{231}Pa	100			1
^{227}Ac	1.38			4 [a]
		^{227}Th	98.62	
		^{223}Ra	100	
		^{219}Rn [a]	100 [a]	
		^{215}Po	100	
		^{211}Bi	99.73	
		^{211}Po	0.273	

[a] Isotopes of radon and uranium have been excluded, per 10 CFR 63.331 [DIRS173273].

[b] ^{232}Th is accompanied in the groundwater by its relatively long-lived decay products, ^{228}Ra and ^{228}Th (and their short-lived decay products). ^{228}Th and its decay products contribute to the alpha activity concentration and even if ^{228}Th is not tracked in TSPA, its contribution must be taken into account. If radioactive equilibrium between ^{232}Th, ^{228}Ra and ^{228}Th is assumed, the number of alpha particles for ^{228}Th should be added to that for ^{232}Th for a total of 5. ^{228}Ra and its decay product ^{228}Ac are beta-emitters so they do not contribute to the alpha particle concentration.

[c] ^{232}U is accompanied in the groundwater by its relatively long-lived decay product, ^{228}Th and its short-lived decay products. If radioactive equilibrium between ^{232}U and ^{228}Th is assumed, the number of alpha particles for ^{228}Th should be attributed to that for ^{232}U for a total of 4.

[d] If concentration of ^{210}Pb in groundwater is not calculated, one could assume that ^{210}Pb is in radioactive equilibrium with ^{226}Ra. If this is the case, the number of alpha particles for ^{210}Pb should be added to that for ^{226}Ra for a total of 4.

Source: Based on the data in Table 6.15-2.

^{232}Th is accompanied in the groundwater by its relatively long-lived decay products, ^{228}Ra and ^{228}Th (and their short-lived decay products). Even if ^{228}Ra and ^{228}Th are not tracked in TSPA, their contribution must be taken into account. If radioactive equilibrium between ^{232}Th, ^{228}Ra, and ^{228}Th is assumed, the number of alpha particles for ^{228}Th should be added to that for ^{232}Th for a total of 5. ^{228}Ra and its decay product ^{228}Ac are beta emitters so they do not contribute to the alpha particle number.

^{232}U is accompanied in the groundwater by its relatively long-lived decay product, ^{228}Th and its short-lived decay products. If radioactive equilibrium between ^{232}U and ^{228}Th is assumed, the number of alpha particles for ^{228}Th should be attributed to that for ^{232}U for a total of 4.

In a similar fashion, if the concentration of ^{210}Pb in groundwater is not calculated and if equilibrium could be assumed to exist between the concentrations ^{226}Ra and ^{210}Pb in the groundwater, their conversion factors should be combined to account for the ^{210}Pb contribution to gross alpha activity concentration for a total number of alpha particles of 4 that are attributable to ^{226}Ra and its decay products.

6.15.1.2 Beta-Photon Dose Conversion Factors

The annual dose limit for beta- and photon-emitting radionuclides is 0.04 mSv (4 mrem) per year to the whole body or any organ, based on the water consumption of 2 L/d (10 CFR 63.331 [DIRS 173273]). This limit applies to radionuclides other than alpha emitters. Alpha emitters are covered under the gross alpha limit of the groundwater protection standards. If a radionuclide decays with emissions of alpha and beta radiation, this analysis considers the radionuclide for both gross alpha and annual dose. This is the case for several radionuclides (Table 6.15-2). Such an approach is conservative and ensures that all types of radiation emitted from a radionuclide are considered.

Dose contributions for beta-photon emitters were calculated using dose coefficients from FGR 13 (EPA 2002 [DIRS 175544]). These dose coefficients include contributions from all emissions for each radionuclide. For example, if the fraction of decays of a radionuclide that primarily is a beta emitter undergoes an alpha decay, the dose from alpha particles is included in the dose coefficient. Radionuclides such as ^{212}Bi that have large fractions of alpha and beta decays are thus double counted (i.e., they are included in the gross alpha component and the dose component to ensure that all radionuclide emissions are counted). Radionuclides classified as alpha-beta emitters (Eckerman and Ryman 1993 [DIRS 107684], Table A.1), with a large fraction of alpha emission (about 99% or more; e.g., ^{218}Po, 99.98% α; ^{211}Bi, 99.73% α), are not included in calculating beta-photon dose; primary radionuclides that were included are listed in Table 6.15-4.

Table 6.15-4. Radionuclides and Their Decay Products Included in Calculation of Conversion Factors for Beta-Photon Emitters

Primary Radionuclide and Mode of Decay		**Short-Lived Decay Product and Mode of Decay**	
^{14}C	β–		
^{36}Cl	EC, β+, β–		
^{79}Se	β–		
^{90}Sr	β–	^{90}Y	β–
^{99}Tc	β–		
^{126}Sn	β–	^{126m}Sb	IT, β–
		^{126}Sb	β–
^{129}I	β–		
^{135}Cs	β–		
^{137}Cs	β–	^{137m}Ba	IT
Thorium Series (4n)			
^{228}Ra	β–	^{228}Ac	β–
^{228}Th	α	^{212}Pb	β–
		^{212}Bi	β– α
		^{208}Tl	β–
Neptunium Series (4n + 1)			
^{237}Np	α	^{233}Pa	β–
^{229}Th	α	^{225}Ra	β–
		^{213}Bi	β– α
		^{209}Tl	β–
		^{209}Pb	β–
Uranium Series (4n + 2)			
^{238}U	SF, α	^{234}Th	β–
		^{234m}Pa	β– IT
		^{234}Pa	β–
^{226}Ra	α	^{214}Pb	β–
		^{214}Bi	β–
		^{210}Tl	β–
^{210}Pb	β–	^{210}Bi	β–
Actinium Series (4n + 3)			
^{243}Am	α	^{239}Np	β–
^{235}U	α	^{231}Th	β–
^{227}Ac	β– α	^{223}Fr	β–
		^{211}Pb	β–
		^{207}Tl	β–

Source: Based on the data in Table 6.15-2.

EC = electron capture, IT = isomeric transition, SF = spontaneous fission.

The annual dose from drinking 2 L/d of water with a given concentration of a primary beta-photon-emitting radionuclide is calculated as:

$$D_i = Cw_i \; CF_i \qquad \text{(Eq. 6.15-2)}$$

where

D_i = annual dose (committed effective dose or committed equivalent dose for an organ) from intake of radionuclide *i* by ingestion resulting from daily consumption of 2 liters of water (Sv/yr)

Cw_i = activity concentration of radionuclide *i* in groundwater (Bq/m^3)

CF_i = conversion factor for calculating beta-photon dose from radionuclide *i* as a result of drinking 2 L/d of water (Sv/yr per Bq/m^3).

The conversion factor, *CF*, is numerically equal to the annual dose resulting from daily consumption of 2 liters of water containing a unit activity concentration of a given primary radionuclide and associated short-lived decay products. Conversion factors are calculated as:

$$\begin{aligned} CF_i\left(\frac{Sv/yr}{Bq/m^3}\right) &= 2\frac{L}{d}\times 365.25\frac{d}{yr}\times 10^{-3}\frac{m^3}{L}\times EDCF_i\left(\frac{Sv}{Bq}\right) \\ &= 7.30\times 10^{-1}\frac{m^3}{yr}\times EDCF_i\left(\frac{Sv}{Bq}\right) \end{aligned} \qquad \text{(Eq. 6.15-3)}$$

where

$EDCF_i$ = effective dose coefficient for ingestion of primary radionuclide *i* (Sv/Bq).

The total dose from ingesting beta-gamma emitters in the groundwater is calculated as:

$$D = \sum_i Cw_i \; CF_i \qquad \text{(Eq. 6.15-4)}$$

The effective dose coefficient for the ingestion of a primary radionuclide includes contributions from dose coefficients for the short-lived decay products. The effective dose coefficient is calculated as the weighted sum of the organ or whole body dose coefficients for a primary radionuclide and its short-lived decay products, with the weights corresponding to the branching fractions:

$$EDCF_i = DCF_i + \sum_s DCF_{s,i} \times BF_{s,i} \qquad \text{(Eq. 6.15-5)}$$

where

DCF_i = dose coefficient for primary radionuclide i (Sv/Bq), equal to zero if a primary radionuclide is not a beta-photon emitter

$DCF_{s,i}$ = ingestion dose coefficient for short-lived beta-photon emitting radionuclide s in a decay chain of a primary radionuclide i (Sv/Bq)

$BF_{s,i}$ = branching fraction for short-lived beta-photon emitting radionuclide s in a decay chain of a primary radionuclide i (dimensionless).

Ingestion dose coefficients for organs and the whole body were obtained from FGR 13 (EPA 2002 [DIRS 175544]). In this case, the effective dose coefficient for a primary radionuclide accounts only for contributions from beta- and photon-emitting radionuclides in the decay chain of this radionuclide. Alpha emitters with a fraction of alpha decays greater than 99% are not included. Effective dose coefficients for calculating annual beta-photon dose resulting from water consumption of 2 L/d are summarized in Table 6.15-5. The calculations were carried out in Excel (see file *GW Protection Conversion Factors.xls* in Appendix A for details).

Table 6.15-6 contains a summary of conversion factors, in the units of Sv/yr per Bq/m^3, for calculating the beta-photon annual doses from daily consumption of 2 liters of water. The conversion factors were calculated using Equation 6.15-3.

^{232}Th is accompanied in the groundwater by its relatively long -lived decay products, ^{228}Ra and ^{228}Th (and their short-lived decay products). ^{232}Th is an alpha emitter and itself does not contribute to the beta-photon dose, but ^{228}Ra and ^{228}Th and their short-lived decay products do. Even if ^{228}Ra and ^{228}Th are not directly tracked in TSPA, their contribution must be taken into account. This could be accomplished by assuming radioactive equilibrium between ^{232}Th, ^{228}Ra, and ^{228}Th. In this case, the conversion factors assigned to ^{232}Th would be the sum of the conversion factors for ^{228}Ra and ^{228}Th. The combined conversion factors are also listed in Table 6.15-6.

Similarly, ^{232}U, an alpha emitter, is accompanied in the groundwater by its relatively long-lived decay product, ^{228}Th (and its short-lived decay products), which contributes to the beta-photon dose. If the concentration of ^{228}Th is not calculated in TSPA, the ^{228}Th concentration in water from the decay of ^{232}U can be assumed to be at equilibrium with ^{232}U and the conversion factors assigned to ^{232}U would be those of ^{228}Th.

In a similar fashion, if equilibrium exists between the concentrations ^{226}Ra and ^{210}Pb in the groundwater, their conversion factors could be combined. Table 6.15-6 includes the value of the conversion factor for ^{226}Ra (and its short-lived decay products), ^{210}Pb (and its short-lived decay products) and, separately, the value for ^{226}Ra that includes a contribution from ^{210}Pb. The latter value was developed so that the contribution of this relatively long-lived radionuclide to the beta-photon dose is accounted for, in case its concentration in groundwater is not separately calculated in TSPA.

Table 6.15-5. Effective Dose Coefficients (Sv/Bq) Calculated Using Federal Guidance Report No. 13 for Radionuclides Included in Calculation of Conversion Factors

Organ or Tissue	^{14}C	^{36}Cl	^{79}Se	^{90}Sr	^{99}Tc	^{126}Sn	^{129}I	^{135}Cs	^{137}Cs	^{228}Ra	^{228}Th
Adrenals	5.72E–10	8.06E–10	9.67E–10	6.64E–10	3.87E–11	9.87E–10	1.23E–10	1.92E–09	1.40E–08	1.55E–07	2.14E–09
Bone Surface	5.72E–10	8.06E–10	9.67E–10	4.09E–07	3.87E–11	5.57E–09	3.99E–10	1.92E–09	1.38E–08	2.25E–05	5.21E–08
Brain	5.72E–10	8.06E–10	9.67E–10	6.64E–10	3.87E–11	7.26E–10	1.43E–10	1.92E–09	1.18E–08	1.53E–07	2.10E–09
Breast	5.72E–10	8.06E–10	9.67E–10	6.64E–10	3.87E–11	4.82E–10	1.14E–10	1.92E–09	1.12E–08	1.52E–07	2.11E–09
Stomach Wall	6.29E–10	1.12E–09	1.03E–09	1.97E–09	2.17E–09	2.05E–09	1.99E–10	2.00E–09	1.34E–08	1.54E–07	5.00E–09
Small Intestine Wall	5.73E–10	8.14E–10	9.99E–10	3.69E–09	1.85E–10	4.81E–09	1.26E–10	1.93E–09	1.40E–08	1.56E–07	7.14E–09
Upper Large Intestine Wall	5.80E–10	9.00E–10	1.42E–09	1.94E–08	1.37E–09	1.73E–08	2.25E–10	2.17E–09	1.44E–08	1.77E–07	1.84E–08
Lower Large Intestine Wall	5.97E–10	1.08E–09	2.30E–09	5.34E–08	3.93E–09	4.66E–08	4.31E–10	2.64E–09	1.67E–08	2.23E–07	2.04E–08
Kidneys	5.72E–10	8.06E–10	3.23E–08	6.64E–10	3.87E–11	9.61E–10	1.21E–10	1.92E–09	1.35E–08	4.33E–07	4.52E–08
Liver	5.72E–10	8.06E–10	1.39E–08	6.64E–10	5.15E–11	7.89E–10	1.22E–10	1.92E–09	1.36E–08	1.04E–06	1.37E–08
Extrathoracic Airways	5.72E–10	8.06E–10	9.67E–10	6.64E–10	3.87E–11	6.39E–10	1.43E–10	1.92E–09	1.31E–08	1.53E–07	2.10E–09
Lung	5.72E–10	8.06E–10	9.67E–10	6.64E–10	3.87E–11	6.56E–10	1.54E–10	1.92E–09	1.27E–08	1.53E–07	2.11E–09
Muscle	5.72E–10	8.06E–10	9.67E–10	6.64E–10	3.87E–11	8.71E–10	3.01E–10	1.92E–09	1.25E–08	1.53E–07	2.14E–09
Ovaries	5.72E–10	8.06E–10	1.82E–09	6.64E–10	3.87E–11	2.92E–09	1.28E–10	1.92E–09	1.43E–08	2.15E–07	2.42E–09
Pancreas	5.72E–10	8.06E–10	5.01E–09	6.64E–10	3.87E–11	9.40E–10	1.25E–10	1.92E–09	1.44E–08	1.53E–07	2.18E–09
Red Bone Marrow	5.72E–10	8.06E–10	9.67E–10	1.79E–07	3.87E–11	2.94E–09	1.40E–10	1.92E–09	1.31E–08	2.31E–06	6.65E–09
Skin	5.72E–10	8.06E–10	9.67E–10	6.64E–10	3.87E–11	5.81E–10	1.42E–10	1.92E–09	1.07E–08	1.53E–07	2.11E–09
Spleen	5.72E–10	8.06E–10	5.57E–09	6.64E–10	3.87E–11	7.82E–10	1.23E–10	1.92E–09	1.35E–08	1.54E–07	2.16E–09
Testes	5.72E–10	8.06E–10	2.86E–09	6.64E–10	3.87E–11	7.16E–10	1.16E–10	1.92E–09	1.26E–08	2.14E–07	2.13E–09
Thymus	5.72E–10	8.06E–10	9.67E–10	6.64E–10	3.87E–11	5.76E–10	1.72E–10	1.92E–09	1.31E–08	1.53E–07	2.11E–09
Thyroid	5.72E–10	8.06E–10	9.67E–10	6.64E–10	1.01E–09	6.39E–10	2.11E–06	1.92E–09	1.31E–08	1.53E–07	2.10E–09
Uterus	5.72E–10	8.06E–10	9.67E–10	6.64E–10	3.87E–11	1.60E–09	1.26E–10	1.92E–09	1.45E–08	1.53E–07	2.27E–09
Urinary Bladder Wall	5.72E–10	2.10E–09	1.11E–09	1.48E–09	1.60E–10	1.29E–09	4.30E–10	2.18E–09	1.45E–08	1.53E–07	2.34E–09
Whole Body	5.81E–10	9.29E–10	2.89E–09	3.04E–08	6.42E–10	5.15E–09	1.06E–07	2.00E–09	1.36E–08	6.97E–07	6.24E–09

Table 6.15-5. Effective Dose Coefficients (Sv/Bq) Calculated Using Federal Guidance Report No. 13 for Radionuclides Included in Calculation of Conversion Factors (Continued)

Organ or Tissue	^{237}Np	^{229}Th	^{238}U	^{226}Ra	^{210}Pb	^{243}Am	^{235}U	^{227}Ac
Adrenals	1.35E–11	1.13E–08	2.25E–12	1.85E–11	8.83E–08	9.00E–12	4.84E–13	4.73E–08
Bone Surface	9.00E–11	3.60E–06	4.73E–11	1.93E–10	2.26E–05	2.57E–11	5.82E–12	9.36E–06
Brain	4.07E–13	1.12E–08	6.51E–13	1.03E–11	8.83E–08	5.13E–14	1.79E–14	4.73E–08
Breast	2.08E–12	1.12E–08	9.12E–13	1.24E–11	8.83E–08	1.09E–12	6.00E–14	4.73E–08
Stomach Wall	2.91E–10	1.29E–08	1.00E–09	1.73E–09	8.89E–08	3.45E–10	1.95E–10	4.85E–08
Small Intestine Wall	7.74E–10	1.26E–08	2.55E–09	7.75E–10	8.95E–08	8.52E–10	4.40E–10	4.80E–08
Upper Large Intestine Wall	3.70E–09	1.87E–08	1.51E–08	2.97E–10	9.74E–08	3.93E–09	1.93E–09	5.62E–08
Lower Large Intestine Wall	1.02E–08	4.81E–08	4.31E–08	4.49E–11	1.15E–07	8.70E–09	3.40E–09	7.52E–08
Kidneys	3.48E–11	3.76E–08	1.92E–11	3.95E–10	3.75E–06	2.10E–11	1.36E–12	7.14E–08
Liver	2.09E–11	1.94E–07	8.11E–12	4.37E–11	1.93E–06	1.37E–11	9.86E–13	2.02E–06
Extrathoracic Airways	5.67E–13	1.12E–08	6.85E–13	1.05E–11	8.83E–08	1.43E–13	1.99E–14	4.73E–08
Lung	3.53E–12	1.12E–08	1.08E–12	1.34E–11	8.83E–08	2.08E–12	1.24E–13	4.73E–08
Muscle	2.65E–11	1.13E–08	4.03E–12	1.49E–11	8.83E–08	1.66E–11	1.37E–12	4.73E–08
Ovaries	2.36E–10	1.34E–08	3.41E–11	2.86E–11	8.83E–08	1.49E–10	1.87E–11	1.87E–07
Pancreas	2.75E–11	1.13E–08	4.10E–12	3.90E–11	8.83E–08	1.98E–11	1.53E–12	4.74E–08
Red Bone Marrow	4.82E–11	3.48E–07	2.93E–11	3.25E–11	2.49E–06	2.59E–11	1.85E–12	4.92E–07
Skin	8.42E–12	1.12E–08	1.74E–12	1.22E–11	8.83E–08	4.93E–12	2.89E–13	4.73E–08
Spleen	2.17E–11	1.13E–08	3.30E–12	3.45E–11	2.82E–06	1.50E–11	9.61E–13	4.76E–08
Testes	2.16E–11	1.34E–08	4.71E–12	1.13E–11	8.83E–08	1.16E–11	5.65E–13	1.86E–07
Thymus	1.68E–12	1.12E–08	8.39E–13	1.18E–11	8.83E–08	7.98E–13	4.32E–14	4.73E–08
Thyroid	5.67E–13	1.12E–08	6.85E–13	1.05E–11	8.83E–08	1.43E–13	1.99E–14	4.73E–08
Uterus	1.07E–10	1.13E–08	1.42E–11	2.54E–11	8.83E–08	7.04E–11	4.86E–12	4.73E–08
Urinary Bladder Wall	7.66E–11	1.13E–08	1.02E–11	1.97E–11	8.92E–08	4.69E–11	2.86E–12	4.75E–08
Whole Body	8.78E–10	9.98E–08	3.40E–09	2.51E–10	6.97E–07	7.99E–10	3.36E–10	3.23E–07

Source: Calculated in Excel using Equation 6.15-5; file name *GW Protection Conversion Factors.xls* (Appendix A).

Table 6.15-6. Conversion Factors (Sv/yr per Bq/m^3) for Calculating Annual Beta-Gamma Dose from Drinking 2 Liters of Water per Day

Organ or Tissue	^{14}C	^{36}Cl	^{79}Se	^{90}Sr	^{99}Tc	^{126}Sn	^{129}I	^{135}Cs	^{137}Cs	^{228}Ra	^{228}Th
Adrenals	4.18E–10	5.89E–10	7.06E–10	4.85E–10	2.83E–11	7.21E–10	8.99E–11	1.40E–09	1.02E–08	1.13E–07	1.57E–09
Bone Surface	4.18E–10	5.89E–10	7.06E–10	2.99E–07	2.83E–11	4.07E–09	2.91E–10	1.40E–09	1.01E–08	1.64E–05	3.81E–08
Brain	4.18E–10	5.89E–10	7.06E–10	4.85E–10	2.83E–11	5.31E–10	1.04E–10	1.40E–09	8.62E–09	1.12E–07	1.53E–09
Breast	4.18E–10	5.89E–10	7.06E–10	4.85E–10	2.83E–11	3.52E–10	8.33E–11	1.40E–09	8.18E–09	1.11E–07	1.54E–09
Stomach Wall	4.59E–10	8.18E–10	7.52E–10	1.44E–09	1.59E–09	1.50E–09	1.45E–10	1.46E–09	9.79E–09	1.12E–07	3.65E–09
Small Intestine Wall	4.19E–10	5.95E–10	7.30E–10	2.70E–09	1.35E–10	3.51E–09	9.20E–11	1.41E–09	1.02E–08	1.14E–07	5.22E–09
Upper Large Intestine Wall	4.24E–10	6.57E–10	1.04E–09	1.41E–08	1.00E–09	1.27E–08	1.64E–10	1.59E–09	1.05E–08	1.30E–07	1.34E–08
Lower Large Intestine Wall	4.36E–10	7.89E–10	1.68E–09	3.90E–08	2.87E–09	3.40E–08	3.15E–10	1.93E–09	1.22E–08	1.63E–07	1.49E–08
Kidneys	4.18E–10	5.89E–10	2.36E–08	4.85E–10	2.83E–11	7.02E–10	8.84E–11	1.40E–09	9.86E–09	3.16E–07	3.30E–08
Liver	4.18E–10	5.89E–10	1.02E–08	4.85E–10	3.76E–11	5.76E–10	8.91E–11	1.40E–09	9.93E–09	7.60E–07	1.00E–08
Extrathoracic Airways	4.18E–10	5.89E–10	7.06E–10	4.85E–10	2.83E–11	4.67E–10	1.04E–10	1.40E–09	9.57E–09	1.12E–07	1.53E–09
Lung	4.18E–10	5.89E–10	7.06E–10	4.85E–10	2.83E–11	4.79E–10	1.12E–10	1.40E–09	9.28E–09	1.12E–07	1.54E–09
Muscle	4.18E–10	5.89E–10	7.06E–10	4.85E–10	2.83E–11	6.36E–10	2.20E–10	1.40E–09	9.13E–09	1.12E–07	1.56E–09
Ovaries	4.18E–10	5.89E–10	1.33E–09	4.85E–10	2.83E–11	2.13E–09	9.35E–11	1.40E–09	1.04E–08	1.57E–07	1.77E–09
Pancreas	4.18E–10	5.89E–10	3.66E–09	4.85E–10	2.83E–11	6.86E–10	9.13E–11	1.40E–09	1.05E–08	1.12E–07	1.59E–09
Red Bone Marrow	4.18E–10	5.89E–10	7.06E–10	1.31E–07	2.83E–11	2.15E–09	1.02E–10	1.40E–09	9.57E–09	1.69E–06	4.86E–09
Skin	4.18E–10	5.89E–10	7.06E–10	4.85E–10	2.83E–11	4.25E–10	1.04E–10	1.40E–09	7.82E–09	1.12E–07	1.54E–09
Spleen	4.18E–10	5.89E–10	4.07E–09	4.85E–10	2.83E–11	5.71E–10	8.99E–11	1.40E–09	9.86E–09	1.13E–07	1.58E–09
Testes	4.18E–10	5.89E–10	2.09E–09	4.85E–10	2.83E–11	5.23E–10	8.47E–11	1.40E–09	9.20E–09	1.56E–07	1.55E–09
Thymus	4.18E–10	5.89E–10	7.06E–10	4.85E–10	2.83E–11	4.21E–10	1.26E–10	1.40E–09	9.57E–09	1.12E–07	1.54E–09
Thyroid	4.18E–10	5.89E–10	7.06E–10	4.85E–10	7.38E–10	4.67E–10	1.54E–06	1.40E–09	9.57E–09	1.12E–07	1.53E–09
Uterus	4.18E–10	5.89E–10	7.06E–10	4.85E–10	2.83E–11	1.17E–09	9.20E–11	1.40E–09	1.06E–08	1.12E–07	1.65E–09
Urinary Bladder Wall	4.18E–10	1.53E–09	8.11E–10	1.08E–09	1.17E–10	9.43E–10	3.14E–10	1.59E–09	1.06E–08	1.12E–07	1.71E–09
Whole Body	4.24E–10	6.79E–10	2.11E–09	2.22E–08	4.69E–10	3.76E–09	7.74E–08	1.46E–09	9.93E–09	5.09E–07	4.56E–09

Table 6.15-6. Conversion Factors (Sv/yr per Bq/m^3) for Calculating Annual Beta-Gamma Dose from Drinking 2 Liters of Water per Day (Continued)

Organ or Tissue	^{232}Th= ^{228}Ra +^{228}Th	^{232}U =^{228}Th	^{237}Np	^{229}Th	^{228}U	^{226}Ra	^{210}Pb	^{226}Ra +^{210}Pb	^{243}Am	^{235}U	^{227}Ac
Adrenals	1.15E–07	1.57E–09	9.86E–12	8.26E–09	1.65E–12	1.35E–11	6.45E–08	6.45E–08	6.57E–12	3.54E–13	3.46E–08
Bone Surface	1.65E–05	3.81E–08	6.57E–11	2.63E–06	3.46E–11	1.41E–10	1.65E–05	1.65E–05	1.88E–11	4.25E–12	6.84E–06
Brain	1.13E–07	1.53E–09	2.97E–13	8.19E–09	4.75E–13	7.50E–12	6.45E–08	6.45E–08	3.75E–14	1.31E–14	3.46E–08
Breast	1.13E–07	1.54E–09	1.52E–12	8.19E–09	6.66E–13	9.04E–12	6.45E–08	6.45E–08	7.96E–13	4.38E–14	3.46E–08
Stomach Wall	1.16E–07	3.65E–09	2.13E–10	9.42E–09	7.32E–10	1.27E–09	6.49E–08	6.62E–08	2.52E–10	1.42E–10	3.54E–08
Small Intestine Wall	1.19E–07	5.22E–09	5.65E–10	9.18E–09	1.87E–09	5.66E–10	6.54E–08	6.59E–08	6.22E–10	3.21E–10	3.51E–08
Upper Large Intestine Wall	1.43E–07	1.34E–08	2.70E–09	1.37E–08	1.10E–08	2.17E–10	7.11E–08	7.13E–08	2.87E–09	1.41E–09	4.10E–08
Lower Large Intestine Wall	1.78E–07	1.49E–08	7.45E–09	3.51E–08	3.15E–08	3.28E–11	8.39E–08	8.39E–08	6.36E–09	2.48E–09	5.49E–08
Kidneys	3.49E–07	3.30E–08	2.54E–11	2.75E–08	1.40E–11	2.89E–10	2.74E–06	2.74E–06	1.53E–11	9.93E–13	5.22E–08
Liver	7.70E–07	1.00E–08	1.53E–11	1.42E–07	5.92E–12	3.20E–11	1.41E–06	1.41E–06	1.00E–11	7.20E–13	1.48E–06
Extrathoracic Airways	1.13E–07	1.53E–09	4.14E–13	8.19E–09	5.01E–13	7.65E–12	6.45E–08	6.45E–08	1.04E–13	1.45E–14	3.46E–08
Lung	1.13E–07	1.54E–09	2.58E–12	8.19E–09	7.91E–13	9.82E–12	6.45E–08	6.45E–08	1.52E–12	9.06E–14	3.46E–08
Muscle	1.13E–07	1.56E–09	1.94E–11	8.26E–09	2.94E–12	1.09E–11	6.45E–08	6.45E–08	1.21E–11	1.00E–12	3.46E–08
Ovaries	1.59E–07	1.77E–09	1.72E–10	9.79E–09	2.49E–11	2.09E–11	6.45E–08	6.45E–08	1.09E–10	1.37E–11	1.37E–07
Pancreas	1.13E–07	1.59E–09	2.01E–11	8.26E–09	3.00E–12	2.85E–11	6.45E–08	6.45E–08	1.45E–11	1.12E–12	3.46E–08
Red Bone Marrow	1.69E–06	4.86E–09	3.52E–11	2.54E–07	2.14E–11	2.38E–11	1.82E–06	1.82E–06	1.89E–11	1.35E–12	3.59E–07
Skin	1.13E–07	1.54E–09	6.15E–12	8.19E–09	1.27E–12	8.88E–12	6.45E–08	6.45E–08	3.60E–12	2.11E–13	3.46E–08
Spleen	1.14E–07	1.58E–09	1.59E–11	8.26E–09	2.41E–12	2.52E–11	2.06E–06	2.06E–06	1.10E–11	7.02E–13	3.47E–08
Testes	1.58E–07	1.55E–09	1.58E–11	9.79E–09	3.44E–12	8.28E–12	6.45E–08	6.45E–08	8.47E–12	4.13E–13	1.36E–07
Thymus	1.13E–07	1.54E–09	1.23E–12	8.19E–09	6.13E–13	8.65E–12	6.45E–08	6.45E–08	5.83E–13	3.16E–14	3.46E–08
Thyroid	1.13E–07	1.53E–09	4.14E–13	8.19E–09	5.01E–13	7.65E–12	6.45E–08	6.45E–08	1.04E–13	1.45E–14	3.46E–08
Uterus	1.13E–07	1.65E–09	7.82E–11	8.26E–09	1.03E–11	1.86E–11	6.45E–08	6.45E–08	5.14E–11	3.55E–12	3.46E–08
Urinary Bladder Wall	1.14E–07	1.71E–09	5.60E–11	8.26E–09	7.47E–12	1.44E–11	6.51E–08	6.51E–08	3.43E–11	2.09E–12	3.47E–08
Whole Body	5.14E–07	4.56E–09	6.41E–10	7.29E–08	2.48E–09	1.83E–10	5.09E–07	5.10E–07	5.84E–10	2.45E–10	2.36E–07

Source: Calculated in Excel using Equation 6.15-3; file name *GW Protection Conversion Factors.xls* (Appendix A).

6.15.2 Inhalation Dose Factors

The purpose of the inhalation dose factors is to provide the means for evaluating inhalation dose that the RMEI could receive during a volcanic eruption, before the deposition of volcanic ash on the ground is completed. The period of volcanic eruption is not included in the calculation of biosphere dose conversion factors for the volcanic ash exposure scenario (volcanic BDCFs) because the BDCFs are calculated for the conditions that exist after the ash deposition and redistribution had taken place. BDCFs include dose contributions from inhalation exposure to resuspended ash and contaminated soil, external exposure, and ingestion exposure and are calculated on the annual basis, regardless of the actual eruption time and day. The period of volcanic eruption is treated separately and its consequences are evaluated as those arising from the exposure occurring during an event of a limited duration (acute or near-acute exposure), rather than from a long-term, chronic exposure thereafter. The latter is evaluated using the BDCFs. The inhalation dose factors are used to evaluate whether the doses received by the RMEI during an eruption need to be included in calculation of the expected dose and, if necessary, incorporate this dose contribution to the first year of exposure as calculated from the BDCFs.

Because during the eruption higher concentrations of airborne radioactive particulates are expected, inhalation of airborne contaminated ash particles is the only pathway considered in the analysis for this phase. The other possible pathways, such as external exposure from contaminated ash, are inherently included in the volcanic BDCFs (Sections 6.3.2 and 6.5). Inhalation exposure arising from direct gaseous volcanic emissions was not considered because gaseous radionuclides were not included among radionuclides of interest (Section 6.3.1).

For the eruption period, inhalation dose factors should be used instead of BDCFs. Radionuclide-specific inhalation dose factors are numerically equal to the daily (committed) effective dose to the RMEI from inhalation (Sv/d) resulting from a unit activity concentration of a given primary radionuclide in the outdoor air (1 Bq/m^3).

This section describes the development of the inhalation dose factors for evaluating doses from inhalation of particulate matter during a volcanic eruption. Section 6.15.2.1 contains a discussion of the results of mass loading measurements taken during volcanic eruptions. These values are presented for reference only to allow comparisons with the values of annual average mass loading for the receptor environments. The latter values were used as input for the biosphere model to calculate volcanic BDCFs (Table 6.6-3). Again, it needs to be recognized, that the mass loading values used in the biosphere model represent annual average conditions, while the values summarized in Section 6.15.2.1 usually represent instantaneous or short-term conditions.

6.15.2.1 Mass Loading Levels During the Volcanic Eruption

This section contains a summary of airborne particle concentration measurements taken during and immediately after volcanic eruptions. This summary is provided to develop an understanding of the levels of airborne ash concentrations that may occur at the location of the receptor following a volcanic eruption. This information may be used to support evaluation of the dose to the RMEI during a volcanic eruption, since the biosphere model does not evaluate the dose during the period of active ash fall. Inhalation dose from airborne particulate concentrations during a volcanic eruption will be calculated, if necessary, as a component of performance assessment. The data presented in this section were not directly used in the biosphere model.

The data in this section were collected following volcanic eruptions at four widely spaced locations. Data at each location include measurements made over time and at different local collecting sites. Most of the measurements reported in this section were taken at ambient monitoring stations during or soon after ash-fall events. Ambient monitoring stations usually are centrally located in communities. The concentrations of airborne particles measured at those stations are representative of regional or local conditions that are not influenced by specific, immediately adjacent activities.

Mount St. Helens—Total suspended particulate (TSP) concentrations at Yakima, Washington, were as high as 35.6 mg/m^3 and averaged 13.3 mg/m^3 during the first week following the May 18, 1980 eruption of Mount St. Helens (Merchant et al. 1982 [DIRS 160102], pp. 912 to 913). Five to 10 mm of ash were deposited at Yakima during that eruption (Sarna-Wojcicki et al. 1982 [DIRS 160227], Figure 336).

The peak, short-term (about 4-hour) TSP concentration measured in Missoula, Montana, on May 19 (the day of greatest ash fall at that location) was 19.9 mg/m^3. The average daily concentrations there decreased from 11.1 mg/m^3 on May 19 to 0.9 mg/m^3 on May 22 (Johnson et al. 1982 [DIRS 164149], pp. 1067 to 1068). Approximately 2.5 to 5 mm of ash was deposited at Missoula (Sarna-Wojcicki et al. 1982 [DIRS 160227], Figure 336).

The daily average TSP concentration in Clarkston, Washington, on May 18 was 0.68 mg/m^3. Approximately 0.5 mm of ash was deposited there from that day's eruption. At Longview, Washington, the average daily concentration on May 27 was 1.42 mg/m^3. Approximately 1 to 2 mm of ash was deposited on that city during an eruption on May 25 (DTN: MO0008SPATSP00.013 [DIRS 151750], EPA monitoring sites 53-003-0003 and 53-015-0008; Sarna-Wojcicki et al. 1982 [DIRS 160227], Figures 336 and 344).

Approximately 10% or less of the ash from Mount St. Helens was ≤10 µm (PM_{10}) (Craighead et al. 1983 [DIRS 160338], p. 6; Buist et al. 1986 [DIRS 144632], p. 40). PM_{10} is defined as particles collected with an upper 50% (collection efficiency) cut point of 10 µm aerodynamic diameter and a specified penetration curve. For brevity and following the common convention, PM_{10} is frequently referred to as particles with an aerodynamic diameter less than or equal to 10 µm, although this term is not entirely accurate because it implies an upper 100% cut point of 10 µm. (The same convention is also used for other values of cut points, e.g., PM_4 or $PM_{2.5}$.)

Soufriere Hills—Peak PM_{10} concentrations at 3 locations during an eruption of the Soufriere Hills volcano (Montserrat, British West Indies) in 1997 were approximately 0.3 to 1.0 mg/m^3 outside a school, 0.1 mg/m^3 inside that school, and 0.4 to 1.5 mg/m^3 outside a hotel (Baxter et al. 1999 [DIRS 150713], Figure 3 and p. 1,142). The fine ashfall deposits from this volcano typically contained 60% to 70% (by weight) of 10 to 125 µm particles and 13% to 20% of particles <10 µm. Using a ratio of PM_{10} to TSP concentrations of 1:5 (calculated based on the average fraction of particles <10 µm in the deposited ash), peak TSP concentrations were approximately 1.5 to 5.0 mg/m^3, 0.5 mg/m^3, and 2.0 to 7.5 mg/m^3, respectively at the three locations. These concentrations likely did not include resuspended particles as they were taken late in the day after activities at the sites had ceased.

Searl et al. (2002 [DIRS 160104], Table 11) estimated mean personal PM_{10} exposure concentrations for various activity levels during and after eruptions of the Soufriere Hills volcano. Using a PM_{10} to TSP ratio of 1:5, estimated TSP concentrations during periods with alert levels to very high levels of ash were 1.5 to 5 mg/m^3 for people inactive indoors, 2.5 to 10 mg/m^3 for active indoors, 5 to 15 mg/m^3 for active outside, and 25 to 50 mg/m^3 for dusty occupations. These estimates include the influence of particle resuspension during activities.

Mt. Spurr—The maximum hourly PM_{10} concentration in Anchorage Alaska, during the 1992 eruption of Mt. Spurr was 3 mg/m^3. The 24-hour average concentration the day after the eruption was 0.565 mg/m^3. Approximately 8% to 15% (by weight) of ash particles from that eruption collected near Anchorage were <15 µm, and 5% to 10% were between 2.5 and 10 µm (McGimsey et al. 2001 [DIRS 160386], Figures 11 and 12), resulting in an approximate PM_{10} to TSP ratio of 1:10. Based on this ratio, the peak TSP concentration in Anchorage was about 30 mg/m^3 and the 24-hour average was about 5.7 mg/m^3 (Gordian et al. 1996 [DIRS 160111], p. 290).

Mt. Sakurijima—Yano et al. (1990 [DIRS 160112], p. 373) stated that peak, 2-minute concentrations higher than 2 mg/m^3 have been measured in high-exposure areas after eruptions of Mount Sakurijima (Japan), and that "these high levels of suspended particulate matter seldom last long, and they usually decrease rapidly to approximately 0.1 mg/m^3."

In summary, daily average concentrations of ash outdoors during an eruption may be as low or lower than 1 mg/m^3 for light ashfall events or as high or higher than 15 mg/m^3 for high ashfall events. Concentrations indoors would be much lower (see also BSC 2006 [DIRS 177101], Section 6.4). It should be noted that high ambient concentrations reported here do not result in an under-representation of the risk estimate because they likely are overestimates of concentrations inhaled because it is well documented that during volcanic eruptions people take protective actions, such as staying indoors and wearing masks, to reduce the amount of ash they inhale (Johnson et al. 1982 [DIRS 164149]; Buist et al. 1986 [DIRS 144632]; Nania et al. 1994 [DIRS 164156]).

6.15.2.2 Development of Inhalation Dose Factors

As noted before, inhalation dose factors were developed to account for the inhalation exposure during a volcanic eruption. The inhalation dose factors are developed separately from BDCFs because BDCFs are representative of annual exposures and do not address the relatively short-term exposure conditions during a volcanic eruption. The inhalation dose factor for a given primary radionuclide is numerically equal to the daily dose (committed effective dose) to the RMEI resulting from a unit concentration (e.g., 1 Bq/m^3) of a given primary radionuclide in the outdoor air. The daily dose refers to the committed dose from an one-day intake of a radionuclide and associated short-lived decay products, if present.

In the biosphere model, the dose to the RMEI from inhalation exposure to a given primary radionuclide i and its short-lived decay products present in airborne particulates is calculated (based on Equation 6.4.8-2 expressed in terms of the daily dose rather than the annual dose) as:

$$D_{inh,p,i} = EDCF_{inh,i}\left[\sum_{n} Ca_{i,n} BR_n \sum_{m}\left(PP_m \; t_{n,m}\right)\right] \quad \text{(Eq. 6.15-6)}$$

where

$D_{inh,p,i}$ = daily dose from inhalation exposure to primary radionuclide i in resuspended particles (Sv/d)

$EDCF_{inh,i}$ = effective dose coefficient for inhalation of primary radionuclide i (Sv/Bq)

n = environment index; n = 1 for active outdoors, 2 for inactive outdoors, 3 for active indoors, 4 for asleep indoors, and 5 for away from the contaminated area

$Ca_{i,n}$ = activity concentration of primary radionuclide i in air for environment n (Bq/m^3)

BR_n = breathing rate for environment n (m^3/h)

m = population group index; m = 1 for local outdoor workers, 2 for local indoor workers, 3 for commuters, and 4 for non-workers

PP_m = fraction of total population in population group m

$t_{n,m}$ = number of hours per day a population group m spends in environment n (h/d).

For calculating the annual inhalation dose in the biosphere model, the exposure times for different population groups and environments, as well as the associated breathing rates, were developed (see Table 6.6-3 for a list of model input parameters). For the duration of volcanic eruption, environment-specific breathing rates and the fractions of time spent indoors versus outdoors are assumed to be relatively unchanged compared to the pre-eruption conditions to avoid speculations about the possible people behaviors. Therefore, the same parameter values for lifestyle characteristics of the RMEI as those used for the BDCF calculation were used to develop inhalation dose factors. Because a volcanic eruption is an unusual event, it is possible that people would not behave as they would under normal circumstances. However, it is difficult to predict how the human behavior would change. Some people may seek shelter from falling ash and spend more time indoors where exposure would be reduced, while other people may, for instance, perform ash removal from their property and spend more time outdoors.

Ash depths 18 km downwind from Yucca Mountain, for the wind blowing to the south, were predicted to range from 3.6×10^{-5} to 12.4 cm, based on 100 realizations of the ASHPLUME model (Appendix G). Approximately 58% of the predicted depths of deposited ash were less than 1 cm, 92% were less than 3 cm. Ash depths at the location of the RMEI (18 km south of Yucca Mountain) under the variable wind conditions would be much lower because the wind at Yucca Mountain blows to the south infrequently (SNL 2007 [DIRS 177431], Figure 8-1).

For the small amount of ashfall and an eruption lasting for several days, it is likely that the airborne particulate concentrations would not be substantially different from the pre-eruption levels. If this is the case, people would not modify their behavior to the extent that their overall average daily breathing rate would be affected, in which case the assumption is realistic. If airborne particulate concentrations were much greater than the pre-eruption levels, people would take actions to reduce the amount of ash they inhale, such as staying indoors and wearing masks (Section 6.15.2.1), and the assumption of a behavior unchanged relative to the pre-eruption conditions would lead to conservative results. In summary, using the same lifestyle characteristics parameter values for the calculation of the inhalation dose factors as those used for the volcanic BDCF calculations is considered technically defensible and not to result in an under-representation of the risk estimate.

The biosphere model divides the biosphere into the five environments (Section 6.4.2.1). These mutually exclusive environments represent the behavioral and environmental combinations for which a person may receive a substantially different rate of exposure via inhalation or external exposure. These environments are:

Away from Potentially Contaminated Area—This category encompasses the region away from areas contaminated by groundwater or volcanic ash. Time spent away from the contaminated area includes time spent working and commuting to work by those that work outside of contaminated areas.

Active Outdoors—This category encompasses those locations within the contaminated area where people actively disturb soil surface thus increasing particulate and contaminant concentration in air. Time spent active outdoors is equivalent to the time spent outdoors in contaminated areas conducting activities that resuspend soil.

Inactive Outdoors—This category represents outdoor locations within the contaminated area not associated with soil-surface disturbing activities. In this environment people spend time commuting and conducting activities that do not resuspend soil.

Asleep Indoors—This category represents indoor locations within the contaminated area where people spend time sleeping.

Active Indoors—This category represents indoor locations within contaminated areas where people spend time awake, including work time. In the biosphere model, time spent in this environment is calculated as the remainder of the day not spent in the other environments.

Two environments that are not associated with activities that may resuspend dust are the inactive outdoor and asleep indoor environments. The modes of the mass loading distributions are 0.060 and 0.030 mg/m^3 for the inactive outdoor and asleep indoor environments, respectively (Table 6.6-3), indicating that dwellings provide about 50% reduction of the outdoor mass loading level under the conditions of no soil disturbance. Based on this comparison, it is postulated that during volcanic eruption, the average level of mass loading indoors arising from the original tephra fallout would be less than that for the outdoor environment. This assumption does not pertain to the concentrations of particulates in air that were resuspended due to atmospheric or mechanical processes following the initial deposition (there are addressed in the BDCFs), but rather to the ash descending through the atmosphere.

To account for the differences in the indoor versus outdoor air concentrations of radionuclides, the indoor reduction factor was defined as the ratio of the atmospheric mass loading values indoor and outdoor that persist in the absence of soil disturbing activities causing resuspension of deposited ash. The indoor reduction factor thus only accounts for the decrease in the outdoor mass loading provided by dwellings. Undisturbed conditions outdoors and indoors were chosen to represent the value of this parameter because the process of resuspension and the resulting inhalation of resuspended particulates are included in the BDCFs.

Thus, assuming that the radionuclide concentration in the indoor air is a fraction of that in the outdoor air, Equation 6.15-6 can be modified as:

$$\begin{aligned} D_{inh,p,i} &= EDCF_{inh,i}\left[\sum_n Ca_{i,outdoor}\ IRF_n\ BR_n \sum_m \left(PP_m\ t_{n,m}\right)\right] \\ &= Ca_{i,outdoor} EDCF_{inh,i}\left[\sum_n IRF_n\ BR_n \sum_m \left(PP_m\ t_{n,m}\right)\right] \\ &= Ca_{i,outdoor}\ DF_i \end{aligned} \qquad \text{(Eq. 6.15-7)}$$

where

$Ca_{i,outdoor}$ = activity concentration of a radionuclide i in outdoor air during the period of tephra fallout (Bq/m^3)

IRF_n = indoor reduction factor for activity concentration in air (dimensionless)

DF_i = inhalation dose factor for a primary radionuclide i (Sv/d per Bq/m^3).

The activity concentration of a radionuclide i in outdoor air for the ash that has not yet fallen on the ground, $Ca_{i,outdoor}$, does not depend on the outdoor environment, as defined for the biosphere model (i.e., active outdoor and inactive outdoor), because this quantity is independent of human activities. The indoor reduction factor is equal to 1 for the outdoor environments (active outdoor and inactive outdoor) and to 0.5 for the indoor environments (asleep indoor and active indoor). The term in the brackets in Equation 6.15-7 is the effective daily breathing rate, i.e., the volume of outdoor air that contains the same amount of contaminant (radionuclide) as the air that is breathed in by a person in one day.

An indoor reduction factor of 0.5 is considered conservative since measurements of indoor to outdoor air concentration ratios during volcanic eruptions were found to be less than 0.5 (Baxter et al. 1999 [DIRS 150713], Figure 3 and p. 1142). However, since the inhalation dose factors are likely to be used as a screening tool, it is appropriate to use more conservative values so as not to underestimate potential dose.

The inhalation dose factor in Equation 6.15-7 is expressed as:

$$DF_i = EDCF_{inh,i}\left[\sum_n IRF_n \; BR_n \sum_m \left(PP_m \; t_{n,m}\right)\right] \qquad \text{(Eq. 6.15-8)}$$

The effective dose coefficients for inhalation include, where applicable, contributions from the associated short-lived decay products. The effective dose coefficients for inhalation and the contributing decay products are listed in Table 6.4-5. These dose coefficients were developed for radiation protection in the workplace and are usually applied to chronic low-dose, low-dose rate exposures. However, the values that are used for chronic exposures are also recommended for conducting radiological assessments for consequence analysis in the case of accidental releases (Sjoreen et al. 2001 [DIRS 164093], Section 4.9.1), where calculated doses can exceed 250 rem (Sjoreen et al. 2001 [DIRS 164093], Table 7.1).

The inhalation dose factors are calculated as deterministic quantities using the mean values of parameters. Calculations of the individual terms in Equation 6.15-8 are shown in Table 6.15-7.

Table 6.15-7. Supplementary Calculations Supporting Development of Inhalation Dose Factors

	Proportion of Population, PP_m	Mean Time Spent in Environment, $t_{n,m}$ (h/d)			
		Active Outdoors	**Inactive Outdoors**	**Asleep Indoors**	**Active Indoors**
Non-workers	39.20%	0.3	1.2	8.3	12.2
Commuters	12.50%	0.3	2	8.3	5.1
Local outdoor workers	5.50%	3.1	4.2	8.3	6.4
Local indoor workers	42.80%	0.3	1.5	8.3	11.9
Results of Calculation of Terms in Equation 6.3-3					
		Active Outdoors	**Inactive Outdoors**	**Asleep Indoors**	**Active Indoors**
$\sum_m (PP_m \ t_{n,m})$ (h/d)		0.454	1.593	8.3	10.865
BR_n (m^3/h)		1.57	1.08	0.39	1.08
IRF_n (dimensionless)		1	1	0.5	0.5
$IRF_n \ BR_n \sum_m (PP_m \ t_{n,m})$ (m^3/d)		0.713	1.721	1.619	5.867
$\sum_n IRF_n \ BR_n \sum_m (PP_m \ t_{n,m})$ (m^3/d)	9.92				

Source: DTN: MO0407SPACRBSM.002 [DIRS 170677]

NOTE: The symbols and formulas in the table are the same as those in Equation 6.15-8.

Excel file *Inhalation Dose Factor Calculations.xls*, Appendix A.

The inhalation dose factors were calculated for 27 primary radionuclides listed in Table 6.15-8. In addition, dose factor sums were produced for the three primary radionuclides, ^{226}Ra, ^{232}Th and ^{232}U, to include the contribution from their long-lived decay products, which themselves are primary radionuclides, in the case the concentrations of these decay products were not separately calculated in the TSPA model. The inhalation dose factor sums included the following radionuclides: ^{226}Ra + ^{210}Pb, ^{232}Th + ^{228}Ra + ^{228}Th, and ^{232}U + ^{228}Th, assuming radioactive equilibrium with a parent radionuclide.

Table 6.15-8. Primary Radionuclides and Decay Products Included in the Inhalation Dose Factors

Primary Radionuclide	Decay Products Included in Inhalation Dose Factor
^{90}Sr	^{90}Y
^{99}Tc	
^{126}Sn	
^{129}I	
^{137}Cs	^{137m}Ba
^{210}Pb	^{210}Bi, ^{210}Po
^{226}Ra	^{222}Rn, ^{218}Po, ^{214}Pb, ^{218}At, ^{214}Bi, ^{214}Po, ^{210}Tl
^{228}Ra	^{228}Ra, ^{228}Ac
^{227}Ac	^{227}Th, ^{223}Fr, ^{223}Ra, ^{219}Rn, ^{215}Po, ^{211}Pb, ^{211}Bi, ^{207}Tl, ^{211}Po
^{228}Th	^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po, ^{208}Tl
^{229}Th	^{225}Ra, ^{225}Ac, ^{221}Fr, ^{223}At, ^{213}Bi, ^{213}Po, ^{209}Tl, ^{209}Pb
^{230}Th	
^{232}Th	
^{231}Pa	
^{232}U	
^{233}U	
^{234}U	
^{235}U	
^{236}U	
^{238}U	^{234}Th, ^{234m}Pa, ^{234}Pa
^{237}Np	^{233}Pa
^{238}Pu	
^{239}Pu	
^{240}Pu	
^{242}Pu	
^{241}Am	
^{243}Am	^{239}Np

Source: Table 6.3-7

^{232}Th is accompanied in the volcanic ash and waste form mix by its relatively long-lived decay products, ^{228}Ra and ^{228}Th (and their short-lived decay products). Although ^{228}Ra and ^{228}Th are the primary radionuclides, they may not be tracked in TSPA because of their short half-lives, which are only 5.75 and 1.91 yr, respectively. However, the dose contribution of ^{228}Ra and ^{228}Th must be taken into account. This can be accomplished by combining inhalation dose factors for ^{228}Ra and ^{228}Th with that of ^{232}Th, under the assumption of radioactive equilibrium between these radionuclides.

^{232}U is accompanied in the ash fall by its relatively long-lived decay product, ^{228}Th and its short-lived decay products. The dose contribution from ^{228}Th in equilibrium with ^{232}U could be included by adding their inhalation dose factors.

In a similar fashion, if the concentration of ^{210}Pb in the ash is not calculated and if equilibrium could be assumed to exist between the concentrations ^{226}Ra and ^{210}Pb in the soil, their inhalation dose factors should be combined to account for the ^{210}Pb dose contribution as a decay product of ^{226}Ra.

Inhalation dose factors for evaluating doses during volcanic eruptions are listed in Table 6.15-9.

Table 6.15-9. Inhalation Dose Factors for Eruptive Phase of the Volcanic Scenario

Radionuclide	Inhalation Dose Factor, Sv/d per Bq/m^3
^{90}Sr	1.57E–06
^{99}Tc	1.32E–07
^{126}Sn	1.54E–06
^{129}I	3.56E–07
^{137}Cs	3.89E–07
^{210}Pb	9.93E–05
^{226}Ra + ^{210}Pb	9.46E–05
^{226}Ra	1.94E–04
^{228}Ra	1.59E–04
^{227}Ac	1.74E–03
^{228}Th	4.29E–04
^{229}Th	2.53E–03
^{230}Th	1.01E–03
^{232}Th	1.09E–03
^{232}Th + ^{228}Ra + ^{228}Th	1.68E–03
^{231}Pa	2.28E–03
^{232}U	3.67E–04
^{232}U + ^{228}Th	7.96E–04
^{233}U	9.51E–05
^{234}U	9.32E–05
^{235}U	8.40E–05
^{236}U	8.67E–05
^{238}U	7.98E–05
^{237}Np	4.93E–04
^{238}Pu	1.07E–03
^{239}Pu	1.18E–03
^{240}Pu	1.18E–03
^{242}Pu	1.12E–03
^{241}Am	9.56E–04
^{243}Am	9.49E–04

Source: Excel file *Inhalation Dose Factor Calculations.xls* (Appendix A).

To calculate the daily dose from inhaling a specific radionuclide during a volcanic eruption, the activity concentration of that radionuclide in air should be multiplied by the appropriate dose factor. The total daily inhalation dose from concentrations of primary radionuclides in air is then calculated as a sum of doses from all those radionuclides:

$$D_{inh} = \sum_i D_{inh,i} = \sum_i DF_i \times Ca_i \qquad \text{(Eq.6.15-9)}$$

where

$D_{inh,\,i}$ = daily inhalation dose for a primary radionuclide *i* (Sv/d)

DF_i = inhalation dose factor for a primary radionuclide *i* (Sv/d per Bq/m^3)

Ca_i = one-day average activity concentration of a primary radionuclide *i* in outdoor air (Bq/m^3).

The dose calculated using Equation 6.15-9 is the daily dose (committed effective dose from daily intake) from inhalation intakes during the eruptive phase of the scenario. To obtain the expected annual dose contribution from inhalation during the entire ash fall event, the daily doses should be calculated for all days when the ash fall occurs. The doses from daily intakes should then be combined, but the number of days included in the sum should not exceed the number of days in a year. If the duration of a volcanic eruption exceeds one year, any daily intakes occurring in the following year would contribute to that year's dose.

The inhalation dose factors were developed using the characteristics of the specified receptor, the RMEI, consistent with the receptor used in the biosphere model. This receptor is identified in 10 CFR 63.312 [DIRS 173273]. The inhalation dose factors only apply for the receptor, for which they were constructed. If used for other situations, the inhalation dose factors may not apply.

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7. VALIDATION

As required by SCI-PRO-006, developed models had to be validated to ensure that they are suitable for the intended purpose. The approach to validating the current biosphere model and the model validation criteria are specified in the TWP (BSC 2006 [DIRS 176938], Section 2.2). Although the minimum validation level of a model is Level I, in this report the biosphere model is validated to Level II (which includes Level I requirements). This is because Level II validation requirements are more stringent and provide a greater level of confidence in the model. The model validation plan, developed under LP-2.29Q-BSC, *Planning for Science Activities*, also meets the requirements for Level II model validation in SCI-PRO-002, Attachment 3.

The biosphere model incorporates the requirements of 10 CFR 63 ([DIRS 173273]; 70 FR 53313 [DIRS 178394]), which established the characteristics of the reference biosphere (10 CFR 63.305) and the RMEI (10 CFR 63.312). The results of the biosphere model are used to demonstrate compliance with the postclosure individual protection standard in 10 CFR 63.311 (70 FR 53313 [DIRS 178394]).

The output of the biosphere model has a direct impact on the results of the TSPA dose calculations because the all-radionuclide dose is calculated as the sum of the products of radionuclide- and exposure scenario-specific BDCFs and the concentrations of individual radionuclides in the groundwater and in the soil contaminated by volcanic tephra.

To determine the validation level for the biosphere model the following factors were taken into consideration. The biosphere model was constructed for a specific assessment context and for a specific environment. It is not extrapolated over large distances, and generally does not depend on time, i.e., the BDCFs are not calculated as a function of time. For radionuclides with high solid-to-liquid partition coefficients, the surface soil submodel includes extended timeframes by assuming long-term irrigation. These radionuclides continue to accumulate in the surface soil during the period of long-term irrigation. Radionuclides with low partition coefficients reach equilibrium concentrations in the surface soil following a shorter irrigation period. Parameters developed for the surface soil submodel incorporate long timeframes using parameter value distributions for the rates of accumulation and depletion, which address uncertainty in the parameter values.

Overall uncertainty in the biosphere model is due to uncertainties in the conceptual representation, mathematical representation, and parameter values in each component submodel (Section 6.6). All of these sources of uncertainty are evaluated; however, uncertainty that is quantified and propagated through the biosphere model is due to uncertainty in the input parameters. A typical range of BDCF values, due to uncertainty in the input parameter values, is about one to two orders of magnitude (Sections 6.13 and 6.14). Uncertainty in the results of the biosphere model is evaluated through submodel comparisons.

All models used to support the license application submittal, the determination of compliance, and the subsequent defense of the license application, including the models providing direct input to the TSPA model shall be validated to at least Level I. The biosphere model was validated to Level II to improve confidence in the model results. As noted before, the biosphere system, as modeled here, does not influence the potential performance of the repository because it is not categorized as a barrier important to safety or waste isolation. Rather, it is used as a tool to evaluate this performance.

A submodel is considered valid if it is consistent with submodels used and documented in other national or international dose assessment programs, and not using an alternative submodel can be justified based on an explanation of the differences between it and the selected submodel. The biosphere model is valid if the model includes the applicable radionuclide transport processes and radiation dose pathways, and if each of the corresponding submodels is validated using the methods and criteria listed above.

The ERMYN biosphere model was validated to establish confidence that the conceptual (Section 6.3) and mathematical models (Sections 6.4 and 6.5) adequately represent the biosphere systems, processes, and phenomena that may affect the dose to the RMEI. The model validation approach, including the selection of published biosphere models for the comparison and the validation criteria are discussed in Section 7.1. The conceptual models (Section 7.2) and mathematical models (Section 7.3) were compared to identify similarities and differences. For submodels that differ, numerical comparisons were made (Section 7.4), and the ERMYN submodels were justified. The range of validation for the input parameters is presented in Section 7.5. The conclusions of an external review are presented in Section 7.6.

7.1 VALIDATION APPROACH

In this section, the biosphere model validation approach, the selection of published biosphere models and supporting information used for corroboration, and the criteria and level of confidence for the ACMs are discussed. The governing procedure, SCI-PRO-006, as well as the planning procedure, SCI-PRO-002, place several requirements on the validation of the mathematical model and its underlying conceptual model and their documentation. The specific requirements are discussed below. Biosphere model limitations are specified in Section 8.2.

7.1.1 Confidence Building During Model Development to Establish the Scientific Basis and Accuracy for Intended Use

Confidence building during model development was achieved by satisfying model validation requirements. Each of these requirements is discussed below to document the decisions made and activities performed to generate confidence in the model during development of the conceptual and mathematical models. The development of the model was documented in accordance with the model documentation outline (SCI-PRO-006, Attachment 2) and addresses the validation requirements as follows:

a) Evaluate and select input parameters and/or input data that are adequate for the model's intended use [SCI-PRO-002, Attachment 3, Level I Validation (1)]—As discussed in Section 6.4, biosphere model inputs include equations from several references that are used to construct the mathematical model. The model input parameters are developed in the other biosphere model documents, as explained in Section 1 and shown in Figure 1-1, with only a few exceptions (Table 6.6-3). The selection of the appropriate mathematical representation of the processes included in the biosphere model was achieved by a review of other biosphere models developed by reputable groups and used to evaluate the consequences of radionuclide transport and exposure. This is described in the following subsections. The development of the model input parameters is discussed in the parameter development reports (shown in Figure 1-1). Input parameter values were developed from site-specific data and surveys, reviews of distributions used in other models, data from analogue sites, and other information contained in applicable publications. The parameter distributions were selected to ensure that risk to the RMEI would not be underestimated. The parameter distributions incorporated the full range of reasonable variation and uncertainty in environmental variables representative of the Yucca Mountain region and the range of reasonable variation and uncertainty about the average for those parameters that represent dietary and lifestyle characteristics of the RMEI. Input parameters were defined in this report when they first appeared in the mathematical model description. The physical meaning and typical ranges were discussed.

b) Formulate defensible approximations and simplifications that are adequate for the model's intended use [SCI-PRO-002, Attachment 3, Level I Validation (2)]—All modeling approximations and simplifications are discussed in Sections 6.3.1.4 and 6.3.2.4 for the biosphere models for the groundwater and volcanic ash exposure scenarios, respectively. Rationales for the assumptions, and their use in the biosphere model, are given in Sections 6.3.1.4 and 6.3.2.4.

c) Ensure consistency with physical principles, such as conservation of mass, energy, and momentum to an appropriate degree commensurate with the model's intended use [SCI-PRO-002, Attachment 3, Level I Validation (3)]—All equations are consistent with basic physical principles (see the summary discussion on equations and their sources in Section 4.1 and Table 4.1). Conservation of mass and radionuclides was preserved in most of the developed equations, except when "double counting" was used to ensure that the risk to the receptor is not underestimated, such as in Assumption 6. Units for the parameters were checked to ensure consistency. In addition, GoldSim, which is dimensionally-aware, provides additional verification of dimensional consistency and internally carries out all unit conversions.

d) Represent important future state (aleatory), parameter (epistemic), and alternative model uncertainties to an appropriate degree commensurate with the model's intended use [SCI-PRO-002, Attachment 3, Level I Validation (4)]—Uncertainties have to be represented to an appropriate degree commensurate with the model's intended use. Also, the impacts of such uncertainties on model results need to be discussed. The model uncertainties are discussed in Section 6.6. The impact of parameter uncertainties on the model results, the BDCFS, is analyzed in Sections 6.13 and 6.14 for the groundwater and volcanic BDCFs, respectively. The range of input parameter values was developed, in the respective reports, such that it is considered to be reasonable and appropriate for the conditions in the Yucca Mountain region and also appropriate for the representation of the receptor characteristics. The source of parameter uncertainty is discussed, and a summary of parameter uncertainty distributions is presented (Table 6.6-3). These parameter ranges are sampled during the biosphere model realizations. Present-day and future climate states are considered in the ERMYN, and different data sets were investigated for the two climate states.

e) Ensure simulation conditions have been designed to span the range of intended use and avoid inconsistent outputs or that those inconsistencies can be adequately explained and demonstrated to have little impact on the results [SCI-PRO-002, Attachment 3, Level I Validation (5)]—The ERMYN is implemented using GoldSim software, which provides the necessary simulation environment. Most input parameters are entered as distributions representing reasonable ranges. These parameter distributions are incorporated in the ERMYN using GoldSim. Outputs from model realizations are obtained while sampling over the full range of input parameters. Therefore, the simulated results are consistent with the input ranges and distributions. The model does not use iterative methods to calculate the results of individual model runs; therefore, there are no instances of run convergences or non-convergences. Calibration was performed by comparison of the ERYMN model to other biosphere models to demonstrate that there is little if any significant difference among predictions. The calibrations by comparison to other models are discussed in Sections 7.2 through 7.4.

f) Ensure that model predications (performance parameters) adequately represent the range of possible outcomes, consistent with important uncertainties, modeling assumptions, conceptualizations, and model implementation [SCI-PRO-002, Attachment 3, Level I Validation (6)]—Most of the parameters are represented by distributions, and the number of realizations is sufficiently large (e.g., 1,000) to ensure that the input parameters are sampled over the full range of values and that the model outcomes encompass the full range of possible values. Also, to demonstrate that the requirement is met, comparisons were made using ERMYN and the other biosphere models to demonstrate that there is little if any significant difference among the model predictions. These issues are discussed in Section 7.2 and 7.3.

7.1.2 Post-Development Model Validation to Support the Scientific Basis of the Model

The model validation approach, including the model validation criteria, is provided in the TWP (BSC 2006 [DIRS 176938], Section 2.2). Level II validation requires confidence building activities as described in Section 7.1.1, plus at least two additional post development model validation methods (SCI-PRO-002, Attachment 3, Level II Validation) selected from a list in SCI-PRO-006, Section 6.3.2, which include:

1. Corroboration of model results with data acquired from the laboratory, field experiments, analogue studies, or other relevant observations, not previously used to develop or calibrate the model.

2. Corroboration of model results with other model results obtained from the implementation of other independent mathematical models developed for similar or comparable intended use/purpose.

3. Corroboration of model results with relevant information published in refereed journals or literature provided that data used to develop and calibrate a model shall not be used to validate a model.

4. Peer review per SO-PRO-001, *Peer Review*.

5. Critical review conducted by technical specialist(s) according to the instructions in Attachment 4 of SCI-PRO-006, *Models*.

6. Corroboration of system model results to the results of the validated mathematical model(s) from which the system model was derived including corroboration with results of auxiliary analyses used to provide additional confidence in the system model results. (This particular approach must be used in combination with at least one other model validation activity from this list.)

7. Corroboration of abstraction model results to the results of the validated mathematical model or process model from which the abstraction model was derived.

8. Performance confirmation studies using validation test model predictions prior to comparison with field or laboratory data.

9. Technical review through publication in a refereed professional journal or review by an external agency. (This approach must be used in combination with at least one other model validation activity from this list.)

Because ERMYN is a complex model and requires hundreds of input values (Section 6.6), it would be difficult to collect all input data through field experiments, laboratory experiments, or other testing on site within a limited time frame. Therefore, comparing model results with data from experimental or other testing (validation method 1) is not realistic. Accordingly, corroboration of ERMYN results with alternative mathematical models and with relevant information published in refereed journals or literature (validation methods 2 and 3) are the principal methods for validating the model. Alternative mathematical models result from ACMs or from different mathematical representations of the same conceptual model.

SCI-PRO-006 allows the use of technical reviews by external agencies to demonstrate additional confidence in models (validation method 9). Technical review activities for the ERMYN included an international peer review of the previous biosphere model by an IAEA International Review Team (IAEA 2001 [DIRS 155188]) and a technical review of the ERMYN model performed by an expert at Lawrence Livermore National Laboratory (Daniels 2003 [DIRS 163016]). Recommendations from the first review were incorporated in the ERMYN. The second review, conducted after the ERMYN was developed, evaluated functions and improvements in the ERMYN (Section 7.7) compared with the previously used model.

As noted in the TWP (BSC 2006 [DIRS 176938], Section 2.2), the previous revision of the biosphere model was validated, as described in *Biosphere Model Report*, Revision 1 (BSC 2004 [DIRS 169460]). The modifications of that model, described in this report, were primarily concerned with the removal of the modeling assumption defining the level of radioactive equilibrium in the surface soil for the groundwater exposure scenario model. The surface soil submodel, which was affected by this modification, already included the appropriate conceptual and mathematical representation of the processes involved (BSC 2004 [DIRS 169460], Equations in Sections 6.4.1.1 and 6.4.1.2). However, a part of the equation that quantifies the fraction of equilibrium radionuclide concentration in the soil was assumed to be equal to unity, i.e., it was assumed that the equilibrium conditions were reached in the soil (BSC 2004 [DIRS 169460], Equations 6.4.1-3 and 6.4.1-4). Although the surface soil model described in this report does not use this assumption, the underlying conceptual and mathematical models in both biosphere model revisions remain the same. Therefore, the findings of the technical reviews described above are still applicable.

The primary validation method for the ERMYN biosphere model was through corroboration of the conceptual approach, the mathematical representation, and the modeling results for each submodel with those of other published biosphere models that have been used elsewhere for dose assessments. The following validation options were considered:

- If the representations from the published models were mathematically equivalent to those used in the ERMYN biosphere model, and resulted in approximately the same numerical values, then the submodel was considered validated.

- If the mathematical representations from the published models were not equivalent to the one used in the Yucca Mountain model, a numerical comparison was conducted by using the appropriate input parameter values to exercise the submodels. Corroboration (i.e. numerical similarity) of the submodels was considered demonstrated if the results of the numerical comparison were within a factor of two over the applicable range of input parameters. A factor of two was chosen for validation of a submodel because such a difference within a submodel was small relative to the approximately order-of-magnitude range of variation in BDCFs and small relative to the order-of-magnitude (or greater) range in variation in some parameters that are likely to have an important influence on the results of the model, such as mass loading, partition coefficients, and transfer factors, as demonstrated in the BDCF pathway, importance, and sensitivity analyses (Sections 6.13 and 6.14).

- If the numerical results differ by more than a factor of two from the expected range of input parameters, corroboration was not assumed, the modeling methods were further evaluated, and the selection of a specific submodel was justified. The justification of the selected submodel was documented in this report.

The main step in validation was corroborating each ERMYN submodel with commonly used published models to ensure that the ERMYN submodels are appropriate. Validation includes the review of the radiation dose assessment context, evaluation of the biosphere conceptual model and ACMs, consideration of scenarios and radiation pathways, comparison of mathematical submodels with published biosphere models, and documentation of ACMs. The selection of applicable published biosphere models (i.e., the validation models) for use in validation is described in Section 7.1.2. The following criteria were used to establish the adequacy of the scientific basis for the model and to determine if the needed level of confidence for the model is met.

If the mathematical representations in the ERMYN or validation models include a parameter that is not used in the other, and if that parameter has no influence on the numerical results for the Yucca Mountain scenarios, the mathematical representations are judged to be equivalent, and no further justification or comparison was required. For example, if a validation model has a parameter that is not used in the ERMYN, but the parameter is multiplicative and equal to 1 for the Yucca Mountain scenarios, the two representations are mathematically equivalent. Similarly, if a parameter used in the ERMYN is not used in the validation models because of approximations or site-specific conditions, the equations are mathematically equivalent.

If the validation and ERMYN submodels are mathematically different, they were compared numerically using input parameter values from Table 6.6-3 and, if necessary, default or reasonable values for the validation model. Simple comparisons are presented in Section 7.3. Complex comparisons requiring a series of calculations or the use of a spreadsheet are presented in Section 7.4. The data from Table 6.6-3 used for model validation were not used to develop the model.

If the validation and ERMYN submodels produced different results, but the difference is less than or equal to a factor of two, the numerical results are similar and no further justification is necessary. Therefore, demonstrating numerical similarity validates the item in the ERMYN. The comparisons were made by evaluating results at the level of submodels or equations in a submodel, which ensures that differences that could substantially influence dose calculations were identified. A factor of two was chosen for validation of a submodel because such a difference within a submodel is small relative to the approximately order-of-magnitude range of variation in BDCFs. In addition, it is small relative to the order-of-magnitude (or greater) range in variation in some parameters that are likely to have an important influence on the results of the model, such as mass loading, partition coefficients, and transfer factors (Sections 6.12 and 6.13). Thus, this criterion is sufficiently accurate for its intended use and consistent with parameter uncertainty.

If the validation and ERMYN submodels produced different results, and the difference was more than a factor of two, the difference is evaluated to ensure that it is reasonable. Justification for the selected approach is provided, which usually is based on site-specific or realistically predictable conditions, better incorporating uncertainty, or avoiding over- or underestimating dose calculations.

The overall approach for validating the ERMYN provides an appropriate level of confidence that the ERMYN methods are appropriate and sufficiently accurate for their intended use because they are similar to, or produce results that are similar to, published state-of-the-art environmental radiation models. In cases where the validation and ERMYN submodels produce different results, this approach ensures that the differences are consistent with available data, incorporated for valid reasons, and that they improve the model.

7.1.3 Selection of Supporting Information

The primary information used to validate the ERMYN were the descriptions of published biosphere models that have been used nationally and internationally for environmental radiation dose assessments. Eleven models were reviewed, and although none use exactly the same pathways as the ERMYN, they all have comparable submodels (Sections 6.4 and 6.5). Five models were selected for validation because they are representative, in common use, and available. The five selected models, referred to as validation models, were:

- **GENII/GENII-S/GENII Version 2** (Napier et al. 1988 [DIRS 157927]; Leigh et al. 1993 [DIRS 100464]; Napier et al. 2006 [DIRS 177331])—This generic computer model for assessing radiation doses was developed by the Pacific Northwest and Sandia National Laboratories. The model supports various sources, including contaminated groundwater, contaminated soil, and air dispersion. This model can be used for evaluating individual and population doses, and for chronic and acute releases. The GENII-S model was used to calculate BDCFs for the TSPA for the site recommendation, and limitations in GENII-S were the basis for developing the ERMYN.

- **BIOMASS ERB2A** (BIOMASS 2003 [DIRS 168563]; BIOMASS 2000 [DIRS 154522])—This model, designed for groundwater contamination scenarios using various generic exposure pathways, provides systematic methods for performing postclosure radiation dose assessments for geologic repositories. It was developed by the IAEA Division of Radiation and Waste Safety. This report is one of a series that provides an example reference biosphere with an agricultural well. Useful information includes the assessment context, biosphere identification, and some input parameter values. BIOMASS ERB2A is not Yucca Mountain specific, but details of the mathematical model were useful.

- **EPRI-YM** (EPRI 2002 [DIRS 158069]; EPRI 2004 [DIRS 171915])—This model was developed in 1996, updated a few years later, and to this date continues to be used by the Electric Power Research Institute to model a groundwater release at Yucca Mountain. It is one of the few published biosphere models for Yucca Mountain. The reports provide a method for identifying biosphere FEPs, identifying other dose assessment requirements for a groundwater scenario at Yucca Mountain, and present the mathematical model, the selection of input data, and useful site-specific information. A current revision of the EPRI-YM model uses the BIOMASS ERB2A model (EPRI 2002 [DIRS 158069], Section 8). The EPRI also developed a biosphere model for the release of radionuclides during a volcanic eruption (EPRI 2004 [DIRS 171915]). That model is also used here.

- **RESRAD** (Yu et al. 2001 [DIRS 159465])—This generic, but comprehensive tool for estimating radiation doses and risks from radioactive materials in the environment was developed by the Argonne National Laboratory. It is designed for soil contamination scenarios and is useful for comparison with the volcanic ash scenario. The methods for evaluating the movement of radionuclides are considered to be among the best, they are widely accepted in the scientific community, and they are widely used by government agencies and institutions (Yu et al. 2001 [DIRS 159465], p. xvii). Although this model uses radionuclide concentrations in the soil as the primary source, it allows modeling of radionuclide leaching from soil to groundwater and subsequent use of contaminated groundwater for irrigation. Therefore, this model was useful for comparison with the Yucca Mountain scenarios.

- **NCRP-129** (NCRP 1999 [DIRS 155894])—This document, developed by the National Council on Radiation Protection and Measurements, provides screening limits for contaminated surface soil and reviews factors relevant to site-specific studies. Designed for soil contamination scenarios, this model was useful for comparison with the volcanic ash scenario. The screening limits are calculated conservatively so that no further action is needed if radionuclide concentrations are below the limits. Although the methods are simple, they provide bounding limits for estimations.

Six other biosphere models were reviewed, but they were not used for direct comparison with the ERMYN because they are similar to the validation models, they do not apply to the Yucca Mountain scenarios, or the methods are not commonly used. These models are described in the following documents:

- **CNWRA 97-009** (LaPlante and Poor 1997 [DIRS 101079])—This document, produced by the Center for Nuclear Waste Regulatory Analyses, provides information and analyses to support the selection of critical groups and reference biospheres for the Yucca Mountain scenarios. Because this model is based on GENII-S, it was not compared with the ERMYN.

- **NUREG/CR-5512** (Kennedy and Strenge 1992 [DIRS 103776])—This document, produced by the Pacific Northwest Laboratory, provides generic and site-specific estimates of radiation doses for exposure to residual radioactive contamination after the decommissioning of NRC-licensed facilities. Although the document does not directly mention using the GENII model, the methods, input parameters, and default values are similar to those in the GENII manual (Napier et al. 1988 [DIRS 157927]). In addition, the scenario in this model is similar to that used in RESRAD.

- **NUREG/CR-3332** (Till and Meyer 1983 [DIRS 101895])—This NRC document provides systematic methods for performing generic radiological assessments. This document is cited in newer models, including GENII/GENII-S and RESRAD. This model was not compared because it is similar to newer models.

- **NCRP-76** (NCRP 1984 [DIRS 103784])—This document, produced by the National Council on Radiation Protection and Measurements, provides systematic methods for performing generic radiological assessments. This document is cited in newer models, including GENII/GENII-S and RESRAD, and was not compared because it is similar to newer models.

- **BIOTRAC** (Zach et al. 1996 [DIRS 103831])—This document, produced by Atomic Energy of Canada Limited, Whiteshell Laboratories, describes the Canadian biosphere model for assessing the radiological consequences of radioactive waste disposal. This model was developed in association with an environmental impact statement for a postclosure assessment case. The Canadian biosphere is considerably different from Yucca Mountain, so this model was not used in the comparisons.

- **Swedish Biosphere Model** (Karlsson et al. 2001 [DIRS 159470])—This document, produced by the Swedish Nuclear Fuel and Waste Management Company, describes a site-specific biosphere model for a Swedish geological repository. Several release scenarios are considered, including a groundwater release, but not a volcanic release. Because this model is similar to BIOMASS ERB2A (BIOMASS 2003 [DIRS 168563]), it was not used in the comparisons.

7.2 COMPARISON OF BIOSPHERE CONCEPTUAL MODELS

The biosphere conceptual models for the groundwater (Section 6.3.1) and volcanic ash exposure scenarios (Section 6.3.2) are based on site-specific biosphere FEPs summarized in Section 6.2 and further discussed in Sections 6.3.4 and 6.7. To validate the ERMYN, the biosphere conceptual model, assessment context, scenarios, submodels, and pathways were examined and compared with the validation models. This section documents the results of the comparisons.

7.2.1 Review of Biosphere Assessment Context

The assessment context is the general overview of the framework and the objective of the modeling problem, including justification of why a particular assessment approach is suitable for the intended purpose. The overall assessment context for the Yucca Mountain repository and for the biosphere model was introduced in Sections 6 and 6.1. Among the five validation models (Section 7.1.3), only two are specific for a groundwater scenario and a geological repository: BIOMASS ERB2A (BIOMASS 2003 [DIRS 168563], Section C3) and EPRI-YM (EPRI 2002 [DIRS 158069]) and only one is specific for a volcanic ash scenario (EPRI 2004 [DIRS 171915]). The authors of these models provide details of the conceptual models, including the biosphere system identification, justification, and description. GENII (including GENII-S and GENII Version 2), RESRAD, and NCRP-129 are generic models that do not have a specific assessment context and, therefore, were not compared in this section.

Nine aspects of the assessment context for the ERMYN (groundwater scenario) were compared with those from the BIOMASS ERB2A and EPRI-YM models (Table 7.2-1). The comparison indicated that, while the purpose of the models may differ, they have many identical or equivalent aspects, and the only major difference is the lower amount of locally produced foodstuffs in the ERMYN (societal assumption). In the BIOMASS ERB2A and EPRI-YM models, most foodstuffs are assumed to be locally produced. Consumption rates for locally produced food in the ERMYN are based on a site-specific survey, which shows that only a small percentage of the Amargosa Valley population are farmers; that the population imports most of their food, i.e., only a small fraction is produced locally; and that agricultural production is limited to a few crops.

The human receptor for the ERMYN and the EPRI-YM models is the RMEI (10 CFR 63.312 [DIRS 173273]), although most models can be used for other receptors. In the BIOMASS model, the human receptor is the critical group. In BIOMASS ERB2A, several groups are considered in finding the most highly exposed critical group, consistent with the assessment philosophy.

Table 7.2-1. Assessment Context for the ERMYN, BIOMASS ERB2A, and EPRI-YM Biosphere Models for Groundwater Contamination

Issue	ERMYN	BIOMASS ERB2A [a]	EPRI-YM [b]	Comparison
Assessment Purpose	Develop dose assessment capability for the TSPA model	Develop reference biosphere modeling capabilities for an agricultural well scenario	Develop biosphere model to facilitate independent dose assessment for the Yucca Mountain repository	ERMYN and EPRI are equivalent (site-specific, same site); BIOMASS is different (generic model).
Assessment Endpoint	BDCF based on annual dose to the RMEI	Annual individual effective dose for critical groups	Annual individual effective dose to the RMEI	All three are equivalent.
Assessment Philosophy	All parameters are developed based on an equitable (realistic or best estimate) but cautious approach, reasonable if possible, and cautious when unsure.	“Equitable” except for definition of the critical group, which should invoke a “cautious” approach	“Cautious” for critical groups, “equitable” for other aspects	All three are equivalent: BIOMASS and EPRI are cautious for human receptor, while ERMYN is equitable in defining the receptor characteristics.
Repository Type	Deep repository for long-lived solid radioactive waste	Deep repository for long-lived solid radioactive waste	Deep repository for long-lived solid radioactive waste	All three are the same.
Site Context	Specific to the Amargosa Valley; groundwater use, limited climate change	Generic inland repository; aquifer at accessible depth, no biosphere change	Vicinity of Yucca Mountain; groundwater use, present-day climate	All three are equivalent: ERMYN and EPRI are site-specific; BIOMASS is generic.
Geosphere-Biosphere Interface	A well from which contaminated groundwater is pumped; water used for drinking, agriculture, and domestic purposes	A well intruding into aquifer plume with pumping at a rate consistent with domestic and agricultural use	A deep well sunk into aquifer adjacent to the repository footprint	All three are the same.
Source Term	Constant unit concentration for each radionuclide (Bq/m^3)	Constant unit concentration for each radionuclide (Bq/m^3)	Constant radionuclide flux from the well (mol/yr), which can be converted to (Bq/m^3)	All three are the same.
Societal Assumptions	Current lifestyle of Amargosa Valley residents; rural community, vegetable gardens, farm animals, and fishponds. Small fraction of foodstuffs locally produced.	Agricultural community, using modern cultivation and animal husbandry practices. Community capable of producing a high proportion of the total diet of most foodstuffs.	Consumption of locally produced food based on the survey of Amargosa Valley residents. For lifestyle characteristics a combination of generic and site-specific values is used.	BIOMASS assumes all foodstuffs locally produced. ERMYN and EPRI-YM use site-specific data.
Time Frame	Up to 10,000 years, up to 1 million years [d]	Up to 1 million years	Up to 1 million years	All three are the same within the model applicability and limitations.

[a] BIOMASS 2003 [DIRS 168563]

[b] EPRI 2002 [DIRS 158069]

[c] Dependent upon applicability of the reference biosphere, as defined for this model, to represent the future biospheres.

Two assessment philosophies, cautious and equitable, are used in the biosphere models. The cautious assessment philosophy is based on the presumption that the disposal of radioactive waste represents an involuntary risk from a man-made source from which future generations will derive no benefit (EPRI 2002 [DIRS 158069], Section 8.2.1). The equitable assessment philosophy is based on the assumption that radioactive waste disposal constitutes a health risk to present and future generations, and that this health risk is similar to other risks that society chooses to tolerate.

In ERMYN, the equitable (realistic or best estimate) assessment philosophy is generally applied to developing environmental transport input parameters for which there is sufficient information. However, parameters for which there is a lack of information (e.g., translocation factor and fraction of radionuclides transferred from water to airstream in evaporative coolers) are developed based on the cautious assessment philosophy. The overall approach could thus be described as equitable but cautious, reasonable if possible, and cautious when unsure.

The receptor for the radiological assessments is usually characterized using the cautious philosophy. Such an assessment philosophy is applied to defining the critical group in the BIOMASS model and the RMEI for the Yucca Mountain performance assessment. The RMEI is selected to represent those persons in the vicinity of Yucca Mountain who are reasonably expected to receive the greatest exposure to radiological material released from the repository at Yucca Mountain (10 CFR 63.102(i) [DIRS 173273]). Such a receptor is constructed to limit speculation about possible futures of the population in the region (66 FR 32074 [DIRS 155216], p. 32,092). The RMEI is required to live in the accessible environment above the highest concentration of radionuclides in the plume of contamination and the radionuclide concentration in groundwater is calculated based on the annual groundwater demand specified in the regulation (10 CFR 63.312 [DIRS 173273]).

The three biosphere models listed in Table 7.2-1 are all specific to a deep geologic repository with a possible radionuclide release through groundwater contamination and an agricultural well pumping contaminated groundwater is the interface between the geosphere and biosphere. A source term of unit concentration of a radionuclide in the groundwater is used to evaluate the biosphere model contribution in the performance assessment. This indicates that the approach of separating the source term and biosphere contribution is reasonable and acceptable.

7.2.2 Consideration of Scenarios, Submodels, and Pathways

The exposure scenarios in the ERMYN arise from radionuclide releases to the biosphere in groundwater and volcanic ash. For the groundwater exposure scenario, groundwater is the only source of water for people living in the Amargosa Valley and thus would be the only source of radionuclides in the biosphere. Other dose assessment models (BIOMASS ERB2A and EPRI-YM) also consider this scenario (Section 7.2.1). The biosphere model developed by EPRI also considers release of radionuclides to the biosphere as a result of a volcanic eruption (EPRI 2004 [DIRS 171915]). The GENII, RESRAD and NCRP-129 models include onsite soil contamination, which is analogous to the source term for the volcanic ash exposure scenario in the ERMYN. These models are also compared with the ERMYN for that scenario.

The biosphere conceptual model is based on selected biotic and abiotic components of the biosphere system. For these components, relevant FEPs are evaluated for inclusion into the model. Radionuclide transfer interaction matrices may then be used to identify essential interactions between the major components of the biosphere system. Such interaction matrices are used in this and some other biosphere models (BIOMASS ERB2A and EPRI-YM), and are all similar. The generic biosphere models (GENII, RESRAD, and NCRP-129) do not use an interaction matrix, but present their conceptual models in their documentation. However, their mathematical models are similar to those that use the interaction matrix. Typical major biosphere components include groundwater, surface soil, air, plants, animals, fish, and human receptors. Some models, developed for wetter environments, include perennial surface water, sediments, and source terms in deep soil. These components are not used in the ERMYN because they are not present in the arid Yucca Mountain region.

The human exposure pathways and the associated submodels for the five validation models and the ERMYN were compared (Table 7.2-2). The results of this comparison indicate that the ERMYN includes all but three of the pathways in the other models. Justification for excluding air submersion and water immersion is given in Section 7.4.8. The ingestion of animal offal is excluded because there is no indication of animal offal in the diet of Amargosa residents. All seven models include most of the exposure pathways, although some pathways are only used in a few models. Detailed comparisons of the ERMYN submodels with the submodels in the validation models are described in the next section.

Table 7.2-2. Pathways and Submodels in Six Biosphere Models

Pathway		Submodel	ERMYN	GENII	BIO-MASS	EPRI-YM	RES-RAD	NCRP-129
External exposure	Contaminated soil	Soil, External	×	×	×	×	×	×
	Air submersion		—	×	—	—	—	—
	Water immersion		—	×	×	—	—	—
Inhalation dose	Resuspended soil (air dust)	Air, Inhalation	×	×	×	×	×	×
	Radioactive gas (^{14}C, ^{222}Rn)		×	—	—	—	×	×
	Water evaporation		×	—	×	—	—	—
Ingestion dose	Soil	Soil, Ingestion	×	×	×	×	×	×
	Drinking water	Ingestion	×	×	×	×	×	—
	Leafy vegetables	Plant, Ingestion	×	×	×	×	×	×
	Root vegetables		×	×	×	×	×	×
	Fruit		×	×	—	×	—	×
	Grain		×	×	×	×	—	×
	Fresh feed for cows	Plant	×	×	×	×	×	×
	Stored feed for birds		×	×	—	×	—	—
Ingestion dose	Meat	Animal, Ingestion	×	×	×	×	×	×
	Milk		×	×	×	×	×	×
	Offal (e.g., liver)		—	—	×	×	—	—
	Poultry		×	×	—	×	—	—
	Eggs		×	×	—	×	—	—
	Fish	Fish, Ingestion	×	×	×	×	×	—
Total Dose	All	All	×	×	×	×	×	×

Sources: Section 6; Napier et al. 2006 [DIRS 177331], BIOMASS 2003 [DIRS 168563]; EPRI 2002 [DIRS 158069], Yu et al. 2001 [DIRS 159465]; and NCRP 1999 [DIRS 155894].

7.3 COMPARISON OF BIOSPHERE MATHEMATICAL SUBMODELS

To validate the ERMYN, details of the mathematical representations of the biosphere processes in the ERMYN are compared with similar representations in the validation models (Section 7.1.2). Detailed comparisons, given in the following sections, begin with a summary table (Table 7.3-1) that lists all items compared. For each submodel, the comparison focuses on the core part of the submodels (Sections 6.4 and 6.5). Equation derivations and simple calculations (e.g., unit conversion and summations) are excluded.

Table 7.3-1. Summary of Mathematical Model Comparisons

Submodel	Table	Item Compared	Equation	Comparison Result
Soil	7.3-2	Radionuclide concentration in surface soil	6.4.1-2, 6.4.1-4, 6.4.1-19 to 6.4.1-21 6.4.1-22	All models use a method equivalent to the ERMYN.
	7.3-3	Removal coefficients for surface soil	6.4.1-26, 6.4.1-28	Same as above
Air	7.3-4	Soil resuspension in air submodel	6.4.2-1, 6.4.2-2, 6.5.2-1, 6.5.2-2	Same as above
	7.3-5	Radon release from radium contaminated soil	6.4.2-4, 6.4.2-7, 6.5.2-8	Only RESRAD and NCRP-129 include the radon pathway. The ERMYN uses the NCRP-129 method, which differs from the RESRAD method.
	7.3-6	Radionuclide concentration indoors from the operation of evaporative coolers	6.4.2-3	This pathway is unique to the ERMYN. No validation models include this pathway.
Plant	7.3-7	Crop contamination due to root uptake	6.4.3-2, 6.5.3-2	All models use the same method as the ERMYN.
	7.3-8	Direct deposition on crop leaf surfaces due to interception of irrigation water	6.4.3-3	All models except BIOMASS ERB2A use the same method as the ERMYN.
	7.3-9	Irrigation deposition rate	6.4.3-4	Same as above
	7.3-10	Interception fraction of irrigation	6.4.3-5	All models use a fixed value independent of irrigation practices.
	7.3-11	Direct deposition on leaf surfaces due to interception of resuspended soil	6.4.3-6, 6.5.3-3	The ERMYN uses the same method as GENII-S and RESRAD. EPRI-YM, BIOMASS ERB2A, and NCRP-129 use a different method.
	7.3-12	Dust deposition rate	6.4.3-7, 6.5.3-4	Same as above
	7.3-13	Interception fraction for resuspended soil	6.4.3-8, 6.5.3-5	Same as above

Table 7.3-1. Summary of Mathematical Model Comparisons (Continued)

Submodel	Table	Item Compared	Equation	Comparison Result
Animal	7.3-14	Animal product contamination due to animal feed	6.4.4-2, 6.5.4-2	Same as above
	7.3-15	Animal product contamination due to drinking water	6.4.4-3	Same as above
	7.3-16	Animal product contamination due to soil ingestion	6.4.4-4, 6.5.4-3	All models except GENII-S use this process.
	7.3-17	Animal product contamination due to dust inhalation	–	This process is only included in the BIOMASS ERB2A model.
Fish	7.3-18	Fish contamination due to fishpond water	6.4.5-1, 6.4.5-2	All models use the same method as the ERMYN, except for not including evaporation of fishpond water.
^{14}C	7.3-19	^{14}C special submodel for soil contamination	6.4.6-1	ERMYN and RESRAD use the same method; GENII-S and BIOMASS ERB2A use different methods; EPRI-YM and NCRP-129 did not include ^{14}C.
	7.3-20	^{14}C special submodel for air contamination	6.4.6-3	Same as above
	7.3-21	^{14}C special submodel for plant contamination	6.4.6-6	Same as above
	7.3-22	^{14}C special submodel for animal product contamination	6.4.6-7	Same as above
External	7.3-23	External exposure to contaminated soil	6.4.7-1, 6.5.5-1	All models use the same method as the ERMYN, except for not using exposure time budgets. Few models consider air submersion and water immersion.
Inhalation	7.3-24	Inhalation dose	6.4.8-2, 6.4.8-3, 6.4.8-4, 6.4.8-7, 6.5.6-2, 6.5.6-3	All models use the same method as the ERMYN for air particle inhalation, except that exposure time budgets are not included. Few validation models use radon and ^{14}C gas inhalation pathways, and none include evaporative coolers.
Ingestion	7.3-25	Water ingestion	6.4.9-2	All models use the same method as the ERMYN, but the number of ingestion pathways differs among models.
	7.3-26	Crop ingestion	6.4.9-3, 6.5.7-2	Same as above
	7.3-27	Animal product ingestion	6.4.9-4, 6.5.7-3	Same as above
	7.3-28	Fish ingestion	6.4.9-5	Same as above
	7.3-29	Soil ingestion	6.4.9-6, 6.5.7-4	Same as above

7.3.1 Validation of Surface Soil Submodels

The surface soil submodels for the groundwater (Section 6.4.1) and volcanic ash (Section 6.5.1) exposure scenarios are different because they have different radionuclide source terms. Under the groundwater scenario, long-term irrigation causes radionuclide buildup in the soil. In contrast, ash deposited on the ground contaminates the surface soil during a single volcanic eruption followed by ash redistribution, but radionuclides do not build up in the surface soil. For the groundwater exposure scenario, radionuclide concentration in surface soil is calculated in the surface soil submodel. For the volcanic ash exposure scenario, radionuclide concentrations in soil are the source term in the ERMYN and are calculated outside this biosphere model. Therefore, separate comparisons are presented for each exposure scenario.

7.3.1.1 Comparison of Surface Soil Submodels for the Groundwater Scenario

For the surface soil submodel in the model for the groundwater scenario, two items are compared: the methods used to calculate radionuclide concentrations in the soil (Table 7.3-2) and removal rate constants (Table 7.3-3). The conversion of radionuclide concentrations in the surface soil to concentrations in the soil mass (Equations 6.4.1-5 and 6.4.1-6) are based on the fundamental relationship between mass and volume, which does not require further comparison and validation. To focus on the important features of the models, radionuclide indexing is omitted in the compared equations.

GENII, BIOMASS ERB2A, and EPRI-YM models address exposure scenarios resulting from groundwater contamination and include radionuclide buildup in the soil. Equilibrium conditions are not used directly in the dose calculations of some models. For the RESRAD model, soil contamination is the primary source term, and although the model includes irrigation, this is a secondary source calculated from radionuclide removal in the surface soil. Contaminated irrigation water is not a radionuclide source in the NCRP-129 model.

Calculations of soil concentration of radionuclides in ERMYN (Equation 6.4.1-1), EPRI-YM (EPRI 2002 [DIRS 158069], Equation 8-6) and BIOMASS models (BIOMASS 2003 [DIRS 168563], p. 339) are based on similar differential equations and similar initial conditions for the long-term irrigation source. The analytical solution of the differential equation (Equation 6.4.1-2) gives radionuclide concentrations in the surface soil at any time. The GENII model although based on the same general equation (Napier et al. 2006 [DIRS 177331], Equation 9.1) does not use the same analytical solution; instead it uses a numerical method that gives results similar to the analytical solution (Table 7.3-2). A comparison of the treatment of decay products in the ERMYN and GENII models is presented in Section 7.4.2.2. The BIOMASS model assumes the constant biosphere, i.e., the radioactive equilibrium between the model components (BIOMASS 2003 [DIRS 168563], Section C3). Results of the comparison indicate that the calculations of radionuclide concentrations in the soil in the ERMYN, GENII, and BIOMASS models are equivalent. The only other differences in the ERMYN, GENII, and BIOMASS models for calculating soil concentrations involve calculating removal coefficients (Tables 7.3-2 and 7.3-3).

The methods for calculating removal rate constants are the same in the ERMYN, GENII, BIOMASS, and EPRI-YM models, with two exceptions (Table 7.3-3). First, the GENII model does not directly include removal by erosion (Napier et al. 2006 [DIRS 177331], Section 9.2). Because this process can be assumed to follow first-order kinetics, similar to the leaching removal, the removal rate constants for these two processes can be combined and the leaching removal rate constant replaced with an effective removal rate constant. Therefore, the mathematical approaches used in these models are equivalent. Second, the GENII and BIOMASS models include harvest removal in calculating radionuclide concentrations in the soil. The ERMYN does not use a harvest removal factor (Section 6.4.1.1) because fertilization with animal manure is assumed to compensate for harvest removal (Assumption 4). Regardless of this assumption, the mathematical expressions are equivalent.

Because the mathematical representations are the same or give equivalent results, the soil submodel for the groundwater scenario is considered validated.

7.3.1.2 Comparison of Surface Soil Submodels for the Volcanic Ash Scenario

The radionuclide concentration in soil is the source term for the volcanic ash exposure scenario and is not calculated in the biosphere model. The only function of the surface soil submodel is to convert the source expressed as the areal radionuclide concentration (Bq/m^2) to mass radionuclide concentration (Bq/kg), for further use in the biosphere model, based on the depth and density of the surface soil (Equation 6.5.1-2). The conversion is based on the fundamental relationship between mass and volume and it does not require further comparison.

GENII, RESRAD, and NCRP-129 include soil contamination in a manner applicable to the volcanic ash scenario. The radionuclide source term for these models is in units of Bq/m^3 or Bq/kg in soil. Environmental radiation dose assessment for contaminated volcanic ash release was published by EPRI (2004 [DIRS 171915], Section 8). In this model, radionuclide source (radionuclide concentration in the soil) is given in the units of mol/m^3 which is then converted to concentration per unit mass by using soil density (EPRI 2004 [DIRS 171915], Section 8.6.2).

Table 7.3-2. Comparison of Radionuclide Concentration in Surface Soil

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.1-1, 6.4.1-2, 6.4.1-3, and 6.4.1-4)	Reference
GENII	To calculate radionuclide concentration in the soil from irrigation water, the GENII model uses the following general equation to evaluate input of activity during one year $$\frac{d}{dt}C_s(t) = R_w - (\lambda_l + \lambda_d)C_s(t)$$ where $C_s(t)$ = deposited amount of radionuclide from air to soil as a function of time (Concentration in soil per unit area) R_w = rate of input of irrigation water (Bq/(m^2 yr)) λ_l = leaching removal rate constant (1/yr) λ_d = decay rate constant (1/yr). The soil concentration calculated form the above equation is combined with the soil concentration that existed before the year for which the calculation is carried out (from previous years of deposition and possibly from different contamination processes) and the annual average radionuclide concentration in soil is calculated (Napier et al. 2006 [DIRS 177331], Equation 9.9). Because of the long timeframe of the calculations for the repository and the assumed constant radionuclide concentration in the water, it is not necessary to calculate the annual average soil concentrations; it is sufficient to calculate point in time values. Equation 9.9 in the source reference (Napier et al. 2006 [DIRS 177331]) was developed by integrating the point-in-time soil concentration, which for one year of irrigation can be expressed as: $$Cs_1 = \frac{R_w}{\lambda_l + \lambda_d}(1 - e^{-(\lambda_l + \lambda_d)t})$$ where Cs_1 = radionuclide activity concentration in soil per unit area after one year of irrigation (Bq/m^2) Cw = radionuclide activity concentration in water (Bq/m^3) I = crop irrigation rate (m/yr) t = time period, equal to 1 yr. The rate of input, R_w, can then be represented by the product of radionuclide concentration in water, Cw, and the irrigation rate, I, which is equivalent to the equation used in ERMYN.	GENII includes removal by leaching and decay, but not erosion, although erosion can be combined with the leaching removal rate constant. The analysis in GENII is performed on an annual basis. GENII calculates long-term radionuclide buildup in the soil by combining single-year net contributions with the number of prior irrigation years. This method is equivalent to the analytical solution used in ERMYN (Eq. 6.4.1-1) because the sum of the exponential terms, Σ[exp(-λ)] can be represented by the expression [1-exp(-λ N)]/[1-exp(-λ)]. Although the execution of the two approaches is different, but the result is the same. Radionuclide indices were omitted in GENII equations.	Based on information in Napier et al. 2006 [DIRS 177331], Equations 9.8 and 9.9. Only the portion of the equation relevant to irrigation water is shown and the radionuclide indexing is not shown.

Table 7.3-2. Comparison of Radionuclide Concentration in Surface Soil (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.1-1, 6.4.1-2, 6.4.1-3, and 6.4.1-4)	Reference
GENII (Continued)	GENII includes radionuclide buildup in the soil using the prior irrigation time with leaching and radionuclide decay. The radionuclide concentration in the soil after *N* years of irrigation is calculated by summing incremental changes in the activity concentration: $$Cs = Cs_1 \sum_{n=1}^{N} e^{-(\lambda_l+\lambda_d)n}$$ where Cs = radionuclide concentration in the soil per unit area after N years of irrigation (Bq/m^2) n = index of number of irrigation years N = total number of years (yr). GENII also includes harvest removal, which is calculated at the end of each year as: $$Cs' = Cs - C_{crop} Y$$ where Cs' = soil activity concentration after harvest removal; used in calculations for the next year (Bq/m^2) Cs = soil activity concentration before harvest removal (Bq/m^2) C_{crop} = crop radionuclide activity concentration (Bq/kg) Y = crop yield (kg/m^2).		
BIOMASS ERB2A	Explicit equation for radionuclide concentration in the soil is not provided. The differential equation shown in the reference can be solved for any irrigation duration. The radionuclide concentration in the soil would be calculated as: $$C_s = \frac{V_{irr}\, C_w}{\lambda_t}\left(1 - e^{-\lambda_t\, t}\right)$$ where C_s = radionuclide activity concentration in the surface soil (Bq/m^2) V_{irr} = irrigation rate, m^3/yr; when applied to 1-m^2 area this is equivalent to units of m/yr	BIOMASS ERB2A includes leaching, harvest removal (cropping), and decay removal. It also gives the method for erosion removal. Harvest removal calculations are based on root uptake and external contamination, but not leaf uptake due to interception of irrigation, which may be the major contributor for most radionuclides. BIOMASS ERB2A equation can be solved for any irrigation duration or under the assumption of equilibrium (BIOMASS 2003 [DIRS 168563], Section C3.5.4.2); therefore, it is the same as the	BIOMASS 2003 [DIRS 168563], Equations in Section C3.5.4.2. Assumes a constant radionuclide concentration in groundwater over the time of interest.

Table 7.3-2. Comparison of Radionuclide Concentration in Surface Soil (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.1-1, 6.4.1-2, 6.4.1-3, and 6.4.1-4)	Reference
BIOMASS ERB2A (Continued)	C_w = radionuclide concentration in groundwater (Bq/m^3) λ_t = total removal rate constant, per year, expressed as: $$\lambda_t = \lambda_N + \lambda_{1C} + \lambda_{1I}$$ where λ_N = radionuclide decay constant (1/yr) λ_{1I} = infiltration removal rate constant (1/yr) λ_{1C} = cropping removal rate constant (1/yr). $$\lambda_{1C} = \frac{\sum_{crop} \frac{1}{4} (CF_{crop} + S_{crop})\, Y_{crop}}{(1-\theta_t)\, \rho\, d}$$ where CF_{crop} = concentration factor from root uptake (Bq/kg $_{\text{fresh weight of crop}}$ per Bq/kg $_{\text{dry weight of soil}}$) S_{crop} = soil contamination on crops (kg $_{\text{dry weight soil}}$ /kg $_{\text{fresh weight of crop}}$) Y_{crop} = wet weight biomass of crops at harvest, obtained from the unit area irrigated (kg/yr) θ_t = total porosity of the cultivated soil compartment (dimensionless) d = thickness of the cultivated soil compartment (m) ρ = dry grain density of the cultivated soil compartment (kg/m^3) t = total number of years for soil accumulation (yr). After a sufficient time, soil concentration reaches an equilibrium concentration.	representation in ERMYN. BIOMASS ERB2A is the same as the ERMYN except that it includes harvest removal and excludes the buildup of long-lived decay products in surface soils. BIOMASS ERB2A does not describe the treatment of long-lived decay products accumulation in surface soils.	
EPRI-YM	Equation for calculating radionuclide concentrations in the surface soil is not explicitly given in the document. However, the model used by EPRI is based on the BIOMASS ERB2A model.	N/A	EPRI 2002 [DIRS 158069], Section 8.2.5.2.1
RESRAD	Soil is a primary contaminated medium, irrigation is a secondary source.	N/A	Yu et al. 2001 [DIRS 159465]
NCRP-129	Not included in the model.	N/A	NCRP 1999 [DIRS 155894]

Table 7.3-3. Comparison of Removal Rate Constants for Surface Soil

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.1-26, and 6.4.1-28)	Reference
GENII	$$\lambda_l = \frac{P + I - E}{d\,\theta\left(1 + \frac{\rho}{\theta} K_d\right)}$$ λ_l = leaching removal rate constant (1/yr) P = precipitation rate (m/yr) I = irrigation rate (m/yr) E = evapotranspiration rate (m/yr) d = depth of surface soil (m) θ = volumetric water content of soil (dimensionless) ρ = soil bulk density (kg/m^3) K_d = surface soil solid-liquid partition coefficient (m^3/kg).	The same equation is used in ERMYN, with the input parameter of overwatering rate (*OW*) replacing the equivalent ($P + I - E$) term. Radionuclide indices were omitted in GENII equations.	Napier et al. 2006 [DIRS 177331], Section 9.2.2, Equation 9.2
BIOMASS ERB2A	**Infiltration** $$\lambda_{1I} = \frac{I}{R\,\theta\,d}$$ where λ_{1I} = rate coefficient for the transfer of radionuclides out of cultivated soil due to infiltration (1/yr) I = annual infiltration or recharge rate (m/yr) θ = water filled porosity of the cultivated soil compartment (dimensionless) d = thickness of the cultivated soil compartment (m) R = retardation coefficient for the cultivated soil compartment (dimensionless), which is calculated as $$R = 1 + \frac{(1-\theta_t)\rho}{\theta} K_d$$ where θ_t = total porosity of the cultivated soil compartment (dimensionless) ρ = dry grain density of the cultivated soil compartment (kg/m^3) K_d = sorption coefficient for the cultivated soil compartment (m^3/kg).	The leaching rate equation is the same as the one used in ERMYN with the following equivalent parameters: • The overwatering rate (OW) in ERMYN is equivalent to annual infiltration (I) in BIOMASS ERB2A • The soil bulk density (ρ) in ERMYN is equivalent to the cultivated soil density $(1-\theta_t)(\rho)$ in BIOMASS ERB2A	BIOMASS 2003 [DIRS 168563], Equations in Section C3.5.4.2

Table 7.3-3. Comparison of Removal Rate Constants for Surface Soil (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.1-26, and 6.4.1-28)	Reference
BIOMASS ERB2A (Continued)	**Erosion** $$\lambda_{1E} = \frac{E}{d}$$ where λ_{1E} = rate coefficient for the transfer of radionuclides from cultivated soil to sinks (i.e., out of system) by erosion (1/yr) E = erosion rate for the soil compartment (m/yr) d = thickness of the cultivated soil compartment (m).		
EPRI-YM	EPRI-YM uses the same method and the same equations as those used in BIOMASS ERB2A model.	EPRI-YM uses the BIOMASS ERB2A model.	EPRI 2002 [DIRS 158069], Section 8.2.5.2.1
RESRAD	RESRAD uses contaminated soil as initial source. Radionuclides can be removed from surface soil to deep soil, and eventually to the groundwater, which can subsequently be used for irrigation.	Not applicable	Yu et al. 2001 [DIRS 159465]
NCRP-129	Not included in the model	Not applicable	NCRP 1999 [DIRS 155894]

7.3.2 Validation of the Air Submodel

Particle resuspension is included in the air submodel for both exposure scenarios (Sections 6.4.2.1 and 6.5.2.1), and both scenarios include exhalation of radon from radium-contaminated soil (Sections 6.4.2.3 and 6.5.2.2). The groundwater scenario also includes generation of contaminated aerosols by evaporative coolers (Section 6.4.2.2) and the release of ^{14}C gas into the air. Validation of the modeling of the processes of particle resuspension from surface soils, radon exhalation from radium-contaminated soil, and generation of contaminated aerosols by evaporative coolers is described in the following sections, and the model for ^{14}C gas in the air is validated in Section 7.3.6.

7.3.2.1 Particle Resuspension from Surface Soil

Particle resuspension from surface soils is treated similarly for both exposure scenarios in ERMYN, because both use an environment-specific mass loading and enhancement factor. The volcanic ash scenario also includes modeling of mass loading decrease following a volcanic eruption. Radionuclide concentrations in the air are calculated differently for direct deposition on crops (Equations 6.4.2-1 and 6.5.2-1) and human inhalation (Equations 6.4.2-2 and 6.5.2-2). Mass loading for calculating human inhalation exposure depends on specific environments with different levels of activities involving soil disturbance.

All five validation models include particle resuspension from surface soils, and the core parts of the submodels are the same (Table 7.3-4) because each is based on the concentration of particulate matter in air (mass loading) and each assumes that the resuspended particles and the surface soil have the same radionuclide concentration per unit mass. The differences between the validation models and ERMYN (Table 7.3-4) are:

- BIOMASS and EPRI-YM models include a correction for partitioning of a radionuclide concentration between the aqueous and solid phase in the soil. The correction uses the retardation coefficient, R, which relates the rate of movement of the contaminant relative to the rate of movement of water, i.e., the infiltration rate. In a system in equilibrium it represents the ratio of the total mass of a contaminant in a unit volume of the soil (i.e., in soil and in water) to the mass in solution in that volume of soil. The correction factor equal to (R-1)/R is thus equal to the ratio of the contaminant associated with the solid phase (soil) to that in the aqueous and solid phase (in soil and in soil water). The correction factor is multiplied by the radionuclide concentration in the soil to calculate radionuclide concentration per unit mass of resuspended soil (that is soil without the water phase). For the highly sorbing radionuclides, the retardation coefficient is much larger than 1 (based on the retardation coefficient calculation in Table 7.3-3 for BIOMASS ERB2A and input parameters in Table 6.6-3), so the term (R-1)/R is about equal to one (also see Table 7.3-4). The highly mobile radionuclides, such as ^{99}Tc and ^{36}Cl, have low partition coefficient (K_d) values (0.14 L/kg; Table 6.6-3), which results in a lower retardation coefficient ($R = 1.5$) and causes the retardation correction term (R−1/R) to be about 0.33. This means that for ^{99}Tc and ^{36}Cl only about a third of radionuclide activity is associated with the solid phase and can become resuspended; the remainder is in the aqueous phase. By not including the correction factor, the ERMYN model allows for 100% of the radionuclide concentration in the soil to be resuspended.

Thus, for poorly sorbing species, the radionuclide concentrations from resuspended dust in air calculated using the two methods can differ by more than a factor of two. However, excluding the retardation correction factor from ERMYN is justified because this factor is only important for those radionuclides that do not significantly accumulate in the soil. For these radionuclides, the inhalation pathway is relatively unimportant (Section 6.13). In addition, some fraction of radionuclides initially present in the aqueous phase could attach to soil particles upon water evaporation from the resuspendable layer and become resuspended, so by using this factor one could underestimate, to some degree, the radionuclide concentrations in the air for radionuclides with low partition coefficients. Therefore, not using the retardation correction factor in ERMYN is justified.

- RESRAD includes an area factor to account for the portion of contaminated land. For the groundwater scenario, most inhalation exposure occurs in the active outdoor environment, i.e., when people actively disturb the soil surface (see analyses in Sections 6.13 and 6.14). Such activities would primarily occur in the agricultural land. Therefore, although only a small portion of the Amargosa Valley would be irrigated, and thus contaminated, the inhalation exposure would largely occur on irrigated land. In the volcanic ash scenario, contaminated ash would be deposited over the entire Amargosa Valley. Thus, the area factor would be about one for both cases and the two methods are mathematically equivalent.

- RESRAD includes a cover-and-depth factor to account for the effects of burying radioactive waste. The cover-and-depth factor is the fraction of resuspendable soil particles at the ground surface that are contaminated. For the scenarios used in ERMYN, all radionuclides are in the surface soil, and this factor would be set at one, i.e., no cover on the contaminated soil layer, so the methods are mathematically equivalent.

- None of the validation models use the microenvironmental approach to determining mass loading, although the EPRI model considers two areas associated with different mass loading levels, occupancy times and breathing rates (EPRI 2004 [DIRS 171915], Section 8.5.2.2). ERMYN uses the microenvironmental method to account for differences in mass loading among, and uncertainty within, various environments. A numerical comparison of the ERMYN and validation model methods is presented in Section 7.4.9. The difference in total activity inhaled per day calculated by the two methods is less than a factor of two (Table 7.4-21), and, therefore, the two methods are numerically similar.

- The ERMYN model uses the enhancement factor to calculate radionuclide concentrations in the air from radionuclide concentrations in the soil (Equations 6.4.2-2 and 6.5.2-2). This factor is only included in the calculations of activity concentrations in air inhaled by the receptor to account for differences in activity concentrations between surface soil and resuspended soil particles and is not used to calculate radionuclide uptake by plants from the deposition of resuspended soil. The enhancement factor is environment-specific with an average value of about one for the active outdoor environment, and an average greater than one for all other environments used in

ERMYN (Table 6.6-3). Including the enhancement factor increases the radionuclide concentration in the air. The enhancement factor is a site-specific multiplier; therefore the two methods are numerically similar.

- Only one of the validation models, the EPRI model, considers time dependence of mass loading after a volcanic eruption. In that model, a high mass loading value at the "nuisance level" (5×10^{-6} kg/m^3), is used for the first year after a volcanic eruption. The mass loading is assumed to return to the pre-eruption conditions by the start of the second year (EPRI 2004 [DIRS 171915], Section 8.5.2.2). ERMYN uses a time function that does not use a pre-determined duration of the time-step to account for the decrease in mass loading after a volcanic eruption (Equation 6.5.2-2). The mass loading decrease function in ERMYN is based on the measurements of airborne particulate levels following volcanic eruptions. Concentrations of airborne particles after volcanic eruptions decreased toward pre-eruption levels within a relatively short time. For example, concentrations of total suspended particles at six sites in Washington returned to pre-eruption levels within three to eight months after the eruption of Mount St. Helens, and concentrations decreased after other eruptions at similar rates (BSC 2006 [DIRS 177101], Sections 6.3 and 6.4). The decrease results from consolidation of ash particles, incorporation of ash into the soil, and removal of ash by residents and natural processes. These processes also would occur in the Yucca Mountain region, although possibly at a different rate (BSC 2006 [DIRS 177101], Section 6.4). Based on these measurements and on the predicted low thickness of ash at the RMEI location (Appendix G) it was concluded that concentrations of resuspended particles during the first year after a volcanic eruption that deposits a relatively thin layer of ash at the location of the receptor likely would not be more than twice as high as those prior to the eruption (BSC 2006 [DIRS 177101], Sections 6.3 and 6.4). For example, average annual concentrations of total suspended particles one year after the eruption of Mount St. Helens at six sites with less than 1 mm to about 10 mm of deposited ash were from about 0% to 90% higher than the year prior to the eruption (BSC 2006 [DIRS 177101], Table 6-13). However, if a large quantity of ash were deposited at the RMEI location, mass loading and radionuclide concentrations in some environments could increase by more than a factor of two. If the submodel does not include the mass loading time function, airborne concentrations can remain at high levels throughout the period of calculation. Therefore, the addition of the time function could result in a difference of two or more for some conditions, and an evaluation and justification are needed to validate this portion of the submodel. Omitting the mass loading time function could result in overestimating airborne activity concentrations during the long period following a volcanic eruption for which doses will be calculated. Because the time function is based on measurement data, because the processes that cause the changes also would occur in the Yucca Mountain region, and because omission of the function results in an invalid overestimation of concentrations, inclusion of the mass loading time function is justified for the ERMYN model and is valid for the volcanic ash scenario.

Based on above discussions, it is concluded that the calculations of particle resuspension from surface soil in the air submodel are mathematically equivalent, numerically similar, or the approach is justified because it includes site-specific or realistically predictable conditions, and, therefore, this portion of the ERMYN air submodel is validated.

Table 7.3-4. Soil Resuspension in the Air Submodel

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.2-1, 6.4.2-2, 6.5.2-1, and 6.5.2-2)	Reference
GENII	$$C_a = C_s RF_a$$ C_a = radionuclide concentration in the air (Bq/m^3) C_s = radionuclide activity concentration in soil (Bq/m^2) RF_a = resuspension factor (1/m), calculated as: $$RF_a = \frac{S}{\rho_s d_{rs}}$$ S = mass loading, or concentration of total resuspended particles (kg/m^3) ρ_s = surface soil density (kg/m^3) d_{rs}.=thickness of surface soil layer.	The GENII model uses average mass loading, which is the same as mass loading for crops in the ERMYN (Equations 6.4.2-1 and 6.5.2-1). Particle resuspension for inhalation in the ERMYN uses an enhancement factor and environment-specific mass loading (Equations 6.4.2-2 and 6.5.2-2). It also uses time dependent mass loading during the transition period after a volcanic eruption (Eq. 6.5.2-3). Also see comparison with the NCRP-129 model for discussion of resuspension factor. Radionuclide and location indices were omitted in GENII equations.	Based on Napier et al. 2006 [DIRS 177331], Section 9.5.2, Equations 9.24 and 9.26; where the mass loading method is used in place of the resuspension factor.
BIOMASS ERB2A	$$C_{airs} = \frac{C_s}{(1-\theta_t)\,\rho}\,\frac{R-1}{R}\,dust_s$$ C_{airs} = radionuclide concentration in the air above cultivated soils (Bq/m^3) C_s = radionuclide concentration in cultivated soils (Bq/m^3) θ_t = total porosity of the cultivated soil compartment (dimensionless) ρ = dry grain density of the cultivated soil compartment (kg/m^3) R = retardation coefficient for cultivated soils (dimensionless) $dust_s$ = soil derived dust level in the air above cultivated soils (kg/m^3).	BIOMASS model is equivalent to the ERMYN model based on: • The *Ca* parameter in ERMYN is equivalent to the $dust_s$ term in the BIOMASS model • The C_s / [(1-θ_t) ρ] term in BIOMASS is equivalent to the C_s / ρ_s term in ERMYN. BIOMASS uses a retardation coefficient (*R*) (defined in Table 7.3-3) which causes the activity concentrations in the air to be element specific. Because *R* is much larger than 1 for most radionuclides, (*R* – 1) / *R* is close to 1 for most radionuclides (see the preceding discussion in this section and the retardation coefficient calculations in Table 7.3-3).	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	EPRI-YM is based on the BIOMASS model and uses the same equations.	EPRI-YM is based on the BIOMASS model and thus is equivalent to that used in ERMYN.	EPRI 2002 [DIRS 158069], Equation 8-12 EPRI 2004 [DIRS 171915], Equation 8-4

Table 7.3-4. Soil Resuspension in the Air Submodel (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.2-1, 6.4.2-2, 6.5.2-1, and 6.5.2-2)	Reference
RESRAD	$C_a = ASR_2\ FA_2\ FCD_2(t)\ S(t)$ *Ca* = radionuclide concentration in the air (Bq/m^3) *S(t)* = time-dependent radionuclide concentration in soil mass (Bq/kg) *FA2* = area factor (dimensionless) *FCD2* = cover and depth factor (dimensionless) *ASR2* = average mass loading of contaminated airborne soil particles (kg/m^3).	RESRAD uses an area factor and a cover-and-depth factor. These two factors are used for underground contaminants with a limited area and depth of contamination, which is not used in the ERMYN. Without these two factors, RESRAD is the same as GENII-S. Only the parts of the equation applicable to activity concentrations in the air are shown. The units are shown in SI.	Yu et al. 2001 [DIRS 159465], Equation B.1
NCRP-129	Method 1: Mass Loading $C_{air} = E_f \times S \times M$ E_f = enhancement factor, the ratio of airborne particle concentration (Bq/kg) to total surface soil concentration (Bq/kg) *S* = total surface soil concentration (Bq/kg) *M* = total resuspended particulate concentration (mass loading; kg/m^3). Method 2: Resuspension Factor $C_{air} = S_f \times D$ S_f = resuspension factor (/m) *D* = total decay-corrected soil deposition (inventory; Bq/m^2) $D = \rho\, S\, h_e$ ρ = soil bulk density (kg/m^3); suggests a typical value of 1,600 kg/m^3 h_e = effective depth of deposition (m); suggests a value of 5 ± 1.5 cm). Method 3: Mass Loading Derived Resuspension Factors Uses Method 2 to calculate air concentration, but combines Methods 1 and 2 to determine the resuspension factor: $S_f = \frac{E_f \times M}{\rho \times h_e}$ Parameters are defined in Methods 1 and 2.	Method 1 is the same as the ERMYN. Methods 2 and 3, suggested in NCRP-129, are applicable to the deposition of contamination on soil surface and are not often used for the scenarios involving deeper soil contamination due to lack of input data on the resuspension factor and the effective depth of deposition.	NCRP 1999 [DIRS 155894], pp. 64 to 71, Equations 4.3 to 4.13

7.3.2.2 Radon from Radium-Contaminated Soil

The ERMYN air submodel includes the release of radon from radium-contaminated soil for both exposure scenarios. Under the groundwater scenario, radon concentrations are calculated separately for outdoor air (radon released from surface soil) and indoor air (based on the outdoor radon and radon released from the soil under the foundation of a house; Section 6.4.2.3). For the volcanic ash scenario, the same model is used for indoor and outdoor air because there would be no contaminated ash under existing buildings or it would be removed during construction of new buildings. Among the five validation models, RESRAD includes indoor and outdoor radon, NCRP-129 only includes calculations of outdoor radon concentrations, and the other three validation models do not include radon models. RESRAD uses a relatively sophisticated radon model that calculates radon emanation from the soil and diffusion in the air. The GENII model currently includes a radon inhalation pathway from radionuclides in domestic water (Napier et al. 2006 [DIRS 177331], Section 9.5.3). This pathway is excluded in ERMYN (Section 7.4.3.1). The other radon-related exposure pathways are not functional in the current version of GENII model (Napier et al. 2006 [DIRS 177331], p. 183).

The indoor air radon calculation for the groundwater scenario (Section 6.4.2.3) is similar to that used in the RESRAD model (Table 7.3-5) with the following exceptions:

- RESRAD uses a radon decay constant that is ignored in the ERMYN because the typical house ventilation rate (0.5/h) is larger than the radon decay constant (0.0076/h).

- RESRAD uses an indoor area factor to account for partially contaminated house foundations, which does not apply to the Yucca Mountain scenarios.

- The parameter of indoor radon flux in the RESRAD model is not defined as proportional to the outdoor radon flux.

In spite of these exceptions, the indoor air radon calculations in the RESRAD model are mathematically equivalent to those in ERMYN.

To determine outdoor radon concentrations for the groundwater scenario, the NCRP-129 and ERMYN models use a simple radon release factor (Equation 6.4.2-4). The ERMYN model also uses a similar method to determine outdoor radon concentrations for the volcanic ash scenario (Equation 6.5.2-8) and the indoor concentration for that scenario is assumed to be the same. The calculational formula includes a release factor calculated by Equation 6.5.2-7 (Section 6.5.2). This is different from RESRAD, and, therefore, the methods are compared numerically (Section 7.4.3.1 and Appendix B). The general differential equation and the boundary conditions given in RESRAD are solved using the ERMYN parameter values or RESRAD default parameter values if the parameters are not used in the ERMYN. Using RESRAD, the ^{222}Rn release factor for ^{226}Ra in the soil is 0.19 (Bq/m^3)/(Bq/kg) (Section 7.4.3.1), which is similar to the value of 0.25 (Bq/m^3)/(Bq/kg) from the ERMYN groundwater scenario (Section 6.4.2.3). For the volcanic scenario, RESRAD produces a ^{222}Rn release factor of 0.0005 (Bq/m^3)/(Bq/m^2) using a radon emanation coefficient of 1 (Section 7.4.3.1). This is similar to the value of 0.0006 (Bq/m^3)/(Bq/m^2) from the ERMYN volcanic scenario (Section 6.5.2.2).

Table 7.3-5. Comparison of Radon Release from Radium Contaminated Soil

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.2-4, and 6.4.2-7)	Reference
GENII	Not included	Not applicable	Napier et al. 2006 [DIRS 177331]
BIOMASS ERB2A	Not included	Not applicable	BIOMASS 2003 [DIRS 168563], Section C3.5.4
EPRI-YM	Not included	Not applicable	EPRI 2002 [DIRS 158069], Section 8 and EPRI 2004 [DIRS 171915], Section 8
RESRAD	The RESRAD radon model for outdoor air (Yu et al. 2001 [DIRS 159465], Section C.2 and C.3, Eq. C.1 to C.9) involves solving a radon diffusion equation. (The mathematical equations are shown in Appendix B). Radon model for indoors: $C_i = \frac{\left(\frac{J_i F_{ai}}{H} + \nu C_o\right)}{(\lambda + \nu)}$ C_i = indoor radon concentration (Bq/m^3) J_I = radon flux from the floor of a house built on a contaminated area (Bq/(m^2 s)) F_{ai} = indoor area factor H = ceiling height for a single story house C_o = outdoor radon concentration (Bq/m^3) λ = decay constant of radon (1/s) ν = ventilation rate of the house (1/s).	The RESRAD submodel for radon concentrations in outdoor air requires site-specific information, such as the diffusion coefficient for radon in the soil and the radon emanation coefficient, which are not available. The numerical comparisons indicate (Appendix B) that when the generic parameters are used, the RESRAD model does not have an advantage over a much simpler NCRP-129 model (see below). For radon concentrations in indoor air, RESRAD is the same as ERMYN (Eq. 6.4.2-7), with the following assumptions and equivalent quantities: The value of ν is much larger than λ; typical house ventilation rates are about 0.5/h, while the radon decay constant is 0.0076/h. The indoor radon flux is a fraction of the outdoor flux, $J_I = f_{house} J_o$, and the ratio of radon concentration to flux (C_o/J_o) could be observed in the natural environment. The indoor area factor, the fraction of the foundation area that is built on contaminated soil, is 100%.	Yu et al. 2001 [DIRS 159465], Appendix C

Table 7.3-5. Comparison of Radon Release from Radium Contaminated Soil (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.2-4, and 6.4.2-7)	Reference
NCRP-129	$f_{m,Rn-222} = \frac{Ca_{g\,Rn-222}}{Cs_{m,Ra-226}}$ Based on the average ^{226}Ra concentration measured in soil of 40 Bq/kg, and an average outdoor air radon gas concentration of 10 Bq/m^3, $f_{m,Rn-222}$ = 0.25 Bq/m^3/Bq/kg	For the groundwater scenario, the radon release factor (or the ratio of average outdoor radon in the air to ^{226}Ra in the soil) used in NCRP-129 is used in the ERMYN for calculating outdoor radon concentration (Equation 6.4.2-4). For the volcanic ash scenario, the radon release factor is defined as the ratio of the average airborne radon concentration to the areal concentration of ^{226}Ra in the soil. The average outdoor airborne radon is calculated using the average outdoor radon flux density from radium contaminated soil.	NCRP 1999 [DIRS 155894], Section 4.3.6

Because the ^{222}Rn release factors calculated using the RESRAD and ERMYN methods differ by less than a factor of two, the two methods are numerically similar. Based on these considerations, the radon calculations are mathematically equivalent or numerically similar, and, therefore, the ERMYN methods are validated.

7.3.2.3 Contaminated Aerosols from the Operation of Evaporative Cooler

Evaporative coolers operated using contaminated water would generate contaminated aerosols, and the air submodel for the groundwater scenario includes this pathway (Section 6.4.2.2). Calculations of radionuclide concentrations in the air are based on the operating characteristics of evaporative coolers (typical rates for water use and airflow) and the conservation of mass (water and radionuclides).

None of the validation models includes the evaporative cooler exposure pathway. Therefore, the ERMYN method is validated by comparing it with a different mathematical model. Radionuclide concentrations in indoor air can be estimated by accounting for evaporation in terms of the difference in absolute humidity between indoor and outdoor air. Based on physical principles, a fraction of the radionuclides in the contaminated water would be released into the indoor air with the water vapor from the evaporative cooler. The evaporation process would create a difference between the absolute humidity in the indoor and outdoor air. This alternative method is presented in Table 7.3-6 based on known absolute humidity values for indoor and outdoor air. Relative humidity can also be used because absolute humidity can be determined if the temperature and relative humidity are known. A numerical comparison of the results from the two approaches is documented in Section 7.4.3.2, and the activity concentrations from the two methods differ by a factor of two (Table 7.4-10). Therefore, the two methods of calculating aerosol concentrations are numerically similar, and this portion of the inhalation submodel is validated.

Table 7.3-6. Comparison of Radionuclide Concentration in Indoor Air from the Operation of an Evaporative Cooler

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.2-3)	Reference
None	$$Ca = \frac{f_{evap}\,(D_{in} - D_{out})\;Cw}{\rho_w}$$ Ca = indoor radionuclide concentration (Bq/m^3) f_{evap} = fraction of radionuclide transferred from water to air D_{in} = absolute indoor humidity (kg/m^3) D_{out} = absolute outdoor humidity (in inlet air) (kg/m^3) ρw = water density (kg/m3) Cw = radionuclide concentration in water (Bq/m^3).	The fundamentals of the two methods are the same, but the ERMYN includes the amount of water used by the evaporative cooler as the amount of water vapor in the air. This alternative conceptual model considers differences between absolute indoor and outdoor humidity, which is from water used by evaporative coolers.	This method is based on physical principles.

7.3.3 Validation of the Plant Submodel

The plant submodel is used in the groundwater (Section 6.4.3) and volcanic ash exposure scenarios (Section 6.5.3). All five validation models use plant submodels to calculate radionuclide concentrations in crops and, indirectly, in other human foodstuffs. The ERMYN model includes all radionuclide transfer mechanisms considered in the validation models, including absorption through roots (both scenarios), direct deposition of contaminated water (groundwater scenario only), and soil or ash (both scenarios) on above-ground plant parts. These three environmental transport pathways of the plant submodel are validated separately in the following sections. Because the modeling of each of these pathways in the ERMYN plant submodel is mathematically equivalent, numerically similar, or the approach is justified because it includes site-specific or realistically predictable conditions, the ERMYN plant submodel is validated.

7.3.3.1 Root Uptake

All validation models use similar methods for crop root uptake (Table 7.3-7), with the following differences:

- GENII model divides the root zone into two compartments and allows a fraction of plant roots to extend beyond the surface soil zone. The fraction of roots in surface soil is a model input parameter (Napier et al. 2006 [DIRS 177331], Equation 9.11). In the ERMYN model, plant roots are assumed to be contained in the surface soil (Assumption 7) and this parameter is not used (it is effectively equal to unity). The two models are thus mathematically equivalent.

- ERMYN includes the parameter dry-to-wet weight ratio because the transfer factors used in Equations 6.4.3-2 and 6.5.3-2 are based on dry plant weight. Of all the models, only the GENII model uses this parameter (Napier et al. 2006 [DIRS 177331], Equation 9.11). The other validation models do not directly use a dry-to-wet weight ratio because their transfer factors are given per wet plant weight. Thus, the methods are mathematically equivalent.

- BIOMASS model, and the EPRI-YM model based on the BIOMASS model, include parameters for the fraction of contamination retained after food processing. The default value for this parameter is one (i.e., no loss during processing). Food processing losses are not included in the ERMYN, which is equal to assuming that the food processing parameters are equal to one. Therefore, the methods are mathematically equivalent.

- RESRAD uses an area factor to account for the portion of contaminated land used to grow crops. Under the groundwater scenario, the crops are grown using contaminated water, therefore, the total area used for agriculture would be contaminated (the factor equal to one). Under the volcanic ash scenario, contaminated ash would be deposited over the entire Amargosa Valley. Thus, the area factor would also be one and for both scenarios, the ERMYN and RESRAD models are mathematically equivalent for this environmental transport pathway.

- RESRAD includes a cover-and-depth factor to account for the effects of burying radioactive waste. Because all radionuclides are in the surface soil for the ERMYN scenarios, this factor would be set at one. Therefore, this calculation is mathematically equivalent to the ERMYN model.

In summary, the crop root uptake portion of the ERMYN plant submodel is mathematically equivalent to the five validation models, and, therefore, it is validated.

Table 7.3-7. Comparison of Crop Contamination Due to Root Uptake

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.3-2 and 6.5.3-2)	Reference
GENII	$$C_{rc} = \frac{C_c RP_{sc} Bv_c f_c}{P}$$ where C_{rc} = plant concentration from root uptake for crop type *c* (Bq/kg) Bv_{ip} = radionuclide-specific soil-to-plant transfer factor for crop type *c* (dimensionless; Bq/kg $_{\text{dry plant}}$ per Bq/kg $_{\text{dry soil}}$) C_c = total areal radionuclide concentration in farmland soil for crop *c* (Bq/m^2) P = soil density of farmland soil (kg/m^2) RP_{sc} = fraction of plant type *c* roots in surface soil (dimensionless) f_c = dry-to-wet weight ratio for plant type *c* (kg $_{\text{dry plant}}$ per kg $_{\text{wet plant}}$).	GENII equation is equivalent to the equation used in ERMYN, except for considering the fraction of roots in surface soil zone, which in ERMYN is equal to one. Radionuclide indices were omitted in the GENII equation.	Napier et al. 2006 [DIRS 177331], Equation 9.11
BIOMASS ERB2A	$$C_{crop,root} = \frac{F_{p2}\, CF_{crop}\, C_s}{(1-\theta_t)\, \rho}$$ $C_{crop,root}$ = plant root uptake (Bq/kg $_{\text{wet plant}}$) C_s = radionuclide concentration in soil (Bq/m^3) θ_t = total soil porosity (dimensionless) ρ = dry grain density of soil (kg/m^3) CF_{crop} = concentration factor from root uptake for crops (Bq/kg $_{\text{wet plant}}$ per Bq/kg $_{\text{dry soil}}$) F_{p2} = fraction of internal contamination associated with edible parts of the plant at harvest that is retained after food processing (dimensionless).	BIOMASS ERB2A is the same as the ERMYN, except for internal contamination losses due to food processing. Because the default value is 1, the two submodels are the same with the following equivalent parameters: C_s / [(1 - θ_t) ρ] in BIOMASS ERB2A is equivalent to C_s / ρ_s in ERMYN CF_{crop} in BIOMASS ERB2A is equivalent to $F_{s \to p}$ *DW* in ERMYN.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3

Table 7.3-7. Comparison of Crop Contamination due to Root Uptake (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.3-2 and 6.5.3-2)	Reference
RESRAD	$$E_{p1} = S(0)\, FA_p\, FCD_{p1}\, B_{jv}$$ E_{p1} = plant root uptake (Bq/g $_{\text{wet plant}}$) $S(0)$ = initial radionuclide concentration in soil (Bq/g $_{\text{dry soil}}$) FA_p = area factor (dimensionless) FCD_{p1} = cover-and-depth factor (dimensionless) B_{jv} = vegetable-soil transfer factor for root uptake (Bq/g $_{\text{wet plant}}$ per Bq/g $_{\text{dry soil}}$).	RESRAD is designed for soil contamination. The equation shown at left is modified to eliminate radionuclide and time dependence, and other subscripts are simplified to reflect root uptake. Two parameters, the area factor and the cover-and-depth factor, are used for underground contaminants with limited area and depth, which is not the case in the scenarios addressed by ERMYN. RESRAD uses the same equation as the ERMYN with the following equivalent parameter: $B_{i,j}$ in RESRAD is equivalent to $F_{s\rightarrow p}\, DW$ in ERMYN.	Yu et al. 2001 [DIRS 159465], Equations 3.11, D.1 and D.8
EPRI-YM	$$C_{crop,root} = \frac{F_{p2} CF_{crop} C_s}{(1-\theta_t)\rho}$$ The equation and the parameters are the same as those used in the BIOMASS model.	EPRI-YM uses the same equation as BIOMASS ERB2A and is the same as the ERMYN.	EPRI 2002 [DIRS 158069], Equation 8-9 and EPRI 2004 [DIRS 171915], Equation 8-11
NCRP-129	$$C_{i,root} = S \times B_v$$ $C_{i,\,root}$ = concentration in a given type of vegetation due to root uptake (Bq/kg $_{\text{wet plant}}$) S = radionuclide concentration in the surface soil (Bq/kg $_{\text{dry soil}}$) B_v = an empirically determined soil-to-vegetation transfer factor for roots (usually expressed as Bq/kg $_{\text{wet vegetation}}$).	NCRP-129 uses the same equation as RESRAD, except for no area factor, and no cover-and-depth factor. Thus, the model is the same as that used in ERMYN.	NCRP 1999 [DIRS 155894], Section 5.1 and Equation 5.2

7.3.3.2 Uptake from Irrigation Water

Four of the five validation models, GENII, BIOMASS ERB2A, EPRI-YM, and RESRAD, include crop uptake from contaminated irrigation water as a result of direct deposition on leaf surfaces. NCRP-129, which applies only to a soil contamination scenario, does not address this process. The BIOMASS ERB2A and EPRI-YM methods for calculating concentrations in fresh forage (animal feed) are different from those used to calculate concentrations in other crops. These methods are not shown in the comparison (Table 7.3-8) because they are based on cattle fed in pastures, which differs from the farming methods in the Amargosa Valley. The methods these two models use for calculating concentrations in human foodstuffs are compared in Table 7.3-8. The two components for calculating radionuclide uptake, the irrigation deposition rate (Table 7.3-9) and the interception fraction due to irrigation water intercepted by leaf surfaces (Table 7.3-10), are compared separately. Based on the comparisons, the calculations are mathematically equivalent, numerically similar, or have differences that result from model improvements and site-specific conditions, and this portion of the ERMYN plant submodel is validated.

Radionuclides in Crops—Among these four validation models, GENII and RESRAD use methods similar to the ERMYN model. The BIOMASS ERB2A method includes more transfer processes, is conceptually different from the ERMYN method, and is an ACM (Section 6.3.3). The numerical comparison is described below and in Section 7.4.4.1. The EPRI-YM equation is identical to that used in the BIOMASS ERB2A model. Therefore, the EPRI-YM approach is not discussed separately here. Differences between the ERMYN and the validation models are:

- None of the validation models use a parameter for the fraction of overhead irrigation (Equation 6.4.3-3). Values of this parameter, ranging from 0 to 1, can be lower than 0.5 for crops such as fruits that normally are drip irrigated (BSC 2004 [DIRS 169673], Section 6.3). Values of 0.5 or lower result in activity concentrations due to irrigation deposition that differ by a factor of two or more, and this portion of the submodel must be further justified. There are three basic methods for irrigating field crops, orchards, and gardens: surface (i.e., flood), drip, and sprinkler irrigation. Of these, only sprinkling deposits radionuclides directly on plant surfaces. Irrigation methods differ among crop types. Drip irrigation often is used on orchard and gardens, and overhead sprinklers and surface irrigation often are used on fields (BSC 2004 [DIRS 169673], Section 6.3). In the Amargosa Valley in 1997, about 85% of field crops were irrigated with overhead sprinklers and all of the fruit and nut crops were irrigated with drip systems (BSC 2004 [DIRS 169673], Table 6.3-1). There is little information about the preferred methods of irrigating gardens in the Amargosa Valley; therefore, there is uncertainty in the proportion of crops that would be contaminated by overhead irrigation. The fraction of overhead irrigation is a justifiable parameter in the ERMYN model because it allows for considering site-specific differences in irrigation methods among crop types, accounts for uncertainty in irrigation methods used, and prevents overestimating contamination via this pathway by avoiding the erroneous assumption that all crops are irrigated with sprinkler systems. Therefore, using this parameter in the ERMYN plant submodel is justified.

- GENII includes parameters that account for radioactive decay during the time from harvest to consumption (holdup time and decay constant). The holdup time, generally, is days to weeks for fresh produce, which is short relative to radioactive decay rates for the long-lived radionuclides in the ERMYN (Table 6.3-7). Thus, the exponential factor in GENII (Napier et al. 2006 [DIRS 177331], Equation 9.13), which includes the holdup time and decay constant, approaches one, and the methods are mathematically equivalent.

The BIOMASS ERB2A method includes two translocation processes for radionuclides deposited on plant surfaces by irrigation water: absorption from external plant surfaces into the plant tissues (F_{abs}) and translocation from plant tissues into the edible portion of the crop (F_{trans}). It also includes internal (F_{p2}) and external (F_{p3}) losses due to food processing. Furthermore, it considers that weathering losses occur only during the interval between the last irrigation and harvest (T) rather than over the entire growing period. Because frequent irrigation is required during the entire growing season in southern Nevada (BSC 2004 [DIRS 169673], Section 6.5), this consideration is invalid for the ERMYN. In addition, several parameters used in the BIOMASS ERB2A model, such as the interval time (T) and the absorption fraction (F_{abs}), are not commonly used in environmental radiation models and, therefore, are difficult to quantify. The BIOMASS and ERMYN methods are numerically compared using input values from Table 6.6-3 and, where necessary, default values from the BIOMASS model (Section 7.4.4.1), and the results differ by a factor of two (Table 7.4-11). Thus, the methods are numerically similar.

Irrigation Deposition Rate—The irrigation deposition rate (Equation 6.4.3-4) is used to calculate the direct deposition rate of radionuclides due to application of irrigation water for crops. The ERMYN and the applicable validation models calculate the deposition rate by multiplying the water concentration by an irrigation rate. The structure of the equations and the input parameters differ in the following ways:

- GENII uses an annual irrigation rate divided by the number of months crops are irrigated. The ERMYN, instead, uses a daily irrigation rate to eliminate the correlation between irrigation rates and growing season lengths. These terms are mathematically equivalent because they both represent the rate of irrigation application per unit time during the growing season.

- RESRAD uses a factor ($F1$) for the proportion of irrigation water that is contaminated. This value equals one in the ERMYN because contaminated groundwater is the only source of irrigation water. Thus, the portion of the RESRAD equation with this factor and the associated ratio of surface water concentration to soil concentration (WSR_2) becomes one, making the methods mathematically equivalent.

- BIOMASS ERB2A, EPRI-YM, and RESRAD use an annual irrigation rate, without considering the length of the growing season, to determine the average deposition rate. When converted to an annualized rate per day, rates based on irrigating over an entire year result in lower deposition rates than rates based on the growing season. This difference is greater than a factor of two for all crops with a growing season of less than six months, and the following evaluation and justification are provided to validate this portion of the submodel. Many of the crops commonly grown in farms and gardens in the Amargosa Valley have growing seasons of less than 4 months, and no crops types are irrigated all year (BSC 2004 [DIRS 169673], Section 6.4). Using an annual irrigation rate for these crops results in underestimating radionuclide deposition because a rate divided over an entire year would be lower than a rate divided over the growing season. The method in the ERMYN is used to match the site-specific gardening and agricultural practices in the Amargosa Valley, and to avoid underestimating the irrigation deposition rate. Thus, this portion of the submodel is justified.

Interception Fraction—The ERMYN method for calculating the proportion of radionuclides in irrigation water intercepted by crops differs from the method in the five validation models, which all include the interception fraction as a single parameter. Default values for the fraction range from 0.05 to 0.3 (Table 7.3-10). In contrast, the ERMYN uses an empirical equation from Hoffman et al. (1989 [DIRS 124110]) for calculating the interception faction. This equation is based on the interception of ^{7}Be, which has a high interception fraction (Section 6.4.3.2). Inputs to this equation are crop biomass, irrigation amount applied per application, and irrigation intensity. The first two inputs differ among crops, so different distributions are calculated for each crop type.

To compare these methods numerically, interception fractions are calculated using average values for each crop type, and the interception fraction values range from 0.24 for leafy vegetables to 0.51 for grains (Table 7.4-12). Some of the values differ by more than a factor of two from the default values used in the validation models, so an evaluation and justification for the ERMYN method is provided. The primary reason the empirical equation is used in the ERMYN is to incorporate variation and uncertainty in irrigation rates and the types of crops grown in the Amargosa Valley. Hoffman et al. (1989 [DIRS 124110]) show that the proportion of radionuclides intercepted differs depending on the size of plants (i.e., aboveground biomass), the rate at which water is applied, the amount of water applied, and the charge carried by the chemical element. Therefore, a single value per crop type is not adequate because there are a substantial number of crops per crop type grown in the Amargosa Valley (BSC 2004 [DIRS 169673], Section 7 and Appendix A). The ERMYN method accounts for differences in irrigation requirements and growth forms of the crops. It also accounts for differences resulting from climate change (different irrigation requirements).

Although experiments indicated that the interception fraction depends on the charge carried by the chemical element (Hoffman et al. 1989 [DIRS 124110]), there is not enough information to calculate radionuclide-specific interception fraction values. Therefore, conservative empirical constants based on the ^{7}Be results are used in ERMYN (Section 6.4.3.2).

The simulated irrigation conditions used by Hoffman et al. (amount of simulated rain = 1 to 30 mm; rain intensity = 2 to 12 cm/h), generally, are comparable with irrigation practices in the Amargosa Valley (Table 6.6-3), except that the amount of irrigation per application for grain and forage (about 55 mm) is higher than the simulated amount of rain. However, the equation is relatively insensitive to the irrigation amount. For example, changing the irrigation application from 15 to 65 mm (and holding the other factors constant at average values) changes the interception fraction from 0.34 to 0.23 (BSC 2004 [DIRS 169673], Section 6.7). The dry biomass of crops in the Amargosa Valley (Table 6.6-3) is generally higher than the experimental conditions used to develop the equation (Hoffman et al. 1989 [DIRS 124110]). However, the interception fraction is asymptotic to one at relatively low values of dry biomass (BSC 2004 [DIRS 169673], Figure 6.1-1), so the equation is insensitive to larger biomass values. Thus, the method is applicable to the site-specific input values in the ERMYN model. The full range of parameter values used to calculate the interception fraction was stochastically sampled as part of the verification of the model (Section 6.10.1.2). The resulting range of interception fractions was from 0.10 to 0.69 for leafy vegetables with a mean value of 0.23, 0.20 to 0.69 for other vegetables with a mean value of 0.33, 0.09 to 1.0 for fruits with a mean value of 0.40, 0.23 to 1.0 for grain with a mean value of 0.49, and 0.08 to 0.81 for forage with a mean value of 0.25.

Anspaugh (1987 [DIRS 123696]) reviewed the literature on the retention of radionuclides deposited on crop surfaces. In general, the interception fractions in that report are within the range of average values calculated using the ERMYN method (Table 7.4-12). A few of the reviewed studies reported interception fractions higher than the mean values shown in Table 7.4-12 (e.g., greater than 0.7) but within the range of results when the full range of input parameters are stochastically sampled. The amount of rainfall or irrigation applied in these studies was only a fraction of a millimeter per wetting event. Because the irrigation applications used to calculate the values in Table 7.4-12 are higher (mean of 15 to 58 mm; Table 6.6-3), the calculated interception fractions (Equation 6.4.3-5) are expected to be lower than the levels obtained experimentally using low application rates.

In summary, the empirical method in ERMYN for calculating the irrigation interception fraction incorporates variation and uncertainty in the fraction resulting from differences among crops and in irrigation practices in the Amargosa Valley. The ERMYN method is applicable to the site-specific conditions and is relatively insensitive to input values outside the range of experimental values. The average values calculated using site-specific inputs are similar to values reported in the literature. This method, therefore, is reasonable, and this portion of the submodel is justified.

Table 7.3-8. Comparison of Direct Deposition on Plant Surfaces Due to the Interception of Irrigation Water

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.3-3)	Reference
GENII	$$C_{dc} = R_w \frac{12 r_c}{M_c} \frac{Tv_c}{B_c} \frac{\left(1 - e^{-\lambda_e Tg_c}\right)}{\lambda_e} e^{-\lambda_d Th_c}$$ C_{dc} = concentration of a radionuclide in crop type *c* from deposition on leaves (Bq/kg) R_w= deposition rate from water onto farmland (Bq/m^2/yr), calculated in Table 7.3-9 r_c = interception fraction for irrigation deposition to crop type *c* (dimensionless); used values shown in Table 7.3-10 Tv_c = translocation factor from crop surfaces to the edible crop parts for crop type *c* (dimensionless) λ_e = effective weathering and decay constant (1/yr) λ_d = decay constant (1/yr) Tg_c = duration of the growing period for plant type *c* (yr) Th_c = time between harvest and consumption for crop type *c* (yr) M_c = irrigation period for plant type *c* (mo) B_c = total standing biomass for crop type *c* (wet weight) (kg/m^2).	Holdup time is not used in ERMYN, because the decrease of radionuclide concentration during the holdup is not important for long-lived radionuclides (Section 6.3.1.6). The fraction of overhead irrigation is used in the ERMYN to consider other irrigation methods used in Amargosa Valley. GENII uses the duration of irrigation (M_c) during the crop growing season to calculate the irrigation rate during that time from the annual average irrigation rate. In ERMYN, such a conversion is not necessary because the model uses irrigation rates that were developed for the periods of time as used in the model. The methods used in GENII and in ERMYN are equivalent. Radionuclide indexing was omitted in when showing GENII equations and only those parts of equations that were pertinent to wet deposition were used.	Napier et al. 2006 [DIRS 177331], Equations 9.10 and 9.13
RESRAD	$$FWR_{j34k} = \frac{I_{rr}\ f'_r\ T_{jvk}}{\lambda_w\ Y_{vk}} \left(1 - e^{-\lambda_w\ t_{ek}}\right)$$ FWR_{j34k} = plant-food/water concentration ratio (m^3/kg) I_{rr} = deposition rate from air or water onto farmland (m/yr) f_r' = fraction of deposited radionuclide retained on vegetation T_{jvk} = foliage-to-food radionuclide transfer coefficient for the *j*th principal radionuclide and *k*th food class (dimensionless) λ_{wi} = weathering removal rate constant for vegetation (1/yr) t_{ek} = time of exposure of the *k*th food class to contamination during the growing season (yr) Y_{vk} = wet weight crop yield for the *k*th food class (kg/m^2).	RESRAD calculates the plant-food/water concentration ratio (m^3/kg). The radionuclide concentrations in plants are calculated by multiplying this value by the water concentration (*Cw* – Bq/m^3). RESRAD is equivalent to ERMYN, except for the addition of the parameter “fraction of overhead irrigation” to the ERMYN.	Yu et al. 2001 [DIRS 159465], Equation D.14

Table 7.3-8. Comparison of Direct Deposition on Plant Surfaces Due to the Interception of Irrigation Water (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.3-3)	Reference
BIOMASS ERB2A	$$C_{crop,irrig} = I_{crop}\, S \left(\frac{(1-F_{abs})\, e^{-WT}\, F_{p3}}{Y_{crop}} + \frac{F_{abs}\, F_{p2}\, F_{trans}}{Y_{crop}} \right)$$ $C_{crop,irrig}$ = radionuclide concentration in the edible part of the crop due to irrigation water deposited on crop leaf surface (Bq/kg $_{\text{fresh weight of crop}}$) I_{crop} = fraction of radionuclides in spray irrigation water initially deposited on standing biomass (dimensionless) S = irrigation deposition rate (Bq m^{-2} yr^{-1}); Table 7.3-9 F_{trans} = fraction of absorbed activity translocated to edible portions of the plant by the time of harvest (translocation fraction) F_{abs} = fraction of intercepted radionuclide initially deposited onto plant surfaces absorbed from external surfaces into plant tissues (dimensionless) F_{p2} = fraction of internal contamination in the edible parts of plants at harvest that is retained after food processing (dimensionless) F_{p3} = fraction of external contamination from interception retained on edible parts of the plant after food processing (dimensionless) W = removal (weathering) rate for radionuclides deposited on plant surfaces by irrigation (weathering processes include mechanical weathering, wash-off, and leaf fall) (1/yr) T = interval between irrigation and harvest (yr) Y_{crop} = wet weight biomass of the crop kg/(m^2 yr).	The BIOMASS ERB2A model uses more transfer processes than ERMYN, including losses due to food processing (F_{p2} and F_{p3}), and absorption into a plant of radioactivity intercepted by external plant surfaces (F_{abs}). It separates internal and external contamination and applies weathering loss to external contamination only. As it assumes infrequent irrigation in this model, weathering loss is only occurring from the last irrigation to harvest. The following parameters are equivalent in the two models: S in BIOMASS is equivalent to Dw in ERMYN I_{crop} in BIOMASS is equivalent to Rw in ERMYN $F_{abs} \times F_{trans}$ in BIOMASS is equivalent to translocation factor in ERMYN Y_{crop} in BIOMASS is equivalent to B in ERMYN W in BIOMASS is equivalent to λ_w in ERMYN Because BIOMASS ERB2A includes more processes, it is a potential ACM that requires numerical comparison.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	The EPRI-YM model is based on the BIOMASS ERB2A model and uses the same equations.	See BIOMASS ERB2A model	EPRI 2002 [DIRS 158069], Equation 8-9
NCRP-129	Not included in the model	Not applicable	NCRP 1999 [DIRS 155894]

Table 7.3-9. Comparison of Irrigation Deposition Rate

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.3-4)	Reference
GENII	$R_w = C_w IR$ R_w= deposition rate by irrigation (Bq/(m^2 yr)) IR = crop irrigation rate (m/yr) Cw = annual average radionuclide concentration in water (Bq/m^3)	The method used in GENII is equivalent to that used in ERMYN. The two models are the same, except for different units and notations. Radionuclide and location indexing as well as unit conversions that is used in GENII was omitted here to show the essence of the model.	Napier et al. 2006 [DIRS 177331], Equation 9.5
BIOMASS ERB2A	$S = V_{irr}\ C_w$ S = activity deposition by irrigation (Bq/yr or Bq m^{-2} yr^{-1} depending on the irrigation rate term) V_{irr} = irrigation rate (m^3/yr); this quantity is equivalent to the amount of irrigation water (m) applied to a unit area (m^2) per unit time (yr) (m/yr) C_w = radionuclide concentration in groundwater (Bq/m^3).	The irrigation deposition rate in BIOMASS ERB2A is uniformly distributed throughout the year, not just during the growing season, as is used in ERMYN and GENII. In addition, a single irrigation rate is applied to all crop types. Most crops do not grow throughout the year, and irrigation would occur only during crop growing season. The difference between annual irrigation rates and daily irrigation rates is not a simple conversion of units because the annual irrigation rate considers the total amount of irrigation in a year and disregards when and how the irrigation occurs.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.2
RESRAD	$D = I_{rr}\ [WSR_1\ F1 + WSR_2\ (1\text{-}F1)]\ S(0)$ D = radionuclide deposition rate (this parameter is added for comparison) (Bq/(m^2 yr^1)) I_{rr} = irrigation rate (m/yr) WSR_1 = ratio of groundwater concentration to the soil concentration of radionuclide (kg/m^3) $F1$ = groundwater use as a fraction of water from a contaminated source (dimensionless) WSR_2 = ratio of surface water concentration to the soil concentration of radionuclide (kg/m^3) $S(0)$ = initial radionuclide concentration in soil (Bq/kg $_{\text{dry soil}}$).	In the RESRAD model (Yu et al. 2001 [DIRS 159465]), the mathematical representation is based on initial soil contamination, and the source term is discussed in Section 3 of that document, not Appendix D. The equation shown at left is modified to eliminate radionuclide and time dependence. Other subscripts are simplified to reflect irrigation deposition. The terms WSR1 × $S(0)$ is equivalent to the calculation of concentrations in groundwater in ERMYN. RESRAD is the same as the ERMYN when there is no surface water (WSR_2 = 0) and all groundwater is contaminated ($F1$ = 1). The units for the RESRAD model parameters are shown in SI for consistency with the other models. Similar to BIOMASS ERB2A, RESRAD does not use irrigation duration; rather, it uses an annual rate for the entire year. In addition, a single irrigation rate is used for all crop types. This was discussed above.	Yu et al. 2001 [DIRS 159465], Equations 3.11, D.14 and D.2
EPRI-YM	The EPRI-YM model is based on the BIOMASS ERB2A model and uses the same equations.	See BIOMASS ERB2A model	EPRI 2002 [DIRS 158069], Equation 8-2
NCRP-129	Not included	Not applicable	NCRP 1999 [DIRS 155894]

Table 7.3-10. Comparison of the Interception Fraction for Irrigation

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.3-5)	Reference
GENII	The interception fraction for irrigation deposition is assumed to be generally equal to the interception fraction for airborne wet deposition (from rainfall) and is based on the empirical formula. The empirical formula used in GENII is based on the same set of experimental data, and the model fitted to those data, as those used by ERMYN.	The interception fraction for irrigation is an important parameter to estimate direct deposition on leaf surfaces due to the interception of irrigation water. A single value for all crops is used in most biosphere models. An empirical equation based on experiments conducted by Hoffman et al. (1989 [DIRS 124110]) is used in the ERMYN and in GENII because the experiments that were conducted are applicable to irrigation practices in the Yucca Mountain area, and because this equation can be used to develop interception fractions for each crop type.	Napier et al. 2006 [DIRS 177331], Sections 9.4.1.2 and 9.4.1.4
BIOMASS ERB2A	Interception fraction (factor) is element-dependent but does not depend on the crop type, i.e., same value is used for all crops.		BIOMASS 2003 [DIRS 168563], Section C3.6
RESRAD	No mathematical representation for the interception fraction of irrigation in RESRAD. A default value of 0.25 is used for all crop types.		Yu et al. 2001 [DIRS 159465], Equation D.9
EPRI-YM	Same as BIOMASS ERB2A		EPRI 2002 [DIRS 158069], Section 8.2.6
NCRP-129	Not included	Not applicable	NCRP 1999 [DIRS 155894]

7.3.3.3 Uptake from Resuspended Soil

Direct deposition of radionuclides on leaf surfaces due to the interception of resuspended soil is another mechanism by which crops could become contaminated. The ERMYN, GENII, and RESRAD models address dust deposition and the subsequent transfer of radionuclides to crops in a manner similar to the interception of irrigation water. The BIOMASS ERB2A, EPRI-YM, and NCRP-129 models address crop surface contamination using a ratio factor (similar to the soil-to-plant transfer factor in the root uptake process). These two approaches are compared mathematically (Table 7-3.11). Two components, the dust deposition rate (Table 7.3-12) and the interception fraction (Table 7.3-13), are compared separately. The results show that the methods are mathematically equivalent, numerically similar, or have differences resulting from model improvements and site-specific conditions, which validates this portion of the ERMYN plant submodel.

Radionuclides in Crops—The ERMYN calculates radionuclide concentrations in plants due to foliar interception of airborne particles (Equations 6.4.3-6 and 6.5.3-3) using a method similar to that used by GENII and RESRAD (Table 7.3-11). This method considers the transfer of radionuclides into crops through dust deposition on leaf surfaces through a mechanism similar to the deposition of irrigation water on leaf surfaces. The only difference among these models is that GENII includes radioactive decay during the time between harvest and consumption (i.e., holdup time). As explained in Section 7.3.3.2 for water interception, the holdup time is short relative to the decay time of the long-lived radionuclides, and has negligible effect on the model results. Therefore, the methods are mathematically equivalent.

BIOMASS ERB2A, EPRI-YM, and NCRP-129 address crop surface contamination using a contamination factor, a method that differs from the ERMYN method and is identified as an ACM (Section 6.3.3). A numerical comparison (Section 7.4.4.3) shows that the activity concentration in other vegetables calculated using the ERMYN method (3.1×10^{-5} Bq/kg; Table 7.4-13) differs by less than a factor of two from the concentration for vegetables and grains calculated using the alternative method (2.0×10^{-5} Bq/kg). In contrast, the ERMYN result for leafy vegetables (2.2×10^{-4} Bq/kg) is an order of magnitude higher than that for the alternative method for vegetables and grains. It is, however, similar to the concentration for forage (2.0×10^{-4} Bq/kg) calculated using the alternative method in BIOMASS, EPRI-YM, and NCRP-129. This is because the ERMYN uses a high translocation factor for leafy vegetables and forage, whereas the analogous factor in the alternative method (the soil contamination factor) is high only for forage (Section 7.4.4). Because leafy vegetables and forage have similar growth forms (i.e., the consumed portion of the plant, the leaves, are aboveground and directly exposed), the same, high translocation factor is justified for both crop types. Therefore, the alternative method could underestimate the radionuclide concentration in leafy vegetables. The models are numerically similar for the applicable comparison of leafy vegetables to forage. Thus, this portion of the submodel is justified.

Dust Deposition Rate—The ERMYN method for calculating the dust deposition rate (Equations 6.4.3-7 and 6.5.3-4) is the same as that in GENII and RESRAD, except for the units and associated unit conversion factors (Table 7.3-12). The alternative approach used in the BIOMASS ERB2A, EPRI-YM, and NCRP-129 models does not require calculating the dust deposition rate. The differences between the ERMYN method and the alternative approach to calculate radionuclide concentrations in plants due to foliar interception of airborne particles are compared above.

Interception Fraction—The ERMYN method for calculating the initial fractional deposition of radionuclides on plant surfaces from dry deposition (Equations 6.4.3-8 and 6.5.3-5) is similar to the GENII method for dry deposition (Table 7.3-13), with one exception described below. RESRAD uses a fixed value for the interception fraction of resuspended soil, with a default value of 0.25 (Table 7.3-13). Justification is provided below based on a numerical comparison between the RESRAD default value and the calculated values in the ERMYN. The alternative approach used in the BIOMASS ERB2A, EPRI-YM, and NCRP-129 models does not require a dust interception fraction. Differences between the ERMYN method and the alternative approach for calculating radionuclide concentrations in plants due to foliar interception of airborne particles are already compared.

- The ERMYN and GENII models use different measurements of dry biomass for calculating the dust interception fraction. The ERMYN uses a parameter of dry biomass (Equations 6.4.3-8 and 6.5.3-5) that is defined as the dry weight of aboveground standing biomass. GENII calculates dry biomass as the product of wet weight biomass and a dry-to-wet weight biomass ratio, which is equivalent to the quantity used in ERMYN.

- RESRAD does not calculate the fraction of resuspended particles intercepted by plants; rather, it uses a default value of 0.25 for all crop types. Dust interception fractions calculated using the ERMYN for average values (Table 6.6-3) range from 0.456 for leafy vegetables to 0.959 for grains (Table 6.10-1). These two approaches produce interception fractions that differ by more than a factor of two, so a justification for the ERMYN method is provided. Field experiments with dry-deposited particles indicate that the interception fraction depends on the deposited materials, particle sizes, and crop types (IAEA 1996 [DIRS 160402], Table I). One experimental result shows that about 96% of the deposited ^{212}Pb is intercepted by leaves (IAEA 1996 [DIRS 160402], p. 13). Based on the experimental results, a single value of interception fraction for all crop types does not reflect differences among crops, and the default value of 0.25 in the RESRAD model may be too low for some crops. Therefore, the method used in the ERMYN is justified.

Table 7.3-11. Comparison of Direct Deposition on Leaf Surface Due to the Interception of Resuspended Soil

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.3-6 and 6.5.3-3)	Reference
GENII	To calculate direct deposition of resuspended soil on crops, GENII uses an equation that is conceptually similar to that used for the irrigation interception, except for a different deposition rate, *R*, and interception fraction, *r* (Table 7.3-8).	GENII is analogous to the ERMYN model. Holdup time is not used in ERMYN because the radionuclides of interest are long-lived.	Napier et al. 2006 [DIRS 177331], Equation 9.10
RESRAD	RESRAD is similar to the equation for irrigation interception, except that irrigation rate, I_{rr}, replaces particle deposition velocity, V_d, with appropriate unit conversions (Table 7.3-8).	The RESRAD method is the same as that used in ERMYN. RESRAD calculates a plant-food to air concentration ratio (m^3/kg). Radionuclide concentrations in plants are calculated using this ratio multiplied by the air concentration, *Ca*, (Bq/m^3).	Yu et al. 2001 [DIRS 159465], Eq. D.9 and D.10.
BIOMASS ERB2A	BIOMASS does not use dust deposition rate; instead, it models crop soil contamination as a factor relating activity in the soil to activity on the crop. The deposition on crops is calculated as: $$C_{crop,dust} = \frac{F_{p1} S_{crop} C_s}{(1-\theta_t)\rho}$$ $C_{crop,dust}$ = dust deposition on crops (Bq/kg $_{\text{wet plant}}$) C_s = radionuclide concentration in soils (Bq/m^3) θ_t = total porosity in the soil (dimensionless) ρ = dry grain density of soil (kg/m^3) S_{crop} = soil contamination on the crop (Bq/kg $_{\text{dry soil}}$ per Bq/kg $_{\text{wet plant}}$) F_{p1} = fraction of external soil contamination on edible crop parts retained after food processing, dimensionless).	These three dose assessments use a different method to calculate dust deposition on crops. A crop soil contamination factor, in units of kg $_{\text{dry soil}}$ per kg $_{\text{wet plant}}$ or kg $_{\text{dry plant}}$, is used. BIOMASS uses an equation similar to EPRI-YM, except F_{p1} in BIOMASS is equivalent to (1 – F_{crop}). NCRP-129 uses a mass soil concentration with no food process losses. These three models use the same method.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	EPRI-YM model is based on the BIOMASS ERB2A model. Same equation is used for dust deposition on crops		EPRI 2002 [DIRS 158069], Equation 8-9 and EPRI 2004 [DIRS 171915], Equation 8-11

Table 7.3-11. Comparison of Direct Deposition on Leaf Surface Due to the Interception of Resuspended Soil (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.3-6 and 6.5.3-3)	Reference
NCRP-129	NCRP-129 does not use dust deposition; instead, it uses transfer factors from soil to vegetation due to soil adhesion for resuspension processes: $C_{i,dust} = S \times B_{v'}$ $C_{i,dust}$ = concentration in a crop type due to dust deposition ($Bq/kg_{wet\ plant}$) S = radionuclide concentration in surface soil ($Bq/kg_{dry\ soil}$) $B_{v'}$ = transfer factor for the net effect of all resuspension processes.		NCRP 1999 [DIRS 155894], Equation 5.2

Table 7.3-12. Comparison of the Dust Deposition Rate

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.3-7 and 6.5.3-4)	Reference
GENII	$$R_a = C_c RF_c Vd = C_{sa} Vd$$ R_a = deposition rate for resuspended soil (Bq/(m^2 s)) C_c = radionuclide concentration in farmland soil for crop type *c* (Bq/m^2) C_{sa}= air concentration of radionuclide from soil resuspension (Bq/m^3) *Vd* = deposition velocity of a radionuclide (m/s). *RF* = resuspension factor.	The GENII equation is the same as the ERMYN. Radionuclide indices were omitted in the GENII equation.	Napier et al. 2006 [DIRS 177331], Equations 9.10 and 9.24
RESRAD	$$D = 3.16\times10^7 \times V_d \times ASR_3 \times S(0)$$ *D* = deposition rate for resuspended soil (this parameter is added for the comparison) (Bq/(m^2 yr)) 3.16×10^7 = unit conversion (s/yr) V_d = deposition velocity for radionuclide (m/s) ASR_3 = air/soil concentration ratio, specified as the average mass loading of airborne contaminated soil particles in a garden during the growing season (g/m^3) *S(0)* = initial radionuclide concentration in soil (Bq/g $_{\text{dry soil}}$).	RESRAD and ERMYN are the same with the following equivalent quantities: $ASR_3 \times S(0)$ in RESRAD is equivalent to C_a, in ERMYN. The unit conversion (to the left) is different from that shown in the manual because the item compared is not presented directly.	Yu et al. 2001 [DIRS 159465], Equations 3.11, D.9 and D.10
BIOMASS ERB2A	Dust deposition is not included; instead, the model uses a crop soil contamination factor.	Not applicable	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	Dust deposition is not included; instead, the model uses a crop soil contamination factor. See the interception fraction for resuspended soil.	Not applicable	EPRI 2002 [DIRS 158069], Equation 8-9 and EPRI 2004 [DIRS 171915], Equation 8-11
NCRP-129	Dust deposition is not included; instead, the model uses transfer factors from soil to vegetation due to soil adhesion for resuspension processes.	Not applicable	NCRP 1999 [DIRS 155894], Equation 5.2

Table 7.3-13. Comparison of Interception Fraction for Resuspended Soil

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.3-8 and 6.5.3-5)	Reference
GENII	$r_{dc} = 1 - e^{-a_c B_c f_c}$ r_{dc} = interception fraction for atmospheric dry deposition of resuspended soil for crop type *c* (dimensionless) a_c = empirical factor (m^2/kg); 2.9 for leafy vegetables, fresh forage feed, and grain; and 3.6 for root vegetables and fruit B_c = standing biomass of the growing vegetation for crop type *c* ($kg_{\text{wet plant}}/m^2$) f_c= dry-to-wet weight biomass ratio for crop type *c* (dimensionless).	The empirical equation for the interception fraction of resuspended soil used in GENII is the same as that used in the ERMYN. ERMYN uses dry biomass to represent the $B_c \times f_c$ term in GENII. The empirical constant, a_c, is in the range of valid values from an IAEA review document (IAEA 1996 [DIRS 160402], Section 2.1.2).	Napier et al. 2006 [DIRS 177331], Equations 9.16 and 9.17
RESRAD	No mathematical representation for the interception fraction of resuspended soil. A default value of 0.25 is used for all plant types.	The default value is comparable to the results of empirical equation.	Yu et al. 2001 [DIRS 159465], Section D.2, p. D-12.
BIOMASS ERB2A	Dust deposition is not included; instead, a crop soil contamination factor is used. A default value of 2×10^{-4} $kg_{\text{dry soil}}$ per $kg_{\text{wet plant}}$ is used for green vegetables, root vegetables, and grain, and 2×10^{-3} is used for fresh forage feed.	Due to differences between the models, it was necessary to conduct the numerical comparison described in Section 7.4.4. The results showed that the contribution of direct deposition on crop leaves due to the interception of resuspended soil were numerically similar.	BIOMASS 2003 [DIRS 168563], Table C27
EPRI-YM	Dust deposition is not included; instead, a crop soil contamination factor is used. A default value of 2×10^{-4} $kg_{\text{dry soil}}$ per $kg_{\text{wet plant}}$ is used for green vegetables, root vegetables, fruit and grain, and 2×10^{-3} is used for fresh forage feed.	Not applicable	EPRI 2002 [DIRS 158069], Table 8-7 EPRI 2004 [DIRS 171915], Table A-2
NCRP-129	Dust deposition is not included; instead, transfer factors from soil to vegetation due to soil adhesion for resuspension processes are used. A value of 1×10^{-3} $kg_{\text{dry soil}}$ per $kg_{\text{wet plant}}$ is suggested for cultivated land use. The range is also suggested to be 10 times lower or higher than the recommended value.	Not applicable	NCRP 1999 [DIRS 155894], Table 5.7

7.3.4 Validation of the Animal Submodel

The animal submodel is used in the groundwater (Section 6.4.4) and volcanic ash (Section 6.5.4) exposure scenarios, except that the animal drinking water pathway is not included in the volcanic ash scenario. All five validation models use an animal submodel, although some of the models include more contamination transfer processes than others. Each part of the ERMYN animal submodel is validated, as discussed in detail in the following four sections. Because the ERMYN animal submodel and the animal submodels in the validation models are mathematically equivalent, numerically similar, or have differences that result from model improvements, the ERMYN animal submodel is validated.

7.3.4.1 Animal Feed

All five validation models use the same method as the ERMYN for calculating radionuclide concentrations in animal products due to contaminated animal feed (Equations 6.4.4-2 and 6.5.4-2), with two exceptions (Table 7.3-14). First, the GENII and NCRP-129 models calculate radionuclide decay during the holdup time for animal forage between harvest and consumption. The holdup time is short (generally days to weeks for fresh forage; weeks to months for grain) relative to the radioactive decay half-life for long-lived radionuclides (Table 6.3-7). Thus, the exponential factor in the GENII and NCRP-129 models, which includes the holdup time and decay constant, approaches one, and the methods are mathematically equivalent. Second, the GENII and NCRP-129 models include a parameter for the fraction of animal feed that is contaminated. In ERMYN, this parameter value is assumed to be one (Assumption 8), and, therefore, the methods are mathematically equivalent.

7.3.4.2 Drinking Water

The NCRP-129 model does not use contaminated water, but the other four validation models use the same method as ERMYN (Equation 6.4.4-3), with one exception (Table 7.3-15). The GENII model uses a parameter for the fraction of animal water intake that is contaminated. Because all water is contaminated in the ERMYN, the value of this parameter is one, and the methods are mathematically equivalent.

7.3.4.3 Soil Ingestion

Four of the validation models (GENII, BIOMASS ERB2A, RESRAD, and EPRI-YM) include soil ingestion, and they all use the same method as ERMYN (Equations 6.4.4-4 and 6.5.4-3; Table 7.3-16). Therefore, they are mathematically equivalent.

The NCRP-129 model does not include this process. The omission of this contamination mechanism is an ACM (Section 6.3.3), and a numerical evaluation is conducted to evaluate the importance of soil ingestion to animal product contamination (Section 7.4.5). Omitting soil ingestion by animals results in a difference in radionuclide concentrations in meat by more than a factor of two because this process may account for about 75% of the total radionuclide concentration in animal products (Table 7.4-14). The ERMYN model includes soil ingestion by animals to avoid underestimating the dose from this pathway. Therefore, this addition to the ERMYN animal submodel is justified.

7.3.4.4 Dust Inhalation

The ERMYN model does not include dust inhalation by animals as a mechanism for animal product contamination. Only two of the validation models (BIOMASS ERB2A and EPRI-YM) include this process (Table 7.3-17). Because of a lack of animal data on transfer coefficients for dust inhalation, the two models use human data. Dust inhalation is an ACM (Section 6.3.3, the same ACM as for animal soil ingestion), and the ERMYN and BIOMASS animal submodels are compared to evaluate the importance of this pathway (Section 7.4.5). The two models (which are similar except for this pathway) produce similar estimates of meat concentrations (ERMYN: 2.64×10^{-5} Bq/kg; BIOMASS: 2.62×10^{-5} Bq/kg), but the contribution from dust inhalation (3.4×10^{-10} Bq/kg) to the total concentration in meat in the BIOMASS model is negligible. Therefore, the methods are numerically similar, and including dust inhalation by animals is unnecessary.

Table 7.3-14. Comparison of Animal Product Contamination Due to Animal Feed

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.4-2 and 6.5.4-2)	Reference
GENII	$C_{af} = Fa\, C_f\, d_{af}\, U_{af}\, e^{-\lambda_d Th_a}$ C_{af} = concentration of a radionuclide in animal product *a*, from ingestion of contaminated feed (Bq/kg, Bq/L for milk) C_f = concentration of a radionuclide in feed crop *f* consumed by animals (Bq/kg) d_{af} = fraction of animal feed that is contaminated (dimensionless) Fa = element-specific transfer coefficient relating daily intake to radionuclide concentrations in edible animal products (d/kg, d/L for milk) U_{af} = consumption rate of feed by animals (kg/d) λ_d = decay constant (1/yr) Th_a = holdup time between harvest or slaughter and consumption of the animal product a (yr).	GENII uses a holdup time for animal products to account for radionuclide decay, which can be ignored for long-lived radionuclides. GENII also uses a parameter for the fraction of contaminated animal feed, which would be 1.0 in ERMYN. Except for these differences, GENII and ERMYN are the same. Radionuclide indices were omitted in the GENII equation.	Napier et al. 2006 [DIRS 177331], Equations 9.14 and 9.15
BIOMASS ERB2A	$C_{prod,fodd} = TF_{proding}\, C_{fodd}\, ING_{fodd}$ $C_{prod, fodd}$ = radionuclide concentration in an animal product due to ingestion of animal fodder (Bq/kg) C_{fodd} = radionuclide concentration in animal fodder (Bq/$kg_{\text{fresh weight of fodder}}$) $TF_{proding}$ = element-specific transfer factor for ingestion for animal products (d/$kg_{\text{fresh weight of product}}$) ING_{fodd} = consumption rate of fodder by animals ($kg_{\text{fresh weight}}$/d).	BIOMASS ERB2A and ERMYN use the same method.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	EPRI-YM uses the same equation as BIOMASS ERB2A.	EPRI-YM and ERMYN use the same method.	EPRI 2002 [DIRS 158069], Equation 8-11 EPRI 2004 [DIRS 171915], Equation 8-13

Table 7.3-14. Comparison of Animal Product Contamination Due to Animal Feed (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.4-2, and 6.5.4-2)	Reference
RESRAD	$FSR_{ij,pq}(t) = FQR_{jp} \times FI_{pq} \times QSR_{ij,pq}(t)$ $FSR_{ij,pq}(t)$ = food/soil concentration ratios for meat and milk FQR_{jp} = radionuclide transfer factor for meat (p = 4) or milk (p = 5), which is the ratio of the concentration of the *j*th principal radionuclide in meat or milk (in Bq/kg or pCi/kg) to the rate of intake of that radionuclide by farm animals in feed, soil, or water (in Bq/d or pCi/d) (d/kg) FI_{pq} = daily intake of feed (q = 1, 2, 3, or 4), water (q = 5), or soil (q = 6) by farm animals (kg/d) $QSR_{ij,pq}(t)$ = feed/soil concentration ratio at time t for meat (p = 4) or milk (p = 5) for the *j*th principal radionuclide and the *q*th subpathway (dimensionless) for q = 1 and 2. For q = 3, 4, or 5, it is the ratio of the feed or water concentration of radionuclide *j* to the initial soil concentration of radionuclide *i* (dimensionless). For soil intake by farm animals (q = 6), $QSR_{ij,p6}$ = 1.	This equation is for the contamination of all animal products, including feed, soil, and water, which are the same animal pathways used in the ERMYN. RESRAD and ERMYN are the same, except that the RESRAD equation is based on food/soil concentration ratios.	Yu et al. 2001 [DIRS 159465], Equation D.15
NCRP-129	$C_{milk,meat} = C_{fodder}\, Q_{milk,meat} TQ_{milk,meat}\, F_{milk,meat}$ $C_{milk,meat}$ = nuclide concentration in animal products (Bq/kg or Bq/L) C_{fodder} = radionuclide concentration in dry fodder (Bq/kg) $Q_{milk,meat}$ = average daily intake of dry contaminated feed (kg/d) by animals $TQ_{milk,meat}$ = fraction of locally grown animal feed $F_{milk,meat}$ = empirically determined transfer factor representing the equilibrium concentration in meat and milk resulting from a given daily animal intake of a radionuclide (d/kg, or d/L).	NCRP-129 is the same as GENII-S, except that the holdup decay term is not shown here, although it is used in the ingestion submodel (NCRP 1999 [DIRS 155894], Equation 5.1).	NCRP 1999 [DIRS 155894], Equation 5.3

Table 7.3-15. Comparison of Animal Product Contamination Due to Drinking Water

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.4-3)	Reference
GENII	$C_{aw} = Fa\, C_w d_{aw} U_{aw} e^{-\lambda_d Th_a}$ C_{aw}= concentration of a radionuclide in animal product *a* from animal ingestion of water (Bq/kg, Bq/L for milk) C_w = concentration of a radionuclide in water used by animals (Bq/L) d_{aw} = fraction of contaminated animal water (dimensionless) Fa = element-specific transfer coefficient to relate daily animal intake rate to concentrations in edible animal products (d/kg, d/L for milk) U_{aw} = consumption rate of water by animals (L/d) λ_d = decay constant (1/yr) Th_a = holdup time between harvest or slaughter and consumption of animal product (yr).	GENII uses animal product holdup time for radionuclide decay, which can be ignored for long-lived radionuclides. It also uses the fraction of animal water contaminated. Except for these two differences, GENII and ERMYN are the same. Radionuclide and location indices were omitted in the GENII equation.	Napier et al. 2006 [DIRS 177331], Equations 9.14 and 9.15
BIOMASS ERB2A	$C_{prod,fodd} = TF_{proding}\, C_w\, ING_{wa}$ $C_{prod,\ fodd}$ = radionuclide concentration in animal products due to ingestion of animal fodder (Bq/kg) C_w = radionuclide concentrations in groundwater (Bq/kg $_{\text{fresh weight of fodder}}$) $TF_{proding}$ = element-specific transfer factor for ingestion for animal products (d/kg $_{\text{fresh weight of product}}$) ING_{wa} = consumption rate of water by animals, kg $_{\text{fresh weight}}$/d).	BIOMASS ERB2A and ERMYN use the same method.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	EPRI-YM uses the same equation as BIOMASS ERB2A.	EPRI-YM and ERMYN use the same method.	EPRI 2002 [DIRS 158069], Equation 8-11 EPRI 2004 [DIRS 171915], Equation 8-13
RESRAD	Mathematical equations are shown in Table 7.3-14.	RESRAD is the same as ERMYN, except that the equation is based on food/soil concentration ratios.	Yu et al. 2001 [DIRS 159465], Equation D.15
NCRP-129	Not included	Not applicable.	NCRP 1999 [DIRS 155894]

Table 7.3-16. Comparison of Animal Product Contamination Due to Soil Ingestion

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.4-4 and 6.5.4-3)	Reference
GENII	$C_{as} = Fa\,C_s d_{as} U_{as} e^{-\lambda_d Th_a}$ C_{as} = concentration of a radionuclide in animal product *a* from animal ingestion of soil (Bq/kg, Bq/L for milk) C_s = concentration of a radionuclide in water used by animals (Bq/L) d_{as} = fraction of animal soil intake that is contaminated (dimensionless) Fa = element-specific transfer coefficient to relate daily animal intake rate to concentrations in edible animal products (d/kg, d/L for milk) U_{as} = consumption rate of soil by animals (L/d) λ_d = decay constant (1/yr) Th_a = holdup time between harvest or slaughter and consumption of animal product (yr).	GENII uses animal product holdup time for radionuclide decay, which can be ignored for long-lived radionuclides. It also uses the fraction of animal water contaminated. Except for these two differences, GENII and ERMYN are the same. Radionuclide and location indices were omitted in the GENII equation.	Napier et al. 2006 [DIRS 177331], Equations 9.14 and 9.15
BIOMASS ERB2A	$C_{prod,water} = TF_{proding} \dfrac{C_s\, ING_{sa}}{(1-\theta_t)\rho + \theta\, \rho_w}$ $C_{prod,water}$ = radionuclide concentrations in animal products due to the ingestion of drinking water (Bq/kg) $TF_{proding}$ = element-specific transfer factor for ingestion for animal products (d/kg $_{\text{fresh weight of product}}$) C_s = radionuclide concentrations in cultivated soil (Bq/m^3) ING_{sa} = consumption rate of cultivated soil by animals (kg $_{\text{wet weight of soil}}$ /d) θ_t = total porosity of the cultivated soil compartment (dimensionless) ρ = dry grain density of the cultivated soil compartment (kg/m^3) θ = water filled porosity of the cultivated soil compartment (dimensionless) ρ_w = density of water (kg/m^3).	BIOMASS ERB2A and ERMYN use the same method, except soil concentration requires a unit conversion.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	EPRI-YM and BIOMASS ERB2A use the same equation.	EPRI-YM and ERMYN use the same method.	EPRI 2002 [DIRS 158069], Equation 8-11 EPRI 2004 [DIRS 171915], Equation 8-13
RESRAD	Mathematical equation is shown in Table 7.3-14.	RESRAD and ERMYN use the same method, except the equation is derived from the food/soil concentration ratios.	Yu et al. 2001 [DIRS 159465], Equation D.15
NCRP-129	Not included	Not applicable	NCRP 1999, [DIRS 155894]

Table 7.3-17. Comparison of Animal Product Contamination Due to Dust Inhalation

Document	Mathematical Model	Comparison with ERMYN (Not considered in ERMYN)	Reference
GENII	Not considered	Not applicable	Napier et al. 2006 [DIRS 177331]
BIOMASS ERB2A	$$C_{prod,inh} = TF_{prodinh}\ BR_a\ O_{an}\ C_{airs}$$ $C_{prod,inh}$ = radionuclide concentration in animal products due to inhalation of resuspended contaminated soil (Bq/kg^3) $TF_{prodinh}$ = inhalation transfer factor for animal products (d/kg $_{\text{wet weight of soil}}$), which is calculated as: $$TF_{prodinh} = TF_{proding} \frac{f_1(inh)}{f_1(ing)}$$ $TF_{proding}$ = element-specific transfer factor for ingestion for animal products (d/kg $_{\text{fresh weight of product}}$) $f_1(inh)$ = fraction of inhaled activity reaching the body fluid in humans $f_1(ing)$ = fraction of ingested activity reaching the body fluids in humans BR_a = animal breathing rate (m^3/h) O_{an} = occupancy time of animals on cultivated soils (h/d) C_{airs} = radionuclide concentrations in the air above cultivated soils (Bq/m^3).	BIOMASS ERB2A includes animal inhalation of contaminated dust using a transfer factor for inhalation based on human data (BIOMASS 2003 [DIRS 168563], Section 3.5.4.3). ERMYN does not include this pathway. A numerical comparison shows that the contribution from this pathway is small compared to other animal intake pathways (Section 7.4.5).	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	The EPRI-YM model is based on the BIOMASS ERB2A models and both use the same equations.	EPRI-YM and ERMYN are similar.	EPRI 2002 [DIRS 158069], Equation 8-11 EPRI 2004 [DIRS 171915], Equation 8-13
RESRAD	Not included	Not applicable	Yu et al. 2001 [DIRS 159465], Appendix D
NCRP-129	Not included	Not applicable	NCRP 1999 [DIRS 155894]

7.3.5 Validation of the Fish Submodel

Two of the five validation models (GENII and RESRAD) include a fish submodel, and both use methods similar to the ERMYN methods (Equation 6.4.5-2) with three exceptions (Table 7.3-18):

- GENII includes radionuclide decay during the holdup period between harvest and consumption. Holdup time is short (generally days to weeks) relative to the half-life for the long-lived radionuclides in the ERMYN (Table 6.3-7). Thus, the exponential factor in GENII that includes the holdup time and decay constant approaches one, making the methods mathematically equivalent.

- RESRAD uses a dietary fraction and a contamination factor in calculating fish contamination. These parameters are incorporated into the fish consumption rate in the ERMYN ingestion submodel; therefore, the methods are mathematically equivalent.

- GENII and RESRAD do not include a water concentration modifying factor because the models are constructed using the radionuclide concentration in water in which the fish are grown. ERMYN uses radionuclide concentration in groundwater, which, as argued below, may be different from the concentration at the source of fish pond water (i.e., the groundwater) because of evaporation. Values of the modifying factor depend on the climate. Typical values are 1 for ^{14}C and 4.15 for other radionuclides under the present-day climate conditions (Table 6.6-3). Omission of the water concentration modifying factor could result in a difference by more than a factor of two in estimates of radionuclide concentrations in fish. The ERMYN includes this factor to account for increases in activity concentrations due to evaporation. This addition is necessary because the fish ponds in Amargosa Valley are shallow, the evaporation rate is high, and the activity concentration likely would increase when additional groundwater is added to compensate for evaporation (Section 6.4.5). This addition is justified because it is based on site-specific conditions in the Amargosa Valley. When the modifying factor is included, the ERMYN model and the two validation models that include this pathway are equivalent.

Thus, the fish submodels are mathematically equivalent and, therefore, the ERMYN submodel is validated.

Table 7.3-18. Comparison of Fish Contamination Due to Fishpond Water

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.5-2)	Reference
GENII	$$C_{fq} = C_w B_q e^{-\lambda_d Th_q}$$ C_{fq} = concentration of a radionuclide in aquatic food type q (fish, mollusks, invertebrates, and water plants) (Bq/kg) C_w = water concentration (Bq/L) B_q = element-specific bioaccumulation factor for aquatic food q (Bq/kg per Bq/L = L/kg) λ_d = decay constant (1/yr) Th_q = decay time (from food harvest to consumption; yr).	The GENII model is capable of including more aquatic foods in fresh and salt water, but only freshwater fish are included in the Yucca Mountain biosphere. The GENII fish submodel is the same as the ERMYN submodel, except that the ERMYN includes a modifying factor for pond water evaporation. Radionuclide indices were omitted in the GENII equation.	Napier et al. 2006 [DIRS 177331], Equations 9.20 and 9.21
BIOMASS ERB2A	Not included. The aquatic food consumption is included in the BIOMASS ERB2B model and the methods are the same as those used in ERMYN.	Not applicable.	BIOMASS 2003 [DIRS 168563], Sections C3.5.4.3 and C4.5.5
EPRI-YM	Not included.	Not applicable.	EPRI 2002 [DIRS 158069], Section 8
RESRAD	$$ETF_{ij,6}(t) = FR_6 \times \left(\sum DF_{6k} \times FWR_{j6k} \right) \times WSR_{ij,2}(t)$$ $ETF_{ij,6}(t)$ = environmental transport factor for the aquatic food pathway (fish, crustaceans, and mollusks) (g/yr) DF_{6k} = dietary factors for annual consumption of fish (k = 1) and crustaceans and mollusks (k = 2) (kg/yr) FR_6 = fraction of aquatic food consumed that is contaminated (dimensionless) FWR_{j6k} = fish/water (k = 1) and crustacean-mollusk/water (k = 2) concentration ratios (bioaccumulation factors) (L/kg) $WSR_{ij,2}(t)$ = ratio of surface water concentration of radionuclide j at time t to the soil concentration ratio of radionuclide i at time 0 (g/L).	RESRAD includes several aquatic food pathways, and it uses a dietary factor and a contamination factor, which are included in the ERMYN consumption rates (ingestion submodel). For the fish pathway, ERMYN, RESRAD, and GENII are equivalent, except the RESRAD equation is based on a food/soil concentration ratio.	Yu et al. 2001 [DIRS 159465], Equation D.21
NCRP-129	Not included	Not applicable.	NCRP 1999 [DIRS 155894]

7.3.6 Validation of the ^{14}C Special Submodel

The ERMYN includes a ^{14}C special submodel. Among the five validation models, three (GENII, RESRAD, and BIOMASS ERB2A) include ^{14}C special submodels. The BIOMASS ERB2A model for ^{14}C (BIOMASS 2000 [DIRS 154522], Appendix A) was not included in the final BIOMASS report for the Theme 1, Radioactive Waste Disposal (BIOMASS 2003 [DIRS 168563]), used elsewhere in Section 7. The GENII submodel only includes crops, animal products, and fish contamination. The ERMYN, RESRAD, and BIOMASS ERB2A models include these three pathways plus soil and air contamination (which can cause external exposure to contaminated soil, inhalation of contaminated air, and inadvertent soil ingestion). Comparisons of the methods for calculating ^{14}C concentrations in soil, air, plants, and animals are presented below. Concentrations of ^{14}C in fish are calculated in the fish submodel and do not involve a special approach (Section 6.4.5).

Soil Contamination–In ERMYN, the calculation of ^{14}C soil contamination resulting from irrigation (Equation 6.4.6-1) is similar to the method used in the soil submodel for other radionuclides (Equation 6.4.1-2). GENII and BIOMASS ERB2A are the only validation models that directly calculate ^{14}C soil contamination from irrigation water; RESRAD includes soil contamination as the initial source term. The ERMYN and BIOMASS ERB2A models use the same methods, with the following exceptions (Table 7.3-19):

- BIOMASS ERB2A includes the weathering of ^{14}C from plants as a soil contamination source. ERMYN assumes that all radionuclides in irrigation water eventually are deposited in the soil (Assumption 6). Therefore, the parameters in the BIOMASS ERB2A model for calculating weathering are unnecessary in the ERMYN, and the methods are mathematically equivalent.

- BIOMASS ERB2A does not include losses of ^{14}C due to erosion or radionuclide decay. These loss mechanisms are used in the ERMYN ^{14}C submodel to maintain consistency with the soil submodel. The rate of loss from erosion and radionuclide decay is inconsequential compared to the losses due to gaseous ^{14}C emission (emission rate constant of about 22/yr; Table 6.6-3). Therefore, including losses due to erosion and radionuclide decay do not affect the results of the equation, and the methods are mathematically equivalent.

Air Contamination–In the air, ^{14}C contamination is caused by the release of ^{14}C from groundwater-contaminated soil (due to the volatility of ^{14}C), as almost all dissolved inorganic ^{14}C introduced into the soil with the irrigation water is quickly released into the air. The BIOMASS ERB2A and RESRAD models include ^{14}C in the air, using methods that are the same as ERMYN, with the following exceptions (Table 7.3-20):

- BIOMASS ERB2A and RESRAD include a factor for the proportion of time that the wind blows from the contaminated source to the receptor. In the ERMYN, the area contaminated by long-term irrigation surrounds the receptor, so this factor would be 1.0. Therefore, these methods are mathematically equivalent.

- BIOMASS ERB2A uses radionuclide concentrations in soil per unit volume (Bq/m^3) and includes parameters for the width and volume of the plant canopy to estimate the rate of carbon turnover in the canopy. The ERMYN uses soil concentrations per unit area and replaces the width and volume parameters with a parameter for the size of the irrigated area and the height of the carbon mixing cell. Thus, the differences are unit conversions, and the methods are mathematically equivalent.

- The calculation of ^{14}C flux density from contaminated soil (evasion rate) differs in the RESRAD and ERMYN because of differences in the expression of the source term. The differences are limited to unit conversions (Table 7.3-20), and the methods are mathematically equivalent.

Plant Contamination–Plant contamination by ^{14}C is included in the GENII, RESRAD, and BIOMASS ERB2A models. The ERMYN method (Equation 6.4.6-6) is the same as that used in RESRAD (Table 7.3-21). BIOMASS ERB2A uses a different method that requires additional input parameters, the measurements of which are not available, and the model documentation (BIOMASS 2000 [DIRS 154522]) does not include recommended values. Therefore, a numerical comparison is not possible, and this portion of BIOMASS ERB2A is not used to validate the ERMYN.

The GENII and ERMYN use different methods for calculating ^{14}C plant contamination, so the models are compared numerically (Section 7.4.7). The ^{14}C concentration in leafy vegetables calculated using the ERMYN method (7.4×10^{-4} Bq/kg; Table 7.4-15) is about 3.5 times higher than the value calculated using the GENII method (2.1×10^{-4} Bq/kg). The ERMYN, BIOMASS ERB2A, and RESRAD models include not only contamination from root uptake but also the uptake of $^{14}CO_2$ from the air during photosynthesis. Because of the high emission rate constant of ^{14}C from the soil (Table 6.6-3), uptake of ^{14}C via photosynthesis is an important transfer process. Therefore, the ERMYN method is justified because it includes this important transfer process to avoid underestimating dose.

Animal Contamination–The GENII, RESRAD, and BIOMASS ERB2A models include animal product contamination by ^{14}C. The ERMYN method (Equation 6.4.6-7) is the same as the RESRAD method (Table 7.3-22). BIOMASS ERB2A uses a different method that requires additional input parameters, the measurements of which are not available, and the model documentation (BIOMASS 2000 [DIRS 154522]) does not include recommended values. Therefore, a numerical comparison is not possible. The GENII model is also similar to the ERMYN model. Therefore, the method used in the ERMYN is justified.

Table 7.3-19. Comparison of ^{14}C Special Model for Soil Contamination

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.6-1)	Reference
GENII	$$C_{sC} = \frac{R_{wC}}{\lambda_{sC}}\left(1 - e^{-\lambda_{sC} t_{gc}}\right)$$ C_{sC} = concentration of ^{14}C in the soil layer (Bq/m^2) R_{wC} = constant deposition rate of ^{14}C from water ($Bq/(m^2$ yr) λ_{sC} = removal rate constant for activity of ^{14}C in the surface soil layer (1/yr) t_{gC} = growing period for crop *c* (yr).	The GENII model for soil contamination is mathematically equivalent to the ERMYN model. The model documentation does not specify whether gaseous emission is included as one of the mechanisms of ^{14}C removal from the surface soil.	Based on: Napier et al. 2006 [DIRS 177331], Equations 9.31
BIOMASS ERB2A	$$C_S = \frac{(C_{SW} + C_{SI})}{D_S}$$ C_S = concentration of ^{14}C in the soil layer (Bq/m^3) C_{SW} = concentration of ^{14}C on the soil surface as a result of weathering, Bq m^{-2}, which can be estimated as: $$C_{SW} = \frac{C_{PS}\lambda_{PSS}}{\lambda_S}$$ C_{PS} = concentration of ^{14}C on plant surfaces, Bq m^{-2} λ_{pss} = radionuclide loss by weathering to the soil surface, 1/yr λ_S = radionuclide loss in the soil root zone,1/yr, can be calculated as: $$\lambda_S = \lambda_{SA} + \lambda_{SDS}$$ λ_{SA} = radionuclide loss due to degassing (or emission) from the soil surface to the air, 1/yr λ_{SDS} = radionuclide loss due to infiltration (leaching) to deeper soil, 1/yr D_s = depth of the soil layer from which infiltration is considered, in this case the rooting layer, m C_{SI} = concentration of ^{14}C in the soil resulting from irrigation water intercepted by soil, Bq/m^2, may be estimated as: $$C_{SI} = \frac{C_{IW} R_{IR} f_{IR}}{\lambda_S}$$ C_{IW} = concentration of ^{14}C in irrigation water, Bq/m^3 R_{IR} = irrigation rate, m/yr f_{IR} = intercepted fraction.	BIOMASS ERB2A includes ^{14}C soil contamination from irrigation and weathering of plant surfaces. This differs from the BIOMASS ERB2A model for all other radionuclides, in which all irrigation water is deposited in the soil (same as Assumption 6). BIOMASS ERB2A uses two loss mechanisms for ^{14}C on soil (leaching and emission). However, erosion loss is negligible compared with the losses by these other mechanisms. BIOMASS ERB2A and ERMYN are similar if it is assumed that the intercepted irrigation water is eventually deposited on the soil.	BIOMASS 2000 [DIRS 154522], Appendix A

Table 7.3-19. Comparison of ^{14}C Special Model for Soil Contamination (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.6-1)	Reference
EPRI-YM	Not included	Not applicable.	EPRI 2002 [DIRS 158069], Section 8
RESRAD	The source term is the concentration of ^{14}C in contaminated soil (*Sc*-14), and, therefore, it is not a calculated value.	Source term in RESRAD	Yu et al. 2001 [DIRS 159465], Appendix L.
NCRP-129	Not included	Not applicable	NCRP 1999 [DIRS 155894].

Table 7.3-20. Comparison of ^{14}C Special Model for Air Contamination

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.6-2 and 6.4.6-3)	Reference
GENII	Not included	GENII-S does not include ^{14}C contamination in the air from irrigation water.	Napier et al. 2006 [DIRS 177331]
BIOMASS ERB2A	$$C_{SA} = \frac{C_S \lambda_{SA}}{\lambda_A}$$ C_{SA} = concentration of ^{14}C in the canopy due to degassing (Bq/m^3) C_S = concentration of ^{14}C on the soil surface (Bq/m^3) λ_{SA} = radionuclide loss due to degassing (or emission) from the soil surface to the air (1/yr) λ_A = radionuclide loss in the canopy (1/yr), calculated as: $$\lambda_A = \frac{f \times U \times w_C \times h_c}{v_C}$$ f = factor to account for the geometry of the contaminated area, varying wind directions U = average wind speed (m/yr) w_c = width of the contaminated plant canopy, perpendicular to the wind direction (m) h_c = assumed height of the canopy layer (m) v_c = volume of the contaminated plant canopy (m^3).	BIOMASS ERB2A and ERMYN are the same, except for the geometry of the contaminated area and the varying wind direction. Because most or all of the area would be contaminated, the geometry parameter is unnecessary in the ERMYN. The BIOMASS model uses radionuclide concentration in units of Bq/m^3, as shown in the equation where v_c is the volume of contaminated plant canopy. In contrast, the ERMYN uses units of Bq/m^2 for radionuclide concentration in the surface soil and an area (A) parameter and the height of the mixing cell (H_{mix}) (Equation 6.4.6-3).	BIOMASS 2000 [DIRS 154522], pp. 69 and 70, Appendix A
EPRI-YM	Not included	Not applicable	EPRI 2002 [DIRS 158069], Section 8

Table 7.3-20. Comparison of ^{14}C Special Model for Air Contamination (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.6-2 and 6.4.6-3)	Reference
RESRAD	$$C_{C-14,a} = \frac{3.17\times10^{-8}\times0.5\times EVSN\times\sqrt{A}}{H_{mix}\times U}$$ $C_{C14,a}$ = average concentration of ^{14}C in the air above a contaminated area of finite size (pCi/m^3) 3.17×10^{-8} = unit conversion factor (yr/s) 0.5 = time fraction for wind blowing towards receptor (dimensionless) *EVSN* = ^{14}C flux (evasion rate) from the contaminated area (pCi/m^2-yr) $$EVSN = 10^{-6}\times S_{C-14}\times E_{C-14}\times\rho_b^{(cz)}\times d_{ref}$$ 10^6 = unit conversion factor (cm^3/m^3) S_{C-14} = concentration of ^{14}C in contaminated soil (pCi/g) E_{C-14} = evasion loss rate constant (22/yr) $\rho_b^{(cz)}$ = bulk density of the contaminated zone (1.5 g/cm^3) d_{ref} = reference soil depth (0.3 m) *A* = area of contaminated zone (m^2) *Hmix* = height to which CO_2 uniformly mixes (2 m for the human inhalation pathway; 1.0 m for the plant, meat, and milk ingestion pathways) *U* = annual average wind speed (m/s).	The ERMYN uses the RESRAD equation, except that the time fraction for wind blowing toward the receptor is set to 1.0 (Section 6.4.6.2) because the ERMYN does not need this parameter. Because of different source terms, the ^{14}C flux density, *EVSN*, calculations are different in the RESRAD and ERMYN: Cs_{C-14} (Bq/m^2) in ERMYN is equivalent to $10^6 \times S_{c-14} \times \rho_b^{(cz)} \times d_{ref}$ in RESRAD.	Yu et al. 2001 [DIRS 159465], Equation L.25
NCRP-129	Not included	Not applicable	NCRP 1999 [DIRS 155894]

Table 7.3-21. Comparison of ^{14}C Special Model for Plant Contamination

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.6-6)	Reference
GENII	$$C_{cwC} = \frac{0.1 F_{Cc}}{0.01 P_3} \frac{R_{wC}}{\lambda_{sC}} \left(1 - e^{-\lambda_{sC} t_{gc}}\right)$$ C_{cwC} = concentration of ^{14}C from waterborne deposition in crop type *c* (Bq/kg) R_{wC} = constant deposition rate of ^{14}C from water (Bq/(m^2 yr) (equal to the product of irrigation rate and radionuclide concentration in water) λ_{sC} = removal rate constant for activity of ^{14}C in the surface soil layer (1/yr) t_{gC} = growing period for crop *c* (yr) 0.1 = assumed uptake of 10% of plant carbon from soil 0.01 = average fraction of soil that is carbon (kg $_{carbon}$/kg $_{soil}$) P_3 = surface soil density (kg/m^2) F_{Cc} = fraction of carbon in plant type *c* (kg $_{carbon}$/kg $_{plant}$).	GENII considers that ^{14}C contamination in plants from waterborne contamination occurs only through root uptake. Because the ^{14}C special model for plant contamination in GENII and ERMYN are different, a numerical comparison between the GENII and ERMYN is carried out in Section 7.4.7.	Napier et al. 2006 [DIRS 177331], Equation 9.31
BIOMASS ERB2A	$$C_P = C_{PSP} + C_{SP} + C_{AP}$$ C_P = concentration of ^{14}C in plants (Bq/kg^3) C_{PSP} = concentration of ^{14}C in plants contributed from plant surfaces (Bq/kg^3), estimated as: $$C_{PSP} = \frac{C_{PS} \lambda_{PSP} f_{PSP}}{\lambda_C}$$ λ_{PSP} = radionuclide loss by translocation into plants (1/yr) f_{PSP} = factor converting surface- (Bq/m^2) to mass contamination (Bq/kg) λ_C = radionuclide loss by annual plant cropping (harvest removal) (1/yr) C_{PS} = concentration of ^{14}C on plant surfaces (Bq/m^2), calculated as: $$C_{PS} = \frac{C_{IW} R_{IR} (1 - f_{IR})}{\lambda_{PS}}$$ C_{IW} = concentration of ^{14}C in irrigation water (Bq/m^3) R_{IR} = irrigation rate (m/yr) f_{IR} = intercepted fraction λ_{PS} = sum of radionuclide losses from plants, calculated as:	The proposed BIOMASS ERB2A model includes plant contamination from plant surfaces, soil, and air. This method requires many input parameters that are not provided in the document, which makes numerical comparisons impossible.	BIOMASS 2000 [DIRS 154522], Appendix A

Table 7.3-21. Comparison of ^{14}C Special Model for Plant Contamination (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.6-6)	Reference
BIOMASS ERB2A (cont.)	(Continued from previous page) $$\lambda_{PS} = \lambda_{PSS} + \lambda_{PSP} + \lambda_{PSA}$$ λ_{PSS} = radionuclide loss by weathering to the soil surface (1/yr) λ_{PSA} = radionuclide loss from plant surfaces to the atmosphere (1/yr), calculated as: $$\lambda_{PSA} = \frac{R_{RA}}{C_{CW} D_R}$$ R_{RA} = rate of evasion per unit area of a water body (mol m^{-2} yr^{-1}) C_{CW} = concentration of C in water (mol/m^3) D_R = water depth on the leaf (m). C_{SP} = concentration of ^{14}C in plants contributed from soil (Bq/kg), estimated as: $$C_{SP} = \frac{f_{CP} f_{SP} C_S}{\rho_S f_{CS}}$$ f_{CP} = fraction of plant mass that is carbon f_{SP} = fraction of all carbon in plants derived from carbon in soil C_S = concentration of ^{14}C in soil (Bq/m^3) ρ_S = soil density (kg/m^3) f_{CS} = fraction of soil that is stable carbon C_{AP} = concentration of ^{14}C in plants contributed from the air (Bq/kg), estimated as: $$C_{AP} = \frac{f_{CP} f_{AP} C_{SA}}{\rho_P f_{CA}}$$ f_{CP} = fraction of plant mass that is carbon f_{AP} = fraction of all carbon in plants derived from CO_2 in the air C_{SA} = concentration of ^{14}C in the air (Bq/m^3) ρ_p = plant density the plant (kg/m^3) f_{CA} = fraction of the air that is CO_2.	The proposed BIOMASS ERB2A model includes plant contamination from plant surfaces, soil, and air. This method requires many input parameters that are not provided in the document, which makes numerical comparisons impossible.	BIOMASS 2000 [DIRS 154522], Appendix A

Table 7.3-21. Comparison of ^{14}C Special Model for Plant Contamination (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.6-6)	Reference
EPRI-YM	Not included	Not applicable	EPRI 2002 [DIRS 158069], Section 8
RESRAD	$$C_{C-14,v} = C_{C,v}\left[\left(F_a \times \frac{C_{C-14,a}}{C_{C,a}}\right) + \left(1000 \times F_s \times \frac{S_{C-14}}{S_C}\right)\right]$$ $C_{C\text{-}14,v}$ = concentration of ^{14}C in plants (pCi/kg) $C_{C,v}$ = fraction of stable carbon in plants (dimensionless; 0.4 for grain and nonleafy vegetables; 0.09 for fruits, vegetables, and fodder) $F_a = C_{C,va} / C_{C,v}$ = fraction of carbon in plants derived from carbon in air (dimensionless; 0.98) $C_{C,va}$ = fraction of plant mass that is carbon derived from photosynthesis $C_{C\text{-}14,a}$ = concentration of ^{14}C in the air (pCi/m^3) $C_{C,a}$ = concentration of stable carbon in the air (1.8 × 10^{-4} kg/m^3) 1,000 = unit conversion factor (g/kg) $F_s = C_{C,vs} / C_{C,v}$ = fraction of carbon in plants derived from carbon in soil (dimensionless; 0.02, $F_s/S_c = 0$ if $S_c = 0$) $C_{C,vs}$ = fraction of plant mass that is carbon derived from soil $S_{C\text{-}14}$ = concentration of ^{14}C in soil (pCi/g) S_C = fraction of the soil that is stable carbon (dimensionless; 0.03).	RESRAD and ERMYN are the same, except for the notations and units for some parameters.	Yu et al. 2001 [DIRS 159465], Equation L.31
NCRP-129	Not included	Not applicable	NCRP 1999 [DIRS 155894]

Table 7.3-22. Comparison of ^{14}C Special Model for Animal Product Contamination

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.6-7)	Reference
GENII	$$C_{caC} = F_{Ca} \frac{\sum_{f=1}^{N_{fa}} C_{fC} U_{af} d_{af}}{\sum_{f=1}^{N_{fa}} F_{Cf} U_{af}}$$ C_{caC} = concentration of ^{14}C in animal product *a* from consumption of animal feed (crops) (Bq/kg or Bq/L) C_{fC} = concentration of ^{14}C in animal feed (Bq/kg) U_{af} = daily feed intake for animal type *a* and feed type *f* (kg/d) F_{Ca} = fraction of carbon in animal product (fixed values used in GENII are 0.24 for beef, 0.2 for poultry, 0.07 for milk, and 0.15 for eggs). d_{af} = fraction of animal type a feed type *f* intake that is contaminated (dimensionless) F_{Cf} = fraction of carbon in animal feed type *f* (dimensionless) N_{fa} = number of feed crops eaten by animal type *a*.	The calculational methods used in GENII and ERMYN are equivalent, except that GENII does not include ^{14}C animal intake by soil and water ingestion. However, GENII allows including more than one feed type. The method for incorporating the individual sources of ^{14}C intake by animals is the same whether these are additional feed crops, water, or soil. Water is omitted in GENII because the carbon content of plants is much higher than that in water. In the GENII equation, indexing related to decay during holdup was omitted as not applicable in the case of long-lived radionuclides.	Napier et al. 2006 [DIRS 177331], Equation 9.35
BIOMASS ERB2A	$$C_{A,C14} = C_{A,C12}\left(f_{A,W} \frac{C_{W,C14}}{C_{W,C12}} + f_{A,S} \frac{C_{S,C14}}{C_{S,C12}} + f_{A,P} \frac{C_{P,C14}}{C_{P,C12}} \right)$$ $C_{x,C12}$ = fraction of the mass of material that is stable carbon, where X = *A* for animal products, *W* is water, *S* is soil, and *P* is plants (Bq/kg) $f_{A,X}$ = fraction of carbon derived from medium *X* (water, soil, or plants); $\sum f_{A,i} = 1$ $C_{X,C14}$ = activity concentration of ^{14}C on the material, where X = *A* is animal product, *W* is water, *S* is soil, and *P* is plants (Bq/kg).	The proposed BIOMASS ERB2A ^{14}C model includes ^{14}C contamination in animal products through water, soil, and plants, which is the same as the ERMYN, but it uses a different method for calculating radionuclide concentrations in animal products. The parameter values are not given in the document, which makes numerical comparison impossible.	BIOMASS 2000 [DIRS 154522], pp. 70 and 71, Appendix A
EPRI-YM	Not included	Not applicable	EPRI 2002 [DIRS 158069], Section 8

Table 7.3-22. Comparison of ^{14}C Special Model for Animal Product Contamination (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.6-7)	Reference
RESRAD	$$C_{C14,p} = C_{C,p} \frac{FI_{C-14,p}}{FI_{C,p}}$$ $C_{C\text{-}14,p}$ = concentration of ^{14}C in meat (p = 4) or milk (p = 5) (pCi/kg) $C_{C,p}$ = fraction of stable carbon in meat (0.24) or milk (0.070) (dimensionless) $FI_{C\text{-}14,p}$ = intake rate of ^{14}C in the diet of beef cattle (p = 4) or dairy cows (p = 5) (pCi/d), calculated as: $$FI_{C14,p} = W_{C-14} \times FI_{p5} + FDR_{C-14,p} \times FI_{pq} + S_{C-14} \times FI_{p6}$$ $W_{C\text{-}14}$ = concentration of ^{14}C in water (pCi/L) FI_{p5} = livestock water intake rate (160 L/d, milk 50/d, beef cattle) $FDR_{C\text{-}14,p}$ = concentration of ^{14}C in livestock feed (pCi/kg) FI_{pq} = livestock feed intake rate (p = 4, 68 kg/d; p = 5, 55) (kg/d) $S_{C\text{-}14}$ = concentration of ^{14}C in soil (pCi/kg) FI_{p6} = livestock soil intake rate (0.5 kg/d) $FI_{C,p}$ = intake rate of stable carbon in the livestock diet (kg/d), calculated as: $$FI_{C,p} = W_C \times FI_{p5} + FDR_{C,p} \times FI_{pq} + S_C \times FI_{p6}$$ W_C = concentration of stable carbon in livestock water (2.0 × 10^{-5} kg/L) $FDR_{C,p}$ = concentration of stable carbon in feed (kg/kg) S_C = fraction of soil that is stable carbon (0.03, dimensionless).	RESRAD and ERMYN are the same, except for notations and units for some parameters.	Yu et al. 2001 [DIRS 159465], Equations L.33, L.34, and L.36
NCRP-129	Not included	Not applicable	NCRP 1999 [DIRS 155894].

7.3.7 Validation of the External Exposure Submodel

The method used to calculate the external exposure dose in the ERMYN is similar to that used in the validation models (Table 7.3-23). All of the validation models include external exposure to contaminated soil and calculate dose as a product of a radionuclide-specific dose coefficient, radionuclide concentrations in the surface soil, and exposure time. In addition, the GENII model includes air submersion and water immersion, and the BIOMASS ERB2A model includes water immersion (Table 7.2-2). A comparison of dose coefficients for external exposure to contaminated soil, air submersion, and water immersion is carried out (Section 7.4.8) to evaluate the importance of these pathways. The potential doses from air submersion and water immersion are inconsequential compared to soil exposure, and they are excluded from the ERMYN dose assessments. Another potential pathway resulting from radionuclides that are initially external to the body is dermal absorption of radionuclides. However, the skin is generally an effective barrier against absorption of radionuclides, so dermal absorption is a very minor exposure pathway. An exception to this is dermal absorption of tritiated water, i.e., water containing some amount of ^{3}H in place of a normal hydrogen atom in the water molecule, which is absorbed through the skin in the same manner as ordinary water. The models for dermal absorption of ^{3}H, but not for other radionuclides, are included in the GENII and RESRAD models. Since ^{3}H is not a radionuclide of interest in the TSPA, the dermal absorption pathway was not included in ERMYN.

There are several differences between the ERMYN methods (Equations 6.4.7-1 and 6.5.5-1) and the validation model methods (Table 7.3-23):

- ERMYN uses environment-specific exposure times and shielding factors for five environments and four population groups. The RESRAD and NCRP-129 models use two environments (indoors and outdoors); the other validation models do not consider different environments for evaluation of external exposure. None of the validation models includes differences among population groups. The ERMYN approach accounts for variation in shielding factors among the various environments where a receptor lives, and variation and uncertainty in exposure times among segments of the receptor population. A numerical comparison of inhalation exposure to particulate matter using the ERMYN micro-environmental approach and the single-environment approach used in other models demonstrates that the exposure rates differ by less than a factor of two (Table 7.4-21). This comparison also is valid for the external exposure submodel because the same parameter values for exposure times and population groups are used for both submodels. Based on the numerical comparison, the ERMYN methods are numerically similar to the validation models.

- The dose coefficients and their units differ among models and scenarios because the type of dose coefficient depends on the type and distribution of contaminants. For example, the dose coefficients for exposure to soil contaminated to an infinite depth (Bq/m^{3}) in the ERMYN groundwater scenario (Assumption 10) are similar to those in the BIOMASS ERB2A model. In contrast, dose coefficients for contaminated soil surface (Bq/m^{2}) in the ERMYN volcanic scenario (Assumption 16) are similar to GENII. There are some differences in notations for dose coefficients and associated factors in ERMYN and validation model equations (e.g., density correction W_s in NCRP-129, which accounts for an increased attenuation of radiation due to soil moisture) resulting from unit conversions. However, the methods are mathematically equivalent.

- The ERMYN, NCRP-129, and RESRAD models include a building shielding factor associated with time spent indoors. In ERMYN, this radionuclide-specific parameter accounts for the reduction in external exposure caused by dwellings. The GENII, BIOMASS ERB2A, and EPRI-YM models do not differentiate between time spent indoors and outdoors and do not include a shielding factor. However, this factor can be incorporated into the exposure time by reducing or excluding time spent indoors, and therefore, the methods are mathematically equivalent.

- The RESRAD model includes factors for the size and shape of the contaminated area. Under the groundwater scenario, the areas around people's homes and the fields are assumed to be contaminated because of long-term irrigation. Under the volcanic ash scenario, contaminated ash could be deposited over the entire Amargosa Valley. Thus, these factors would be about 1.0 for both scenarios and this method is mathematically equivalent to the ERMYN.

- RESRAD includes a cover-and-depth factor for the effects of burying radioactive waste. For both scenarios in the ERMYN, all radionuclides are in the surface soil, so this factor would be set at 1.0. Therefore, this method is mathematically equivalent to the method used in ERMYN.

- The NCRP-129 model includes different exposure rates for children and adults. 10 CFR 63.312(e) requires basing the characteristics of the RMEI on an adult, so this factor would equal 1.0, making the methods mathematically equivalent.

Because the mathematical representations are mathematically equivalent or the results are numerically similar, the external exposure submodel is validated.

Table 7.3-23. Comparison of External Exposure to Contaminated Soil

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.7-1 and 6.5.5-1)	Reference
GENII	$$I_{es} = C_{es} U_{es} \left(SH_h FT_h + SH_o FT_o \right) T_{es} / 8{,}760$$ I_{es} = exposure factor for external exposure to contaminated ground (Bq/kg) C_{es} = radionuclide concentration in soil (Bq/kg) U_{es} = daily exposure factor giving hours of exposure to contaminated ground (h/d) SH_h = shield factor for exposure to soil while inside a home (dimensionless) FT_h = fraction of time spent inside a home (dimensionless) SH_o = shield factor for exposure to soil while outside (dimensionless) FT_h = fraction of time spent outside (dimensionless) T_{es} = annual exposure factor giving the number of days of exposure to the ground per year (d/yr) 8,760 = unit conversion factors (h/yr). $$IE_{es} = I_{es} EC\ TE\ 3.15 \times 10^7 \rho_s d_s$$ IE_{es} = effective dose from external exposure to contaminated ground (Sv) EC = effective dose coefficient for external exposure to ground (Sv/s per Bq/m^2) TE = exposure time, here equal to 1 year (yr) ρ_s = bulk density of soil (kq/m^3) d_s = thickness of surface soil layer (m) 3.15×10^7 = unit conversion (s/yr).	GENII calculates doses from external exposure (and other pathways) in a two-step process. The, so called, exposure factors are calculated first, which are then used in combination with the dose coefficients and other parameters, as necessary, to calculate doses. The method used in GENII is analogous to that used in ERMYN for the volcanic scenario, where the areal radionuclide concentration in the soil (Bq/m^2) is used as a source. After the adjustment for the format of the source term (volumetric radionuclide concentration) and the dose coefficients (per unit volume rather than per unit surface area) the same equation is used in ERMYN to calculate doses from external exposure for the groundwater scenario. The calculations as shown can be applied to a population group and an environment or to the RMEI if the weighted exposure times are used. Age group and radionuclide indexing was omitted in GENII equations shown in this table. Age groups are not considered in ERMYN because the assessment is conducted for an adult. Also, averaging of the values over the period of exposure (here one year) is not shown because it is not relevant for the chronic exposure conditions and long-lived radionuclides.	Napier et al. 2006 [DIRS 177331], Equations 10.2 and 11.6

Table 7.3-23. Comparison of External Exposure to Contaminated Soil (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.7-1 and 6.5.5-1)	Reference
BIOMASS ERB2A	$$D_{exsoil} = O_s \, DC_{exts} \, C_s$$ D_{exsoil} = individual dose from external irradiation from the soil (Sv/yr) DC_{exts} = dose factor for external irradiation from the soil (Sv/h per Bq/m^3) C_s = radionuclide activity concentration in cultivated soil (Bq/m^3) O_s = individual occupancy in the soil compartment (h/yr).	BIOMASS ERB2A uses a method equivalent to that in the ERMYN (Equation 7.1), except for the lack of a shielding factor and environment- and population group-specific time budgets.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	$$D_{exsoil} = \frac{O_s DC_{exts} C_s}{(1-\theta_t)\rho + \theta\rho_w}$$ D_{exsoil} = individual dose from external irradiation from the soil (Sv/yr) O_s = individual occupancy on the soil compartment (h/yr) DC_{exts} = dose factor for external irradiation from soil (Sv/h per Bq/kg) C_s = radionuclide concentration in the soil compartment (Bq/m^3) θ_t = total porosity of the cultivated soil compartment (dimensionless) ρ = grain density of the cultivated soil compartment (kg/m^3) θ = water filled porosity of the cultivated soil compartment (dimensionless) ρ_w = the density of water (kg/m^3).	EPRI-YM uses a method equivalent to BIOMASS ERB2A. The units for dose coefficients are different (Sv/h per Bq/kg in EPRI-YM and Sv/h per Bq/m^3 in BIOMASS ERB2A), which changes the mathematical form of the equation but the results are the same. Also, the same equation, although again with a different set of units, is used for the igneous scenario of the EPRI-YM model.	EPRI 2002 [DIRS 158069], Equation 8-16 and EPRI 2004 [DIRS 171915], Equation 8-7
RESRAD	$$ETF_{i1}(t) = FO_1 \times FS_{i1}(t) \times FA_{i1}(t) \times FCD_{i1}(t)$$ $ETF_{i1}(t)$ = environmental transport factor for the external ground radiation pathway $FS_{i1}(t)$ = shape factor (dimensionless) $FA_{i1}(t)$ = nuclide-specific area factor (dimensionless) $FCD_{i1}(t)$ = depth-and-cover factor (dimensionless) FO_1 = occupancy and shielding factor (dimensionless), calculated as: $$FO_1 = f_{otd} + (f_{ind} \times F_{sh})$$ f_{otd} = fraction of a year spent outdoors, on site, 0.25 (dimensionless) f_{ind} = fraction of a year spent indoors, on site, 0.50 (dimensionless) F_{sh} = indoor shielding factor for external gamma, 0.7 (dimensionless).	The RESRAD model includes several factors, including shape, area, depth, and cover factors that are not included in ERMYN. An indoor shielding factor is also used. The equation calculates the environmental transport factor (*ETF*). To convert *ETF* to dose, *ETF* is multiplied by the effective dose equivalent conversion factor (DCF_{i1} – mrem/yr per pCi/g) and the source term (*S(t)* – pCi/g).	Yu et al. 2001 [DIRS 159465], Appendix A, Equation A-7

Table 7.3-23. Comparison of External Exposure to Contaminated Soil (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.7-1 and 6.5.5-1)	Reference
NCRP-129	$E_{ext} = Df_{ext} \times [T_{out} + (T_{in} \times SF)] \times (C/A) \times W_s \times S(z,t)$ E_{ext} = average annual exposure to an exposed individual per unit radionuclide concentration in soil from external radiation (Sv per Bq/kg) Df_{ext} = dose factor for a particular radionuclide and the geometry of soil contamination (i.e., the concentration depth profile, $S(z,t)$) (Sv/yr per Bq/kg) $S(z,t)$ = radionuclide concentration in the soil, averaged over the 1 year interval (*t*) for which the dose is calculated (Bq/kg $_{dry\ soil}$); varies with depth (*z*) beneath the ground surface T_{out} = the mean fraction of time spent outdoors on a contaminated site T_{in} = the mean fraction of time spent indoors in a dwelling on a contaminated site *SF* = shielding factor or ratio of the dose indoors to the unshielded outdoor dose W_s = density correction due to soil moisture (i.e., the ratio of dry soil density to the actual in situ bulk density) *C/A* = ratio of the external dose to children to that for adults when children are present.	NCRP-129 uses soil density and child-exposure correction factors that are not in ERMYN. E_{ext} should be in units of Sv in the equation when $S(z,t)$ is the radionuclide concentration in the soil (in units of Bq/kg). NCRP-129 is equivalent to ERMYN, except that the soil density correction factor and exposure for children are not used in the ERMYN. Not using the soil density correction factor in ERMYN is conservative.	NCRP 1999 [DIRS 155894], Equation 3.1

7.3.8 Validation of the Inhalation Submodel

The ERMYN (Equation 6.4.8-2 and 6.5.6-2) and all of the validation models (Table 7.3-24) use the same general approach for calculating the dose from inhalation of particulate matter as the product of radionuclide-specific inhalation dose coefficients, breathing rates, airborne particle concentrations, and exposure times. The ERMYN also uses this approach for calculating exposure to aerosols generated from operating evaporative coolers (Equation 6.4.8-3), inhalation of ^{14}C (Equation 6.4.8-4), and inhalation of radon decay products (Equation 6.4.8-5 and 6.5.6-3). Differences between the ERMYN methods for calculating the inhalation dose for all airborne contaminants and the methods used in the validation models are:

- Four of the five validation models provide equations for calculating either average inhalation exposure using average breathing rates, air concentrations, and inhalation times (Table 7.3-24) or the inhalation exposure under specific exposure conditions. The NCRP-129 model considers two environments (indoors and outdoors) in an explicit manner, which is similar to the microenvironment concept in the ERMYN. The BIOMASS and EPRI-YM models also use a dual-environment approach although the combined equation is not shown. In these models the two environments represent the conditions of high and low dust levels as well as the corresponding occupancies and breathing levels for hard physical activity and normal activity. In this respect, the simple approach to calculating inhalation exposure can be easily modified to accommodate more than one exposure environment with regard to the characteristics of the airborne contaminants and the receptor. The ERMYN includes five environments and four population groups to incorporate variation and uncertainty in concentrations of radionuclides within the receptor environment and exposure times among segments of the receptor population. A numerical comparison of the ERMYN micro-environment method and the single-environment method evaluates the effects of these differences (Section 7.4.9). Using average values for the single-environment method, the two approaches produce similar results for inhaled activity (7.0×10^{-6} versus 6.1×10^{-6} Bq/d; Table 7.4-21), and additional validation of this portion of the submodel is not required.

- Of the validation models, only the EPRI-YM model for the igneous scenario considers the inhalation dose as a function of time by using different radionuclide concentrations in air in the first year after a volcanic eruption. The inhalation dose for the ERMYN volcanic scenario is treated as a function of time (Equation 6.5.6-2) to account for decreases in mass loading following a volcanic eruption. This approach is evaluated and justified in the validation of the air submodel (Section 7.3.2).

- None of the validation models includes inhalation of aerosols from evaporative coolers. This pathway is site-specific or more precisely region-specific (i.e., it is only pertinent to those regions where air humidity is low when the cooling is needed) and is not included in the generic models. The ERMYN method for calculating this inhalation dose (Equation 6.4.8-3) is similar to the methods in the validation models for particulate matter, except that the ERMYN calculation includes parameters to quantify the proportion of houses with evaporative coolers and the proportion of the year that coolers are used. The calculation of the inhalation dose from radon decay products

(Equation 6.4.8-7) also includes these factors because of different radon accumulation levels in indoor air when evaporative coolers are tuned on and off. When the factors related to evaporative cooler usage are included, the dose from inhalation of radon decay products could differ by more than a factor of two compared to the dose calculated without considering these factors. Therefore, further evaluation of this pathway is presented in Section 7.4.3.1. Excluding these parameters results in overestimating the inhalation dose. These parameters are justified because they account for site-specific conditions and prevent overestimating dose.

- BIOMASS ERB2A includes the inhalation of aerosols from water sprays, but it does not provide the method for calculating aerosol concentrations, although it does give a default value of 1.0×10^{-11} m^3_{water}/m^3_{air} (BIOMASS 2003 [DIRS 168563], Table C27), which corresponds to 1.0×10^{-11} Bq/m^3 for a unit radionuclide concentration in groundwater (1 Bq/m^3). This airborne concentration is orders of magnitude lower than the typical concentration for resuspended particles (10^{-5} to 10^{-8} Bq/m^3, Table 6.10-1). In addition, the BIOMASS ERB2A default value for exposure time to aerosols is 36.5 h/yr (BIOMASS 2003 [DIRS 168563], Table C27), which is lower than exposure time to resuspended particles (Table 7.4-21) in the ERMYN. Therefore, excluding this pathway from the ERMYN would change the estimated inhalation dose by less than a factor of two, and, therefore, it does not require further justification.

- RESRAD includes a factor for the size of the contaminated area. Under the groundwater scenario, the areas around people's homes and the fields are assumed to be contaminated because of long-term irrigation. Under the volcanic ash scenario, contaminated ash is deposited over the entire Amargosa Valley. Thus, this factor would be about 1.0 for both scenarios, and the RESRAD and ERMYN methods are mathematically equivalent.

- RESRAD includes a cover-and-depth factor for the effect of burying radioactive waste. Under both ERMYN scenarios, all radionuclides are in the surface soil, so this factor would be 1.0. Therefore, the RESRAD and ERMYN methods are mathematically equivalent.

Because the models are mathematically equivalent or produce similar results, the inhalation submodel is validated.

Table 7.3-24. Comparison of Inhalation Pathway

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.8-2 and 6.5.6-2)	Reference
GENII	$$I_{sa} = C_{sa} U_{sa} T_{sa} F_{sa} ED_{sa}$$ I_{sa} = total radionuclide intake from resuspension inhalation (Bq) C_{sa} = radionuclide concentration in air from resuspended soil (Bq/m^3) U_{sa} = inhalation rate for the resuspension pathway (m^3/d) T_{sa} = annual intake factor giving days per year that resuspension inhalation occurs (d/yr) F_{sa} = fraction of a day that resuspension inhalation exposure occurs (dimensionless) ED_{sa} = exposure duration for the resuspension inhalation, here equal to 1 yr. $$IE_{sa} = I_{sa} EC$$ IE_{sa} = effective dose from inhalation intake of a radionuclide in resuspended soil for exposure over a defined time period (here 1 yr) (Sv) EC = effective dose coefficient for inhalation intake (Sv/ Bq). This parameter includes a selection of inhalation class for a radionuclide; in ERMYN the highest values of dose coefficients are used, regardless of the chemical form (class).	GENII calculates doses from inhalation exposure (and other pathways) in a two-step process. The, inhalation intake is calculated first, and is then used in combination with the dose coefficient to calculate inhalation dose. Calculations are carried out separately for the outdoor and indoor environments and for different types of contaminants. Because the mathematical methods are the same for different inhalation pathways (although parameter values and conversion factors are different), the method is shown here for one pathway only, the inhalation of resuspended soil. The method used in GENII is analogous to that used in ERMYN. Radionuclide, age group, and location indexing was omitted in GENII equations shown in this table. Age groups are not considered in ERMYN because the assessment is conducted for an adult. Also, averaging of the values over the period of exposure (here one year) is not shown because it is not relevant for the chronic exposure conditions and long-lived radionuclides.	Napier et al. 2006 [DIRS 177331], Equations 10.14 and 11.30 for inhalation of resuspended soil outdoors and Equations 10.15 and 11.31 for inhalation of indoor contaminants.

Table 7.3-24. Comparison of Inhalation Pathway (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.8-2 and 6.5.6-2)	Reference
BIOMASS ERB2A	$D_{dust} = DC_{inh}\ C_{airs}\ BR\ O_s$ D_{dust} = individual dose from dust inhalation (Sv/yr) DC_{inh} = dose coefficient for inhalation (Sv/Bq) C_{airs} = radionuclide concentration in the air above the cultivated soil compartment (Bq/m^3) BR = breathing rate of humans in the soil compartment (m^3/h) O_s = individual occupancy in the soil compartment (h/yr) $D_{aero} = DC_{inh}\ AIR_{aero}\ BR\ O_{aero} C_w$ D_{aero} = individual dose from the inhalation of aerosols (Sv/yr) AIR_{aero} = aerosol level in the air in the area affected by aerosol/spray (m^3/m^3) O_{aero} = individual occupancy in the area affected by aerosols (h/yr) C_w = radionuclide concentration in water (Bq/m^3).	In BIOMASS, the inhalation of dust is modeled the same as in the ERMYN and GENII models. BIOMASS includes the inhalation of aerosols and sprays pathway, which is not an important inhalation pathway, as discussed in the text.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	EPRI-YM uses the BIOMASS model for inhalation of resuspended soil and spray aerosols for the contaminated water scenario. For the igneous scenario, an equation that is mathematically similar is used. For this scenario the exposure in the first year after an eruption is elevated because of the higher radionuclide concentration in air.	The EPRI-YM inhalation submodel is the same as that in the BIOMASS submodel.	EPRI 2002 [DIRS 158069], Equations 8-18 and 8.19 EPRI 2004 [DIRS 171915], Equation 8-29
RESRAD	$ETF_{i2}(t) = ASR_2 \times FA_2 \times FCD_2(t) \times FO_2 \times FI_2$ $ETF_{i2}(t)$ = environmental transport factor at time t for dust inhalation for the ith principal radionuclide (g/yr) ASR_2 = air/soil concentration ratio = average mass loading of airborne contaminated soil particles (g/m^3) FA_2 = area factor (dimensionless) $FCD_2(t)$ = cover-and-depth factor (dimensionless) FO_2 = occupancy factor (dimensionless) FI_2 = annual intake of air (m^3/yr).	RESRAD includes several factors, including contaminated soil depth, uncontaminated soil cover, and area contaminated, which are not used in ERMYN (or their values would be equal to one, if used). To convert ETF into dose, ETF is multiplied by the dose coefficient for inhalation (DCFi2 – mrem/pCi) and the radionuclide concentration in the soil source (S(t) – pCi/g). Notwithstanding these factors, the RESRAD inhalation submodel is analogous to the one used in ERMYN.	Yu et al. 2001 [DIRS 159465], Eq. B.1.

Table 7.3-24. Comparison of Inhalation Pathway (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.8-2 and 6.5.6-2)	Reference
NCRP-129	$E_{inh} = Df_{inh} \times C_{air} \times [R_{out} \times T_{out} + (I/O) \times R_{in} \times T_{in}]$ E_{inh} = committed effective dose for inhalation (Sv/yr) Df_{inh} = inhalation dose factor (Sv/Bq) C_{air} = average annual outdoor air concentration (Bq/m^3) R_{out} = average breathing rate outdoors (m^3/d) R_{in} = average breathing rate indoors (m^3/d) (I/O) = ratio of nuclide concentration in air indoors versus outdoors T_{out} = time spent outdoors on contaminated land (d/yr) T_{in} = time spent indoors on contaminated land (d/yr).	The NCRP-129 inhalation submodel uses breathing rates and radionuclide concentrations in the air for indoor and outdoor environments, which is similar to the concept used in the ERMYN for environment-specific inhalation exposures. The NCRP-129 model is similar to ERMYN, except for using fewer human activity and environment categories.	NCRP 1999 [DIRS 155894], p. 64, Eq. 4.2.

7.3.9 Validation of the Ingestion Submodel

The ERMYN and the five validation models use the same methods for calculating ingestion doses, although the number of ingestion pathways differs among the models. All five validation models use crop (Table 7.3-26) and animal (Table 7.3-27) ingestion pathways. Vegetables, beef, and milk are the most common types of food included in the submodels. Water ingestion may not be shown as included in some of the models (e.g., the NCRP-129) (Table 7.3-25) but this pathway uses the same straight-forward approach to calculating ingestion doses, so it can be added if needed. The ingestion of aquatic foods (e.g., fish) is included in the GENII and RESRAD models (Table 7.3-28). The BIOMASS ERB2A model does not include this pathway, but the BIOMASS ERB2B model does and it is used in the comparison. (The example reference biosphere 2B used in the analyses in this section (BIOMASS 2003 [DIRS 168563], Section C3) is constructed for natural release of contaminated groundwater to the surface environment. Fish farming is an unlikely activity under the agricultural well scenario addressed by the ERB2A model). All of the models also include soil ingestion by humans and use similar methods (Table 7.3-29).

The ERMYN and the five validation models calculate ingestion doses using the same general methods, as the product of radionuclide concentrations in the ingested media, ingestion rates, and radionuclide-specific ingestion dose coefficients. The validation models differ from the ERMYN submodel in the following ways:

- GENII and NCRP-129 include radionuclide decay during the holdup time before consumption. The time between harvest or groundwater pumping and consumption is short relative to the half-life of long-lived radionuclides (Table 6.3-7). Thus, the terms in the GENII and NCRP-129 models that correct the radionuclide concentration in the ingested media for decay during the holdup time approach 1.0, making the methods mathematically equivalent.

- NCRP-129 includes a parameter for the fraction of crop consumption derived from the contaminated site (Table 7.3-26). Because all crops grown in the Amargosa Valley are assumed to be contaminated in the ERMYN model, this parameter would be 1.0, and the methods are mathematically equivalent.

- BIOMASS ERB2A includes a water content correction in the estimate of soil density in the soil ingestion dose calculation; radionuclide concentration in soil in Bq/m^3 is divided by the density of moist soil to calculate radionuclide concentration per unit mass (Table 7.3-29). This correction is not used in the ERMYN because ingested soil on hands and crops would likely be dry. The ERMYN uses the dry bulk density of surface soil (Equation 6.4.1-6), which is about 1,500 kg/m^3 for soils in the Amargosa Valley (Table 6.6-3). The additional factor in the BIOMASS equation, equal to the density of soil water, is calculated as the product of the soil volumetric water content (about 0.23; Table 6.6-3) and water density (1,000 kg/m^3), and is equal to about 230 kg/m^3. Including the water content factor would change the estimate of soil density by a factor of less than 1.2 and decrease the radionuclide concentration in the soil by the same factor. This difference is small, does not result in underestimating the dose to the RMEI, and, therefore, requires no further justification.

- NCRP-129 uses an occupational exposure modification factor to account for differences in soil ingestion rates among people working in different occupations (Table 7.3-29). Soil ingestion rates in the ERMYN are based on the lifestyles consistent with those of Amargosa Valley residents (BSC 2005 [DIRS 172827], Section 6.4.3). Thus, this parameter is not required in the ERMYN submodel and the methods are mathematically equivalent.

Based on these comparisons, the ERMYN ingestion submodel is supported by the validation models and, therefore, is validated.

Table 7.3-25. Comparison of Water Ingestion Pathway

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.9-2)	Reference
GENII	$$I_{dw} = C_{dw} U_{dw} T_{dw}\ ED_{dw}$$ I_{dw} = total radionuclide intake from drinking water ingestion (Bq) C_{dw} = radionuclide concentration in drinking water (Bq/L) U_{dw} = drinking water ingestion rate (L/d) T_{dw} = annual intake factor giving days per year that water is consumed (d/yr) ED_{dw} = exposure duration for the drinking water pathway, here equal to 1 yr. $$IE_{dw} = I_{dw} EC$$ IE_{dw} = effective dose from ingestion intake of a radionuclide in drinking water for exposure over a defined time period (here 1 yr) (Sv) *EC* = effective dose coefficient for ingestion intake (Sv/Bq). This parameter includes a selection of radionuclide class; in ERMYN the FGR 13 ingestion dose coefficients are used, which do not give a user a choice between classes for almost all radionuclides.	GENII calculates doses from ingestion in a two-step process. The, ingestion intake is calculated first, which is then used in combination with the dose coefficient to calculate ingestion doses. Although the water intake is calculated as a multi-step process, the GENII and ERMYN method are the same. Radionuclide, age group and location indexing was omitted in GENII equations shown in this table.	Napier et al. 2006 [DIRS 177331], Equations 10.9 and 11.19
BIOMASS ERB2A	$$D_w = ING_w DC_{ing} C_w$$ D_w = individual dose from consumption of groundwater (Sv/yr) DC_{ing} = dose coefficient for ingestion (Sv/Bq) ING_w = individual consumption rate for groundwater (m^3/yr) C_w = radionuclide activity concentration in groundwater (Bq/m^3).	The BIOMASS ERB2A water ingestion dose calculations are the same as those in the ERMYN.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	EPRI model is based on the BIOMASS model and uses the same equation.	The EPRI-YM and ERMYN submodels are the same.	EPRI 2002 [DIRS 158069], Equation 8-7

Table 7.3-25. Comparison of Water Ingestion Pathway (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.9-2)	Reference
RESRAD	$H_{E,ip}(t) = DSR_{ij}(t) \times S_i(0)$ $H_{E,ip}(t)$ = average annual dose received at time t by a member of the critical population group from the ith principal radionuclide transported through the pth environmental pathway together with its associated decay products (mSv/yr or mrem/yr) $DSR_{ip}(t)$ = dose to soil-concentration ratio for the ith principal radionuclide and pth environmental pathway ((mSv/yr)/(Bq/g) or (mrem/yr)/(pCi/g)) $S_i(0)$ = initial concentration of the ith principal radionuclide in a uniformly contaminated zone (Bq/g or pCi/g).	RESRAD calculates the environmental transport factor for various pathways, then calculates the dose/soil-concentration ratios (*DSR*), and then the dose (H_E). (In RESRAD, soil is a primary contaminated medium; contamination of water results from radionuclide transport from soil). Although the equation has a different layout, the method is the same as that used in ERMYN and in the other models.	Yu et al. 2001 [DIRS 159465] Equations 3.6 and 3.9
NCRP-129	Not included	Not applicable	NCRP 1999 [DIRS 155894]

Table 7.3-26. Comparison of Crop Ingestion Pathway

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.9-3 and 6.5.7-2)	Reference
GENII	$$I_c = C_c U_c T_c \ ED_c$$ I_c = total radionuclide intake in food crop *c* from ingestion (Bq) C_c = radionuclide concentration in food crop *c* (Bq/kg) U_c = ingestion rate of food crop *c* (kg/d) T_c = annual intake factor giving days per year that food crop *c* is consumed (d/yr) ED_c = exposure duration for consumption of food crop *c*, here equal to 1 yr. $$IE_c = I_c EC$$ IE_c = effective dose from ingestion intake of a radionuclide in food crop *c* for exposure over a defined time period (here 1 yr) (Sv) EC = effective dose coefficient for ingestion intake (Sv/Bq). This parameter includes a selection of radionuclide class; in ERMYN the FGR 13 ingestion dose coefficients are used, which do not give a user a choice between classes for almost all radionuclides.	GENII calculates doses from ingestion in a two-step process. The ingestion intake is calculated first, which is then used in combination with the dose coefficient to calculate ingestion doses. Despite a different process, the GENII and ERMYN methods are the same. Radionuclide, age group and location indexing was omitted in GENII equations shown in this table.	Napier et al. 2006 [DIRS 177331], Equations 10.6 and 11.14
BIOMASS ERB2A	$$D_{crop} = ING_{crop} DC_{ing} C_{crop}$$ D_{crop} = individual dose from consumption of crops (Sv/yr) ING_{crop} = individual consumption rate for crops (kg/yr) DC_{ing} = dose coefficient for ingestion (Sv/Bq) C_{crop} = radionuclide activity concentration in edible crop parts (Bq/kg).	BIOMASS ERB2A and ERMYN use the same method to calculate the crop ingestion dose.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	EPRI model is based on the BIOMASS model and uses the same equation.	EPRI-YM and ERMYN are the same.	EPRI 2002 [DIRS 158069], Equation 8-8 EPRI 2004 [DIRS 171915], Equation 8-10

Table 7.3-26. Comparison of Crop Ingestion Pathway (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.9-3 and 6.5.7-2)	Reference
RESRAD	The same equation for water ingestion dose (Table 7.3-25)	RESRAD calculates the environmental transport factor for various pathways, then calculates the dose to soil-concentration ratios (*DSR*), and then the dose (H_E). Although the equation has a different layout, the method is the same as in ERMYN and in the other models.	Yu et al. 2001 [DIRS 159465], Equations 3.6 and 3.9.
NCRP-129	$E_{ing} = Df_{ing} \times \sum (C_i \times R_i) \times f_i \times \exp[-\lambda(t - t_0)]$ E_{ing} = annual committed effective dose from ingestion (Sv/yr) Df_{ing} = committed effective dose for ingestion that would result from an intake of 1 Bq of this radionuclide (Sv/Bq) C_i = concentration of a particular radionuclide in foodstuff *I* at harvest (Bq/kg) R_i = average annual intake of foodstuff *I* (kg) f_I = fraction of R_i derived from the contaminated site $exp[-\lambda(t-t_0)]$ = correction factor to account for radioactive decay between harvest (t0) and ingestion (t).	NCRP-129 uses holding times, which are negligible for long-lived radionuclides. It also uses the fraction of contaminated food consumed, which is incorporated into the consumption rate in ERMYN.	NCRP 1999 [DIRS 155894], Equation 5.1

Table 7.3-27. Comparison of Animal Product Ingestion Pathway

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.9-4 and 6.5.7-3)	Reference
GENII	$$I_a = C_a U_a T_a \; ED_a$$ I_a = total radionuclide intake in animal product *a* from ingestion (Bq) C_a = radionuclide concentration in animal product *a* (Bq/kg) U_a = ingestion rate of animal product *a* (kg/d) T_a = annual intake factor giving days per year that animal product *a* is consumed (d/yr) ED_a = exposure duration for consumption of animal product *a*, here equal to 1 yr. $$IE_a = I_a EC$$ IE_a = effective dose from ingestion intake of a radionuclide in animal product *a* for exposure over a defined time period (here 1 yr) (Sv) EC = effective dose coefficient for ingestion intake (Sv/Bq). This parameter includes a selection of radionuclide class; in ERMYN the FGR 13 ingestion dose coefficients are used, which have only one value for almost all radionuclides.	GENII calculates doses from ingestion in a two-step process. The ingestion intake is calculated first, which is then used in combination with the dose coefficient to calculate ingestion doses. Despite a different process, the GENII and ERMYN methods are the same. Radionuclide, age group and location indexing was omitted in GENII equations shown in this table.	Napier et al. 2006 [DIRS 177331], Equations 10.7 and 11.16
BIOMASS ERB2A	$$D_{prod} = ING_{prod} DC_{ing} C_{prod}$$ D_{prod} = individual dose from consuming animal products (Sv/yr) ING_{prod} = individual consumption rate of animal products (kg/yr) DC_{ing} = dose coefficient for ingestion (Sv/Bq) C_{prod} = radionuclide concentrations in animal products (Bq/kg).	BIOMASS and ERMYN are the same.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	EPRI model is based on the BIOMASS model and uses the same equation.	EPRI-YM and ERMYN use the same method.	EPRI 2002 [DIRS 158069], Equation 8-10 EPRI 2004 [DIRS 171915], Equation 8-12

Table 7.3-27. Comparison of Animal Product Ingestion Pathway (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.9-4 and 6.5.7-3)	Reference
RESRAD	The same equation is used as that for water ingestion dose (Table 7.3-25).	RESRAD calculates the environmental transport factor for various pathways, then calculates the dose to soil-concentration ratios (*DSR*), then calculates the dose (H_E). Although the equation has a different layout, the method is the same as in the other models.	Yu et al. 2001 [DIRS 159465], Equations 3.6 and 3.9
NCRP-129	The same equation is used as that for crop ingestion (Table 7.3-26).	NCRP-129 model includes holding time, which is negligible for long-lived radionuclides.	NCRP 1999 [DIRS 155894], Equation 5.1

Table 7.3-28. Comparison of Fish Ingestion Pathway

Document	Mathematical Model	Comparison with ERMYN (Equation 6.4.9-5)	Reference
GENII	$I_f = C_f U_f T_f \ ED_f$ I_f = total radionuclide intake in aquatic food *f* from ingestion (Bq) C_f = radionuclide concentration in aquatic food *f* (Bq/kg) U_f = ingestion rate of aquatic food *f* (kg/d) T_f = annual intake factor giving days per year that aquatic food *f* is consumed (d/yr) ED_f = exposure duration for consumption of aquatic food *f*, here equal to 1 yr. $IE_f = I_f EC$ IE_f = effective dose from ingestion intake of a radionuclide in aquatic food *f* for exposure over a defined time period (here 1 yr) (Sv) *EC* = effective dose coefficient for ingestion intake (Sv/Bq). This parameter includes a selection of radionuclide class; in ERMYN the FGR 13 ingestion dose coefficients are used, which have only one value for almost all radionuclides.	GENII calculates doses from ingestion in a two-step process. The ingestion intake is calculated first, which is then used in combination with the dose coefficient to calculate ingestion doses. Despite a different process, the GENII and ERMYN methods are the same. Age group, radionuclide, and location indexing was omitted in GENII equations shown in this table.	Napier et al. 2006 [DIRS 177331], Equations 10.8 and 11.17
BIOMASS ERB2A	Not included The aquatic food consumption is included in the BIOMASS ERB2B model and the methods are the same as those used in ERMYN.	Not applicable	BIOMASS 2003 [DIRS 168563], Sections C3.5.4.3 and C4.5.5
EPRI-YM	Not included	Not applicable	EPRI 2002 [DIRS 158069], Section 8
RESRAD	The same equation as that used for water ingestion dose (Table 7.3-25)	RESRAD calculates the environmental transport factor for various pathways, calculates the dose to soil-concentration ratios (*DSR*), and then calculates the dose (H_E). Although the equation has a different layout, the method is the same as that used in the other models.	Yu et al. 2001 [DIRS 159465], Equations 3.6 and 3.9
NCRP-129	Not included	Not applicable	NCRP 1999 [DIRS 155894].

Table 7.3-29. Comparison of Soil Ingestion Pathway

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.9-6 and 6.5.7-4)	Reference
GENII	$$I_d = 10^{-6} C_d U_d T_d \; ED_d$$ I_d = total radionuclide intake in from inadvertent soil ingestion (Bq) C_d = radionuclide concentration in soil (Bq/kg) U_d = ingestion rate of soil (mg/d) T_d = annual intake factor giving days per year that soil is consumed (d/yr) ED_d = exposure duration for consumption of soil, here equal to 1 yr 10^{-6} = unit conversion (kg/mg) $$IE_d = I_d EC$$ IE_d = effective dose from ingestion intake of a radionuclide in soil for exposure over a defined time period (here 1 yr) (Sv) EC = effective dose coefficient for ingestion intake (Sv/Bq). This parameter includes a selection of radionuclide class; in ERMYN the FGR 13 ingestion dose coefficients are used, which do not give a user a choice between classes for almost all radionuclides.	GENII calculates doses from ingestion in a two-step process. The ingestion intake is calculated first, which is then used in combination with the dose coefficient to calculate ingestion doses. Despite a different process, the GENII and ERMYN methods are the same. Radionuclide, age group, radionuclide, and location indexing was omitted in GENII equations shown in this table.	Napier et al. 2006 [DIRS 177331], Equations 10.10 and 11.22
BIOMASS ERB2A	$$D_{soil} = ING_{soil} DC_{ing} \frac{C_s}{(1-\theta_t)\rho + \theta\rho_w}$$ D_{soil} = individual dose from soil consumption (Sv/yr) DC_{ing} = dose coefficient for ingestion (Sv/Bq) ING_{soil} = individual consumption rate of soil ($kg/yr_{wet\ weight}$) C_s = radionuclide activity concentration in cultivated soil (Bq/m^3) θ_t = total porosity of the cultivated soil compartment ρ = dry grain density of the cultivated soil compartment (kg/m^3) θ = water filled porosity of the cultivated soil compartment (dimensionless) ρ_w = density of water (kg/m^3).	BIOMASS and ERMYN are equivalent. BIOMASS includes water content in the soil concentration. Because inadvertent soil ingestion by humans is from hands and food, not directly from cultivated soil, the water content should be lower than that for cultivated soil. The method used in the ERMYN is a more conservative because including water content in the equation reduces radionuclide concentrations compared with those in dry soil.	BIOMASS 2003 [DIRS 168563], Section C3.5.4.3
EPRI-YM	EPRI model is based on the BIOMASS model and uses the same equation.	EPRI-YM and ERMYN use the same method.	EPRI 2002 [DIRS 158069], Equation 8-15 EPRI 2004 [DIRS 171915], Equation 8-6

Table 7.3-29. Comparison of Soil Ingestion Pathway (Continued)

Document	Mathematical Model	Comparison with ERMYN (Equations 6.4.9-6 and 6.5.7-4)	Reference
RESRAD	$ETF_{j8}(t) = FSI \times FA_8 \times FCD_8(t) \times FO_8$ $ETF_{j8}(t)$ = environmental transport factor at time t for soil ingestion for the ith principal radionuclide (g/yr) FSI = annual intake of soil (g/yr) FA_8 = area factor (dimensionless) $FCD_8(t)$ = cover-and-depth factor (dimensionless) FO_8 = occupancy factor (dimensionless).	RESRAD uses several factors, including depth of the contaminated soil, uncontaminated soil cover, and contaminated area, which are not used in ERMYN. To convert ETF to dose, ETF is multiplied by the dose coefficients (*DCF* – mrem/pCi) and the source terms (*S(t)* – pCi/g) (Yu et al. 2001 [DIRS 159465], Eq. 3.6 and 3.9).	Yu et al. 2001 [DIRS 159465], Equation F.2
NCRP-129	$E_{soil} = Df_{ing} \times C_{soil} \times I_{soil} \times T \times OF$ E_{soil} = committed effective dose for soil ingestion (Sv/yr) Df_{ing} = ingestion dose factor (Sv/Bq) C_{soil} = average concentration in top 5 cm of soil (Bq/kg) I_{soil} = average soil ingestion rate during the exposure period (kg/d) T = exposure duration (d/yr) OF = occupational exposure modification factor.	NCRP-129 uses an occupational exposure modification factor, which is used for workers. This factor is included in the ERMYN soil consumption rate. Therefore, NCRP-129 and ERMYN use equivalent methods.	NCRP 1999 [DIRS 155894], Equation 5.4

7.4 NUMERICAL COMPARISON OF MODEL RESULTS

This section describes some of the numerical comparisons conducted to evaluate the assumptions (Sections 6.3.1.4 and 6.3.2.4) and ACMs (Section 6.3.3), to validate the ERMYN model, and to determine if the effective dose coefficients (Section 6.4), used to include the dose contribution from short-lived decay products together with that of their long-lived progeny, are valid.

The model validation criteria for numerical comparisons are specified in the TWP (BSC 2006 [DIRS 176938], Section 2.2.1), and implementation of the criteria is described in Section 7.1. In all cases where the ERMYN and the five validation models are not mathematically equivalent, a numerical comparison is required. Simple comparisons are presented in Section 7.3, and more complex numerical comparisons are presented in this section. If the difference in the results between the ERMYN and the validation model are within a factor of 2, numerical similarity between the models is demonstrated. If the results differ by more than a factor of 2, further evaluation and justification of the selected method is included in Section 7.3.

To make the model comparisons more realistic, input parameters are selected mainly from the ERMYN input values (Section 6.6.3), and, if possible, the same parameter values are used in all of the comparisons. When parameters are specific to a particular validation model, default values for that model are used.

7.4.1 Radionuclide Decay and Ingrowth

This section presents a validation of the methods used for calculating effective dose coefficients for external exposure (Section 6.4.7.2), inhalation (Section 6.4.8.5), and ingestion (Section 6.4.9.6) by comparing the ERMYN results with those from the RESRAD model (Yu et al. 2001 [DIRS 159465]). This comparison does not involve an ACM (Sections 6.3.3 and 7.3).

As discussed in Section 6.3.5, ERMYN assumes that a radionuclide with a half-life of less than 180 d is always in secular equilibrium with the long-lived parent radionuclide (Assumption 2). The half-life cutoff is based on the intended use of the model. From a data file, *RMDLIB.DAT* (Appendix A) in the GENII-S model (SNL 1998 [DIRS 117076]), it can be determined that GENII-S uses a one-hour cutoff for the half-life, as that model is also suitable for acute radionuclide releases. Using a high value for the half-life cutoff simplifies ERMYN by eliminating many short-lived radionuclide decay chains, while still maintaining the accuracy of the model for a long-term dose assessment.

This simplification is used in the RESRAD code, a code widely used by the DOE and its contractors, the NRC, U.S. Environmental Protection Agency, and many other organizations (Yu et al. 2001 [DIRS 159465], p. xi). The effective dose coefficients calculated in ERMYN (Sections 6.4.7.2, 6.4.8.5, 6.4.9.6, and 6.5.5.2) are compared with the RESRAD values (Tables 7.4-1, 7.4-2 and 7.4-3, and 7.4-4 respectively). These comparisons indicate that the values derived from the two models are the comparable, except for a few instances where the differences are due to using more current dosimetric quantities or absorption types that were previously not available. The values used in the ERMYN model are the most recent dose coefficients available. These dose coefficients were developed using tissue weighting factors consistent with ICRP Publication 60 (ICRP 1991 [DIRS 101836]) and are therefore compliant with the regulatory requirement to use the dosimetric factors consistent with the ICRP Publication 60 [DIRS 101836]).

Table 7.4-1. Effective Dose Coefficients for Exposure to Soil Contaminated to an Infinite Depth

Primary Radionuclide	Effective Dose Coefficient			Effective Dose Coefficient Ratio RESRAD/ ERMYN [d]
	ERMYN		RESRAD	
	Sv/s per Bq/m^3 [a]	mrem/yr per pCi/g [b]	mrem/yr per pCi/g [c]	
^{14}C	5.90E–23	1.10E–05	1.34E–05	1.22
^{36}Cl	1.33E–20	2.48E–03	2.39E–03	0.96
^{79}Se	8.21E–23	1.53E–05	1.86E–05	1.21
^{90}Sr	2.18E–19	4.08E–02	2.46E–02	0.60
^{99}Tc	5.81E–22	1.09E–04	1.26E–04	1.16
^{126}Sn	5.94E–17	1.11E+01	NA	NA
^{129}I	5.14E–20	9.60E–03	1.29E–02	1.34
^{135}Cs	1.72E–22	3.21E–05	3.83E–05	1.19
^{137}Cs	1.71E–17	3.20E+00	3.41E+00	1.07
^{242}Pu	5.32E–22	9.94E–05	1.28E–04	1.29
^{238}U	8.34E–19	1.56E–01	1.37E–01	0.88
^{238}Pu	6.25E–22	1.17E–04	1.51E–04	1.29
^{234}U	1.84E–21	3.44E–04	4.02E–04	1.17
^{230}Th	5.73E–21	1.07E–03	1.21E–03	1.13
^{226}Ra	5.67E–17	1.06E+01	1.12E+01	1.06
^{210}Pb	4.01E–20	7.48E–03	6.10E–03	0.81
^{240}Pu	6.03E–22	1.13E–04	1.47E–04	1.30
^{236}U	9.53E–22	1.78E–04	2.15E–04	1.21
^{232}Th	2.44E–21	4.56E–04	5.21E–04	1.14
^{228}Ra	3.03E–17	5.66E+00	5.98E+00	1.06
^{232}U	4.25E–21	7.94E–04	9.02E–04	1.14
^{228}Th	5.18E–17	9.67E+00	1.02E+01	1.05
^{243}Am	4.36E–18	8.14E–01	8.95E–01	1.10
^{239}Pu	1.41E–21	2.63E–04	2.95E–04	1.12
^{235}U	3.70E–18	6.92E–01	7.57E–01	1.09
^{231}Pa	9.44E–19	1.76E–01	1.91E–01	1.08
^{227}Ac	1.00E–17	1.87E+00	2.01E+00	1.08
^{241}Am	1.99E–19	3.72E–02	4.37E–02	1.18
^{237}Np	5.41E–18	1.01E+00	1.10E+00	1.09
^{233}U	6.77E–21	1.26E–03	1.40E–03	1.11
^{229}Th	7.92E–18	1.48E+00	1.60E+00	1.08

Sources: [a] From Table 6.4-4.

[b] Converted from Sv/s per Bq/m^3 to mrem/yr per pCi/cm^3 using soil density of 1.6 g/cm^3 and the unit conversion factor of 1.87 × 10^{17}, to compare the ERMYN values with RESRAD values.

[c] RESRAD (Yu et al. 2001 [DIRS 159465], Table A.1).

[d] The values of dose coefficients used in the ERMYN biosphere model are compliant with the regulatory requirement to use the dosimetric factors based on ICRP Publication 60 and are, therefore, different from the values used in RESRAD, which uses dosimetric factors based on earlier ICRP recommendations.

Table 7.4-2. Effective Dose Coefficients for Inhalation

Primary Radionuclide	ERMYN Absorption Type [a]	ERMYN Effective Dose Coefficient Sv/Bq [a]	ERMYN Effective Dose Coefficient mrem/pCi [b]	RESRAD Inhalation Class [c]	RESRAD Effective Dose Coefficient mrem/pCi [c]	Effective Dose Coefficient Ratio RESRAD/ ERMYN [d]
^{14}C	CO_2	6.24E–12	2.31E–08	CO_2	2.35E–08	1.02
^{36}Cl	S	3.80E–08	1.41E–04	W	2.19E–05	0.16
^{79}Se	S	6.77E–09	2.50E–05	W	9.84E–06	0.39
^{90}Sr	S	1.59E–07	5.86E–04	D	2.47E–04	0.42
^{99}Tc	S	1.33E–08	4.92E–05	W	8.33E–06	0.17
^{126}Sn	S	1.55E–07	5.75E–04	W	NA	NA
^{129}I	F	3.59E–08	1.33E–04	D	1.74E–04	1.31
^{135}Cs	S	8.53E–09	3.16E–05	D	4.55E–06	0.14
^{137}Cs	S	3.92E–08	1.45E–04	D	3.19E–05	0.22
^{242}Pu	F	1.13E–04	4.18E–01	W	4.11E–01	0.98
^{238}U	S	8.05E–06	2.98E–02	Y	1.18E–01	3.96
^{238}Pu	F	1.08E–04	4.00E–01	W	3.92E–01	0.98
^{234}U	S	9.40E–06	3.48E–02	Y	1.32E–01	3.80
^{230}Th	F	1.02E–04	3.77E–01	W	3.26E–01	0.86
^{226}Ra	S	9.54E–06	3.53E–02	W	8.60E–03	0.24
^{210}Pb	S	1.00E–05	3.70E–02	D	2.32E–02	0.63
^{240}Pu	F	1.19E–04	4.40E–01	W	4.29E–01	0.97
^{236}U	S	8.74E–06	3.23E–02	Y	1.25E–01	3.87
^{232}Th	F	1.10E–04	4.07E–01	W	1.64E+00	4.03
^{228}Ra	S	1.60E–05	5.93E–02	W	5.08E–03	0.09
^{232}U	S	3.70E–05	1.37E–01	Y	6.59E–01	4.81
^{228}Th	S	4.33E–05	1.60E–01	Y	3.45E–01	2.15
^{243}Am	F	9.57E–05	3.54E–01	W	4.40E–01	1.24
^{239}Pu	F	1.19E–04	4.40E–01	W	4.29E–01	0.97
^{235}U	S	8.47E–06	3.13E–02	Y	1.23E–01	3.92
^{231}Pa	F	2.30E–04	8.51E–01	W	1.28E+00	1.50
^{227}Ac	F	1.75E–04	6.47E–01	D	6.72E+00	10.38
^{241}Am	F	9.64E–05	3.57E–01	W	4.44E–01	1.24
^{237}Np	F	4.97E–05	1.84E–01	W	5.40E–01	2.94
^{233}U	S	9.59E–06	3.55E–02	Y	1.35E–01	3.80
^{229}Th	F	2.55E–04	9.44E–01	W	2.16E+00	2.29

Sources: [a] From Table 6.4-5.

[b] Converted from Sv/Bq to mrem/pCi using unit conversion factor of 3,700, to compare the ERMYN values with RESRAD values.

[c] RESRAD (Yu et al. 2001 [DIRS 159465], Table B.1).

[d] The values of dose coefficients used in the ERMYN biosphere model are compliant with the regulatory requirement to use the dosimetric factors based on ICRP Publication 60 and are, therefore, different from the values used in RESRAD, which uses dosimetric factors based on earlier ICRP recommendations.

Table 7.4-3. Effective Dose Coefficients for Ingestion

Primary Radionuclide	ERMYN			RESRAD		Effective Dose Coefficient Ratio RESRAD/ ERMYN [d]
	Fractional Uptake to Blood [a]	Effective Dose Coefficient		Fractional Uptake to Blood (f1) [c]	Effective Dose Coefficient mrem/pCi [c]	
		Sv/Bq [a]	mrem/pCi [b]			
^{14}C	1.E+00	5.81E–10	2.15E–06	1.E+00	2.09E–06	0.97
^{36}Cl	1.E+00	9.29E–10	3.44E–06	1.E+00	3.03E–06	0.88
^{79}Se	8.E–01	2.89E–09	1.07E–05	8.E–01	8.70E–06	0.81
^{90}Sr	3.E–01	3.04E–08	1.12E–04	3.E–01	1.53E–04	1.36
^{99}Tc	5.E–01	6.42E–10	2.38E–06	8.E–01	1.46E–06	0.61
^{126}Sn	2.E–02	5.15E–09	1.91E–05	2.E–02	NA	NA
^{129}I	1.E+00	1.06E–07	3.92E–04	1.E+00	2.76E–04	0.70
^{135}Cs	1.E+00	2.00E–09	7.40E–06	1.E+00	7.07E–06	0.96
^{137}Cs	1.E+00	1.36E–08	5.03E–05	1.E+00	5.00E–05	0.99
^{242}Pu	5.E–04	2.38E–07	8.81E–04	1.E–03	3.36E–03	3.82
^{238}U	2.E–02	4.79E–08	1.77E–04	5.E–02	2.69E–04	1.52
^{238}Pu	5.E–04	2.28E–07	8.44E–04	1.E–03	3.20E–03	3.79
^{234}U	2.E–02	4.95E–08	1.83E–04	5.E–02	2.83E–04	1.55
^{230}Th	5.E–04	2.14E–07	7.92E–04	2.E–04	5.48E–04	0.69
^{226}Ra	2.E–01	2.80E–07	1.04E–03	2.E–01	1.33E–03	1.28
^{210}Pb	2.E–01	1.91E–06	7.06E–03	2.E–01	7.27E–03	1.03
^{240}Pu	5.E–04	2.51E–07	9.29E–04	1.E–03	3.54E–03	3.81
^{236}U	2.E–02	4.69E–08	1.74E–04	5.E–02	2.69E–04	1.55
^{232}Th	5.E–04	2.31E–07	8.55E–04	2.E–04	2.73E–03	3.19
^{228}Ra	2.E–01	6.97E–07	2.58E–03	2.E–01	1.44E–03	0.56
^{232}U	2.E–02	3.36E–07	1.24E–03	5.E–02	1.31E–03	1.05
^{228}Th	5.E–04	1.43E–07	5.28E–04	2.E–04	8.08E–04	1.53
^{243}Am	5.E–04	2.04E–07	7.54E–04	1.E–03	3.63E–03	4.81
^{239}Pu	5.E–04	2.51E–07	9.29E–04	1.E–03	3.54E–03	3.81
^{235}U	2.E–02	4.70E–08	1.74E–04	5.E–02	2.67E–04	1.53
^{231}Pa	5.E–04	4.79E–07	1.77E–03	1.E–03	1.06E–02	5.98
^{227}Ac	5.E–04	4.36E–07	1.61E–03	1.E–03	1.48E–02	9.17
^{241}Am	5.E–04	2.04E–07	7.55E–04	1.E–03	3.64E–03	4.82
^{237}Np	5.E–04	1.08E–07	3.99E–04	1.E–03	4.44E–03	11.12
^{233}U	2.E–02	5.13E–08	1.90E–04	5.E–02	2.89E–04	1.52
^{229}Th	5.E–04	6.38E–07	2.36E–03	2.E–04	4.03E–03	1.71

Sources: [a] From Table 6.4-6.

[b] Converted from Sv/Bq to mrem/pCi using unit conversion factor of 3700, to compare the ERMYN values with RESRAD values.

[c] RESRAD (Yu et al. 2001 [DIRS 159465], Table D.1).

[d] The values of dose coefficients used in the ERMYN biosphere model are compliant with the regulatory requirement to use the dosimetric factors based on ICRP Publication 60 and are, therefore, different from the values used in RESRAD, which uses dosimetric factors based on earlier ICRP recommendations.

Table 7.4-4. Effective Dose Coefficients for Exposure to Contaminated Ground Surface

Primary radionuclide	Effective Dose Coefficients			Effective Dose Coefficient Ratio RESRAD/ ERMYN [d]
	ERMYN		RESRAD	
	Sv/s per Bq/m^2 [a]	mrem/y per pCi/cm^2 [b]	mrem/y per pCi/cm^2 [c]	
^{90}Sr	1.12E–16	1.30E–01	6.55E–03	0.05
^{99}Tc	6.49E–20	7.58E–05	9.11E–05	1.20
^{126}Sn	1.97E–15	2.30E+00	NA	NA
^{137}Cs	5.50E–16	6.42E–01	6.48E–01	1.01
^{242}Pu	4.98E–19	5.81E–04	7.79E–04	1.34
^{238}U	1.22E–16	1.42E–01	3.25E–02	0.23
^{238}Pu	6.26E–19	7.31E–04	9.79E–04	1.34
^{234}U	5.86E–19	6.84E–04	8.74E–04	1.28
^{230}Th	6.37E–19	7.44E–04	8.76E–04	1.18
^{226}Ra	1.69E–15	1.97E+00	1.94E+00	0.99
^{210}Pb	3.72E–17	4.35E–02	4.12E–03	0.09
^{240}Pu	6.01E–19	7.02E–04	9.38E–04	1.34
^{236}U	5.03E–19	5.87E–04	7.59E–04	1.29
^{232}Th	4.55E–19	5.31E–04	6.44E–04	1.21
^{228}Ra	9.38E–16	1.10E+00	1.08E+00	0.99
^{232}U	8.08E–19	9.43E–04	1.18E–03	1.25
^{228}Th	1.44E–15	1.68E+00	1.64E+00	0.98
^{243}Am	2.02E–16	2.36E–01	2.53E–01	1.07
^{239}Pu	2.84E–19	3.32E–04	4.29E–04	1.29
^{235}U	1.56E–16	1.82E–01	1.94E–01	1.07
^{231}Pa	3.78E–17	4.41E–02	4.75E–02	1.08
^{227}Ac	4.66E–16	5.44E–01	4.52E–01	0.83
^{241}Am	2.33E–17	2.72E–02	3.21E–02	1.18
^{237}Np	2.11E–16	2.47E–01	2.61E–01	1.06
^{233}U	6.00E–19	7.01E–04	8.36E–04	1.19
^{229}Th	3.46E–16	4.04E–01	3.72E–01	0.92

Sources: [a] From Table 6.5-1.

[b] Converted from Sv/s per Bq/m2 to mrem/yr per pCi/cm2 using the unit conversion factor of 1.17 × 1015, to compare the ERMYN values with RESRAD values.

[c] Source: RESRAD (Yu et al. 2001 [DIRS 159465], Table A.1).

[d] The values of dose coefficients used in the ERMYN biosphere model are compliant with the regulatory requirement to use the dosimetric factors based on ICRP Publication 60 and are, therefore, different from the values used in RESRAD, which uses dosimetric factors based on earlier ICRP recommendations.

7.4.2 Surface Soil Submodel

The surface soil submodel for the groundwater scenario is used to calculate the accumulation of radionuclides in cultivated soils after long-term irrigation. It is assumed that irrigation continues for a long period of time, up to 250 years for the gardens and up to 1,000 years for the fields. During this time, some radionuclides will reach equilibrium conditions in the surface soil. At the same time, if the soil is not disturbed by plowing, as could occur with perennial crops such as alfalfa, grapes, and fruit trees, radionuclides will build up in the thin layer of surface soil that is available for resuspension (critical thickness). The radionuclide concentration in this layer is then compared with the radionuclide concentration in the surface soil and the greater of the two is used in the pathways that involve the surface layer of the soil, such as the inhalation of resuspended soil particles, inadvertent soil ingestion by people and animals, and deposition on crop surfaces. Radionuclide uptake by crops through their roots and radon exhalation from the soil is calculated using the radionuclide concentration in the surface soil, down to the tillage depth.

An evaluation was conducted (Section 7.4.2.1) to verify radionuclide concentrations in the surface soil and in the resuspendable soil layer, and to compare them with the equilibrium concentrations in the surface soil. In addition, the radionuclide decay chains in the ERMYN were compared with those in the GENII-S model to evaluate whether the results are comparable, and to ensure that the ERMYN includes all of the important radionuclides (Section 7.4.2.2).

7.4.2.1 Fraction of Equilibrium and Time Required to Establish Equilibrium Radionuclide Concentration in Soil

Radionuclide concentrations in the surface soil and in the resuspendable soil layer were calculated and compared with the equilibrium concentrations in the surface soil. These calculations were performed deterministically, using a modified version of the model verification Excel spreadsheet referred to in Section 6 (Excel file *ERMYN Validation_Soil Model.xls*, Appendix A). The results are presented in Table 7.4-5. The shaded cells in Table 7.4-5 contain the greater of the surface soil and the critical thickness concentrations. The shading in a given cell does not necessarily mean that the same selection would be made in the GoldSim model, especially for the values that are comparable. This is because the deterministic calculations used representative values, which in many cases are not equal to the mean of the distribution. The results in Table 7.4-5 indicate that radionuclide concentrations in garden soil are between 0.13 and 1.00 of the equilibrium concentration, depending on the radionuclide. For the field soil, the fractions of equilibrium are between 0.42 and 1.00, depending on the radionuclide. The time that is needed to reach 95% of the equilibrium concentration is presented in Table 7.4-6. As discussed in Section 6.4.1, the time required to reach 95% equilibrium can be calculated using the effective removal rate constant. The effective removal is controlled mainly by a leaching constant (Equation 6.4.1-28), unless the leaching removal rate constant is less than the erosion removal rate constant (1.3×10^{-3} 1/yr), which corresponds to a partition coefficient value of about 140 L/kg (Table 7.4-5). All radionuclides reach the 95% equilibrium concentrations in less than 2,200 years. If uncertainties in the partition coefficients and erosion rates are considered, variation in the leaching removal rate constants could be large. However, when the leaching rate is low, erosion is a more important removal process.

Table 7.4-5. Radionuclide Concentrations in Garden and Field Soil and Fractions of Equilibrium Concentrations for Average Irrigation Duration

Primary Radionuclide	Decay Products	Gardens, Surface Soil			Fields, Surface Soil			Critical Thickness	
		Concentration[a] Bq/kg	Equilibrium Concentration Bq/kg	Fraction of Equilibrium	Concentration[b] Bq/kg	Equilibrium Concentration Bq/kg	Fraction of Equilibrium	Equilibrium Concentration in Garden Soil Bq/kg	Equilibrium Concentration in Field Soil Bq/kg
^{14}C		1.10E–04	1.10E–04	1.00	2.16E–04	2.16E–04	1.00	7.82E–03	1.09E–02
^{36}Cl		3.14E–03	3.14E–03	1.00	6.15E–03	6.15E–03	1.00	2.75E–04	2.75E–04
^{79}Se		2.12E–01	8.87E–01	0.24	1.15E+00	1.73E+00	0.67	1.40E–01	1.45E–01
^{90}Sr		6.62E–02	6.82E–02	0.97	1.33E–01	1.33E–01	1.00	2.00E–02	2.02E–02
^{99}Tc		3.14E–03	3.14E–03	1.00	6.15E–03	6.15E–03	1.00	2.75E–04	2.75E–04
^{126}Sn		2.22E–01	1.34E+00	0.17	1.35E+00	2.62E+00	0.51	3.63E–01	4.02E–01
^{129}I		5.14E–02	5.19E–02	0.99	1.01E–01	1.01E–01	1.00	4.66E–03	4.66E–03
^{135}Cs		2.27E–01	1.76E+00	0.13	1.46E+00	3.44E+00	0.42	1.29E+00	1.97E+00
^{137}Cs		9.05E–02	9.91E–02	0.91	1.94E–01	1.94E–01	1.00	1.17E+00	1.83E+00
^{242}Pu		2.09E–01	7.98E–01	0.26	1.10E+00	1.56E+00	0.70	9.51E–01	1.28E+00
^{238}U		1.69E–01	3.16E–01	0.54	5.89E–01	6.17E–01	0.95	3.28E–02	3.31E–02
^{238}Pu		1.57E–01	2.58E–01	0.61	4.93E–01	5.04E–01	0.98	7.13E–01	8.92E–01
^{234}U		1.69E–01	3.15E–01	0.54	5.88E–01	6.17E–01	0.95	3.28E–02	3.31E–02
	^{230}Th	8.17E–05	2.01E–03	0.04	1.24E–03	3.93E–03	0.31	1.10E–06	8.20E–07
	^{226}Ra	1.21E–06	4.91E–04	0.00	7.51E–05	9.61E–04	0.08	2.73E–09	1.94E–09
^{230}Th		2.26E–01	1.72E+00	0.13	1.45E+00	3.36E+00	0.43	1.14E+00	1.63E+00
	^{226}Ra	4.73E–03	4.20E–01	0.01	1.09E–01	8.21E–01	0.13	2.80E–03	3.86E–03
	^{210}Pb	2.61E–03	4.02E–01	0.01	9.19E–02	7.87E–01	0.12	4.03E–04	5.12E–04
^{226}Ra		2.22E–01	1.37E+00	0.16	1.36E+00	2.68E+00	0.51	1.73E+00	3.23E+00
	^{210}Pb	1.53E–01	1.31E+00	0.12	1.23E+00	2.57E+00	0.48	2.48E–01	4.29E–01
^{210}Pb		7.19E–02	7.48E–02	0.96	1.46E–01	1.46E–01	1.00	1.40E+00	2.53E+00
^{240}Pu		2.24E–01	1.50E+00	0.15	1.40E+00	2.94E+00	0.48	7.26E–01	9.03E–01
^{236}U		1.69E–01	3.15E–01	0.54	5.89E–01	6.17E–01	0.95	3.28E–02	3.31E–02
^{232}Th		2.26E–01	1.73E+00	0.13	1.45E+00	3.38E+00	0.43	1.14E+00	1.63E+00
	^{228}Ra	2.07E–01	1.71E+00	0.12	1.41E+00	3.34E+00	0.42	4.63E–01	6.49E–01
	^{228}Th	2.00E–01	1.70E+00	0.12	1.40E+00	3.33E+00	0.42	2.67E–01	3.24E–01

Table 7.4-5. Radionuclide Concentrations in Garden and Field Soil and Fractions of Equilibrium Concentrations for Average Irrigation Duration (Continued)

Primary Radionuclide	Decay Products	Gardens, Surface Soil			Fields, Surface Soil			Critical Thickness	
		Concentration [a] Bq/kg	Equilibrium Concentration Bq/kg	Fraction of Equilibrium	Concentration [b] Bq/kg	Equilibrium Concentration Bq/kg	Fraction of Equilibrium	Equilibrium Concentration in Garden Soil Bq/kg	Equilibrium Concentration in Field Soil Bq/kg
^{228}Ra		1.99E–02	1.99E–02	1.00	3.89E–02	3.89E–02	1.00	1.03E+00	1.95E+00
	^{228}Th	1.98E–02	1.98E–02	1.00	3.88E–02	3.88E–02	1.00	5.91E–01	9.76E–01
^{232}U		1.15E–01	1.40E–01	0.82	2.74E–01	2.74E–01	1.00	3.27E–02	3.31E–02
	^{228}Th	1.14E–01	1.40E–01	0.81	2.73E–01	2.73E–01	1.00	1.88E–02	1.65E–02
^{228}Th		6.67E–03	6.67E–03	1.00	1.31E–02	1.31E–02	1.00	4.82E–01	8.18E–01
^{243}Am		2.25E–01	1.58E+00	0.14	1.42E+00	3.10E+00	0.46	9.56E–01	1.29E+00
	^{239}Pu	3.16E–04	2.97E–02	0.01	7.34E–03	5.80E–02	0.13	6.59E–05	5.64E–05
^{239}Pu		2.25E–01	1.58E+00	0.14	1.42E+00	3.09E+00	0.46	7.26E–01	9.03E–01
^{235}U		1.69E–01	3.16E–01	0.54	5.89E–01	6.17E–01	0.95	3.28E–02	3.31E–02
	^{231}Pa	1.92E–04	4.54E–03	0.04	2.88E–03	8.87E–03	0.32	2.08E–06	1.42E–06
	^{227}Ac	1.10E–04	4.34E–03	0.03	2.51E–03	8.48E–03	0.30	1.66E–07	7.64E–08
^{231}Pa		2.26E–01	1.65E+00	0.14	1.44E+00	3.23E+00	0.44	9.08E–01	1.20E+00
	^{227}Ac	1.55E–01	1.58E+00	0.10	1.29E+00	3.08E+00	0.42	7.24E–02	6.47E–02
^{227}Ac		7.02E–02	7.29E–02	0.96	1.43E–01	1.43E–01	1.00	7.60E–01	1.00E+00
^{241}Am		2.25E–01	1.61E+00	0.14	1.43E+00	3.14E+00	0.45	7.26E–01	9.03E–01
^{237}Np		1.55E–01	2.50E–01	0.62	4.79E–01	4.89E–01	0.98	2.50E–02	2.51E–02
^{233}U		1.69E–01	3.15E–01	0.54	5.88E–01	6.17E–01	0.95	3.28E–02	3.31E–02
	^{229}Th	8.55E–04	1.99E–02	0.04	1.28E–02	3.89E–02	0.33	1.16E–05	8.60E–06
^{229}Th		2.25E–01	1.62E+00	0.14	1.43E+00	3.17E+00	0.45	1.14E+00	1.63E+00

[a] Calculated assuming 100 years of prior irrigation (average of the distributions).

[b] Calculated assuming 400 years of prior irrigation (average of the distributions).

Source: Calculations were done in Excel file *ERMYN Validation_Soil Model.xls* (Appendix A).

NOTES: The shaded cells contain the greater of the surface soil and the critical thickness concentrations.
Indented radionuclides are decay products of primary radionuclides.

Table 7.4-6. Time to Reach 95% Equilibrium in Surface Soil for Primary Radionuclides

Primary Radionuclide	Radioactive Decay Constant 1/yr	Erosion Removal Rate Constant 1/yr	Partition Coefficient L/kg	Leaching Removal Rate Constant 1/yr	Effective Removal Rate Constant 1/yr	Equilibrium Time at 95% yr
^{14}C	1.21E–04	5.33E–04	1.8E+01	1.2E–02	22 [a]	1
^{36}Cl	2.30E–06	5.33E–04	1.4E–01	7.7E–01	7.71E–01	4
^{79}Se	6.10E–07	5.33E–04	1.5E+02	1.4E–03	1.94E–03	1,094
^{90}Sr	2.38E–02	5.33E–04	2.0E+01	1.0E–02	3.48E–02	84
^{99}Tc	3.25E–06	5.33E–04	1.4E–01	7.7E–01	7.71E–01	4
^{126}Sn	6.93E–06	5.33E–04	4.5E+02	4.7E–04	1.01E–03	1,657
^{129}I	4.41E–08	5.33E–04	4.5E+00	4.5E–02	4.60E–02	64
^{135}Cs	3.01E–07	5.33E–04	4.4E+03	4.8E–05	5.82E–04	2,168
^{137}Cs	2.31E–02	5.33E–04	4.4E+03	4.8E–05	2.37E–02	122
^{242}Pu	1.84E–06	5.33E–04	1.2E+03	1.8E–04	7.11E–04	1,983
^{238}U	1.55E–10	5.33E–04	3.3E+01	6.4E–03	6.89E–03	389
^{238}Pu	7.90E–03	5.33E–04	1.2E+03	1.8E–04	8.61E–03	318
^{234}U	2.83E–06	5.33E–04	3.3E+01	6.4E–03	6.89E–03	389
^{230}Th	9.00E–06	5.33E–04	3.0E+03	7.0E–05	6.13E–04	2,121
^{226}Ra	4.33E–04	5.33E–04	3.6E+04	5.9E–06	9.72E–04	1,690
^{210}Pb	3.11E–02	5.33E–04	1.6E+04	1.3E–05	3.16E–02	92
^{240}Pu	1.06E–04	5.33E–04	1.2E+03	1.8E–04	8.15E–04	1,855
^{236}U	2.96E–08	5.33E–04	3.3E+01	6.4E–03	6.89E–03	389
^{232}Th	4.93E–11	5.33E–04	3.0E+03	7.0E–05	6.04E–04	2,134
^{228}Ra	1.21E–01	5.33E–04	3.6E+04	5.9E–06	1.21E–01	25
^{232}U	9.63E–03	5.33E–04	3.3E+01	6.4E–03	1.65E–02	173
^{228}Th	3.62E–01	5.33E–04	3.0E+03	7.0E–05	3.63E–01	8
^{243}Am	9.39E–05	5.33E–04	2.0E+03	1.1E–04	7.33E–04	1,955
^{239}Pu	2.88E–05	5.33E–04	1.2E+03	1.8E–04	7.38E–04	1,948
^{235}U	9.85E–10	5.33E–04	3.3E+01	6.4E–03	6.89E–03	389
^{231}Pa	2.12E–05	5.33E–04	1.8E+03	1.2E–04	6.72E–04	2,036
^{227}Ac	3.18E–02	5.33E–04	1.5E+03	1.4E–04	3.25E–02	90
^{241}Am	1.60E–03	5.33E–04	2.0E+03	1.1E–04	2.24E–03	985
^{237}Np	3.24E–07	5.33E–04	2.5E+01	8.4E–03	8.29E–03	308
^{233}U	4.37E–06	5.33E–04	3.3E+01	6.4E–03	6.90E–03	389
^{229}Th	9.44E–05	5.33E–04	3.0E+03	7.0E–05	6.98E–04	2,000

Sources: Calculations were performed using Excel (ERMYN Validation_Soil Model.xls listed in Appendix A). Columns 2 and 4 are based on the data from Tables 6.3-7 and 6.6-3, respectively. Column 3 is calculated using Equation 6.4.1-32. Column 5 is calculated using Equation 6.4.1-28. The last two columns are calculated using the method provided in Section 6.4.1.1. All input data are taken from Table 6.6-3; erosion rate was taken at its mean value.

[a] This value is the ^{14}C emission rate constant (Table 6.6-3).

7.4.2.2 Comparison of Radionuclide Decay Chains in GENII and ERMYN

When radionuclide decay and ingrowth are modeled, decay chains often are evaluated to determine where the chains approximately stop, permitting the calculations to be terminated and the computational problem to be simplified. This is especially true for the transuranic radionuclides with long-decay chains. The only decay and ingrowth included in the ERMYN is related to radionuclide buildup in the soil, where radionuclide decay chains are included in the surface soil submodel (Section 6.4.1.2). In this section, radionuclide decay chains in the GENII and ERMYN are compared to determine if all of the decay products are properly considered.

A data file, *RMDLIB.DAT* (Appendix A), is used in the GENII-S model [DIRS 117076] to control radionuclide decay chains. Part of this data file is shown in the GENII-S manual (Leigh et al. 1993 [DIRS 100464], p. 5-69). Only the high atomic number (Z greater than or equal to 82) radionuclides are compared. Comparisons are made for each high-Z primary radionuclide and associated decay chain (Table 7.4-7). The comparison indicates that the two models use similar methods to control the decay chains, and, therefore, the radionuclide decay chains are properly considered in the ERMYN.

Table 7.4-7. Radionuclide Decay Chains Included in the GENII Model and ERMYN

Primary Radionuclide	GENII [a]	ERMYN [b]	Notes
^{242}Pu	No decay chain	No decay chain	Same
^{238}U	Decay chain: ^{234}Th (^{234m}Pa) / ^{234}Pa	^{238}U D	Same
^{238}Pu	Decay chain: ^{234}U	No decay chain	Low contribution from ingrowth of ^{234}U due to long half-life
^{234}U	No decay chain	Decay chain: ^{230}Th / ^{226}Ra D / ^{210}Pb D	ERMYN includes the decay chain, which adds a small contribution from the decay products
^{230}Th	Decay chain: ^{226}Ra / ^{222}Rn (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po) / ^{210}Pb / ^{210}Bi / ^{210}Po	Decay chain: ^{226}Ra D / ^{210}Pb D	Equivalent
^{226}Ra	Decay chain: ^{222}Rn (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po) / ^{210}Pb / ^{210}Bi / ^{210}Po	Decay chain: ^{226}Ra D / ^{210}Pb D	Equivalent
^{210}Pb	Decay chain: ^{210}Pb / ^{210}Bi / ^{210}Po	^{210}Pb D	Equivalent
^{240}Pu	Decay chain: ^{236}U	No decay chain	Equivalent
^{236}U	No decay chain	No decay chain	Same
^{232}Th	Decay chain: ^{228}Ra / ^{228}Ac / ^{228}Th / ^{224}Ra (^{220}Rn, ^{216}Po) / ^{212}Pb / ^{212}Bi	Decay chain: ^{228}Ra D / ^{228}Th D	Equivalent
^{228}Ra	Decay chain: ^{228}Ac / ^{228}Th / ^{224}Ra (^{220}Rn, ^{216}Po) / ^{212}Pb / ^{212}Bi	Decay chain: ^{228}Ra D / ^{228}Th D	Equivalent
^{232}U	Decay chain: ^{228}Th / ^{224}Ra (^{220}Rn, ^{216}Po) / ^{212}Pb / ^{212}Bi	Decay chain: ^{228}Th D	Equivalent
^{228}Th	Decay chain: ^{224}Ra (^{220}Rn, ^{216}Po) / ^{212}Pb / ^{212}Bi	^{228}Th D	Equivalent
^{243}Am	Decay chain: ^{239}Np / ^{239}Pu	Decay chain: ^{243}Am D / ^{239}Pu	Same
^{239}Pu	No decay chain	No decay chain	Same
^{235}U	Decay chain: ^{231}Th / ^{231}Pa / ^{227}Ac / ^{227}Th / ^{223}Fr / ^{223}Ra (^{219}Rn, ^{215}Po, ^{211}Pb, ^{211}Bi, ^{207}Tl)	Decay chain: ^{235}U D / ^{231}Pa / ^{227}Ac D	Equivalent
^{231}Pa	Decay chain: ^{227}Ac / ^{227}Th / ^{223}Fr / ^{223}Ra (^{219}Rn, ^{215}Po, ^{211}Pb, ^{211}Bi, ^{207}Tl)	Decay chain: ^{227}Ac D	Equivalent
^{227}Ac	Decay chain: ^{227}Th / ^{223}Fr / ^{223}Ra (^{219}Rn, ^{215}Po, ^{211}Pb, ^{211}Bi, ^{207}Tl)	^{227}Ac D	Equivalent

Table 7.4-7. Radionuclide Decay Chains Included in the GENII Model and ERMYN (Continued)

Primary Radionuclide	GENII [a]	ERMYN [b]	Notes
^{241}Am	Decay chain: ^{237}Np / ^{233}Pa	No decay chain	Low contribution from ^{237}Np, due to long half-life
^{237}Np	Decay chain: ^{233}Pa	^{237}Np D	Same
^{233}U	Decay chain: ^{229}Th / ^{225}Ra / ^{225}Ac (^{221}Fr, ^{217}At, ^{213}Bi, ^{213}Po, ^{209}Tl, ^{209}Pb)	Decay chain: ^{229}Th D	Equivalent
^{229}Th	Decay chain: ^{225}Ra / ^{225}Ac (^{221}Fr, ^{217}At, ^{213}Bi, ^{213}Po, ^{209}Tl, ^{209}Pb)	^{229}Th D	Equivalent

[a] Decay products in parenthesis are short-lived and considered in a secular equilibrium with the parent radionuclides; the long-lived members of the decay chain are separated by a slash (/). From file *RMDLIB.DAT* in Appendix A.

[b] "D" indicates that a short-lived (half-life less than 180 d) decay products are considered together with the primary radionuclide (Section 6.3.5 and Table 6.4-1).

7.4.3 Air Submodel

The GENII model does not include inhalation dose contributions from radon decay products and radioactive aerosols generated by evaporative coolers. Therefore, the importance of these pathways is evaluated to determine if they warrant inclusion in ERMYN. In addition, a numerical comparison of an ACM for calculating the dose contribution from inhalation of decay products of ^{222}Rn (ACM 1, Sections 6.3.3 and 7.3.2.2) is documented in this section.

7.4.3.1 Radon Pathway

The contribution of ^{222}Rn to the total dose from ^{226}Ra was evaluated (Table 7.4-8). For the groundwater and volcanic ash scenarios, 74% and 33%, respectively, of the ^{226}Ra dose is from ^{222}Rn inhalation (Table 7.4-8). The ERMYN includes this pathway because the dose contribution from ^{222}Rn is high. It should be noted that the factor of two lower fractional contribution of ^{222}Rn to the ^{226}Ra dose for the volcanic scenario, relative to the groundwater scenario, is due to a greater contribution of the external exposure pathway. For the volcanic scenario, the contaminants are assumed to be located at the ground surface and their radiations are unattenuated, which is not the case for the groundwater scenario.

Table 7.4-8. Radon Contribution to the ^{226}Ra Dose

Scenario	% Contribution to BDCF from ^{222}Rn	
	^{226}Ra	^{230}Th
Groundwater [a]	73.7	8.4
Volcanic Ash [b]	33.2 [c]	0.0

[a] Data from Table 6.13-1.

[b] Data from Table 6.14-1.

[c] This value represents the BDCF component for external exposure, ingestion, and inhalation of radon decay products.

The method for assessing concentration of ^{222}Rn in the air is based on a release factor, i.e., the ratio of the average concentration of ^{222}Rn in the air (Bq/m^3) and the average concentration of ^{226}Ra in the soil (Bq/kg for groundwater scenario, Section 6.4.2.3; Bq/m^2 for volcanic ash scenario, Section 6.5.2.2). This ERMYN method is different from the RESRAD radon diffusion method (Yu et al. 2001 [DIRS 159465], Appendix C; see also Section 7.3.2.2). The RESRAD method is considered an ACM (Section 6.3.3). According to the model validation approach, a numerical comparison between these two methods is required. The detailed analytical solution for radon diffusion is discussed in Appendix B. The general differential equation and the boundary conditions given in RESRAD are solved using the ERMYN input parameter values or RESRAD default parameter values if the parameters are not included in ERMYN. The ^{222}Rn release factor for volumetric ^{226}Ra in the soil is 0.15 (Bq/m^3)/(Bq/kg) (Table B-1) (see calculations in Excel file *ERMYN Validation.xls*, worksheet *Radon Diffusion*, Appendix A). This value is comparable to the ERMYN value, which is 0.25 (Bq/m^3)/(Bq/kg) for the groundwater scenario (Section 6.4.2.3).

To compare ^{222}Rn release factors for the volcanic scenario, the amount of ^{222}Rn released into air from a thin contaminated layer on the ground surface must be calculated. This calculation is documented in Appendix B, and the results (Table 7.4-9) are taken from Table B-2.

Table 7.4-9. Radon Release Factors Due to Radium Contaminated Soil

Depth of Contaminant m	Source Exponential Term	^{222}Rn Release Factor (Bq/m^3)/(Bq/kg)	Surface Soil Density kg/m^2	^{222}Rn Release Factor (Bq/m^3)/(Bq/m^2)
0.003	0.0031	4.47E–04	4.5	0.00010
0.01	0.0102	1.49E–03	15	0.00010
0.02	0.0205	2.98E–03	30	0.00010
0.05	0.0512	7.44E–03	75	0.00010
0.1	0.1021	1.48E–02	150	0.00010
0.2	0.2020	2.94E–02	300	0.00010
0.5	0.4716	6.86E–02	750	0.00009
1	0.7716	1.12E–01	1,500	0.00007
2	0.9673	1.41E–01	3,000	0.00005
5	0.9999	1.45E–01	7,500	0.00002
10	1.0000	1.45E–01	15,000	0.00001

Source: This table is taken from Appendix B, Table B-2.

Compared with the ERMYN radon release factor for the volcanic ash scenario, 0.0006 (Bq/m^3)/(Bq/m^2) (Section 6.5.2.2), the calculated result for a thin layer of contaminated soil, 0.00010 (Bq/m^3)/(Bq/m^2), is 6 times lower than the ERMYN value. The difference is due to the assumption that all radon produced in the soil from contaminated volcanic ash is exhaled into the air (Assumption 15), which involves the radon emanation coefficient (ε) equal to 1 and no losses during radon transport in soil. The default coefficient for soil used in the RESRAD calculation is 0.25 (Table B-1). The higher ERMYN value accounts for the possible differences in the radon emanation properties of contaminated media (soil versus volcanic ash) and the geometry (volume versus surface contamination). If a coefficient of 1 were used in RESRAD, the calculated radon release factor would be 0.0004 (Bq/m^3)/(Bq/m^2), which is 33% lower than the value used in ERMYN.

In conclusion, the ERMYN radon release factors for the groundwater and volcanic ash scenarios, 0.25 (Bq/m^3)/(Bq/kg) and 0.0006 (Bq/m^3)/(Bq/m^2), respectively, are within a factor of 2 of the

RESRAD values for the two scenarios, 0.15 (Bq/m^3)/(Bq/kg) and 0.0004 (Bq/m^3)/(Bq/m^2), respectively. Because, the radon pathway contributes significantly to the inhalation dose from ^{226}Ra, it should be included in the ERMYN model. The selected radon model is simple and valid, and ACM 1 (Section 6.3.3) does not need further consideration for comparable input values.

Another isotope of radon, ^{220}Rn, is a member of the ^{228}Th decay chain, which contains its parent, ^{224}Ra. The following evaluation is used to estimate the potential contribution to BDCFs from inhalation of ^{220}Rn (commonly referred to as thoron).

- Typical concentration of ^{232}Th in soil is 30 Bq/kg (UNSCEAR 2000 [DIRS 158644], p. 90).
- Typical concentration of ^{220}Rn (thoron) in air indoors and outdoors is 10 Bq/m^3 (UNSCEAR 2000 [DIRS 158644], p. 108).
- Thoron release factor is thus 0.33 Bq/m^3 per Bq/kg (comparable to that of ^{222}Rn).
- Typical equilibrium equivalent concentration (EEC) of ^{220}Rn in outdoor air is 0.1 Bq/m^3; typical equilibrium equivalent concentration of ^{220}Rn indoors is 0.3 Bq/m^3 (this is for the typical ^{220}Rn gas concentration of 10 Bq/m^3) (UNSCEAR 2000 [DIRS 158644], p. 108).
- When the water containing 1 Bq/m^3 of ^{232}Th (^{220}Rn is in the decay chain of and can be considered in equilibrium with ^{232}Th) is used for irrigation, the concentration of this radionuclide in the soil is about 0.226 Bq/kg for the gardens and 1.45 Bq/kg for the fields (Excel file *ERMYN Validation _Soil Model*, worksheet *Th-232*). Using the garden concentration for the indoor exposure and the field concentration of the outdoor exposure and scaling these concentrations in relation to the typical concentration of ^{232}Th in the soil of 30 Bq/kg, the EEC levels of this radionuclide would be 4.8×10^{-3} Bq/m^3 outdoors and 2.3×10^{-3} Bq/m^3 indoors.
- The EEC can be converted to annual dose from inhalation of thoron decay products using the RMEI's 1.9 h outdoor and 17.75 h of indoor exposure time as (based on UNSCEAR 2000 [DIRS 158644], p. 108):

  4.8×10^{-3} Bq/m^3 (EEC) × 1.9 h/d × 365 d/yr × 40 nSv/(Bq/m^3 h) = 1.3×10^{-7} Sv/yr (outdoors)

  2.3×10^{-3} Bq/m^3 (EEC) × 17.75 h/d × 365 d/yr × 40 nSv/(Bq/m^3 h) = 5.9×10^{-7} nSv/yr (indoors)

- The annual dose from inhalation of thoron decay products of 7.2×10^{-7} Sv can be compared with the BDCF for ^{232}Th (including ^{228}Ra and ^{228}Th) equal to 3.1×10^{-6} Sv/yr per Bq/m^3 (Table 6.11-8). The contribution from inhalation of ^{220}Rn decay products is about 20% of the BDCF for ^{232}Th, much less than the contribution of ^{222}Rn to the BDCF for ^{226}Ra.

As noted in Section 6.4.2.2, ^{222}Rn released from evaporative coolers is not considered in the air submodel because the amount of radon released from the water would be relatively low compared to that released from soils. The ^{222}Rn in the groundwater used in evaporative coolers would be in equilibrium with ^{226}Ra. The ratio of the ^{222}Rn concentration in the air to the ^{226}Ra concentration in the water, assuming that ^{222}Rn concentration in water is at secular equilibrium with ^{226}Ra concentration, is on the order of 10^{-6} for the evaporation rate of 20 L/h and the air flow rate of 8,000 m^3/h. This ratio is lower than a typical value of 10^{-4} for radon dissolved in water entering indoor air through de-emanation (UNSCEAR 2000 [DIRS 158644], p. 102).

Radon concentrations in indoor air resulting from water use (other than in evaporative coolers) can be estimated based on the rates of water use and house ventilation. A typical radon release ratio between the concentration of ^{222}Rn in the air and the concentration of ^{226}Ra in the water is about 1×10^{-4} (Yu et al. 2001 [DIRS 159465], p. C-13; UNSCEAR 2000 [DIRS 158644], p. 102). This value can be verified using:

$$\frac{Ca_{g,Rn-222}}{Cw_{Ra-226}} = \frac{f_{wa} U_w}{(\lambda_{Rn-222} + v)V} \qquad \text{(Eq. 7.4.3-1)}$$

where

f_{wa} = transfer efficiency of radon from water to air (dimensionless)

U_w = household water use rate (L/h)

λ_{Rn-222} = decay constant of ^{222}Rn (0.0076/h)

v = house ventilation rate (1/h)

V = volume of the house (L).

Using typical values suggested in RESRAD, $f_{wa} = 0.55$, $U_w = 9.5$ L/h for each individual (assuming 4 people in a household), $V = 75{,}000$ L, $v = 1$/h (when evaporative coolers are not in operation), and $\lambda_{Rn-222} = 0.0076$/h (Yu et al. 2001 [DIRS 159465], p. C-15), the concentration ratio of ^{222}Rn in the air to ^{226}Ra in the water can be calculated as 2.8×10^{-4}. Equation 7.4.3-1 can also apply to a room, such as a bathroom, where water use would be high. Using values for a shower, $f_{wa} = 0.7$, $U_w = 300$ L/h, $v \times V = 0.13$ m^3/min = 7,800 L/h (McKone and Bogen 1992 [DIRS 160440], p. 93; McKone and Daniels 1991 [DIRS 160441], p. 50), the ratio in Equation 7.4.3-1 for a shower would be 0.027, which is two orders of magnitude higher than that for the house. (This ratio was calculated using a ventilation rate of 1 air exchange per hour. For a typical bathroom, the ventilation rate would be about an order of magnitude higher and the corresponding levels of ^{222}Rn much lower.) A typical shower lasts for only about 10 min, while a person typically spends more than 8 h/d in the house. Therefore, a 10 min shower may cause only twice as much radon exposure as would 8 h of home occupancy due to radon released from domestic use of water.

A typical outdoor radon concentration over soil contaminated by the long-term use of irrigation water was estimated at about 0.06 Bq/m^3 for the gardens and 0.4 Bq/m^3 for the fields. The indoor concentration for ^{222}Rn are 1.0 Bq/m^3 and 1.9 Bq/m^3 with and without evaporative coolers, respectively (Excel file *ERMYN Verification.xls*, Appendix A). This implies the concentration ratios of ^{222}Rn in the air to ^{226}Ra in the contaminated irrigation water of about 0.06 to 1.9 (the higher values are for the indoor conditions, where people spend most of their time; Table 6.6-3). These ratios are higher than the ratios for radon dissolved in water entering indoor air (10^{-4} to 10^{-3}) and for radon released by evaporative coolers (10^{-6}), which are discussed in Section 6.4.2.2. Therefore, it is reasonable to ignore the indoor radon contributions from the use of contaminated household water and evaporative coolers because the radon exposure from contaminated soil is several orders of magnitude higher.

7.4.3.2 Evaporative Cooler Pathway

ERMYN includes an inhalation pathway that evaluates the annual dose from inhalation of radioactive aerosols generated by evaporative coolers. This is accomplished by using a submodel based on the mechanical operation of an evaporative cooler (Section 6.4.2.2). To validate this submodel, it is compared with an alternative method based on the difference between absolute humidity values in indoor and outdoor air caused by evaporative coolers (Table 7.4-10).

The results from the two methods differ by a factor of 2 (Table 7.4-10), which meets the validation criteria for numerical similarity, and the selected method is valid. This difference can be explained by analyzing the quantity of water introduced into the indoor air by an evaporative cooler. For the water usage and airflow that is characteristic of the coolers in Amargosa Valley, the water concentration in the air added by a cooler is 17 L/h ÷ 8,300 m^3/h = 2.0 g/m^3. To increase the relative humidity of the indoor air to 40%, a value assumed in the ACM, the added concentration of water ($D_{in} - D_{out}$ in equation shown in Table 7.4-10) is 3.9 g/m^3, a factor of 2 greater. There is less uncertainty in defining the operating parameters of evaporative coolers, such as air flow rate and water evaporation rate, than required to quantify temporal variation in absolute humidity values. This evaluation indicates that ACM 2 (Section 6.3.3) does not need further consideration, and the chosen method is valid.

Table 7.4-10. Comparison of Evaporative Cooler Model

Model	ERMYN			Alternative		
Equation	$Ca_e = f_{evap} \frac{M_{water}}{F_{air}} Cw$			$Ca = \frac{f_{evap}\,(D_{in} - D_{out})\; Cw}{\rho_w}$		
Parameter	Notation	Value	Units	Notation	Value	Units
Release fraction	f_{evap}	0.5	—	f_{evap}	0.5	—
Concentration in water	Cw	1	Bq/m^3	Cw	1	Bq/m^3
Water evaporation rate	M_{water}	17	L/h	—	—	—
Air flow rate	F_{air}	8,300	m^3/h	—	—	—
Absolute humidity (outdoors)	—	—	—	D_{out}	4.8	g/m^3
Absolute humidity (indoors)	—	—	—	D_{in}	8.7	g/m^3

Table 7.4-10. Comparison of Evaporative Cooler Model (Continued)

Model	ERMYN			Alternative		
Equation	$Ca_e = f_{evap} \frac{M_{water}}{F_{air}} Cw$			$Ca = \frac{f_{evap}\ (D_{in} - D_{out})\ Cw}{\rho_w}$		
Parameter	Notation	Value	Units	Notation	Value	Units
Water density	—	—	—	ρ_w	1,000	kg/m^3
Concentration in air	Ca_e	1.0E–6	Bq/m^3	Ca_e	2.0E–6	Bq/m^3

NOTE: Outdoor absolute humidity is representative of conditions at Yucca Mountain Weather Station #9 (Gate-510; CRWMS M&O 1997 [DIRS 100117] p. A-9), and indoor absolute humidity is based on 24ºC and 40% relative humidity. The calculation of absolute humidity from relative humidity and temperature is documented in Appendix C. All other values from the "mean, mode, average" column in Table 6.6-3.

7.4.4 Plant Uptake Submodel

Three numerical comparisons (direct deposition of irrigation water on crop surfaces, crop interception fraction for irrigation water, and direct deposition of resuspended soil on crop surfaces) are required to validate the plant submodel (Section 7.3.3). These comparisons are discussed in this section.

7.4.4.1 Direct Deposition of Irrigation Water on Crop Surfaces

The methods in the ERMYN (Section 6.4.3.2) and BIOMASS ERB2A (Section 7.3.3.2) models for calculating concentrations from the direct deposition of irrigation water on crop surfaces are compared (Table 7.4-11). The results indicate that the two methods could differ by a factor of two. Some input parameters in the BIOMASS ERB2A model (e.g., absorption fraction and interval time) are not commonly used in the validation models, but they have a large influence on the results of the model. For example, the absorption fraction, which is 0.5 in BIOMASS ERB2A, is a high value for leaf water absorption (this value quantifies the fraction of externally deposited activity that is absorbed internally and incorporated into plant tissues). If a lower, perhaps more realistic, value is used (e.g., 0.3), the differences between the two models would be even smaller. The fraction of radionuclides that transfer from irrigation water to crops can be estimated using data in Table 7.4-12. The amount of radioactive material in crops per unit area of the soil is small, about 0.03 Bq/m^2 (0.015 Bq/kg × 2 kg/m^2), while the total amount of radioactive material in irrigation water is larger, 0.45 Bq/m^2 (1 Bq/m^3 × 0.006 m/d × 75 d).

In conclusion, the two methods are numerically similar. This evaluation shows that ACM 3 (Section 6.3.3) does not need further consideration, and the chosen method is justified.

Table 7.4-11. Comparison of Direct Deposition of Irrigation Water on Crop Surfaces

Model	ERMYN [a]			BIOMASS ERB2A [b]		
Equation	$Cp_w = \dfrac{Cw\, IRD\, f_o\, Rw\, T}{\lambda_w\, Y}\left(1 - e^{-\lambda_w\, t_g,}\right)$			$C_{crop,w} = \dfrac{I_{crop}\, V_{irr}\, C_w}{Y_{crop}} \times \left[(1 - F_{abs})\, e^{-WT}\, F_{p3} + F_{abs}\, F_{p2}\, F_{trans}\right]$		
Parameter	Notation	Value	Units	Notation	Value	Units
Yearly Irrigation Rate	—	—	—	V_{irr}	0.45	m/yr
Daily irrigation rate	*IRD*	0.006	m/d	—	—	—
Concentration	C_w	1	Bq/m^3	C_w	1	Bq/m^3
Absorption fraction	—	—	—	F_{abs}	0.5	—
Internal wash left	—	—	—	F_{p2}	1	—
External wash left	—	—	—	F_{p3}	0.1	—
Translocation	*T*	1	—	F_{trans}	1	—
Overhead fraction	f_o	1	—	—	—	—
Interception	R_w	0.25	—	I_{crop}	0.25	—
Weathering	λ_w	0.05	1/d	*W*	18	1/yr
Wet yield	*Y*	2	kg/m^2	Y_{crop}	2	kg/m^2/yr
Growing time	*tg*	75	d	—	—	—
Interval time	—	—	—	*T*	0.02	yr
Fraction – weather	f_w	0.976	—	—	—	—
Fraction – external	—	—	—	F_{ext}	0.035	—
Fraction – internal	—	—	—	F_{int}	0.5	—
Leaf water deposition	Cp_w	1.5E–2	Bq/kg	$C_{crop,w}$	3.0E–2	Bq/kg

NOTE: To simplify the equations, the radionuclide and crop-type indices (subscripts) are not shown.

Sources: [a] Input values from Table 6.6-3 if available; reasonable values used when there are multiple values per crop type.

[b] Input values are the same as those for the ERMYN, or default values from BIOMASS ERB2A (BIOMASS 2003 [DIRS 168563], Section C3.6).

7.4.4.2 Crop Interception Fraction for Irrigation Water

The crop interception fraction for irrigation is calculated in the ERMYN using an empirical equation (Equation 6.4.3-5), while all five validation models use a fixed value. Therefore, the models are compared to determine if the results are similar. The calculated results (mean values) for five crop types (Table 7.4-12) range from 0.22 to 0.47, with higher values for crops with more leaf surface (i.e., larger surface area). The results for some of the values differ by more than a factor of two, and an evaluation of the differences and justification for selecting the ERMYN method is presented in Section 7.3.3.2. The irrigation interception fraction for various crop types is also evaluated, from the perspective of its impact on BDCFs, in Section 6.13.4.3, where it is concluded that this parameter does not have a large influence on the BDCF values. It is thus concluded that the selected method is justified, and this part of the ERMYN plant submodel is validated.

Table 7.4-12. Calculated Interception Fraction for Irrigation Water

Interception Fraction	Notation	Calculated Mean Value
Leafy vegetables	Rw_1	0.216
Other vegetables	Rw_2	0.301
Fruit	Rw_3	0.360
Grain	Rw_4	0.470
Forage	Rw_5	0.258

Source: The values were taken from Table 6.13-12.

7.4.4.3 Direct Deposition of Resuspended Soil on Crop Surfaces

The ERMYN (Section 6.4.3.3) and BIOMASS ERB2A (Section 7.3.3.3) models use different methods for calculating crop contamination by direct deposition of resuspended soil on crop surfaces. The BIOMASS ERB2A method is an ACM (Section 6.3.3), and, therefore, the two methods are compared. The equations presented here are simplified by eliminating radionuclide and crop-type indices. Input parameter values are taken from Table 6.6-3, except that some default values for unique parameters are taken from the BIOMASS ERB2A model (BIOMASS 2003 [DIRS 168563], Section C3.6). Because the method used in the ERMYN is sensitive to crop type due to translocation factor values, which are crop-type specific, leafy vegetables and other vegetables are used to calculate radionuclide concentrations in crops from dust deposition (Table 7.4-13). The results of this comparison are evaluated in Section 7.3.3.3. The ERMYN overestimates radionuclide concentrations in leafy vegetables relative to the BIOMASS ERB2A method, primarily because of the translocation equal to unity. However, the models are numerically similar for the applicable comparison of leafy vegetables to forage, and, therefore, the method selected for the ERMYN plant submodel is justified. This evaluation shows that ACM 4 (Section 6.3.3) does not need further consideration.

Table 7.4-13. Comparison of Direct Deposition of Resuspended Soil on Crop Surfaces

Model	ERMYN [a]				BIOMASS ERB2A [b]		
Equation	$Cp_d = \frac{Cs_m S\, V_d Ra\, T}{\lambda_w\, Y}\left(1-e^{-\lambda_w\, t_g}\right)$				$C_{crop,d} = \frac{F_{p1} S_{crop} C_s}{(1-\theta_t)\rho}$		
Parameter	Notation	Leafy Vegetables	Other Vegetables	Units	Notation	Value	Units
Soil volume concentration	—	—	—	—	C_s	1,500	Bq/m^3
Soil grain density	—	—	—	—	ρ	2,650	kg/m^3
Total porosity	—	—	—	—	θ_t	0.434 [c]	—
Soil mass concentration	Cs_m	1	1	Bq/kg	Cs_m	1	Bq/kg
Mass loading	S	1.2E–7	1.2E–7	kg/m^3	—	—	—
Deposition velocity	V_d	0.008	0.008	m/s	—	—	—
External soil left	—	—	—	—	F_{p1}	0.1	—

Table 7.4-13. Comparison of Direct Deposition of Resuspended Soil on Crop Surfaces (Continued)

Model	ERMYN [a]				BIOMASS ERB2A [b]		
Soil contamination	—	—	—	—	S_{crop}	2.0E–4 (all others) 2.0E–3 (forage)	kg/kg
Translocation	T	1	0.1	—	—	—	—
Weathering	λ_w	0.05	0.05	1/d	—	—	—
Wet yield	Y	3.3	4.13	kg/m^2	—	—	—
Growing time	t_g	75	80	d	—	—	—
Air interception [d]	Ra	0.456	0.787	—	—	—	—
Dust deposition	Cp_d	2.2E–4	3.1E–5	Bq/kg	$C_{crop,d}$	2.0E–5 (all others) 2.0E–4 (forage)	Bq/kg

Sources: [a] Input values from the "mean, mode, average" column in Table 6.6-3 if available. ERMYN equation also includes a unit conversion factor of 86,400 s/d.

[b] Input values are the same as those for the ERMYN or default values from the BIOMASS ERB2A report (BIOMASS 2003, [DIRS 168563], Section C3.6).

[c] Value from Table 6.6-3 as the ERMYN has this parameter, although it is not used in this calculation.

[d] Values from Table 6.10-1, "Dust interception fraction."

7.4.5 Animal Submodel

Three mechanisms for the contamination of animal products are included in ERMYN: animal consumption of contaminated feed, water, and soil (Sections 6.4.4 and 6.5.4). These mechanisms are also included in the GENII Version 2 model. GENII and GENII-S did not include animal ingestion of contaminated soil. The BIOMASS ERB2A model also includes animal dust inhalation (Section 7.3.4) as an additional mechanism. Animal soil ingestion and animal dust inhalation are identified as ACMs (Section 6.3.3), and the importance of these alternative pathways is evaluated in this section.

This evaluation uses "meat" as an example animal product and ^{239}Pu as a test radionuclide. The equations are shown in Sections 6.4.4 and 6.5.4, and ERMYN results are taken from Table 6.10-1. The BIOMASS ERB2A model is described in Section 7.3.4, and the equations for calculating radionuclide concentrations in feed and animal products are shown in Table 7.4-14. Because BIOMASS ERB2A uses one irrigation rate for all crops and for soil accumulation, a direct comparison is not meaningful. Thus, radionuclide concentrations in the soil are from the results of ERMYN for the surface soil submodel, soil grain density is from the default values in the BIOMASS model, and total porosity, a BIOMASS ERB2A parameter, is calculated to match the soil bulk density in ERMYN. The retardation coefficient is calculated from the partition coefficient and other parameters in ERMYN. All other parameter values are from the "mean, mode, average" column in Table 6.6-3, if possible, or use default values from BIOMASS ERB2A (BIOMASS 2003 [DIRS 168563], Section C3.6). The calculations (Table 7.4-14) are performed in an Excel file, *ERMYN Validation.xls*, which is listed in Appendix A.

Table 7.4-14. Numerical Calculation of Animal Uptake Submodel

Model	ERMYN [a]			BIOMASS ERB2A [b]		
Equation	Equations shown in Sections 6.4.3 and 6.4.4, calculations shown in Table 6.10-1.			$C_{fodd} = \frac{(CF_{past}+S_{past})C_s}{(1-\theta_t)\rho} + \frac{I_{past}V_{irr}C_w}{SB_{past}W_{past}+365ING_{fodd}SD}$ $C_{prod} = TF_{proding}\left(C_{fodd}ING_{fodd}+C_wING_{wa}\right)+ \frac{C_s\ ING_{sa}TF_{proding}}{(1-\theta_t)\rho+\theta\ \rho_w}+(BR_aO_{an}C_{air})TF_{prodi}$		
Parameter	Notation	Value	Units	Notation	Value	Units
Concentration in soil mass	*Cs*$_m$	1.64	Bq/kg	*Cs*$_m$	1.64	Bq/kg
Concentration in soil volume	—	—	—	*Cs*	2466	Bq/m^3
Retardation coefficient	—	—	—	*R*	9000	—
Grain density	—	—	—	ρ	2.650	kg/m^3
Total porosity	—	—	—	θ_t	0.434	—
Mass loading for crops	*S*	1.20E–07	kg/m^3	$Dust_s$	1.20E–07	kg/m^3
Concentration in air for crop	*Ca*	1.99E–07	Bq/m^3	C_{air}	1.97E–07	Bq/m^3
Soil-to-plant transfer factor	$F_{s\to p\ 5}$	1.0E–03	(dry)	CF_{past}	2.2E–04 [c]	(wet)
Soil contamination on pasture	—	—	—	S_{past}	2.0E–03	kg/kg
Daily irrigation rate	IRD_5	6.54	mm/d	V_{irr}	2.39	m/yr
Interception fraction for irrigation	Rw_5	0.258	—	I_{past}	0.258	—
Equation	Equations shown in Sections 6.4.3 and 6.4.4, calculations shown in Table 6.10-1.			$C_{fodd} = \frac{(CF_{past}+S_{past})C_s}{(1-\theta_t)\rho} + \frac{I_{past}V_{irr}C_w}{SB_{past}W_{past}+365ING_{fodd}SD}$ $C_{prod} = TF_{proding}\left(C_{fodd}ING_{fodd}+C_wING_{wa}\right)+ \frac{C_s\ ING_{sa}TF_{proding}}{(1-\theta_t)\rho+\theta\ \rho_w}+(BR_aO_{an}C_{air})TF_{prodi}$		
Parameter	Notation	Value	Units	Notation	Value	Units
Crop wet yield	Y_5	2.14	kg/m^2	SB_{past}	2.14	kg/m^2
Weathering half-life or decay constant	*Lw*	14	d	*W*	18.1	1/yr
Animal consumption rate of feed	$Qf_{,\ 1}$	75	kg/d	ING_{fodd}	48.5	kg/d
Number of animals in the area	—	—	—	*SD*	2.0E–04	—
Concentration due to root uptake	$Cp_{,r,5}$	3.62E–04	Bq/kg	$C_{fodd,root}$	3.62E–04	Bq/kg
Concentration due to water deposition	$Cp_{,w,5}$	1.40E–02	Bq/kg	$C_{fodd,irri}$	1.46E–02	Bq/kg

Table 7.4-14. Numerical Calculation of Animal Uptake Submodel (Continued)

Model	ERMYN [a]			BIOMASS ERB2A [b]		
Concentration due to dust deposition	$Cp_{,d,5}$	9.44E–04	Bq/kg	$C_{fodd,dust}$	3.29E–03	Bq/kg
Concentration in crops	Cp_5	1.53E–02	Bq/kg	C_{fodd}	1.82E–02	Bq/kg
Animal consumption rate of feed	$Qf_{,1}$	48.5	kg/d	ING_{fodd}	48.5	kg/d
Animal consumption rate of water	$Qw_{,1}$	60	L/d	ING_{wa}	0.06	m^3/d
Animal consumption rate of soil	$Qs_{,1}$	0.7	kg/d	ING_{soil}	0.7	kg/d
Animal product transfer coefficient, ingestion	Fm_1	1.30E–05	d/kg	$TF_{proding}$	1.30E–05	d/kg
Water density	—	—	—	ρ_w	1000	kg/m^3
Volumetric water content	—	—	—	θ	0.2	—
Animal breathing rate	—	—	—	BR_a	5.4	m^3/h
Animal occupancy time	—	—	—	O_{an}	24	h/d
Animal product transfer coefficient, inhalation	—	—	—	$TF_{prodinh}$	1.3E–05 [d]	d/kg
Concentration in meat from animal feed (Bq/kg)	$Cd_{,f,1}$	9.65E–06	Bq/kg	$C_{prod,fodd}$	1.15E–05	Bq/kg
Concentration in meat from animal water (Bq/kg)	$Cd_{,w,1}$	7.80E–07	Bq/kg	$C_{prod,wa}$	7.80E–07	Bq/kg
Concentration in meat from animal soil ingestion (Bq/kg)	$Cd_{,s,1}$	1.50E–05	Bq/kg	$C_{prod,soil}$	1.32E–05	Bq/kg
Concentration in meat from animal dust inhalation (Bq/kg)	—	—	—	$C_{prod,inh}$	3.3E–10	Bq/kg
Meat concentration (Bq/kg)	Cd_1	2.54E–05	Bq/kg	C_{prod}	2.55E–05	Bq/kg

Sources: [a] Results from Table 6.10-1. Some input values shown for comparison.

[b] BIOMASS ERB2A calculations are based on the equations in this table and input parameter values from the ERMYN (Table 6.6-3), if possible, or default values suggested in BIOMASS ERB2A (BIOMASS 2003 [DIRS 168563], Section C3.6).

[c] Value from soil-to-plant transfer factor (dry) × dry-to-wet weight ratio (forage) = 0.001 × 0.22 = 2.2×10^{-4}; Table 6.6-3.

[d] Same value as for the transfer coefficient for ingestion (BIOMASS 2003 [DIRS 168563], Section C3.5.4.3).

The two models are equivalent, as the calculated concentrations in meat differ by only a few percent (Table 7.4-14). The ingestion of soil accounts for about 52% to 59% of the total concentration in meat (Table 7.4-14), and, therefore, animal soil ingestion is an important mechanism that must be included in the animal submodel (also, see evaluations in Section 6.14.4.4). In contrast, animal inhalation of resuspended soil contributes little to dose (about five orders of magnitude less than the total concentration in meat calculated with the BIOMASS ERB2A model; Table 7.4-14) and is not necessary. This evaluation shows that ACM 5 (Section 6.3.3) does not need further consideration.

7.4.6 Fish Submodel

There are no ACMs for the fish submodel (Section 6.3.3), and no complex numerical comparisons are required to validate the submodel.

7.4.7 ^{14}C Special Submodel

The ^{14}C special submodel in the ERMYN is different from the GENII submodel (used in all versions of GENII). The major difference is that ERMYN explicitly models the process of the release of ^{14}C from the soil into the air as radioactive carbon dioxide gas ($^{14}CO_2$). Furthermore, the ERMYN plant uptake submodel includes the uptake of $^{14}CO_2$ gas by plants from the air (during the process of photosynthesis). In the GENII model, plants obtain their carbon directly from soil, bypassing the uptake from the air, and this model can be considered an ACM. The ERMYN and GENII methods for calculating concentrations of ^{14}C in plants are compared to validate the ^{14}C special submodel (Section 7.3.6).

The ERMYN and GENII ^{14}C special submodels are described in Sections 6.4.6 and 7.3.6, respectively. The ^{14}C concentrations in crops are calculated using the ERMYN model in Table 6.10-2 (also see Excel file *ERMYN Verification.xls* in Appendix A). For comparison, ^{14}C concentration in leafy vegetables are calculated using both methods (Table 7.4-15) using the same input parameter values as for the ERMYN (Table 6.10-2). The comparisons, including the input parameters, are shown in Table 7.4-15 (Excel file *ERMYN Validation.xls*, worksheet *C-14 Submodel*). The removal rate constant for ^{14}C from soil is effectively that for the emission rate constant of carbon dioxide (22 1/yr). For leafy vegetables, a daily irrigation rate of 5.40 mm/d and a growing time of 75 d are used in ERMYN. Thus, the corresponding annual irrigation rate of 15.9 in/yr and irrigation duration of 2.5 mo/yr are used for GENII. The calculations using the GENII equation (Table 7.4-15) are performed in an Excel spreadsheet, *ERMYN Validation.xls*, which is listed in Appendix A.

The ERMYN submodel gives a ^{14}C concentration for leafy vegetables that is about 3.5 times higher that the GENII value (Table 7.4-15). However, ERMYN includes an additional plant carbon uptake mechanism and is conceptually more appropriate in that plants obtain their carbon mostly from air, instead of directly from the soil. Therefore, the ^{14}C submodel in the ERMYN is valid because it includes this additional uptake process. The RESRAD and BIOMASS ERB2A models also include carbon uptake during photosynthesis. An evaluation of these methods, and a justification for selecting the method used in the ERMYN ^{14}C special submodel, is presented in Section 7.3.6. This evaluation shows that ACM 6 (Section 6.3.3) does not need further consideration.

Table 7.4-15. Evaluation of Plant Uptake in ^{14}C Special Submodel

Model	ERMYN [a]			GENII [b]		
Equation	Equation shown in Section 6.4.6, calculations shown in Table 6.10-2			$Cc_p = \frac{25.4 \times I \times Cw_c}{\rho_s \ \lambda s_c} \times \frac{12}{ID} \times \frac{0.1}{0.01} \times Fc_p$		
Parameter	Notation	Value	Units	Notation	Value	Units
Removal rate constant	Λ_a	22	1/yr	λs_c	22	1/yr
Surface density	ρ_s	375	kg/m^2	ρ_s	375	kg/m^2
Concentration in water	Cw	1	Bq/m^3	Cw_c	0.001	Bq/L
Fraction of carbon	fc_{plant}	0.09	—	Fc_p	0.09	—

Table 7.4-15. Evaluation of Plant Uptake in ^{14}C Special Submodel (Continued)

Model	ERMYN [a]			GENII [b]		
Irrigation rate	*IRD*	5.40	mm/d	*I*	15.9	in/yr
Irrigation duration	*Tg*	75	d	*ID*	2.5	mo/yr
C-14 concentration	*Cp*	7.4E–04	Bq/kg	Cc_p	2.1E–04	Bq/kg

Sources: [a] Results from Table 6.10-2; some input values shown for comparison.
[b] Calculation described in Table 7.3-21; input values from Table 6.6-3.

7.4.8 External Exposure Submodel

The external exposure submodel of ERMYN only includes external exposure from contaminated surface soil, although external exposure to air and water contamination is possible (Sections 6.4.7 and 6.5.5). In this section, calculations are presented to evaluate the importance of air submersion and water immersion relative to exposure to contaminated soil.

7.4.8.1 Air Submersion

Air submersion is applicable to both exposure scenarios. To evaluate the importance of air submersion, dose coefficients for air submersion (including short-lived decay products) are developed (Table 7.4-16) and compared with dose coefficients for soil contamination (Table 7.4-17).

The dose coefficients for air submersion (Table 7.4-16) are expressed in the same units as those for exposure to soil contaminated to an infinite depth (Table 6.4-4). However, the contaminated medium that is the source of the radiation is different: air for air submersion versus soil for external exposure to contaminated soil. The ratio of the dose coefficients for air submersion to those for soil exposure (air/soil; Table 7.4-16) range from 1,477 to 55,233 (i.e., on the order of 10^3 to 10^4).

To compare the relative importance of air submersion and soil exposure, activity concentrations in the air and soil are estimated. A soil contamination level of 1 Bq/m^3 corresponds to an activity concentration (in mass units) of 1×10^{-3} Bq/kg, based on a soil density of 1×10^3 kg/m^3. If air contamination is only from contaminated resuspended soil, activity concentrations in the air can be calculated using equations included in the air submodel (Section 6.4.2, Equation 6.4.2-1). Using typical values of air mass loading (ranging from 10^{-6} to 10^{-7} kg/m^3; BSC 2006 [DIRS 177101], Section 6.2), the air concentration would be about 10^{-9} to 10^{-10} Bq/m^3. Therefore, the activity concentration ratio between air submersion and soil exposure is on the order of 10^{-9} (10^{-9} Bq/m^3 / 1 Bq/m^3). Considering the ratio of dose coefficients at the level of 10^3 to 10^4, the air submersion dose is about 5 to 6 orders of magnitude lower than soil exposure if the exposure times are the same, which is the case because both exposures occur simultaneously. Because air submersion is much less important than soil exposure, there is no impact when this pathway is excluded from the ERMYN model.

Table 7.4-16. Effective Dose Coefficients for Air Submersion

Primary Radionuclide [a,b]	Decay Product [c] (Branching Fraction if not 100%, Half-life)	Dose Coefficient [d] (Sv/s)/(Bq/m^3)	Effective Dose Coefficient (Sv/s)/(Bq/m^3)
^{14}C	—	2.60E–18	2.60E–18
^{36}Cl	—	1.66E–16	1.66E–16
^{79}Se	—	3.94E–18	3.94E–18
^{90}Sr D	 ^{90}Y (64.0 h)	9.83E–17 7.93E–16	8.91E–16
^{99}Tc	—	2.87E–17	2.87E–17
^{126}Sn D	 ^{126m}Sb (19.0 min) ^{126}Sb (14%, 12.4 d)	1.85E–15 7.02E–14 1.28E–13	9.00E–14
^{129}I	—	2.83E–16	2.83E–16
Cs-135	—	9.50E–18	9.50E–18
^{137}Cs D	 ^{137m}Ba (94.6%, 2.552 min)	9.28E–17 2.69E–14	2.55E–14
^{242}Pu	—	2.91E–18	2.91E–18
^{238}U D	 ^{234}Th (24.10 d) ^{234m}Pa (99.80%, 1.17 min) ^{234}Pa (0.33%, 6.7 h)	2.51E–18 2.95E–16 1.21E–15 8.73E–14	1.79E–15
^{238}Pu	—	3.51E–18	3.51E–18
^{234}U	—	6.13E–18	6.13E–18
^{230}Th	—	1.49E–17	1.49E–17
^{226}Ra D	 ^{222}Rn (3.8235 d) ^{218}Po (3.05 min) ^{214}Pb (99.98%, 26.8 min) ^{218}At (0.02%, 2 s) ^{214}Bi (19.9 min) ^{214}Po (99.98%, 1.64×10^{-4} s) ^{210}Tl (0.02%, 1.3 min)	2.84E–16 1.78E–17 4.21E–19 1.10E–14 9.76E–17 7.25E–14 3.81E–18 0.00E+00	8.38E–14
^{210}Pb D	 ^{210}Bi (5.012 d) ^{210}Po (138.38 d)	4.51E–17 2.58E–16 3.89E–19	3.03E–16
^{240}Pu	—	3.43E–18	3.43E–18
^{236}U	—	3.87E–18	3.87E–18
^{232}Th	—	3.87E–18	3.87E–18
^{228}Ra D	 ^{228}Ac (6.13 h)	0.00E+00 4.49E–14	4.49E–14
^{232}U	—	1.18E–17	1.18E–17
^{228}Th D	 ^{224}Ra (3.66 d) ^{220}Rn (55.6 s) ^{216}Po (0.15 s) ^{212}Pb (10.64 h) ^{212}Bi (60.55 min) ^{212}Po (64.07%, 0.305 μs) ^{208}Tl (35.93%, 3.07 min)	8.13E–17 4.30E–16 1.72E–17 7.75E–19 6.26E–15 8.96E–15 0.00E+00 1.69E–13	7.65E–14

Table 7.4-16. Effective Dose Coefficients for Air Submersion (Continued)

Primary Radionuclide [a,b]	Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Dose Coefficient [d] (Sv/s)/(Bq/m^3)	Effective Dose Coefficient (Sv/s)/(Bq/m^3)
^{243}Am D		1.86E–15	8.82E–15
	^{239}Np (2.355 d)	6.96E–15	
^{239}Pu	—	3.49E–18	3.49E–18
^{235}U D		6.48E–15	6.94E–15
	^{231}Th (25.52 h)	4.59E–16	
^{231}Pa	—	1.57E–15	1.57E–15
^{227}Ac D		5.13E–18	1.74E–14
	^{227}Th (98.62%, 18.718 d)	4.44E–15	
	^{223}Fr (1.38%, 21.8 min)	2.21E–15	
	^{223}Ra (11.434 d)	5.48E–15	
	^{219}Rn (3.96 s)	2.46E–15	
	^{215}Po (1.78 ms)	7.80E–18	
	^{211}Pb (36.1 min)	2.59E–15	
	^{211}Bi (2.14 min)	2.04E–15	
	^{207}Tl (99.72%, 4.77 min)	4.53E–16	
	^{211}Po (0.28%, 0.516 s)	3.56E–16	
^{241}Am	—	6.77E–16	6.77E–16
^{237}Np D		8.90E–16	9.46E–15
	^{233}Pa (27.0 d)	8.57E–15	
^{233}U	—	1.42E–17	1.42E–17
^{229}Th D		3.37E–15	1.39E–14
	^{225}Ra (14.8 d)	2.41E–16	
	^{225}Ac (10.0 d)	6.38E–16	
	^{221}Fr (4.8 min)	1.33E–15	
	^{217}At (32.3 ms)	1.37E–17	
	^{213}Bi (45.65 min)	6.17E–15	
	^{213}Po (97.84%, 4.2 μs)	0.00E+00	
	^{209}Tl (2.16%, 2.2 min)	9.66E–14	
	^{209}Pb (3.253 h)	1.00E–16	

[a] A “D” indicates that the radionuclide is treated with its short-lived (less than 180 d) decay products.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Branching fractions and half-lives are from Table 6.3-7.

[d] Dose coefficient source: EPA 2002 [DIRS 175544]

Effective dose coefficients were calculated in Excel spreadsheet *Calculation_Effective Dose Coefficients.xls* (Appendix A).

Table 7.4-17. Comparison of Dose Coefficients for Air Submersion and for Exposure to Soil Contaminated to Infinite Depth

Primary Radionuclide [a]	Effective Dose Coefficient (Sv/s)/(Bq/m^3)		Dose Coefficient Ratio [d] (Air/Soil)
	Air Submersion [b]	Exposure to Soil Contaminated to Infinite Depth [c]	
^{14}C	2.60E–18	5.90E–23	44068
^{36}Cl	1.66E–16	1.33E–20	12481
^{79}Se	3.94E–18	8.21E–23	47990
^{90}Sr D	8.91E–16	2.18E–19	4080
^{99}Tc	2.87E–17	5.81E–22	49398
^{126}Sn D	9.00E–14	5.94E–17	1514
^{129}I	2.83E–16	5.14E–20	5506
^{135}Cs	9.50E–18	1.72E–22	55233
^{137}Cs D	9.28E–17	1.71E–17	1491
^{242}Pu	2.91E–18	5.32E–22	5470
^{238}U D	1.79E–15	8.34E–19	2151
^{238}Pu	3.51E–18	6.25E–22	5616
^{234}U	6.13E–18	1.84E–21	3332
^{230}Th	1.49E–17	5.73E–21	2600
^{226}Ra D	8.38E–14	5.67E–17	1478
^{210}Pb D	3.03E–16	4.01E–20	7575
^{240}Pu	3.43E–18	6.03E–22	5688
^{236}U	3.87E–18	9.53E–22	4061
^{232}Th	3.87E–18	2.44E–21	1586
^{228}Ra D	4.49E–14	3.03E–17	1482
^{232}U	1.18E–17	4.25E–21	2776
^{228}Th D	7.65E–14	5.18E–17	1477
^{243}Am D	8.82E–15	4.36E–18	2025
^{239}Pu	3.49E–18	1.41E–21	2475
^{235}U D	6.94E–15	3.70E–18	1874
^{231}Pa	1.57E–15	9.44E–19	1663
^{227}Ac D	1.74E–14	1.00E–17	1745
^{241}Am	6.77E–16	1.99E–19	3402
^{237}Np D	9.46E–15	5.41E–18	1748
^{233}U	1.42E–17	6.77E–21	2097
^{229}Th D	1.39E–14	7.92E–18	1761

[a] "D" after a radionuclide symbol denotes that the radionuclide is treated together with the short half-life (less than 180 d) decay product.

[b] Data from Table 7.4-16.

[c] Data from Table 6.4-4.

[d] Calculated from Column 2 divided by Column 3.

Calculations are shown in Excel spreadsheet *Calculation_Effective Dose Coefficients.xls* (Appendix A).

7.4.8.2 Water Immersion

Immersion in contaminated water only applies to the groundwater scenario, where water immersion can occur during activities such as swimming or bathing in contaminated water. To evaluate the importance of the water immersion exposure pathway, dose coefficients (including short-lived decay products) were developed for water immersion (Table 7.4-18), similar to the dose coefficients for soil contamination (Table 6.4-4).

The dose coefficients for water immersion (Table 7.4-18) are expressed in the same units as those for exposure to soil contaminated to an infinite depth (Sv/s)/(Bq/m^3). However, the source of radionuclides is different: water versus soil. The ratio of dose coefficient for water immersion (Table 7.4-18) to dose coefficient for exposure to contaminated soil (Table 6.4-4) were calculated and are presented in Table 7.4-19. The ratios range from 3.2 to 60.5 (Table 7.4-19), with ^{135}Cs and ^{79}Se having the largest ratios (greater than 50).

To compare the relative importance of water immersion and soil exposure, exposure times and media concentrations were evaluated. Typically, daily baths last about 20 min, while showers last about 10 min (EPA 1997 [DIRS 116135], p. 15-16). Typical rates for swimming are one swim per month that lasts for about 60 min (EPA 1997 [DIRS 116135], p. 15-17), which gives an average swimming time of about 2 min/d. Therefore, the average daily water immersion time is about 17 min/d, based on equal frequency of bathing and showering. The effective soil exposure time is radionuclide dependent because of the external shielding factor. Based on the calculated environment-specific outdoor time of 1.90 h/d, an indoor time of 17.75 h/d (Table 6.10-1), and the shielding factors, the average effective exposure times and the ratios of soil exposure time to water immersion time are calculated (Table 7.4-20).

Radionuclide concentration in the water was assumed to be 1 Bq/m^3; radionuclide concentration in the soil was assumed to be that for gardens as calculated in Section 7.4.2.1 (Excel file *ERMYN Validation_Soil Model.xls* in Appendix A). It was then converted from concentration per unit mass to concentration per unit volume using the soil density of 1,500 kg/m^3. The soil exposure and water immersion doses depend on exposure time, media concentrations, and dose coefficients. The ratio of external doses from soil and water exposure can be calculated as the soil/water exposure time ratio times the soil/water radionuclide concentration ratio, divided by the water/soil dose coefficient ratio. These ratios were calculated in Excel file *ERMYN Validation.xls*, worksheet *Equilibrium&Immersion* (Appendix A) and the results are presented in Table 7.4-20.

Table 7.4-18. Effective Dose Coefficients for Water Immersion

Primary Radionuclide [a,b]	Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Dose Coefficient [d] (Sv/s)/(Bq/m^3)	Effective Dose Coefficient (Sv/s)/(Bq/m^3)
^{14}C	—	2.88E–21	2.88E–21
^{36}Cl	—	1.95E–19	1.95E–19
^{79}Se	—	4.35E–21	4.35E–21
^{90}Sr D	 ^{90}Y (64.0 h)	1.09E–19 9.87E–19	1.10E–18
^{99}Tc	—	3.13E–20	3.13E–20
^{126}Sn D	 ^{126m}Sb (19.0 min) ^{126}Sb (14%, 12.4 d)	4.10E–18 1.52E–16 2.78E–16	1.95E–16
^{129}I	—	6.57E–19	6.57E–19
^{135}Cs	—	1.04E–20	1.04E–20
^{137}Cs D	 ^{137m}Ba (94.6%, 2.552 min)	1.04E–19 5.83E–17	5.53E–17
^{242}Pu	—	6.75E–21	6.75E–21
^{238}U D	 ^{234}Th (24.10 d) ^{234m}Pa (99.80%, 1.17 min) ^{234}Pa (0.33%, 6.7 h)	5.85E–21 6.57E–19 1.98E–18 1.89E–16	3.26E–18
^{238}Pu	—	8.17E–21	8.17E–21
^{234}U	—	1.39E–20	1.39E–20
^{230}Th	—	3.34E–20	3.34E–20
^{226}Ra D	 ^{222}Rn (3.8235 d) ^{218}Po (3.05 min) ^{214}Pb (99.98%, 26.8 min) ^{218}At (0.02%, 2 s) ^{214}Bi (19.9 min) ^{214}Po (99.98%, 1.64×10^{-4} s) ^{210}Tl (0.02%, 1.3 min)	6.24E–19 3.86E–20 9.10E–22 2.38E–17 2.23E–19 1.57E–16 8.26E–21 0.00E+00	1.81E–16
^{210}Pb D	 ^{210}Bi (5.012 d) ^{210}Po (138.38 d)	1.04E–19 2.98E–19 8.43E–22	4.03E–19
^{240}Pu	—	7.97E–21	7.97E–21
^{236}U	—	8.89E–21	8.89E–21
^{232}Th	—	1.64E–20	1.64E–20
^{228}Ra D	 ^{228}Ac (6.13 h)	0.00E+00 9.70E–17	9.70E–17
^{232}U	—	2.66E–20	2.66E–20
^{228}Th D[b]	 ^{224}Ra (3.66 d) ^{220}Rn (55.6 s) ^{216}Po (0.15 s) ^{212}Pb (10.64 h) ^{212}Bi (60.55 min) ^{212}Po (64.07%, 0.305 μs) ^{208}Tl (35.93%, 3.07 min)	1.80E–19 9.38E–19 3.74E–20 1.68E–21 1.37E–17 1.90E–17 0.00E+00 3.65E–16	1.65E–16

Table 7.4-18. Effective Dose Coefficients for Water Immersion (Continued)

Primary Radionuclide [a,b]	Decay Product [c] (Branching Fraction if not 100%, Half-Life)	Dose Coefficient [d] (Sv/s)/(Bq/m^3)	Effective Dose Coefficient (Sv/s)/(Bq/m^3)
^{243}Am D		4.19E–18	1.95E–17
	^{239}Np (2.355 d)	1.53E–17	
^{239}Pu	—	7.83E–21	7.83E–21
^{235}U D		1.43E–17	1.53E–17
	^{231}Th (25.52 h)	1.01E–18	
^{231}Pa	—	3.43E–18	3.43E–18
^{227}Ac D		1.14E–20	3.74E–17
	^{227}Th (98.62%, 18.718 d)	9.71E–18	
	^{223}Fr (1.38%, 21.8 min)	4.67E–18	
	^{223}Ra (11.434 d)	1.20E–17	
	^{219}Rn (3.96 s)	5.36E–18	
	^{215}Po (1.78 ms)	1.69E–20	
	^{211}Pb (36.1 min)	5.31E–18	
	^{211}Bi (2.14 min)	4.45E–18	
	^{207}Tl (99.72%, 4.77 min)	6.33E–19	
	^{211}Po (0.28%, 0.516 s)	7.71E–19	
^{241}Am	—	1.54E–18	1.54E–18
^{237}Np D		1.99E–18	2.07E–17
	^{233}Pa (27.0 d)	1.87E–17	
^{233}U	—	3.15E–20	3.15E–20
^{229}Th D		7.49E–18	3.01E–17
	^{225}Ra (14.8 d)	5.26E–19	
	^{225}Ac (10.0 d)	1.41E–18	
	^{221}Fr (4.8 min)	2.90E–18	
	^{217}At (32.3 ms)	2.97E–20	
	^{213}Bi (45.65 min)	1.31E–17	
	^{213}Po (97.84%, 4.2 µs)	0.00E+00	
	^{209}Tl (2.16%, 2.2 min)	2.09E–16	
	^{209}Pb (3.253 h)	1.12E–19	

[a] A “D” indicates that the radionuclide is treated with its short-lived (less than 180 d) decay products.

[b] Indented radionuclides are long-lived decay products considered separately from the parents.

[c] Branching fractions and half-lives are from Table 6.3-7.

[d] Dose coefficient source: DOE 2007 [DIRS 180783]

Effective dose coefficients were calculated in Excel spreadsheet *Calculation_Effective Dose Coefficients.xls* (Appendix A).

Table 7.4-19. Comparison of Effective Dose Coefficients for Water Immersion and for Exposure to Soil Contaminated to Infinite Depth

Primary Radionuclide [a]	Effective Dose Coefficient (Sv/s)/(Bq/m^3)		Dose Coefficient Ratio [d] (Air/Soil)
	Water Immersion [b]	Exposure to Soil Contaminated to Infinite Depth [c]	
^{14}C	2.88E–21	5.9E–23	48.8
^{36}Cl	1.95E–19	1.33E–20	14.7
^{79}Se	4.35E–21	8.21E–23	53.0
^{90}Sr D	1.10E–18	2.18E–19	5.0
^{99}Tc	3.13E–20	5.81E–22	53.9
^{126}Sn D	1.95E–16	5.94E–17	3.3
^{129}I	6.57E–19	5.14E–20	12.8
^{135}Cs	1.04E–20	1.72E–22	60.5
^{137}Cs D	5.53E–17	1.71E–17	3.2
^{242}Pu	6.75E–21	5.32E–22	12.7
^{238}U D	3.26E–18	8.34E–19	3.9
^{238}Pu	8.17E–21	6.25E–22	13.1
^{234}U	1.39E–20	1.84E–21	7.6
^{230}Th	3.34E–20	5.73E–21	5.8
^{226}Ra D	1.81E–16	5.67E–17	3.2
^{210}Pb D	4.03E–19	4.01E–20	10.1
^{240}Pu	7.97E–21	6.03E–22	13.2
^{236}U	8.89E–21	9.53E–22	9.3
^{232}Th	1.64E–20	2.44E–21	6.7
^{228}Ra D	9.70E–17	3.03E–17	3.2
^{232}U	2.66E–20	4.25E–21	6.3
^{228}Th D	1.65E–16	5.18E–17	3.2
^{243}Am D	1.95E–17	4.36E–18	4.5
^{239}Pu	7.83E–21	1.41E–21	5.6
^{235}U D	1.53E–17	3.70E–18	4.1
^{231}Pa	3.43E–18	9.44E–19	3.6
^{227}Ac D	3.74E–17	1.00E–17	3.7
^{241}Am	1.54E–18	1.99E–19	7.7
^{237}Np D	2.07E–17	5.41E–18	3.8
^{233}U	3.15E–20	6.77E–21	4.7
^{229}Th D	3.01E–17	7.92E–18	3.8

[a] "D" after a radionuclide symbol denotes that the radionuclide is treated together with the short half-life (less than 180 d) decay product.

[b] Data from Table 7.4-14.

[c] Data from Table 6.4-4.

[d] Calculated from Column 2 divided by Column 3.

Calculations are shown in Excel spreadsheet *Calculation_Effective Dose Coefficients.xls* (Appendix A).

Table 7.4-20. Evaluation of Water Immersion Pathway

Radionuclide	Radionuclide Concentration in Soil (Bq/kg)	Radionuclide Concentration Ratio (Soil/Water)	Effective Exposure Time for Soil (h/d)	Effective Exposure Time Ratio (Soil/Water)	Dose Coefficient Ratio (Water/Soil)	Dose Contribution Ratio (Soil/Water)
^{14}C	1.10E–04	1.65E–01	5.5	19	48.8	0.1
^{36}Cl	3.14E–03	4.71E+00	9.0	32	14.7	10
^{79}Se	2.12E–01	3.18E+02	3.7	13	53.0	78
^{90}Sr	6.62E–02	9.93E+01	9.0	32	5.0	629
^{99}Tc	3.14E–03	4.71E+00	5.5	19	53.9	2
^{126}Sn	2.22E–01	3.33E+02	9.0	32	3.3	3224
^{129}I	5.14E–02	7.71E+01	3.7	13	12.8	78
^{135}Cs	2.27E–01	3.40E+02	3.7	13	60.5	73
^{137}Cs	9.05E–02	1.36E+02	9.0	32	3.2	1337
^{242}Pu	2.09E–01	3.14E+02	3.7	13	12.7	321
^{238}U	1.69E–01	2.54E+02	9.0	32	3.9	2062
^{238}Pu	1.57E–01	2.36E+02	3.7	13	13.1	234
^{234}U	1.69E–01	2.54E+02	5.5	19	7.6	647
^{230}Th	2.26E–01	3.39E+02	7.2	26	5.8	1485
^{226}Ra	2.22E–01	3.34E+02	9.0	32	3.2	3312
^{210}Pb	7.19E–02	1.08E+02	9.0	32	10.1	341
^{240}Pu	2.24E–01	3.36E+02	3.7	13	13.2	330
^{236}U	1.69E–01	2.54E+02	3.7	13	9.3	353
^{232}Th	2.26E–01	3.40E+02	5.5	19	6.7	972
^{228}Ra	1.99E–02	2.99E+01	9.0	32	3.2	296
^{232}U	1.15E–01	1.73E+02	7.2	26	6.3	705
^{228}Th	6.67E–03	1.00E+01	9.0	32	3.2	100
^{243}Am	2.25E–01	3.37E+02	9.0	32	4.5	2396
^{239}Pu	2.25E–01	3.37E+02	7.2	26	5.6	1550
^{235}U	1.69E–01	2.54E+02	9.0	32	4.1	1951
^{231}Pa	2.26E–01	3.38E+02	9.0	32	3.6	2959
^{227}Ac	7.02E–02	1.05E+02	9.0	32	3.7	894
^{241}Am	2.25E–01	3.38E+02	5.5	19	7.7	840
^{237}Np	1.55E–01	2.33E+02	9.0	32	3.8	1935
^{233}U	1.69E–01	2.54E+02	9.0	32	4.7	1733
^{229}Th	2.25E–01	3.38E+02	9.0	32	3.8	2828

Sources: Values in Column 2 are from Table 7.4-4. Column 3 calculated using soil density of 1,500 kg/m^3 and radionuclide concentration in water of 1 Bq/m^3. Column 4 calculated using part of Equation 6.4.7-1 (outdoor time + indoor time × external shielding factor). Column 5 calculated as the ratio of Column 4 to an average water immersion time of 17 minutes. Column 6 taken from Table 7.4-18. Column 7 calculated as Column 3 × Column 5 ÷ Column 6. These calculations are performed using Excel spreadsheet, *ERMYN Validation.xls* listed in Appendix A.

For most radionuclides, soil exposure doses are at least two orders of magnitude greater than the doses from water immersion. The exceptions are radionuclides that emit low-energy radiations primarily absorbed in the skin, such as ^{36}Cl, ^{99}Tc, and ^{135}Cs. For these radionuclides, the BDCF contribution from external exposure to soil is less than one-tenth of a percent (Table 6.13-1), but the dose from exposure to soil still exceeds the dose from immersion in water. The exception is

^{14}C. For this radionuclide, the dose from water immersion is greater than the dose from exposure to soil. However, the dose from the soil accounts for only 7×10^{-8} of the BDCF (Excel file *GW BDCF Pathway Analyses PDC.xls*, *Pathway Summary* worksheet, Appendix A), and the dose from water immersion would account for about 7×10^{-7} of the BDCF value.

The water immersion pathway contribution is negligible, regardless of the radionuclide, and it is reasonable to not include it in the model. Because the water immersion exposure pathway is much less important than soil exposure, there is no impact when this pathway is excluded from the ERMYN and the dose to the RMEI is not underestimated.

7.4.9 Inhalation Submodel

The ERMYN inhalation submodel uses human activity and environment-specific exposure times, breathing rates, and mass loading. The other factors, such as resuspension enhancement factors, also depend on human activities. Site-specific and analogue information on human activity and environments was used to develop input parameter values for this submodel and to include uncertainty about the input parameters. The validation models use simpler methods than those applied in ERMYN, using, for example, average exposure times rather than population and activity dependent exposure times (Section 7.3.8). Therefore, a comparison of activity inhaled per day, using average values, is performed to evaluate differences between the two approaches (Table 7.4-21).

The average activity inhaled daily was calculated using representative inputs from Table 6.6-3, and the result was 7.0×10^{-6} Bq/d. In the alternative approach, the receptor inhalation intake was evaluated for two exposure conditions: for the normal activity and for hard physical activity in dry soil conditions, consistent with the BIOMASS methods (BIOMASS 2003 [DIRS 168563]). The exposure time for hard physical activity in dry soil conditions was assumed to be equal to the weighted exposure time in the active outdoor environment; the exposure time for normal activity was assumed to be equal to the weighted exposure time in the remaining RMEI environments within the contaminated area. The other parameter values were obtained from the BIOMASS model report (BIOMASS 2003 [DIRS 168563], Table C27). The calculations were done in Excel file *ERMYN Validation.xls*, worksheet *Inhalation* (Appendix A). Using the alternative approach from the validation model, the daily intake of activity was calculated as 6.1×10^{-6} Bq/d. The parameter values and the results of calculations are presented in Table 7.4-21. The results of the two methods are comparable, and ACM 7 (Section 6.3.3) does not need further consideration.

Table 7.4-21. Evaluation of Population and Environmental Features of Inhalation Submodel

Parameter	Units	Notation	Environment						
			ERMYN					BIOMASS	
			Active Outdoors	**Inactive Outdoors**	**Active Indoors**	**Asleep Indoors**	**Away**	**Hard Physical Activity in Dry Soil Conditions**	**Normal Activity**
Exposure time, commuter	h/d	t(n,m)	0.3	1.4	6.0	8.3	8.0	NA	NA
Exposure time, outdoor worker	h/d	t(n,m)	3.1	4.0	6.6	8.3	2	NA	NA
Exposure time, indoor worker	h/d	t(n,m)	0.3	1.3	12.1	8.3	2	NA	NA
Exposure time, nonworker	h/d	t(n,m)	0.3	1.2	12.2	8.3	2	NA	NA
Exposure time, weighted average	h/d	t(n,m)	0.45	1.45	9.45	8.30	4.35	0.45	19.2
Breathing rate	m^3/h	BR(n)	1.57	1.08	1.08	0.39	1.08	1.7	1.2
Mass loading	kg/m^3	S(n)	3.0E–6	6.0E–8	1.0E–7	3.0E–8	0	5.00E–06	1.00E–07
Enhancement factor	none	$f_{enhance,n}$	1	4	4	4	0	1.0	1
Calculated inhaled activity per day	Bq/d		2.1E–06	3.8E–07	4.1E–06	3.9E–07	0.0E+00	3.8E–6	2.3E–06
Sum	Bq/d		7.0E–06					6.1E–06	

Sources: Parameter values were taken from Table 6.6-3.

Calculations based on population group fractions: commuters = 0.392; outdoor workers = 0.055; indoor workers = 0.161; nonworkers = 0.392. Calculation performed using an Excel spreadsheet *ERMYN Validation.xls* listed in Appendix A.

7.4.10 Ingestion Submodel

The ERMYN ingestion submodel is similar to the validation models (Section 7.3.9). There are no ACMs for the ingestion submodel (Section 6.3.3), and no complex numerical comparisons are required to validate the submodel.

7.5 MODEL VALIDATION RANGE

The previous detailed discussion has shown that ERMYN is valid over the ranges of input parameter values, which are reasonably expected to occur in the arid to semi-arid region surrounding Yucca Mountain. To reach this conclusion, it was not necessary to conduct detailed mathematical evaluations over the reasonable ranges of all parameters because the model is based primarily on the concentration ratios, i.e., linear equations for the proportional transfer of radionuclides from one medium to another. Accordingly, the equations produce proportional results across the entire ranges of the input parameters for which the model has been validated. For the few equations that include nonlinear calculations either the results asymptotically approach reasonable limits (e.g., the weathering function in the calculation of the fraction of intercepted dust retained on crops, Equation 6.4.3-6, asymptotes to 1.0 at relatively low values of growing time) or are limited in GoldSim to prevent invalid results (e.g., the irrigation interception fraction, Equation 6.4.3-5, is limited to a maximum of 1.0; Section 6.8.4).

Numerical comparisons for model validation and ACM evaluations (Section 7.4) use the mean, mode, or other single values representative of the input parameters distributions listed in Table 6.6-3. The same values are used for both methods being compared (unless the ERMYN does not use a parameter value). Using values representative of distributions other than those in Table 6.6-3 would cause the results of both methods to change proportionally. Therefore, conclusions of the validation analyses, generally, are independent of input parameter values.

The input parameters for the biosphere model were developed largely based on the appropriate experimental values reported in the scientific literature or the values from such experiments that were consolidated and compiled for the purpose of supporting radiological assessment models. In either case, these values represent observable conditions that can reasonably be expected to occur and if such values are used, the model validation range is not exceeded.

The outputs of the ERMYN model, BDCFs, represent the annual dose to the RMEI, a receptor with average characteristics of the Amargosa Valley population, and the use of the model, including the input data, for other time frames or for specific individuals and environments might produce invalid results. In particular, seven parameters might cause problems if unreasonable values are used (Table 7.5-1). These parameters appear in the denominator of the model equations and if the very low parameter values are used, the equations would produce unreasonably high results. Thus, input parameters representative of periods other than a year or representative of individual people, dwellings, cultivated fields, or other items may cause invalid results. For example, using a minimum daily wind speed rather than the average annual wind speed in Equation 6.4.6-3 would result in invalid output.

Table 7.5-1. Unreasonable Parameters Input Values

Parameter name	Used in Equation	Discussion
Evaporative cooler air flow rates	6.4.2-3	Unreasonably low air flow rates would result in invalid, high concentrations of radionuclides in indoor air. Typical air flow rates for evaporative coolers range from about 2,000 to 10,000 m^3/h (BSC 2004 [DIRS 169672] Section 6.5.2). Much lower rates are unreasonable because building cooling would be ineffective.
House ventilation rate	6.4.2-7 6.4.2-8	Unreasonably low house ventilation rates would result in an accumulation of indoor radon and high estimates of indoor radon concentrations. Typical ventilation rates are about 0.5 exchanges per hour or greater (BSC 2004 [DIRS 169672], Section 6.6.2), and according to the *Manufactured Home Construction and Safety Standards*, the whole house ventilation rate for manufactured homes should be at least 0.35 air exchanges per hour (24 CFR 3280.103(b) [DIRS 180843]).
Crop wet yield	6.4.3-3 6.4.3-6 6.5.3-3	Very low values of crop yield would result in invalid, high estimates of radionuclide concentrations in crops. Typical values of average annual yield for all production in a region range from about 1 to 8 kg/m^2 for leafy vegetables to 0.3 to 1.2 kg/m^2 for grain (BSC 2004 [DIRS 169673], Section 6.11). Much lower values are unreasonable because few or no contaminated foodstuffs would be available for consumption.
Annual average wind speed	6.4.3-3	Very low wind speeds, such as daily minimum wind speeds or wind speeds on very calm days, would result in an invalid, high estimate of the annual average ^{14}C concentration in air. Parameter values must represent annual average speeds to ensure that a reasonable annual average concentration is calculated. In addition, mixing of ^{14}C in the atmospheric boundary layer would occur even on calm days.
Fraction of stable carbon in soil	6.4.6-4	If the fraction of stable carbon in the soil is zero, calculations of root uptake of ^{14}C in crops would be invalid. This value is unreasonable because there is always some stable carbon in the soil.
Concentration of stable carbon in air	6.4.6-5	If the fraction of stable carbon in the air is zero, calculations of leaf uptake of ^{14}C in crops would be invalid. This value is unreasonable because there is always some stable carbon in the air.

7.6 EXTERNAL REVIEW OF THE ERMYN MODEL

At the conclusion of the initial model development (Revision 00), an external review was conducted by J. I. Daniels (D.Env.) of the Environmental Science Division in the Energy & Environment Directorate of the Lawrence Livermore National Laboratory in accordance with the procedure governing models in effect at the time of the review (see also Section 7.1.1). The findings of this review (Daniels 2003 [DIRS 163016]) add to confidence in the model. The external review concluded:

> The ERMYN model is a more complete biosphere modeling tool than its predecessor. It is well constructed, it conforms to design requirements prescribed by site-specific features, events, and processes, and it is appropriate for the specified human receptor (the reasonably maximally exposed individual). The model contains a thorough assembly of applicable multimedia, multipathway exposure-related processes, and it uses a credible dose-assessment strategy using reliably calculated, acceptable, and applicable biosphere dose conversion factors for the radionuclides of interest. The authors provide a more transparent framework and a better explanation of the applicability and validity of the submodels, and they better document the assumptions.
>
> The ERMYN model contains several new exposure pathways, including inhalation of aerosols generated by residential evaporative cooling, animal soil ingestion, and radon-

> gas inhalation, particularly from surface deposited ^{226}Ra. The outputs (biosphere dose conversion factors) are understandable and appropriate, and I agree that differences in biosphere dose conversion factors between those generated by the ERMYN model and those produced by the earlier model are reasonable and can be explained by changes in the input parameters necessary to accommodate the ERMYN model framework. Thus, the ERMYN model displays progress and commitment to applying a scientifically defensible approach to a comprehensive assessment of the biosphere as a consequence of a potential release of radionuclides from the proposed repository.
>
> Accordingly, the ERMYN model is an improvement over the previous model. Furthermore, the modeling deficiencies noted in the *Model Validation Status Review* technical report have been addressed adequately through the construction and description of the ERMYN model.

As discussed in Section 7.1.2, the modifications of that model, described in this report, were primarily concerned with the removal of the modeling assumption defining the level of radioactive equilibrium in the surface soil for the groundwater exposure scenario model. Although the surface soil model described in this report does not use this assumption, the underlying conceptual and mathematical models in both biosphere model revisions remain the same. Therefore, the findings of the technical review described above are still applicable.

7.7 SUMMARY OF MODEL VALIDATION

Requirements for confidence building during model development (Section 7.1.1) have been satisfied. The descriptions of the comparisons between various representations of the many biosphere processes in the previous sections demonstrate that there is a great deal of commonality in the approaches used in the various models. This is because the radiological assessment methods used in biosphere modeling are mature and widely used by the scientific community. Because there are few differences in the methods used in modeling the biosphere processes and their resulting predictions, the methods used in the ERMYN are considered valid and accepted by the scientific community, and the results are consistent with the results generated by other process-level models.

Also, the post-development validation requirement defined in Section 7.1.2 has been fulfilled, including corroboration of model results with the alternative conceptual models. The model development and post-development validation activities described establish the scientific bases for the biosphere model. No future activities need to be accomplished for model validation. Based on this, the biosphere model is considered to be adequate and sufficiently accurate for the intended purpose and validated to the level of confidence required by the model's relative importance to the potential performance of the repository system.

8. CONCLUSIONS

This report documents the development of the ERMYN biosphere model, which supports the TSPA. The reference biosphere, the human receptor, two exposure scenarios, and the primary radionuclides used in the model are described. The conceptual model incorporates site-specific FEPs, the requirements for the site-specific reference biosphere, a theoretical human receptor, and justifiable assumptions. The mathematical model is constructed based on the conceptual model, site-specific information, and other information from five published models. The mathematical model input parameters are described. The GoldSim stochastic simulation software package is used for building the ERMYN implementation tool. The ERMYN implementation tool (i.e., the constructed ERMYN) is verified by comparing outputs with hand calculations to ensure that the GoldSim implementation works in the manner described by the mathematical model. The ERMYN is validated by corroboration of conceptual models, mathematical models, and the necessary numerical results. The NRC acceptance criteria (NRC 2003 [DIRS 163274], Sections 2.2.1.3.13 and 2.2.1.3.14) listed in Section 4.2 are addressed in detail in Section 6. The model and model inputs are discussed in Sections 6.3 to 6.5. Uncertainty in the model and input parameters is discussed in Section 6.6, and it is also considered in the model implementation in Sections 6.8 and 6.9. The subject of model and parametric uncertainty is expanded in Sections 6.13 and 6.14, which contain the results of uncertainty and sensitivity analyses for the BDCFs. Model verification is described in Section 6.10.

8.1 MODEL AND OTHER OUTPUTS

There are several outputs of this model report. The outputs that constitute TSPA input are discussed in Section 8.1.1. The other outputs of this report are listed in Section 8.1.2.

8.1.1 TSPA Inputs

The DTNs that contain the information used in the TSPA model are listed in Table 8-1. The biosphere TSPA inputs include the groundwater and volcanic BDCFs, which are the outputs of the biosphere model. The BDCFs are used in the TSPA model to calculate the annual dose to the RMEI for evaluation of compliance with the individual protection standards. The other TSPA inputs are the conversion factors, which are used in evaluating compliance with the groundwater protection standards. The biosphere model is not used to develop these conversion factors. In addition, the inhalation dose factor provides the means of evaluating inhalation dose during a volcanic eruption.

Table 8-1. Biosphere Inputs to TSPA

DTN	DTN Title	DTN Description and Comments
MO0702PAGBDCFS.001	Groundwater Biosphere Dose Conversion Factors	BDCFs for the groundwater exposure scenario (groundwater BDCFs)
MO0702PAVBPDCF.000	Volcanic Biosphere Dose Conversion Factors	BDCFs for the volcanic ash exposure scenario (volcanic BDCFs)
MO0702PAGWPROS.001	Groundwater Protection Standards Conversion Factors	This DTN contains the following data: – Conversion factors for organs or whole body for calculating beta-photon dose from drinking 2L/d of water – Multipliers to be used with activity concentration of a primary radionuclide in groundwater to obtain alpha activity concentration associated with this radionuclide
MO0702PAINHALA.001	Inhalation Dose Factors	Inhalation dose factor for calculating doses from daily exposure to a given concentration of radionuclides in the air

8.1.2 Other Model Outputs

The other biosphere model outputs that are not used in the TSPA are the two biosphere model implementation tools: for the groundwater exposure scenario (*ERMYN_GW_Rev01.gsm*) and for the volcanic ash exposure scenario (*ERMYN_VA_Rev01.gsm*). These model files were used to calculate the groundwater and volcanic BDCFs. The model runs, including the results that constitute the TSPA inputs as well as the intermediate results that are used to conduct the pathway, uncertainty, and sensitivity analyses, are contained in a separate DTN (Table 8-2).

Table 8-2. Other Outputs of Biosphere Model Report

DTN	DTN Title	DTN Description and Comments
MO0705GOLDSIMB.000	GoldSim Biosphere Model Files for Calculating Groundwater and Volcanic Biosphere Dose Conversion Factors	This data set contains GoldSim biosphere model files for calculating groundwater and volcanic BDCFs with consideration of climate change (present-day climate and upper bound of the glacial transition climate).
MO0705GOLDSIMA.000	GoldSim Biosphere Model Base Files for Groundwater and Volcanic Ash Exposure Scenarios	This DTN contains the basic GoldSim biosphere model implementation files: for the groundwater exposure scenario (*ERMYN_GW_Rev01.gsm*) and for the volcanic ash exposure scenario (*ERMYN_VA_Rev01.gsm*).

8.2 BIOSPHERE MODEL LIMITATIONS

The biosphere model applies to the specific environment identified in 10 CFR 63.305 and the receptor identified in 10 CFR 63.312 [DIRS 173273]. It uses certain assumptions and simplifications that are appropriate for these regulatory requirements. Therefore, the model only applies within the assessment context for which it was constructed. If used for other situations, the BDCFs may not apply. The model applies to assessing chronic radiation doses.

The radionuclide sources for the biosphere model are specific to the two exposure scenarios considered (contaminated groundwater and contaminated volcanic ash deposited on the ground). Although the mathematical models described in Sections 6.4 and 6.5 apply to all radionuclides, the ERMYN focuses on the radionuclides that were screened for the TSPA (DTN: MO0701RLTSCRNA.000 [DIRS 179334]). This model is valid for values of input parameters reasonably expected to occur in the arid to semi-arid region surrounding Yucca Mountain. Users should be aware that some unreasonable input parameters values could produce invalid results (Section 7.6).

For the groundwater exposure scenario, ERMYN applies to an agricultural situation with long-term irrigation and ensuing soil contamination. If the irrigation duration is less than that assumed for the model, ERMYN might overestimate the radiation dose for some radionuclides. The biosphere model applies to an arid or semi-arid climate (Section 6.1.1.1), and it is valid only for limited groundwater discharge to the surface and limited surface water transport, as long as the radionuclide concentration in the surface water is the same as in the groundwater, and the reference biosphere is not greatly altered. For example, if permanent surface waters such as rivers or lakes are present, the environment would be sufficiently different to change the reference biosphere, and other radionuclide transport and receptor exposure pathways would have to be added for the ERMYN to remain valid.

For the volcanic ash exposure scenario, the model applies to either small ash particles that could be resuspended into the air or to the soil that became contaminated by volcanic ash. The contaminant could be deposited directly on the land surface or redistributed by wind or water from other locations. The model does not apply to other volcanic media, such as contaminated gas, lava, or coarse tephra. Some assumptions (Assumptions 12 and 15) used in the model development are based on ash deposits that are relatively thin and do not substantially change soil properties. However, these are justified considering the distribution of ash thickness predicted by the TSPA model to occur at the location of the RMEI (Appendix G). In addition, the ERMYN model does not apply for the period during a volcanic eruption, before settling of ash on the ground. If radionuclide concentrations in the air and the exposure time are known, a dose assessment for this period can be estimated using the inhalation dose factors.

8.3 HOW ACCEPTANCE CRITERIA WERE ADDRESSED

The following information describes how this analysis addresses the acceptance criteria in *Yucca Mountain Review Plan Final Report* (NRC 2003 [DIRS 163274], Sections 2.2.1.3.13 and 2.2.1.3.14). Only those acceptance criteria that are applicable to this report (Section 4.2) are discussed. In most cases, the applicable acceptance criteria are not addressed solely by this report; rather, the acceptance criteria are fully addressed when this report is considered in conjunction with other analysis and model reports that describe the Yucca Mountain biosphere model and its input parameters.. Where a subcriterion includes several components, only some of those components may be addressed. How these components are addressed is summarized below.

Acceptance Criteria from Section 2.2.1.3.13, *Redistribution of Radionuclides in Soil*

Acceptance Criterion 1, **System Description and Model Integration are Adequate**

Subcriterion (1): This model, which supports the TSPA, incorporates relevant important features, physical phenomena, and couplings related to redistribution of radionuclides in soil. Section 6.2 describes how the FEPs related to the biosphere were identified and why they are important. The included FEPs and the reasons for their inclusion are listed in Table 6.2-1. Section 6.3.1 explains how connected sequences of FEPs were used to construct the exposure scenarios. Section 6.3.1.2 identifies the components of the biosphere model. Section 6.3.4 and Table 6.3-6 show how the FEPs were mapped into the submodel constituents of the biosphere model to ensure that it addresses all of the included FEPs. Section 6.7 describes how these FEPs are dispositioned in the base case model.

Sections 6.3.1.4 and 6.3.2.4 discuss the assumptions incorporated in the groundwater and volcanic biosphere models. For each assumption, a rationale is provided for its basis and cross-references are provided to where it is used in the model. Because this model calculates BDCFs (the annual dose per unit concentration of radionuclides) that are independent of the concentration of the radionuclides, there are few assumptions that are shared with other TSPA process models. Those that are shared, such as amount of ash expected to be deposited at the receptor location (Section 6.5.1) are consistent and traceable to a common source with those other process models.

Subcriterion (2): Section 6.3.1.6 describes the conceptual model for the groundwater scenario and includes the supporting technical bases. Section 6.3.2.6 provides the equivalent information for the volcanic ash scenario. Included are the groundwater scenario submodels required to account for the radionuclides accumulation and removal processes in surface soil and depth distribution of radionuclides. Important individual components are rates of irrigation with water containing radionuclides and the removal mechanisms of decay, leaching, and erosion. For the biosphere model, soil is divided into the surface soil layer encompassing the crop root zone and the deep soil where radionuclides are assumed inaccessible to plants and other redistribution mechanisms. Radionuclide concentrations in the surface soil layer are discussed in Section 6.4.1 for the groundwater scenario and Section 6.5.1 for the volcanic ash scenario.

Subcriterion (3): Section 6.2 describes how the important FEPs related to redistribution of radionuclides from surface processes were identified. The included FEPs and the reasons for their inclusion are noted in Table 6.2-1. Of these FEPs, many are associated with radionuclide redistribution in soil for the groundwater scenario. The models and their technical bases developed to predict the redistribution of radionuclides are discussed in Sections 6.4.1 and 6.4.2. For the volcanic scenario, the appropriate sections are 6.5.1 and 6.5.2.

Acceptance Criterion 2, Data are Sufficient for Model Justification

Subcriterion (1): Applicable behavioral, hydrological, and geochemical values used in developing this model and its input parameters are described and justified in Section 6. Section 4.1 explains that this biosphere model report describes the development and validation of the base case model, but that this report does not include a description of the development of the hundreds of input parameters used in the model. The descriptions of how the data with the attendant uncertainty were used, interpreted, and synthesized into the model are provided in Section 6. Justifications for the input parameter values used are developed in the five separate input analysis reports, which are related to this report, as shown in Figure 1-1.

Subcriterion (2): The conceptual model and the model input parameters were developed based on the data that appropriately characterized site specific conditions. Natural analogue data and site-specific experiments were used for that purpose. The model parameters related to the redistribution of radionuclides in the soil are described in the separate analysis report depicted in Figure 1-1.

Acceptance Criterion 3, Data Uncertainty is Characterized and Propagated through the Model Abstraction

Subcriterion (1): Section 4.1 explains that parameter values are developed in related reports, which show that assumed ranges, probability distributions, and bounding assumptions are technically defensible; reasonably account for uncertainties; and are consistent with the requirements for the reference biosphere and for the RMEI. Technical review activities for the ERMYN included an international peer review of the previous biosphere model by an IAEA International Review Team (IAEA 2001 [DIRS 155188]) and a technical review of the ERMYN implementation by another expert at Lawrence Livermore National Laboratory (Daniels 2003 [DIRS 163016]). These reviews and the empirical nature of the data and parameters that are employed by the model ensure that use of the model presents an accurate representation of the processes by which radionuclides in the soil expose individuals to doses from radioactivity. This process also ensures that the model does not result in an under-representation of the risk estimate.

Subcriterion (2): Section 4.1 explains that parameter values and ranges in the abstractions are developed in related reports specific to Yucca Mountain, which show that the parameter values are consistent with site characterization data, applicable laboratory testings, and natural analogs and are technically defensible. Section 6.4.1 presents the model developed to predict the radionuclide accumulation in soil for the groundwater scenario. Section 6.5.1 provides the approach to modeling radionuclides in soil after an ashfall. The input parameters developed for these submodels include site specific information on soil (SNL 2007 [DIRS 179993]) and current farming practices (BSC 2004 [DIRS 169673]). This model fulfills the requirements in 10 CFR 63.312 [DIRS 173273] by calculating exposure using receptor-specific external exposure times, inhalation exposure times, food consumption rates, and resuspension of soil particles and level of disturbance expected in the location of the RMEI. Among the factors considered are diet, gardens, employment, commute time, housing type, metabolism, and physiology.

Subcriterion (3): Uncertainty is represented in parameter development for the conceptual model related to redistribution of radionuclides in soil through adoption of a conservative approach of long-term irrigation, which results in radionuclide soil buildup. Also, the model developed in Section 6 has the capability to stochastically sample all of those parameters that are represented by statistical distributions. Section 6.6.3 identifies those parameters that are represented in the model by distributions and provides details of the uncertainty in Table 6.6-3, where the correlation between stochastic variables is also identified. Thus, the model and the modeling results that are the output for this effort include the consideration for parametric uncertainty inherent in the redistribution of radionuclides in soil. Uncertainty in the parameters developed in related process models that feed the TSPA is discussed in the other process model reports. Parameters for alternative conceptual models discussed in this report were typically those used in the conceptual model, and the uncertainties would be the same as those for the parameters in the conceptual model (Section 6.6.3).

Subcriterion (4): Parameters that are important for determining redistribution of radionuclides in soil were identified and implemented in the surface soil submodel (Section 6.4.1). These parameters include those related to repository performance measure (e.g., groundwater concentrations) and the characteristics of the local soils and agriculture. The discussion of importance of the soil submodel parameters is presented in Sections 6.13.4.1 and 6.14.4.1.

Acceptance Criterion 4, Model Uncertainty is Characterized and Propagated through the Model Abstraction

Subcriterion (1): As explained in Sections 6.3.4 and 6.6.1, the biosphere model is based on the inclusion of all potentially significant FEPs. Alternative models for the FEPs considered are discussed in Section 6.3.3 (Table 6.3-5). The discussion in Table 6.3-5 indicates that the approaches are consistent with available data and current scientific understanding. Results of the alternative models in Table 6.3-5 are typically shown to be comparable to those of the conceptual model (ERMYN), but the alternative models were less consistent with available data and scientific understanding or do not have an important effect on the model results.

Subcriterion (2): Seven existing, published ACMs are addressed in Section 6.3.3 for various submodels and submodel components, features and processes. These ACMs are either conceptually or mathematically different from the base-case model alternatives. The ACMs were screened and evaluated qualitatively and quantitatively, and results using mathematical representations of them are compared with the results for the base case model in Section 7.3. Justifications for not adopting the ACMs into the base case model are provided in Sections 7.3 and 7.4.

Subcriterion (3): Conceptual model uncertainty is discussed in general in Section 6.6.1. As stated in section 6.6.1, all applicable human exposure pathways were considered during development of the conceptual model (Sections 6.3.1 and 6.3.2), and only applicable pathways shown to have little influence on the results are excluded. Uncertainties in the conceptual model are consistent with those of available Yucca Mountain data, related laboratory experiments, field measurements, natural analog information, and process-level modeling studies (Section 6.6.1). Uncertainty in mathematical models is discussed in Section 6.6.2. Uncertainties in the model assumptions are discussed qualitatively and their magnitudes and impacts are such that the dose to the RMEI is not underrepresented, as shown in Table 6.6-1. Section 6.6.4 explains how uncertainty in model results is taken into account. This stochastic approach, which uses the reasonably conservative model approximations discussed in Section 6.6.2, produces results that do not under-represent the risk estimate.

Acceptance Criterion 5, Model Abstraction Output is Supported by Objective Comparisons

Subcriterion (1): The individual models developed in Section 6 to quantify the movement of radionuclides between the various biosphere compartments are based on empirical observations (e.g., transfer factors, accumulation factors, transfer coefficients, etc.) and, as such, are consistent with the laboratory testing, field measurements, and natural analogs from which they were derived.

Acceptance Criteria from Section 2.2.1.3.14, *Biosphere Characteristics*

Acceptance Criterion 1, System Description and Model Integration are Adequate

Subcriterion (1): The biosphere model incorporates important site features, physical phenomena, and couplings as shown in Section 6.2, which describes how the FEPs related to the biosphere were identified. The included FEPs and the reasons for their inclusion are in Table 6.2-1. Section 6.3.1 explains how connected sequences of FEPs were used to construct the exposure scenarios. Section 6.3.1.2 identifies the components of the biosphere model. Section 6.3.4 and Table 6.3-6 show how the FEPs were mapped into the submodel constituents of the biosphere model to ensure that it addresses all of the included FEPs. Section 6.7 describes how these FEPs are dispositioned in the base case model.

Section 6.3.1.4 discusses the assumptions and simplifications that were determined to be appropriate and that were applied consistently throughout the biosphere modeling abstraction process. For each assumption, a rationale is provided for its basis, and cross-references are provided to where it is used in the model.

Subcriterion (2): Section 6.1.1 describes how the model abstraction identifies and describes aspects of the biosphere characteristics modeling that are important to repository performance, and includes the technical bases for these descriptions. Section 6.1.1.1 addresses site geography, geology, and physiology; Section 6.1.1.2 addresses site climate, flora, and fauna; and Section 6.1.1.3 addresses groundwater, human activities, and agriculture in the Yucca Mountain vicinity.

Section 6.3.1.6 describes the conceptual model for the groundwater scenario and includes the supporting technical bases consistent with arid to semi-arid conditions (Section 6.3). Included are the submodels for the groundwater source, surface soil, air, plant uptake, animal uptake, fish, ^{14}C, external exposure, inhalation, and ingestion. Section 6.3.2.1 describes the conceptual model for the volcanic ash exposure scenario.

Subcriterion (3): Assumptions employed in the biosphere model are consistent with the assumptions made in other abstractions. Section 6.2 describes how the FEPs related to the biosphere were identified and included. A few of these FEPs are shared with the other modeling areas. Because the biosphere model calculates BDCFs (the annual dose per unit concentration of radionuclides) that are independent of the concentration of the radionuclides, most assumptions are specific to this model and are not shared with other TSPA process models. Those that are shared generally pertain to characteristics of the reference biosphere and climate and are consistent across other process models incorporated in the TSPA.

Acceptance Criterion 2, Data are Sufficient for Model Justification

Subcriterion (1): Applicable behavioral values used in developing this model are justified in Section 6 and are consistent with the definition of the RMEI. Section 4.1 explains that this biosphere model report describes the development and validation of the base case model, but that this report does not include a description of the development of the hundreds of input parameters used in the model. Descriptions of how the data with the attendant uncertainty were used, interpreted, and appropriately synthesized into the model are provided in Section 6. Justifications for the input parameter values used are developed in the five separate input analysis reports, which are related to this report as shown in Figure 1-1.

Subcriterion (2): Section 6.2 describes the features, events, and processes that have been considered and incorporated in the biosphere model. Table 6.2-1 discusses each of the FEPs considered, their characteristics, and provides an explanation for their applicability within the model. This table also presents the basis for the FEPs, which indicates that they are consistent with present knowledge of conditions in the Yucca Mountain region. The descriptions of how the data with the attendant uncertainty were used, interpreted, and synthesized into the model are provided in Section 6. The input parameter values used in the biosphere model are developed and justified in the five separate input analysis reports, which are related to this report, as shown in Figure 1-1.

Acceptance Criterion 3, Data Uncertainty is Characterized and Propagated through the Model Abstraction

Subcriterion (1): Section 4.1 explains that parameter values are developed in related reports, which document that assumed ranges, probability distributions and assumptions are technically defensible, reasonably account for uncertainties, and are consistent with the requirements for the reference biosphere and the RMEI. The mathematical model, as implemented in GoldSim (Section 6.8), has the capability of representing any input parameter by a predefined distribution. This approach allows a stochastic approach to be adopted where uncertainty and variability in the input parameters can be propagated to the end results (BDCFs) while retaining the correlation of inputs for each radionuclide so modeled. The five parameter-generating reports (Figure 1-1) focus on deriving site, climate, and receptor specific input parameter distributions from site data, scientific analysis, and natural analog information that are technically defensible.

Technical review activities for the ERMYN included an international peer review of the previous biosphere model by an IAEA International Review Team (IAEA 2001 [DIRS 155188]) and a technical review of the ERMYN implementation by another expert at Lawrence Livermore National Laboratory (Daniels 2003 [DIRS 163016]). These reviews and the empirical nature of the data and parameters that will be employed by the model ensure that use of the model presents an accurate representation of the processes by which radionuclides in the soil expose individuals to doses from radioactivity. This process also ensures that the model does not result in an under-representation of the risk estimate.

Subcriterion (2): The technical bases for the parameter values and ranges in the abstraction were developed based on the appropriate natural analogue, site-specific, and generic data and are consistent with site characterization data, and are technically defensible. The majority of input parameter values used in the biosphere model are developed and justified in the five separate input analysis reports, which are related to this report, as shown in Figure 1-1.

Subcriterion (3): Parameter values for the biosphere characteristics modeling are primarily based on the appropriate values reported in published literature sources for natural analogues and on site-specific measurements and are consistent with site characterization data, field measurements, and natural analog research. The majority of parameter values are described in the five separate documents, shown in Figure 1-1.

Subcriterion (4): Uncertainty is included in the conceptual model and parameters related to biosphere characteristics through adoption of a cautious but reasonable approach and/or bounding values. Also, the model developed in Section 6 has the capability to stochastically sample all parameters that are represented by statistical distributions. Section 6.6.3 identifies those parameters that are represented in the model by distributions and provides details of the uncertainty in Table 6.6-3, where the correlation, if any, between stochastic model parameters is identified. Thus, the model as well as the model results that are the product output for this effort are generated with due consideration for parametric uncertainty inherent in the biosphere characteristics.

Subcriterion (6): Parameters and models that are important for determining biosphere characteristics were identified and implemented in the various submodels (Sections 6.4 and 6.5). Section 6.3.3 discusses those alternate submodels and parameters that were considered to not be important in determining dose.

Acceptance Criterion 4, Model Uncertainty is Characterized and Propagated through the Model Abstraction

Subcriterion (1): Seven alternate modeling approaches of FEPs are analyzed in Section 6.3.3. Section 7.3 compares the current GoldSim model with other models and submodels, including those that are considered as alternate models. These approaches are consistent with current scientific understanding and characteristics of the Yucca Mountain region. In many cases, the fundamental models in use by the radiological protection community have general acceptance and, as a result, are not subject to having alternative approaches. Differences between the models were identified and are discussed in Section 7.3. The stochastic approach described in Sections 6.8 and 6.9 allow the defined uncertainty and variability in parameters (including those parameters necessary to characterize the RMEI from the available data on the Amargosa Valley residents) to be propagated to the model output.

Subcriterion (2): Seven alternate conceptual models are discussed in Section 6.3.3. Section 7.3 compares the model implemented in GoldSim to represent the Yucca Mountain biosphere with a suite of other models that have been independently developed to perform similar radiological assessments of doses from radionuclides introduced into the accessible environment. Processes considered include plant and animal uptake, human ingestion of water and locally produced food, soil resuspension, and inhalation dose for both scenarios. In many cases, each of the modeling capabilities identified employ the same model for a process. In these cases, it is considered that the models are accepted and no alternative conceptual model is required. In those cases where the modeling approaches were not identical, these other methodologies were evaluated and justification was provided for selection of the included method.

Subcriterion (3): Conceptual model uncertainty is discussed in general in Section 6.6.1. As stated in section 6.6.1, all applicable human exposure pathways were considered during development of the conceptual model (Sections 6.3.1 and 6.3.2), and only applicable pathways shown to have little influence on the results are excluded. For example, air submersion and water immersion pathways are not included because numerical comparisons indicate that they are not important when compared with the included pathways. By virtue of the general acceptance of the individual submodels (Section 7.3) and the discussions of conceptual model uncertainty (Section 6.6.1) and mathematical model uncertainty (Section 6.6.2) with the approach to their development being reasonable but cautions, the dominant contribution to total uncertainty arises from parametric uncertainty and variability. Uncertainties in the conceptual model are consistent with those of available Yucca Mountain data, related laboratory experiments, field measurements, natural analog information, and process-level modeling studies (Sections 6.4 through 6.6). As a result, risk (dose) estimates based on the BDCFs provided to the TSPA compliance calculations do not result in an under representation of risk.

Acceptance Criterion 5, Model Abstraction Output is Supported by Objective Comparisons

Subcriterion (1): The biosphere model provides the total system performance assessment the capability of calculating dose arising from two sources of radionuclides in the biosphere. The model developed in Section 6 is based upon accepted radiological transport predictive practices. The parameters and submodels reflect many simple linear relationships that are based upon experimental data and, as such, have an empirical basis. Accordingly, this model provides a mechanism for the TSPA abstraction to determine dose levels based on empirical observations.

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9.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

10 CFR 63. 2005. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. ACC: MOL.20050405.0118. 173273

24 CFR 3280. 2006. Housing and Urban Development: Manufactured Home Construction and Safety Standards. 180843

40 CFR 141. 2004. Protection of Environment: National Primary Drinking Water Regulations. ACC: MOL.20050331.0079. 173245

66 FR 32074. 40 CFR Part 197, Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV; Final Rule. ACC: MOL.20050418.0113. 155216

66 FR 55732. Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, NV, Final Rule. 10 CFR Parts 2, 19, 20, 21, 30, 40, 51, 60, 61, 63, 70, 72, 73, and 75. ACC: MOL.20050324.0102; MOL.20050418.0124. 156671

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NWI-RSD-002Q, *Scientific Investigation of Economic, Demographic, and Agricultural Characteristics of the Vicinity of Yucca Mountain.*

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SCI-PRO-002, *Planning for Science Activities.*

SCI-PRO-006, *Models.*

SO-PRO-001, *Peer Review.*

9.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

LA0612DK831811.001. Magma and Eruption Properties for Potential Volcano at Yucca Mountain. Submittal date: 03/23/2007. 179987

LA0702PADE03GK.002. Input Parameter Values for ASHPLUME V2.1_DLL_LA Model for TSPA. Submittal date: 03/23/2007. 179980

MO0008SPATSP00.013. Total Suspended Particle Concentrations - Washington 1979-1982. Submittal date: 08/02/2000. 151750

MO0009YMP00093.000. Great Basin and Basin and Range Province. Submittal date: 09/06/2000. 154403

MO0403SPAAEIBM.002. Agricultural and Environmental Input Parameters for the Biosphere Model. Submittal date: 03/22/2004. 169392

MO0406SPAETPBM.002. Environmental Transport Input Parameters for the Biosphere Model. Submittal date: 06/24/2004. 170150

MO0407SPACRBSM.002. Characteristics of the Receptor for the Biosphere Model. Submittal date: 07/19/2004. 170677

MO0408SPADRWSD.002 Desert Rock Wind Speed and Wind Direction Analyses for Years 1978-2006. Submittal date: 08/19/2004 171751

MO0503SPADCESR.000. Dose Coefficients for Internal and External Exposure to Selected Radionuclides Consistent with ICRP 72 Dosimetric Methods. Submittal date: 08/22/2005. 172896

MO0605SPAINEXI.003. Inhalation Exposure Input Parameters for the Biosphere Model. Submittal date: 05/04/2006. 177172

MO0609SPASRPBM.004. Soil Related Parameters for the Biosphere Model. Submittal date: 03/28/2007. 179988

MO0701RLTSCRNA.000. Results of Screening Analysis. Submittal date: 01/30/2007. 179334

MO0706SPAFEPLA.001 . FY 2007 LA FEP List and Screening. Submittal date: 06/20/2007. 181613

9.4 OUTPUT DATA, LISTED BY DATA TRACKING NUMBER

MO0702PAGBDCFS.001	Groundwater Biosphere Dose Conversion Factors.
MO0702PAVBPDCF.000	Volcanic Biosphere Dose Conversion Factors.
MO0702PAGWPROS.001	Groundwater Protection Standards Conversion Factors.
MO0702PAINHALA.001	Inhalation Dose Factors.
MO0705GOLDSIMB.000	GoldSim Biosphere Model Files for Calculating Groundwater and Volcanic Biosphere Dose Conversion Factors.
MO0705GOLDSIMA.000	GoldSim Biosphere Model Base Files for Groundwater and Volcanic Ash Exposure Scenarios.

9.5 SOFTWARE CODES

ASHPLUME_DLL_LA V2.1. WINDOWS 2000. STN: 11117-2.1-00. 178870

GoldSim V. 8.02.500. 2005. WINDOWS 2000. STN: 10344-8.02-05. 174650

GoldSim V. 9.60. 2007. WINDOWS 2000. WINDOWS XP, WINDOWS 2003. STN: 10344-9.60-00. 180224

Software Code: GENII-S V1.4.8.5 VV1.4.8.5. 1998. PC, Windows NT. 30034 V1.4.8.5. 117076

APPENDIX A
ELECTRONIC FILES USED FOR THE MODEL REPORT

ELECTRONIC FILES USED FOR THE MODEL REPORT

This appendix lists all of the electronic files generated for this report in addition to the files included in the output DTNs. All of the files are stored on a data compact disk titled *BioModFiles*. The CD includes Excel files and GoldSim files used in the sensitivity and confirmatory analyses.

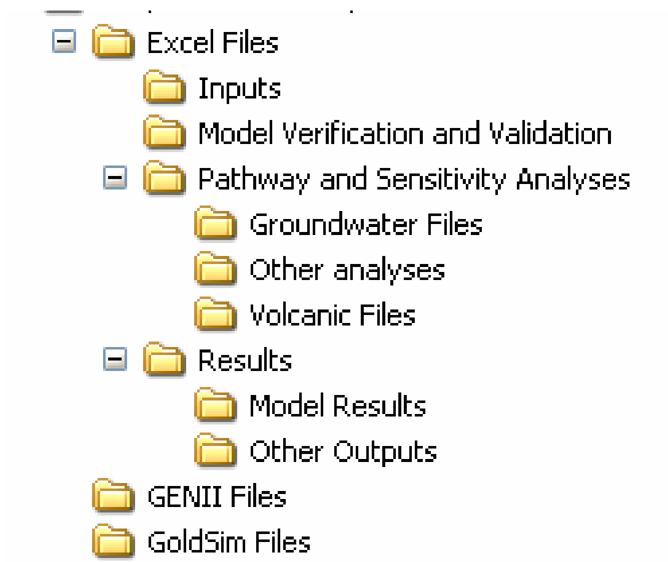

Figure A-1. Directories with Files that Accompany Biosphere Model Report

For each file in the folders shown in Figure A-1, Table A-1 lists the file name, size, type, and date modified. The purpose of each file is explained below. The sources of data that were used in the calculations are listed in the individual files. The Excel files use only standard functions of Excel and do not contain any macros.

The use of software that was used to generate the files listed in this section is discussed in Section 3.

Table A-1. List of Files Included on Compact Disk

Path	**Files**

Excel Files
  Inputs

Name	Size	Type	Date Modified
Calculation_Annual Irrigation.xls	19 KB	Microsoft Excel Worksheet	5/15/2007 12:47 PM
Calculation_Effective Dose Coefficients.xls	71 KB	Microsoft Excel Worksheet	6/21/2007 11:03 AM
Water Interception Fraction.xls	168 KB	Microsoft Excel Worksheet	6/21/2007 4:19 PM

Excel Files
  Model Verification and Validation

Name	Size	Type	Date Modified
ERMYN Validation.xls	77 KB	Microsoft Excel Worksheet	6/21/2007 4:22 PM
ERMYN Validation_Soil Model.xls	392 KB	Microsoft Excel Worksheet	5/9/2007 3:22 PM
ERMYN Verification.xls	267 KB	Microsoft Excel Worksheet	6/21/2007 11:27 AM
Validation_Effective Dose Coefficients.xls	84 KB	Microsoft Excel Worksheet	5/4/2007 4:24 PM

Excel Files
  Pathway and Sensitivity Analyses
    Groundwater Files

Name	Size	Type	Date Modified
Correlations for GW BDCFs PDC.xls	835 KB	Microsoft Excel Worksheet	6/21/2007 5:04 PM
Dependence of GW BDCFs on Inputs_Part 1.xls	1,549 KB	Microsoft Excel Worksheet	8/10/2007 10:23 AM
Dependence of GW BDCFs on Inputs_Part 2.xls	2,337 KB	Microsoft Excel Worksheet	8/13/2007 1:47 PM
Dependence of GW BDCFs on Inputs_Part 3.xls	1,934 KB	Microsoft Excel Worksheet	8/10/2007 10:23 AM
Detailed Pathway Analysis GW_PDC.xls	10,885 KB	Microsoft Excel Worksheet	7/20/2007 9:24 AM
GW BDCF Variability Plots.xls	3,401 KB	Microsoft Excel Worksheet	7/17/2007 5:51 PM
GW BDCFs Pathway Analysis FC.xls	13,048 KB	Microsoft Excel Worksheet	5/3/2007 4:11 PM
GW BDCFs Pathway Analysis PDC.xls	16,218 KB	Microsoft Excel Worksheet	5/9/2007 3:51 PM
GW PDC Correlations.xls	250 KB	Microsoft Excel Worksheet	5/3/2007 4:31 PM

Excel Files
  Pathway and Sensitivity Analyses
    Other Analyses

Name	Size	Type	Date Modified
Correlations for Climate Dependent Parameters.xls	1,052 KB	Microsoft Excel Worksheet	5/15/2007 12:47 PM
Dependence of BDCFs on Irrigation Rate.xls	191 KB	Microsoft Excel Worksheet	6/19/2007 2:05 PM
Random Seed Variations.xls	217 KB	Microsoft Excel Worksheet	6/12/2007 5:47 PM

Excel Files
  Pathway and Sensitivity Analyses
    Volcanic Files

Name	Size	Type	Date Modified
Ash at RMEI Results.xls	43 KB	Microsoft Excel Worksheet	6/28/2007 12:17 PM
Dependence of VA BDCFs on Inputs.xls	480 KB	Microsoft Excel Worksheet	5/3/2007 4:58 PM
Detailed Pathway Analysis VA.xls	3,343 KB	Microsoft Excel Worksheet	7/20/2007 5:27 PM
VA BDCF Pathway Analysis.xls	10,507 KB	Microsoft Excel Worksheet	5/16/2007 9:42 AM
VA BDCF Variability Plots.xls	137 KB	Microsoft Excel Worksheet	5/4/2007 7:28 AM
VA Correlations.xls	273 KB	Microsoft Excel Worksheet	6/14/2007 8:25 AM

Excel Files
  Results
    Model Results

Name	Size	Type	Date Modified
GW BDCFs Present-Day and Future Climates.xls	6,267 KB	Microsoft Excel Worksheet	5/3/2007 4:47 PM
VA BDCF Present-Day and Future Climates.xls	7,653 KB	Microsoft Excel Worksheet	5/20/2007 7:55 AM

Excel Files
  Results
    Other Outputs

Name	Size	Type	Date Modified
GW Protection Conversion Factors.xls	90 KB	Microsoft Excel Worksheet	1/31/2007 6:40 PM
Inhalation Dose Factor Calculations.xls	28 KB	Microsoft Excel Worksheet	2/13/2007 2:21 PM

GoldSim Files

Name	Size	Type	Date Modified
Ash at RMEI - 100rlz Ashplume v2-1.gsm	467 KB	GSM File	7/23/2007 7:10 AM
ERMYN_GW_Rev01_Base_Det.gsm	3,899 KB	GSM File	5/16/2007 7:29 AM
ERMYN_GW_Rev01_C14verf.gsm	3,902 KB	GSM File	5/16/2007 7:18 AM
ERMYN_GW_Rev01_Pu239verf.gsm	3,902 KB	GSM File	5/16/2007 7:17 AM
ERMYN_GW_Rev01_Ra226verf.gsm	3,902 KB	GSM File	5/16/2007 7:19 AM
ERMYN_GW_Rev01_Th232verf.gsm	3,902 KB	GSM File	5/16/2007 7:21 AM
ERMYN_VA_Rev01_Base_Det.gsm	2,376 KB	GSM File	5/16/2007 7:30 AM
ERMYN_VA_Rev01_Pu239verf.gsm	2,376 KB	GSM File	5/16/2007 7:23 AM
ERMYN_VA_Rev01_Ra226verf.gsm	2,376 KB	GSM File	5/16/2007 7:24 AM

GENII File

Name	Size	Type	Date Modified
RMDLIB.DAT	14 KB	DAT File	5/16/2007 8:03 AM

Excel Files → Inputs

Calculation_Annual Irrigation.xls—This file contains calculation of annual average irrigation rates for field and garden crops. It includes the data for the representative crops and the calculation of the weighting factors that quantifies the percentage of the acreage used to grow alfalfa and other field crops.

Calculation_Effective Dose Coefficients.xls—This file contains calculation of effective dose coefficients for radionuclide intakes by inhalation and ingestion and for external exposure. The effective dose coefficients incorporate contributions of short-lived decay products into a dose coefficient for a long-lived radionuclide (i.e., the radionuclide with a half-life greater than 180 days)

Water Interception Fraction.xls—This Excel file produces graphs of interception fractions appearing in Figure 6.13-23. Data in this spreadsheet were transferred from a groundwater GoldSim file (they appear in any groundwater exposure scenario model run).

Excel Files → Model Verification and Validation

ERMYN Validation.xls—This file contains numerical comparisons of ACMs with the equivalent calculations in ERMYN and other calculations supporting the model validation.

ERMYN Validation_Soil Model.xls—This file contains calculations of radionuclide concentration in soil for all primary radionuclides.

ERMYN Verification—This file contains deterministic calculations using biosphere model equations and representative parameter values for selected radionuclides. The results of these calculations are compared with the results of deterministic runs of ERMYN model. The calculations are performed for four radionuclides for the groundwater exposure scenario and two radionuclides for the volcanic ash exposure scenario.

Validation_Effective Dose Coefficients.xls—This file contains comparison of effective dose coefficients used in ERMYN with the equivalent dose coefficients used in RESRAD model.

Excel Files → Pathway and Sensitivity Analyses → Groundwater Files

Correlations for GW BDCFs PDC.xls—This file contains calculations of the correlation coefficients for groundwater exposure scenario BDCFs for different radionuclides for the present-day climate. The BDCF values were copied from the file *GW BDCFs Present-Day and Future Climates.xls*. The rows beneath the row below the correlation results contain supplementary calculations of the Student's *t* values for the range of correlation coefficient values.

Dependence of GW BDCFs on Inputs_Part 1.xls*; *Dependence of GW BDCFs on Inputs_Part 2.xls*; and *Dependence of GW BDCFs on Inputs_Part 3.xls—These files contain, in individual worksheets, the graphs, and the data used to prepare the graphs, that show the dependence of the groundwater exposure scenario BDCFs for selected radionuclides on the values of various input parameters. BDCF results for the groundwater scenario were copied from the appropriate GoldSim files provided in DTN: MO0705GOLDSIMB.000. The graphs were plotted using averaged values of the independent and dependent variables.

Detailed Pathway Analysis GW_PDC.xls—This file contains calculations of pathway contributions to groundwater exposure scenario BDCFs for the present-day climate. The file consists of worksheets containing the summary of the environmental transport pathway analysis, environmental transport pathway analysis for selected radionuclides, analysis of the inhalation and ingestion pathway, as well as the graphs showing pathway contributions for individual radionuclides. The results of model realizations were copied into the worksheets from the appropriate GoldSim files listed in the worksheets included in DTN: MO0705GOLDSIMB.000.

GW BDCF Variability Plots.xls—This file contains several worksheets showing statistics for the groundwater exposure scenario BDCFs and their pathway BDCFs and the graphs illustrating the variability and uncertainty in the BDCFs and their contributing pathways.

GW BDCF Pathway Analysis PDC.xls and ***GW BDCF Pathway Analysis FC.xls***—These Excel files contain calculations of pathway contributions to BDCFs for the present-day climate and upper bound of the glacial transition climate. The files contain worksheets for individual radionuclides and a summary worksheet. The first worksheet (*Pathway Summary*) contains the summary of the mean pathway BDCFs; the following worksheets contain the pathway BDCFs from individual realizations for radionuclides of interest, as well as their mean values. The pathway BDCF values were copied from GoldSim files included in DTN: MO0705GOLDSIMB.000. The *Pathway Summary* worksheet contains the summary of the mean values of pathway BDCFs for the individual radionuclides copied from the radionuclide worksheets as well as calculation of the fractional and percent contributions of the individual pathways to BDCFs.

GW PDC Correlations.xls—This file contains correlation coefficients for the stochastic model input parameters and BDCFs for the groundwater exposure scenario for the selected radionuclides. Data in this spreadsheet were transferred from the GoldSim files included in DTN: MO0705GOLDSIMB.000.

Excel Files → Pathway and Sensitivity Analyses → Other Analyses

Correlations for Climate Dependent Parameters.xls—This file contains calculations of correlation coefficients for the climate-dependent parameters and the BDCFs, which were calculated by replacing the values of climate-dependent parameters with uniform distributions between the values for the extreme climates (i.e., for the present-day climate and the upper bound of the glacial transition climate). The workbook consists of two worksheets: *Summary* and *Raw Correlations Calculation*.

Dependence of BDCFs on Irrigation Rate.xls—This file is used to generate graphs showing the linear dependence of BDCFs on annual average irrigation rate. These graphs appear in Figure 6.11-1.

Random Seed Variations.xls—This file includes the results and the associated statistics of BDCF runs using different random seeds.

Excel Files → Pathway and Sensitivity Analyses → Volcanic Files

Ash at RMEI Results—This file contains the results of the ASHPLUME model runs with the wind to the south, as described in Appendix G of the report. The histogram of ash depth at the RMEI location appearing in that appendix is also generated in this Excel file.

Dependence of VA BDCFs on Inputs.xls—This file is analogous to the *Dependence of GW BDCFs on Inputs_1, _2*, and *_3.xls* except that it applies to the volcanic ash exposure scenario. It generates graphs showing dependence of the BDCF components on the model input parameters.

Detailed Pathway Analysis VA.xls—This file contains calculations of pathway contributions to volcanic ash exposure scenario BDCFs for the present-day climate. The files consist of worksheets containing the summary of the environmental transport pathway analysis as well as the graphs showing pathway contributions for individual radionuclides, environmental transport pathway analysis for selected radionuclides, and analysis of the inhalation pathway. The results of model realizations were copied into the worksheets from the appropriate GoldSim files included in DTN: MO0705GOLDSIMB.000.

VA BDCF Pathway Analysis.xls—This file contains calculations of pathway contributions to BDCFs for the present-day climate. The workbook consists of worksheets containing pathway BDCFs for individual realizations and individual radionuclides. The first worksheet (*Pathway Summary*) contains the summary of the mean pathway BDCFs. The pathway BDCF values were copied from GoldSim files included in DTN: MO0705GOLDSIMB.000.

VA BDCF Variability Plots.xls—This file contains several worksheets showing statistics for the volcanic ash exposure scenario BDCF components and their pathway BDCFs (for the external exposure, ingestion, radon inhalation component) and the graphs illustrating the variability and uncertainty in the BDCFs and their contributing pathways.

VA Correlations.xls—This file contains the correlation coefficients for the stochastic model input parameters and BDCF components calculated in GoldSim for the volcanic ash exposure scenario. Data in this spreadsheet were transferred from the GoldSim files included in DTN: MO0705GOLDSIMB.000.

Excel Files → Results → Model Results

GW BDCFs Present-Day and Future Climates.xls—This file contains the groundwater BDCF results of 1,000 GoldSim biosphere model realizations for individual radionuclides for the present-day and the upper bound of the glacial transition climate. The file also contain the calculated values of BDCFs for the monsoon and the glacial transition climates. The values from the present-day climate and the upper bound of the glacial transition climate were copied from GoldSim files for individual radionuclides included in DTN: MO0705GOLDSIMB.000.

VA BDCFs Present-Day and Future Climates.xls—This Excel file contains the results of 1,000 biosphere model realizations that generated BDCFs for the volcanic ash exposure scenario for the present-day climate and for the upper bound of the glacial transition climate. The file also contains BDCF comparisons for these two climates. For each realization and each radionuclide, three BDCF components were generated: external exposure – ingestion – radon, short-term inhalation, and long-term inhalation. The values were copied from GoldSim files for individual radionuclides included in DTN: MO0705GOLDSIMB.000.

Excel Files → Results → Other Outputs

Groundwater Protection Conversion Factors.xls—This file contains calculations of conversion factors for calculating beta-photon annual dose resulting from drinking 2 liters of water per day. The values are calculated using Equation 6.15-3.

Inhalation Dose Factor Calculations.xls—This file contain calculations of the inhalation dose factors computed using Equation 6.15-8.

GENII Files

RMDLIB.dat—This text file contains the library of radionuclides used in the runs of GENII model.

GoldSim Files

The following files are included in the GoldSim files:

Ash at RMEI - 100rlz Ashplume v2-1.gsm—GoldSim file containing the results of 100 realizations of Ashplume model (quantity of ash deposited at the RMEI location) with wind direction fixed to the south. The results are presented in Appendix G.

ERMYN_GW_Rev01_Base_Det.gsm—Base deterministic GoldSim model for the groundwater exposure scenario; used in importance and sensitivity analyses in Section 6.13.

ERMYN_VA_Rev01_Base_De.gsm—Base deterministic GoldSim model for the volcanic ash exposure scenario; used in importance and sensitivity analyses in Section 6.14.

ERMYN_GW_Rev01_Pu239verf.gsm—Deterministic run for ^{239}Pu, groundwater exposure scenario; used in model verification in Table 6.10-1.

ERMYN_GW_Rev01_C14verf.gsm—Deterministic run for ^{14}C, groundwater exposure scenario; used in model verification in Table 6.10-2.

ERMYN_GW_Rev01_Ra226verf.gsm—Deterministic run for ^{226}Ra, groundwater exposure scenario; used in model verification in Table 6.10-3.

ERMYN_GW_Rev01_Th232verf.gsm—Deterministic run for ^{232}Th, groundwater exposure scenario; used in model verification in Table 6.10-4.

ERMYN_VA_Rev01_Pu239verf.gsm—Deterministic run for ^{239}Pu, volcanic ash exposure scenario; used in model verification in Table 6.10-7.

ERMYN_VA_Rev01_Ra226verf.gsm—Deterministic run for ^{226}Ra, volcanic ash exposure scenario; used in model verification in Table 6.10-8.

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APPENDIX B
ANALYTICAL SOLUTION FOR RADON CONCENTRATIONS IN THE AIR DUE TO RADIUM CONTAMINATED SOIL

ANALYTICAL SOLUTION FOR RADON CONCENTRATIONS IN THE AIR DUE TO RADIUM CONTAMINATED SOIL

An analytical solution for the radon diffusion equation used in the RESRAD model (Yu et al. 2001 [DIRS 159465], Appendix C) and typical numerical results from this method are presented in this appendix. The purpose of this analytical solution is to evaluate radon concentrations in the air using the RESRAD method, which is considered an ACM for the ERMYN radon submodel (Section 6.3.3). The numerical results presented here are compared to the selected radon model, which is suggested by the NCRP in the Report No. 129 (NCRP 1999 [DIRS 155894] Section 4.3.6). By using the analytical solution, use of the RESRAD software can be avoided, and, therefore, software qualification is unnecessary.

As discussed in the RESRAD manual (Yu et al. 2001 [DIRS 159465], p. C-9), the annual average radon concentration in outdoor air is calculated as:

$$C_0 = \frac{J_0 F_{ao}}{\lambda H_0}\left[1 - e^{-\left(\frac{\lambda X}{2U}\right)}\right] \quad \text{(Eq. B-1)}$$

where

C_0 = annual average concentration of radon outdoors (Bq/m^3)

J_0 = radon flux at the soil surface outdoors (Bq/(m^2 s))

F_{ao} = outdoor area factor (dimensionless), it is equal to 1 if A > 100 m^2

H_0 = height into which plume is uniformly mixed (m)

λ = radon decay constant (1/s)

U = annual average wind speed (m/s).

X = effective length of the contaminated zone (m), and can be calculated as:

$$X = \sqrt{A} \quad \text{(Eq. B-2)}$$

where

A = area of the contaminated zone (m^2).

In Equation B-1, all parameters on the right-hand side are known except J_0 (the radon flux at the soil surface outdoors), but solving for J_0 requires the solution to the applicable radon diffusion equation for radium contaminated soil (not given in text). Normally, this radon diffusion equation can only be solved by numerical methods, which are used in the RESRAD code, due to the complicated geometry of the contaminated soil and uncontaminated cover. However, considering only a special, but applicable, case (large area of radium contaminated soil, uniform contamination over depth, and equilibrium conditions), the radon diffusion equation can be solved analytically.

The radon concentration in a slab of contaminated soil is governed by the differential equation and boundary conditions discussed in the RESRAD manual (Yu et. al. 2001 [DIRS 159465], pp. C-5 to C-7). To assist the reader, the following derivation is reproduced here from the RESRAD manual (Yu et al. 2001 [DIRS 159465]). For steady state conditions, these equations are:

$$\begin{cases} -\dfrac{d}{dz}\left(D\dfrac{dC}{dz}\right) + \lambda C = Q \\ C(z_a) = 0 \\ J(0) = \left.\dfrac{dC}{dz}\right|_{z=0} = 0 \end{cases} \qquad \text{(Eqs. B-3 to B-5)}$$

where

C = radon concentration in the pore space of soil (Bq/m^3)

D = diffusion coefficient of radon in soil (m^2/s)

z = vertical axial distance in the direction of diffusion (m). $z = 0$ is the bottom of the contaminated soil, while $z = z_a$ is the interface between the ground and the air.

$C(z_a)$ = radon concentration at the upper boundary of the contaminated soil

$J(0)$ = radon flux at the bottom boundary of the contaminated soil.

Q = radon source term into the pore space (Bq/(m^3 s)).

The radon source term into the pore space (Bq/(m^3 s)) is evaluated as:

$$Q = \frac{\varepsilon \rho_b S_{Ra} \lambda}{p_t} \qquad \text{(Eq. B-6)}$$

where

ε = radon emanation coefficient, which represents the fraction of radon generated by radium decay that escapes from the soil particles (dimensionless)

ρ_b = soil bulk density (kg/m^3)

S_{Ra} = radium concentration in the soil (Bq/kg)

p_t = total porosity (dimensionless)

λ = radon decay constant (1/s).

Because the radon concentration and flux are continuous across the interface of the two media (i.e., air and ground), radon flux at the soil surface outdoors, J_0, is numerically equal to radon flux at the upper boundary of the contaminated soil. It can be calculated as:

$$J_0 = -J(z_a) = -p_t D \frac{dC}{dz}\bigg|_{z=z_a} \qquad \text{(Eq. B-7)}$$

As the diffusion coefficient, *D,* does not change with distance *z*, the differential equation (Equation B-3) can be solved with a general solution of:

$$C = C_1 e^{-z/k} + C_2 e^{z/k} + C_3 \qquad \text{(Eq. B-8)}$$

where

C_1, C_2, and C_3	=	constants to be determined by the differential equation and its boundary conditions (Equations B-3 to B-5) (Bq/m^3)
k	=	diffusion length (m).

which, by substituting Equation B-8 into Equation B-3, can be shown to be:

$$k = \sqrt{\frac{D}{\lambda}} \qquad \text{(Eq. B-9)}$$

Taking the first and second derivatives of Equation B-8 gives:

$$\frac{dC}{dz} = -\frac{C_1}{k} e^{-z/k} + \frac{C_2}{k} e^{z/k} \qquad \text{(Eq. B-10)}$$

$$\frac{d^2C}{dz^2} = \frac{C_1}{k^2} e^{-z/k} + \frac{C_2}{k^2} e^{z/k} \qquad \text{(Eq. B-11)}$$

By inserting Equations B-11 and B-8 into the differential equation (Equation B-3), the constant C_3 can be determined as:

$$C_3 = \frac{Q}{\lambda} \qquad \text{(Eq. B-12)}$$

Using the second boundary condition (Equation B-5) within Equation B-10, the relationship between C_1 and C_2 can be determined as:

$$C_1 = C_2 \qquad \text{(Eq. B-13)}$$

Using the first boundary condition (Equation B-4) and Equation B-13 into Equation B-8, the constants C_1 and C_2 can be determined as:

$$C(z_a) = C_1 e^{-z_a/k} + C_2 e^{z_a/k} + C_3 = 0$$

(Eqs. B-14 and 15)

$$C_1 = C_2 = \frac{-C_3}{e^{-z_a/k} + e^{z_a/k}}$$

Then the radon flux at the soil surface outdoors, J_0, can be calculated using Equations B-7, B-10, B-12, B-13, and B-15 as:

$$\begin{aligned} J_0 &= -J(z_a) = -p_t D \left.\frac{dC}{dz}\right|_{z=z_a} \\ &= p_t k Q \left(\frac{e^{z_a/k} - e^{-z_a/k}}{e^{z_a/k} + e^{-z_a/k}} \right) \end{aligned} \qquad \text{(Eq. B-16)}$$

By inserting Equation B-13 into Equation B-1, the annual average radon concentration in the air (C_0) can be calculated as a function of the contaminated soil depth (z_a). When contaminated soil is very deep, and $z_a \rightarrow \infty$, radon flux at soil surface becomes independent of z_a and reaches the maximum value:

$$J_0 = p_t k Q \qquad \text{(Eq. B-17)}$$

The annual average radon concentration in the air can be calculated by combining Equations B-17, B-1, and B-6 as:

$$\begin{aligned} C_0 &= \frac{p_t k Q F_{ao}}{\lambda H_0} \left[1 - e^{-\left(\frac{\lambda X}{2U}\right)} \right] \\ &= \frac{k F_{ao} \varepsilon \rho_{\mathrm{b}} S_{Ra}}{H_0} \left[1 - e^{-\left(\frac{\lambda X}{2U}\right)} \right] \end{aligned} \qquad \text{(Eq. B-18)}$$

The radon concentration ratio between outdoor air and soil, which is the radon release factor used in the ERMYN, can be evaluated using Equation B-18:

$$\frac{C_0}{S_{Ra}} = \frac{k F_{ao} \varepsilon \rho_{\mathrm{b}}}{H_0} \left[1 - e^{-\left(\frac{\lambda X}{2U}\right)} \right] \qquad \text{(Eq. B-19)}$$

Using typical values from the ERMYN, or using default values from the RESRAD code if the parameters are unique to that radon model, the radon release factor can be calculated using Equation B-19. The inputs and calculated results are shown in Table B-1.

Table B-1. Calculation of the Radon Release Factor

Parameter name	Notation	Value	Units	Data Source
Outdoor area factor	F_{ao}	1	—	RESRAD default
Radon emanation coefficient	ε	0.25	—	RESRAD default
Soil bulk density	ρ_b	1500	kg/m^3	ERMYN input
Diffusion coefficient of radon in soil	D	2.0E–06	m^2/s	RESRAD default
Radon decay constant	λ	2.1E–06	/s	ERMYN input
Diffusion length	k	0.976	m	Calculated
Radon plume height	H_0	2	m	RESRAD default
Area of the contaminated zone	A	2.30E+06	m^2	ERMYN input
Effective length of contaminated zone	X	1.51E+03	m	Calculated
Annual average wind speed	U	2	m/s	RESRAD default
Radon release factor	C_0 / S_{Ra}	0.15	kg/m^3	Calculated

The calculated radon release factor used by the RESRAD radon diffusion model, 0.15 kg/m^3, is close to the selected value, 0.25 kg/m^3, in the ERMYN. To calculate the radon release factor as a function of contaminated soil depth, z_a, the exponential term in Equation B-16 is applied to Equation B-19:

$$\frac{C_0}{S_{Ra}} = \frac{kF_{ao}\varepsilon\rho_b}{H_0}\left[1-e^{-\left(\frac{\lambda X}{2U}\right)}\right]\left(\frac{e^{z_a/k}-e^{-z_a/k}}{e^{z_a/k}+e^{-z_a/k}}\right) \quad \text{(Eq. B-20)}$$

Using the data in Table B-1, the concentration of radon in the air can be calculated as shown in Table B-2.

Table B-2. Radon Release Factors Due to Radium Contaminated Soil

Depth of Contaminant (m)	Source Exponential Term	^{222}Rn Release Factor (Bq/m^3)/(Bq/kg)	Surface Soil Density (kg/m^2)	^{222}Rn Release Factor (Bq/m^3)/(Bq/m^2)
0.003	0.0031	4.47E–04	4.5	0.00010
0.01	0.0102	1.49E–03	15	0.00010
0.02	0.0205	2.98E–03	30	0.00010
0.05	0.0512	7.44E–03	75	0.00010
0.1	0.1021	1.48E–02	150	0.00010
0.2	0.2020	2.94E–02	300	0.00010
0.5	0.4716	6.86E–02	750	0.00009
1	0.7716	1.12E–01	1500	0.00007
2	0.9673	1.41E–01	3000	0.00005
5	0.9999	1.45E–01	7500	0.00002
10	1.0000	1.45E–01	15000	0.00001

NOTE: Column 1 is input for the calculations. Column 2 is the source exponential term in Equation B-20. Column 3 is the result of using Equation B-20 and input values from Table B-1. Column 4 is converted from Column 1 with soil density of 1,500 kg/m^3. Column 5 is calculated as Column 3 / Column 4.

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APPENDIX C
CALCULATION OF ABSOLUTE HUMIDITY FROM RELATIVE HUMIDITY

CALCULATION OF ABSOLUTE HUMIDITY FROM RELATIVE HUMIDITY

In dry weather, an evaporative cooler may deliver air at 60% relative humidity. However, the relative humidity of air discharged from the house that uses an evaporative cooler is only about 40% because of the temperature increase upon mixing with the indoor air (Watt and Brown 1997 [DIRS 159497], p. 24). If the indoor temperature is 75°F (24°C), the absolute humidity corresponding to this temperature can be estimated from the ideal gas law as:

$$\frac{p \times V}{T} = n \times R \qquad \text{(Eq. C-1)}$$

where

p	=	water vapor pressure (partial pressure of water vapor)
V	=	volume (m^3)
T	=	temperature (K)
n	=	number of moles
R	=	universal gas constant.

After rearranging and multiplying Equation C-1 by the molecular weight of water, *mw*, the density of water vapor in the air, ρ_w , can be calculated as:

$$\frac{n \times mw}{V} = \frac{mw \times p}{R \times T} = \rho_w \qquad \text{(Eq. C-2)}$$

The molecular weight of water is 18.016 g/mole. The partial pressure of water vapor at saturation depends on temperature. For 24°C (297 K), the partial water pressure is 2.9850 kPa (Lide and Frederikse 1997 [DIRS 103178], p. 6-8). The numerical value of the universal gas constant, R, depends on the units of p, V, n, and T. For the units used in this calculation, R = 0.00831451 (m^3 kPa)/(mole K) (Lide and Frederikse 1997 [DIRS 103178], p. 1-40). The absolute humidity at saturation (the density of water vapor in the air), ρ_w, can be calculated as:

$$\rho_w = \frac{mw \times p}{R \times T} = \frac{18.016 \frac{g}{mole} \quad 2.985\,kPa}{0.008315 \frac{m^3\ kPa}{mole\ K} \quad 297\,K} = 21.8 \frac{g}{m^3} \qquad \text{(Eq. C-3)}$$

At 40% relative humidity, the concentration of water vapor in the air is about 8.7 g/m^3.

Average absolute humidity at Yucca Mountain Weather Station #9 is calculated based on measured data in *Engineering Design Climatology and Regional Meteorological Conditions Report* (CRWMS M&O 1997 [DIRS 100117], Table A-9). From this table, monthly averaged relative humidity and temperature are given. Because evaporative coolers are used during the summer, average relative humidity and temperature from May to September are used to calculate the average absolute humidity (Table C-1).

Table C-1. Average Relative Humidity and Temperature at the Weather Station 9

	May	June	July	August	September	Average
Temperature (°C)	21.3	27.6	31.4	30.5	25.4	27.2
Relative Humidity (%)						
Time = 0400 h	42.5	26.4	23.7	24.2	26.6	18.5
Time = 1000 h	23.5	14.1	12.6	14.0	15.6	
Time = 1600 h	16.0	7.8	7.2	8.2	9.1	
Time = 2200 h	30.1	17.0	15.4	16.6	19.0	

Using the same calculation method described above, the partial water pressure for 27.2°C (300.2 K) is 3.6100 kPa (Lide and Frederikse 1997 [DIRS 103178], p. 6-8). The absolute humidity at saturation (the density of water vapor in the air), ρ_w, can be calculated as 26.1 g/m^3. At 18.2% relative humidity, the concentration of water vapor in the air is about 4.8 g/m^3.

APPENDIX D
EVAPORATIVE COOLER PATHWAYS

EVAPORATIVE COOLER PATHWAYS

D1. INTRODUCTION

The biosphere model includes a submodel for the use of evaporative coolers fed by groundwater containing radionuclides (Section 6.4.2.2). The model only considers the inhalation pathway arising from the transfer of radionuclides from the water to the air injected into the dwelling for the purpose of cooling. The model assumes that a fraction (represented by a uniform distribution from 0 to 1) of each radionuclide in the source is transferred to the cooling airflow.

There are other exposure pathways associated with evaporative coolers. These units are effective in cooling ambient air with a low relative humidity by inducing forced evaporation of water in water-saturated (evaporator) filter pads and, thereby, utilizing the latent heat of evaporation of the water to cool the air that is then ducted to the dwelling. The process of ongoing forced evaporation leaves behind a residue of solid matter originally in solution. Any radionuclides, if not transferred to the airflow as modeled, will accumulate with this residue. This process will continue through the period that cooling is used. The residue will persist until routine service and maintenance to the cooling unit is conducted. Such a service is usually rendered before the onset of cold weather at the time the cooling system is "winterized" to minimize corrosion during the dormant period and reduce heat loss when indoor heating is required. Part of this process is to drain the reservoir and water supply line to preclude damage caused by freezing. The cooling pads, with the attached residue scale, are, generally, replaced in the spring months when the unit is made ready for the next cooling season.

This appendix provides the scoping calculations to identify important exposure pathways that could arise from evaporative cooler operation and maintenance for inclusion in the biosphere model.

D2. THE INHALATION PATHWAY

To model the pathway for the dose contribution from inhalation of the cooling system air, a simple conceptual model has been defined. For a given radionuclide present in a known concentration in the groundwater used to feed the evaporative cooler, this model assumes that a known fraction of that radionuclide is transferred to the air flowing through the system. The receptor inhales this air while indoors, thus, receiving a committed dose from the exposure.

The formula representing the transfer of the radionuclide from the water to the air is given by Equation 6.4.2-3. For the purpose of this scoping calculation, it is conservative to allow all of the radionuclide present in the water to be transferred to the airflow (i.e., to assume that f_{evap} in Equation 6.4.2-3 is equal to unity). Equation 6.4.2-3 now reduces to:

$$Ca_{e,i} = \frac{M_{water}}{F_{air}} Cw_i \qquad \text{(Eq. D-1)}$$

where

$Ca_{e,i}$	=	activity concentration of radionuclide i in the air resulting from the operation of an evaporative cooler (Bq/m^3)
M_{water}	=	water evaporation rate (water use) for an evaporative cooler (m^3/h)
F_{air}	=	air flow rate for an evaporative cooler (m^3/h)
Cw_i	=	activity concentration of radionuclide i in the groundwater (Bq/m^3).

Having determined the radionuclide concentration in the air during the period the cooling system is running, Equation 6.4.8-3 can then be used to calculate the annual dose contribution from evaporative coolers:

$$D_{inh,e,i} = EDCF_{inh,i}\ Ca_{e,i}\ f_{use} \sum_n BR_n t_{n,indoors} \qquad \text{(Eq. D-2)}$$

where

$D_{inh,e,i}$	=	annual dose from inhalation of primary radionuclide i from evaporative cooler operation (Sv/yr)
$EDCF_{inh,i}$	=	effective dose coefficient for inhalation of radionuclide i (Sv/Bq)
BR_n	=	breathing rate for environment n (m^3/h)
$t_{n,\ indoors}$	=	population-weighted time spent in indoor environment n (h/yr).

The population-weighted time is the sum of the products of time spent in a given environment by a population group and the proportion of population constituting a given population group (Equation 6.4.8-3). The values of the time spent in indoor environments and the corresponding breathing rates are summarized in Table D-1. The sum of the products of the breathing rate and the weighted time indoors (i.e., $\sum_n BR_n t_{n,indoors}$) gives the mean value of the volume of air inhaled per year indoors ($\overline{V}$).

Table D-1. Time Spent in Indoor Environments and Corresponding Breathing Rates

Environment	Weighted Time Indoors, $t_{n,\ indoors}$ h/d	Breathing Rate, BR_n m^3/h	Volume of Air Inhaled Indoors, $BR_n\ t_{n,\ indoors}$ m^3/d
Active indoors	9.45	1.08	10.21
Asleep indoors	8.30	0.39	3.24
Total indoors	17.75		13.44
Annual values	6482 h/yr		$\overline{V}$ = 4908 m^3/yr

Source: Table 7.4-21 (time indoors) and Table 6.6-3 (breathing rates).

By combining Equations D-1 and D-2, the equation for annual dose from an evaporative cooler for groundwater containing a unit concentration of radionuclide *i* (i.e., $Cw_i = 1$ Bq/m^3) is:

$$D_{inh,e,i} = EDCF_{inh,i} \frac{M_{water}}{F_{air}} f_{use} \overline{V} \qquad \text{(Eq. D-3)}$$

The values of other radionuclide-independent parameters used in Equation D-3 are shown in Table D-2.

Table D-2. Representative Parameter Values and Their Sources

Parameter Name, Symbol, and Units		Value
Water evaporation rate, m^3/h	M_{water}	0.017
Air flow rate for evaporative cooler, m^3/h	F_{air}	8300
Evaporative cooler use factor, present-day climate, dimensionless	f_{use}	0.39

Source: Table 6.6-3.

The evaporative cooler pathway dose contribution can be compared with the dose resulting from drinking 2 L/d (0.73 m^3/yr) of water, which establishes a lower dose limit for the RMEI. The drinking water dose is calculated as (from Equation 6.4.9-2):

$$D_{ing,w,i} = EDCF_{ing,i}\, Uw \qquad \text{(Eq. D-4)}$$

where

$EDCF_{ing,i}$ = effective dose coefficients for ingestion of radionuclide *i* (Sv/Bq); calculation of effective dose coefficients for ingestion is discussed in Section 6.4.9.6

Uw = annual consumption rate of contaminated drinking water by humans (L/yr).

The example calculations were performed for three primary radionuclides: two fission products (^{126}Sn and ^{137}Cs), known to have penetrating gamma ray emissions, and a radionuclide chain headed by ^{227}Ac due to its high effective dose coefficient for external exposure (see the effective dose coefficients for external exposure to contaminated soil in Table 6.4-4). The effective dose coefficients for inhalation and ingestion of these radionuclides are presented in Table D-3. Substitution of these values and values from Tables D-1 and D-2 in equations D-3 and D-4, give the annual doses for both pathways, also shown in Table D-3.

Table D-3 illustrates that, under a very conservative assumptions of 100% contaminant transfer to the airstream, the dose from inhalation of aerosols generated by evaporative coolers is, for some radionuclides, comparable to that from drinking water.

Table D-3. Effective Dose Coefficients and Annual Doses for Ingestion and Inhalation

Radionuclide	Effective Dose Coefficient for Inhalation [a] (Sv/Bq)	Annual Inhalation Dose (Sv)	Effective Dose Coefficient for Ingestion [b] (Sv/Bq)	Annual Ingestion Dose (Sv)
^{126}Sn	1.55E–07	6.08E–10	5.15E–09	3.76E–09
^{137}Cs	3.92E–08	1.54E–10	2.00E–09	1.46E–09
^{227}Ac	1.75E–04	6.86E–07	4.36E–07	3.18E–07

[a] From Table 6.4-3.
[b] From Table 6.4-4.

D3. EXTERNAL DOSE PATHWAY

Most residential dwellings only require a single cooling unit. The cooled air output from the unit is generally ducted within the outer shell of the building to each room where cooling is required. The system is designed to reduce costs by keeping the ducting requirements close to the minimum to satisfy the cooling specification. Depending on the dwelling design, the centralized cooling unit may be located on the roof of the dwelling or against one wall.

The biosphere model already includes the external exposure pathway from radionuclides deposited in soil from irrigation. This section presents scoping calculations to compare the external dose contributions from soil to those from coolers.

D3.1 ACTIVITY REMAINING IN EVAPORATIVE COOLERS

Considering the case where radionuclides in the water system do not get transferred to the airflow (i.e., the case opposite to that assumed in Section D2), the continual evaporation of water gives rise to sediment that contains all of the radionuclides originally present in the water. For the case of this scoping calculation, the cooling unit considered will be one that does not have a built in flushing system. At the start of the cooling season, the cooling system is considered to be cleaned (no sediment) when new evaporation pads are installed. The sediment builds up during cooler use in the hot periods of the year and remains there until the owner closes the system down for winter. For this scoping calculation, it will be assumed that the pad contains all the activity accumulated during use and the pads remain in place until they are replaced the following spring.

Until the system is serviced, the only exposure pathway is direct radiation. This pathway will be assessed. The dose from the evaporative cooler pathway will be compared to the dose from external exposure to soil.

If the activity of radionuclide i in the evaporative cooler residue is A_i (Bq), at the end of the cooling season it is given by:

$$A_i = Cw_i M_{water} t_{ec} \qquad \text{(Eq. D-5)}$$

where

t_{ec} = time evaporative cooler is operated in a year (h/yr).

Over the cooling period of 3,419 h/yr (calculated as the product of number of hours in a year and the evaporative cooler use factor from Table D-2), the accumulation of activity in the cooler pads and water reservoir is 58.1 Bq per Bq/m^3 of activity in the groundwater. The cooler operates for a fraction of a year equal to, on average, 0.39 for the present-day climate (for the future climate this fraction is less). During this time, the activity will accumulate in the cooler. This will be followed by the dormant period during which the activity is constant. If it were to be assumed that the activity were accumulating at a linear rate over the period of operation, the average activity over this period would be half of the total accumulated activity for the period of cooler operation combined with the rest of a year of fixed activity. If credit is taken for the time required for the accumulation of this activity to occur, the annual average activity in the cooler can be calculated as 46.8 Bq.

D3.2 ACTIVITY IN IRRIGATED SOIL

The exposure to contaminated soil is discussed in Section 6.4.7.1. The dose from external exposure is a product of radionuclide concentration in soil volume, exposure time and the dose coefficient for exposure to contaminated soil. The calculation of radionuclide concentration in surface soil is presented in Section 7.4.2.1 with the soil concentration values shown in Table 7.4-5. The effective exposure time to soil was calculated in Section 7.4.8.2 and is presented in Table 7.4-20. The dose coefficients for exposure to soil contaminated to infinite depth are shown in Table 6.4-4. Using this information, the dose from external exposure to radionuclides in the soil can be calculated, and is shown in Table D-4.

Table D-4. Estimated Annual Dose from External Exposure to Irrigated Soils

Radionuclide	Activity Concentration in Surface Soil		Exposure Time		Dose Coefficient Sv/s per Bq/m^3 [c]	Annual Dose Sv/yr
	Bq/kg [a]	Bq/m^3	hr/d [b]	s/yr		
^{126}Sn	2.22E–01	3.33E+02	9	1.18E+07	5.94E–17	2.34E–07
^{137}Cs	9.05E–02	1.36E+02	9	1.18E+07	1.71E–17	2.75E–08
^{227}Ac	7.02E–02	1.05E+02	9	1.18E+07	1.00E–17	1.25E–08

Sources: [a] From Table 7.4-5.
[b] From Table 7.4-20.
[c] Effective dose coefficient for exposure to soil from Table 6.4-4.

D3.3 EXTERNAL RADIATION IN EVAPORATIVE COOLER FROM WATER EVAPORATION

The data presented in *The Health Physics and Radiological Health Handbook* (Shleien 1992 [DIRS 127299], Table 6.1.2) can be used to estimate dose for the accumulation of activity in an evaporative cooler. These data provide, for a single radionuclide source, the parameter named "specific gamma ray dose constants at 1 meter." The units used in the publication are mSv/h per MBq at 1 meter. No credit is taken for attenuation by the building.

Given that the units used in this analysis are Bq for the source term and Sv per year for the exposure, the equation implied in the handbook by Shleien (1992 [DIRS 127299], pp. 57 to 58; Table 6.1.2) can be written as:

$$D_{ps,i} = E\Gamma_i \times SA_i \times \overline{d^{-2}} \quad \text{(Eq. D-6)}$$

where

$D_{ps,i}$ = dose from exposure to the source (Sv/h)

$E\Gamma_i$ = effective specific gamma ray constant for a point source (Sv/hr per Bq/m^2)

SA_i = source activity (Bq)

$\overline{d^{-2}}$ = annual average of the inverse square distance between the source and the receptor (m^{-2}).

D3.3.1 Effective Gamma Ray Constant for a Point Source

The values of gamma ray constants were taken from *The Health Physics and Radiological Health Handbook* (Shleien 1992 [DIRS 127299], Table 6.1.2). The data provided in this reference are for individual radionuclides. The biosphere model combines the dose contributions of the primary radionuclides and their short-lived decay products. Therefore, the effective gamma ray constants were calculated to add the contribution from the decay products to that of the primary radionuclide. Table D-5 shows the results.

The specific gamma ray constant is based on the ICRP Publication 26 set of tissue weighting factors (Shleien 1992 [DIRS 127299], Table 13.1.3). However, the difference between the quantities for external exposure based on ICRP Publication 60 tissue weighting factors (that, for instance, were used to calculated dose coefficients in Table 6.4-4) and the corresponding quantities based on the ICRP Publication 26 tissue weighting factors is only a few percent and does not influence the results of this scoping analysis. For example, compare the dose coefficients for ^{126}Sn, ^{137}Cs, and ^{227}Ac provided in the previous revision of this report (BSC 2004 [DIRS 169460], Table D-9) with those in Table D-4 in this report.

Table D-5. Effective Specific Gamma Ray Constants for a Point Source

Primary Radionuclide	Decay Product	Branching Fraction	Specific Gamma Ray Constant Γ [a] mSv/h MBq^{-1} m^2	Effective Specific Gamma Ray Constant $E\Gamma$ [b] mSv/h MBq^{-1} m^2
^{126}Sn		1	3.41E–05	3.84E–04
	^{126m}Sb	1	2.82E–04	
	^{126}Sb	0.14	4.86E–04	
^{137}Cs		1		1.02E–04
	^{137m}Ba	0.946	1.08E–04	
^{227}Ac		1	2.36E–06	2.42E–04
	^{227}Th	0.9862	1.15E–04	
	^{223}Fr	0.0138	8.93E–05	
	^{223}Ra	1	8.79E–05	
	^{219}Rn	1	1.42E–05	
	^{215}Po	1	2.86E–08	
	^{211}Pb	1	9.84E–06	
	^{211}Bi	1	1.27E–05	
	^{207}Tl	0.9972	3.52E–07	
	^{211}Po	0.0028	1.33E–06	

[a] Shleien (1992 [DIRS 127299], Table 6.1.2).

[b] Calculated as a weighted sum of gamma ray constants for a primary radionuclide and its decay products, with branching fractions being the weights.

D3.3.2 Mean Inverse Square of Distance

The 2000 Census data indicated that approximately 90% of the total Amargosa Valley population lived in manufactured homes (Bureau of the Census 2002 [DIRS 159728], Table H33). Therefore, manufactured homes are representative of a typical dwelling in Amargosa Valley.

Most manufactured homes are single- or doublewide. Single-wide homes are 12 to 18 feet wide and 30 to 80 feet long; double-wide houses are 24 to 28 feet wide and 40 to 80 feet long. According to the report prepared by the NAHB Research Center for the U.S. Department of Housing and Urban Development, the average square footage is 1,056 ft^2 for the single-wide (single-section) homes and 1,629 ft^2 for double-wide (double-section) homes and 1,955 ft^2 for multisection homes (NAHB Research Center 1998 [DIRS 160428], p. 35). Single-wide houses constitute 46.2% and double-wide homes 51.2% of the manufactured homes in the United States, with the remainder (2.6%) being multisection structures.

Evaporative cooler water usage in Table D-2 is based on the average for the region. It is, therefore, reasonable to use a weighted average for the area of a dwelling (i.e., the average dwelling has the average cooler water usage). From the numbers cited in the above paragraph, this value is 1,373 ft^2 (or 128 m^2).

The time averaged mean inverse square distance from the cooler residue source will be dependent upon the layout of the dwelling (and time spent in each room) with respect to the location of the cooler. The cooler could be mounted against either the long or short wall or on the roof. To derive a simple mean value for this parameter, the dwelling will be taken to be the square with the cooler mounted outside against the middle of one wall. The effective source (point source) of the radiation will be taken to be one meter from the inside wall.

With these simplifying approximations, the wall length will be 11.3 m (square root of 128 m^2). The receptor will be placed on the center line of the dwelling; i.e., no credit will be taken for the reduction in the mean value of the inverse square for a receptor off the center line.

The average value of a function f(x) over an interval from $x = a$ to $x = b$ is expressed as:

$$\overline{f(x)} = \frac{1}{b-a}\int_a^b f(x)\,dx \qquad \text{(Eq. D-7)}$$

For $f(x) = 1/x^2$ and a receptor located at a distance of x from the wall adjacent to the cooler unit, the average value of the function of the distance from the cooler is given by:

$$\overline{d^{-2}} = \frac{1}{\mathrm{x_u} - \mathrm{x_l}}\int_{x_l}^{x_u} \frac{dx}{(x+1)^2} \qquad \text{(Eq. D-8)}$$

where

x_l = lower value of x (0.0 m)

x_u = upper value of x (11.3 m).

Making the substitution, $y = x + 1$, gives:

$$\overline{d^{-2}} = \frac{1}{\mathrm{x_u} - \mathrm{x_l}}\int_{x_l+1}^{x_u+1} \frac{dy}{y^2} \qquad \text{(Eq. D-9)}$$

$$\overline{d^{-2}} = \frac{1}{\mathrm{x_u} - \mathrm{x_l}}\left[\frac{-1}{y}\right]_{x_l+1}^{x_u+1} \qquad \text{(Eq. D-10)}$$

Substitution of the values above gives $\overline{d^{-2}}$ (distance factor) to be 8.1×10^{-2} m^{-2}.

D3.3.3 Estimated Annual External Exposure for an Evaporative Cooler from Radionuclides in Water

Substitution of the values developed above along with the total activity in a cooler from water evaporation (46.8 Bq per Bq/m^3 from Section D.3.1) into equation D-6 allows an estimate to be obtained for the use of an evaporative cooler (Table D-11). Note that, as was done for the soil exposure, no credit has been taken for the building shielding factors. Dose per year was calculated by taking into consideration weighted time spent indoors per year (from Table D-1) and the cooler use factor (Table D-2).

Table D-6. Estimated Annual Dose from External Exposure to Evaporative Coolers

Radionuclide	Specific Gamma Ray Constant, Γ mSv h^{-1} MBq^{-1} m^2	Specific Gamma Ray Constant, Γ Sv h^{-1} Bq^{-1} m^2	Distance Factor, d^{-2} m^{-2}	Dose Rate Sv h^{-1}	Annual Dose Sv y^{-1}
^{126}Sn	3.84E–04	3.84E–13	0.0813	1.46E–12	3.69E–09
^{137}Cs	1.02E–04	1.02E–13	0.0813	3.89E–13	9.82E–10
^{227}Ac	2.42E–04	2.42E–13	0.0813	9.21E–13	2.33E–09

D3.4 Estimated Annual External Exposure for an Evaporative Cooler from Radionuclides in Particulate Matter

During operation of the cooling system, particulate matter present in the air will be entrained with air into the cooler intake. During this time, the cooler would behave as an external source as addressed in Section D3.3. Assuming that all particles in the air are trapped by the cooler pads, the mass of particulate matter remaining in the cooler can be estimated from the following expression:

$$Mpm_{sw} = F_{air}\ Ca_{e,i}\ \mathrm{TSP}\ t_{ec} \qquad \text{(Eq. D-11)}$$

where

Mpm_{sw} = mass of particulate matter in evaporative cooler at the end of the cooling season (kg)

F_{air} = air flow rate for cooler (m^3/h) (8,300 m^3/h from Table D-2)

$Ca_{e,i}$ = activity concentration of radionuclide i in the air resulting from the operation of an evaporative cooler (Bq/m^3)

TSP = atmospheric particulate matter mass loading (kg/m^3) (6×10^{-8} kg/m^3 from Table 6.6-3 entry for inactive outdoors)

t_{ec} = time cooling system is operating in year (h) (3,419 h/yr – see Section D.3.1).

Substitution of these values into Equation D-11 indicates that a cooler system will capture 1.7 kg of resuspended particulate matter over an operating season. The activity concentration per unit mass of these particles, assuming that it is the same as that for the soil, is provided in Table D-4. By using these values, it can be calculated that 1.7 kg of matter trapped in a cooler contain a total activity of between 0.12 Bq (^{227}Ac) and 0.38 Bq (^{126}Sn). This activity is significantly less than that predicted as being deposited directly from the water (46.8 Bq). Thus, this pathway can be ignored.

In the case of the volcanic eruption (volcanic ash exposure scenario), the approach adopted involves comparing the external dose from ground shine to that from the cooler. A deposited activity (As) of 1 Bq/m^2 will be used for the comparison. Assuming ash density, ρ, of 1,000 kg/m^3 and the mean value of the resuspendable soil/ash thickness, d_c, of 2 mm (0.002 m) and that the ash thickness is equal to the critical thickness, the activity density is 0.5 Bq/kg ($As/(d_c\ \rho)$). Thus, the cooler unit will contain 0.85 Bq of activity.

Annual dose estimates for this activity in a cooling system can be arrived at by scaling the prediction given in Table D-6 for a cooler activity of 46.8 Bq by the ratio of 0.85/46.8 (i.e., by multiplying the annual dose in Table D-6 by the ratio of activities accumulated in the cooler from volcanic particles and from groundwater). The estimates of external dose due to activity deposited on the ground can be generated from effective dose coefficients for contaminated ground surface given in Table 6.5-1 (converted to annual exposure), exposure time of 17.75 h/d, and the activity density of 1 Bq/m^2. The results are presented in Table D-7. These comparisons indicate that the additional annual dose due to the accumulation of ash in an evaporative cooler can be neglected.

Table D-7. Estimated Annual Dose from Ground Shine and Evaporative Cooler Units for the Volcanic Scenario

Radionuclide	Annual External Dose Due to Ground Shine Sv/yr	Annual External Dose Due to Evaporative Cooler Sv/yr
^{126}Sn	4.60E–08	6.71E–11
^{137}Cs	1.28E–08	1.78E–11
^{227}Ac	1.09E–08	4.23E–11

D3.5 ADDITIONAL PATHWAYS

Cooler Maintenance

To maintain unit efficiency and to reduce heat loss during the winter months, some operations must be performed on the system. As mentioned in Section D.1, winterizing takes place in fall and evaporator pad replacement is generally performed in spring. Both operations for a domestic unit take about one hour. During this time the operator is close to the unit and, by virtue of the inverse square law, is subject to higher radiation levels.

An estimate of the exposure can be obtained by simple scaling of the in-house exposure. The exposure time is reduced from about 4,000 hours per year to two. If the operator is about three quarters of a meter away for the source (at this close range the sources of radiation, i.e., the pads and the water reservoir, are extended sources, but for the purposes of this estimate this will be overlooked), then the geometric factor increases from 0.08 m^{-2} to $(4/3)^{2,}$ or 1.7, an increase by a factor of 22. Thus it would be estimated that the cooling system annual maintenance would increase the external exposure dose from the evaporative cooler by about 1%. This pathway is inconsequential.

D4. SUMMARY

Estimating the dose (disregarding the shielding factor for the dwelling as this has the same value for a given radionuclide for both the cooler and soil irradiation sources) using parameter values given in Tables D-3, D-4, and D-6 yields the results shown in Table D-8 for unit activity in groundwater.

Table D-8. Annual Dose Estimates from External Exposure from Radionuclides in Soil and in Evaporative Coolers and from Drinking Water

Pathway		Annual Dose (Sv) From Indicated Pathway from Unit Concentration of Specified Radionuclide in Groundwater		
		^{126}Sn	^{137}Cs	^{227}Ac
Inhalation	A - Evaporative Cooler	6.1E–10	1.5E–10	6.9E–07
External	B1 – Evaporative Cooler	3.7E–09	9.8E–10	2.3E–09
	B3 - Surface Soil	2.3E–07	2.8E–08	1.3E–08
Ingestion	C - Drinking Water (2 L/d)	3.8E–09	1.5E–09	3.2E–07
All pathways (BDCFs)		4.3E–07	1.3E–07	1.3E–06

The results show that external exposure from evaporative coolers is a relatively insignificant contributor to the all-pathway dose (Table 6.11-8) and, thus, can be neglected.

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APPENDIX E
EVALUATION OF FISH INGESTION DOSE AFTER A VOLCANIC EVENT

EVALUATION OF FISH INGESTION DOSE AFTER A VOLCANIC EVENT

In developing the reference biosphere for the volcanic ash exposure scenario, the ingestion pathway of eating contaminated fish raised on the local fish-farm was not included in the volcanic ash exposure scenario. The rationale for this decision was based on five factors. These are discussed below.

A. Unlike the groundwater exposure scenario, in the volcanic ash scenario the water used in the ponds is considered to contain no radionuclides and, as a result, will not be subject to concentration increase from replenishment of evaporated water.

B. Fish consumption by the local population is small compared to the intake of other locally grown foods (Table 6.6-3).

C. Fish farming efficiency is, generally, susceptible to rapid changes in the aqueous environment. This was substantiated by the fish farm operators in Amargosa Valley (BSC 2004 [DIRS 169672], Section 6.4) who stated that a distant forest fire created sufficient pollution that the fish died. Ashfall would have a similar effect.

D. In the volcanic ash exposure scenario, the radioactive waste deposited in Amargosa Valley would be in the form of small particles of waste that would be relatively insoluble. As such, the radionuclides would only slowly leach into the water where they would be available for uptake by the fish.

E. The pond water is changed on a regular basis as the fish mature and are harvested. BSC (2004 [DIRS 169672], Section 6.4) indicated that this drain/refill cycle is performed at least once every two years. Thus, if the waste form is solubility or dissolution limited, the activity available to the fish would be so reduced. If the waste form were to rapidly dissolve, the exposure duration of the fish eating pathway would be limited to a maximum of two years.

To evaluate the reasonableness of not considering the fish ingestion pathway in the volcanic ash exposure scenario, the following analysis was conducted with the conservative assumption that all available radionuclides in the waste deposited by the ashfall into the fishponds instantaneously became available for uptake by the fish.

The contribution to the volcanic BDCFs from ingestion of fish raised in a fishpond that has been contaminated by an ashfall event can be calculated as follows. The annual dose from fish consumption is calculated as (Section 6.4.9.4)

$$D_{ing,f,i} = EDCF_{ing,i}\ Cf_i\ Uf \qquad \text{(Eq. E-1)}$$

where

$D_{ing,f,i}$ = annual dose contribution to BDCF from ingestion of primary radionuclide i in fish (Sv/yr per Bq/m^2)

Cf_i = activity concentration of primary radionuclide i in fish (Bq/kg per Bq/m^2)

Uf = annual consumption rate of locally produced fish (kg/yr).

The activity concentration in fish can be calculated as (Section 6.4.5)

$$Cf_i = Cw_{f,i}\ BF_i \qquad \text{(Eq. E-2)}$$

where

$Cw_{f,i}$ = activity concentration of radionuclide i in fishpond water, at the time of harvest (Bq/m^3 per Bq/m^2)

BF_i = bioaccumulation factor for radionuclide i in freshwater fish (m^3/kg).

The activity concentration in fishpond water from an ashfall event can be calculated as

$$Cw_{f,i} = \frac{Cs_i}{PD} \qquad \text{(Eq. E-3)}$$

Cs_i = activity concentration of radionuclide i in ash deposited on the ground surface (1 Bq/m^2)

PD = fishpond depth (m).

The ashfall source term appropriate for this pathway (one of the source terms used to derive the BDCFs for the volcanic ash scenario) is 1 Bq/m^2. The average fishpond depth, *PD*, can be determined from the dimensions of fishponds (BSC 2004 [DIRS 169672], Table 6-66) and reproduced in Table E-1. The depth of the ponds is in the range from 0.8 to 1.7 m.

Table E-1. Dimensions of the Grow-Out Ponds

Pond No.	Length	Width	Depth	Surface Area	Volume
1	192 ft (59.2 m)	70 ft (21.6 m)	2.5 ft (0.8 m)	13,440 ft^2 (1,278 m^2)	33,600 ft^3 (986 m^3 = 9.86 × 10^5 L)
2	200 ft (61.7 m)	82 ft (25.3 m)	5.5 ft (1.7 m)	16,400 ft^2 (1,560 m^2)	90,200 ft^3 (2,646 m^3 = 2.65 × 10^6 L)
3	182 ft (56.1 m)	82 ft (25.3 m)	5.5 ft (1.7 m)	14,924 ft^2 (1,419 m^2)	82,082 ft^3 (2,408 m^3 = 2.41 × 10^6 L)
Total				44,764 ft^2 (4,258 m^2)	205,882 ft^3 (6,039 m^3 = 6.04 × 10^6 L)

Source: BSC 2004 [DIRS 169672], Table 6-66.

The average fishpond depth is calculated as an area-weighted average by dividing the total volume by total surface area in Table E-1 as follows:

$$PD\ (m) = \frac{6{,}039\, m^3}{4{,}258\, m^2} = 1.42\, m \qquad \text{(Eq. E-4)}$$

Inserting the result of Equation E-4 into Equation E-3 results in an activity concentration in fishpond water of 0.705 Bq/m^3 per Bq/m^2. The mean annual consumption rate of locally produced fish, *Uf*, is 0.23 kg/yr (Table 6.6-3). Since these two values are independent of the primary radionuclide, *i*, Equations E-1 and E-2 can be consolidated as follows:

$$D_{ing,f,i} = 0.705 \times 0.23 \times EDCF_{ing,i}\ BF_i = 0.162 \times EDCF_{ing,i}\ BF_i \qquad \text{(Eq. E-5)}$$

Three representative principal radionuclides were selected for comparison based on the different pathways that dominate their BDCFs (dominant pathway in parenthesis): ^{99}Tc (ingestion), ^{137}Cs (external exposure), and ^{239}Pu (inhalation) (Table 6.13-1). Table E–2 lists the effective dose coefficients for ingestion and the bioaccumulation factors for these three radionuclides, as well as the calculation of the fish ingestion dose using Equation E-5.

Table E-2. Fish Ingestion Dose for Representative Radionuclides Resulting from Ashfall Event

Radionuclide	Effective Dose Coefficient for Ingestion [a] Sv/Bq	Bioaccumulation Factor [b] m^3/kg	Fish Ingestion Dose[c] Sv/yr per Bq/m^2
^{99}Tc	6.42E–10	2.0E–02	2.08E–12
^{137}Cs	1.36E–08	3.5E+00	7.71E–09
^{239}Pu	2.51E–07	4.1E–02	1.67E–09

[a] Source: Table 6.4-6.
[b] Source: Table 6.6-3, converted from L/kg to m^3/kg by factor of 1000.
[c] Calculated using Equation E–5.

Table E-3 is a comparison between the total of the three volcanic ashfall scenario BDCF components combined under the assumption of uniform distribution of radionuclide concentration in the soil (as used in Section 6.14.2 to produce the percent pathway contributions appearing in Table 6.14-2; the combined BDCFs are in Excel file *VA BDCF Pathway Analysis.xls* , worksheet *Pathway Summary*) and the fish ingestion dose calculated in Table E-2.

Table E-3. Comparison of Fish Ingestion Dose and BDCFs from Volcanic Ashfall Event

Radionuclide	Fish Ingestion Dose [a] Sv/yr per Bq/m^2	Total BDCF[b] Sv/yr per Bq/m^2	Ratio of Fish Pathway BDCF to Total BDCF
^{99}Tc	2.08E–12	2.73E–10	7.63E–03
^{137}Cs	7.71E–09	7.17E–09	1.08E+00
^{239}Pu	1.67E–09	4.93E–09	3.38E–01

[a] Source: Table E-2
[b] Source: Excel file *VA BDCF Pathway Analysis.xls*, worksheet *Pathway Summary*.

While the dose from the fish ingestion pathway is a small fraction (less than one percent) of the BDCF from all other pathways for ^{99}Tc, for ^{239}Pu and ^{137}Cs it is comparable in magnitude to the total BDCF.

If the fish ingestion pathway were included in ERMYN for the volcanic ash scenario, it would double the total BDCF for ^{137}Cs for the period of time until the pond is drained and refilled. However, this estimate is an unlikely upper bound of the annual dose from fish consumption for the following reasons:

1. It is unlikely that a total dissolution of the waste form would occur during the time period it takes to produce full-grown fish (1 to 2 years), thus, reducing the activity concentration in the water available for fish uptake.

2. Bioaccumulation factors for fish were developed by using literature values that are not fully applicable for the farmed fish (BSC 2004 [DIRS 169672], Section 6.4.3). This is because the bioaccumulation factors reported in the literature were established for the natural aquatic systems. In natural aquatic systems, fish receive radionuclides directly from the water and the food. However, this is not the case for the fish farm, where the fish are fed commercial, uncontaminated feed. Therefore, bioaccumulation factors provide an upper bound of the estimated uptake.

3. If a volcanic eruption occurred with an ensuing ash deposition on fish ponds, fish would likely die and thus not contribute to the human food chain.

In addition, the fish consumption pathway, as described above, would only contribute to the annual dose for the first and, possibly, the second year after a volcanic eruption. Such a contribution would be negligible for the expected dose calculated in the TSPA model, which is weighted by the probability of an eruption occurring in a given time period. Therefore, it is reasonable to not include this pathway in the BDCFs for the volcanic ash exposure scenario.

APPENDIX F
DATA QUALIFICATION PLAN FOR ACREAGE OF FIELDS PLANTED IN ALFALFA AND OTHER CROPS IN AMARGOSA VALLEY

DATA QUALIFICATION PLAN FOR ACREAGE OF FIELDS PLANTED IN ALFALFA AND OTHER CROPS IN AMARGOSA VALLEY

YMP

Data Qualification Plan

Complete only applicable items.

QA: QA
Page 1 of 1

Section I. Organizational Information

Qualification Title

Acreage of fields planted in alfalfa and other crops in Amargosa Valley

Requesting Organization

Performance Assessment/Natural Systems

Section II. Process Planning Requirements

1. List of Unqualified Data to be Evaluated

Data on acres planted in alfalfa and other field crops collected during socioeconomic surveys conducted in Amargosa Valley in the years 1996 through 1999 and documented in the following reports: CRWMS M&O 1997 [DIRS 101090], Tables 3-12 and 3-13; YMP 1999 [DIRS 158212] Tables 10 and 11.

2. Type of Data Qualification Method(s) [Including rationale for selection of method(s) (Attachment 3) and qualification attributes (Attachment 4)]

The data will be qualified using Method 5, Technical Assessment. This method was selected because it was determined that it is suitable to raise the confidence of the data to a level appropriate for the intended use. The data collection procedures are available for review; however, these procedures were not developed under a Quality Assurance program.

Data qualification attributes that will be considered in the qualification process include the following: (1) qualification of personnel or organizations generating the data; (2) technical adequacy if equipment and procedures used to collect and analyze the data; (3) extent to which the data demonstrate the property of interest; (6) the extent to which conditions under which the data were generated may partially meet the Quality Assurance program that supports the YMP license application process or postclosure science.

3. Data Qualification Team and Additional Support Staff Required

Maryla Wasiolek, chairperson and technical representative. Maryla Wasiolek is a principal member of technical staff with Sandia National Laboratories and is the lead for the biosphere modeling effort. She has Ph.D. in physical sciences, over 20 years experience in radiological assessment and 10 years experience on the Yucca Mountain Project.

John Arnish, Argonne National Laboratory (M.Sc. in Nuclear Engineering) has over 12 years of experience conducting environmental radiological risk assessment. He is the co-developer and principal instructor for the RESRAD family of radiological assessment codes.

4. Data Evaluation Criteria

The data on acreage of fields planted in alfalfa and other crops will be qualified if it can be demonstrated that the qualification attributes listed in Section 2 can be answered affirmatively or if any negative responses can be shown to have negligible effect on the quality of the data and its appropriateness for intended use in Biosphere Model Report.

5. Identification of Procedures Used

The primary procedure used to control the data qualification process will be SCI-PRO-001, *Qualification of Unqualified Data*. The documentation of the qualification process and findings will be conducted in accordance with SCI-PRO-006, *Models*. Other procedures will be followed, as required by SCI-PRO-006, *Models*.

6. Plan coordinated with the following known organizations providing input to or using the results of the data qualification

No other organizations were identified.

Section III. Approval

Qualification Chairperson Printed Name	Qualification Chairperson Signature	Date
Maryla A. Wasiolek	Maryla Wasiolek	05/15/2007
Responsible Manager Printed Name	**Responsible Manager Signature**	**Date**
Stephanie P. Kuzio for	Kenneth Rehfeldt	05/15/2007

SCI-PRO-001.1-R1

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APPENDIX G
CALCULATION OF AVERAGE TEPHRA THICKNESS AT THE RMEI LOCATION

CALCULATION OF AVERAGE TEPHRA THICKNESS AT THE RMEI LOCATION

A Monte Carlo analysis was conducted using the ASHPLUME_DLL_LA V2.1 code (STN: 11117-2.1-00 [DIRS 178870]) and the modeling tool GoldSim V9.60 (STN: 10344-9.60-00 [DIRS 180224]) to provide an estimate of the mean tephra deposit thickness that could occur at the RMEI location 18 km south of the Yucca Mountain Repository due to a hypothetical volcanic conduit intersection with the repository. The analysis consisted of the calculation of one hundred realizations of tephra thickness at the RMEI location due to a single eruption by sampling one hundred values of all stochastic ASHPLUME V2.1 input parameters except wind direction, which was held constant, fixed to the South for all realizations to provide a worst-case analysis. The ASHPLUME V2.1 code calculates tephra deposition in g/cm^2 on the surface and this surface concentration was converted to deposit thickness in cm by dividing by the ash settled density in g/cm^3.

ASHPLUME_DLL_LA V.2.1 allows parameters that are distributions to be sampled outside of the ASHPLUME code (within the TSPA GoldSim model). GoldSim then passes the sampled point values for each parameter into the ASHPLUME_DLL_LA V.2.1 code. Each realization simulates only one volcanic event at a time, and the single volcanic event in each realization represents the entire output of the volcano as one violent Strombolian eruption.

Parameter values used in this analysis are identical to those used in TSPA calculations for the Igneous Eruptive Modeling Case (SNL 2007 [DIRS 177431], Section 6.5.2). Details of the ASHPLUME conceptual model and its implementation within the TSPA Igneous Eruptive Modeling Case are provided in *Atmospheric Dispersal and Deposition of Tephra from a Potential Volcanic Eruption at Yucca Mountain, Nevada* (SNL 2007 [DIRS 177431]). All ASHPLUME_DLL_LA V.2.1 input parameter values used in the calculation are shown in Table G-1. Because this analysis is only concerned with estimating tephra thickness at the RMEI location and does not consider waste concentration, the parameter U, mass of waste to incorporate, was set to zero to simplify the calculation. Table G-2 shows the eruption volume and the distribution of the settled ash density parameters used for the calculation of eruption duration and tephra thickness.

Table G-1. ASHPLUME V2.1 Input Parameters

Parameter	Description	Units	Value	Distribution Type
iscrn	Run type (0 = no screen output)	none	0	point value
X_Min_Grid	Minimum X grid location	km	0	point value
X_Max_Grid	Maximum X grid location	km	0	point value
Y_Min_Grid	Minimum Y grid location	km	-18	point value
Y_Max_Grid	Maximum Y grid location	km	-18	point value
Nxx_Grid	Number of X grid locations	none	1	point value
Ny_Grid	Number of Y grid locations	none	1	point value
AshDen_MaxD	Ash particle density at max size	g/cm^3	1.04	point value
AshDen_MinD	Ash particle density at min size	g/cm^3	2.08	point value
LogD_maxDen	Log ash particle size at min density	log (cm)	-3	point value
LogD_minDen	Log ash particle size at max density	log (cm)	0	point value
Fshape	Ash particle shape factor	none	0.5	point value

Table G-1. ASHPLUME V2.1 Input Parameters (Continued)

Parameter	Description	Units	Value	Distribution Type
AirDen	Air density	g/cm^3	0.001734	point value
AirVis	Air viscosity	g/cm/s	0.000185	point value
C	Eddy diffusivity constant	$cm^2/s^{5/2}$	400.0	point value
Dmax_trans	Maximum particle diameter for transport	cm	10	point value
D_min	Minimum waste particle size	cm	0.0001	point value
D_mode	Mode waste particle size	cm	0.0013	point value
D_max	Maximum waste particle size	cm	0.2	point value
H_min	Minimum height of eruption column	km	0.001	point value
A_cutoff	Threshold limit on ash accumulation	g/cm^2	1×10^{-10}	point value
Beta_dist_a	Column diffusion constant (Beta)	none	0.01 – 0.5	uniform
Dash_mean_a	Mean ash particle diameter	cm	0.001 – 0.01 – 0.1	log triangular
Dash_sigma_a	Ash particle diameter standard dev.	log (cm)	0.301 – 0.903	uniform
Rhocut	Waste incorporation ratio	none	0.0	point value
U	Mass of waste to incorporate (not considered in this calculation)	g	0.0	point value
Wind_Direction	Wind Direction (Fixed toward South for this calculation)	degrees	-90	point value
Wind_Speed	Wind Speed	cm/s	tabular	CDF tables
Erupt_Velocity_a	Initial rise velocity	cm/s	1 – 10,000	uniform
Erupt_Power_a	Eruptive power	W	1×10^9 – 1×10^{12}	log uniform
Erupt_Time_a	Eruption duration (Derived from eruptive volumes)	s	Calculated by GoldSim	log uniform
Min_Rad	Minimum radius (polar grid)	none	0	point value
R_Factor	Radial increment factor	none	0	point value
Nrr_Grid	Number of radial divisions (0 for no polar grid)	none	0	point value
Ntheta_Grid	Number of angular increments	none	0	point value
Num_pts	Number of points in ash/waste histogram output (0 for no hist)	none	0	point value

Sources:
DTN: LA0702PADE03GK.002 [DIRS 179980] (ASHPLUME Parameters)
DTN: MO0408SPADRWSD.002 [DIRS 171751] (Wind Speed)

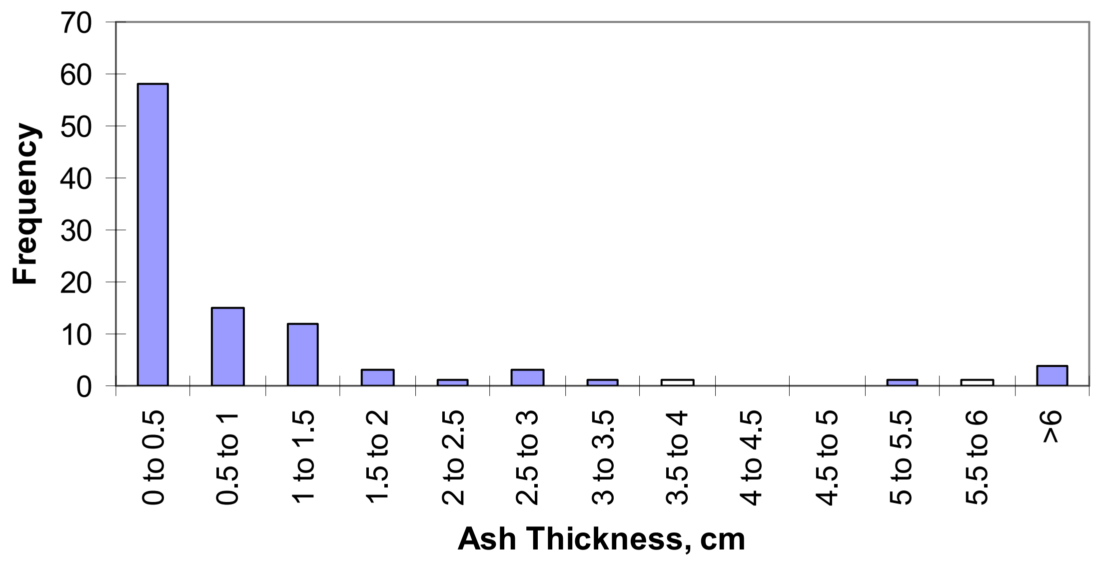
Table G-2. Tephra Volume and Settled Density Input Parameters

Parameter	Description	Units	Value	Distribution Type
Volcano_Vol_ Max	Maximum total eruption volume	km^3	0.14	point value
Volcano_Vol_ Min	Minimum total eruption volume	km^3	0.004	point value
Vol_Time_ Converter	Eruption duration conversion factor	$J\text{-}m^3/kg\text{-}km^3$	10^{15}	point value
Ash_Density_a	Ash Settled Density	kg/m^3	300 to 1500 mean 1000 std. dev. 100	Truncated Normal

Sources: DTN: LA0702PADE03GK.002 [DIRS 179980] (Volumes and Converter)
DTN: LA0612DK831811.001 [DIRS 179987] (Ash Density)

The results of this Monte Carlo analysis are presented in Table G-3. All one hundred values of calculated tephra thickness at the RMEI location are given in the table along with the corresponding one hundred realizations of the stochastic input parameters. The arithmetic mean of the one hundred calculated tephra thickness values is 0.97 cm and the geometric mean is 0.172 cm. These mean values were calculated in an Excel spreadsheet using built-in functions "AVERAGE" and "GEOMEAN" respectively.

The histogram of the ash thickness at the RMEI location is presented in Figure G-1. Under the conservative assumption of wind direction fixed to the South so that the mid-line of the plume would be the same in each realization, 58% of the realizations resulted in ash thickness less than 0.5 cm; 73% of realizations resulted in ash thickness less than 1 cm; and 92% had ash thickness less than 3 cm. Under variable wind conditions, the ash thickness would be less than that.



Source: Excel file *Ash at RMEI Results.xls* in Appendix A.

Figure G-1. Histogram of 100 Ash Thickness Results for Wind Blowing to the South

Table G-3. Calculated Tephra Thickness at the RMEI Location with Corresponding Sampled Input Parameter Values

Realization	Calculated Tephra Thickness (cm)	Sampled Values of Stochastic Input Parameters							
		Eruption Power (W)	Eruption Velocity (cm/s)	Ash Particle Size Standard Deviation Log(cm)	Mean Ash Particle Size (cm)	Column Diffusion Constant (Beta)	Eruption Duration (s)	Wind Speed (cm/s)	Ash Density (g/cm^3)
1	1.06E+00	2.52E+11	3219.0	0.897	0.0189	0.1086	3.71E+04	2592.4	1.1297
2	4.39E–01	6.66E+11	81.2	0.607	0.0033	0.2034	1.02E+05	1922.5	1.0612
3	5.53E+00	4.25E+11	1314.4	0.643	0.0359	0.4871	1.19E+05	3483.4	1.1719
4	1.55E–01	1.94E+11	5736.2	0.727	0.0056	0.4746	6.28E+04	1031.1	0.86147
5	1.72E–04	1.98E+10	5044.6	0.329	0.0034	0.0191	1.23E+06	956.9	0.91689
6	5.17E–03	4.33E+09	3503.9	0.673	0.0012	0.1258	8.51E+05	823.5	0.90482
7	8.41E–02	5.62E+10	3921.6	0.761	0.0465	0.4033	1.33E+05	66.0	0.92102
8	5.40E–02	1.04E+10	4396.7	0.580	0.0072	0.3403	4.79E+05	620.6	0.93854
9	3.11E–01	2.14E+09	7550.1	0.564	0.0103	0.1484	5.65E+06	964.7	0.99491
10	9.66E–02	1.54E+09	9806.5	0.433	0.0062	0.4935	2.35E+07	585.2	1.0449
11	1.24E+01	1.06E+11	3824.3	0.789	0.0240	0.3915	1.34E+06	2074.8	1.1189
12	2.67E+00	2.92E+11	2462.6	0.831	0.0042	0.2373	3.92E+05	2683.1	0.9739
13	1.55E+00	1.13E+11	1775.2	0.860	0.0030	0.3290	7.95E+05	2346.4	1.0139
14	5.74E–03	2.36E+09	8420.7	0.620	0.0015	0.1414	2.50E+06	1317.1	1.0881
15	1.38E+00	1.40E+10	4915.6	0.862	0.0192	0.3245	1.39E+06	955.9	0.93058
16	9.03E–01	2.82E+11	9911.1	0.815	0.0226	0.0976	3.65E+04	1671.4	0.85852
17	2.65E+00	1.55E+11	307.1	0.515	0.0100	0.0616	6.73E+05	1699.3	1.1363
18	7.30E–02	4.10E+09	3103.3	0.386	0.0183	0.1802	1.10E+06	926.7	1.0684
19	3.59E+00	3.93E+09	9324.6	0.732	0.0094	0.1130	2.85E+07	744.4	1.0094
20	1.20E–01	5.69E+11	2644.7	0.524	0.0110	0.1650	4.84E+04	207.2	0.87967
21	6.42E–02	2.27E+10	2129.6	0.618	0.0021	0.2488	2.50E+06	1503.9	1.0356

Table G-3. Calculated Tephra Thickness at the RMEI Location with Corresponding Sampled Input Parameter Values (Continued)

Realization	Calculated Tephra Thickness (cm)	Sampled Values of Stochastic Input Parameters							
		Eruption Power (W)	Eruption Velocity (cm/s)	Ash Particle Size Standard Deviation Log(cm)	Mean Ash Particle Size (cm)	Column Diffusion Constant (Beta)	Eruption Duration (s)	Wind Speed (cm/s)	Ash Density (g/cm^3)
22	7.90E–01	2.86E+10	9592.4	0.902	0.0113	0.4179	3.70E+05	1383.3	0.8376
23	1.06E+00	6.42E+09	5995.1	0.598	0.0307	0.3453	1.54E+06	1665.8	1.1166
24	2.91E–01	1.50E+09	3742.7	0.555	0.0122	0.0573	4.53E+06	1577.3	0.99188
25	5.22E–02	3.09E+11	7727.2	0.409	0.0172	0.4958	4.87E+04	893.1	1.005
26	7.16E–01	2.15E+10	7231.9	0.776	0.0052	0.0534	2.08E+06	733.6	0.91439
27	6.48E–01	1.54E+11	8693.6	0.451	0.0356	0.3968	7.71E+04	1212.1	0.73299
28	5.16E–01	3.59E+09	7195.7	0.820	0.0131	0.4007	5.14E+06	417.1	1.0546
29	5.64E–03	1.31E+11	9281.3	0.361	0.0160	0.2217	1.28E+05	2143.8	1.0509
30	5.27E–02	5.06E+11	1574.5	0.691	0.0084	0.3698	1.09E+04	411.0	0.88779
31	3.31E–04	8.39E+11	7304.2	0.341	0.0070	0.0406	9.88E+03	811.4	0.81564
32	8.74E–01	5.81E+11	8255.2	0.788	0.0068	0.0803	8.35E+04	1723.3	1.1873
33	6.36E–01	8.21E+10	2276.8	0.478	0.0102	0.2074	1.65E+06	466.2	1.1035
34	5.85E–01	1.10E+09	4882.9	0.521	0.0047	0.0202	7.05E+07	1278.6	0.96608
35	2.72E–02	9.04E+11	5480.6	0.337	0.0254	0.2999	8.35E+03	559.6	1.0634
36	2.59E–01	3.52E+10	503.2	0.502	0.0054	0.4548	2.42E+06	4681.3	1.0182
37	1.49E+00	2.29E+09	3341.1	0.661	0.0109	0.0110	2.39E+07	471.7	0.9408
38	3.59E–05	4.98E+11	4736.7	0.456	0.0020	0.1675	1.05E+04	845.0	0.89242
39	6.48E+00	2.12E+11	9707.9	0.498	0.0634	0.1341	2.98E+05	1420.8	1.1058
40	5.02E–02	1.79E+09	3643.0	0.755	0.0017	0.4628	5.34E+06	560.6	0.9007
41	2.37E–01	7.11E+10	2042.7	0.586	0.0058	0.1525	8.62E+05	527.2	1.2193
42	4.31E–01	5.17E+10	8752.9	0.878	0.0177	0.4134	9.54E+04	1575.2	0.98368
43	4.88E–01	3.69E+11	4666.1	0.717	0.0152	0.1184	2.34E+04	3346.0	1.1474

Table G-3. Calculated Tephra Thickness at the RMEI Location with Corresponding Sampled Input Parameter Values (Continued)

Realization	Calculated Tephra Thickness (cm)	Sampled Values of Stochastic Input Parameters							
		Eruption Power (W)	Eruption Velocity (cm/s)	Ash Particle Size Standard Deviation Log(cm)	Mean Ash Particle Size (cm)	Column Diffusion Constant (Beta)	Eruption Duration (s)	Wind Speed (cm/s)	Ash Density (g/cm^3)
44	4.09E–02	2.60E+09	1437.0	0.632	0.0018	0.2530	8.93E+06	690.7	1.0828
45	3.89E–03	1.06E+09	9672.0	0.424	0.0025	0.0458	2.47E+07	677.6	0.92638
46	2.08E+00	2.66E+10	8065.6	0.346	0.0384	0.2333	3.49E+06	2020.1	0.9748
47	1.42E+00	2.70E+09	2972.5	0.796	0.0210	0.4341	1.68E+07	354.0	1.0171
48	1.23E+00	1.22E+10	734.5	0.706	0.0274	0.3545	3.26E+06	383.8	1.0387
49	1.16E–01	3.37E+10	271.2	0.373	0.0164	0.4256	2.95E+05	1858.2	1.08
50	5.37E–01	2.33E+11	8924.4	0.534	0.0144	0.1720	2.36E+05	1545.8	1.1605
51	6.10E+00	7.57E+09	1629.6	0.369	0.0431	0.2712	9.13E+06	1190.7	0.97873
52	2.85E–02	3.83E+10	4208.8	0.470	0.0066	0.4433	6.28E+05	1472.7	0.86758
53	7.79E–02	6.26E+11	615.1	0.492	0.0073	0.0280	8.47E+03	2932.4	0.78993
54	2.76E–01	7.20E+09	5231.2	0.715	0.0224	0.0318	2.40E+06	190.5	0.94366
55	5.31E+00	4.92E+10	199.8	0.699	0.0320	0.1604	3.88E+05	2641.5	0.96047
56	1.62E–02	1.05E+10	5109.9	0.575	0.0027	0.3068	1.46E+06	1445.0	1.067
57	3.64E–01	4.79E+09	5646.9	0.868	0.0080	0.4366	1.83E+06	964.7	1.0212
58	7.52E–02	2.55E+10	7977.9	0.650	0.0048	0.3865	3.85E+05	569.6	0.88723
59	6.97E–01	2.92E+09	8199.7	0.679	0.0061	0.4767	1.19E+07	653.0	0.8762
60	1.23E–01	4.74E+10	6759.9	0.412	0.0138	0.3149	5.46E+05	709.2	1.0555
61	1.24E–02	1.86E+11	6564.2	0.462	0.0097	0.4493	2.22E+04	507.6	0.94913
62	1.49E+00	2.36E+11	6427.5	0.843	0.0295	0.3098	1.05E+05	675.1	0.83154
63	4.37E–01	1.51E+10	3422.6	0.766	0.0064	0.2954	2.41E+06	349.2	0.98532
64	4.14E–02	1.18E+09	4467.0	0.383	0.0076	0.2305	1.37E+07	612.9	0.97182
65	3.08E–02	3.04E+10	4114.3	0.542	0.0039	0.3667	5.48E+05	395.8	0.89852

Table G-3. Calculated Tephra Thickness at the RMEI Location with Corresponding Sampled Input Parameter Values (Continued)

Realization	Calculated Tephra Thickness (cm)	Sampled Values of Stochastic Input Parameters							
		Eruption Power (W)	Eruption Velocity (cm/s)	Ash Particle Size Standard Deviation Log(cm)	Mean Ash Particle Size (cm)	Column Diffusion Constant (Beta)	Eruption Duration (s)	Wind Speed (cm/s)	Ash Density (g/cm^3)
66	6.22E–01	8.67E+10	406.0	0.812	0.0053	0.1047	1.24E+05	1849.8	0.95379
67	1.70E–02	5.57E+09	6385.4	0.318	0.0086	0.0730	2.24E+07	1254.5	0.95318
68	2.53E+00	1.70E+11	982.9	0.696	0.0118	0.3190	3.80E+05	1611.9	0.94628
69	6.21E+00	4.64E+11	840.3	0.738	0.0329	0.1920	7.47E+04	2488.2	0.96901
70	1.73E+00	6.59E+10	5368.4	0.883	0.0505	0.1995	1.75E+05	2103.2	1.1522
71	1.65E–02	1.91E+10	9159.9	0.552	0.0023	0.0377	1.18E+06	521.6	0.9571
72	5.55E–04	5.25E+09	4047.0	0.354	0.0024	0.4570	6.26E+06	230.8	1.0273
73	2.99E–02	1.20E+10	6644.7	0.399	0.0088	0.1850	5.47E+06	2759.1	0.91056
74	3.13E–01	4.11E+10	1212.7	0.362	0.0120	0.0907	2.11E+06	1012.8	0.98815
75	7.90E–01	1.01E+11	2594.5	0.842	0.0216	0.2643	5.07E+04	2626.9	0.80184
76	1.07E+00	1.28E+09	7684.3	0.539	0.0125	0.2144	4.24E+07	334.3	1.0285
77	1.27E+00	3.07E+09	5588.6	0.614	0.0082	0.3361	1.88E+07	818.4	0.93555
78	1.61E–01	3.39E+09	8851.8	0.303	0.0158	0.2849	4.51E+07	1245.4	1.0943
79	1.37E–01	1.21E+11	6857.3	0.309	0.0197	0.1299	6.86E+05	596.0	1.2855
80	9.62E–03	8.23E+09	8335.6	0.485	0.0038	0.0758	1.88E+06	104.8	1.1274
81	1.05E–04	3.32E+11	9415.5	0.421	0.0046	0.2898	2.89E+04	1624.9	0.99508
82	1.19E+00	1.37E+10	7887.4	0.568	0.0107	0.1440	6.00E+06	563.2	1.0979
83	7.13E–01	7.63E+11	5864.5	0.851	0.0029	0.3768	1.37E+05	3532.1	1.0245
84	8.08E–02	7.48E+11	2822.7	0.666	0.0090	0.2403	5.87E+03	4512.1	0.92287
85	3.37E+00	3.92E+11	1844.5	0.653	0.0410	0.2670	9.54E+04	1576.3	1.1091
86	6.06E–01	5.79E+09	2751.8	0.743	0.0043	0.4288	8.29E+06	657.2	1.0418
87	8.03E–04	6.23E+10	1003.5	0.320	0.0092	0.4825	3.23E+05	1657.7	1.0493

Table G-3. Calculated Tephra Thickness at the RMEI Location with Corresponding Sampled Input Parameter Values (Continued)

Realization	Calculated Tephra Thickness (cm)	Sampled Values of Stochastic Input Parameters							
		Eruption Power (W)	Eruption Velocity (cm/s)	Ash Particle Size Standard Deviation Log(cm)	Mean Ash Particle Size (cm)	Column Diffusion Constant (Beta)	Eruption Duration (s)	Wind Speed (cm/s)	Ash Density (g/cm^3)
88	3.04E–01	1.66E+09	1105.2	0.590	0.0076	0.2584	7.91E+06	1654.3	1.0009
89	1.29E+00	9.51E+10	7083.3	0.686	0.0523	0.3622	1.19E+06	59.7	0.98104
90	3.65E–01	1.66E+10	9012.5	0.508	0.0128	0.4700	1.49E+06	1002.9	1.037
91	2.78E–01	1.37E+11	6976.5	0.803	0.0609	0.3824	4.85E+04	419.9	1.0869
92	4.64E–02	1.74E+10	3028.6	0.439	0.0147	0.2198	3.17E+05	305.2	1.2028
93	1.71E–01	6.56E+09	1964.2	0.464	0.0051	0.0660	9.98E+06	1039.7	0.84457
94	1.36E+00	7.52E+10	7407.5	0.887	0.0723	0.1903	3.75E+05	498.1	1.0763
95	1.86E+00	8.69E+09	2368.3	0.831	0.0251	0.0859	1.16E+07	246.2	1.0066
96	6.62E–01	9.39E+09	8590.9	0.627	0.0271	0.2828	8.33E+05	1106.6	0.9985
97	1.61E–01	9.77E+11	4504.8	0.779	0.0135	0.2787	4.80E+03	1366.4	0.96365
98	1.82E–03	1.32E+09	6105.1	0.440	0.0031	0.4071	4.33E+06	743.2	1.0117
99	7.44E–04	4.23E+10	6069.8	0.394	0.0041	0.3528	2.69E+06	1706.7	1.0725
100	2.86E–01	1.89E+09	6297.9	0.752	0.0036	0.1012	1.24E+07	616.6	1.0322
Mean	0.970	1.44E+11	4997.4	0.602	0.0152	0.2549	5.09E+06	1251.7	1.000
Geometric Mean	0.172								

Source: Excel file *Ash at RMEI Results.xls* in Appendix A.
GoldSim file *Ash at RMEI - 100rlz Ashplume v2-1.gsm*