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QA: N/A
Project No. WM-00011

SEP 24 2003

OVERNIGHT MAIL

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TRANSMITTAL OF REPORT *TECHNICAL BASIS DOCUMENT NO. 12: BIOSPHERE TRANSPORT* ADDRESSING SEVEN KEY TECHNICAL ISSUE (KTI) AGREEMENTS RELATED TO BIOSPHERE TRANSPORT

This letter transmits *Technical Basis Document No. 12: Biosphere Transport* (enclosure 1) and a CD format of this report (enclosure 2). This technical basis document contains a summary of the current conceptual understanding of biosphere transport and provides the context within which individual KTI agreements related to biosphere transport are addressed. Appendices A through G each provide a direct response to the following Igneous Activity (IA) and Total System Performance Assessment and Integration (TSPAI) KTI agreements:

Appendix A - Surface-Disturbing Activities (Response to IA 2.11)
Appendix B - Mass Loading and Ash Depth (Response to IA 2.14)
Appendix C - External Exposure (Response to IA 2.15)
Appendix D – Soil-Sorption (Response to TSPAI 3.33)
Appendix E - Radionuclide-Specific Biosphere Parameters (Response to TSPAI 3.34)
Appendix F - Crop Interception Fraction (Response to TSPAI 3.35)
Appendix G - Leaching Coefficients (Response to TSPAI 3.36)

The subject report is one in a series of technical basis documents that are being prepared to describe the Yucca Mountain, Nevada, repository system components and processes that are important for predicting the likely postclosure performance of the repository. The information presented in these documents, along with the associated references, responds to open KTI Agreements made between the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE). Placing the DOE responses to individual KTI agreements in the context of the applicable repository system components and processes allows for a more direct discussion of the relevance of the agreements to the postclosure safety analyses. The goal of this approach is to provide a more direct and transparent discussion of the relevant KTI agreements.

NMSS07
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The enclosed technical basis document discusses the methods used to model the conceptual understanding of transport of radionuclides that may be released from the repository through the biosphere. It includes a description of the reference biosphere, characteristics of the receptor, and the methods used to model environmental transport exposure pathways. This document places the responses to individual KTI agreements related to biosphere transport within the context of the overall biosphere transport and exposure model, explains their relationship to the postclosure safety analyses, and provides a discussion of the relevance of the agreements in the context of biosphere transport.

The DOE considers the KTI agreements covered in *Technical Basis Report 12: Biosphere Transport* and its appendices to be fully addressed, and pending review by the NRC, they should be closed.

There are no new regulatory commitments in the body or the enclosures of this letter. Please direct any questions concerning this letter and its enclosures to Eric T. Smistad at (702) 794-5073 or April V. Gil at (702) 794-5578.

Joseph D. Ziegler, Director
Office of License Application and Strategy

OLA&S:TCG-1848

Enclosures:
1. *Technical Basis Document No. 12: Biosphere Transport*, Revision 1 (hard copy)
2. CD of Enclosure 1

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BECHTEL
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QA: NA

September 2003

Technical Basis Document No. 12: Biosphere Transport

Revision 1

Kurt R. Rautenstrauch, Anthony J. Smith, and Robert Andrews

Prepared for:
U.S. Department of Energy
Office of Civilian Radioactive Waste Management
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Under Contract Number
DE-AC28-01RW12101

QA: NA

September 2003

Technical Basis Document No. 12: Biosphere Transport

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ACRONYMS AND ABBREVIATIONS

BDCF	biosphere dose conversion factor
DOE	U.S. Department of Energy
ERMYN	Environmental Radiation Model for Yucca Mountain, Nevada
FEPs	features, events, and processes
IA	igneous activity
KTI	key technical issue
NRC	U.S. Nuclear Regulatory Commission
RMEI	reasonably maximally exposed individual
TSPA	total system performance assessment
TSPAI	total system performance assessment and integration
TSPA-LA	total system performance assessment for the license application

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1. INTRODUCTION

This Technical Basis Document summarizes the methods used to model the transport through the biosphere of radionuclides that may be released from the repository at Yucca Mountain. It includes a description of the reference biosphere, characteristics of the receptor, and the methods used to model environmental transport and exposure pathways. This is one in a series of Technical Basis Documents that are being prepared to describe components of the Yucca Mountain repository system that are important for predicting the likely post-closure performance of the repository. The relationship of biosphere transport to the other post-closure performance components is illustrated in Figure 1-1.

This Technical Basis Document was written to respond to open key technical issue (KTI) agreements made between the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE). The appendices address KTI agreements associated with biosphere modeling. This document places the responses to KTI agreements within the context of the overall biosphere transport and exposure model, explains their relationship to the post-closure safety analyses, and allows for a more complete discussion of the relevance of the agreements. The information in this document, along with the associated references, also describes the biosphere characteristics and modeling to be used in the postclosure safety analysis that will be presented in the license application.

This Technical Basis Document and appendices are responsive to agreements made between the DOE and the NRC during Technical Exchange and Management Meetings on Total System Performance Assessment and Integration (Reamer 2001a), and Igneous Activity (Reamer and Williams 2000; Crump 2001; Reamer 2001b). Most of the agreements were based on questions that NRC staff developed from their review of the site recommendation support documents and DOE presentations at the technical exchanges. The agreements, in general, required the DOE to present additional information or perform sensitivity or validation activities for models or assumptions used in the *Yucca Mountain Site Suitability Evaluation* (DOE 2002). Since the technical exchanges, the DOE has conducted the additional work designed to meet those agreements.

1.1 OBJECTIVE AND SCOPE

The objectives of this Biosphere Transport Technical Basis Document are to:

- Synthesize the methods and data used to model transport of radionuclides within the biosphere
- Synthesize the methods and data used to model exposure to the applicable receptor
- Summarize the results of the biosphere transport models used in the assessment of postclosure performance at Yucca Mountain.

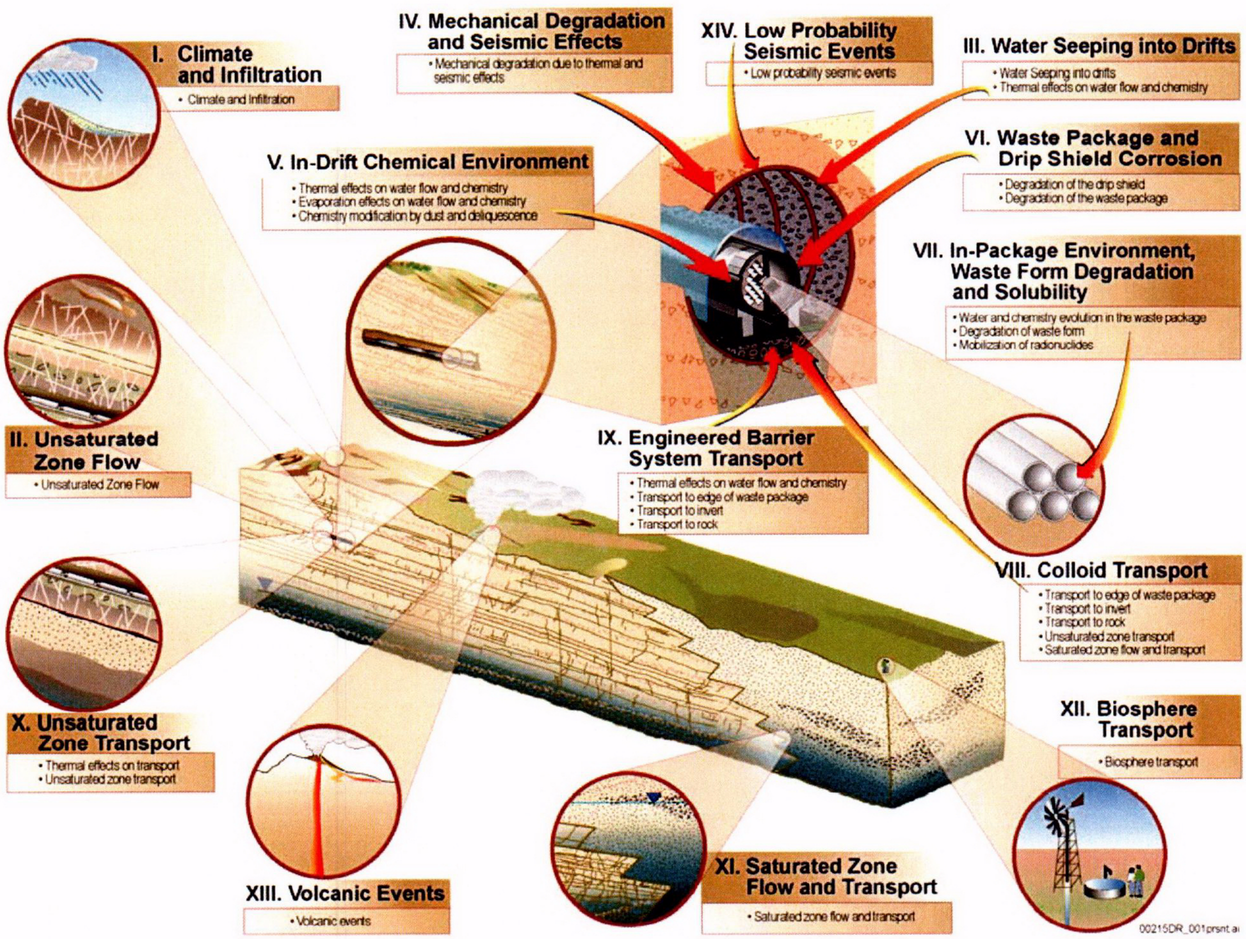

Figure 1-1. Components of the Post-Closure Technical Basis for the License Application

Transport of radionuclides through the biosphere and evaluation of exposure to a receptor are considered in the Environmental Radiation Model for Yucca Mountain Nevada (ERMYN). This model calculates the concentrations of radionuclides in environmental media (e.g., soil, food) per unit concentration of radionuclides in two sources of contaminants, groundwater and volcanic ash. It also calculates the dose to a human receptor per unit concentration of radionuclides in the sources. These dose estimates, called biosphere dose conversion factors (BDCFs), are combined in the Total System Performance Assessment (TSPA) with estimates of radionuclide concentrations in groundwater and ash to perform human radiation dose assessments.

The biosphere model developed to support the license application has been substantially revised since completion of the TSPA for the site recommendation. This model includes additional relevant pathways, provides the capability to stochastically sample all input parameters, and further enhances the model of biosphere transport (BSC 2003a, Section 6.7.2).

This document presents a summary and synthesis of the detailed technical information presented in analyses and model reports written to describe the modeling of biosphere transport. The *Biosphere Model Report* (BSC 2003a) describes the ERMYN conceptual and mathematical models, model validation, and software implementation. Input parameters values developed for use in the ERMYN model are described and justified in five analysis reports.

- *Inhalation Exposure Input Parameters for the Biosphere Model* (BSC 2003b)
- *Characteristics of the Receptor for the Biosphere Model* (BSC 2003c)
- *Agricultural and Environmental Input Parameters for the Biosphere Model* (BSC 2003d)
- *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2003e)
- *Soil-Related Input Parameters for the Biosphere Model* (BSC 2003f).

The calculation of BDCFs for use in the TSPA is described in the reports *Nominal Performance Biosphere Dose Conversion Factor Analysis* (BSC 2003g) and *Disruptive Event Biosphere Dose Conversion Factor Analysis* (BSC 2003h).

1.2 SUMMARY OF BIOSPHERE TRANSPORT PROCESSES AND MODELING

The biosphere transport and exposure pathways included in the biosphere model were selected based on potential sources of radionuclides from a repository at Yucca Mountain (groundwater and volcanic ash), the site-specific conditions in the Yucca Mountain region, and the lifestyle of the people living in Amargosa Valley. There are about 2,000 acres of commercial agricultural crops, a dairy, and a fish farm in Amargosa Valley. Because the region is arid, all crops must be irrigated. The only source of irrigation water is groundwater, which is not treated prior to use. Many of the people living in Amargosa Valley have gardens and some raise livestock; thus, many inhabitants consume local produce and animal products. About 40 percent of the residents of Amargosa Valley are not employed. Of those employed, the largest group is miners, and only about six percent work on farms. Most residents live in mobile homes and use evaporative coolers.

Based on this site-specific information, six environmental media that could result in exposure to a human receptor are considered in the biosphere model: groundwater, soil, air, crops, animal products, and fish. The model calculates exposure to radionuclides in those media that are external to the body and to radionuclides that are inhaled and ingested. Because the two possible sources of radionuclides, groundwater and volcanic ash, would result in different transfer pathways, separate conceptual and mathematical models have been developed for these two exposure scenarios.

For the groundwater exposure scenario, radionuclides enter the biosphere from wells drilled into the aquifer. The model considers use of that groundwater for drinking, irrigating commercial and garden crops, watering livestock, raising fish, and running evaporative coolers. Irrigation of crops could result in radionuclide transport to topsoil and crops. The soil could be resuspended and deposited on crops, inhaled by the receptor, and inadvertently ingested by the receptor and farm animals. Radioactive gasses escaping from the soil also may be taken up by crops and inhaled by the receptor. The crops may be eaten by the receptor and fed to farm animals. Products from those farm animals and fish also may be eaten by the receptor. Based on these pathways, the model calculates BDCFs (annual dose per unit concentration of radionuclides in groundwater) from external exposure to the soil; from inhaling resuspended soil, radioactive

gasses and their decay products, and aerosols from evaporative coolers; and from ingesting water, crops, fish, animal products, and soil.

For the volcanic ash exposure scenario, ash from an eruption at the repository could be deposited throughout the reference biosphere by initial deposition or by redistribution following a volcanic eruption. The model considers transport of radionuclides from the ash to soil, air, crops, and animal products. Radionuclide transport to crops may arise from deposition of resuspended particles of ash and contaminated soil and from uptake through the roots. Farm animals may be fed those crops and may ingest soil containing radionuclides. The receptor could receive a dose from external exposure to soil; from inhaling radon decay products and resuspended ash; and from ingesting crops, animal products, and soil. Pathways and environmental media related to radionuclides in groundwater are not considered in this exposure scenario. Because the dose resulting from exposure to volcanic ash could vary depending on the depth of ash in the biosphere and could change over time, for this exposure scenario the model calculates BDCFs (annual dose per unit concentration of radionuclides in ash) as a function of ash depth and time.

The mathematical representations of the biosphere transport processes and exposure pathways were constructed based on a review of applicable calculations in other environmental radiation models. Distributions of the input parameters that may contribute to variation in the BDCFs are stochastically sampled in the model. Input parameter values were developed from site-specific data and surveys, from reviews of distributions used in other models, data from analog sites, and other applicable publications. The selected distributions incorporate the full range of variation and uncertainty in environmental parameters and the range of uncertainty about the average of parameters that represent dietary and lifestyle characteristics of the receptor. Propagation of that uncertainty and variation has resulted in BDCFs that generally vary by less than an order of magnitude.

1.3 ORGANIZATION OF THIS REPORT

The characteristics of the biosphere and human receptor that have an important influence on development of the model and input parameters are described in Section 2. The radionuclide transport pathways and exposure pathways included in the two biosphere exposure scenarios considered in the ERMYN model, and the manner in which radionuclide decay and ingrowth is handled, are described in Section 3. Descriptions of the submodels used to track radionuclide transport and calculate exposure for the groundwater and volcanic ash exposure pathways are presented in Sections 4 and 5. The results of the ERMYN model are summarized in Section 6. Appendices to this report address KTI agreements related to biosphere modeling.

- Appendix A – Surface-Disturbing Activities (Response to IA 2.11)
- Appendix B - Mass Loading and Ash Depth (Response to IA 2.14)
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- Appendix G - Leaching Coefficients (Response to TSPAI 3.36).

2. DESCRIPTION OF THE BIOSPHERE AND RECEPTOR

This section describes the reference biosphere and receptor considered in the postclosure performance assessment of the repository. This information was derived from surveys of Amargosa Valley and its residents conducted by or for the DOE (e.g., DOE 1997; Horak and Carns 1997; CRWMS M&O 2000a) and from information about the region reported by other agencies such as the U.S. Bureau of the Census and U.S. Department of Agriculture. The information here was used to select the relevant transfer and exposure pathways to include the ERMYN model.

2.1 DESCRIPTION OF THE BIOSPHERE

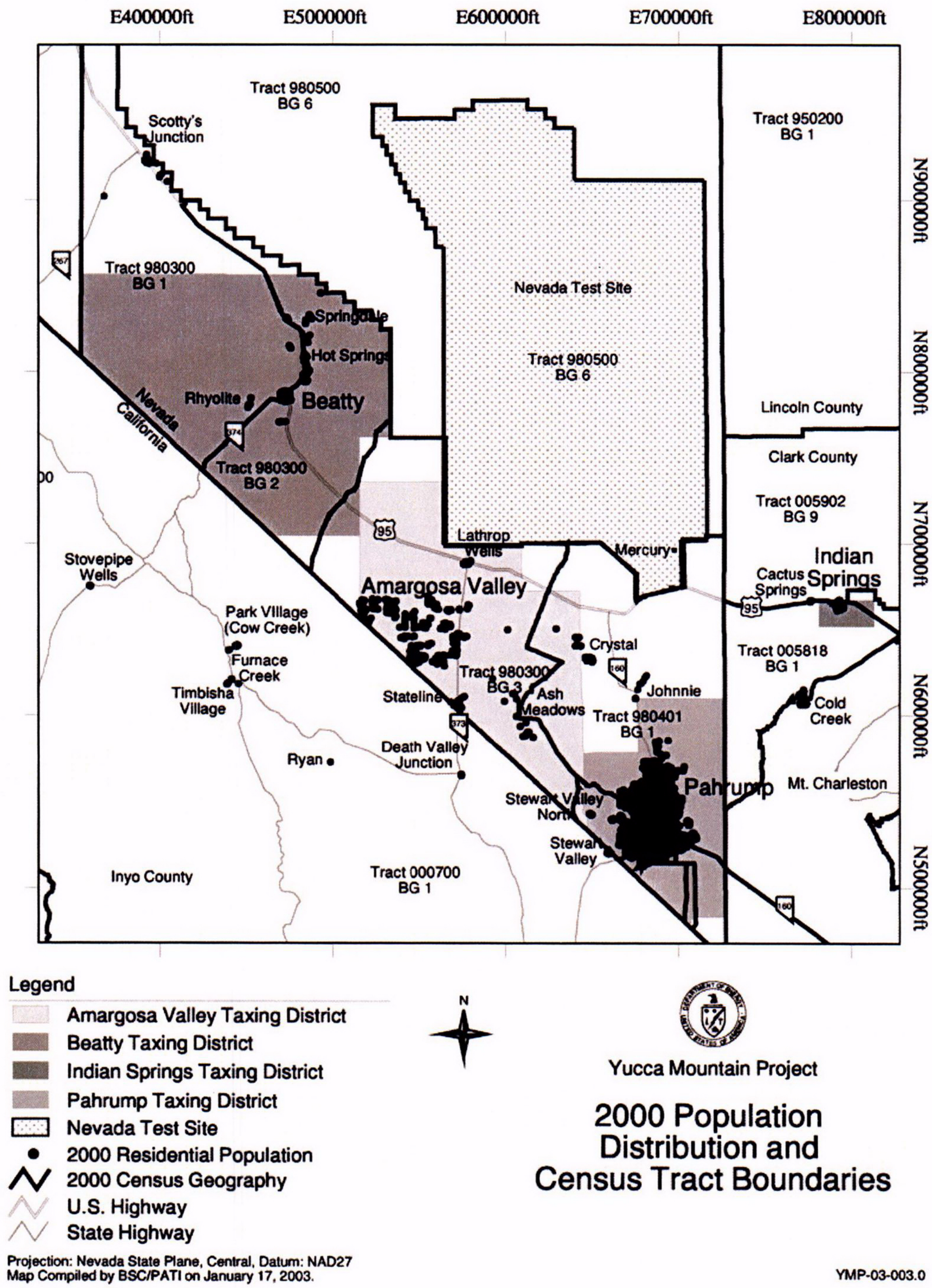
During development of the biosphere model, the region surrounding Yucca Mountain was characterized to better understand the reference biosphere. The characterization focused on north-central Amargosa Valley, the location of the receptor specified in 10 CFR Part 63. Information on the geography, climate, infrastructure, communities, and other aspects of the region was obtained. That information was used to select the features, events, and processes (FEPs) applicable to the model, select the exposure pathways that must be considered for inclusion in the model, and develop input parameter values that are representative of the reference biosphere. More detailed descriptions of the reference biosphere are presented in the *Yucca Mountain Site Description* (CRWMS M&O 2000b) and the *Biosphere Model Report* (BSC 2003a, Section 6.1.1).

Communities–The region surrounding Yucca Mountain is sparsely populated. The closest residents to the potential repository live in northern Amargosa Valley at the intersection of U.S. Highway 95 and Nevada State Route 373, about 20 km south of Yucca Mountain. Most people in Amargosa Valley live more than 30 km south of Yucca Mountain (Figure 2-1). At the time of the 2000 census, it was estimated that 1,176 people in 429 households resided in the approximately 1,300-km^2 Amargosa Valley Census County Division (Bureau of the Census 2001). 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), Pahrump (70 km), Indian Springs (70 km), and Las Vegas (120 km). This information was used to characterize the size of the reference biosphere and to define the receptor (BSC 2003c, Sections 5.1.1 and 6.1, and the analysis reports listed in Section 1.1).

Infrastructure–In 2000, there was a small general store, a community center, a senior center, a library, a small medical clinic, an elementary school, a restaurant, a hotel-casino, and a motel in Amargosa Valley. 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 and Las Vegas. Because some Amargosa Valley residents likely leave the area for employment and to obtain some goods and services, the model accounts for the receptor spending some time away from areas where radionuclides may be present in the environment (BSC 2003c, Sections 5 and 6).

All water used for domestic, municipal, and agricultural purposes in Amargosa Valley comes from local groundwater wells. 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). Therefore, it is assumed that water used by the receptor is from groundwater wells and that water is not treated prior to use.



Source: CRWMS M&O 2000a.

NOTE: Each dot represents one occupied residence.

Figure 2-1. South-Central Nevada Census Geography

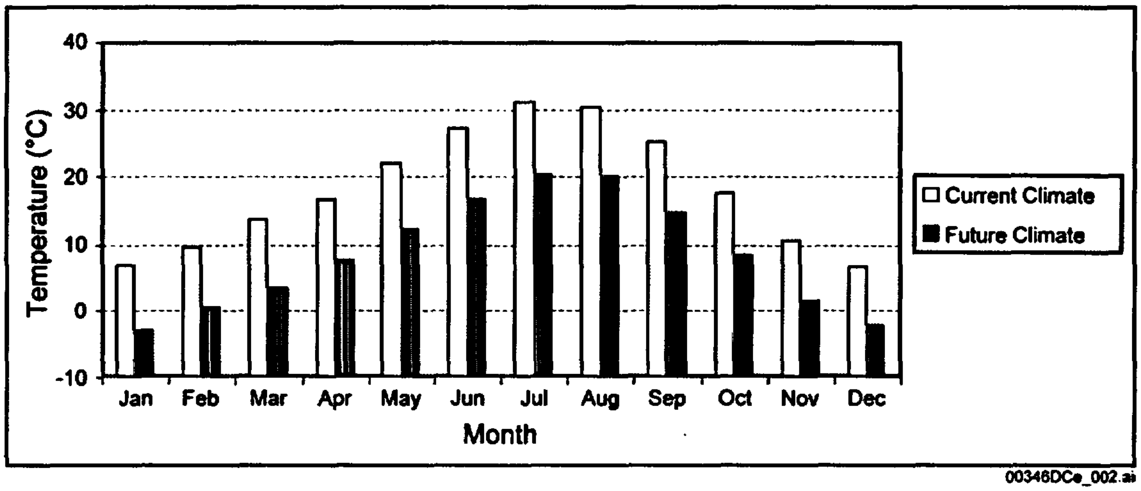
Agriculture–There is a small agricultural industry in Amargosa Valley. Approximately 2,000 acres are commercially farmed, of which over 90 percent is planted in alfalfa or other hay. Commercial crops are irrigated with groundwater, primarily using center pivot and other overhead sprinkler systems. Small grains, pistachios, grapes, orchard crops, garlic, and onions also are grown commercially. There is a dairy with more than 5,000 cows and there was a fish farm in the 1990s that had about 15,000 fish. Many residences have gardens with vegetable plots and some have a few cattle, sheep, chickens, and other farm animals (CRWMS M&O 1997, Section 3.4; Horak and Carns 1997; USDA 1999a; YMP 1999, Section 3.4).

The same crops, plus many others, are grown in eastern Washington, which is the analog location for the upper bound of the predicted future glacial transition climate. The most common crops grown there, wheat and other grains, are not irrigated (USDA 1999b; Washington State University Cooperative Extension 2002).

This information was used to identify some of the important environmental media to include in the model (e.g., commercial and garden crops, locally grown feed for livestock, and locally raised fish). This information was also used to select representative crops and animal products for developing input parameters related to crop and livestock production (e.g., BSC 2003d, Appendix A).

Climate–Currently, the Yucca Mountain region has low precipitation, hot summers, cool winters, low relative humidity, and a high rate of evaporation (CRWMS M&O 2000b, Section 6.2). Five years of weather data collected at Yucca Mountain meteorological monitoring Site 9, located in northern Amargosa Valley, were used to characterize the current climate. Average annual precipitation at Site 9 was about 100 mm (BSC 2003d, Table 4.1-2), and average monthly temperatures ranged from 6.9°C in December to 31.0°C in July (Figure 2-2). Data reported by the National Climatic Data Center of the National Oceanic and Atmospheric Administration for analog weather stations were used to characterize the predicted future climates of the region. The selection of analog weather stations representative of the predicted future climates are justified in the *Future Climate Analysis* (USGS 2001, Sections 6.6.1 and 6.6.2). Average annual precipitation for the upper bound of the future climate state predicted to occur during most of the next 10,000 years (glacial transition, based on conditions in Spokane, Washington) is about 400 mm and average monthly temperatures are about 10°C cooler than current conditions (Figure 2-2). These arid to semi-arid climatic conditions were used to determine irrigation requirements of crops (BSC 2003d) and the proportion of the year that people living in Amargosa Valley would use evaporative coolers (BSC 2003c, Section 6.3.4).

Soils–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 thick and subsurface soils are up to 150 cm deep. Soil textures are very gravelly with fine sands to sandy loams. The soils are calcareous and moderately alkaline. This information is from the Natural Resource Conservation Service (Dollarhide 1999; CRWMS M&O 1999) and was used to develop soil erosion and leaching rates (BSC 2003f) and to determine growth characteristics and irrigation requirements of plants grown in Amargosa Valley (BSC 2003d).



Source: Based on BSC 2003d, Tables 4.1-2 and 4.1-5.

Figure 2-2. Average Monthly Temperature for the Current and Predicted Future Climate (upper bound of the glacial transition climate) in Amargosa Valley

2.2 DESCRIPTION OF THE RECEPTOR

Regulation 10 CFR Part 63 requires that the human receptor considered in dose calculations for the license application be the reasonably maximally exposed individual (RMEI). According to 10 CFR 63.312, the RMEI is a hypothetical person who meets the following criteria:

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

b) Has a diet and lifestyle representative of the 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 mean values of these factors in the assessments conducted for 10 CFR 63.311 and 10 CFR 63.321.

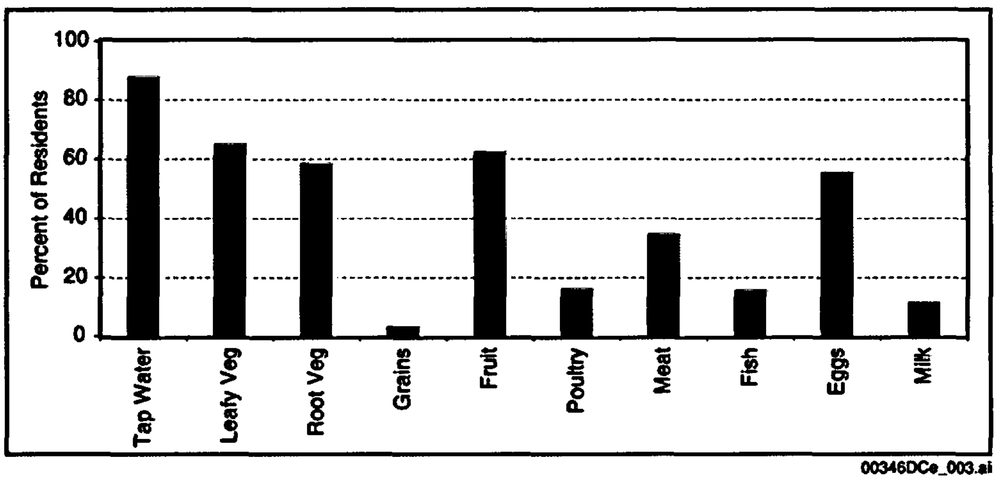
c) Uses well water with average concentrations of radionuclides based on an annual water demand of 3,000 acre-feet.

d) Drinks 2 liters of water per day from wells drilled into the ground water at the location specified in paragraph (a).

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

The following information on the diet and lifestyle of the residents of Amargosa Valley was used to develop a biosphere model that meets the requirements of 10 CFR Part 63 and to develop input parameter values that characterize the RMEI.

Diet–Based on a survey of Amargosa Valley residents conducted in 1997 (DOE 1997), it was determined that many people in that region consume some locally produced vegetables, fruit, grain, meat, poultry, fish, eggs, and milk (Figure 2-3). This information was used to identify the ingestion pathways that must be included in the model. Information from the survey on the frequency that Amargosa Valley residents ate locally produced foods was combined with information from the U.S. Department of Agriculture on daily rates of food intake in the western United States to calculate consumption rates of locally produced foods (BSC 2003c, Section 6.4). In general, locally produced foods comprise a small portion of the total diet of Amargosa Valley residents. For example, it is estimated that residents eat, on average, about 13 kg of locally produced fruits (including tomatoes) per year, compared to a total annual consumption rate of about 150 kg per year by people in the western United States (BSC 2003c, Tables 6.4-1 and 6.4-2).



Source: Based on DOE 1997, Table 2.3.1.

Figure 2-3. Percent of Amargosa Valley Residents Surveyed that Consumed Any Tap Water and Locally Produced Foods

Use of Evaporative Coolers–About 73 percent of Amargosa Valley residents surveyed in 1997 used evaporative coolers and they used them for an average of five months per year (DOE 1997, Table 2.4.2; BSC 2003c, Section 6.3.4). Therefore, the model includes exposure to radionuclides that may be present in indoor air resulting from the use of evaporative coolers during part of the year.

Gardens–About 46 percent of Amargosa Valley residents surveyed in 1997 had gardens (DOE 1997, Table 2.4.2). This and other information from the survey was used to select representative crops and identify methods used to grow crops that were considered during development of input parameters that characterize irrigation requirements and methods (BSC 2003d).

Employment–About 39 percent of Amargosa Valley residents (16 or more years old) were not employed in 2000 (Bureau of the Census 2002, Table P47; BSC 2003c, Table 6.3-1). Of the residents who worked, the largest proportion (26 percent) worked in mining and only about 6 percent (26 of 449) worked in agriculture (Table 2-1). This information was used to determine

the proportion of the population that worked indoors and outdoors in Amargosa Valley (BSC 2003c, Section 6.3.1). Those population proportions are used to calculate exposure times (Section 4.7 and 5.5).

Table 2-1. Industry of Employed Amargosa Valley Residents

Industry of Employment	Number of Males	Number of Females	Total
Agriculture	26	0	26
Mining	101	18	119
Construction	7	0	7
Retail trade	19	14	33
Transportation and warehousing	23	26	49
Utilities	8	0	8
Educational services	0	47	47
Health care and social assistance	20	8	28
Arts, entertainment, recreation, accommodation, and food services	22	71	93
Other services (except public administration)	6	15	21
Public administration	0	18	18
Total	232	217	449

Source: Bureau of the Census 2002, Table P49.

NOTES: Data represents employed residents 16 or more years old measured during the week prior to the April 2000 census.

Commute Time–About 64 percent of Amargosa Valley residents (16 or more years old) who worked commuted 10 minutes or more to work one way. About 21 percent commuted 35 minutes or more one way (Bureau of the Census 2002, Table P31). This information was used to determine 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 2003c, Section 6.3).

Housing Type–About 89 percent (375 of 422) of occupied housing units in Amargosa Valley during 2000 were mobile homes and about 91 percent (1,043 of 1,142) of the total population lived in mobile homes (Bureau of the Census 2002, Tables H30, H31, H33). This information was used to select building shielding factors for lightly constructed housing (BSC 2003c, Section 6.6), and parameters related to evaporative coolers, house ventilation rates, and equilibrium factors for radon decay products indoors (BSC 2003e, Sections 6.5. and 6.6).

Physiology–The dose conversion factors and dose coefficients (from Eckerman et al. 1988 and Eckerman and Ryman 1993) used in the model to convert exposure to committed effective dose equivalents and effective dose equivalents are based on a hypothetical 'average' adult person with the anatomical and physiological characteristics defined in the *Report of the Task Group on Reference Man* by the International Commission on Radiological Protection (ICRP 1975). Metabolic models used in the development of the dose conversion factors are also consistent with the Reference Man representation of an adult. Breathing rates used in the model were based on the more recent biometric results for adult persons used in the respiratory track model developed by the International Commission on Radiological Protection (ICRP 1994).

3. RADIONUCLIDE TRANSPORT AND EXPOSURE PATHWAYS

Two human exposure scenarios are included in the ERMYN model: groundwater and volcanic ash. These scenarios are considered separately because the initial radionuclide source terms and radionuclide transport mechanisms in the biosphere differ between the scenarios. The relationship between these human exposure scenarios and the TSPA modeling cases and scenario classes (BSC 2002a, Section 4) is fully described in the *Biosphere Model Report* (BSC 2003a, Section 6.1.3).

For the groundwater exposure scenario, radionuclides potentially released from the repository would enter the biosphere from groundwater wells. Human exposure could arise from use of the water for domestic and agricultural purposes. BDCFs for the groundwater scenario apply to the modeling cases included in the TSPA for the license application (TSPA-LA) that consider groundwater releases of radionuclides, including the nominal scenario class, the igneous intrusion case of the igneous scenario class, the seismic scenario class, and the human intrusion analysis (BSC 2002a, Section 4).

For the volcanic ash scenario, the source of radionuclides is ash from a volcanic eruption at the repository. This scenario applies to the TSPA volcanic eruption modeling case of the igneous scenario class. The biosphere model for the volcanic ash scenario and BDCFs generated using the model support only the TSPA volcanic eruption modeling case of the igneous scenario class (BSC 2002a, Section 4). The remaining disruptive event scenario classes evaluate radionuclide releases to groundwater and are supported by the biosphere model for the groundwater scenario.

Based on these mechanisms of potential radionuclide release into and movement within the biosphere and the characteristics of the reference biosphere and receptor described in Section 2, conceptual models were developed for the groundwater and volcanic ash exposure scenarios. The first step in the process was to identify the FEPs that are applicable to these models. From the total list of FEPs to be considered for the TSPA, 31 were identified as applicable to the biosphere model (BSC 2003a, Section 6.2). These FEPs represent features of the arid to semi-arid environment in the Yucca Mountain area and the possible events and processes leading to radionuclide transport in the environment and exposure to the receptor. The environmental transport pathways, human exposure pathways, and related environmental media that address the FEPs and are applicable to each scenario were then identified and described (BSC 2003a, Section 6.3). Environmental transport pathways are the routes by which radionuclides move from the source to other environmental media. Human exposure pathways arise when people are exposed, internally or externally, to contaminated media. The environmental and exposure pathways for the groundwater and volcanic ash exposure scenarios are described in Sections 3.1 and 3.2, respectively. The radionuclides considered in the biosphere model and the methods used to incorporate radionuclide decay and ingrowth are discussed in Section 3.3.

3.1 GROUNDWATER SCENARIO PATHWAYS

Under the groundwater exposure scenario, radionuclides could be released into the biosphere from groundwater drawn from a well. Human exposure could occur when the local community where the receptor resides uses the water for domestic and agricultural purposes. The groundwater scenario is used to evaluate the radiological consequences of nominal performance

of the geologic repository and performance under disrupted conditions (igneous intrusions and seismic events) that can lead to radionuclide releases into the groundwater. Use of groundwater could result in radionuclide concentrations in the following six environmental media to which the receptor may be exposed (BSC 2003a, Section 6.3.1).

- Groundwater.
- Irrigated soil.
- Indoor and outdoor air.
- Crops consumed by the receptor and farm animals.
- Animal products consumed by the receptor.
- Fish raised at a fish farm and consumed by the receptor.

Migration of radionuclides through the biosphere occurs due to a number of environmental transport processes that lead to accumulation of radionuclides in the media (Figure 3-1). The environmental transport processes explicitly included in the biosphere model for the groundwater scenario are listed in Table 3-1. Exposure could occur when the receptor is exposed to radionuclides in environmental media external to the body (i.e., external exposure) or by inhalation or ingestion of media into the body. The typical activities that may lead to radiation exposure are summarized in Table 3-2. Other environmental media and transport pathways that could lead to exposure were considered during development of the model (e.g., external exposure to air and water, inhalation of soil particles by farm animals) but were excluded because they have a negligible influence on the model results (BSC 2003a, Sections 6.3.3, 7.4.2, 7.4.3).

Table 3-1. Transport Pathways Explicitly Included for the Groundwater and Volcanic Ash Scenarios

Transport Pathway	Groundwater	Volcanic
Radionuclide accumulation in soil from irrigation with water	✓	
Resuspension of soil	✓	✓
Deposition of resuspended soil on crops	✓	✓
Deposition of irrigation water on crops	✓	
Translocation of radionuclides to the edible tissues of crops	✓	✓
Post-deposition retention by crops (including weathering processes)	✓	✓
Radionuclide uptake by crops through the roots	✓	✓
Release of gaseous radionuclides (Radon-222, $^{14}CO_2$) from the soil	✓	
Absorption of $^{14}CO_2$ by crops from the atmosphere	✓	
Radionuclide uptake by animals through consumption of feed, water, and soil, followed by transfer to animal products	✓	✓
Radionuclide transfer from water to air via evaporative coolers	✓	
Radionuclide transfer from water to fish (aquatic food).	✓	

Source: BSC 2003a, Sections 6.3, 6.4, 6.5.

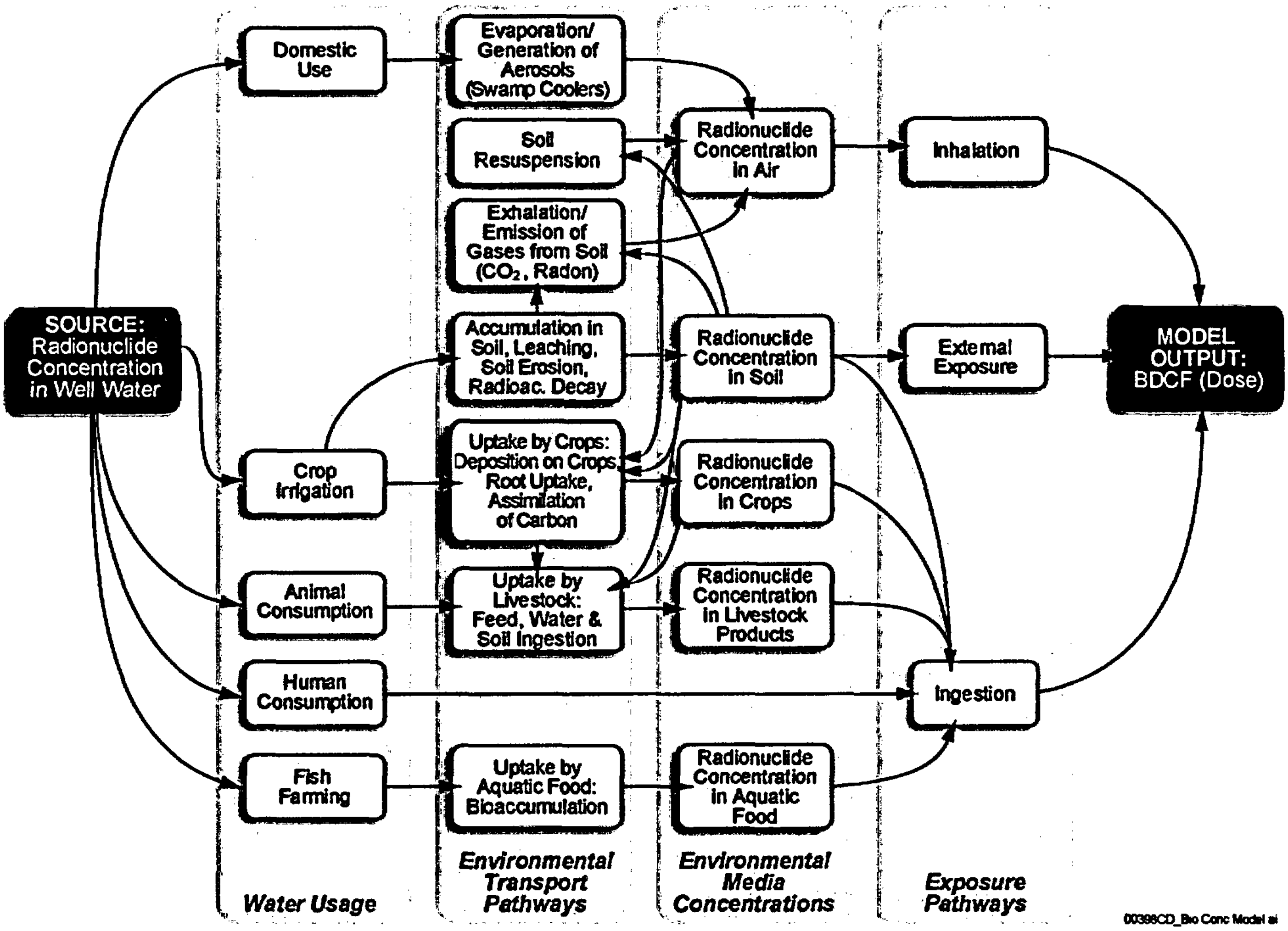


Figure 3-1. Conceptual Representation of the Transport and Exposure Pathways for the Groundwater Exposure Scenario

Table 3-2. Exposure Pathways for the Groundwater Scenario

Environmental Medium	Exposure Mode	Exposure Pathway	Examples of Typical Activities
Water	Ingestion	Water intake	Drinking water and water-based beverages. Water used in food preparation.
Soil	Ingestion	Inadvertent soil ingestion	Recreational activities, occupational activities, gardening, consumption of fresh fruits and vegetables.
Soil	External	External radiation exposure	Time spent on or near soil containing radionuclides.
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 crops.
Animals	Ingestion	Consumption of locally produced animal products (meat, poultry, milk, and eggs)	Eating animal products.
Fish	Ingestion	Consumption of locally produced freshwater fish	Eating fish.

Source: BSC 2003a, Table 6.3-1.

In summary, groundwater may be used to irrigate crops, water farm animals, raise fish, run evaporative coolers, and for drinking. Irrigation of crops could result in radionuclides in topsoil and crops. The soil may be resuspended and deposited on crops, inhaled by the receptor, and inadvertently eaten by the receptor and farm animals. Radioactive gasses from the soil also may be taken up by crops and inhaled by the receptor. The crops may be eaten by the receptor and fed to farm animals. Products from those farm animals and fish also may be eaten by the receptor. The receptor could receive a dose from external exposure to the soil; from inhaling resuspended soil, radioactive gasses, and aerosols from evaporative coolers; and from ingesting water, crops, fish, animal products, and soil.

3.2 VOLCANIC ASH SCENARIO PATHWAYS

The biosphere model for the volcanic ash exposure scenario considers the same reference biosphere and receptor as the groundwater scenario. The major difference between the models is the radionuclide source. For the volcanic scenario, the source is ash on the ground surface; radionuclides in groundwater are not considered for this biosphere exposure scenario. The ash could come directly from a volcanic eruption or it could be transported into the biosphere by aeolian and fluvial processes. On cultivated soils, the ash would mix with surface soil and radionuclides could be transferred to crops and animal products. That could result in exposure when those crops and products are ingested. On all lands, the volcanic ash could be resuspended, causing exposure from inhalation of ash particles. The ash also may be inadvertently ingested and may cause external exposure (BSC 2003a, Section 6.3.2).

Because of the different radionuclide sources, only those environmental media and transport processes related to radionuclides in soil are considered in the volcanic ash model; media and processes related only to radionuclides in water are excluded (Table 3-1 and Figure 3-2). Thus,

only four of the six media listed in Section 3.1 are included in this model (soil, air, plants, and animals); groundwater and fish are excluded. The human exposure pathways included in the biosphere model for the volcanic ash scenario, and the typical activities that may cause radiation exposure are summarized in Table 3-3. Exposure of fish from deposition of ash on ponds is excluded for the following reasons. Fish in small ponds are susceptible to suffocation when their water is polluted by particulates (e.g., catastrophic loss of fish in Amargosa Valley ponds occurred when smoke from a forest fire drifted into the valley, Roe 2002) and, therefore, likely would die after an eruption. Even if they survived, fish ponds in Amargosa Valley are cleaned at least once every other year. Ash particles probably would be removed and future crops of fish would not be exposed to radiation (BSC 2003e, Section 6.4; Roe 2002). In addition, ingestion is an unimportant pathway for this scenario for most radionuclides (BSC 2003h, Section 6.2.5); therefore, inclusion of fish ingestion would have a negligible contribution to BDCFs.

In summary, ash from an eruption at the repository could be deposited throughout the reference biosphere by initial deposition or by redistribution following a volcanic eruption. Crops may take up radionuclides from resuspended ash particles, from roots, and from exhalation of radon from the soil. Farm animals may be fed those crops and may ingest soil containing radionuclides. The receptor could receive a dose from external exposure to soil; from inhaling radon and resuspended ash; and from ingesting crops, animal products, and soil.

Table 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.
Soil	External	External radiation exposure	Activities on or near soil containing radionuclides.
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 and drinking plant materials.
Animals	Ingestion	Consumption of locally produced animal products, including meat, poultry, milk, and eggs	Eating and drinking animal products.

Source: BSC 2003a, Table 6.3-3.

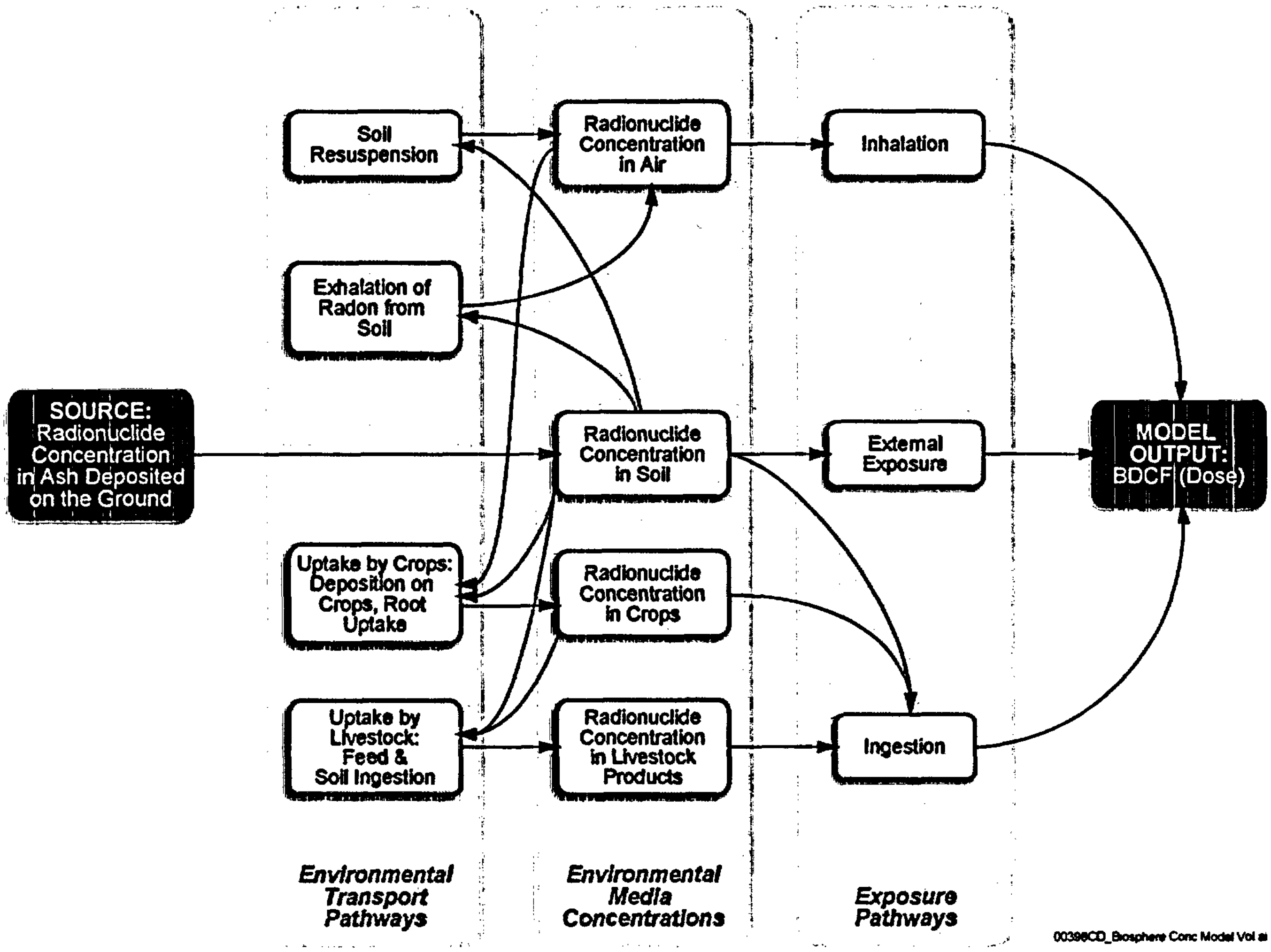


Figure 3-2. Conceptual Representation of the Transport and Exposure Pathways for the Volcanic Ash Scenario

3.3 RADIONUCLIDE DECAY AND INGROWTH

The radionuclides to be considered in the TSPA are identified in *Radionuclide Screening* (BSC 2002b, Section 7), which lists 28 radionuclides (called primary radionuclides) representing the 17 elements that are major contributors to the postclosure dose calculated by the TSPA. The TSPA analysis only considered radionuclides with a half-life of greater than 10 years. Although this is reasonable for TSPA calculations because of the long-term physical processes considered in that model, the short-lived decay products of the primary radionuclides must be considered in the biosphere model dose calculations.

To include the effects of decay products in the biosphere model, the decay chain of each primary radionuclide was defined (BSC 2003a, Section 6.3.5). Within each decay chain, radionuclides were classified as long-lived or short-lived (i.e., half-life longer or shorter than 180 days, respectively). Long-lived decay products that are not primary radionuclides (e.g., Radium-228 and Thorium-228) are tracked separately from the primary radionuclides in the model. This is

done because these radionuclides may have different environmental transport properties and may not be in radioactive equilibrium with their parent radionuclide.

Short-lived radionuclides in each decay chain are assumed to be in equilibrium with the long-lived parent. This assumption is reasonable because the primary radionuclides have long half-lives, so equilibrium in an environmental medium would occur after a relatively short period of time. This assumption is conservative because the activities of the decay products are highest when in equilibrium with the long-lived parent radionuclides (BSC 2003a, Section 5.2). The dose contribution of short-lived radionuclides are included in the effective dose coefficients (external exposure) and effective dose conversion factors (inhalation and ingestion) developed for primary radionuclides (e.g., BSC 2003a, Sections 6.3.5 and 6.4.7.2).

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4. GROUNDWATER SCENARIO MODEL

The conceptual and mathematical models developed to calculate BDCFs for the groundwater scenario are described in this section. Included are summaries of the structure of the ERMYN groundwater model and associated submodels; methods used to calculate radionuclide concentrations in the environmental media; methods used to calculate exposure from inhalation, ingestion, and external exposure via the three pathways; assumptions upon which the calculations are based; and the input parameters used to make the calculations. The *Biosphere Model Report* (BSC 2003a, Sections 5 and 6) presents detailed descriptions.

The purpose of the biosphere model is to provide to the TSPA the inputs needed to calculate the annual dose to a human receptor from any release into the biosphere of radionuclides from the repository. Because the biosphere calculations are conducted independently of the TSPA calculations of radionuclide concentrations, the biosphere model calculates conversion factors that are equal to the annual dose per unit concentration of radionuclides in the source of contamination (groundwater or volcanic ash). These concentration factors, BDCFs, are the primary output of the biosphere model.

A BDCF for this scenario is numerically equal to an all-pathway dose that the RMEI would receive when exposed to the concentration of a radionuclide in environmental media arising from a unit concentration of the radionuclide in groundwater (i.e., Bq/m^3). The concentrations of radionuclides in groundwater are time dependent and are calculated outside the ERMYN model by the TSPA model; thus, the groundwater concentrations are unknown until the TSPA model is run. To calculate BDCFs that are independent of time (and thus independent of the TSPA model), it is assumed in the biosphere model that radionuclide concentrations in groundwater do not change over time. This assumption is valid because the time required for radionuclides considered in the TSPA to approach equilibrium concentrations in surface soils is much less than the 10,000-year compliance period for the TSPA-LA (BSC 2003a, Sections 5.1 and 7.4.2). Based on this assumption, BDCFs can be calculated in the ERMYN model based on unit concentrations of radionuclides in groundwater (i.e., 1 Bq/m^3), and the annual dose can be calculated in the TSPA as the product of the BDCFs and radionuclide concentrations in groundwater.

Based on this assumption, BDCFs are calculated in the ERMYN model as the annual dose per unit concentrations of radionuclides in groundwater (i.e., Sv/year per Bq/m^3), and the annual dose is calculated in the TSPA as the product of the BDCFs and radionuclide concentrations in groundwater. The TSPA calculates the annual dose in terms of the total effective dose equivalent (10 CFR 63.2) to the specified human receptor. In this context, the annual total effective dose equivalent is the sum of the effective dose equivalent for external exposures received in one year and the committed effective dose equivalent resulting from one-year intake of radionuclides. The commitment period used is 50 years.

The conceptual and mathematical models for the groundwater scenario are developed in the ERMYN as a series of eight submodels, representing five of the environmental media (the source of radionuclides, groundwater, is not included as a submodel) and the exposure pathways described in Section 3.1. Figure 4-1 shows the interactions among those submodels (i.e., the transfer pathways). In addition to the eight submodels, a special submodel is included to

calculate Carbon-14 concentrations in surface soil, air, crops, and animal products because the transfer mechanisms for this radionuclide are different from the other radionuclides considered.

The methods used in the ERMYN model to calculate radionuclide concentrations in environmental media and exposure rates were selected based on a review of applicable methods used in other environmental radiation models (BSC 2003a, Section 6.4 and 7.3). The input parameter values used in the model were developed based on site-specific data, such as those obtained during the survey of Amargosa Valley residents (DOE 1997), and from reviews of values used in other environmental radiation models, data from analog sites, and from other applicable publications. All input parameters that could contribute to variation in the model results are input as distributions and stochastically sampled in the model.

Climate change is incorporated into the ERMYN groundwater model by using different values for input parameters that are influenced by temperature and precipitation (e.g., irrigation rate and evaporative cooler use) and calculating separate sets of BDCFs for each climate state considered in the TSPA (BSC 2003g, Section 6.2.2). The future climate for the region around Yucca Mountain is predicted to be cooler and wetter than the current climate (USGS 2001). A wetter climate may cause the water table to rise and discharge groundwater at springs. The ERMYN model applies to the discharge of groundwater from springs if the use of spring water remains the same as the use of well water, and there is no mixing of contaminated and uncontaminated water (or other processes that would cause the radionuclide concentrations to change). The model does not apply to a biosphere with permanent rivers or lakes because they do not occur in Amargosa Valley now and are not likely to occur there in the future, and because these features would require additional pathways (e.g., water immersion due to swimming and external exposure due to contaminated sediments) that are not in the ERMYN model.

The following sections describe the submodels of the ERMYN model for the groundwater exposure scenario.

4.1 SOIL SUBMODEL

Radionuclide concentrations in the surface soil (i.e., the soil layer down to the tilling depth, which contains the majority of plant roots) are calculated in this submodel. The source of radionuclides is groundwater used for crop irrigation. Based on agricultural practices in Amargosa Valley, groundwater is the only source of irrigation water considered. Because the objective of the postclosure dose assessment is to evaluate the potential dose from the repository, continuous irrigation with groundwater for hundreds to thousands of years is assumed. This would result in the buildup of radionuclides in irrigated soil until equilibrium conditions are reached. Thus, the biosphere model assumes that radionuclides in irrigated soil are at saturation concentrations (BSC 2003a, Section 5.5). This assumption is conservative for the period when radionulcide concentrations in groundwater are increasing, as would be expected during the 10,000-year compliance period. However, it is not conservative when applied to the period long after closure of the repository when groundwater concentrations are declining, because soil concentrations may be underestimated (BSC 2003a, Section 6.4.10.3).

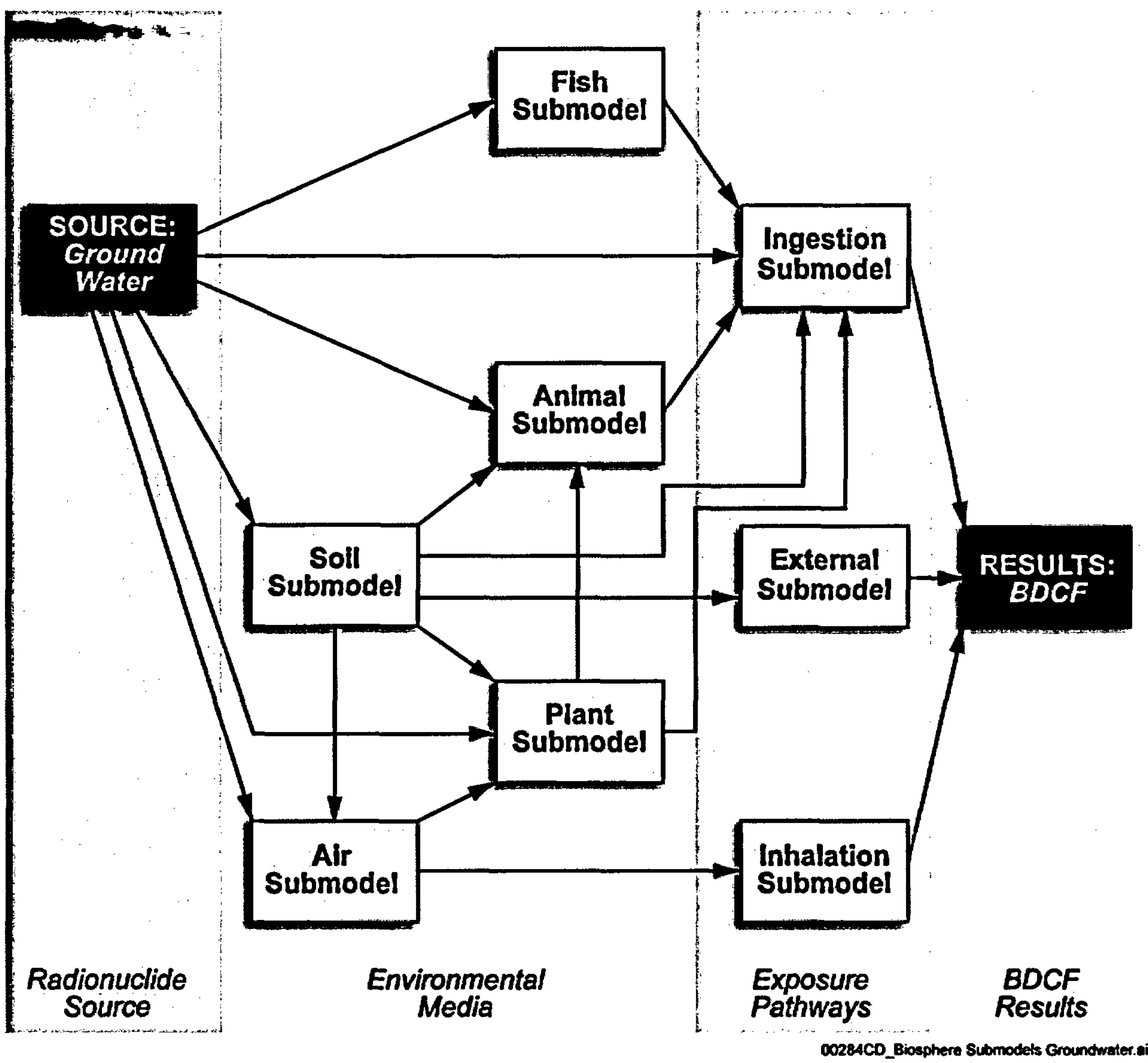

Figure 4-1. Relationship among Biosphere Submodels for the Groundwater Scenario

The equilibrium concentrations of radionuclides in the soil are calculated as a function of groundwater concentrations (which are considered constant at 1 Bq/m^3); the annual irrigation rate for crops; and loss by radionuclide decay, leaching, and erosion (BSC 2003a, Section 6.4.1). This calculation is based on the conservation of the mass of radionuclides in the topsoil. The rate of increase of radionuclides in topsoil is equal to the rate of addition from irrigation water less the rate of loss from radioactive decay, leaching, and erosion. The solution to the resulting equation is time dependent, so the ERMYN model uses the time-independent asymptotic solution to the rate equations. This is a conservative approach and avoids speculation about changes in agricultural practices and land use over the 10,000-year compliance period.

As discussed in Section 3.3, short-lived radionuclides (half-life less than 180 days) are considered to be in equilibrium with the primary radionuclides. Long-lived non-primary radionuclides are treated numerically similar to the primary radionuclides, but the rate of their

addition to the system is from decay of the primary radionuclide rather than application of groundwater.

The annual irrigation rate, which is used to calculate the addition of radionuclides into the soil, was estimated from 26 garden crops, commercial crops, and horticultural plants representative of all crop types considered in the ERMYN model (BSC 2003d, Section 6.5). This was done because it is likely that a variety of field, garden, and horticultural crops would be grown on a plot of land over a long period. Methods developed by the Food and Agriculture Organization of the United Nations (Allen et al. 1998; Doorenbos and Pruitt 1977) were used to calculate irrigation rates, as described in *Agricultural and Environmental Input Parameters for the Biosphere Model* (BSC 2003d). The average annual irrigation rates estimated for the current climate and upper bound of the glacial transition climate are 0.94 and 0.50 m/year, respectively (BSC 2003d, Section 6.5).

Leaching is included in the soil submodel to account for the residence time of radionuclides in the surface soil and their removal to deeper soil. The leaching rate is a function of the amount of water that percolates below the surface soil (i.e., the overwatering rate), element-specific solid-liquid partition coefficients, and other soil properties (e.g., bulk density, soil porosity, and soil moisture content at field capacity). In the current arid conditions at Yucca Mountain, leaching occurs primarily when irrigation water is added to flush accumulated salts from the surface soil to maintain plant productivity. In wetter climates, such as those predicted to occur in the future at Yucca Mountain, leaching also occurs when excess precipitation flows through the surface soil, primarily during winter. The annual average overwatering rates estimated for the current climate and upper bound of the glacial transition climate are 0.079 and 0.067 m/year, respectively (BSC 2003d, Section 6.9). The partition coefficients used in the ERMYN model were selected based on site-specific soil conditions and range over several orders of magnitude (i.e., a lower limit of about 1×10^{-2} L/kg for Technetium to an upper limit of 4.8×10^{4} L/kg for Americium), as described in *Soil-Related Input Parameters for the Biosphere Model* (BSC 2003f, Sections 4.1.2 and 6.3).

Soil erosion accounts for the loss of radionuclides via wind and water erosion. The upper limit of the erosion rate is based on the minimum average loss measured in Nevada for cultivated and non-cultivated land and the maximum annual soil loss tolerable before crop yields are reduced. The lower limit of erosion loss is estimated from soil influx and an equal loss (no net loss or gain in soil), such that the average atmospheric dust level is maintained in association with an appropriate dry settling velocity. Erosion rates typical for soils in northern Amargosa Valley range from 0.19 to 1.1 kg m^{-2} y^{-1} (BSC 2003f, Section 6.4).

When overhead irrigation is used, radionuclides in irrigation water can be intercepted by crop leaves. However, crop weathering by wind and other mechanisms will displace some initially intercepted radionuclides onto the soil. Therefore, the model conservatively assumes that all radionuclides in the irrigation water, including the fraction calculated to have been intercepted by crops, reach the soil (BSC 2003a, Section 5.6). It is also assumed that the loss of radionuclides due to crop harvest is compensated by the addition of contaminated animal manure and non-harvested plant residue as fertilizer. This assumption is reasonable because the use of animal manure to fertilize fields is a common practice in Amargosa Valley (BSC 2003a, Section 5.4).

Radionuclide concentrations in the soil calculated in this submodel are used in most of the other submodels (Figure 4-1) because most environmental transport and exposure pathways require estimates of radionuclide concentrations in the surface soil.

4.2 AIR SUBMODEL

The air submodel calculates the concentrations of radionuclides in air resulting from three transport pathways: soil resuspension, release of radioactive gases, and the generation of aerosols by evaporative coolers.

4.2.1 Soil Resuspension

Soil particles may be resuspended by wind or during mechanical disturbances (e.g., tilling of fields). These resuspended particles would result in exposure when deposited on plants or inhaled by the receptor. Separate calculations are used in the ERMYN model to estimate the concentrations of radionuclides in the air around plants and inhaled by the receptor.

Radionuclide concentrations in the air resulting from resuspension of soil particles that may be directly deposited on plants are calculated as the product of activity concentrations in cultivated soil and atmospheric mass loading (i.e., the mass concentration of resuspended particles) in the environment around plants (BSC 2003a, Section 6.4.2). Mass loading in agricultural fields and gardens during the latter part of the growing season is estimated to range from 0.025 to 0.200 mg/m^3, similar to or higher than that measured outdoors in rural, agricultural environments (BSC 2003b, Section 6.1.5). Radionuclide concentrations in the air, calculated using this method, are used in the plant submodel to estimate dry deposition of radionuclides on plant surfaces.

To account for variation and uncertainty in the characteristics of the RMEI and concentrations of radionuclides throughout the biosphere, the ERMYN model uses a micro-environmental modeling approach to calculate inhalation exposure (this method is also used to evaluate external exposure). For micro-environmental models, the total exposure environment (i.e., the biosphere) is divided into segments, or environments, with different concentrations of contaminants. The contaminant concentration, time spent in each environment, and intake rates or exposure factors (e.g., breathing rates and shielding factors) are determined for each environment, and the total dose is calculated as the sum of the doses from all environments (Mage 1985, pp. 409 and 410; BSC 2003a, Section 6.4.8). Micro-environmental models are commonly used to evaluate exposure to particulate matter and other contaminants (Duan 1982; Mage 1985; Klepeis 1999).

To evaluate inhalation exposure in an environment, activity concentrations in the air are calculated as the product of activity concentrations in cultivated soil, an environment-specific enhancement factor, and mass loading in each environment (BSC 2003a, Section 6.4.2). The enhancement factor is defined as the ratio of the mass activity concentration of resuspended particles to the mass activity concentration in surface soil for a radionuclide. This parameter is included because the size distribution of resuspended particles may be different from the particle size distribution of the host soil and because the activity concentration per unit mass may be a function of particle size. For soil particles contaminated by irrigation water, contaminants would be adsorbed onto particles in the form of a thin film on the particle surface. The surface coating

would result in a higher activity concentration on smaller particles compared to larger particles (because surface area per unit mass is greater for smaller particles). Distributions of enhancement factors used in the ERMYN model range from 2.2 to 6.5 for outdoor environments and 0.21 to 1.04 for other environments (BSC 2003f, Section 6.5).

Five environments associated with different human activities are considered in the ERMYN model. 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 (BSC 2003c, Section 6.2). The mass loading distributions for each environment are representative of the average annual concentration of resuspended particles to which the receptor would be exposed. Therefore, triangular distributions that incorporate variation and uncertainty in the annual average value, but do not include the entire range of concentrations for all activities and situations in Amargosa Valley, are used in the model. Distributions of mass loading for these environments are developed in the analysis report *Inhalation Exposure Input Parameters for the Biosphere Model* (BSC 2003b, Section 6.1).

Active Outdoors–This category includes time spent outdoors in contaminated areas conducting activities that would resuspend soil, including dust-generating activities while working (e.g., plowing, excavating, livestock operations) and recreating outdoors (e.g., gardening, landscaping, riding horses or motorbikes). Mass loading in this environment is estimated to range from 1.0 to 10.0 mg/m^3. This range was selected based on measurements of personnel exposed to resuspended dust during soil-disturbing activities (BSC 2003b, Section 6.1.1).

Inactive Outdoors–This category includes time spent outdoors in contaminated areas engaged in activities that do not resuspend soil (e.g., sitting, swimming, walking, barbecuing, and equipment maintenance). This category also includes time spent commuting within the contaminated area because the major roads in Amargosa Valley are paved (thus soil is not resuspended). The distribution of mass loading in the inactive outdoor environment ranges from 0.025 to 0.100 mg/m^3 and was developed from measurements taken at static air-quality monitoring stations located in rural agricultural settings in arid to semi-arid environments (BSC 2003b, Section 6.1.2).

Active Indoors–This category includes time spent awake indoors in contaminated areas, including work time. The mass loading distribution for this environment ranges from 0.060 to 0.175 mg/m^3, and is based on static and personnel exposure measurements taken indoors while people were active (BSC 2003b, Section 6.1.3).

Asleep Indoors–This category includes time spent indoors in contaminated areas sleeping. Mass loading in this environment is quite low, with a range of 0.010 to 0.050 mg/m^3. This range is based on measurements taken indoors while people were sleeping or inactive (BSC 2003b, Section 6.1.4).

Away from Potentially Contaminated Area–This category includes time spent away from areas potentially contaminated by groundwater or ash, including time spent commuting to work and working outside the contaminated areas. No mass loading estimate is required for this distribution.

4.2.2 Evaporative Cooler Operation

The contribution to the inhalation dose from operation of evaporative coolers was added to the ERMYN model because a large proportion of the Amargosa Valley population uses evaporative coolers (Section 2.2). The concentration of radionuclides in indoor air resulting from the operation of evaporative coolers is calculated as a function of the concentration of radionuclides in groundwater, the rate at which water evaporates from coolers while in operation, the air flow rate, and the fraction of radionuclides in the water that transfer to the air (BSC 2003a, Section 6.4.2.2). This method is 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 evaporation and air flow rates are estimated from specifications of evaporative cooling units typically used in mobile homes. Because there is no information available on the fraction of radionuclides in water that transfer to air during the operation of evaporative coolers, a distribution of 0.0 to 1.0 is used. A lower bound of 0.0 is reasonable because coolers are designed such that most or all minerals dissolved in water precipitate out on the pads or in the sump of the cooler (BSC 2003e, Section 6.5).

4.2.3 Radon Exhalation from Surface Soil

Airborne concentrations resulting from gaseous release from the soil are considered in the ERMYN model for two radionuclides, Carbon-14 and Radon-222. The calculation of Carbon-14 concentrations in air is described in Section 4.6. Concentrations of radon are calculated in the air submodel separately for indoor and outdoor air. The contribution of radon to airborne radionuclide concentrations is included in the ERMYN model because inhalation of radon decay products is an important contributor to the dose resulting from Radium-226 in groundwater (BSC 2003a, Section 7.4.3.1).

The concentration of radon outdoors is estimated from the amount of radon released from the soil. It is calculated as the product of activity concentration of Radium-226 in surface soil and a radon release factor of 0.25 kg/m^3 (BSC 2003a, Section 6.4.2.3). That release factor is based on the global average value of the concentration ratio of Radon-222 activity in air to Radium-226 in soil (BSC 2003e, Section 6.6.1).

The method for calculating the indoor concentration of radon 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 outdoor air and the soil beneath the house, which is assumed to have a saturation concentration of radium. This assumption is conservative because it is unlikely that all houses would be built on soil irrigated long enough to reach a saturation concentration of radium. The indoor radon concentration is calculated as a function of the concentration of radon in outdoor air, home ventilation rate, interior wall height, flux density of radon from outdoor soil, and fraction of that radon that would enter a home (BSC 2003a, Section 6.4.2.3). Values of the ventilation rate and wall height are based on conditions in manufactured homes. The ventilation rate differs substantially when evaporative coolers are off (0.3 to 2.9 air exchanges per hour) and when they are operated (1 to 30 exchanges per hour); therefore, the radon concentration in indoor air is calculated separately for periods when coolers are on and off (BSC 2003a, Section 6.4.2.3).

Values for input parameters used to calculate radon concentrations are developed in *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2003e, Section 6.6).

Radon concentrations due to the use of evaporative coolers and household water (e.g., showers) are not included in the ERMYN model because those concentrations contribute little to the total inhalation and external exposure radon doses (BSC 2003a, Section 7.4.3.1).

The activity concentrations of airborne radionuclides (as particles, aerosols, and gases) calculated in this submodel are used in the inhalation submodel to calculate the dose from inhalation exposure. They are also used in the plant submodel to calculate the transfer of radionuclides to crops from particle deposition and uptake of carbon via photosynthesis (Figure 4-1).

4.3 PLANT SUBMODEL

Radionuclide concentrations in plant parts consumed by humans and farm animals are calculated in the plant submodel. Three transport pathways are included in this submodel: root uptake, water interception, and dust interception. The addition of radionuclides from soil splash during irrigation is not included in the ERMYN model because it is equivalent to direct deposition of resuspended particles (BSC 2003a, Sections 6.4.3 and 7.4.4.3). In addition, this submodel does not include radionuclide decay following harvest because the radionuclides considered are long lived and would decay very little during the short time between harvest and consumption of fresh produce and forage.

The ERMYN model 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 having aboveground, edible portions (i.e., the leaves) that are exposed and eaten with little processing. Other vegetables include root crops (e.g., carrots and potatoes) and crops with edible parts that are not directly exposed (e.g., peas and beans that grow inside pods). Fruits include a variety of products such as berries, grapes, melons, and apples. Grains include seed-producing crops such as wheat, corn, and barley. Crops consumed by farm animals are also considered in the plant submodel. It is assumed that beef cattle and dairy cows are fed fresh, locally produced forage (e.g., alfalfa) and poultry and laying hens are fed locally produced grain (BSC 2003a, Section 5.8).

Many of the input parameters in this submodel vary substantially among crops (e.g., irrigation rates and growing season length). To ensure that variation among crops within each crop type is included in the parameter distributions, a set of representative crops was selected for each crop type. Five to seven representative crops were selected for leafy vegetables, root vegetables, and fruits. Crops grown in gardens, orchards, and fields in Amargosa Valley and commonly eaten (based on national food consumption data) were selected. Fewer representative crops were selected for grains and cattle forage because there is little diversity in the types of field crops that are grown in the region. Cumulative distributions were then developed for each parameter that incorporate the values for each crop within a crop type and uncertainty about environmental factors that influence the parameters, as described in *Agricultural and Environmental Input Parameters for the Biosphere Model* (BSC 2003d, Section 6 and Appendix A).

4.3.1 Root Uptake

The concentration of radionuclides in edible portions of crops due to uptake through roots of radionuclides in soil is calculated as the product of activity concentrations in soil (from the soil submodel; Section 4.1), a radionuclide-specific soil-to-plant transfer factor for each crop type, and the dry-to-wet ratio of foodstuffs within each crop type (BSC 2003a, Section 6.4.3.1).

The soil-to-plant transfer factor is the ratio of the activity concentration of a radionuclide in dry edible parts of plants to the activity concentration in dry soil. Observed values of transfer factors vary widely, mainly because of differences among soils, crops, and environmental conditions. The values of soil-to-plant transfer factors for each radionuclide and crop type are developed in *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2003e, Section 6.2.1). Transfer factors were selected from published technical information, mainly review reports, compendia of biosphere parameter values, and dose assessment reports. Selection of these factors included consideration of site-specific soil characteristics and the crops typically grown in Amargosa Valley. Truncated lognormal probability distribution functions that include all relevant transfer factors reported in the literature are used in the ERMYN model (BSC 2003e, Section 6.2.1.1.5). Dry-to-wet ratios are based on well-established values for foodstuffs and animal feed; the average ratio is 0.9 for grains and from 0.07 to 0.22 for the other crop types (BSC 2003d, Section 6.2).

4.3.2 Water Interception

The calculation of radionuclide concentrations in foodstuffs resulting from irrigation water sprayed on plants incorporates the processes of deposition, interception, translocation, and retention (BSC 2003a, Section 6.4.3.2). The activity concentration of radionuclides initially sprayed on crops is calculated as the product of concentrations in groundwater, daily irrigation rates per crop type, and the fraction of irrigation applied using overhead methods. Average daily irrigation rates over the entire growing season were determined by calculating evapotranspiration, effective precipitation, and overwatering requirements for representative crops. Average values per crop type for the current climate range from 4.6 mm per day for grains to 7.6 mm per day for other vegetables. Values for the glacial transition climate are about 25 to 50 percent lower (BSC 2003d, Section 6.8). The fraction of overhead irrigation is included in the model because some crop types, such as fruit trees and some vegetables, may not be irrigated using overhead spray methods. Because most field crops in Amargosa Valley are irrigated using center pivot or rolling sprinklers, the average fraction of overhead irrigation for grains and cattle forage used in the ERMYN model is 0.9 (BSC 2003d, Section 6.3).

The fraction of activity concentration in irrigation water that is initially intercepted by plants is estimated using an empirical formula derived by Hoffman et al. (1989). This formula is used to calculate the water interception fraction from crop biomass, the amount and intensity of irrigation, and empirical constants that quantify differences in interception of radionuclides with different charges and particle sizes. Because there is no information available to calculate radionuclide-specific constants for most radionuclides considered in the ERMYN model, and because radionuclides in the groundwater may be present in different chemical forms (e.g., have different ionic charges) or as suspended particles, one set of empirical constants are used in the ERMYN model for all radionuclides. To ensure that interception is not underestimated, the

constants used were derived from experiments involving the radionuclide that had the highest interception fraction (cationic beryllium). Distributions of the other input parameters required to calculate the interception fraction were developed from average values per crop type (biomass and irrigation application) and the soil types and irrigation methods in Amargosa Valley (irrigation intensity) (BSC 2003d, Sections 6.1, 6.6, and 6.7). Interception fractions calculated using this method for the current climate range from about 0.1 to 1.0; averages per crop type range from 0.24 for leafy vegetables to 0.51 for grains (BSC 2003a, Section 7.3.3.2 and Attachment I [file ERMYN_GW_Pu239verf.gsm]).

The translocation factor in the water interception calculation quantifies the fraction of radionuclides initially intercepted by plant surfaces that is absorbed and translocated to edible plant parts. Values used in the ERMYN model were selected based on a review of interception fractions reported in the literature and used in other environmental radiation models (BSC 2003e, Section 6.2.2.2). A fixed value of 1.0 is used for leafy vegetables and cattle forage because radionuclides are deposited directly on the edible plant parts (i.e., the leaves). A distribution ranging from 0.05 to 0.30 is used for other crop types.

The calculation of the retention of intercepted activity includes a loss component to account for weathering and other field losses. This component is calculated as a function of weathering half life and growing time per crop type. The weathering half life is the time it takes for the activity concentration on plants to be reduced by 50 percent. A distribution of 5 to 30 days is used in the model (BSC 2003e, Section 6.2.2.3). Growing time was selected from information on the length of the growing season for field and garden crops in arid and semiarid regions (BSC 2003d, Section 6.4).

4.3.3 Dust Interception

The calculation of the fraction of dust intercepted by plants incorporates the processes of deposition, initial interception, translocation, and retention (as a function of weathering half life and growing season length) and uses the same input parameter distributions for the translocation factor, weathering half life, and growing time that are used for water interception. A parameter analogous to the fraction of overhead irrigation is not included in the calculation of dust interception because all crops would be exposed to resuspended dust. Because the process of dust interception differs from water interception, different methods are used to estimate the deposition rate and the intercepted fraction of dust.

The deposition rate of resuspended particles quantifies the combined effects of contaminant removal from the atmosphere by several processes (e.g., gravitational settling, diffusion, turbulent transport). It is calculated in the ERMYN model as a function of activity concentrations in the air around crops (calculated in the air submodel) and the dry deposition velocity. The deposition velocity was developed based on wind speeds in Amargosa Valley, surface roughness, and the expected particle size distribution of resuspended particles in fields and gardens (BSC 2003e, Section 6.2.2.1).

The fraction of airborne particles intercepted by plant surfaces is calculated as an exponential function of dry biomass per crop type and an empirical factor that quantifies differences among crop types. Distributions of dry biomass per crop type were developed from published

measurements of crop yield, dry-to-wet ratios of crop foodstuffs, and harvest indices (the ratio of foodstuff dry biomass to total aboveground dry biomass) (BSC 2003d, Section 6.1). The empirical factors used in the model result in higher estimates of dust interception (per unit biomass) for leafy vegetables and cattle forage than for other crop types (because the edible parts of leafy vegetables and forage are directly exposed). This method results in average interception fractions that range from 0.46 for leafy vegetables (the crop type with the lowest biomass) to 0.96 for grains (highest biomass) (BSC 2003a, Section 7.3.3.3).

The total activity concentration in plants is calculated as the sum of the concentrations due to root uptake, water interception, and dust interception. These estimates are then used in the animal submodel to calculate the transfer of radionuclides from feed to farm animals and in the ingestion submodel to calculate the dose from eating locally produced crops (Figure 4-1).

4.4 ANIMAL SUBMODEL

This submodel is used to calculate the concentration of radionuclides in animal products due to ingestion of feed, water, and soil (BSC 2003a, Section 6.4.4). Inhalation of soil particles is not included because it contributes very little to the total radionuclide concentration in animal products (BSC 2003a, Section 7.3.4.4).

Four types of animal products are included in the ERMYN model: meat, milk, poultry, and eggs. The meat category includes beef, pork, lamb, and game animals. Milk includes that from dairy cows, goats, and sheep. Poultry includes chickens, turkey, duck, geese, and game hens, and eggs come from laying hens (chickens) and ducks. The parameter distributions that are specific to each animal product were developed primarily based on information from cattle and chickens, although variation and uncertainty related to other farm animals are considered (BSC 2003a, Section 5.9 and 6.4.4).

Activity concentrations in animal products due to ingestion of the three media considered in this submodel (feed, water, and soil) are calculated as the product of the concentration of radionuclides in those media, ingestion rates of the media, and animal-intake to animal-product transfer coefficients. Activity concentrations in feed and soil are taken from the plant and soil submodels, respectively. Consumption rates for each animal product were primarily from published consumption rates of feed, water, and soil by beef cattle, dairy cows, and chickens (BSC 2003e, Section 6.3.2). Transfer coefficients quantify the fraction of daily intake of a radionuclide by animals that is transferred to one kilogram of animal product. These coefficients differ among elements, chemical forms, and animal products, and uncertainty is considerable for most elements. Truncated lognormal distributions of transfer coefficients are used in the ERMYN model. These distributions were selected from published compendia of generic values and reports containing recommendations or applications of coefficients in other models.

Concentrations of radionuclides in animal products calculated with this submodel are used in the ingestion submodel to calculate the dose from ingestion of locally produced farm animals, milk, and eggs (Figure 4-1).

4.5 FISH SUBMODEL

The ERMYN model includes radionuclide transport through an aquatic food chain because there was a fish farm in Amargosa Valley during the 1990s (Section 2.1). Although most of the fish were used to stock ponds and lakes elsewhere in Nevada, the farm owner allowed Amargosa Valley residents to fish the ponds (BSC 2003e, Section 6.4.2).

In this submodel, accumulation of radionuclides in fish is caused by the use of groundwater in the fishponds. The addition to water of radionuclides from resuspended soil particles also is not included because it contributes negligibly to the total activity concentration in the pond water (BSC 2003a, Section 6.4.5).

The activity concentration in fish is calculated as the product of radionuclide concentrations in water, a bioaccumulation factor, and a water concentration modifying factor (BSC 2003a, Section 6.4.5). The bioaccumulation factor is the ratio of the activity concentration in edible portions of fish tissue to that in the water. There is a large amount of uncertainty and variation in this factor, so the distributions used in the ERMYN model range over several orders of magnitude (BSC 2003e, Section 6.4.3). Bioaccumulation factors have been developed for natural systems and include accumulation of radionuclides in fish from food. Fish in Amargosa Valley were fed commercial feed that was not produced locally; therefore, the accumulation factor is an upper bound of conditions in Amargosa Valley ponds. The modifying factor is included because radionuclide concentrations will increase over time as additional water is added to the ponds to replace that lost by evaporation. Distributions of the modifying factor were developed based on the assumption that activity accumulates in the ponds for up to two years (after which fish are harvested and the ponds drained and cleaned) and that water is replaced at a rate equal to the annual evaporation rate for the climate (about 2 m for the current climate and 0.8 m for the glacial transition climate). These distributions range from 2.2 to 6.1 m for the current climate (i.e., the radionuclide concentration in pond water is about 2 to 6 times higher than in groundwater) and 1.5 to 3.3 m for the glacial transition climate (BSC 2003e, Section 6.4.3 and 6.4.5).

The output of this model is used in the ingestion submodel to calculate the dose from the ingestion of locally raised fish (Figure 4-1).

4.6 CARBON-14 SPECIAL SUBMODEL

Carbon is an abundant and ubiquitous element and moves through the environment as a gas in the form of carbon dioxide. Consequently, some of the environmental transport pathways for Carbon-14, a radioactive isotope of carbon, are different from those for other radionuclides that are present in solid form. The transport of gaseous carbon in the environment is calculated in the Carbon-14 special submodel. This submodel includes calculations of Carbon-14 concentrations in soil and air; in crops from root uptake and photosynthesis; and in animal products from the ingestion of feed, water, and soil. The bioaccumulation of Carbon-14 in fish is calculated in the same manner as other radionuclides, as described in Section 4.5, with one exception. Carbon-14 can be lost from pond water by emission of $^{14}CO_2$ to the atmosphere. This additional loss mechanism is included in calculations of water concentration modifying factor.

The method used to calculate soil concentrations of Carbon-14 is the same as that used for other radionuclides (Section 4.1), with two exceptions (BSC 2003a, Section 6.4.6.1). First, an additional loss mechanism, gaseous emission loss, is included because Carbon-14 is volatile and quickly released from soil as $^{14}CO_2$. The emission rate used in the ERMYN model is 22 times per year (i.e., six percent of Carbon-14 in the soil is lost per day), based on rates measured for sandy soils (BSC 2003e, Section 6.7.1). Thus, Carbon-14 concentrations in surface soils will reach equilibrium conditions within 1 to 2 months and emission is the dominant mechanism for removing Carbon-14 from the soil. Second, Carbon-14 concentrations in the soil are calculated separately for each crop type based on crop-type-specific daily irrigation rates (versus a single soil concentration for all crops, calculated based on the annual average irrigation rate as is used for other radionuclides, Section 4.1). This is done because Carbon-14 is rapidly released from the soil, and, therefore, irrigation must be considered locally and only during the growing season.

Because Carbon-14 is quickly released from the soil as a gas, the activity concentration of this radionuclide in air cannot be calculated using the soil resuspension method (Section 4.2). Thus, a separate calculation is used that is based on the flux density of gaseous Carbon-14 from soil (calculated as the product of soil concentration and emission rate) and the movement or dilution of the released gas in a mixing cell of defined dimensions (BSC 2003a, Section 6.4.6.2). Because Carbon-14 would only be released from irrigated land, the size of the mixing cell is equal to the estimated surface area of irrigated land. The height of the cell is 2 m for human environments and 1 m for crops. The mixing rate also differs for human environments and crops, with a lower rate for crops (based on a slower wind speed closer to the ground). The mixing rate is based on wind speeds measured in northern Amargosa Valley and local terrain conditions (BSC 2003e, Section 6.7.2).

The activity concentration of Carbon-14 in crops due to photosynthesis is calculated as a function of the concentration in the air, the fraction of carbon in plants that is derived from this pathway, and the ratio of the concentration of stable carbon in plants to stable carbon in air (BSC 2003a, Section 6.4.6.3). Similarly, the concentration of Carbon-14 in crops from root uptake is calculated as a function of the fraction of concentration in soil, the fraction of soil-derived carbon in plants, and the ratio of the concentration of stable carbon in plants to stable carbon in soil. The fractions of carbon in plants derived from air and soil used in the ERMYN model are 0.98 and 0.02, respectively (BSC 2003e, Section 6.7.3). Thus, Carbon-14 concentrations in crops are due primarily to uptake during photosynthesis.

The activity concentration of Carbon-14 in animal products is derived from animal feed, soil, and drinking water. The transfer of Carbon-14 from these media to animal products is modeled by calculating the ratio of total Carbon-14 intake over all ingestion pathways to total carbon intake over the same pathways. Multiplication of this ratio by the fraction of stable carbon in the animal product provides the required Carbon-14 activity per unit mass of the product (BSC 2003a, Section 6.4.6.4). Because there is only a small amount of carbon in the soil and water, the primary source of Carbon-14 in animal products is feed.

The results of these calculations are included with the outputs of the soil, air, plant, and animal submodels.

4.7 EXTERNAL EXPOSURE SUBMODEL

This submodel calculates the annual dose (per unit concentration of radionuclides in groundwater) to the RMEI from external exposure. The next two submodels (inhalation and ingestion) calculate the dose from the other exposure pathways considered in the biosphere model (Table 3-2). All doses discussed in this and the following sections refer to annual doses per unit radionuclide concentration in groundwater.

The external exposure submodel is used to calculate the annual dose due to radiation emitted by radioactive materials outside the human body. The annual effective dose equivalent is calculated for this pathway. Contaminated materials typically considered in calculations of external exposure doses include soil, air, and water. The ERMYN model only considers exposure to soil. External exposure to air and water are not considered because they contribute little to the annual dose (BSC 2003a, Section 7.4.8). For example, the dose due to external exposure to water (e.g., during showers, baths, and while swimming) is 1 to 5 orders of magnitude lower (depending on the radionuclide) than that from soil exposure, in part because the time exposed to water is much lower than time exposed to soil (BSC 2003a, Section 7.4.8.2). Likewise, the dose from external exposure to contaminants in air is about 6 orders of magnitude lower than that from exposure to soil, because activity concentrations in the air are much lower than those in the soil (BSC 2003a, Section 7.4.8.1). External exposure from other media (e.g., building material, furniture, and clothing) is possible, but few or no building materials, clothes, or other materials are produced in Amargosa Valley using groundwater. Furthermore, it is assumed that the size and depth of contaminated soils are infinite (BSC 2003a, Section 5.10), and residents are considered to be exposed to contaminated soil at all times while within their community. Thus, the soil exposure time is longer than for other media, and therefore it is reasonable to exclude exposure from those media in the ERMYN model.

External exposure to soil is calculated for each primary radionuclide and long-lived decay product as the product of a radionuclide-specific effective dose coefficient, the saturation concentration of the radionuclide in the soil (from the soil submodel), the average time spent by the RMEI in each of five environments, and an environment-specific shielding factor. The total annual external exposure for a primary radionuclide is then calculated as the sum of doses for that radionuclide and its long-lived decay products (BSC 2003a, Section 6.4.7).

Effective dose coefficients calculated in the ERMYN model include dose contributions of long-lived radionuclides and short-lived decay products (Section 3.3; BSC 2003a, Section 6.4.7.2). Although radionuclide concentrations calculated in the soil submodel and used here apply only to surface soil, dose coefficients for soil contaminated to an infinite depth are used to calculate the external exposure dose for the groundwater scenario. This choice of dose coefficients is appropriate because the radiation contributing to external exposure may also originate in deep soil contaminated due to long-term radionuclide leaching from the surface soil (BSC 2003a, Section 5.10).

As described in Section 4.2, a micro-environmental modeling approach is used to calculate external exposure and inhalation doses. The biosphere is divided into five environments (active outdoors, inactive outdoors, active indoors, asleep indoors, and away from the contaminated area). To account for variation and uncertainty in the characteristics of the receptor population

that influence exposure times, the population is divided into four mutually exclusive groups, and exposure times are estimated separately for each group.

The four population groups represent the range of behaviors that would most influence the amount of time that people are exposed to radionuclides through the external exposure and inhalation pathways. Variation among individuals in these exposure pathways is influenced primarily by the amount of time they spend indoors and outdoors within contaminated areas and the amount of time they spend 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 differently from those who remain indoors. Therefore, the categories are based on work location and type of occupation. Estimates of the proportion of the adult Amargosa Valley population in each of the following four groups, and the average time they spend in each environment, are developed in *Characteristics of the Receptor for the Biosphere Model* (BSC 2003c, Sections 6.3.1 and 6.3.2). Time spent in environments was estimated based on information collected during the 2000 census on the amount of time people in Amargosa Valley spent commuting and working (Bureau of the Census 2002) and from information in the U.S. Environmental Protection Agency's *Exposure Factors Handbook* (EPA 1997).

Local Outdoor Workers–This group includes residents who work outdoors and disturb (and, therefore, resuspend) contaminated soil. Based on an assumption that this group includes all adult Amargosa Valley residents identified in the 2000 census (Table 2-1) that worked in agriculture, 25 percent of those working in construction, 10 percent of utility workers, and 10 percent of miners, 5.5 percent of the population is classified as local outdoor workers. These workers are estimated to spend an average of 3.1 hours per day active outdoors, 4.0 hours inactive outdoors, 6.6 hours active indoors, 8.3 asleep, and 2.0 hours away from contaminated areas.

Commuters–This group includes residents who work outside of contaminated areas. Thirty-nine percent of the population is classified as commuters, based on an assumption that all employed adult Amargosa Valley residents who commute 10 minutes or more to work are employed outside of the contaminated area. This time limit was developed by considering the amount of land that could be irrigated by 3,000 acre-feet of water (10 CFR 63.312) and the amount of time it would take to drive out of that area. Commuters are estimated to spend an average of 0.3 hours per day active outdoors, 1.4 hours inactive outdoors, 6.0 hours active indoors, 8.3 asleep, and 8.0 hours away from the contaminated area.

Local Indoor Workers–Local indoor workers are residents who work indoors (or outdoors in enclosed vehicles) in areas contaminated by groundwater or ash. Sixteen percent of the population is in this group. This includes employed adults who were not classified as local outdoor workers or commuters. Local indoor workers are estimated to spend an average of 0.3 hours active outdoors, 1.3 hours inactive outdoors, 12.1 hours active indoors, 8.3 asleep, and 2.0 hours away from contaminated areas.

Non-workers–Non-workers are residents who are unemployed or are not in the labor force (e.g., retired people). Thirty-nine percent of the resident adult population met this criterion in

2000. Non-workers are estimated to spend an average of 0.3 hours active outdoors, 1.2 hours inactive outdoors, 12.2 hours active indoors, 8.3 asleep, and 2.0 hours away from contaminated areas.

To meet the requirement of 10 CFR 63.312 that average values of lifestyle characteristics be used in the TSPA dose assessments, the average exposure time per environment is calculated as the average of exposure times per group weighted by the proportion of the population in each group (BSC 2003a, Section 6.4.7). These average exposure times are 0.45 hours per day in the active outdoor environment, 1.45 inactive outdoors, 9.45 hours active indoors, 8.3 hours asleep indoors, and 4.35 hours away from contaminated areas (BSC 2003a, Table 6.10-1).

The shielding factor is included in the external exposure dose calculation to account for the effects of shielding from radiation provided by buildings when the receptor is indoors. Shielding factor values used in the ERMYN model range from zero for radionuclides that emit no penetrating radiation (e.g., Polonium-212 and Radium-228) to 0.4 for radionuclides with highly penetrating radiation (gamma emitters of energy greater than 100 keV) (BSC 2003c, Section 6.6). These factors were developed for lightly constructed housing and are applicable to Amargosa Valley because most residents live in mobile homes (Section 2.2). Shielding factors are only applied to indoor environments (i.e., the shielding factor for outdoor environments equals 1.0).

The output of this submodel, the total annual external exposure for each primary radionuclide, is used to calculate the all-pathway BDCFs, as described in Section 4.10.

4.8 INHALATION EXPOSURE SUBMODEL

The inhalation submodel is used to calculate exposure from the inhalation of radionuclides in air. Inhalation exposure is estimated using radionuclide concentrations in the air (from the air submodel), parameters describing conditions of human exposure, and dose conversion factors for inhalation exposure that convert radionuclide intake to a committed effective dose equivalent. 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 effective dose equivalent, which represents the effective dose equivalent integrated over a 50-year commitment period. The annual committed effective dose equivalent, although delivered over the commitment period, is assigned to the one-year period of intake.

This submodel is used to calculate the dose (per unit concentration of radionuclides in groundwater) from the inhalation of three types of radionuclides from three sources: resuspended soil; aerosols from evaporative coolers; and gaseous emissions from soil, which includes exhalation of Radon-222 and gaseous emissions of Carbon-14. The total inhalation dose is the sum of the doses resulting from these three inhalation exposure pathways.

Exposure to the three sources of radionuclides is calculated similarly. Dose due to inhalation of each primary radionuclide and long-lived decay product is the product of a radionuclide-specific effective dose conversion factor, the concentration of radionuclides in the air within each of the

receptor environments (calculated in the air submodel), the time spent by the RMEI in each environment, and environment-specific breathing rates. The dose for a primary radionuclide is then calculated as the sum of doses for that radionuclide and its long-lived decay products (BSC 2003a, Section 6.4.7). As described in Section 3.3, the effective dose conversion factors include the contribution to dose from short-lived decay products (BSC 2003a, Sections 6.4.8.1 and 6.4.8.5). The same exposure times and population proportions described in Section 4.7 for the external exposure submodel are used to calculate inhalation exposure. Breathing rates used in this calculation are based on the expected level of activity within each environment, and they range from 0.39 m^3/hour for time spent asleep to 1.57 m^3/hour for time spent active outdoors (BSC 2003c, Section 6.3.3).

The calculation of inhalation exposure to radionuclides introduced into the air from evaporative coolers includes factors that quantify the proportion of residences with coolers and the proportion of the year that coolers are operated. Those factors are also included in the calculation of dose from inhalation of Radon-222 because the home ventilation rate influences the buildup of Radon-222 indoors (Section 4.2.3). The proportion of homes with coolers (average equals 73 percent) is from the 1997 survey of Amargosa Valley residents (DOE 1997). The range of the proportion of time coolers are operated is calculated as the average percentage of days per year that the daily maximum temperature exceeds 80°F to 90°F. This distribution ranges from 32 to 46 percent for the current climate, and it ranges from 3 to 14 percent for the glacial transition climate (BSC 2003c, Section 6.3.4). The contribution of radionuclides from evaporative coolers to inhalation in outdoor environments is not considered in the model because the air from coolers would be diluted quickly when blown outside.

The output of this submodel, the total annual inhalation exposure for each primary radionuclide, is used to calculate the all-pathway BDCFs, as described in Section 4.10.

4.9 INGESTION EXPOSURE SUBMODEL

The ingestion submodel determines exposure to the receptor from ingesting drinking water, four types of crops (leafy vegetables, other vegetables, fruits, and grains), four types of animal products (meat, poultry, milk, and eggs), freshwater fish, and soil. Ingestion exposure is calculated as the committed effective dose equivalent for the 50-year period resulting from one year of intake.

Ingestion exposure is calculated for each of the 11 media listed above as the product of the effective dose conversion factor, activity concentration (from the groundwater source and the soil, plant, and animal submodels), and annual consumption rate. The dose contribution of all short-lived radionuclides is included in the effective dose conversion factors for the long-lived primary radionuclides (Section 3.3). In addition, for ingestion of plants, animal products, and soil, the contribution due to radionuclide decay and ingrowth in surface soil is added into the primary radionuclides. Total ingestion exposure is calculated as the sum of the dose from the 11 media.

The annual consumption rate of water is 2 liters per day, or 730 liters per year, as specified in 10 CFR 63.312(d). The soil ingestion rate is representative of the amount of soil that adults inadvertently ingest (e.g., from dirty hands, from food, while breathing through the mouth) and

does not include purposeful soil ingestion. Based on the dry, dusty conditions in Amargosa Valley, a range of 50 to 200 mg/day is used in the ERMYN model (BSC 2003c, Section 6.4.3). Ingestion rates of locally produced crops and animal products are based on the 1997 survey of a sample of Amargosa Valley residents (DOE 1997). During that survey, people were asked how often they ate locally produced items. To develop distributions of annual consumption rates, the information on frequency of consumption from the survey was combined with information obtained from the U.S. Department of Agriculture on the consumption rate of foods by people in the western United States (BSC 2003c, Section 6.4.2). Statistical uncertainty associated with surveying a sample of the population was incorporated into the distributions of the ingestion-rate parameters (BSC 2003c), Section 6.4).

The output of this submodel, the total annual ingestion dose for each primary radionuclide, is used to calculate the all-pathway BDCFs, as described in the next section.

4.10 BIOSPHERE DOSE CONVERSION FACTORS

The all-pathway annual dose per unit concentration of each primary radionuclide is expressed as the total effective dose equivalent, and is the sum of the annual effective dose equivalent from external exposure to each radionuclide and the committed effective dose equivalent from annual intake of that radionuclide into the body by inhalation and ingestion (BSC 2003a, Section 6.4.10.1).

The results of all calculations of radionuclide concentrations in environmental media (Sections 4.1 through 4.6) and dose for each exposure pathway (Sections 4.7 through 4.9) are linearly proportional to the concentration of radionuclides in the groundwater (BSC 2003a, Section 6.4.10.2). Therefore, the all-pathway annual dose per unit concentration of each radionuclide (i.e., BDCF) calculated in this model is independent of the concentration of radionuclides in groundwater estimated in the TSPA. Although the ERMYN model can be used to calculate the dose for any predefined concentration, the BDCFs calculated for the TSPA are based on a unit concentration of radionuclides in water (i.e., 1 Bq/m^3). Therefore, the dose to the RMEI from exposure to contaminated groundwater can be calculated in the TSPA as the product of the BDCFs and groundwater concentrations estimated in the TSPA for the hypothetical location of the well at a specified time.

5. ERMYN VOLCANIC SCENARIO MODEL

This section describes the conceptual and mathematical models used to calculate the transfer of radionuclides in the biosphere and exposure to the receptor for the volcanic ash exposure scenario. As discussed in Section 3.2, the transport and exposure pathways for this scenario are similar to the pathways considered for the groundwater analysis. This discussion focuses on differences between the methods used in the groundwater submodels and those used in the volcanic ash scenario.

The source of radionuclides for the volcanic scenario is ash from a volcanic eruption at the repository. Ash at the location of the receptor could be deposited during the initial fallout after the eruption or it could be transported into the region by fluvial or aeolian processes. These redistribution processes are modeled in the TSPA. Groundwater is not considered to contain radionuclides, and, therefore, transfer pathways resulting from use of water (e.g., irrigation water, on soil and plants, fish farms, ingestion of water by farm animals and the receptor) are not considered for the volcanic ash scenario.

The conceptual and mathematical models for the volcanic scenario are developed in seven submodels that represent the four contaminated environmental media (soil, air, plants, and animals), and external, inhalation, and ingestion exposure (Figure 5-1). A special submodel for Carbon-14 is not included because Carbon-14 is not a primary radionuclide for this scenario (BSC 2003a, Section 6.3.2).

For the groundwater scenario, the dose from all exposure pathways is combined into one set of BDCFs for use in the TSPA. Calculation of BDCFs is much more complicated for the volcanic scenario because inhalation exposure would decrease over time following an eruption as the concentration of radionuclides in the air decreases. Inhalation exposure also would be affected by the depth of the tephra deposit, which is not calculated in the biosphere model. To account for the effects of time and ash depth, a set of three BDCF components is calculated for the volcanic ash scenario. The first component accounts for the exposure pathways that would not be affected by time or ash depth (ingestion, inhalation of radon decay products, and external exposure). The second accounts for inhalation of particulates following a volcanic eruption when airborne concentrations would be increased. This short-term inhalation component is time-dependent because mass loading would decrease after an eruption. The third component accounts for inhalation when mass loading would not be elevated as the result of the volcanic eruption. The latter two components are affected by ash thickness. All three components are numerically equal to the annual doses from a radionuclide per pathway that the RMEI would receive when exposed to radionuclide contamination in environmental media arising from a unit areal concentration of the radionuclide in the ash deposited on the ground (BSC 2003a, Section 6.5.8).

One set of outputs from the volcanic ash scenario biosphere model is used for current and predicted future climate states because the important input parameters (e.g., mass loading, (BSC 2003b, Section 6) and the model results (BSC 2003h, Section 6.2.6) are insensitive to the changes in climate predicted to occur at Yucca Mountain during the next 10,000 years.

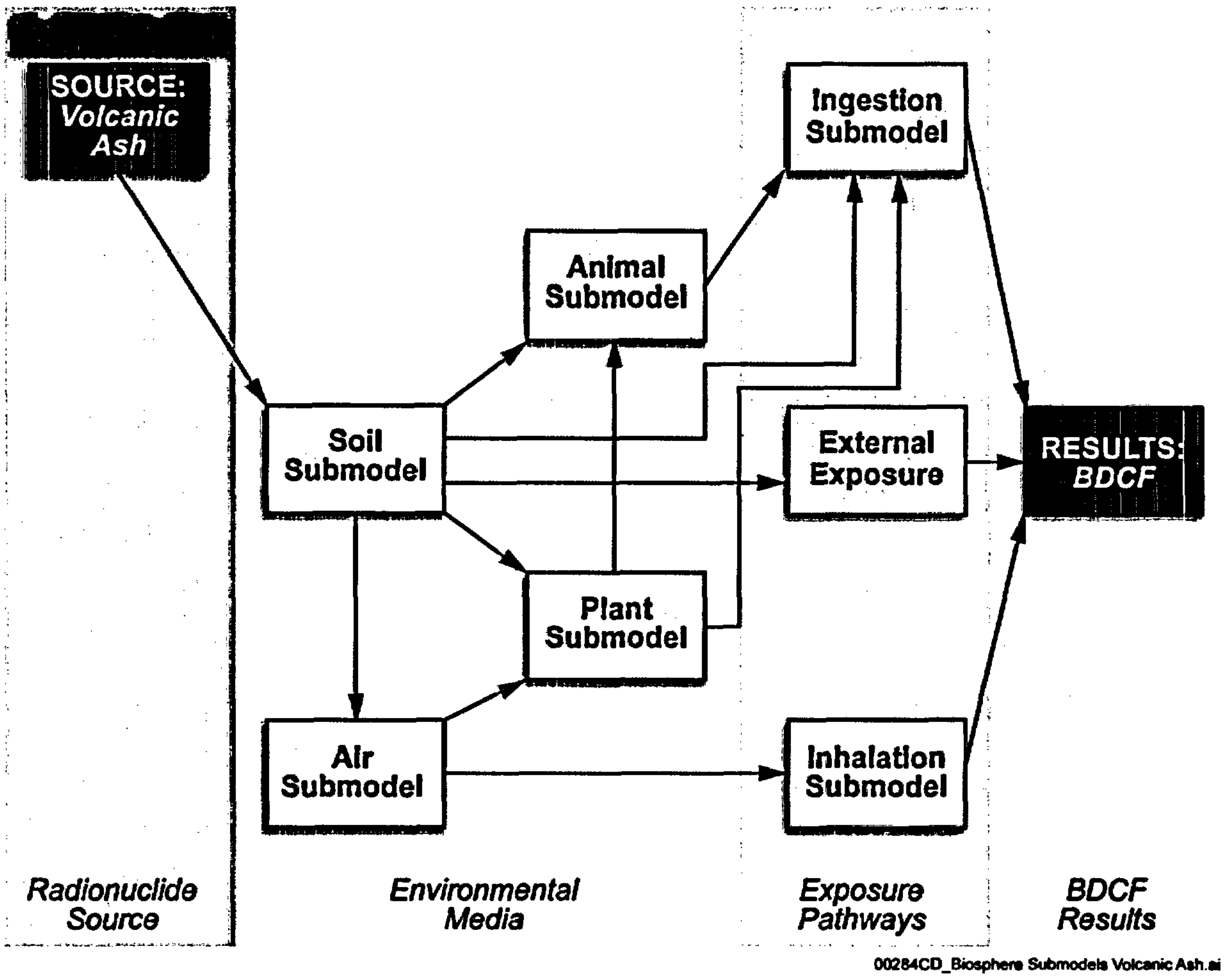

Figure 5-1. Relationship between the Biosphere Submodels for the Volcanic Ash Scenario

The biosphere model for the volcanic ash scenario applies for the period after the initial deposition of contaminated ash from an eruption has ceased. Independent of the biosphere model, dose factors for the eruptive phase were developed in the *Disruptive Event Biosphere Dose Conversion Factor Analysis* (BSC 2003h, Section 6.3). These factors are used in the TSPA to calculate dose accrual to the RMEI during the ash-fall event. Exposure during this period may be important because airborne concentrations of radioactive particulate matter may be high during an eruption. Only the inhalation of airborne ash particles is considered for this phase. The dose factor for each primary radionuclide is numerically equal to the dose resulting from one day of intake of the radionuclide (and any short-lived decay products) from inhaling air containing a unit activity concentration of the radionuclide. Inhalation exposure depends on the exposure time and breathing rate, as described Section 4.8.

5.1 SOIL SUBMODEL

The surface soil submodel for the volcanic ash scenario differs from the groundwater scenario primarily because a volcanic eruption would spread ash over a large area, while irrigating would deposit radionuclides on the relatively small farming area. In addition, radionuclides would not accumulate in the surface soil because they are not continuously added to the environment.

Radionuclide concentrations in soil are calculated separately in this submodel for cultivated and uncultivated soils (BSC 2003a, Section 6.5.1). The calculation for cultivated land is the same as that used in the soil submodel for the groundwater scenario. Radionuclides are assumed to be mechanically mixed by normal farming operations over the 5- to 30-cm tillage depth. If the predicted ash thickness is greater than the tillage depth, the contaminants are conservatively assumed to be uniformly distributed within the tillage depth (BSC 2003a, Section 5.12). The activity concentrations calculated using this method are used to evaluate radionuclide transport to plant foodstuffs and animal products, and for inadvertent soil ingestion (BSC 2003a, Section 6.5.1.1).

On uncultivated lands, volcanic ash would not quickly mix with surface soil, and the proportion of resuspended particles comprised of ash (versus clean soil) would depend on the thickness of the ash deposit. To account for this, a critical thickness is considered in the submodel and an ash-depth function is developed for use in the TSPA. The critical thickness is the layer from which particles would be resuspended, which is, at most, a few millimeters (BSC 2003e, Section 6.8). For an ash thickness equal to or greater than the critical thickness, only ash would be resuspended because clean soil is covered by too much ash to be resuspended. In this case, only a portion of the ash (and the activity concentration it contains) would be available for resuspension. The portion of the activity concentration in the soil that would be resuspended is calculated as the ratio of critical thickness to ash depth. If the deposit is thinner than the critical thickness, the resuspended material would be a mix of ash particles and clean soil, and all radionuclides in the ash would be available for resuspension. The TSPA calculates ash thickness and activity concentration in ash as a function of time; therefore, the loss factors (leaching, erosion, and radioactive decay) considered in the soil submodel for the groundwater scenario are not included in the calculations of radionuclide concentrations for the volcanic ash scenario.

5.2 AIR SUBMODEL

The air submodel calculates concentrations of radionuclides in air resulting from two transport pathways: resuspension of ash and soil and exhalation of radon from the mixture of ash and soil (BSC 2003a, Section 6.5.2).

Resuspension of ash into the atmosphere is considered separately for cultivated and uncultivated lands. Activity concentrations in the air resulting from resuspension of particles on cultivated land is used to calculate surface contamination of crops in the plant submodel and is calculated in the same manner as described in Section 4.2. The mode of the mass loading distribution for post-volcanic conditions in cultivated fields is two times greater than that used for the groundwater scenario (BSC 2003b, Section 6.2.5).

Activity concentrations in the air resulting from resuspension of particles on uncultivated land are used in the inhalation model to calculate inhalation exposure. The concentration of radionuclides in the soil available for resuspension is calculated in the soil submodel. To evaluate inhalation exposure, the ERMYN model uses a microenvironmental modeling method that considers five receptor environments (see Section 4.2), each having a mass loading distribution that is representative of typical activities conducted within the environment. To allow for the possibility of radionuclides being preferentially resuspended from the surface soil and inhaled, an empirical enhancement factor is used to quantify the net airborne activity

concentration relative to surface soil activity concentration. Distributions of enhancement factors for the volcanic scenario range from 2.8 to 8.4 for the outdoor active environment (about 20 percent higher than the bounds of the distribution used for the groundwater scenario) and 0.21 to 1.04 for other environments (BSC 2003f, Section 6.5).

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 erode, become mixed into the soil, become buried, or otherwise become stabilized. The ERMYN model, therefore, assumes that mass loading would eventually return to levels experienced before the eruption (BSC 2003a, Section 5.14). This assumption is based on measurements of mass loading after the eruption of Mount St. Helens and other volcanoes (BSC 2003b, Section 6.2 and 6.3). To account for this effect, two sets of mass loading distributions and a mass loading time function are developed (BSC 2003b, Section 6.3). The first mass loading set is for the period immediately after the eruption and before the ash stabilizes and is representative of the average annual concentration of resuspended particles the first year following a volcanic eruption. The second set is representative of conditions after resuspended particle concentrations have returned to pre-eruption levels. This second set is the same as that used for the groundwater scenario. Mass loading distributions for the first year following an eruption generally are two to three times higher than those for stabilized conditions (BSC 2003b, Section 6.2). The time function quantifies the rate at which mass loading is expected to return to pre-eruption levels. Mass loading distributions are used to calculate radionuclide concentrations in the air. Radionuclide concentrations in the air associated with both sets of mass loading are influenced by ash depth, but only the first is time dependent. By separating the time and ash thickness components, changes in radionuclide concentrations immediately after the eruption can be evaluated (BSC 2003a, Section 6.5.2.1).

The calculation of radon exhalation for the volcanic ash scenario is simpler than that used in the groundwater scenario. Because ash thickness is expected to be relatively thin, it is conservatively assumed that all radon created by decay in the ash-soil layer is released to the atmosphere, where it decays and contributes to the inhalation dose (BSC 2003a, Section 5.15). Unlike the groundwater scenario, indoor radon concentrations are considered to be the same as outdoor concentrations because there are no mechanisms for increased infiltration of radon into buildings and the initial amount of indoor volcanic ash would be limited. Even if new buildings were built on contaminated land, the infiltration of Radon-222 from the ground into indoor spaces would be limited because the thin layer of ash would be removed or mixed with surface soil during construction. Because it is assumed that all radon from outdoor soil is released, it is not necessary to consider an additional source of indoor radon (BSC 2003a, Section 6.5.2.2).

5.3 PLANT SUBMODEL

Two transfer pathways are considered in this submodel to calculate radionuclide concentrations in plants consumed by humans and farm animals: root uptake from soil and foliar uptake from intercepted resuspended matter. Root uptake is calculated using the same methods and transfer factors as for the groundwater scenario (Section 4.3). Plant uptake from deposition of resuspended soil on plant surfaces also uses the same methods as in the groundwater scenario, but atmospheric concentrations are higher because mass loading is likely to be higher following

an eruption. The other parameters in this submodel (translocation factors, weathering constants, crop growing time, and crop biomass) are the same as those used in the groundwater scenario (BSC 2003a, Section 6.5.3).

5.4 ANIMAL SUBMODEL

The animal product submodel considers two pathways for the accumulation of radionuclides in animal products, ingestion of feed and soil. The methods and input parameters used to calculate activity concentrations are the same as those described in Section 4.4. Inhalation of resuspended ash was not included because this pathway has a negligible influence on the concentrations of radionuclides in animal products (BSC 2003a, Section 7.4.5).

5.5 EXTERNAL EXPOSURE SUBMODEL

As with the groundwater scenario, this submodel only considers exposure to radionuclides in soil. Air submersion is excluded because of the low contribution to the results of this submodel (BSC 2003a, Section 7.4.8). All doses discussed in this and the following sections refer to annual effective doses equivalent per unit radionuclide concentration in volcanic ash.

The methods used to calculate external exposure are the same as those described in Section 4.7, but the effective dose coefficients and distributions of population proportions and exposure times are different than those used for the groundwater scenario. The effective dose coefficients used to calculate external exposure to ash were selected based on the assumption that, regardless of the predicted thickness of the ash, all radionuclides would be located on the soil surface. This assumption is valid because thin deposits are more likely than thicker deposits and only a small portion of the soil in Amargosa Valley is cultivated. It is conservative because it eliminates self-shielding within the ash-soil mixture (BSC 2003a, Section 5.16). As with the other exposure submodels, the decay products of primary radionuclides are treated as discussed in Section 3.3. For the volcanic scenario, ingrowth in the soil of the long-lived decay products of primary radionuclides is not considered because it is accounted for in the TSPA as part of the time-dependent source.

Population proportions and exposure times differ from those used for the groundwater scenario because it is likely that radionuclides would be spread over a larger area following an eruption than would occur as a result of using groundwater for irrigation. It is, therefore, assumed that all Amargosa Valley residents that commute 35 minutes or less (versus 10 minutes for the groundwater scenario) work within areas containing radionuclides (BSC 2003c, Section 5.1). Based on this assumption and data on commute time from the 2000 census (Bureau of the Census (2002), 13 and 43 percent of the population are classified as commuters and local indoor workers, respectively (versus 39 and 16 percent for the groundwater scenario). The only difference in exposure times between scenarios is for time spent in the inactive outdoor environment, because commute times within the area containing radionuclides are longer for the volcanic scenario (BSC 2003c, Sections 6.3.1 and 6.3.2). The average exposure times per environment, weighted by the proportion of the population in each group, are 0.45 hours per day in the active outdoor environment, 1.59 hours inactive outdoors, 10.87 hours active indoors, 8.3 hours asleep indoors, and 2.79 hours away from the area containing radionuclides (BSC 2003a, Table 6.10-5).

5.6 INHALATION EXPOSURE SUBMODEL

The inhalation dose is calculated as the committed effective dose equivalent for the 50-year committed period resulting from annual intake of radionuclides by inhalation. Two sources of radionuclides in air are considered, resuspended particles and radon gas, and the inhalation dose is the sum of the dose from both sources (BSC 2003a, Section 6.5.6).

As is done for the groundwater scenario, the inhalation dose is calculated considering specific environments associated with human activities and population groups. However, for the volcanic scenario, there are two components to the radionuclide concentrations in the air (see Section 5.2), one related to post-volcanic, time-dependent mass loading and one related to conditions after mass loading concentrations are stabilized. Both components depend on ash thickness. Annual inhalation exposure is calculated separately for the first year following a volcanic eruption and for the long-term period when airborne concentrations have stabilized (BSC 2003a, Section 6.5.6). The total resuspension dose is considered to be the sum of the doses during the short-term and long-term periods. The change in dose during the period when mass loading is decreasing is modeled as exponential in time with a defined time constant (BSC 2003b, Section 6.3).

5.7 INGESTION EXPOSURE SUBMODEL

The ingestion exposure pathway for the volcanic scenario is the same as that for the groundwater scenario except that only 9 of the 11 media are used: (4 crops, 4 animal products, and soil). Ingestion of water and fish are not included because groundwater is not considered to contain radionuclides in this scenario.

5.8 BIOSPHERE DOSE CONVERSION FACTORS

The calculation of BDCFs, and the use of those BDCFs to calculate the dose in the TSPA for the post-eruptive phase, is more complicated for the volcanic scenario than for the groundwater scenario. This is because the inhalation dose changes over time (as mass loading decreases with time from a maximum concentration the first year following an eruption) and varies depending on ash depth (because radionuclide concentrations in the air from resuspension of particles from uncultivated soil are a function of ash depth). To incorporate these time and depth functions, three BDCF components, a critical ash thickness, and two functions (time and ash thickness) are developed for use in the TSPA to calculate the dose for the post-eruptive phase (BSC 2003a, Section 6.5.8; BSC 2003h, Section 7). In addition, dose factors are provided to calculate the inhalation dose during the eruptive phase (BSC 2003h, Section 6.3).

The first BDCF component includes the dose contribution (per unit activity concentration of radionuclides in soil) from external exposure, inhalation of radon, and ingestion. These exposure pathways are not affected by time or ash depth; therefore, their dose contribution can be calculated by multiplying the BDCF component for a radionuclide by the areal concentration of that radionuclide in the soil at a specified time.

The second BDCF component addresses the short-term dose contribution from inhaling increased concentrations of resuspended particulates following a volcanic eruption. This dose contribution decreases through time and is also affected by ash depth, so in the TSPA the BDCFs

must be multiplied by the areal activity concentration in the soil, the ash depth function, and the mass loading time function.

The third component of the BDCFs is for the long-term contribution to the dose from inhaling resuspended particles at concentrations expected after mass loading has decreased to pre-eruption levels (i.e., long-term inhalation dose contribution). This dose contribution is affected by ash depth and therefore this BDCF component must be multiplied in the TSPA by the areal activity concentrations in soil and the ash depth function.

The mass loading time function defines the rate of decrease in mass loading after a volcanic eruption. It is modeled as an exponential function, and the rate of change is controlled by the mass loading decrease constant (BSC 2003b, Section 6.3; BSC 2003h, Section 7.3). That decrease constant was developed based on the rate of change in mass loading following Mount St. Helens and other volcanic eruptions and the consideration of uncertainty about the influence of climate change and ash depth, redistribution, and particle sizes. Because of the uncertainty in changes in mass loading over time for deep ash deposits, separate distributions of the mass loading decrease constant were developed for deposits less than 10 mm and those equal to or greater than 10 mm. The minimum and maximum decrease constants of the distribution for shallow deposits would result in mass loading decreasing to five percent of the initial concentration within 2 to 15 years. For deeper deposits, mass loading would decrease to five percent of the initial concentration within about 3 to 25 years (BSC 2003b, Section 6.3.3).

The ash depth function is described in Section 5.1 and accounts for the fact that, for an ash thickness greater than the critical thickness, only a fraction of the ash on the soil surface (and the activity it contains) would be available for resuspension. For ash depths less than the critical depth, this function equals one because all radionuclides in the ash/soil are available for resuspension. For ash depths deeper than the critical depth, this function is calculated as the critical depth divided by ash depth (BSC 2003a, Section 6.5.1; BSC 2003h, Section 7.3). The value of the critical thickness is randomly sampled in each biosphere model realization and included with the values of the three BDCF components for each radionuclide (one vector) as input to the TSPA-LA model. The initial depth of ash deposited at the location of the receptor and changes in depth through time due to fluvial and aeolian processes are calculated in the TSPA. The TSPA model randomly samples from the vectors containing BDCF components and critical thickness to predict dose at a given time for a radionuclide concentration in ash (BSC 2003a, Section 6.5.8).

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6. BIOSPHERE MODEL RESULTS

The BDCFs calculated by the ERMYN model are used in the TSPA to calculate the annual dose from a concentration of radionuclides in groundwater or volcanic ash. A single realization generated using the ERMYN model consists of a (row) vector of BDCFs, within which numerical elements represent the BDCFs for each radionuclide of interest. The sampling of inputs to the ERMYN model is fixed for a given realization, thereby capturing the inherent correlation among the BDCFs for each radionuclide. This sampling process is repeated to generate the required number of realizations for the TSPA. When used by TSPA, this set of row vectors is sampled at random within the TSPA code to propagate uncertainty from the biosphere calculations into the TSPA dose calculations.

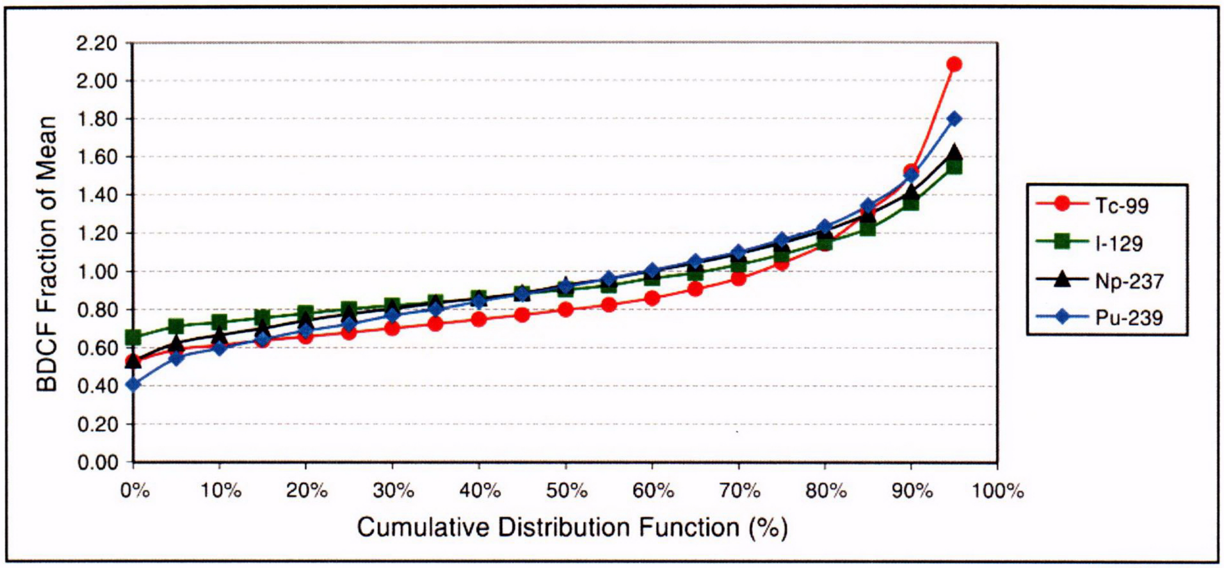
6.1 GROUNDWATER SCENARIO

For the groundwater scenario, each realization of the model produces BDCFs for 28 radionuclides and three climate states (current, monsoon, and glacial transition). Mean BDCFs and standard deviations are presented (Table 6-1) for comparison and to convey information on the uncertainty in their values propagated through the model.

The total annual dose is calculated in the TSPA as the sum of the products of radionuclide-specific BDCFs and time-dependent activity concentrations of radionuclides in groundwater (BSC 2003a, Section 6.4.10). This calculation is based on a linear relationship between radionuclide concentrations in groundwater and the BDCF for each radionuclide.

The BDCFs for the groundwater scenario are developed in *Nominal Performance Biosphere Dose Conversion Factor Analysis* (BSC 2003g). To illustrate variability in BDCF values, normalized BDCFs (i.e., BDCF value per realization divided by mean BDCF) were calculated for a set of four radionuclides likely to have an important contribution to the dose at 10,000 years (Figure 6-1). The shape of the resulting cumulative distribution functions for these radionuclides is similar, although there are some differences, especially for Technetium-99 at the upper end of the range. These differences are due to variation among radionuclides in the contribution of the pathways considered (Table 6-2) and the influence of stochastically sampled input parameters on the calculated rate of transport of each radionuclide through the biosphere. The distributions in Figure 6-1 show the degree of variability in BDCFs after all uncertainties have been propagated through the biosphere model. From the fifth to the ninety-fifth percentile of the distributions, the BDCF values extend by a factor of up to two below and above the mean value.

To illustrate the effect of climate change on the results of the ERMYN model, BDCFs for the two extreme climates, current (interglacial) and glacial transition, are summarized in Table 6-1. Average BDCFs for the glacial transition climate are 4 to 26 percent lower, and standard deviations for most BDCFs are smaller than those for the current climate. This change is due primarily to a decrease in irrigation rates for the future climate, reducing the input of radionuclides onto cultivated soil. The change in BDCFs due to climate change is small compared to the total amount of variation in the BDCFs for each radionuclide. For example, the ratios of the standard deviations to means is greater than 0.25 for most radionuclides (Table 6-1).



Source: Based on data from DTN: MO0307MWDNPBDC.001 (see Rautenstrauch 2003).

Figure 6-1. Normalized Distributions of Groundwater Scenario Biosphere Dose Conversion Factors for Selected Radionuclides

For each radionuclide, the relative importance of exposure pathways is summarized in Tables 6-2 and 6-3. Pathways excluded from the biosphere model used for the site recommendation (CRWMS M&O 2000c), but included in the ERMYN model (e.g., inhalation of radon decay products, inhalation of aerosols generated by evaporative coolers), have a large contribution for some radionuclides.

Pathway contributions differ among radionuclides (Tables 6-2 and 6-3). Ingestion of water is an important pathway for most radionuclides. Inhalation of particulate matter dominates doses for many actinides (e.g., isotopes of thorium, uranium, plutonium, and americium), and inhalation of radioactive aerosols generated by evaporative coolers is an important inhalation exposure pathway for some of those radionuclides. Other pathways are only important for a few radionuclides. For example, external exposure is a dominant pathway for Tin-126 and Cesium-137; inhalation of radon decay products for Radium-226 and Thorium-230; and fish consumption for isotopes of Cesium, Lead-210, and Neptunium-237. Consumption pathways generally are more important for radionuclides with atomic numbers less than about 88. For the future climate, the importance of the evaporative cooler pathway is greatly reduced, and for most radionuclides, the inhalation of particulate matter and the consumption of water are dominant pathways (BSC 2003g, Section 6.2.5).

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Table 6-1. Groundwater Scenario Biosphere Dose Conversion Factors for the Current and Glacial Transition (GT) Climate States (in units of rem/year per pCi/L)

Radionuclide	Mean			Standard Deviation		
	Current	GT	Ratio (%)	Current	GT	Ratio (%)
C-14	9.06E-06	8.73E-06	96	6.05E-06	6.04E-06	100
Cl-36	1.95E-05	1.65E-05	85	2.84E-05	2.29E-05	81
Se-79	6.49E-05	5.19E-05	80	1.29E-04	1.06E-04	82
Sr-90	1.64E-04	1.52E-04	93	2.46E-05	2.02E-05	82
Tc-99	2.21E-06	2.03E-06	92	1.48E-06	1.32E-06	89
Sn-126	6.29E-03	4.68E-03	74	3.95E-03	3.02E-03	76
I-129	3.37E-04	3.12E-04	93	1.17E-04	9.74E-05	83
Cs-135	5.59E-05	4.39E-05	79	3.99E-05	3.08E-05	77
Cs-137	4.87E-04	3.74E-04	77	2.54E-04	2.02E-04	80
Pb-210	9.04E-03	8.16E-03	90	3.48E-03	2.64E-03	76
Ra-226	9.58E-02	7.34E-02	77	4.65E-02	3.64E-02	78
Ac-227	3.09E-02	2.32E-02	75	1.08E-02	7.45E-03	69
Th-229	3.37E-02	2.51E-02	74	1.77E-02	1.36E-02	77
Th-230	2.87E-02	2.19E-02	76	2.42E-02	1.88E-02	78
Th-232[a]	4.41E-02	3.33E-02	76	2.21E-02	1.77E-02	80
Pa-231	9.91E-02	7.58E-02	76	6.31E-02	4.88E-02	77
U-232[a]	5.78E-03	4.33E-03	75	2.36E-03	1.67E-03	71
U-233	1.74E-03	1.31E-03	75	2.04E-03	1.54E-03	75
U-234	1.21E-03	9.11E-04	75	1.02E-03	7.80E-04	76
U-236	1.08E-03	8.19E-04	76	8.58E-04	6.64E-04	77
U-238	1.08E-03	8.20E-04	76	8.55E-04	6.56E-04	77
Np-237	6.92E-03	5.90E-03	85	2.27E-03	1.76E-03	78
Pu-238	4.67E-03	3.93E-03	84	1.13E-03	8.77E-04	78
Pu-239	9.16E-03	7.35E-03	80	3.59E-03	2.89E-03	81
Pu-240	8.93E-03	7.19E-03	81	3.37E-03	2.70E-03	80
Pu-242	8.83E-03	7.09E-03	80	3.52E-03	2.74E-03	78
Am-241	6.78E-03	5.57E-03	82	1.93E-03	1.52E-03	79
Am-243	9.43E-03	7.45E-03	79	3.89E-03	2.93E-03	75

Source: BSC 2003g, Tables 6.2-5 and 6.2-7.

NOTES: To convert from rem/year pCi/L to Sv/year per Bq/m^3 divide by 3.7×10^3.
Ratios are of values for the future and current climates.
[a]Th-232 includes contribution from Ra-228 and Th-228; U-232 includes contribution from Th-228.

Table 6-2. Relative Contribution of Exposure Pathways per Radionuclides for the Current Climate

Radionuclide	External Exposure	Inhalation			Ingestion	
		Particulate Matter	Evaporative Cooler	Radon	Water	Total Ingestion
C-14					16.8	83.2
Cl-36	0.1		0.2		11.3	88.2
Se-79		0.1			9.8	90.2
Sr-90	0.5	0.1	0.3		68.2	30.9
Tc-99			0.7		48.3	50.8
Sn-126	98.2				0.2	1.4
I-129	0.1	0.1	0.1		59.8	40.0
Cs-135		0.1			9.2	90.7
Cs-137	42.2				7.5	50.3
Pb-210		0.2	0.5		58.8	40.5
Ra-226	6.8	0.3		89.3	1.0	2.6
Ac-227	0.3	16.4	42.8		34.8	5.6
Th-229	3.1	71.5	12.6		8.7	4.0
Th-230	5.7	13.6	2.2	74.3	1.4	2.6
Th-232[a]	25.2	53.4	8.9		8.2	4.3
Pa-231	1.3	84.5	2.6		7.8	3.8
U-232[a]	12.4	20.0	34.2		26.8	6.7
U-233	1.4	66.4	15.3		12.1	5.0
U-234	0.4	50.2	21.5	4.8	17.1	5.9
U-236		52.7	22.9		18.1	6.4
U-238	3.8	49.9	21.7		18.2	6.5
Np-237	2.6	21.8	15.4		46.9	13.2
Pu-238		20.2	16.5		50.0	13.1
Pu-239		52.1	9.2		28.2	10.5
Pu-240		51.1	9.5		28.9	10.5
Pu-242		52.6	9.2		27.8	10.3
Am-241	0.1	37.8	12.9		39.2	9.9
Am-243	5.6	48.4	9.2		28.1	8.6

Source: BSC 2003g, Table 6-2.10.

NOTES: Entries shown by a blank are less than 0.05 percent.
[a]Th-232 includes contribution from Ra-228 and Th-228; U-232 includes contribution from Th-228.

Table 6-3. Relative Contribution of Ingestion Pathways Excluding Water for the Current Climate

Radionuclide	Overall Ingestion	Crops	Animal Products	Fish	Soil
C-14	83.2	21.5	16.6	45.1	
Cl-36	88.2	28.6	47.6	12.0	
Se-79	90.2	3.0	82.9	3.7	0.6
Sr-90	30.9	17.2	8.1	5.2	0.4
Tc-99	50.8	21.9	27.3	1.6	
Sn-126	1.4		0.4	1.0	
I-129	40.0	6.7	27.2	5.3	0.8
Cs-135	90.7	6.8	26.9	55.9	1.1
Cs-137	50.3	1.0	3.8	45.4	0.1
Pb-210	40.5	5.7	1.8	32.6	0.4
Ra-226	2.6	1.0	0.9	0.1	0.6
Ac-227	5.6	3.0	0.1	2.3	0.2
Th-229	4.0	1.0	0.2	1.9	0.9
Th-230	2.6	0.9	0.8	0.3	0.6
Th-232[a]	4.3	1.6	0.2	1.6	0.9
Pa-231	3.8	1.7	0.1	0.2	1.8
U-232[a]	6.7	2.4	1.2	2.8	0.3
U-233	5.0	1.6	2.1	0.4	0.9
U-234	5.9	1.9	2.8	0.5	0.7
U-236	6.4	2.0	3.0	0.6	0.8
U-238	6.5	2.0	3.1	0.6	0.8
Np-237	13.2	8.1	0.8	3.1	1.2
Pu-238	13.1	4.6		7.4	1.1
Pu-239	10.5	3.3	0.1	4.2	2.9
Pu-240	10.5	3.3	0.1	4.3	2.8
Pu-242	10.3	3.2	0.1	4.1	2.9
Am-241	9.9	4.0	0.1	3.7	2.1
Am-243	8.6	3.2	0.1	2.6	2.7

Source: BSC 2003g, Table 6.2-10.

NOTES: Entries shown by a blank are less than 0.05 percent.

[a] Th-232 includes contribution from Ra-228 and Th-228; U-232 includes contribution from Th-228.

6.2 VOLCANIC SCENARIO

For the volcanic ash exposure scenario, the ERMYN model provides three BDCF components for each radionuclide, the critical thickness, and two functions (mass loading time function and ash depth function). The results of the BDCF calculations are in the format of row vectors, one for each model realization, consisting of three BDCF components for each of the 23 primary radionuclides (i.e., 69 BDCF components per vector) and the critical thickness. The BDCFs are used in the TSPA model to calculate the expected dose during the post-eruptive phase (Section 6.2.1). In addition, dose factors are provided to calculate the dose during the eruptive phase (Section 6.2.2).

6.2.1 Post-Eruptive Phase Biosphere Dose Conversion Factors

The dose for the post-eruptive phase is calculated in the TSPA model as discussed in Section 5.8. Three BDCF components are required to calculate annual dose for each radionuclide. Typical results of mean BDCF values are provided in Table 6-4 (BSC 2003h). For actinides, the dose is dominated by the inhalation component, while for Strontium-90 and Cesium-137 the other pathways dominate the dose.

Table 6-4. Representative Biosphere Dose Conversion Factors for the Volcanic Ash Scenario

	BDCF Component	Mean (rem/y per pCi/m^2)	Standard Deviation (rem/y per pCi/m^2)
Sr-90	Ingestion, External, Radon	2.11E-09	1.68E-09
	Inhalation Short-term	5.27E-10	3.19E-10
	Inhalation Long-term	1.06E-09	6.52E-10
Cs-137	Ingestion, External, Radon	2.67E-08	5.53E-10
	Inhalation Short-term	6.79E-11	4.11E-11
	Inhalation Long-term	1.37E-10	8.40E-11
Np-237	Ingestion, External, Radon	2.06E-08	2.30E-08
	Inhalation Short-term	1.15E-06	6.95E-07
	Inhalation Long-term	2.31E-06	1.42E-06
Pu-239	Ingestion, External, Radon	1.24E-09	1.58E-09
	Inhalation Short-term	9.12E-07	5.52E-07
	Inhalation Long-term	1.84E-06	1.13E-06
Am-241	Ingestion, External, Radon	2.08E-09	1.63E-09
	Inhalation Short-term	9.44E-07	5.71E-07
	Inhalation Long-term	1.90E-06	1.17E-06

Source: BSC 2003h, Tables 6.2-1, 6.2-2, and 6.2-3.

NOTE: To convert from rem/year per pCi/m^2 to Sv/year per Bq/m^2 divide by 3.7.

The distributions for the short-term and long-term inhalation components are only influenced by input parameters that are not radionuclide specific (e.g., mass loading). Therefore, the shape of these distributions is the same for all radionuclides. The cumulative distribution functions of BDCFs, normalized to mean values, for the inhalation BDCF component are shown in Figure 6-2. The similarity of the two curves indicates that there is little difference between the inhalation exposure scenarios for the long and short term components.

The BDCF contributions for ingestion and external exposure are radionuclide specific. Differences are illustrated in Figure 6-3 for five radionuclides. The dominant contribution for Cesium-137 is from external exposure (Table 6-5) and there is very little variation in BDCFs for this radionuclide. For the other radionuclides, inhalation is much more important than external exposure or ingestion (Table 6-5) and there is about a factor of two to three difference between the mean values and the lower and upper ends of the distributions.

The fractional contribution of pathways to the BDCF for each radionuclide the first year after a volcanic eruption that results in a thickness of ash equal to the critical thickness (as discussed in

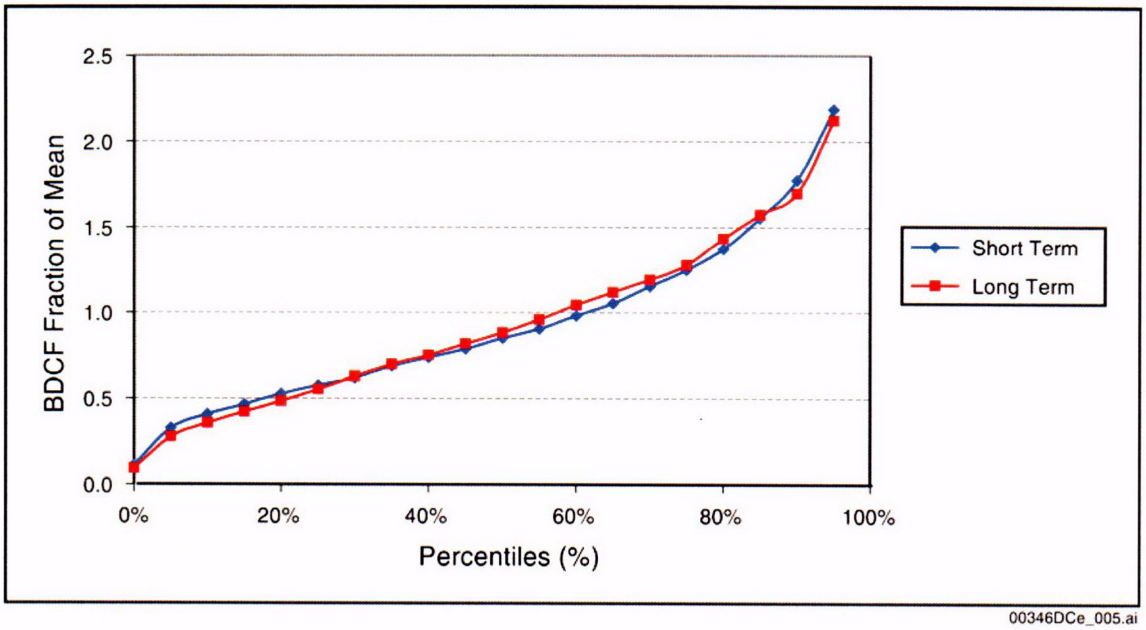
Section 5.1) is given in Table 6-5. The dominant pathway for isotopes of actinides is inhalation, with the long-term component contributing about two-thirds of the dose and the short-term component contributing about one-third of the dose. The pathway contributions for the other radionuclides are more diverse. For example, the food consumption pathways are dominant for Technetium-99 and the external exposure pathway is dominant for Cesium-137.

Table 6-5. Relative Contribution of Exposure Pathways per Radionuclides to Biosphere Dose Conversion Factors the First Year Following a Volcanic Eruption

Radionuclide	External	Inhalation (Short-term)	Inhalation (Long-term)	Radon	Ingestion inc. Soil
^{90}Sr	7.2	14.2	28.7		49.9
^{99}Tc	0.3	2.7	5.4		91.5
^{126}Sn	99.2	0.2	0.5		0.1
^{137}Cs	98.2	0.3	0.5		1.0
^{210}Pb	0.1	31.7	63.9		4.3
^{226}Ra	36.6	8.4	17.0	37.5	0.4
^{227}Ac		33.1	66.8		
^{229}Th	0.1	33.1	66.8		
^{230}Th		33.2	66.8		
^{232}Th	0.9	32.9	66.2		
^{231}Pa		33.1	66.8		
^{232}U	1.0	32.8	66.1		
^{233}U		33.2	66.8		
^{234}U		33.2	66.8		
^{236}U		33.2	66.8		
^{238}U	0.2	33.1	66.7		
^{237}Np	0.3	33.0	66.4		0.2
^{238}Pu		33.1	66.8		
^{239}Pu		33.1	66.8		
^{240}Pu		33.1	66.8		
^{242}Pu		33.1	66.8		
^{241}Am		33.1	66.8		
^{243}Am	0.4	33.0	66.6		

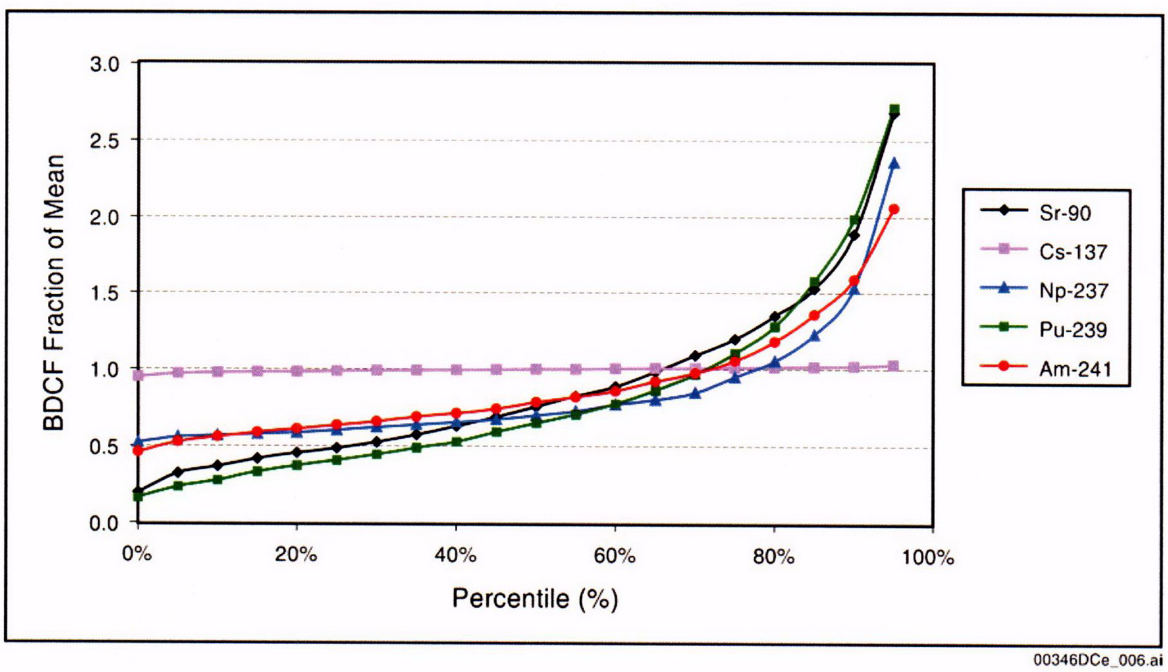
Source: Adapted from BSC 2003h, Table 6.2-7.

NOTE : Entries shown by a blank are less than 0.05 percent.



Source: Based on data from DTN: MO0307MWDDEBDC.001 (see Rautenstrauch 2003).

Figure 6-2. Normalized Distributions of Inhalation Biosphere Dose Conversion Factors for Long-Term and Short-Term Inhalation Components



Source: Based on data from DTN: MO0307MWDDEBDC.001 (see Rautenstrauch 2003).

Figure 6-3. Normalized Distributions of Non-Inhalation Biosphere Dose Conversion Factors for Five Selected Radionuclides

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6.2.2 Eruptive Phase Dose Factors

Dose factors were developed for the eruption phase, rather than the BDCFs, because BDCFs are developed for annual exposures and do not address the relatively short-term exposure conditions that occur during a volcanic eruption. The dose factor for a given primary radionuclide is numerically equal to the dose resulting from a one-day intake of this radionuclide (and associated short-lived decay products, if present) by inhaling air containing a unit activity concentration of the radionuclide under consideration (1 Bq/m^3). Radionuclide intake depends on inhalation exposure time and breathing rate (BSC 2003h, Section 6.3).

For calculating the inhalation dose, the exposure times for different population groups and environments, as well as the associated breathing rates, were developed (BSC 2003h, Section 6.3.2). It was postulated that, for the duration of volcanic eruption, human breathing rates and the fractions of time spent indoors versus outdoors remain relatively unchanged compared to the pre-eruption conditions. Therefore, parameter values for lifestyle characteristics used to develop dose factors for the eruption phase were the same as those used for the BDCF calculations. The dose factors for radionuclides of interest for the volcanic ash scenario are summarized in Table 6-6.

6.3 SUMMARY OF THE BIOSPHERE TRANSPORT MODEL

This report synthesizes the methods and data used to model the transport of radionuclides within the biosphere and calculate exposure to a human receptor. It also summarizes the results of the biosphere model used in the assessment of postclosure performance of a geological repository at Yucca Mountain.

The biosphere model has been substantially modified since the site recommendation. It includes all radionuclide transport pathways that could contribute substantially to human exposure following the release of radionuclides from a repository at Yucca Mountain. Concentrations of radionuclides are calculated for soil, air, crops, animal products, and fish. Exposure pathways included are external exposure to soil; inhalation exposure to resuspended particles, aerosols from evaporative coolers, and radioactive gasses; and ingestion of water, fruits, vegetables, grains, animal products, fish, and soil. The input parameters used to calculate these concentrations and receptor exposure are based on site-specific information or analog data when possible and are sampled as distributions to propagate uncertainty and variation in the parameter values. When required separate sets of input parameters are used for current and future climate states.

The biosphere model calculates the annual dose to the receptor per unit concentration of radionuclides (BDCFs) in groundwater and volcanic ash. These BDCFs are combined in the TSPA with estimates of radionuclide concentrations in groundwater or ash to calculate the potential annual dose resulting from the release of radionuclides to groundwater or from a volcanic eruption at Yucca Mountain. Propagation of uncertainty and variability in the input parameters through the biosphere model results in BDCF distributions with ninety percent or more of values within a range of an order of magnitude or less. BDCF values for the coolest climate predicted to occur at Yucca Mountain over the next 10,000 years (glacial transition) are about 4 to 26 percent lower than those for the current climate. For the groundwater scenario,

ingestion or inhalation are the most important pathways for most radionuclides. For the volcanic ash scenario, inhalation of resuspended particulates is the most important exposure pathway for most radionuclides, although ingestion or external exposure is important for a few radionuclides.

Table 6-6. Dose Factors for the Eruptive Phase of the Volcanic Scenario

Radionuclide	Effective Dose Conversion Factor (Sv/Bq)	Dose Factor	
		Sv/d per Bq/m^3	rem/d per pCi/m^3
^{90}Sr	6.70E-08	6.65E-07	2.46E-06
^{99}Tc	2.25E-09	2.23E-08	8.26E-08
^{126}Sn	2.74E-08	2.72E-07	1.01E-06
^{137}Cs	8.63E-09	8.56E-08	3.17E-07
^{210}Pb	6.26E-06	6.21E-05	2.30E-04
^{226}Ra	2.32E-06	2.30E-05	8.51E-05
^{227}Ac	1.82E-03	1.81E-02	6.68E-02
^{229}Th	5.85E-04	5.80E-03	2.15E-02
^{230}Th	8.80E-05	8.73E-04	3.23E-03
^{232}Th [a]	5.38E-04	5.33E-03	1.97E-02
^{231}Pa	3.47E-04	3.44E-03	1.27E-02
^{232}U [a]	2.71E-04	2.69E-03	9.95E-03
^{233}U	3.66E-05	3.63E-04	1.34E-03
^{234}U	3.58E-05	3.55E-04	1.31E-03
^{236}U	3.39E-05	3.36E-04	1.24E-03
^{238}U	3.20E-05	3.17E-04	1.17E-03
^{237}Np	1.46E-04	1.45E-03	5.36E-03
^{238}Pu	1.06E-04	1.05E-03	3.89E-03
^{239}Pu	1.16E-04	1.15E-03	4.26E-03
^{240}Pu	1.16E-04	1.15E-03	4.26E-03
^{242}Pu	1.11E-04	1.10E-03	4.07E-03
^{241}Am	1.20E-04	1.19E-03	4.40E-03
^{243}Am	1.19E-04	1.18E-03	4.37E-03

Source: BSC 2003h, Table 6.3-3.

NOTE: [a] Th-232 includes contribution from Ra-228 and Th-228; U-232 includes contribution from Th-228.

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7.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Readily available.

7.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

MO0307MWDDEBDC.001. Disruptive Event Biosphere Dose Conversion Factors. Submittal date: 07/08/2003.

MO0307MWDNPBDC.001. Nominal Performance Biosphere Dose Conversion Factors. Submittal date: 07/08/2003.

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APPENDIX A

SURFACE-DISTURBING ACTIVITIES (RESPONSE TO IA 2.11)

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application (LA) as the approved analyses of record at the time of LA submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

APPENDIX A

SURFACE-DISTURBING ACTIVITIES (RESPONSE TO IA 2.11)

This appendix provides a response to igneous activity (IA) key technical issue (KTI) IA 2.11. This KTI agreement requires clarification of how the methods used to estimate concentrations of resuspended volcanic ash particles (i.e., mass loading) are appropriate for the expected types of activities that would result in ash resuspension.

A.1 KEY TECHNICAL ISSUE AGREEMENT

A.1.1 IA 2.11

KTI agreement IA 2.11 was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on IA held June 21–22, 2001 (Reamer 2001) in Las Vegas, Nevada, which was convened primarily to discuss IA KTI Subissue 2, Consequences of Future Igneous Activity. Preliminary discussions of these issues had taken place at an Appendix 7 meeting in Las Vegas, Nevada, on May 18, 2001 (Crump 2001). During the Technical Exchange, six biosphere KTI agreements were reached, IA 2.11 through IA 2.16. An additional agreement from this Technical Exchange, IA 2.17, covers related aspects of biosphere, volcanic events, and performance assessment analyses. A prior agreement, IA 2.07 from the NRC/DOE Technical Exchange and Management Meeting on IA held on August 29–31, 2000 (Reamer and Williams 2000), was superceded and is considered complete by NRC staff as a result of the new agreements IA 2.11 through IA 2.16 from the June 2001 meeting.

Wording of the agreement is as follows:

> Provide an analysis that shows the relationship between any static measurements used in the TSPA and expected types and durations of surface disturbing activities associated with the habits and lifestyles of the critical group. DOE will provide an analysis that shows the relationship between any static measurements used in the TSPA and expected types and durations of surface disturbing activities associated with the habits and lifestyles of the critical group in a subsequent revision to the AMR Input Parameter Values for External and Inhalation Radiation Exposure Analysis (ANL-MGR-MD-000001) or equivalent document. This will be available to the NRC in FY02.

A.1.2 Related Key Technical Issue Agreements

The following KTI agreements cover material related to agreement IA 2.11:

- IA 2.12 addresses extrapolation of measurements of concentrations of particles smaller than 10 microns to concentrations of total suspended particles under both static and disturbed conditions. This agreement item is complete (Schlueter 2002).

- IA 2.14, which addresses the method used to calculate how deposit thickness affects the average mass load over the transition period, is addressed in Appendix B.

- IA 2.17 pertains to the assumption made in the calculation of radionuclide concentrations in air for the total system performance assessment (TSPA) for the site recommendation that soil in the air and soil on the ground have equivalent concentrations of radionuclides. This agreement is to be addressed as part of the volcanic events response group.

A.2 RELEVANCE TO REPOSITORY PERFORMANCE

This agreement is based on a concern by the NRC that static measurements of resuspended particle concentrations used to develop mass loading distributions for the biosphere model for the site recommendation are not representative of concentrations that would occur during soil-disturbing activities such as farming (NRC 2002, Section 3.3.13.4). Static measurements of resuspended particle concentrations are taken at stationary monitoring sites centrally located in the community or environment being monitored. Measurements from these sites generally are representative of regional air quality conditions, but they may not be representative of conditions in the immediate vicinity of activities that disturb soil or otherwise result in the resuspension of particles. Therefore, using static measurements may result in an underestimate of mass loading concentrations (and, therefore, the dose) for a receptor such as a farmer that spends a substantial amount of time conducting surface-disturbing activities.

Mass loading quantifies the mass concentration of resuspended particles and is used in the biosphere model to calculate activity concentrations of airborne radionuclides. These radionuclide concentrations are then used to calculate the dose due to inhalation of resuspended particles (see Sections 4.2 and 5.2). For the volcanic ash scenario, the dominant pathway for isotopes of actinides is inhalation, and mass loading is a significant contributor to the biosphere dose conversion factors (BDCFs) for those radionuclides (CRWMS M&O 2000a, Section 6.3.2 and 6.3.3; BSC 2003a, Section 6.2.5). Inhalation of particulate matter also is an important pathway for the groundwater scenario for some radionuclides (BSC 2003b, Section 6.2.5).

A.3 RESPONSE

The methods used to calculate airborne radionuclide concentrations and inhalation exposure in the biosphere model for the license application (BSC 2003c) have been substantially modified since the site recommendation. This was done in part to better incorporate variation and uncertainty in the types and durations of activities associated with the habits and lifestyles of the receptor. In the revised model, the biosphere is divided into five environments; separate distributions of mass loading are used for each environment (see Section 4.2). The duration of surface-disturbing activities is incorporated into estimates of exposure times, not mass loading as was done in the site recommendation model. This approach results in appropriate use of static measurements only for the environments to which they best apply. Static measurements are used primarily to estimate mass loading in environments with no associated surface-disturbing activities and to estimate relative spatial and temporal changes in mass loading. Measurements of personal exposure to resuspended particles taken during surface-disturbing activities similar to those that occur in Amargosa Valley are used to estimate mass loading in environments where

the receptor would be active and causing the resuspension of soil particles (BSC 2003d, Section 6). Thus, static measurements of particle concentrations used in the TSPA are appropriately related to the expected types of activities associated with the habits and lifestyles of the receptor. The scope of information in this report provides a complete response to agreement IA 2.11.

A.4 BASIS FOR THE RESPONSE

Static measurements of resuspended particle concentrations are taken at stationary monitoring sites centrally located in the environment being monitored (e.g., community or building). In contrast, measurements of personal exposure to resuspended particles are taken using portable monitoring equipment with the inlet of the sampling device located close to the head of the person being monitored. Measurements of personal exposure are more appropriate than static measurements for estimating particle inhalation when people are active and causing the resuspension of dust; however, static measurements are appropriate when people are inactive or in environments having no internal or nearby sources of resuspended particles (Mage 1985; Clayton et al. 1993; Linn et al. 1999; Evans et al. 2000; Monn 2001).

For the site recommendation biosphere model, separate distributions of mass loading were used for the groundwater and volcanic ash exposure scenarios, and those distributions were intended to be representative of average conditions in the biosphere. The distribution for the groundwater exposure scenario (normal distribution, average = 0.105 mg/m^3, range = 0.038 to 0.173 mg/m^3) was developed based on airborne particle concentrations measured at five pollution monitoring stations in rural agricultural settings. The monitoring sites were centrally located in rural communities or farming areas; therefore, they were representative of static conditions (CRWMS M&O 2000b, Section 6.1.1). The mass loading distribution used for the volcanic eruption scenario (log uniform distribution, average = 0.864 mg/m^3, range = 0.105 to 3.0 mg/m^3) was based in part on static measurements taken at community monitoring sites in Washington before and after the eruption of Mount St. Helens (CRWMS M&O 2000b, Sections 5.1 and 6.1.2).

As described in Section 4, the biosphere model for the license application uses a microenvironmental modeling approach to calculate inhalation and external exposure. This method is used to better incorporate variation and uncertainty in the types and duration of activities associated with the habits and lifestyles of the receptor (BSC 2003c, Sections 6.4 and 6.5). The biosphere is divided into five environments (active outdoors, inactive outdoors, active indoors, asleep indoors, and away from the environment containing radioncuclides) within which a receptor may experience substantially different rates of inhalation or external exposure, as described in the *Biosphere Model Report* (BSC 2003c, Section 6.4.2.1). The inhalation dose is calculated as the product of radionuclide concentrations in the air, exposure times within each environment, environment-specific breathing rates, and dose conversion factors applicable to all environments (Sections 4.8 and 5.6). Using this approach, estimates of mass loading are more clearly associated with the types of surface-disturbing activities expected within the environments (BSC 2003d, Section 6), and consideration of the expected duration of those activities is incorporated into estimates of exposure times (BSC 2003e, Section 6.3.2). All parameter estimates developed for the license application are based on a reasonably maximally exposed individual, not the critical group referenced in IA 2.11. This was done to comply with 10 CFR 63.311 and 10 CFR 63.312.

Two sets of mass loading distributions are required for the two biosphere exposure scenarios considered in the biosphere model (Sections 4.2 and 5.2). The first is representative of nominal conditions when no volcanic ash is present in the environment or when volcanic ash has been stabilized or removed and no longer affects resuspended particle concentrations. This distribution is used for the groundwater scenario. It is also used for the volcanic ash scenario for the period after a volcanic event when mass loading has returned to pre-eruption levels. The second set is representative of conditions during the first year following a volcanic eruption at Yucca Mountain. In addition, a mass loading time function is required in the TSPA model to characterize the decrease in mass loading from first-year conditions to nominal conditions. The mass loading decrease constant controls the rate at which that decrease occurs. Distributions of mass loading (Table A-1) and the mass loading decrease constant were developed in the *Inhalation Exposure Input Parameters for the Biosphere Model* report (BSC 2003d) and are summarized in Sections 4.2, 5.2, and 5.8.

Table A-1. Mass Loading Distributions (mg/m^3) Used in the Biosphere Model

Condition	Environment	Type of Distribution	Mode	Minimum	Maximum
Nominal	Active Outdoors	Triangular	5.000	1.000	10.000
	Inactive Outdoors	Triangular	0.060	0.025	0.100
	Active Indoors	Triangular	0.100	0.060	0.175
	Asleep Indoors	Triangular	0.030	0.010	0.050
Postvolcanic [a]	Active Outdoors	Triangular	7.500	1.000	15.000
	Inactive Outdoors	Triangular	0.120	0.050	0.300
	Active Indoors	Triangular	0.200	0.120	0.350
	Asleep Indoors	Triangular	0.060	0.020	0.110

Source: Modified from BSC 2003d, Sections 6 and 7.

NOTES: [a] Distributions for postvolcanic conditions are presented here as the total concentrations of resuspended ash and soil the first year following a volcanic eruption. Input distributions of this parameter used in the biosphere model only include the increase in mass loading the first year following an eruption.

The microenvironmental modeling approach allows for appropriate use of static and personal exposure measurements. Measurements of personal exposure to resuspended particles were used primarily to develop the distributions of mass loading during soil-disturbing activities. For example, only published measurements of personal exposure taken during studies of dust-disturbing activities such as farming (e.g., Clausnitzer and Singer 1997; Molocznik and Zagorski 1998; Nieuwenhuijsen et al. 1999) were used to develop distributions for the nominal and postvolcanic active outdoor environments (BSC 2003d, Sections 6.1.1 and 6.2.1). The selected distribution, which ranges from 1 to 10 mg/m^3 for nominal conditions (Table A-1), encompasses average concentrations for most activities evaluated in those studies. The distribution for this environment is greater than those for other environments (Table A-1) and has the greatest influence on estimates of the total mass of resuspended particles inhaled (BSC 2003d, Appendix A). In addition, the primary sources of information used to develop distributions of mass loading for the active indoor environment were published measurements of personal exposure to resuspended particles taken while people were active indoors (BSC 2003d, Sections 6.1.3 and 6.2.3).

As described and justified below, static measurements were used to develop distributions for the inactive outdoor environment, supplement personal exposure measurements considered for indoor environments, and predict changes in mass loading following a volcanic eruption.

Inactive Outdoor Environment–Static measurements of total suspended particles taken at 21 rural agricultural monitoring stations were used to develop the distribution of mass loading for the inactive outdoor environment for nominal conditions (BSC 2003d, Section 6.1.2). Annual average concentrations of total suspended particles for rural agricultural monitoring stations were obtained from the U.S. Environmental Protection Agency, Office of Air Quality and Standards AirData database (BSC 2003d, Section 4.1.2). The 21 monitoring sites were located in 7 western states and had an annual average precipitation of less than 20 inches. These data are appropriate because the conditions under which they were collected are the same as those that would be experienced by a person who is outdoors and not conducting surface-disturbing or other activities that would resuspend soil.

Indoor Environments–Published static measurements taken in homes, apartments, and offices while people were present and active were evaluated to supplement the personal exposure measurements considered for the active indoor environments and to better understand the range of variability in indoor concentrations (BSC 2003d, Sections 6.1.3 and 6.2.3). The static measurements used are representative of conditions experienced indoors while a person is active or those around that person are active; therefore, they are applicable to this environment.

Personal exposure and static measurements taken indoors while people were sleeping or otherwise inactive were considered for the asleep indoor environment (BSC 2003d, Sections 6.1.4 and 6.2.4). Because this environment only considers the period of time while people are sleeping (and thus there are no nearby sources of resuspended particles), static and personal exposure measurements are equally applicable.

Changes in Mass Loading after a Volcanic Eruption–Static measurements of total suspended particle concentrations recorded before and after the eruption of Mount St. Helens at six monitoring sites were examined to predict changes in mass loading following a volcanic eruption. Measurements of 24-hour concentrations of total suspended particles taken in Washington during 1979 through 1982 were obtained from the U.S. Environmental Protection Agency, Office of Air Quality and Standards AirData database (BSC 2003d, Section 4.1.3). Average annual concentrations the year before and two years following the eruption were calculated to determine the relative change in mass loading following an eruption. Published reports of changes in static measurements following other volcanic eruptions also were reviewed. It was concluded that annual average concentrations no more than doubled following eruptions and that concentrations returned to pre-eruption levels within one year. This information was used with measurements of personal exposure to resuspended particles taken after volcanic eruptions to develop distributions of mass loading for the postvolcanic inactive outdoor and indoor environments (BSC 2003d, Section 6.2). This information also was used to develop the mass loading time function (BSC 2003d, Section 6.3). The static measurements used are applicable because measurements that were not influenced by specific behaviors or activities were required to analyze relative changes in concentrations over time.

Relationship between Indoor and Outdoor Concentrations–Because little information was available on mass loading indoors following a volcanic eruption, it was assumed that changes in outdoor concentrations of mass loading have a proportional effect on mass loading indoors (BSC 2003d, Section 5.2). That assumption was based on an evaluation of 11 published data sets of static measurements of mass loading taken concurrently indoors and outdoors (BSC 2003d, Table 5-1). Static measurements were applicable because relative differences between indoor and outdoor concentrations that were not influenced by specific behaviors or levels of activities, were required for this evaluation. Measurements of personal exposure and static measurements taken indoors following volcanic eruptions were used to confirm the use of this assumption (BSC 2003d, Sections 6.2.3 and 6.2.4).

In summary, the biosphere model for the license application has been modified to better incorporate variation and uncertainty in the types and durations of activities associated with the habits and lifestyles of the receptor. The biosphere is divided into five environments and new estimates of mass loading within those environments have been developed that are based on the habits and lifestyles of the receptor. Estimates of mass loading in active environments were based only on measurements of personal exposure to resuspended particles taken during surface-disturbing activities similar to activities that occur in the Amargosa Valley. Static measurements were used to estimate mass loading in environments with no associated surface-disturbing activities and to estimate relative spatial and temporal changes in mass loading. The duration of surface-disturbing and other activities conducted by the receptor are incorporated into estimates of exposure time.

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APPENDIX B

MASS LOADING AND ASH DEPTH (RESPONSE TO IA 2.14)

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application (LA) as the approved analyses of record at the time of LA submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

APPENDIX B

MASS LOADING AND ASH DEPTH (RESPONSE TO IA 2.14)

This appendix provides a response to igneous activity (IA) key technical issue (KTI) IA 2.14. This KTI agreement requests more information about how the effects of the depth of ash deposits are considered in the analysis of concentrations of resuspended ash particles (i.e., mass loading).

B.1 KEY TECHNICAL ISSUE AGREEMENT

B.1.1 IA 2.14

The KTI agreement was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on Igneous Activity held June 21 to 22, 2001 (Reamer 2001) in Las Vegas, Nevada, which was convened primarily to discuss IA KTI subissue 2, Consequences of Future Igneous Activity. Preliminary discussions of these issues had taken place at an Appendix 7 meeting in Las Vegas, Nevada, on May 18, 2001 (Crump 2001). During the Technical Exchange, six KTI agreements were reached, IA 2.11 through IA 2.16. An additional agreement from this Technical Exchange, IA 2.17, covers related aspects of biosphere, volcanic events, and performance assessment analyses. A prior agreement, IA 2.07 from the NRC/DOE Technical Exchange and Management Meeting on IA held on August 29 to 31, 2000 (Reamer and Williams 2000), was superceded and is considered complete by NRC staff as a result of the new agreements IA 2.11 through IA 2.16 from the June 2001 meeting.

Wording of the agreement is as follows:

> Provide information clarifying the method used in TSPA to calculate how deposit thickness effects the average mass load over the transition period. DOE will provide information clarifying the method used in TSPA to calculate how deposit thickness effects the average mass load over the transition period in a subsequent revision to the AMR Input Parameter Values for External and Inhalation Radiation Exposure Analysis (ANL-MGR-MD-000001) or equivalent document. This will be available to the NRC in FY02.

B.1.2 Related Key Technical Issue Agreements

The following KTI agreements cover material related to agreement IA 2.14:

- IA 2.11 addresses how the methods used to estimate concentrations of resuspended volcanic ash are appropriate for the expected types of surface-disturbing activities. This agreement is discussed in Appendix A.

- IA 2.12 addresses extrapolation of measurements of concentrations of particles smaller than 10 microns to concentrations of total suspended particles under both static and disturbed conditions. This agreement item is complete (Schlueter 2002).

- IA 2.17 pertains to the assumption made in the calculation of radionuclide concentrations in air for the total system performance assessment (TSPA) for the site recommendation that soil in the air and soil on the ground have equivalent concentrations of radionuclides. This agreement is to be addressed in an appendix to be submitted as part of the volcanic events response group.

B.2 RELEVANCE TO REPOSITORY PERFORMANCE

This agreement item requires an explanation of the methods used to model the effects of tephra-deposit thickness on concentrations of resuspended particles (i.e., atmospheric mass loading). This item is based on the concern by the NRC that the mass loading distribution used for the site recommendation and the associated methods used to model decreases in mass loading following a volcanic eruption do not adequately incorporate variation and uncertainty due to the thickness of the tephra deposit at the location of the receptor. Specifically, the NRC was concerned that the distribution of mass loading used was not representative of conditions that would occur over a thick deposit, and that the methods used to account for decreases over time involved combining temporal variation with data uncertainty and were based on an assumption that mass loading would be proportional to thickness (NRC 2002, Section 3.3.13.4).

The mass loading input parameter quantifies the mass concentration of resuspended particles and is used in the biosphere model to calculate the concentration of radionuclides in air (see Sections 4.2 and 5.2). These radionuclide concentrations are then used to calculate exposure due to inhalation of resuspended particles. Radionuclide concentrations in the air are also used to calculate deposition of particulates on crop surfaces (Section 4.3); however, this environmental transport pathway is outside the scope of this agreement item. For the volcanic ash scenario, the dominant pathway for isotopes of actinides is inhalation, and mass loading is a significant contributor to the biosphere dose conversion factors (BDCFs) for those radionuclides (CRWMS M&O 2000a, Section 6.3.2 and 6.3.3; BSC 2003a, Section 6.2.5). Inhalation of particulate matter also is an important pathway for the groundwater scenario for some radionuclides (BSC 2003b, Section 6.2.5).

B.3 RESPONSE

The methods used in the TSPA to calculate dose following a volcanic eruption have been substantially revised. The most important change relevant to this issue is that the influence of ash depth on initial mass loading, the proportion of particles that are radioactive, and the rate of decrease of mass loading now are considered separately in the TSPA. This revised modeling approach is summarized in Section 5 and described in detail in the *Biosphere Model Report* (BSC 2003c, Sections 6.3.2 and 6.5).

Revised distributions of mass loading have been developed to support the current modeling approach. The set of distributions representative of the increase in mass loading the first year following an eruption were developed primarily based on analog sites having 1 to 10 mm of ash and a climate similar to that predicted for the Yucca Mountain region in the future. To account for the effects of deeper tephra deposits and other sources of uncertainty, maximum values selected for these distributions are higher than atmospheric concentrations of particulates measured for postvolcanic conditions at analog sites. A new parameter, the mass loading

decrease constant, has been defined to control the rate of decrease in mass loading following an eruption. Separate distributions of that parameter were developed for predicted tephra deposits less than 10 mm and greater than or equal to 10 mm in thickness. Modal and minimum rates of decrease lower than those measured at analog sites were selected for these distributions to account for uncertainty about the effects of ash depth and other factors that would influence the rate at which mass loading would return to pre-eruption levels. These distributions are described in *Inhalation Exposure Input Parameters for the Biosphere Model* (BSC 2003d, Sections 6.2 and 6.3).

Because the various effects of tephra-deposit thickness on mass loading are now separately modeled in the TSPA, and because distributions of mass loading and the mass loading decrease constant incorporate uncertainty due to deposit thickness, the information in this report provides a complete response to agreement IA 2.14.

B.4 BASIS FOR THE RESPONSE

In the TSPA for the site recommendation (CRWMS M&O 2000b, Section 3.10.3.1), the effects of tephra-deposit thickness on initial concentrations of airborne particles and changes in concentrations through time were combined into the distributions of mass loading and associated BDCFs. The set of BDCFs used in that TSPA for the volcanic scenario were developed using a distribution of mass loading based on an exponential decrease in particle concentrations from 3 mg/m^3 to 0.1 mg/m^3 over 10 years (CRWMS M&O 2000c, Section 6.1). Although intended to represent mass loading associated with the maximum predicted ash depths for the first 10 years following an eruption, this set was used conservatively in the TSPA for the site recommendation for the entire calculation period following an eruption (CRWMS M&O 2000b, Table 3.10-7). A second distribution of mass loading was developed to represent average conditions for all predicted ash depths during the 10 years following an eruption. That distribution was log-uniform with a minimum equal to average nominal conditions of 0.1 mg/m^3 (i.e., very shallow tephra deposit with no influence on mass loading) and a maximum of 0.864 mg/m^3, the integrated 10-year average of the distribution for the maximum predicted depth. The distribution was based on an implicit assumption that mass loading is proportional to ash depth. To ensure that the predicted dose was not underestimated, BDCFs based on this distribution of mass loading were not used in the TSPA for the site recommendation.

For the TSPA-LA, the influences of tephra-deposit thickness on initial concentrations of resuspended particulates and their changes through time have been separated. This is done by calculating separate BDCF components for the contributions to dose from radon inhalation, ingestion, and external exposure; inhalation of resuspended particles at elevated, postvolcanic conditions; and inhalation of resuspended particles at nominal (i.e., pre-eruption) conditions (Section 5.8). Both components of the BDCFs for particle inhalation are treated as a function of ash depth, and the postvolcanic inhalation component also is treated as a function of time. Because ash depth and time are tracked in the TSPA, not the biosphere model, the ash depth and mass loading time functions must be executed in TSPA, as shown in Equation B-1 (BSC 2003c, Section 6.5.8.3).

$$D_i(t) = BDCF_i \times Cs_i(t) + \left(BDCF_{inh,v,i} f(t) + BDCF_{inh,p,i}\right) f(d_a) \times Cs_i(t) \qquad \text{(Eq. B-1)}$$

where

$D_i(t)$	=	time-dependent annual dose resulting from the release of radionuclide i from the repository (Sv/year)
$BDCF_i$	=	BDCF for radionuclide i for external exposure, radon inhalation, and ingestion (Sv/year per Bq/m^2)
$BDCF_{inh,v,i}$	=	BDCF for radionuclide i for inhalation of mass loading in addition to nominal mass loading following a volcanic eruption (Sv/year per Bq/m^2)
$BDCF_{inh,p,i}$	=	BDCF for radionuclide i for inhalation of nominal mass loading following a volcanic eruption (Sv/year per Bq/m^2)
$Cs_i(t)$	=	time-dependent activity concentration of radionuclide i in volcanic ash deposited on the ground (Bq/m^2)
$f(t)$	=	mass loading time function
$f(d_a)$	=	ash depth function.

To implement this model, two sets of mass loading distributions, nominal and postvolcanic, are required. The nominal mass loading distributions are estimates of average annual concentrations after the tephra deposit has been stabilized and concentrations of resuspended particles have returned to those prior to the eruption. They are used in the calculation of the long-term inhalation component, $BDCF_{inh,p,i}$. The postvolcanic distributions are estimates of the average annual concentrations during the first year following an eruption and are used to calculate the short-term inhalation component, $BDCF_{inh,v,i}$.

The mass loading time function, $f(t)$, describes the rate of change in mass loading and the associated inhalation dose after a volcanic eruption. This function is implemented in the TSPA, as shown in Equation B-2 (BSC 2003d, Section 6.3; BSC 2003c, Section 6.5.8).

$$BDCF_{inh,v,i}\, f(t) = BDCF_{inh,v,i}\; e^{-\lambda t} \qquad \text{(Eq. B-2)}$$

where

λ	=	mass loading decrease constant (1/year)
t	=	time (years); $t = 0$ is the first year after a volcanic eruption.

The time function applies to the short-term components of the BDCFs ($BDCF_{inh,v,i}$), which represent the contribution to inhalation exposure from elevated resuspended ash concentrations during the first year after an eruption. Thus, this function controls the rate at which the effect of elevated mass loading decreases to zero. After that time, all effects of mass loading on the inhalation exposure are contained in the long-term inhalation component of the BDCFs ($BDCF_{inh,p,i}$) calculated using nominal, pre-eruption concentrations of resuspended particles.

The ash depth function, $f(d_a)$, is used to model the influence of ash depth on concentrations of radionuclides resuspended from noncultivated lands. On these lands, volcanic ash would not quickly mix with surface soil, and the proportion of resuspended particles composed of ash (versus clean soil) would depend on the thickness of the ash deposit. To account for this process, a critical thickness is considered in the biosphere and TSPA models. The critical thickness is the layer from which particles are resuspended, which is, at most, a few millimeters (BSC 2003e, Section 6.8). For an ash layer equal to or thicker than the critical thickness, only ash would be resuspended. For deposits thinner than the critical thickness, the resuspended material would be a mix of ash and clean soil (BSC 2003c, Sections 6.5.1 and 6.5.2). Thus, the ash depth function determines the proportions of resuspended particles that are radioactive, but it does not influence estimates of resuspended particle concentrations. The ash depth function is expressed in the TSPA as shown in Equation B-3 (BSC 2003c, Section 6.5.1).

$$f(d_a) = \begin{cases} 1 & \text{when } d_a < d_c \\ \dfrac{d_c}{d_a} & \text{when } d_a \geq d_c \end{cases} \qquad \text{(Eq. B-3)}$$

where

d_c = critical thickness for resuspension on noncultivated lands (m)

d_a = thickness of ash deposited on the ground (m).

To implement this model, new distributions of mass loading and the mass loading decrease constant were developed, as described in *Inhalation Exposure Input Parameters for the Biosphere Model* (BSC 2003d). As described below, variation and uncertainty related to the influence of ash depth on initial concentrations of resuspended ash particles are incorporated into the distributions of postvolcanic mass loading. Variation and uncertainty about the influence of ash depth on the rate of change in mass loading following an eruption is incorporated into the mass loading decrease constant.

Mass Loading Distributions–The parameter distributions representative of mass loading during the first year following a volcanic eruption were developed primarily from concentrations of resuspended particles measured before and after the eruption of Mount St. Helens. Measurements taken following the eruptions of Mount Spurr (Alaska), Mount Sakurijima (Japan), Soufriere Hills (Montserrat), and Cerro Negro (Nicaragua) also were considered to better understand variation and uncertainty in postvolcanic concentrations of resuspended particles. It was concluded that concentrations of resuspended particles following those eruptions generally were no more than twice as high as pre-eruption levels and that the concentrations returned to pre-eruption levels within one year or less (BSC 2003d, Sections 6.2 and 6.3).

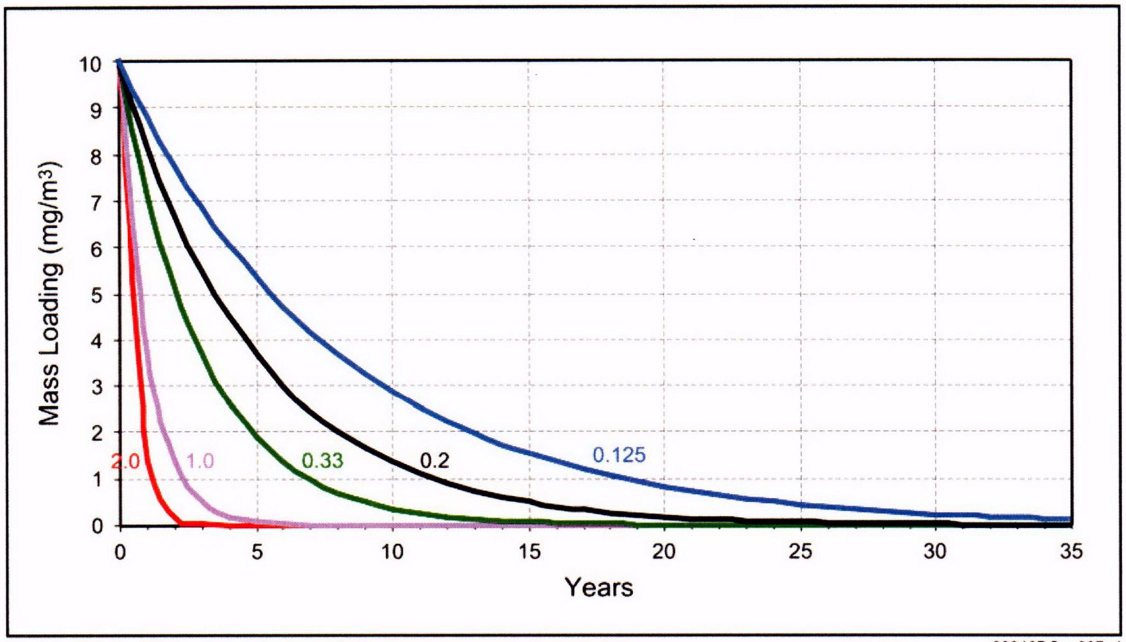
The conditions at the locations where mass loading was measured following the eruption of Mount St. Helens generally are analogous to tephra-deposit thickness and climatic conditions predicted for the area south of Yucca Mountain. Ash thickness ranged from about 1 to 10 mm at four analog sites in eastern Washington from which mass loading measurements were considered (BSC 2003d, Section 6.2.2.3). This is similar to the ash depth predicted during most realizations

of the TSPA for the site recommendation using variable wind directions (CRWMS M&O 2000b, Section 3.10.5.1). The climate at the analog sites in eastern Washington is similar to that predicted to occur at Yucca Mountain over much of the next 10,000 years (USGS 2001, pp. 67 and 74; BSC 2003d, Section 6.3.3). Therefore, the influence of precipitation and vegetation on consolidation and removal of ash after an eruption at Yucca Mountain likely would be similar to what occurred at those sites.

Because none of the analog sites had tephra deposits as thick as the maximum predicted south of Yucca Mountain by the TSPA for the site recommendation (CRWMS M&O 2000b, Section 3.10.5.1), there is uncertainty about the influence of deep deposits on the mass loading for postvolcanic conditions. There also is uncertainty about the predicted maximum depth of tephra deposits at the location of the receptor (because the results of the TSPA for the license application are not yet available) and the influence of redistribution of ash from aeolian and fluvial processes on mass loading (BSC 2003d, Section 6.2.2.3). To account for these sources of uncertainty, the maximum values selected for the mass loading distributions are higher than those indicated from the analog measurements. For example, a maximum mass loading of 15 mg/m^3 was selected for the active outdoor environment even though the maximum concentration measured or anticipated for that environment is about 10 mg/m^3 (BSC 2003d, Section 6.2.1). Similarly, although data from Mount St. Helens and other eruptions indicate that average annual concentrations outdoors during the year following an eruption would be no more than twice as high as those prior to an eruption, a maximum value three times greater than nominal conditions was selected for the inactive outdoor environment (BSC 2003d, Section 6.2.2). Similar distributions were used for indoor environments. Increasing the maximum values of these distributions adequately accounts for these sources of uncertainty and ensures that the influence of tephra-deposit thickness on mass loading is incorporated.

Mass Loading Decrease Constant–To account for uncertainty about how tephra-deposit thickness would influence the rate at which mass loading would decrease following an eruption, separate distributions of the mass loading decrease constant were developed for thin and thick deposits (BSC 2003d, Section 6.3.3). A triangular distribution with a mode of 0.33 per year, maximum of 2.0 per year, and minimum of 0.2 per year was developed for TSPA runs having a predicted ash depth of less than 10 mm. To illustrate differences among these decrease constants, changes in mass loading from a hypothetical initial value of 10 mg/m^3 are plotted for each constant in Figure B-1. The maximum value (i.e., fastest rate of decrease) for this distribution is similar to, or lower than (i.e., slower rate of decrease), that measured following the eruptions of Mount St. Helens, Mount Spurr, and Mount Sakurijima. Also, lower modal and minimum rates of this distribution were selected to account for uncertainty about the influence of the current arid climate, differences in particle size distributions between analog eruptions and that predicted from Yucca Mountain, and the effects of aeolian and fluvial redistribution of ash into the northern Amargosa Valley. For example, the modal value of 0.33 per year corresponds to a rate that takes at least 10 times longer to approach pre-eruption levels, and an average annual concentration over 10 years about six times greater than that of the maximum rate of 2.0 per year. For TSPA runs with predicted ash depths greater than or equal to 10 mm, a triangular distribution with a mode of 0.2 per year, maximum of 1.0 per year, and minimum of 0.125 per year was selected. Because no data were available on the rate of change in mass loading in areas having tephra deposits thicker than 10 mm, this distribution has slower rates than those measured following Mount St. Helens and other eruptions. The modal value of this distribution results in a

decrease in mass loading of about 86 percent in 10 years and 98 percent in 20 years, and it has an average annual concentration over 10 years that is about nine times greater than that predicted from analog data. The minimum value (i.e., slowest rate of decrease) for this distribution results in a decrease of about 71 percent over 10 years and 98 percent over 30 years.



Source: BSC 2003d, Figure 6.3-1.

Figure B-1. Rate of Change in Mass Loading from a Hypothetical Initial Concentration of 10 mg/m^3 for Five Values of the Mass Loading Decrease Constant

In summary, the influence of tephra-deposit thickness on mass loading over the transition period is incorporated into the postvolcanic mass loading distributions and the mass loading decrease constant. These distributions are based on measurements taken over tephra deposits of 10 mm or less. The maximum values selected for the mass loading distributions are higher than measured values to account for the effects of deeper deposits. Separate distributions of the mass loading decrease constant were developed for predicted deposits less than 10 mm and greater than or equal to 10 mm. Minimum rates of decrease lower than those measured at analog sites were selected to account for uncertainty about the effects of ash depth and other factors that would influence the rate at which mass loading would return to pre-eruption levels.

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APPENDIX C

EXTERNAL EXPOSURE
(RESPONSE TO IA 2.15)

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application (LA) as the approved analyses of record at the time of LA submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

APPENDIX C

EXTERNAL EXPOSURE (RESPONSE TO IA 2.15)

This appendix provides a response for igneous activity (IA) key technical issue (KTI) IA 2.15. This KTI agreement requires clarification of how the dose from external exposure to contaminated ash is calculated.

C.1 KEY TECHNICAL ISSUE AGREEMENT

C.1.1 IA 2.15

The KTI agreement was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on Igneous Activity held June 21 to 22, 2001 (Reamer 2001) in Las Vegas, Nevada, which was convened primarily to discuss IA KTI subissue 2, Consequences of Future Igneous Activity. Preliminary discussions of these issues had taken place at an Appendix 7 meeting in Las Vegas, Nevada, on May 18, 2001 (Crump 2001). During the Technical Exchange, six biosphere KTI agreements were reached, IA 2.11 through IA 2.16. An additional agreement from this Technical Exchange, IA 2.17, covers related aspects of biosphere, volcanic events, and performance assessment analyses. A prior agreement, IA 2.07 from the NRC/DOE Technical Exchange and Management Meeting on IA held on August 29-31, 2000 (Reamer and Williams 2000), was superceded and is considered complete by NRC staff as a result of the new agreements IA 2.11 through IA 2.16 from the June 2001 meeting.

Wording of the agreement is as follows:

> Clarify that external exposure from HLW-contaminated ash, in addition to inhalation and ingestion, was considered in the TSPA. Include in this clarification the consideration of external exposure during indoor occupancy times, or provide basis for dwelling shielding from outdoor gamma emitters. DOE will clarify that external exposure from HLW-contaminated ash, in addition to inhalation and ingestion, was considered in the TSPA. DOE will include in this clarification the consideration of external exposure during indoor occupancy times, or provide basis for dwelling shielding from outdoor gamma emitters in a subsequent revision to the AMR Input Parameter Values for External and Inhalation Radiation Exposure Analysis (ANL-MGR-MD-000001) or equivalent document. This will be available to the NRC in FY02.

C.1.2 Related Key Technical Issue Agreements

There are no other KTI agreements that cover material related to agreement IA 2.15.

C.2 RELEVANCE TO REPOSITORY PERFORMANCE

The biosphere model used for the site recommendation included external exposure to ash from a volcanic eruption at Yucca Mountain as one of the exposure pathways; however, only exposure

experienced outdoors was included. Although the external exposure pathway contributes little to the total dose for most radionuclides (CRWMS M&O 2000a, Section 6.3.3), this method may result in underestimating the dose for high-energy gamma-emitting radionuclides. Only a few radionuclides, such as cesium-137 and tin-126, have a high contribution from external exposure pathway (Section 6.2; BSC 2003a, Section 6.2.5).

C.3 RESPONSE

The biosphere model for the license application considers three exposure pathways: external exposure, inhalation, and ingestion (Section 5.5; BSC 2003b). A microenvironmental modeling approach is used to assess external exposure in this model (Sections 4.7 and 5.5). External exposure is calculated as the product of a radionuclide-specific effective dose coefficient, the saturation concentration of the radionuclide in the soil, the average time spent by the reasonably maximally exposed individual in indoor and outdoor environments, and an environment-specific shielding factor. The shielding factor quantifies the effects of shielding from radiation provided by buildings when the receptor is indoors. Values of the shielding factors selected for use in the model range from 0.0 to 0.4 and were developed by the National Council on Radiation Protection and Measurements (NCRP 1999, p. 52 and Appendix C) for persons living in lightly constructed housing. The scope of information provided in this report provides a complete response to agreement IA 2.15.

C.4 BASIS FOR THE RESPONSE

The biosphere model used for the site recommendation (CRWMS M&O 2000b) calculated the dose from external exposure to radionuclides in soil and ash as the product of radionuclide concentrations in soil, exposure time, and radionuclide-specific dose coefficients. The effects of shielding from radiation provided by buildings could only be included by proportionally adjusting the value of one of those three parameters. The distribution of exposure time used to calculate the external exposure dose for the site recommendation included 100 percent of the time spent outdoors and no time spent indoors (CRWMS M&O 2000c, Section 6.4). Thus, it was implicitly assumed that buildings provided 100 percent shielding from external exposure. Although this is not conceptually correct, especially for radionuclides such as cesium-137 that emit high-energy gamma radiation, it likely did not underestimate the total dose because external exposure contributes very little to the total dose for most radionuclides (CRWMS M&O 2000a, Section 6.3.3).

The biosphere model for the license application (BSC 2003b) uses a microenvironmental modeling approach to evaluate external exposure. For this approach, the biosphere is divided into five environments within which a receptor may experience substantially different rates of inhalation and external exposures (active outdoors, inactive outdoors, active indoors, asleep indoors, and away from the area containing radionuclides) (BSC 2003b, Section 6.4.2.1). To calculate exposure time, the receptor population is divided into four groups and the average time spent in the five environments is estimated for each group (Sections 4.7 and 5.5). The annual dose to a receptor from external exposure to a unit concentration of a radionuclide in volcanic ash (Equation C-1; BSC 2003b, Section 6.5.5) is calculated as

$$D_{ext,i} = EDCs_{soil,i}\, Cs_i \sum_n f_{ext,i,n} \left(\sum_m PP_m \left(3600 \times t_{n,m}\right) \right) \qquad \text{(Eq. C-1)}$$

where

$D_{ext,i}$	=	dose from external exposure to radionuclide i in deposited volcanic ash (Sv/year)
$EDCs_{soil,i}$	=	effective dose coefficient for exposure to radionuclide i in soil (Sv/sec per Bq/m^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 the area containing radionuclides
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) (hours/year)
3600	=	unit conversion of hours to seconds.

The equation used for the groundwater scenario is similar to Equation C-1, but the effective dose coefficients are for exposure to soil uniformly contaminated to an infinite depth (BSC 2003b, Section 6.4.7). Effective dose coefficients for long-lived radionuclides tracked in the total system performance assessment include contributions from their short-lived decay products (Section 3.3).

Shielding factors recommended by the National Council on Radiation Protection and Measurements for use in screening models (NCRP 1999, p. 52 and Appendix C) were selected for use in this equation (BSC 2003c, Section 6.6). These shielding factors were developed by the National Council on Radiation Protection and Measurements for a receptor population living in lightly constructed housing. They are appropriate for the Amargosa Valley population because an estimated 89 percent (375 of 422) of occupied housing units in Amargosa Valley during the 2000 Census were mobile homes (Bureau of the Census 2002, Tables H30 and H31). The largest shielding factor of those for the primary radionuclide or its short-lived decay products was selected for each primary radionuclide (BSC 2003c, Table 6.6-1). Values of shielding factors ranged from 0.0 for radionuclides that emit no penetrating radiation (e.g., ^{212}Po and ^{228}Ra) to 0.4 for radionuclides with highly penetrating radiation (gamma emitters of energy greater than 100 keV). These shielding factors (Table C-1) are applied only to indoor environments (i.e., the shielding factors for outdoor environments equal 1.0).

In summary, the biosphere model for the license application calculates the dose from external exposure to radionuclides while the receptor is indoors and outdoors. A shielding factor is included in this calculation to account for the effects of shielding from radiation provided by buildings while the receptor is indoors. Values of the shielding factor used in the model are appropriate for the type of housing in Amargosa Valley.

Table C-1. Shielding Factors for Long-Lived Radionuclides

Primary Radionuclide	Shielding Factor	Primary Radionuclide	Shielding Factor
Carbon-14 (^{14}C)	0.2		
Chlorine-36 (^{36}Cl)	0.4		
Selenium-79 (^{79}Se)	0.1		
Strontium-90 (^{90}Sr)	0.4		
Technetium-99 (^{99}Tc)	0.2		
Tin-126 (^{126}Sn)	0.4		
Iodine-129 (^{129}I)	0.1		
Cesium-135 (^{135}Cs)	0.1		
Cesium-137 (^{137}Cs)	0.4		
Thorium Series (4n)		**Neptunium Series (4n+1)**	
Plutonium-240 (^{240}Pu)	0.1	Americium-241 (^{241}Am)	0.2
Uranium-236 (^{236}U)	0.1	Neptunium-237 (^{237}Np)	0.4
Thorium-232 (^{232}Th)	0.2	Uranium-233 (^{233}U)	0.4
Radium-228 (^{228}Ra)	0.4	Thorium-229 (^{229}Th)	0.4
Uranium-232 (^{232}U)	0.3		
Thorium-228 (^{228}Th)	0.4		
Uranium Series (4n+2)		**Actinium Series (4n+3)**	
Plutonium-242 (^{242}Pu)	0.1	Americium-243 (^{243}Am)	0.4
Uranium-238 (^{238}U)	0.4	Plutonium-239 (^{239}Pu)	0.3
Plutonium-238 (^{238}Pu)	0.1	Protactinium-231 (^{231}Pa)	0.4
Uranium-234 (^{234}U)	0.2	Actinium-227 (^{227}Ac)	0.4
Thorium-230 (^{230}Th)	0.3		
Radium-226 (^{226}Ra)	0.4		
Lead-210 (^{210}Pb)	0.4		

Source: BSC 2003c, Table 6.6-1; NCRP 1999, Appendix C.

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APPENDIX D

SOIL–SORPTION
(RESPONSE TO TSPAI 3.33)

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application (LA) as the approved analyses of record at the time of LA submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

APPENDIX D

SOIL–SORPTION (RESPONSE TO TSPAI 3.33)

This appendix provides a response to total system performance assessment and integration (TSPAI) key technical issue (KTI) TSPAI 3.33. This KTI agreement relates to the justification of the partition coefficient (K_d) values used in the modeling of transport processes in the soil. K_d is the ratio of the quantity of a solute on unit mass of the solid phase to the quantity of the solute in a unit volume of solution (BSC 2003a, Section 4.1.2). As discussed in Section 4.1 and Appendix G, K_d is an element-specific parameter that plays an important role in quantifying the leaching process.

D.1 KEY TECHNICAL ISSUE AGREEMENT

D.1.1 TSPAI 3.33

This KTI agreement was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on TSPAI held August 6–10, 2001 (Reamer 2001) in Las Vegas, Nevada, which was convened to discuss four TSPAI KTI subissues: (1) system description and demonstration of multiple barriers, (2) scenario analysis within the total systems performance assessment (TSPA) methodology, (3) model abstraction within the TSPA methodology, and 4) demonstration of the overall performance objective.

Wording of the agreement is as follows:

> Provide justification that the Kd values used for radionuclides in the soil in Amargosa valley based on the results of a literature review are realistic or conservative for actual conditions at the receptor location (DOSE2.2.1). DOE will provide justification that the Kd values used for radionuclides in the soil in Amargosa Valley are realistic or conservative for actual conditions at the receptor location. The justification will be provided in Evaluate Soil/Radionuclide Removal by Erosion and Leaching AMR (ANL-NBS-MD-000009) or other document expected to be available to NRC in FY 2003.

DOSE2.2.1 in this agreement refers to NRC integrated subissue Dose 2 (NRC 2002, Table 1.1-2).

D.1.2 Related Key Technical Issue Agreements

TSPAI 3.36 provides information on incorporation of uncertainty in the values of the leaching removal constant into the TSPA model. This agreement is addressed in Appendix G.

D.2 RELEVANCE TO REPOSITORY PERFORMANCE

This agreement is based on a concern by the NRC that insufficient justification was provided to support that K_d values developed for the soils in Amargosa Valley are conservative for actual

conditions at the receptor location. The K_d values have a direct influence on the predicted leaching rate and any uncertainties propagate through the model to the total radionuclide removal rate, thereby affecting the predicted concentration of the radionuclide in the surface soil. This process is relevant because, once in the soil, radionuclides are available for transport to other biosphere media and may become part of one or more of the exposure pathways (BSC 2003b, Section 6.3.1.4), thereby having the potential to affect the predicted dose to the receptor. Therefore, distributions of K_d values should be conservative for conditions in Amargosa Valley and should be used in a model that can accommodate these uncertainties (Section 4.1; TSPAI 3.36 is addressed in Appendix G).

The biosphere model for site recommendation, GENII-S (Leigh et al. 1993), used a leaching model based on the approach proposed by Baes and Sharp (1983). Of the parameters required to quantify the leaching process, it was known that the value of the K_d parameter is subject to large uncertainty (BSC 2003a, Section 4.1.2). However, GENII-S could only accommodate a fixed deterministic value of K_d in calculations, so uncertainty in K_d values could not be propagated through the calculation to influence the final biosphere dose conversion factor (BDCF) distributions. Because of the potential importance of the radionuclide concentration in soil for the food and ingestion pathways, the new biosphere model uses a distribution of K_d values to capture the uncertainty in the actual location-specific values.

D.3 RESPONSE

The methods used to calculate radionuclide concentrations in soil in the biosphere model for the license application (BSC 2003b) have been substantially modified since the site recommendation. The biosphere model is implemented using GoldSim Graphical Simulation Environment (GoldSim Technology Group 2002), which provides the capability to perform stochastic simulations by defining any parameter as a distribution. The biosphere model includes a soil submodel (BSC 2003b, Section 6.4.1; see also Section 4.1) that accounts for the addition and removal of radionuclides from surface soil. Removal processes considered are radioactive decay, leaching, and soil removal by erosion. The distributions of K_d values are used to determine the leaching rates of radionuclides from the soil and thus affect the predicted concentration of the radionuclides in soil.

The approach taken to select the K_d values was chosen so that radionuclide concentrations in soil would not be underestimated. The element-specific K_d values and distributions were taken from Sheppard and Thibault (1990, Tables A-1 through A-4). These data were presented for four soil types: sand, loam, clay, and organic. As discussed in *Soil-Related Input Parameters for the Biosphere Model* (BSC 2003a, Section 6.2), the appropriate soil type for Amargosa Valley is between sand and loam. The K_d values showed no systematic change over all elements as the soil type changed from sand to loam (BSC 2003a, Section 6.3). That is, no one soil type always exhibited the higher set of K_d values for all elements.

Higher K_d values lead to lower leaching rates (Section D.4) because a higher K_d implies that a greater fraction of the element originally in solution becomes attached to the soil particles and is not available to be leached out of the surface soil. To avoid the possibility of underestimating the K_d value and, therefore, the radionuclide concentrations in soil, the soil type (sand or loam) with the higher arithmetic mean value of the K_d (assuming a lognormal distribution of the K_d)

was used to represent Amargosa Valley soils. The range of reported K_d values generally covered several orders of magnitude, but the effects of these large variations in the K_d values on BDCFs (and dose) are relatively small (Section D.4).

A further aspect of the conservatism in the model is not related to the values selected for the K_d, but to how the model is implemented. For a given set of parameters (irrigation rate, K_d, overwatering rate, soil density), the effect of repeated irrigation is to increase the activity concentration in soil until saturation (equilibrium) conditions are reached when the inflow of radionuclides is completely balanced by radionuclide losses in the soil layer considered. To eliminate the need to consider a time-dependent solution to the equation describing radionuclide buildup in the soil, a conservative approach was adopted to use the equilibrium solution to the equation. This conservative approximation also permitted decoupling of the biosphere model from TSPA calculations. Furthermore, this approach removed the need to speculate about actual times a given area of agricultural land is subject to continuous irrigation. The conservatism introduced by the saturation approach is considered reasonable to offset any additional uncertainties in the K_d values used, particularly, when the range of variation in K_d values results in small changes to BDCFs (Section D.4).

The implementation of the biosphere model using GoldSim software allowed propagation of parametric uncertainties in the soil submodel. The GENII-S model could only use fixed values (i.e., deterministic data) of parameters that quantified radionuclide leaching from the surface soil. In the current model, parameters that influence radionuclide balance in the surface soil, including the K_d values, are represented by the distribution functions to propagate the uncertainty in the parameter value into the modeling results. This capability of the biosphere model to statistically sample K_ds from the distributions also allowed evaluation of the effect of uncertainty in the K_d values on the BDCF values (Section D.4).

The information in this appendix provides a complete response to agreement TSPAI 3.33.

D.4 BASIS FOR THE RESPONSE

The climate in Amargosa Valley is now, and will be in the future, arid or semiarid. In such a climate, the continuous use of groundwater for irrigation can result in a buildup in the soil of salts that are present in the groundwater. This buildup of salts eventually reduces agricultural efficiency and can inhibit crop growth. To preclude excessive buildup and to keep the land as productive as possible requires a regimen of systematic overwatering to flush (i.e., leach) the solutes from the surface soil. Overwatering will also cause leaching of radionuclides out of the soil where they would otherwise be available to increase ingestion dose (from crop uptake) and inhalation dose (from resuspension of soil containing radionuclides). The degree of leaching of radionuclides from the surface soil is quantified in the surface soil submodel of the biosphere model (Section 4.1) through element-specific leaching removal constants (BSC 2003b, Section 6.4.1.3). The leaching removal constant for a given element is calculated using a relationship developed by Baes and Sharp (1983) as:

$$\lambda_l = \frac{OW}{d \times \theta \left(1 + \frac{\rho}{\theta} K_d\right)} \qquad \text{(Eq. D-1)}$$

where

λ_l	=	average annual leaching removal constant (yr^{-1})
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 in surface soil (Bq/kg_{solid})/(Bq/m^3_{liquid}) = (m^3_{liquid}/kg_{solid})

D.4.1 Selection of the Partition Coefficient Values

As is shown in Equation D-1 and discussed in the *Biosphere Model Report* (BSC 2003b, Section 6.4.1.3), K_d values are required by the biosphere model for determining the rate of leaching of radionuclides from the surface soil. The element-specific K_d values used in the model are those recommended by Sheppard and Thibault (1990, Tables A-1, A-2, A-3, and A-4) for sand, loam, clay, and organic soils, respectively. Sheppard and Thibault (1990, p. 471) used texture (i.e., fractional composition of soil by particle size) to categorize mineral soils into sand, clay, and loam.

Review of the soil types present in Amargosa Valley in the vicinity of the receptor allow the four soil types considered by Sheppard and Thibault (1990) to be reduced to two: sand and loam (BSC 2003a, Section 6.3). Partition coefficients for these two soil types for the elements of importance to TSPA (BSC 2002) are presented in Table D-1.

The K_d values observed for a given element encompass a large range. Sheppard and Thibault (1990) recommended using a lognormal distribution to represent the distribution of K_ds. This distribution was selected for the model, and the data with the higher (arithmetic) mean of the estimated lognormal distribution were used (BSC 2003a, Section 6.3) to generate BDCFs. Because the arithmetic mean depends on the mean and standard deviation of the logarithm of the K_d values, the data with the higher expected value (arithmetic mean) do not necessarily coincide with the data having the higher mean of the logarithm of the K_d. In Table D-1, americium is an example for which the data for sandy soil have a higher expected value than the expected value for loamy soil, despite the mean value of the logarithm being higher for loamy soil.

Table D-1 Logarithmic Parameters and the Associated Arithmetic Means of the Partition Coefficients for the Elements of Concern

Element	Sand			Loam			Conservative Case		
	Mean $\ln(K_d)$	SD $\ln(K_d)$	Mean K_d	Mean $\ln(K_d)$	SD $\ln(K_d)$	Mean K_d	Soil Type	Mean $\ln(K_d)$	SD $\ln(K_d)$
Actinium (Ac)	6.1	-	4.46×10^2	7.3	-	1.48×10^3	loam	7.3	-
Americium (Am)	7.6	2.6	5.87×10^4	9.2	1.4	2.64×10^4	sand	7.6	2.6
Carbon (C)	1.1	0.8	4.14×10^0	2.9	-	1.82×10^1	loam	2.9	-
Cesium (Cs)	5.6	2.5	6.15×10^3	8.4	1.3	1.04×10^4	loam	8.4	1.3
Iodine (I)	0.04	2.2	1.17×10^1	1.5	2.0	3.31×10^1	loam	1.5	2.0
Neptunium (Np)	1.4	1.7	1.72×10^1	3.2	1.2	5.04×10^1	loam	3.2	1.2
Protactinium (Pa)	6.3	-	5.45×10^2	7.5	-	1.81×10^3	loam	7.5	-
Plutonium (Pu)	6.3	1.7	2.31×10^3	7.1	1.2	2.49×10^3	loam	7.1	1.2
Radium (Ra)	6.2	3.2	8.25×10^4	10.5	3.1	4.43×10^6	loam	10.5	3.1
Strontium (Sr)	2.6	1.6	4.84×10^1	3.0	1.7	8.52×10^1	loam	3.0	1.7
Technetium (Tc)	-2	1.8	6.84×10^{-1}	-2.3	1.1	1.84×10^{-1}	sand	-2.0	1.8
Thorium (Th)	8.0	2.1	2.70×10^4	8.1	-	3.29×10^3	sand	8.0	2.1
Uranium (U)	3.5	3.2	5.54×10^3	2.5	3.3	2.82×10^3	sand	3.5	3.2

Source: The mean and standard deviations of $\ln(K_d)$ are from Sheppard and Thibault 1990, Tables A-1 and A-2.

NOTE: $\ln(K_d)$ is the natural logarithm of K_d. All K_d values are in units of L/kg. Dashes (-) indicate that data are not available.

For those elements in Table D-1 where the standard deviations of the natural logarithm of K_d (i.e., $\ln(K_d)$) are not known (i.e., shown by a "-"), the reported K_d values were not measured but were inferred from measured soil-to-plant concentration ratios (Sheppard and Thibault 1990, Tables A-1 and A-2), also called the soil-to-plant transfer factors. The soil-to-plant transfer factor is the ratio of activity of a given radionuclide in unit mass of dry edible parts of the plant to that in unit mass of dry soil. Such inferences about K_d can be made as available data indicate that there is an inverse relationship between transfer factor and the K_d, of the form $TF \propto K_d^{-2}$, with a correlation of about –0.8 between transfer factor and K_d (BSC 2003c, Section 6.2.1.5). This correlation was incorporated into the biosphere model.

In those cases where there are no data for the standard deviation of the logarithm of the K_d measurements (Table D-1), the standard deviation of $\ln(K_d)$ was represented by the average of the standard deviations of the K_d of elements for which data were presented. In this case the average of the existing standard deviations for $\ln(K_d)$ in loam soils (Table D-1) is 1.77. This value was rounded up to 1.8 and used to estimate the standard deviation for elements where standard deviation was not provided. Using this standard deviation makes the expected value (i.e., the arithmetic mean) of the lognormal distribution greater than the mean value inferred from soil-to-plant transfer cooefficients. This approach allows a distribution to be defined and a representative uncertainty propagated through the model (BSC 2003a, Section 6.3).

The approach of selecting K_d distributions with higher mean values, along with the use of equilibrium concentrations in soil (BSC 2003b, Section 6.4.1.1), is reasonable while possibly introducing some conservatism.

D.4.2 Effect of Partition Coefficient Uncertainty on Biosphere Dose Conversion Factor Value To Generate the Biosphere Dose Conversion Factors

To illustrate the overall effect of the uncertainty in the K_d values on the BDCF distributions, an analysis was conducted on the biosphere model outputs used to generate the BDCFs for the groundwater scenario for TSPA. One thousand stochastic realizations were performed using the model for radionuclides of interest (BSC 2003d, Section 6). The BDCFs for a given radionuclide are the result of sampling more than 100 input parameter distributions defined in *Nominal Performance Biosphere Dose Conversion Factor Analysis* (BSC 2003d, Section 6.2). When these results are viewed as 1,000 data points on a plot of BDCFs as a function of K_d, it appears that the sampling of many individual input parameters masks information on the trends in the data. However, if the data pairs (i.e., a sampled K_d value and the calculated BDCF value) are first sorted in ascending K_d order, some trends can be seen when the data are placed into 10 groups of 100 data points (Figures D-1 to D-3). Each of the 10 groups is represented by the mean values of their K_ds and BDCFs. This procedure reduces the statistical noise apparent in the original data. Using standard sampling theory and the standard deviation of each group of data allows an estimate of the 95th percentile confidence limits of the mean value of each group to be made (Figures D-1 to D-3). This analysis was done for three representative radionuclides. Radionuclides were chosen to represent distributions with high (plutonium-239), moderate (neptunium-237), and low (technetium-99) mean values of K_ds. Also shown in Figures D-1 to D-3, as a horizontal line, is the contribution of water ingestion of two liters per day (10 CFR 63.312[d]) to the BDCF. The BDCF component attributable to drinking water represents the lowest value that the BDCF could reach if other pathways were insignificant contributors.

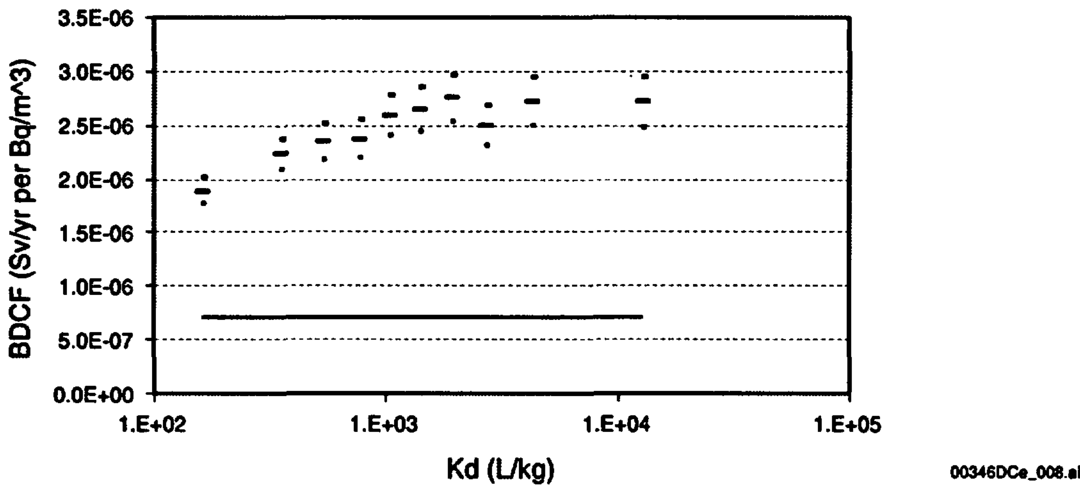
The analysis showed that although the range of K_d values covers several orders of magnitude (Figures D-1 to D-3), the impact of these large changes in K_d values on BDCF values is less than a factor of two about the mean value. BDCF values for a radionuclide with high K_d (plutonium-239) as shown in Figure D-1 gradually increases with K_d value, but the BDCF appears to converge to a fixed value at high K_d values. It should be noted that the mean value for the eighth data point lies at about the lower 95th percentile confidence limit of the mean value of adjacent points. There is sufficient overlap of the confidence intervals of these points to attribute this low mean value to statistical variation from the sampling process rather than the manifestation of a physical process in the model.

For neptunium-237, an element 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 retention in the soil.

Technetium has the lowest mean K_d of those considered for TSPA (a geometric mean of 0.14 L/kg compared to the next lowest of 4.5 L/kg for iodine, values obtained from Table D-1 by raising e to the power of the mean $\ln(K_d)$ value). The BDCF data for technetium-99 show the effect of increased plant uptake at low K_d values from the inverse correlation between soil-to-plant transfer factor and K_d, as described in Section D.4.1. For a low K_d, leaching is an efficient radionuclide removal mechanism, but 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 begins to increase as leaching become less efficient as a removal

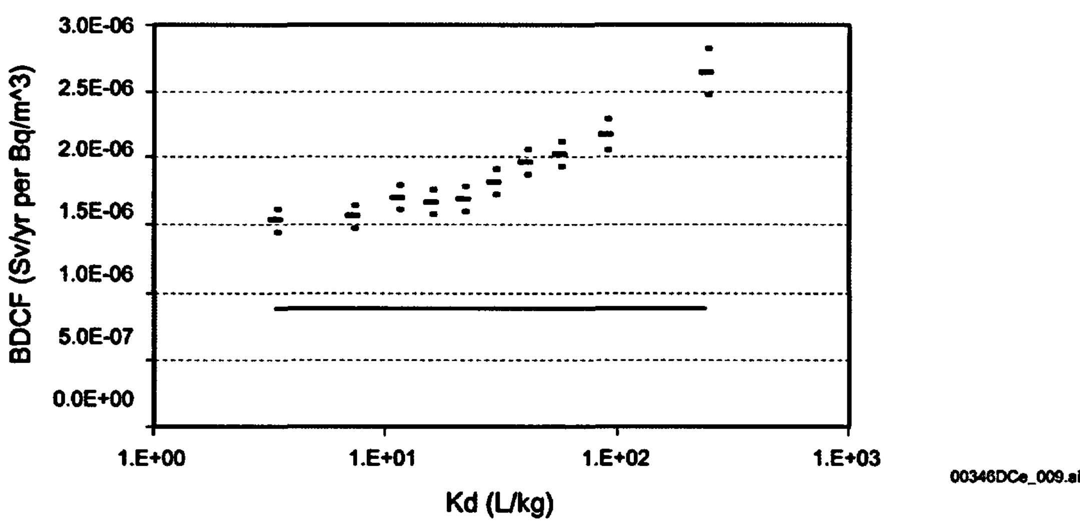
mechanism. This process causes increased radionuclide buildup in surface soil and, consequently, causes an increase in the BDCF components that depend on radionuclide concentration in the soil.

The relative insensitivity of the BDCF value to order-of-magnitude changes in the K_d value, along with the conservative approach of using the saturation radionuclide concentration in the soil, adds confidence that the selection of the K_d values for the biosphere model is justified. If the data used in the soil model overestimate the BDCFs, the degree of overestimation above the drinking water ingestion pathway exposure is less than a factor of two (Figures D-1 to D-3).



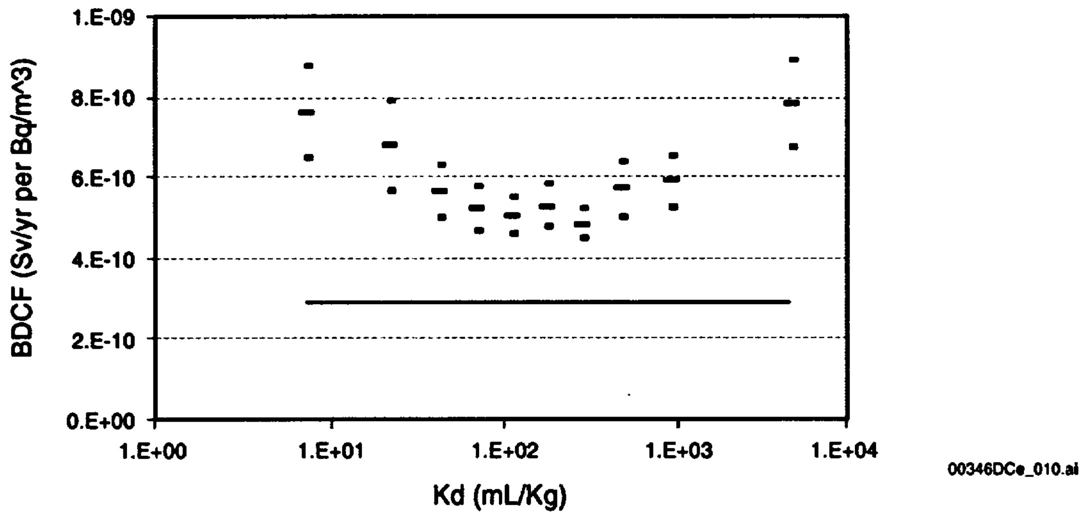
Source: BSC 2003d, Attachment II, file ERMYN_GW_CCB Pu239; see Rautenstrauch 2003.

Figure D-1. Biosphere Dose Conversion Factor Values Plotted as a Function of K_d for Plutonium-239



Source: BSC 2003d, Attachment II, file ERMYN_GW_CCB Np237D; see Rautenstrauch 2003.

Figure D-2. Biosphere Dose Conversion Factor Values Plotted as a Function of K_d for Neptunium-237



Source: BSC 2003d, Attachment II, file ERMYN_GW_CCB Tc99; see Rautenstrauch 2003.

Figure D-3. Biosphere Dose Conversion Factor Values Plotted as a Function of K_d for Technetium-99

In summary, the biosphere model for license application has been modified to allow for the stochastic treatment of the leaching and erosion processes in soil. The previous approach used a deterministic leaching rate based on a fixed elemental K_d value. The new soil submodel allowed parametric uncertainty in the leaching and erosion processes to be considered when generating the BDCF distributions. The K_d distributions and defining parameters, discussed above, were based on a published review of experimental results and were selected to be conservative with regard to soil texture while representing uncertainty in a realistic manner.

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APPENDIX E

RADIONUCLIDE-SPECIFIC BIOSPHERE PARAMETERS (RESPONSE TO TSPAI 3.34)

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application (LA) as the approved analyses of record at the time of LA submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

APPENDIX E

RADIONUCLIDE-SPECIFIC BIOSPHERE PARAMETERS (RESPONSE TO TSPAI 3.34)

This appendix provides a response to total system performance assessment and integration (TSPAI) key technical issue (KTI) TSPAI 3.34. This KTI agreement relates to the justification of the selection of radionuclide- or element-specific biosphere parameters that are important in the biosphere dose conversion factor (BDCF) calculations.

E.1 KEY TECHNICAL ISSUE AGREEMENT

E.1.1 TSPAI 3.34

This KTI agreement was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on Total System Performance Assessment and Integration held August 6–10, 2001 (Reamer 2001) in Las Vegas, Nevada. This meeting was convened to discuss four TSPAI KTI subissues: (1) system description and demonstration of multiple barriers, (2) scenario analysis within the TSPA methodology, (3) model abstraction within the TSPA methodology, and (4) demonstration of the overall performance objective.

Wording of the agreement is as follows:

> For the Radionuclides that dominate the TSPA dose, provide the technical basis for selection of Radionuclide or element specific biosphere parameters that are important in the BDCF calculations (e.g. soil to plant transfer factors) (DOSE3.2.1). For the radionuclides that dominate the TSPA dose, DOE will provide the technical basis for selection of radionuclide or element specific biosphere parameters (except for Kds which are addressed in TSPAI 3.33) that are important in the BDCF calculations (e.g. soil to plant transfer factors). The technical basis will be documented in the Transfer Coefficient Analysis AMR (ANL-MGR-MD-000008) or other document and is expected to be available to NRC in FY 2003.

DOSE3.2.1 in this agreement refers to NRC integrated subissue Dose 3 (NRC 2002, Table 1.1-2).

E.1.2 Related Key Technical Issue Agreements

TSPAI 3.35 addresses the need for technical justification to support the crop interception fraction for appropriate radionuclides. This agreement is addressed in Appendix F.

E.2 RELEVANCE TO REPOSITORY PERFORMANCE

Within the biosphere model developed to support the license application TSPA (BSC 2003a), three exposure pathways are considered (i.e., external radiation, inhalation, and ingestion). The relative contribution to dose from these pathways depends on the radionuclide. For many

radionuclides, especially in the groundwater release scenario, the ingestion pathway is the most important contributor to dose (BSC 2003b; BSC 2003c).

To develop BDCFs for calculating dose in the TSPA, predictions for the transport of each radionuclide from the site of its introduction into the biosphere to the receptor are required. For many transport pathways, especially those in the food chain leading to ingestion exposure, the parameters needed to quantify transport depend on the element being considered. A similar condition holds for inhalation of resuspended soil, but in this case the relevant parameter is the elemental partition coefficient (K_d). The values of this parameter and its use in the biosphere model are respectively discussed in Appendices D and G.

The element-dependent parameters in the food chain part of the biosphere model are the soil-to-plant transfer factor, the animal-diet to animal-product transfer coefficient, and the bioaccumulation factor for aquatic food. The biosphere model considers five classes of crops: leafy vegetables, other vegetables, fruits, grains and forage. Each of these crop types requires an element-dependent soil-to-plant transfer factor. In a similar way, there are multiple animal products considered in the model: meat, poultry, milk, and eggs. Each of these animal products pathways requires an element-specific animal-diet to animal-product transfer coefficient. The bioaccumulation factor for aquatic food (fish), a parameter that relates activity concentration in water to that in the fish at time of harvest, also is element specific.

The biosphere model for the groundwater exposure scenario explicitly addresses three exposure pathways, some of which are further subdivided for modeling purposes, as discussed in Section 3. Pathway analyses indicate the relative importance of individual exposure pathways in terms of contributions to BDCFs for various radionuclides. Inhalation of particulate matter tends to dominate doses for actinides (e.g., isotopes of thorium, uranium, plutonium, and americium). Inhalation of radioactive aerosols generated by evaporative coolers also is an important inhalation exposure pathway for those radionuclides. Ingestion of water is a consistently high contributor to dose. Other pathways are only important for a few radionuclides. For instance, external exposure is a dominant pathway for tin-126 and cesium-137, inhalation of radon decay products for radium-226 and thorium-230, and fish consumption for isotopes of cesium, lead-210, and neptunium-237. Consumption pathways are generally more important for radionuclides with atomic numbers less than about 88 (BSC 2003c, Section 6.2.5). The water ingestion pathway is an important contributor to the BDCFs for almost all radionuclides and, subsequently, to the annual dose to the reasonably maximally exposed individual. The dose contribution from water ingestion is not dependent upon any biosphere parameters other than quantity of water ingested. Thus, this pathway determines a minimum exposure for a given concentration of a radionuclide in groundwater against which the exposure from other contributing pathways can be compared.

E.3 RESPONSE

The radionuclides to be considered for the postclosure assessment for license application were defined in *Radionuclide Screening* (BSC 2002, Section 7, Table 13). This analysis identified 28 radionuclides that represent 17 elements. Within the biosphere model, two additional radionuclides were included to allow consideration of long-lived decay chain products (BSC 2003a, Section 6.3.5). These additional radionuclides did not increase the number of

elements under consideration for determining the transport properties. Element-specific biosphere parameters were derived in *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2003d). This analysis report determined the parameter values that affect the transport of radionuclides in the biosphere, including those that are element dependent, by performing a literature survey to collate a reasonable cross-section of available data, reviewing these data, and then making recommendations for parameter distributions.

The information in this report provides a complete response to the agreement TSPAI 3.34.

E.4 BASIS FOR THE RESPONSE

E.4.1 General Overview

This report presents a summary of biosphere modeling developed to support the license application. In particular, Sections 4 and 5 identify and discuss the individual submodels that make up the modeling capability (BSC 2003a) for the groundwater and volcanic scenario models, respectively. Several of these submodels (e.g., soil, plant, animal, and fish submodels) are dependent on element-specific parameters. These parameters are the subject of this KTI.

The biosphere model was constructed to allow uncertainty in all parameters to be considered in the model. Stochastic modeling techniques were used to propagate the uncertainty in each input parameter through the biosphere model to the resultant BDCFs.

E.4.1.1 Sources of Information

Parameter values for the biosphere model were developed primarily through a literature review, with site-specific information being used when possible (BSC 2003d, Section 6.1.1). This analysis focused on review articles and comprehensive dose assessment reports that included selection of input parameter values, rather than on publications reporting individual experimental results. Documents reporting specific experimental results were used only if they provided data not included in the literature already considered.

These review articles and other publications identified, evaluated, and used a broad range of published information to make recommendations on parameter values. In many cases, authors of two or more reviews used the same or overlapping information sources to develop a representative value for a given parameter, but they obtained somewhat different results. This indicates that there is inherent uncertainty associated with the experimental data and their interpretation. In this analysis, the use of results from multiple reviews incorporated this uncertainty into the developed distributions.

E.4.1.2 Parameter Value Development Methods

Parameter values for the biosphere model were based on multiple sources of technical information and data, so it was important to apply a consistent method to develop parameter values (BSC 2003d, Section 6.1.2). The arithmetic mean is justified if data came from a consistent set of observations. To estimate the value of a parameter, the geometric mean is recommended in the literature as a way to average data over space and time. For this approach to be valid, the data sources should be qualitatively similar (e.g., a compilation of experimental

data only or a set of values obtained from literature reviews). If this condition is not met (e.g., if data averages from one source were mixed with individual data points from another), the averaging would be difficult to control and justify.

The geometric mean is considered to be the best representation of parameters for which reported values span more than an order of magnitude (BSC 2003d, Section 6.1.2). This was the case with the soil-to-plant transfer factors (BSC 2003d, Section 6.2.1.2), the animal intake-to-animal product transfer coefficients (BSC 2003d, Section 6.3.3), and the bioaccumulation factor (BSC 2003d, Section 6.4.3), where the range of values often spanned several orders of magnitude. For these parameters, the lognormal distribution was used for parameter uncertainty and variability.

Technical judgment often was necessary in cases where data were sparse or were obtained from experiments that were incompatible with the reference biosphere (BSC 2003d, Section 6.1.2). When judgments were used to determine expected values, the minimum and maximum values were considered to establish a confidence interval representing uncertainty due to incomplete knowledge about the actual range of data. Specific methods for developing parameter values are addressed in the report *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2003d, Section 6.1.2).

E.4.1.3 Site Specificity

Most of the environmental transport parameters used in the biosphere model are influenced, to some degree, by local conditions such as the climate and soil types (BSC 2003d, Section 6.1.3). In most instances, data related to environmental transport pathways were not collected in the region surrounding Yucca Mountain. Although ideally all parameters would be obtained through site-specific studies, many parameters, especially those for pathways that make a small contribution to the BDCFs, can be adequately represented by generic values. The pathway analysis that is needed to identify parameters that are of little consequence for the biosphere model cannot be completed a priori. Because the biosphere model (BSC 2003a) uses mathematical representations that are similar to those used by the model used for site recommendation, the results of the pathway analysis for the site recommendation biosphere model (CRWMS M&O 2001a, p. 78; CRWMS M&O 2001b, pp. 73 to 77) were used to inform the parameter development process. The selection of parameter values for the biosphere model relied heavily on published information on biosphere transport. It usually was possible to evaluate the basis for applying the literature-derived parameter value to Yucca Mountain conditions in lieu of site specific data.

E.4.2 Soil-to-Plant Transfer Factors

Activity concentration in crops resulting from radionuclide uptake through roots is estimated in the biosphere model (BSC 2003a, Section 6.4.3.1) as:

$$Cp_{root,i,j} = Cs_{m,i}\, F_{s\rightarrow p\ i,j}\, DW_j \qquad \text{(Eq. E-1)}$$

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 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 part of plant (kg $_{dry\ plant}$ per kg $_{wet\ plant}$).

The report *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2003d) developed values of element- and crop-type-specific soil-to-plant transfer factors used in Equation E-1. The transfer factors relate the dry- or wet-weight activity concentration in the edible parts of plants (Bq/kg) to the dry-weight activity concentration in soil (Bq/kg), assuming equilibrium between the two media. In the analysis, transfer factors are based on plant dry-weight, following the format used in the biosphere model (BSC 2003a, Section 6.4.3.1). The conversion between the dry-weight-based and wet-weight-based transfer factors can be accomplished using dry-to-wet-weight ratios. The dry-to-wet-weight ratio values range from a few percent for fruit to over 90 percent for grain (BSC 2003a, Section 6.4.3.1). Observed values of transfer factors differ, mainly as a result of soil characteristics, vegetation types, and environmental conditions. Crop uptake through roots is affected by soil management practices (e.g., plowing, fertilizing, and irrigation). There are also differences between the transfer factors for various parts of the plant, for example the whole plant and the grain.

As discussed in Section E.2, five classes of crops were considered: leafy vegetables, other vegetables (including root vegetables and legumes), fruit, grain for human consumption as well as feed for chickens and laying hens, and forage for beef cattle and diary cows. Transfer factors for each of these food categories and each defined element were generated. Eleven sources of data were used for transfer factors, as described in *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2003d, Section 4.1.1).

Most of the eleven sources derived information on soil-to-plant transfer factors from experiments performed on soils typical of temperate climates, and the generic transfer factor values (i.e., values that are recommended if site-specific data are lacking) reflect such conditions (BSC 2003d, Section 6.2.1.1.5). The soils of Amargosa Valley region are characterized by a high pH, high mineral concentrations, and higher sand content (low clay content) than typical soils of temperate climates. Relying on generic transfer factor information to develop the parameter values for soils in Amargosa Valley will introduce parametric uncertainty into the model. In all instances where there was detailed soil information, a value corresponding most closely to the properties of Amargosa Valley soil was used. For example, if a distinction was made between soil types in a reference, values for sandy soils or low clay content soils were used. Regarding soil pH, higher pH values result in decreased uptake of elements, while lower values produce increased uptakes. If a transfer factor value for higher pH soils was available, it was used in the analysis. Transfer factor selection also considered the mineral content of the soils (e.g., the concentration of a specific mineral) and the organic matter content (e.g., mineral

soils versus organic soils). The instances of using specific transfer factor values are listed in the notes section of the transfer factor tables (BSC 2003d, Tables 6-2 to 6-31). Transfer factors for plant species not known to be grown in Amargosa Valley were not used in the calculation of distribution parameters. Specifically, the transfer factors for tropical plants were not considered.

Transfer factor values, selected using the criteria above, were aggregated in the manner described in *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2003d, Section 6.2.1.1.5). The geometric mean was calculated using transfer factor values from all relevant references.

The transfer factors used in the biosphere model not only represent composite values for many crop species within a crop type, but also capture potential temporal changes (BSC 2003d, Section 6.2.1.1.5). Because temporal changes may cause a wider distribution of parameter values, the geometric standard deviation of the values reported in the literature was used as a measure of uncertainty in the transfer factor value for a given element and crop type.

As noted previously, the sources of information on transfer factors (BSC 2003d, Table 4-2) were summary reviews and reports containing recommendations of generic transfer factor values or reports describing biosphere models that include selections of input parameters. In either case, the values of transfer factors are best estimates based on relevant data for a given radionuclide, pathway, and application (BSC 2003d, Section 6.2.1.1.5). When the geometric mean of such data is calculated, as is done in this analysis, the result represents the estimate of the parameter value based on the best estimate of other authors. The variability of values, characterized by the geometric standard deviation, indicates the level of agreement among the authors. Usually there is good agreement between the transfer factor values from different reports, which, in most cases, differ by less than two orders of magnitude (BSC 2003d, Tables 6-2 to 6-31). In a few instances, transfer factor values reported by different authors differed by several orders of magnitude. For such cases, the calculated geometric standard deviation is large.

To determine the realistic representation of the transfer factor values, the upper and lower limits for the geometric standard deviation were set based on an analysis of the transfer factors by Sheppard and Evenden (1997, p. 727). The analysis concerned the expected uncertainty in transfer factor values for a range of possible conditions from fully generic to site-specific situations. It was concluded that the most site-specific data (single site, single crop) have a geometric standard deviation of about 1.5. When data are fully generic, the geometric standard deviation generally is above 3, with a typical value of about 6. A geometric standard deviation of 10 was chosen for all elements in support of biosphere modeling for the Canadian nuclear fuel waste assessment (Davis et al. 1993, p. 232). Compared to published data (Sheppard and Evenden 1997, p. 730), this value is an upper limit for geometric standard deviation values. Because higher values of geometric standard deviations are not supported by the other data sources, the geometric standard deviation of 10 was chosen as an upper limit for the transfer factors for the biosphere model (BSC 2003d, Section 6.2.1.1.5).

The transfer factors used in the biosphere model represent the composite mean values for the crop species within the crop type (BSC 2003d, Section 6.2.1.1.5). The lower limit for the geometric standard deviation was set at 2 because the typical site- and crop-specific transfer factor geometric standard deviation was about 1.5. Because transfer factors in the biosphere

model represent values for crop types, rather than individual crops, it is unlikely that the corresponding geometric standard deviation would be lower than the site- and crop-specific value. The value of 1.5 was rounded up to the nearest integer (i.e., 2) and used as the lower limit of the geometric standard deviation. In practice, when the geometric standard deviation of the published values was less than 2, it was set at 2, and if it was greater than 10, it was set at 10. Such an approach is appropriate because the distributions of transfer factor values do not represent variability in the expected values of the transfer factors for different individual crops but, rather, uncertainty in the generic value of the parameter.

The lognormal distribution, used to represent the uncertainty, was truncated at the 0.5 percent and 99.5 percent limits to capture 99 percent of values predicted by the distribution. This prevented the biosphere model from sampling extreme values far smaller or larger than the range of experimental observations.

E.4.3 Transfer Coefficients

Transfer coefficients are defined as the mass or volume activity concentration in the tissue or product of an animal (Bq/kg wet mass or Bq/L) divided by the transfer rate (Bq/d) of the radionuclide to the animal by ingestion (BSC 2003d, Section 6.3.3). The transfer coefficient is the fraction of the daily animal intake of a radionuclide that is transferred to one kilogram of animal product at equilibrium or at the time of slaughter. The availability for gut uptake of radionuclides differs markedly, depending on the chemical and physical form of the radionuclide and constituents of the diet. To incorporate uncertainty associated with the process of activity transfer from animal food to animal products, transfer coefficient values for the biosphere model were developed as probability distribution functions, as described in *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2003d, Section 6.3.3).

Data from direct measurements of transfer coefficients are scarce (BSC 2003d, Section 6.3.3). Many of the published values were 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 assumption of analogous behavior of elements that are chemically similar. Many documents use the value for beef to be representative of all meat, and cow milk to represent all kinds of milk. For example, IAEA transfer coefficients (IAEA 2001, p. 69) for meat and milk are based on values for beef and dairy cattle. However, these values are stated to be conservative and they are not expected to substantially underestimate concentration of radionuclides in meat or milk of other animals. The same approach was followed in this analysis (i.e., beef was used to represent meat and cow milk was used to represent milk).

Transfer coefficients for the biosphere model were developed using a method similar to that used for the development of transfer factors for radionuclide transfer to plants (BSC 2003d, Section 6.3.3; see also Section E.4.2). The method was based on review of the pertinent published compendia of generic values or reports containing the recommendations or applications of transfer coefficient values in other biosphere models. Some 16 data sources were used (BSC 2003d, Table 4-7). Such an approach is appropriate for development of transfer coefficient values for the biosphere model. Because of the diversity of information sources and the wide range of the published transfer coefficient values, geometric means of the transfer coefficient values from relevant references are considered best representations of the parameter

values. The distributions for transfer coefficients are considered to be lognormal (BSC 2003d, Section 6.3.3). As discussed in Section E.4.2, a truncated lognormal distribution (99 percent level) with a geometric mean and standard deviation defined as discussed above was used to represent uncertainty. The results of the analysis are presented in *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2003d, Section 7.2).

E.4.4 Bioaccumulation Factors

Bioaccumulation factors for freshwater fish were developed based on a literature review (BSC 2003d, Section 6.4.3). A comparison of the bioaccumulation factor values from the reviewed documents is presented in *Environmental Transport Input Parameters for the Biosphere Model* (BSC 2003d, Table 6-64) with geometric means and geometric standard deviations for the reported values. The range of values is wide because it includes planktivorous, piscivorous, and bottom-feeding fish. Bottom-feeding fish take up more radioactivity than the piscivorous fish, and the piscivorous fish, which occupy a higher trophic level, take up more radioactivity than the planktivorous fish. Channel catfish, farmed in the Amargosa Valley, are bottom-feeders, and thus should be associated with higher values of bioaccumulation factors. In natural aquatic systems, for which the bioaccumulation factors were developed, fish receive radionuclides directly from the water and the food. However, this is not the case for a fish farm where the fish are fed commercial, uncontaminated feed. Therefore, bioaccumulation factors provide an upper bound of the estimated uptake, and their mean values should not underestimate the transfer of radionuclides from water to aquatic food. The bioaccumulation factors are represented by a lognormal distribution with the geometric mean and geometric standard deviation calculated based on the values in the selected references (BSC 2003d, Section 6.4.3). Analogous to the calculations of the soil-to-plant transfer factors (BSC 2003d, Section 6.2.1.1) and the transfer coefficients for animal products (BSC 2003d, Section 6.3.3), truncated distributions are used for the bioaccumulation factor and the geometric standard deviation was rounded up to 2.0 for values less than 2.0. The upper and lower truncation limits embrace the 99 percent confidence interval. The distribution of bioaccumulation factors represents the uncertainty in the upper bound of the parameter value, rather than the uncertainty in the parameter itself.

In the summary, to model radionuclide transport in the biosphere, there are three submodels (other than the soil model using partition coefficients) that have parameters dependent on the element involved. The three submodels were discussed in the preceding sections. In all cases the parameters were subject to large variation and were modeled in the biosphere by truncated lognormal distributions. The parameters defining the distribution for each pathway and element were determined from published data, primarily those published in review papers. The approach used as the basis to select element specific parameters and distributions follows the recommendations and methods used in radiological assessments (BSC 2003d) and as such provides a sound basis for biosphere modeling effort.

The uncertainty and variability of these, and other non-element dependent parameters quantified by use of a distribution, allowed stochastic sampling to be conducted in the biosphere model to propagate input uncertainties through all pathways to generate the BDCF distributions for use in TSPA.

E.5 REFERENCES

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APPENDIX F

CROP INTERCEPTION FRACTION (RESPONSE TO TSPAI 3.35)

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application (LA) as the approved analyses of record at the time of LA submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

APPENDIX F

CROP INTERCEPTION FRACTION (RESPONSE TO TSPAI 3.35)

This appendix provides a response to total system performance assessment and integration (TSPAI) key technical issue (KTI) TSPAI 3.35. This agreement relates to the method used to calculate the fraction of radionuclides in water that are intercepted by plant surfaces.

F.1 KEY TECHNICAL ISSUE AGREEMENT

F.1.1 TSPAI 3.35

This agreement was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on TSPAI held August 6–10, 2001 (Reamer 2001) in Las Vegas, Nevada, which was convened to discuss four TSPAI KTI subissues: (1) System description and demonstration of multiple barriers; (2) Scenario analysis within the TSPA methodology; (3) Model abstraction within the TSPA methodology; and (4) Demonstration of the overall performance objective.

Wording of the agreement is as follows:

> Provide additional justification to support that the assumed crop interception fraction is appropriate for all radionuclides considered and does not result in underestimations of dose. Discussions should address the impacts of electrostatic charge and particle size on the interception fraction for all radionuclides considered in the TSPA (DOSE3.2.5). DOE will provide additional justification to support that the assumed crop interception fraction is appropriate for all radionuclides that dominate the TSPA dose and does not result in underestimations of dose. The justification will include the impacts of electrostatic charge and particle size on the interception fraction. This justification will be documented in Identification of Ingestion Exposure Parameters (ANL-MGR-MD-000006) or other document expected to be available to NRC in FY 2003.

DOSE3.2.5 in this agreement refers to NRC integrated subissue Dose 3 (NRC 2002, Table 1.1-2).

F.1.2 Related Key Technical Issue Agreements

TSPAI 3.34, which addresses selection of radionuclide- and element-specific parameters, is addressed in Appendix E.

F.2 RELEVANCE TO REPOSITORY PERFORMANCE

The crop interception fraction (called water interception fraction in the *Biosphere Model Report* (BSC 2003a) and throughout the remainder of this appendix) is an input parameter in the biosphere model that specifies the proportion of radionuclides in irrigation water sprayed on

plants that is transferred to plant surfaces. It influences estimates of radionuclide concentrations in plants and livestock (via ingestion of forage) and the subsequent dose resulting from ingestion of crops and animal products in the biosphere groundwater scenario. The water interception fraction is an important parameter in the calculation of groundwater biosphere dose conversion factors (BDCFs) for many radionuclides considered in the total system performance assessment (TSPA) (CRWMS M&O 2000a, Section 6.3.2), especially those with a high contribution from ingestion pathways. Therefore, low values of the interception fraction may result in an underestimate of the dose resulting from use of groundwater. This parameter is not used in the calculation of dose from ash.

This agreement is based on a concern raised by the NRC that the distribution of the crop interception fraction used to calculate BDCFs for the site recommendation may not be representative of all important radionuclides considered for the TSPA (NRC 2002, Section 3.3.14.4.2). That distribution had a mean of 0.259, with minimum and maximum values of 0.044 and 0.474, respectively. It was used for all crop types considered in the model. The NRC (2002, pp. 3.3.14-9 and 3.3.14-10) has pointed out that the maximum value of that distribution is lower than some measurements of interception fractions obtained during laboratory and field experiments summarized by Anspaugh (1987).

Results of pathway analysis indicate that ingestion pathways are generally important only for radionuclides with atomic numbers less than about 88 (BSC 2003b, Section 6.2.5) and ingestion of water has the highest contribution to the ingestion dose for all radionuclides. Ingestion of crops contributes more than 10 percent of the total BDCFs for only a few radionuclides (carbon-14, chlorine-36, strontium-90, and technetium-99) (Table 6-3; BSC 2003b, Section 6.2.5).

F.3 RESPONSE

The method used to calculate the water interception fraction in the biosphere model for the license application (BSC 2003a) is based on the same equation that was used in the site-recommendation biosphere model. This equation was selected because it is the best available method for quantifying uncertainty and variation in the important parameters that influence water interception. Revised distributions of most input parameters are used and separate values of the interception fraction are stochastically calculated for each crop type. Those input parameter distributions incorporate variation and uncertainty in the irrigation methods used in Amargosa Valley and the irrigation requirements and morphology of crops grown there. The empirical constants required for the calculation are the same as those used in the site recommendation and are based on results from one radionuclide. This was done because no data are available on interception coefficients for most radionuclides, and because it is not possible to predict the chemical form that all radionuclides will take in the groundwater. The constants used are from experimental results of several radionuclides and suspended particle sizes (Hoffman et al. 1989; Hoffman et al. 1995). The values for the radionuclide with the highest interception fraction were selected to ensure that the water interception fraction is not underestimated. The range of water interception fractions calculated by the new model is from 0.08 to 1.0, much greater than the distribution used for the site recommendation. This new range encompasses estimates of water interception fractions measured during laboratory and field experiments for numerous radionuclides and for various particle sizes and charges. Because this

method results in a wide range of values, and because the maximum values are as high or higher than those measured experimentally, it is concluded that this method adequately bounds uncertainty associated with the electrostatic charge and particle size of radionuclides and does not result in an underestimation of dose. The information in this report provides a complete response to agreement TSPAI 3.35.

F.4 BASIS FOR THE RESPONSE

In the biosphere model for the site recommendation, an experimentally derived formula (Hoffman et al. 1989; Hoffman et al. 1992) was used to develop a distribution for the crop interception fraction (CRWMS M&O 2000b, Appendix C). This formula predicts the fraction of dissolved cationic beryllium intercepted by plants as a function of plant dry biomass, the irrigation application amount, and the irrigation intensity. Typical values of dry biomass (mean = 0.251 kg/m^2, standard deviation [sd] = 0.052), irrigation application amount (mean = 13.3 mm, sd = 4.043), and irrigation intensity (mean = 3.95 cm/hr, sd = 2.158) for alfalfa grown under current conditions in Amargosa Valley were used in the calculation (CRWMS M&O 2000b, Appendix C). The resulting normal distribution (mean = 0.259, sd = 0.065, lower bound of 99 percent confidence interval = 0.044, upper bound of 99 percent confidence interval = 0.474) was used to calculate the fraction of all radionuclides in irrigation water intercepted by all crop types (CRWMS M&O 2001, Table 8).

The approach used to calculate the water interception fraction in the revised biosphere model is described in the *Biosphere Model Report* (BSC 2003a, Section 6.4.3) and *Agricultural and Environmental Input Parameters for the Biosphere Model* (BSC 2003c). This calculation is part of the plant submodel for the groundwater exposure scenario (Section 4.3). The water interception fraction is used to quantify the initial fraction of radionuclides in irrigation water that are deposited on plant surfaces during overhead (i.e., spray) irrigation.

The experimentally derived equation (Hoffman et al. 1989; Hoffman et al. 1992) shown below is used to calculate the water interception fraction (BSC 2003a, Section 6.4.3).

$$Rw_j = K_1 \, DB_j^{\,K_2} \, IA_j^{\,K_3} \, I^{K_4} \qquad \text{(Eq. F-1)}$$

where

Rw_j	=	water interception fraction for crop type j, truncated at a maximum value of 1.0 (dimensionless)
K_1, K_2, K_3, and K_4	=	empirical constants (K_1 is in units of $(kg/m^2)^{-K2}$ $(mm)^{-K3}$ $(cm/hr)^{-K4}$, and K_2, K_3 *and* K_4 are dimensionless)
DB_j	=	standing biomass of crop type j ($kg_{\text{dry weigh}}/m^2$)
IA_j	=	amount of irrigation per application event for crop type j (mm)
I	=	irrigation intensity (cm/hr).

This method was selected because it incorporates variation and uncertainty in irrigation rates and the types of crops grown in the Amargosa Valley. The proportion of radionuclides intercepted is influenced primarily by the size of plants (i.e., above-ground biomass), the chemical form of radionuclides, and the rate and amount of water applied (Hoffman et al. 1989; Hoffman et al. 1992; IAEA 1996). A single value per crop type, or a single distribution for all crop types, may not be adequate because each crop type includes many crops grown in Amargosa Valley and there are differences in plant morphology and irrigation requirements among the crops (BSC 2003c, Appendix A). This calculation incorporates important differences among crops and can be used to account for some differences in irrigation requirements resulting from climate change.

The following evaluation was conducted to assess this method. First, the input parameters and empirical constants were evaluated to determine whether they incorporate variation and uncertainty among crop types and are suitable for use in the equation. Then, the model was used to stochastically calculate 1,000 estimates of the water interception fraction. Those results were evaluated to determine whether the calculation method adequately incorporated uncertainty and variation related to particle size and charge, and to determine if the methods result in a range of values similar to those measured in laboratory and field experiments.

F.4.1 Evaluation of Model Inputs

Empirical Constants–Hoffman et al. (1992) and Hoffman et al. (1995) measured interception fractions for six dissolved radionuclides and three sizes of suspended particle. Dissolved anionic particles (^{35}S and ^{131}I) had lower interception fractions than dissolved cationic radionuclides or particles suspended in water. Cationic beryllium generally had the highest interception fraction. Interception fractions of suspended particles were similar to, or slightly higher than, interception fractions of beryllium. Based on this information, the following empirical constants, characteristic of beryllium ions, are used in the biosphere model for all radionuclides: K_1 = 2.29, K_2 = 0.695, K_3 = -0.29, and K_4 = -0.341 (Hoffman et al. 1992, Table 1).

The same empirical constants are used for all radionuclides because there is no information available to calculate radionuclide-specific constants for most radionuclides considered in the TSPA for the license application and because radionuclides in the groundwater may be present in different chemical forms (e.g., have different charges) or as suspended particles. Because the empirical constants used in the model are derived from the radionuclide tested with the highest interception fraction and are similar to those for dissolved particles, they will not result in underestimating the water interception fraction for other radionuclides. To demonstrate that omitting the influence of electrostatic charge and particle size (by using the same constants for all radionuclides) does not result in underestimation of the dose, the results of the biosphere model are compared in Section F.4.2 with experimentally derived measurements of water interception fractions.

Dry Biomass–Distributions of dry biomass were developed for each of the five crop types in the biosphere model based on the biomass of three to seven representative crops per crop type (Table F-1; BSC 2003c, Section 6.1). Information on commonly grown agricultural and garden crops in Amargosa Valley and analog future climate sites, food consumption patterns, and crop growth patterns were used to select representative crops (BSC 2003c, Appendix A). Because

most or all commonly grown or consumed crops were selected for each crop type (Table F-1), these crops represent the range of variation within the reference biosphere for each crop type.

Table F-1. Representative Crops

Crop Type	Representative Crops
Leafy Vegetables	Broccoli, Cabbage, Cauliflower, Celery, Head Lettuce, Leaf Lettuce, and Spinach
Other Vegetables	Bell Peppers, Carrots, Cucumbers, Onions, Potatoes, Squash, and Sweet Corn
Fruits	Apples, Grapes, Melons, Strawberries, and Tomatoes
Grains	Barley, Feed Corn, Oats, and Wheat
Cattle Forage	Alfalfa, Corn Silage, and Oat hay

Source: Adapted from BSC 2003c, Table 6-1 and Appendix A.

Estimates of dry biomass were based on commercial yield and dry to wet ratios of the representative crops. For other vegetables, fruits, and grains, resulting values were divided by harvest indices, which are used to convert harvested biomass to total standing biomass (Hay 1995; Prince et al. 2001). Cumulative distributions were developed having 10th and 90th percentiles equal to the lowest and highest biomass values for representative crops within a crop type (Table F-2; BSC 2003c, Section 6.1). To account for uncertainty in yield and dry to wet ratios, the minimum and maximum values of the distributions were calculated based on the representative crops with extreme yields and dry to wet ratios. These distributions are within the range of experimental conditions used to develop Equation F-1 (0.07 to 2.77 kg/m^2), although more than 90 percent of the experimental plots had a biomass of less than 1.0 kg/m^2 (Hoffman et al. 1989, Tables A.V.1 and A.VI.4).

Irrigation Application–The predicted amount of water applied during each crop irrigation event in the last 30 days of growth was used to develop distributions of irrigation application per crop type (BSC 2003c, Section 6.7). Crop water requirements and soil moisture balance were calculated using methods developed by the Food and Agriculture Organization of the United Nations (Doorenbos and Pruitt 1977; Allen et al. 1998). Cumulative distributions were developed having 10th and 90th percentiles equal to the lowest and highest irrigation requirements for representative crops within a crop type (Table F-2). To account for uncertainty and variation in climate and water management practices, minimum and maximum values were selected based on minimum water requirements and likely overwatering rates, respectively. Separate distributions were developed for the current and predicted future glacial transition climate states.

Table F-2. Parameter Distributions to be Used in the Biosphere Model to Calculate Water Interception Fraction

Parameter	Crop Type	Units	Distribution	Mean	Distribution Characteristics
Dry Biomass	Leafy Vegetables	kg/m^2	Cumulative	0.21	(0.10; 0%), (0.13; 5%), (0.14; 20%), (0.15; 35%), (0.16; 50%), (0.18; 65%), (0.30; 80%), (0.42; 95%), (0.50; 100%)
.	Other Vegetables	.	.	0.43	(0.30; 0%), (0.40; 5%), (0.41; 28%), (0.43; 51%), (0.44; 73%), (0.46; 95%), (0.60; 100%)
.	Fruits	.	.	0.62	(0.10; 0%), (0.56; 5%), (0.60; 35%), (0.65; 65%), (0.68; 95%), (1.30; 100%)
.	Grains	.	.	1.13	(0.50; 0%), (0.61; 5%), (0.74; 35%), (1.20; 65%), (1.97; 95%), (2.20; 100%)
.	Cattle Forage	.	.	0.48	(0.10; 0%), (0.23; 5%), (0.34; 73%), (1.38; 95%), (1.50; 100%)
Irrigation Intensity	All Crops	cm/hr	Uniform		Minimum = 1.0, Maximum = 7.5
Irrigation Application (Current Climate)	Leafy Vegetables	mm	Cumulative	14.7	(6.0; 0%), (7.4; 5%), (8.4; 20%), (10.0; 35%), (10.9; 50%), (20.8; 65%), (22.0; 80%), (23.6; 95%), (27.8; 100%)
.	Other Vegetables	.	.	25.4	(8.0; 0%), (9.0; 5%), (18.7; 20%), (19.7; 35%), (21.2; 50%), (32.9; 65%), (34.9; 80%), (41.2; 95%), (48.6; 100%)
.	Fruits	.	.	33.9	(5.0; 0%), (6.0; 5%), (30.2; 28%), (35.5; 51%), (48.4; 72%), (49.2; 95%), (58.1; 100%)
.	Grains	.	.	56.8	(43.0; 0%), (48.7; 5%), (50.1; 35%), (50.3; 65%), (77.9; 95%), (91.9; 100%)
.	Cattle Forage	.	.	57.8	(50.0; 0%), (56.5; 5%), (57.5; 72%), (60.2; 95%), (71.0; 100%)
Irrigation Application (Future Climate)	Leafy Vegetables	mm	Cumulative	14.6	(7.0; 0%), (7.8; 5%), (8.0; 20%), (9.0; 35%), (10.1; 50%), (19.3; 65%), (22.0; 80%), (26.1; 95%), (30.8; 100%)
.	Other Vegetables	.	.	25.0	(10.0; 0%), (11.3; 5%), (14.4; 20%), (17.7; 35%), (20.1; 50%), (34.1; 65%), (37.2; 80%), (40.3; 95%), (47.6; 100%)
.	Fruits	.	.	34.2	(6.0; 0%), (7.3; 5%), (31.4; 28%), (34.6; 51%), (43.2; 72%), (54.4; 95%), (64.2; 100%)
.	Grains	.	.	51.3	(28.0; 0%), (32.2; 5%), (46.2; 35%), (59.9; 65%), (66.7; 95%), (78.7; 100%)
.	Cattle Forage	.	.	53.5	(43.0; 0%), (48.3; 5%), (52.5; 73%), (61.9; 95%), (73.0; 100%)

Source: Adapted from BSC 2003c, Table 7-1.

NOTES: The average is for all representative crops per crop type; these values are used in deterministic calculations of water interception fraction. The characteristics of the cumulative distributions are the upper bounds of each interval and the cumulative probability associated with each interval. Dots mean "same as above."

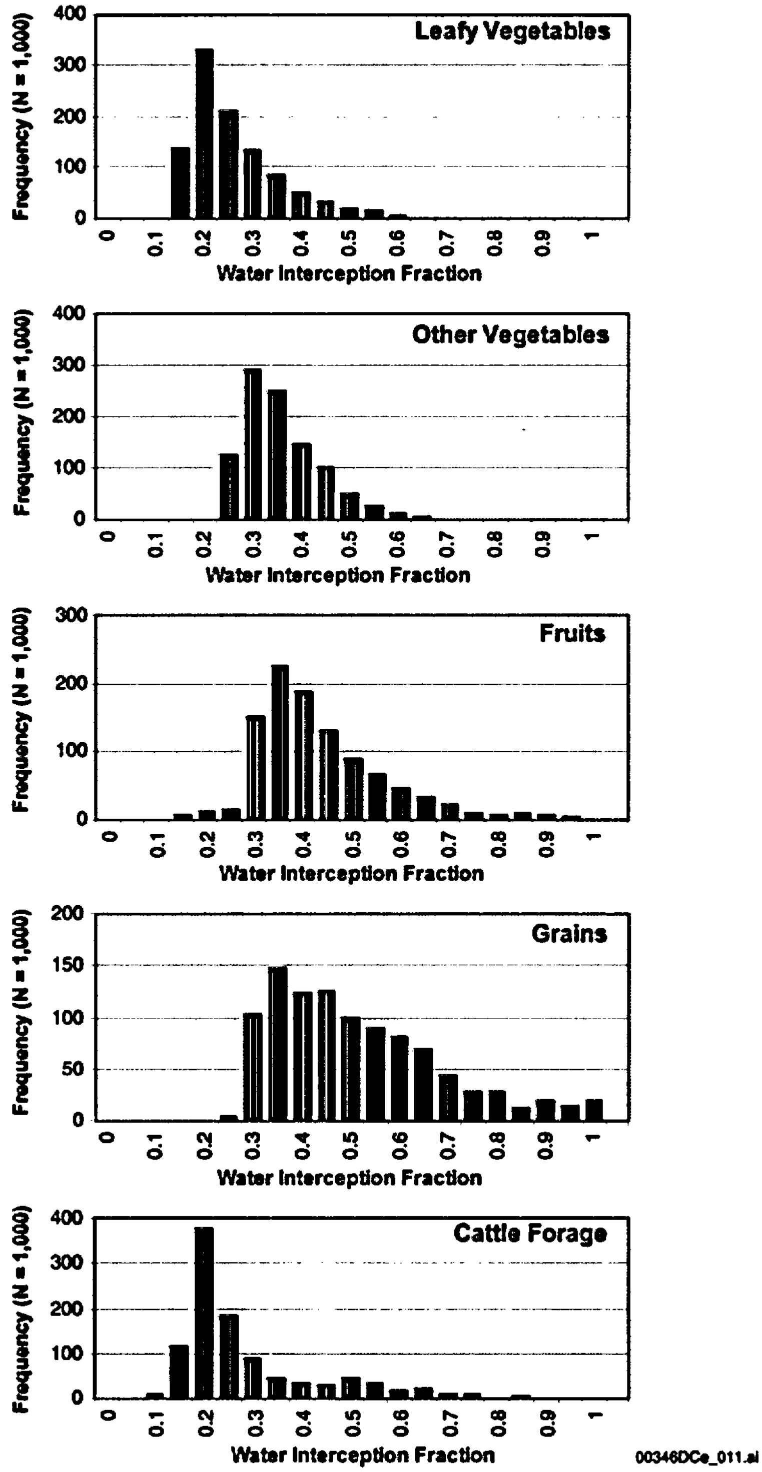
The amount of water applied during the experiments conducted to develop Equation F-1 (1 to 30 mm) (Hoffman et al. 1992) was less than the predicted irrigation requirements for some crops in the Amargosa Valley (Table F-2; BSC 2003c, Section 6.7). However, the equation is relatively insensitive to changes in irrigation amount above about 20 mm. For example, changing the irrigation amount for fruits from 20 to 60 mm (and holding the other factors constant at average values) changes the interception fraction from 0.42 to 0.31. This probably is because plant surfaces become saturated during long rainfall or irrigation events and most additional radionuclides are washed away (Hoffman et al. 1989; Hoffman et al. 1992).

Irrigation Intensity–One distribution of irrigation intensity was developed for all crop types because the rate at which water is applied during overhead or spray irrigation is influenced primarily by the type of irrigation equipment used and the infiltration rate of soils (BSC 2003c, Section 6.6). Irrigation intensity for the sprinkler types and spacings typically used in commercial agriculture ranges from less than 0.5 cm/hr to more than 10 cm/hr. Soils in the northern Amargosa Valley are sandy to sandy loam and have an infiltration rate of about 5 to 15 cm/hr. Based on this information, a uniform distribution of irrigation application with a minimum of 1.0 cm/hr and maximum of 7.5 cm/hr was selected (Table F-2; BSC 2003c, Section 6.7). A minimum value lower than the minimum infiltration rate of soils in the Amargosa Valley was selected to account for uncertainty about irrigation methods used and irrigation efficiencies in the Amargosa Valley. Although application rates higher than this value are possible for most soils in the Amargosa Valley and are likely for irrigation methods such as gardens irrigated with a hose, a higher maximum value was not selected because higher values have little influence on the calculation of water interception fractions (BSC 2003c, Section 6.6 and Figure 6.6-1). For example, an increase in irrigation intensity from 7 to 10 cm/hr results in a change in the water interception fraction for fruit from about 0.30 to 0.27. The selected distribution is within the range of 1.4 to 12.2 cm/hr used during experiments by Hoffman et al. (1992).

F.4.2 Results of Calculations

To validate the biosphere model, 1,000 stochastic simulations were conducted using, among others, the input parameter distributions shown in Table F-2 (BSC 2003a, Section 6.10.1.2 and Attachment I, ERMYN_GW_Pu239verf.gsm). Values of the crop interception fraction calculated for those simulations are summarized in Figure F-1 and Table F-3.

Water interception fractions generally are lowest for leafy vegetables and cattle forage, and they are highest for fruits and grains. The range of interception fractions also is greatest for fruits and grains, ranging from less than 0.15 to 1.0. These differences among crop types are expected because fruits and grains have the highest biomass values and greatest variation in biomass (Table F-2).



Source: BSC 2003a, Attachment I, file ERMYN_GW_Pu239verf.gsm. See Rautenstrauch 2003.

Figure F-1. Water Interception Fractions Resulting from 1,000 Simulations per Crop Type of the Biosphere Model

Table F-3. Summary Statistics for Water Interception Fraction

Crop Type	Mean	Standard Deviation	Minimum	Percentile 5	25	50	75	95	Maximum
Leafy Vegetables	0.23	0.09	0.10	0.13	0.17	0.21	0.28	0.42	0.69
Other Vegetables	0.33	0.08	0.20	0.23	0.27	0.31	0.38	0.49	0.69
Fruit	0.40	0.13	0.09	0.27	0.31	0.37	0.47	0.65	1.00
Grains	0.49	0.17	0.23	0.28	0.35	0.45	0.59	0.85	1.00
Cattle Forage	0.25	0.14	0.08	0.14	0.17	0.20	0.29	0.56	0.82

Source: BSC 2003a, Attachment I, file ERMYN_GW_Pu239verf.gsm.

NOTES: Results of 1,000 calculations of the water interception fraction using Equation F-1 and stochastic sampling of the distributions in Table F-1 for the current climate.

The distribution of calculated interception fractions for leafy vegetables (mean = 0.23, range = 0.10 to 0.69, Table F-3) is similar to that used in the biosphere model for the site recommendation (mean = 0.259, range = 0.044 to 0.474; CRWMS M&O 2000c). The mean value for cattle forage also is similar (0.25), but the maximum (0.82) is higher. The distributions of interception fractions for the other crop types (Table F-3) generally are higher than the distribution used for the site recommendation.

Hoffman et al. (1989) and Hoffman et al. (1992) measured interception fractions for beryllium of about 0.1 to 0.6. The mean of the calculated values for each crop type is within this range (Table F-3). The range of values for leafy vegetables, other vegetables, and cattle forage also generally are within the experimentally measured range. In contrast, more than about 10 percent of the calculated interception fractions for fruit, and more than 25 percent of the values for grains are greater than 0.6. This is probably because the biomass of many of those crops is at the extreme end of the experimental range. Although the validity of those high fractions cannot be conclusively determined from the experimental results, it can be concluded that they are not underestimates of the interception fraction because they are larger than the experimental values.

Anspaugh (1987) reviewed studies of the retention on vegetation of radionuclides deposited in water. Measurements of water interception fractions for numerous radionuclides and a variety of particle sizes and charges ranged from about 0.03 to more than 1.0. Mean fractions ranged from 0.06 to 0.80, with a mean of all studies of 0.38 (excluding one study with a negative mean value). Anspaugh (1987, p. 22) concluded that, for modeling purposes, an average interception fraction of 0.4 to 0.5 would be appropriate, and a value of 1.0 would not be unreasonable for a scoping model, particularly for high vegetation densities. The range of water interception fractions measured during these studies is similar to that calculated by the model (Table F-3 and Figure F-1), with highest values for crop types with the greatest biomass. The distributions of interception fractions for fruits and grains—the crop types with the greatest vegetation densities (Table F-3)—are similar to those recommended by Anspaugh (1987). Thus, the distributions calculated by the ERMYN model adequately encompass the variation in interception fractions reported by Anspaugh (1987), which addresses the concern raised by the NRC (2002, pp. 3.3.14-9 and 3.3.14-10).

In summary, it is concluded that the input parameters used in the biosphere model to calculate the water interception fraction adequately incorporate uncertainty and variation in the types of

crops grown, the growth characteristics of the crops, and the irrigation requirements. The empirical constants selected are conservative (i.e., they do not result in underestimating the interception fraction) because they are from the radionuclide having the highest interception fraction. The method used to calculate the water interception fraction in the biosphere model results in values that are similar to, or higher than, those measured during experiments of a variety of particle sizes and charges. Therefore, this method is appropriate for all radionuclides considered it adequately bounds uncertainty associated with the electrostatic charge and particle size of radionuclides and provides a reasonable expectation that the dose is not underestimated.

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APPENDIX G

LEACHING COEFFICIENTS
(RESPONSE TO TSPAI 3.36)

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application (LA) as the approved analyses of record at the time of LA submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

APPENDIX G

LEACHING COEFFICIENTS (RESPONSE TO TSPAI 3.36)

This appendix provides a response to total system performance assessment and integration (TSPAI) key technical issue (KTI) TSPAI 3.36. This KTI agreement relates to the methodology for incorporating uncertainty in soil leaching factors into the total system performance assessment (TSPA) analysis.

G.1 KEY TECHNICAL ISSUE AGREEMENT

G.1.1 TSPAI 3.36

This KTI agreement was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on Total System Performance Assessment and Integration held August 6–10, 2001 (Reamer 2001) in Las Vegas, Nevada, which was convened to discuss four TSPAI KTI subissues: (1) system description and demonstration of multiple barriers; (2) scenario analysis within the TSPA methodology; (3) model abstraction within the TSPA methodology; and (4) demonstration of the overall performance objective.

Wording of the agreement is as follows:

> Document the methodology that will be used to incorporate the uncertainty in soil leaching factors into the TSPA analysis, if that uncertainty is found to be important to the results of the performance assessment (DOSE3.3.1). DOE will document the methodology used to incorporate the uncertainty in soil leaching factors into the TSPA analysis. This will be documented in Nominal Performance Biosphere Dose Conversion Factor Analysis AMR (ANL-MGR-MD-000009), Disruptive Event Biosphere Dose Conversion Factor Analysis (ANL-MGR-MD-000003) or other document expected to be available to NRC in FY 2003.

DOSE3.3.1 in this agreement refers to NRC integrated subissue Dose 3 (NRC 2002, Table 1.1-2).

G.1.2 Related Key Technical Issue Agreement

TSPAI 3.33 covers material that is related to agreement TSPAI 3.36. TSPAI 3.33 provides information on the development of the partition coefficients (K_d) values that are appropriate, (i.e., justifiably realistic or conservative), for the conditions at the receptor location. This agreement is addressed in Appendix D.

G.2 RELEVANCE TO REPOSITORY PERFORMANCE

This agreement is based on a concern by the NRC that the uncertainty in the value of the leaching factor may be important to the results of the performance assessment but was not incorporated into the TSPA model. The GENII-S code (Leigh et al. 1993) was used for

modeling the biosphere component of the TSPA model for the site recommendation. For many input parameters, the GENII-S code permitted the user to represent input parameter values by probability distribution functions to reflect parameter uncertainty and variability. However, the leaching factor (i.e., leaching rate constant) could only be represented by a single fixed input value for all biosphere model realizations. This limitation of GENII-S resulted in the concern addressed in the TSPAI 3.36 agreement. Because of the potential importance of the radionuclide concentration in soil for the food and ingestion pathways, the new biosphere model uses a leaching submodel that stochastically samples from a distribution of K_d values and other parameters to capture the uncertainty and variability in the leaching process.

G.3 RESPONSE

The methods used to calculate radionuclide concentrations in the soil in the revised biosphere model for the license application (BSC 2003a), have been substantially modified since the site recommendation. This was done in part to incorporate uncertainty associated with the modeling of the leaching process. The biosphere model includes a soil submodel (Section 4.1 and 5.1; see also BSC 2003a, Section 6.4.1) that accounts for the addition and removal of radionuclides from surface soil. One of the removal mechanisms included in the model is leaching, which is caused by overwatering of agricultural soils. In the soil submodel, the process of leaching is quantified through the leaching removal constant. The leaching removal constant is calculated as a function of several parameters, K_d being one of these parameters (BSC 2003a, Section 6.4.1.3). Each of the parameters in the biosphere soil submodel is represented by probability distribution functions and is randomly sampled for the individual biosphere model realizations. In this process, the uncertainty and variability in the parameter values is propagated first into the value of the leaching removal constant and then into the biosphere model output. The information in this report provides a complete response to agreement TSPAI 3.36.

G.4 BASIS FOR THE RESPONSE

The surface soil submodel evaluates radionuclide accumulation in the upper layer of the soil (down to the tilling depth) where all plant roots are assumed to be located. In the groundwater scenario, the source of radionuclides in the 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 (the subject of this appendix), surface soil erosion, and radioactive decay (a removal mechanism for the parent radionuclide, but a source for the decay product). Crop removal was considered in the conceptual model, but it was not included in the mathematical model. Crop removal was excluded because the main use of crops is animal feed, and it was assumed that radionuclides would be returned to the soil by the use of manure for fertilizer (BSC 2003a, Section 5.4).

The soil submodel uses radionuclide conservation in the surface soil layer where the radionuclide concentration is considered distributed uniformly due to tilling. The change in radionuclide concentration in the soil layer is equal to the rate of radionuclide input (irrigation), minus the rate of radionuclide loss. The change in radionuclide concentration in the surface soil is time dependent. After radionuclide concentrations in the surface soil reach saturation, the rate of radionuclide addition is equal to the rate of radionuclide removal and the radionuclide concentration in the surface soil remains constant. The model uses saturation (equilibrium)

radionuclide concentrations in surface soil 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. The biosphere model was developed to generate BDCFs for a constant radionuclide concentration in groundwater (BSC 2003a, Section 5.1). The radionuclide concentration in surface soil is calculated in the biosphere model as:

$$Cs = \frac{Cw_i\, IR}{\lambda_d + \lambda_l + \lambda_e} \qquad \text{(Eq. G-1)}$$

where

Cs	=	saturation activity concentration of the radionuclide in surface soil per unit area (Bq m^{-2})
Cw	=	activity concentration of radionuclide i in the groundwater (Bq m^{-3})
IR	=	annual average irrigation rate on land (annual irrigation rate) (m yr^{-1})
λ_d	=	radioactive decay constant for the radionuclide (yr^{-1})
λ_l	=	average annual leaching removal constant for the radionuclide (yr^{-1})
λ_e	=	average annual surface soil erosion removal constant (yr^{-1}).

In the biosphere model, it is assumed that short-lived decay products are in equilibrium with the parent. The soil submodel (BSC 2003a, Section 6.4.1.2) accounts for the decay and ingrowth in the soil of the long-lived radionuclides not tracked in the TSPA (BSC 2002).

The annual average irrigation rate, IR, in Equation G-1 is developed based on irrigation rates for the crops grown in Amargosa Valley. The typical range of irrigation rates is from 0.5 to 1.0 m/yr (BSC 2003b, Section 6.5). The average irrigation rate is time-dependent because of climate changes predicted for the Yucca Mountain region over the time period of interest. However, as stochastic BDCFs are defined for each climate state predicted to occur to 10,000 years in the future, the average irrigation rate for a given climate is not a function of time (i.e., $IR(t) = IR$).

The surface soil erosion removal 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 the uniform surface erosion from occasional heavy precipitation (an important contributor to erosion in the future climate). The value of this radionuclide-independent parameter is strongly site-specific and depends on environmental characteristics and land use.

The process of leaching radionuclides from the surface soil is evaluated using element-specific leaching removal constants (BSC 2003a, Section 6.4.1.3). The leaching removal constant for each radionuclide (λ_l) is calculated using a relationship developed by Baes and Sharp (1983) as

$$\lambda_l = \frac{OW}{d \times \theta \left(1 + \frac{\rho}{\theta} K_d\right)} \qquad \text{(Eq. G-2)}$$

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 $_{solid}$)

In arid regions, the overwatering rate usually is determined by calculating the amount of water required to transport accumulated salts out of the surface soil to maintain productivity. The value of this parameter is on the order of 10 cm/yr (BSC 2003b, Section 6.9). 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), with typical values of about 0.2 to 0.3. Partition coefficients depend on soil characteristics, with values ranging over several orders of magnitude (with geometric means from 0.14 L/kg for technetium to 3.6×10^3 L/kg for radium) (BSC 2003c, Section 7.2).

With the exception of the radionuclide concentration in groundwater (taken to be unity for calculation of BDCFs) and the radionuclide decay constant, most other parameters, including those that determine the leaching rate, in the soil submodel are represented by distributions to reflect parameter uncertainty and variability. Propagation of the parameter uncertainties and variabilities into the model output is accomplished by using stochastic sampling. This includes uncertainty in the values of parameters that influence the modeling of radionuclide removal from surface soil by leaching.

In the groundwater scenario, the area of land affected by radionuclide buildup is limited. The size of this area can be estimated because groundwater use is limited to 3,000 acre-feet/yr (10 CFR Part 63). A typical crop in an agricultural plot in Amargosa Valley requires 5 to 8 feet of water annually, which implies that the land area under cultivation at the location of the receptor would be about 600 acres (a square mile is 640 acres). In the volcanic eruption scenario, the extent of the ash (either direct or from redistribution) is much larger and is effectively a distributed source with only a small part being on irrigated land. Because irrigation is needed to initiate leaching, the leaching process can only apply to a small fraction of the affected area. In the biosphere model, no credit is taken for leaching when generating BDCFs for volcanic ash exposure scenario. Therefore, the KTI TSPAI 3.36 issue is not relevant to the volcanic ash scenario.

In summary, one modification of the biosphere model for license application has been the development of an enhanced soil submodel. The revised soil submodel treats the process of radionuclide buildup in soil in a stochastic manner, with leaching and erosion considered as removal mechanisms. The submodel allows distributions to be used for most parameters to incorporate uncertainty in the leaching and erosion processes. These uncertainties are propagated through the entire biosphere model to the BDCF distributions that are used in the TSPA to calculate annual dose.

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