A Biosphere Sensitivity Analysis Using BDOSE™ Version 2.0

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ABSTRACT

The Ronald W. Reagan National Defense Authorization Act of 2005 requires the U.S. Department of Energy (DOE) to consult with the U.S. Nuclear Regulatory Commission on non-high-level waste determinations. These consultations evaluate whether DOE can demonstrate that the Ronald W. Reagan National Defense Authorization Act of 2005 criteria, including dose-based performance objectives found in 10 CFR Part 61, Subpart C, can be met.

These consultations will likely involve the review of performance assessments, which stochastically evaluate fate and transport of radionuclide releases. Biosphere models will be an important component of these performance assessments. The description of a biosphere used within a modeling analysis typically contains a large number of parameters, which are often derived from national or regional data. Identifying the influence of these input parameters is a key step in evaluating the model output. Because of the large number of parameters in a biosphere model, it is important to identify and focus on parameters that significantly influence risk or dose estimates.

Using the biosphere radiological does model (BDOSE™) Version 2.0, a sensitivity analysis has been performed. The result of this sensitivity analysis is an assessment of model parameter significance for a selected set of radionuclides. In addition, pathway dose contributions for individual radionuclides are provided using box-whisker plots.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT DATA

DATA: No CNWRA-generated original data are contained in this report. Sources of other data should be consulted for determining the level of quality of those data.

ANALYSES AND CODES: The Biosphere Dose (BDOSE™) assessment code (Mancillas, 2008) software was used to generate results for this report and is controlled in accordance with the CNWRA Technical Operating Procedure (TOP)–018, Development and Control of Scientific and Engineering Software. GoldSim [registered trademark of GoldSim Technology Group, LLC (2003)], Mathematica® (Wolfram Research, Inc., 2004), and Microsoft® Excel® 2002 (Microsoft Corporation, 2002) were also used but are considered uncontrolled software in accordance with TOP–018.

References:

GoldSim Technology Group LLC. GoldSim (registered trademark of GoldSim Technology Group LLC). "User's Guide: GoldSim Contaminant Transport Module." Issaquah, Washington: GoldSim Technology Group LLC. 2003.

Mancillas, J.W. "BDOSE™ Version 2.0." San Antonio, Texas: CNWRA. 2008.[1]

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[1]Copyright 2007 by Southwest Research Institute®. BDOSE 2.0 was originally prepared by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–02–012.

1 INTRODUCTION

The Ronald W. Reagan National Defense Authorization Act of 2005 (NDAA) requires the U.S. Department of Energy (DOE) to consult with the U.S. Nuclear Regulatory Commission (NRC) on non-high-level waste determinations. These consultations evaluate whether DOE can demonstrate that the NDAA criteria, including dose-based performance objectives found in 10 CFR Part 61, Subpart C, can be met.

To support these consultations, Center for Nuclear Waste Regulatory Analyses (CNWRA®) and NRC staffs have developed a biosphere radiological dose model (BDOSE™) in the GoldSim [registered trademark of GoldSim Technology Group, LLC (2003)] probabilistic simulation environment. BDOSE (Mancillas, 2008) probabilistically calculates radiological doses to potential receptors from groundwater radionuclide contaminant concentrations and environmental parameters. Exposure pathways include direct exposure from radiologically contaminated ground surface, air, and water; internal exposure from inhalation of air; and ingestion of drinking water, crops, animal products, and soil. BDOSE Version 2.0 is detailed in Simpkins, et al. (2008).

This report documents the use of BDOSE Version 2.0 in a sensitivity analysis performed for the Savannah River Site (SRS) in South Carolina. An accurate characterization of this site required the development of a detailed, site-specific biosphere data set. The development process for this data set was consistent with NRC guidance [such as NUREG–1549 (NRC, 1998), NUREG–1757 (NRC, 2006), and NUREG/CR–5512 (Beyeler, et al., 1999)], which recommends an iterative and hierarchical approach to data set development. For this analysis, data were first compiled from generic NRC and other accepted guidance [i.e., International Atomic Energy Agency (IAEA) Technical Reports Series (TRS)–472 (IAEA, 2010), Federal Guidance Reports No. 11 (EPA, 1988) and 12 (EPA, 1993), and NUREG/CR–5512 (Beyeler, et al., 1999)]. The data set was then refined by considering regional and site-specific data, where available. The refined data set was then used as a basis for the sensitivity analyses to quantify the significance of parameter uncertainty or environmental variability on dose estimates. These results were then evaluated to elucidate the risk significance of individual radionuclides within the biosphere modeling domain and to identify influential model parameters for each radionuclide.

This report is presented in several parts. Chapter 2 provides a general description of the receptor scenario and significant modeling assumptions for the sensitivity analysis. Chapter 3 then provides detailed descriptions and discussions about the parameter values and distributions used to describe the environment and receptors. Chapter 4 describes the analytical method used to perform the sensitivity analysis, and Chapter 5 presents results and conclusions drawn from the sensitivity analyses. Appendix A provides additional plots of radionuclide dose distributions by pathway. BDOSE Version 2.0 conceptual and mathematical models are described in Appendix B of this report.

2 GENERAL MODELING ASSUMPTIONS AND SCENARIO DESCRIPTION

The biosphere modeling evaluated in this sensitivity analysis implements a conceptual model that defines the general features and processes of the biosphere and receptor that facilitate the transport of radionuclides through the biosphere pathways and expose the receptor to radiation. This conceptual model, hereafter referred to as exposure scenario, consists of a defined receptor, the physical environment where the receptor lives (the biosphere), and descriptions of how the receptor interacts with the biosphere to lead to radiation exposure. Within this report, the description of the biosphere and receptor are addressed in two parts. This chapter provides a high-level description of the exposure scenario and important modeling assumptions associated with the performance of this sensitivity analysis. Chapter 3 provides detailed descriptions and bases for the selected BDOSE model input parameter values and distributions that implement the exposure scenario described in this chapter.

The exposure scenario used for the sensitivity analysis considers an individual member of a hypothetical community that is located in the vicinity of SRS downgradient along the path of groundwater flow. The characteristics of the receptor and community that are important for modeling the biosphere pathways and dose have been defined based on evaluation of applicable site- or region-specific information that is documented in Chapters 2 and 3 of this report. The objective of the exposure scenario is to include local and regional practices, including agricultural, residential, and recreational activities, that would be expected to facilitate human exposure to postulated site releases rather than to pinpoint a specific subgroup of individuals with a more limited set of practices. Based on this inclusive approach, the receptor modeled for this analysis is expected to receive a dose that is higher than the average member of the community but not so conservative as to be considered implausible. Where site- or region-specific information is not available, information was obtained and assumptions were made that are considered to be generally applicable for use in a variety of dose assessment activities.

Biosphere models, including BDOSE, are general and stylized in many respects. While the exposure scenario is intended to apply to conditions surrounding SRS, the resulting parameterized site-specific model used for this sensitivity analysis is intended to be applicable to regional characteristics surrounding SRS rather than any specific location relative to the facility nor any specific individual who may presently live there. Parameters and pathways were selected to be reasonably conservative so that the model would produce results that would be protective of the majority of individuals in the population surrounding the site without being excessively conservative. The generalization of the exposure scenario allows flexibility in applying it to dose calculations that may be applicable to a variety of specific locations (and subpopulations surrounding SRS).

The implementation of the exposure scenario in the BDOSE model involves use of the residential receptor modeling option (rather than the intruder receptor option or the recreational receptor option). The residential receptor modeling option in BDOSE provides a complete set of biosphere pathway models to implement the planned calculations that involved a variety of agricultural, residential, and recreational activities.

Because only 25 percent of farms in Georgia and 16 percent of farms in South Carolina are irrigated (USDA, 2007a,b), the inclusion of irrigation in the exposure scenario used for this sensitivity analysis is a conservative selection and therefore more closely represents a critical group style of analysis (i.e., selection of a hypothetical receptor for dose modeling that is based on local and regional characteristics and conceptually represents a segment of the local population that would be expected to receive higher exposures from postulated radionuclide releases relative to the general population).

2.1 Radionuclide Source-Term Assumptions

BDOSE calculates radiation dose to an individual human receptor resulting from the introduction of radionuclides into the biosphere. While this model is capable of calculating doses from a large, predefined set of radionuclides (see Simpkins, et al., 2008, for more detail), this sensitivity analysis focuses on a subset of radionuclides listed in Table 2-1.

The radionuclides were selected based on expected radionuclide risk significance with respect to current understanding of waste incidental to reprocessing. In the model, an assumed water well pumps radionuclide-contaminated groundwater to the surface to support a variety of water uses that facilitate transport of radionuclides within the biosphere and lead to receptor dose. To expand the applicability of this sensitivity analysis, generalized source terms have been used. For the groundwater scenario that was evaluated, the source was defined as an assumed 1-pCi/L concentration of each radionuclide at the water uptake point (e.g., well).

Using unit concentrations allows for comparison between the results of this analysis and other analyses and provides a simple route to use the results of this analysis to develop biosphere dose conversion factors for radionuclide-specific total effective dose equivalents (TEDE).

2.2 Water

BDOSE can model several different water types, including groundwater, rivers and streams, and ponds. The latter two water types were implemented as diluted derivatives of groundwater, with their concentrations determined by separate dilution calculations. For the sensitivity analysis documented in this report, several modeling assumptions were made regarding water consumption and dilutions, as follows:

- Water ingested by the residents is assumed to be groundwater with a 1-pCi/L concentration of each radionuclide evaluated. The radionuclide concentration in this water is assumed to be unaffected by any treatment and filtration process.

- Water used for irrigation is assumed to be groundwater with a 1-pCi/L concentration of each radionuclide evaluated. The concentration of radionuclides in this water is assumed to be unaffected by any treatment and filtration processes.

- Water ingested by livestock and used for irrigation is assumed to be groundwater with a 1-pCi/L concentration of each radionuclide evaluated. The concentration of

Table 2-1. Radionuclides for Sensitivity Analysis

C-14	Tc-99	Th-230
Se-79	I-129	Np-237
Sr-90	Cs-137	U-233, 234, 236, and 238
Y-90	Pb-210	Am-241
Nb-94	Ra-226	Pu-239, 240, and 242

radionuclides in this water is assumed to be unaffected by any treatment and filtration process.

- Water used for recreation, such as boating and swimming, is modeled as river and stream waters that have radionuclide concentrations set to one-twentieth that of the groundwater concentration. This modeling assumption is a reasonably conservative estimate. This estimate is based on the assumptions that (i) small tributaries to large flowing water bodies may be primarily fed by groundwater (contaminated) seeps at their heads and (ii) the bulk of water in large flowing water bodies is composed of water that is derived from waters containing little or no radionuclides.

- Fish, which have radionuclide concentrations proportional to the water they inhabit, are assumed to live in river and stream waters, which have radionuclide concentrations set to one-twentieth of the groundwater. This modeling assumption, which also applies to recreational water, is made based on the assumptions that (i) small tributaries to large flowing water bodies may be primarily fed by groundwater (contaminated) seeps at their heads allowing for dilution with natural water during transport to the water body and (ii) the bulk of water in large flowing water bodies is composed of water that is derived from waters containing little or no radionuclides.

2.3 Soil

BDOSE can model five types of soil, including four commonly identified soil types: sandy, loam, clay, organic, and a fifth user-defined soil. Each soil type is defined by a set of radionuclide-specific partition coefficients that model the process of sorption (i.e., retention) of infiltrating radionuclides onto soil particles. Of these soil types, the first four are based on soil descriptions given by Sheppard and Thibault (1990) and data provided in TRS–472 (IAEA, 2010). For this sensitivity analysis, a user-defined soil was selected so an updated set of distribution coefficients could be used. Site-specific soil survey results in Washington Savannah River Company (WSRC) (2006) indicate SRS soils are predominantly sandy. Individual radionuclide partition coefficients applicable to sandy soils and distribution statistics were selected from available sources (Section 3.2.1). The correlation of partition coefficient input parameter sampling with the sampling of other biosphere input parameters was considered but not implemented in the sensitivity analysis. Sheppard and Sheppard (1989) describe studies that support a negative correlation between partition coefficients and concentration ratios (i.e., plant transfer factors). This correlation was not included in the sensitivity analysis because the plant transfer factors were not sampled. Sheppard and Sheppard (1989) provide a recommended value (−0.7) for that correlation which could be used in future analyses. Currently, the GoldSim software accommodates input correlation for only simple *one-to-one* parameter correlations and does not presently support a *one-to-many* type of correlation that would be necessary to correlate the sampling of partition coefficients and plant transfer factors.

For this sensitivity analysis, the modeled soil contamination is derived from deposition of contaminated groundwater, for which an equilibrium model (i.e., BDOSE Soil Model 3) was used. This soil model assumes the soil is in equilibrium with groundwater concentrations, where the equilibrium values are dependent on groundwater contaminant concentrations, irrigation and erosion rates, soil retention properties, plow depths, and several other parameters (see Simpkins, et al., 2008, Section 2.3.2.1 and Soil Model 3).

The results of these soil modeling assumptions for soils contaminated by contaminated groundwater are summarized next.

- Radionuclide concentrations in the soil are calculated based on the equilibrium soil model in BDOSE that was derived from concepts Baes and Sharp (1983) described. More specifically, the radionuclide soil concentrations are calculated assuming steady state conditions for the year of the dose calculation. The calculated soil concentration is the product of the annual radionuclide-specific irrigation deposition rate and a factor that approximates the average residence time of the radionuclide in soil (calculated as the inverted sum of the first order removal rate constants for decay, leaching, and erosion). The calculated soil concentration can be described conceptually as the total radionuclide accumulation in soil based on the annual deposition rate occurring for the average residence time. This modeling assumption therefore does not address the significance of time-varying deposition and buildup or loss of radionuclides in the environment. However, the approach is a reasonable yet conservative option for conducting long-term biosphere dose assessments from time-varying releases as part of a total system performance assessment model because the approach approximates soil retention of radionuclides from multiple years of irrigation, as applicable, based on a single estimate that is practical and conservative for the radionuclides in this sensitivity analysis.

- Individual radionuclide partition coefficients are sampled from independent, uncorrelated distributions. While a correlation between radionuclide soil partition coefficients is plausible, the significance of this correlation affects only the total dose. However, because this sensitivity analysis examines parameter significance on an individual radionuclide basis, this assumption has no effect on the analysis.

- Correlation of partition coefficients with plant transfer factors, described in previous studies as summarized by Sheppard and Sheppard (1989), was not implemented in this analysis, because plant transfer factors were not sampled. Sampling plant transfer factors would have added variability to output, but initial tests showed sampling the transfer factors was not affecting sensitivity analysis results. Sheppard and Sheppard (1989) indicate adding correlations between partition coefficients and plant transfer factors would be expected to increase the range of calculated doses but may not affect mean dose results.

2.4 Receptor

The biosphere modeling conducted for the sensitivity analysis was based on a resident exposure scenario. The resident scenario describes the residential use of property and groundwater for drinking and irrigation of a small farm or garden that produces crops and animal products to support the modeled consumption of locally derived food. This scenario includes consideration of recreational activities such as swimming, boating, and fishing. While the BDOSE model includes the capacity to model a recreational scenario separate from the resident scenario, the sensitivity analysis calculations were performed using only the resident BDOSE model because the recreational activities are also included in that model.

The resident scenario pathways include

- Ingestion of contaminated water

- Ingestion of contaminated soil
- Ingestion of crops irrigated with contaminated water and grown in contaminated soil
- Ingestion of animal products raised with contaminated feed, water, and soil
- Ingestion of fish raised in contaminated waters (if present)
- Inhalation of resuspended contaminants and radioactive gases (C-14 and H-3)
- External exposure from contaminated soil
- External exposure from contaminated waters (via swimming and boating activities)
- External exposure from resuspended contaminants and radioactive gases

Dose to the receptor is evaluated using dose coefficients, which convert human radionuclide intake (e.g., ingestion, inhalation) or direct exposure to radiation from a contaminated ground surface into dose values. For this sensitivity analysis, these dose coefficients are those described in Federal Guidance Reports No. 11 and 12 (EPA, 1988, 1993). When a choice of dose coefficient values was available in the source documents, the maximum values were selected.

3 INPUT PARAMETER DATA FOR THE BIOSPHERE MODEL

The purpose of this sensitivity analysis is to identify and evaluate the importance of the environmental and behavioral characteristics that most affect dose assessments of SRS using the BDOSE™ assessment code. Figure 3-1 shows the location of SRS in the south central region of South Carolina along the Savannah River, which establishes the border between South Carolina and Georgia. This environment is characterized by a subtropical climate on the Atlantic Coastal Plain with predominantly sandy soils at elevations between 76 and 122 meters above sea level and clayey soils along the lower fertile stream terraces and floodplains. The landscape in the SRS region supports abundant terrestrial and aquatic wildlife, including several commercially and recreationally important species. In addition to the Savannah River, which provides the major source of drinking water in the area, the SRS region contains extensive surface-water features including lakes, reservoirs, streams, numerous creeks, and marsh lands. These surface waters support recreational activities (e.g., swimming and boating), as well as commercial and sport fishing.

To develop an accurate description of this area of interest, a literature search was performed to identify regional climate and agricultural data, as well as behaviors representative of regional receptor lifestyles. During the initial search, several key references where identified, from which most of the input parameter values were derived for use in the BDOSE sensitivity analysis. These references are identified in Table 3-1.

Table 3-1. Primary References for BDOSE Parameter Values

Reference	Title
Lee and Coffield (2008)	Lee, P.L. and T.W. Coffield. “Baseline Parameter Update for Human Health Input and Transfer Factors for Radiological Performance Assessments at the Savannah River Site.” Aiken, South Carolina: Savannah River National Laboratory, Washington Savannah River Company. 2008.
IAEA (2010)	IAEA. “Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments.” Technical Reports Series No. 472. Vienna, Austria: International Atomic Energy Agency. 2010.
Staven, et al. (2003)	Staven, L.H., K. Rhoads, B.A. Napier, and D.L. Strenge. “A Compendium of Transfer Factors for Agricultural and Animal Products.” PNNL–13421. Richland, Washington: Pacific Northwest National Laboratory. 2003.
EPA (1997)	EPA. “Exposure Factors Handbook.” EPA/600/P–95/002Fc. Vols. 1–3. Washington, DC: EPA, Office of Research and Development. 1997.
Beyeler, et al. (1999)	Beyeler, W.E., W.A. Hareland, F.A. Duran, T.J. Brown, E. Kalinina, D.P. Gallegos, and P.A. Davis. NUREG/CR–5512, “Residual Radioactive Contamination From Decommissioning, Parameter Analysis, Draft Report for Comment.” Vol. 3. Washington, DC: NRC. 1999.

3.1 Regional Agricultural Information

Agricultural conditions in the counties surrounding SRS have been described by Hamby (1991) and more recently by the U.S. Department of Agriculture (USDA) Census of Agriculture (USDA, 2007c–i). This regional agricultural information was reviewed to gain insights to local characteristics and practices to support the development of a generally applicable exposure scenario that is representative of the region. Data sources that form the bases for specific input parameter choices are cited, as applicable, in following sections that provide detailed descriptions of specific input parameter values.

Hamby (1991) surveyed agricultural extension agents in the region regarding livestock grazing habits, sources of forage, beef preparation practices, and vegetable production. This reference described beef and milk production in the region with local farmers relying predominantly on forage for feed. Hamby (1991) also noted that hogs and chickens are raised locally, although they are normally fed commercial feed rather than locally derived feed. Agricultural vegetable production was associated mostly with home gardens.

According to the 2007 Census of Agriculture (USDA, 2007c–f), the nearby Georgia counties of Columbia, Richmond, Burke, and Screven reported top livestock inventory as cattle and calves and laying chickens. In South Carolina, Aiken and Barnwell Counties reported top livestock inventory as broilers and meat chickens, laying hens, and cattle and calves (USDA, 2007h–i). Allendale County, South Carolina, reported cattle and calves as top livestock inventory (USDA, 2007g). Top agricultural crops for these counties included forage (e.g., hay, haylage, grass silage, greenchop), soybeans, nuts, corn for grain, and wheat for grain (USDA, 2007c–i). Fruits and berries were not reported as top crops for any of the counties; however, they were listed as commodities produced in all the aforementioned counties in the vicinity of SRS. The available information supports an exposure scenario that includes raising livestock for local beef and milk; producing poultry and eggs; and growing crops that include forage for livestock feed, garden vegetables, grains, and fruit.

3.2 Soil

In the groundwater contamination scenario, the radionuclide concentration in agricultural soil was modeled to approximate a soil in equilibrium with the radionuclide input from irrigation deposition and radionuclide losses from leaching, soil erosion, and radionuclide decay. A variety of input parameters affect this equilibrium, including soil irrigation rates, precipitation and evapotranspiration rates, soil sorption coefficients, soil depth, and water content. The BDOSE model uses separate irrigation rate input parameters for calculating soil concentrations and for modeling deposition of radionuclides from irrigation water to plant surfaces. Therefore, the irrigation input described in this section applies only to calculating soil radionuclide concentrations. The calculated soil concentrations are subsequently used in the model as a source of radionuclides that is available for further biosphere transport from soils to crop and animal products. Additional irrigation parameters that are used to calculate plant surface deposition from irrigation of crops are described in Section 3.3. For the radionuclides H-3 and C-14, the soil model also considers losses by the process of off gassing. For a detailed description of the BDOSE soil model, see Appendix B. The following sections describe the selected soil model input parameters in more detail.

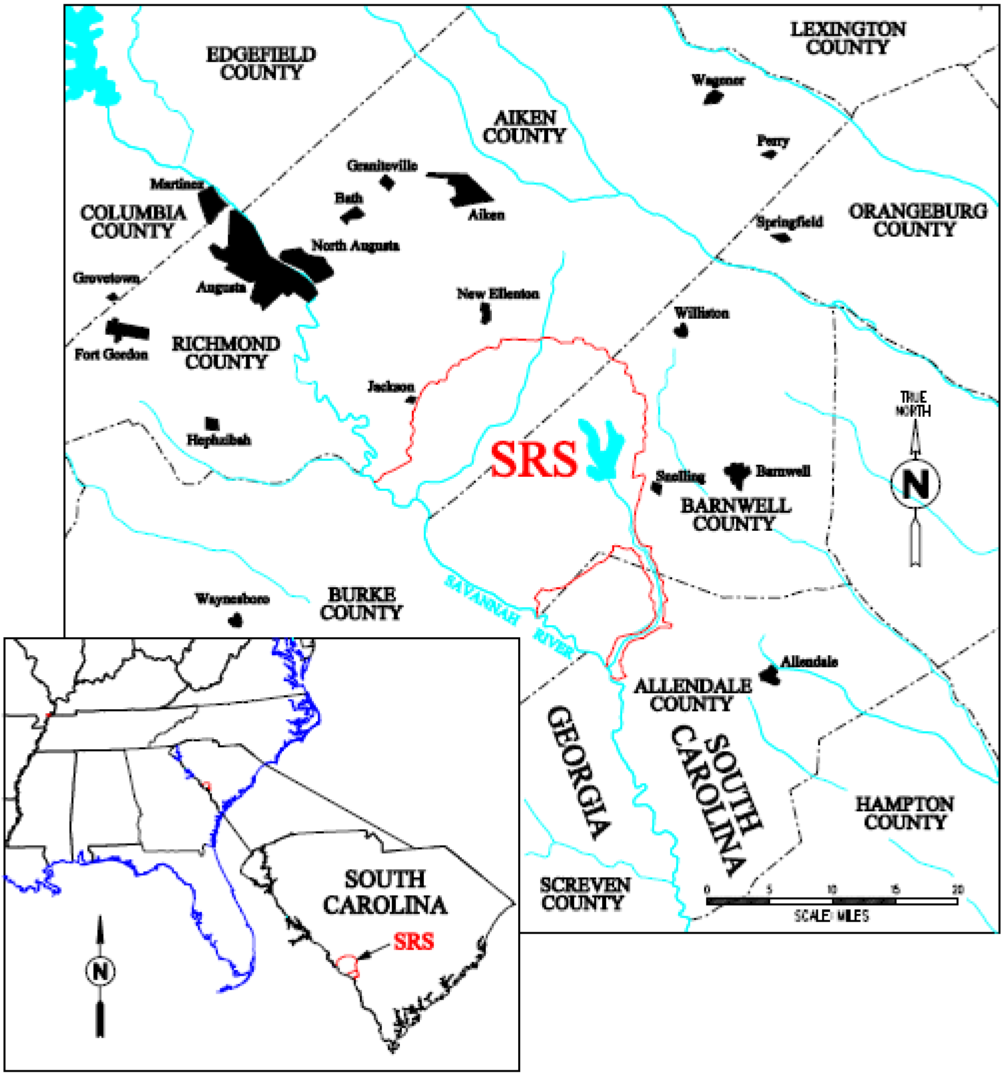


Figure 3-1. Location of Savannah River Site (Savannah River Remediation Closure and Waste Disposal Authority, 2009)

3.2.1 Soil Distribution Coefficients

The processes that facilitate transfer of radionuclides in infiltrating irrigation water to soil particles, or sorption (as well as the reverse of this process, leaching) are approximated in the model by the use of soil distribution coefficient input parameters. Specifically, these inputs are called soil solid to liquid partition coefficient or distribution coefficient and are commonly defined as the ratio of the radionuclide activity concentration in soil to the radionuclide activity concentration in the infiltrating water.

Distribution coefficients are highly variable input parameters that are ideally derived from site-specific measurements. This sensitivity analysis involved a large number of radionuclides where no site-specific values could be located; therefore, soil distribution coefficient (K_d) values were selected from two literature compilations: Beyeler, et al. (1999), which builds upon data Sheppard and Thibault (1990) reported; and TRS-472 (IAEA, 2010), a recently published update to the prior IAEA (1994) compilation. While Sheppard and Thibault (1990) had reported values by soil texture and noted an effect of soil texture on K_d values for some elements, the values reported in Beyeler, et al. (1999) are not stratified by soil type, because their statistical correlation analysis of the data could not justify a functional relationship between soil type and K_d value. Values from IAEA TRS-472 (2010) were reported either by soil type (sand, loam, or clay) or class (mineral or organic) or as pertaining to “all soils,” depending on data availability. Because the environment of interest is predominantly composed of sandy soils (WSRC, 2006), values selected from IAEA TRS-472 (2010) were preferentially selected as either sand, mineral, or all soils. To benefit from the most recent research, values were selected preferentially from the most recent literature compilation (IAEA, 2010) unless that compilation had reported no values orprovided no distribution information, or the alternative source had derived values based on a much larger number of data points.

Table 3-2(a) lists the K_d values and distributions selected for this sensitivity analysis. Distributions are assumed lognormal, which is consistent with discussions of K_d distributions in the referenced studies that evaluated original data IAEA (2009, 2010), Sheppard and Thibault (1990), and Beyeler, et al. (1999). IAEA (2009) indicates partition coefficients are typically lognormally distributed, but does not provide detailed discussion. Sheppard and Thibault (1990) cite prior studies that support the lognormal assumption and do not elaborate further on the shape of the distribution. Beyeler, et al. (1999) evaluated a large experimental data set (ranging from 4 to 564 data values per element) and conducted curve fitting on logtransformed data resulting in a normal fit for most of the elements (which translates to a lognormal distribution for the raw data). The only exception to the reported data distribution from the source report used in this sensitivity analysis was identified for C-14. For the carbon element, the logtransformed distribution coefficient data were curve fitted to a lognormal distribution in Beyeler et al. (1999); therefore, the use of the lognormal distribution assumption for the raw data values (what was done for this analysis) would be a conservative selection. For the sensitivity analysis, most distributions were bounded at both the lower and upper reported data values to avoid sampling values outside the reported data range. Additionally, the number of data points used to derive each radionuclide K_d distribution and the data source have been provided in Table 3-2(a).

3.2.2 Precipitation, Irrigation, and Other Soil Parameters

The radionuclide concentration in agricultural soil has been modeled to approximate soil that is in equilibrium with the radionuclide input from irrigation deposition and the radionuclide losses from leaching, soil erosion, and radionuclide decay. Soil model input parameters used to calculate irrigation deposition to soil and the leach rate and soil erosion rate constants that are used in the BDOSE soil concentration calculations are provided in Table 3-2(b). Conceptually, the leach rate constant calculated in BDOSE models the effect of infiltrating water in the soil column leaching sorbed radionuclides from the soil solids. This model includes soil properties such as density, depth, water content, and K_d, and estimates the amount of infiltrating water based on irrigation and precipitation input and losses from evapotranspiration (i.e., water balance). This model does not explicitly account for runoff processes nor was runoff implicitly included in the derivation of the input parameters (i.e., all irrigation and rainfall water were assumed to be water that infiltrates the soil). The water balance input data are principally derived from sources [see Table 3-2(b)] that are representative of the environment of interest and have been adapted to address BDOSE modeling assumptions.

The annual soil irrigation rate was based on state-level data collected in 2008 (USDA, 2010) as part of a separate farm and ranch survey for the 2007 USDA Agricultural Census. That survey reported the annual volume of irrigation water applied per acre as 0.828 ac-ft/ac for

Table 3-2(a). Soil Distribution Coefficients (K_d)						
Element (Radionuclide)	**Geometric Mean (L/kg)**	**Geometric Standard Deviation**	**Minimum Value (L/kg)**	**Maximum Value (L/kg)**	**Number of Data Points**	**References*†**
Carbon (C-14)	20.9	6.16	0	100	66	Beyeler, et al. (1999)†
Selenium (Se-79)	56	5.2	4	1,600	15	IAEA (2010) (TRS-472)
Strontium (Sr-90)	31.6	8.32	10	100	539	Beyeler, et al. (1999)
Yttrium (Y-90)	794	25.1	0	unbounded	15	Beyeler, et al. (1999)
Niobium (Nb-94)	631	25.1	1	5,012	nd	Beyeler, et al. (1999)‡
Technetium (Tc-99)	7.41	21.4	0	5	206	Beyeler, et al. (1999)
Iodine (I-129)	7	5.2	0.01	540	196	IAEA (2010) (TRS-472)
Cesium (Cs-137)	447	10.2	100	10,000	564	Beyeler, et al. (1999)
Lead (Pb-210)	220	3.6	25	1300	9	IAEA (2010) (TRS-472)
Radium (Ra-226)	1,900	12	12	120,000	39	IAEA (2010) (TRS-472)
Thorium (Th-230)	2,600	10	35	250,000	25	IAEA (2010) (TRS-472)
Uranium (U-233, U-234, U-236, and U-238)	180	13	0.7	67,000	146	IAEA (2010) (TRS-472)
Neptunium (Np-237)	20	3.6	1.3	120	22	IAEA, 2010 (TRS-472)
Plutonium (Pu-239, Pu-240, and Pu-242)	955	6.61	316	100,000	205	Beyeler, et al. (1999)
Americium (Am-241)	1,440	23.4	100	100,000	219	Beyeler, et al. (1999)

*Complete reference information can be found in Chapter 6.
†Values were selected preferentially from the most recent literature compilation (IAEA, 2010) or from Beyeler, et al., (1999) when values were derived based on a much larger number of data points than the preferred reference. A few values were selected from Beyeler, et al. (1999) because either the preferred source reported no values (references marked with †), or provided no distribution information (references marked with ‡).

South Carolina and 0.870 ac-ft/ac for Georgia. These values were converted to 25.2 and 26.5 cm/yr and an approximate midpoint value rounded to 25.4 cm/yr was selected as representative of the region. Because the leach rate model estimates infiltrating water on an annual basis, the values for precipitation and evapotranspiration (referred to as evaporation rate in BDOSE) were selected based on annual average data. Local climate information was obtained from the South Carolina State Climatology Office (SCSCO) (2010a,b), including average annual rainfall and pan evaporation rates. The pan evaporation values have been multiplied by 0.7 to approximate evapotranspiration rates based on information in

Table 3-2(b). Soil Parameters—Loss Rate Inputs		
Parameter	**Value**	**References**
Soil irrigation rate	0.25 m/yr	Representative value based on state annual irrigation rates for South Carolina and Georgia (USDA, 2010)*
Precipitation rate	1.23 m/yr	1948 to 2005 average annual precipitation for Aiken, South Carolina [South Carolina State Climatology Office (SCSCO) (2010a)]
Evaporation rate	1.10 m/yr	1953 to 1992 average annual pan evaporation for Athens, Georgia (SCSCO, 2010b)
Soil density	1600 kg/m^3	Lee and Coffield (2007, Table 2)
Plow depth	0.15 m	Lee and Coffield (2007, Table 2)
Volumetric water content of soil	0.15	Baes and Sharp (1983)
Soil erosion rate	1.05 $kg/m^2/yr$	National average annual cropland soil erosion value for 2003 of 4.7 tons/acre (USDA, 2003)
*Complete reference information can be found in Chapter 6.		

SCSCO (2010a,b). Pan evaporation is a commonly used method for measuring evaporation rates, however, the correction is necessary because water evaporates faster from a pan than from the natural environment.

Other input parameters used for the calculation of the leach rate constant in the soil model include the soil density, plow depth, and soil water content. These physical parameters are do not exhibit wide variability and are therefore treated as constants. The soil density was obtained from SRS dose assessment support documents. The plow depth is also from SRS documents, but it matches a commonly used 15 cm value. A soil–water content for SRS soils was not identified; therefore, the water content of the soil is the midpoint between reported geometric mean values for field capacity and wilting point for sandy loam soils as provided by Baes and Sharp (1983) for the leach rate model. The reported values are based on an analysis of 48 pasture and cropland soils. Baes and Sharp (1983) recommend using the midpoint values between wilting point and field capacity as a reasonable choice when data are not available.

The erosion rate is used in the model to calculate the erosion rate constant that accounts for annual losses of radionuclide from erosion for the calculation of soil concentration. The value selected for the sensitivity analysis is a national value that includes both wind and water erosion. A national value was used because no wind erosion data for South Carolina or Georgia were located.

3.3 Crops

Agricultural crops grown for human consumption are identified in BDOSE as grain, fruits, vegetables, and leafy green vegetables. In addition, the model includes crops grown explicitly for livestock feed, such as beef grain, milk grain, poultry grain, egg grain, as well as a generic feed referred to as fodder (i.e., forage). The edible portions of these crops incorporate contaminants via uptake from direct deposition of contaminated irrigation water and from contaminated soil through both the root system and through soils deposited on leaf surfaces (for a more detailed model description see Appendix B).

In general, the extent to which these contaminants are incorporated into crop material is determined by

- Crop irrigation rates and durations
- Crop yields and growth durations
- The extent of contaminant transfer from the soils into the edible portion of the crops
- The extent of contaminant transfer from irrigation water deposited onto plant surfaces

The irrigation rates and durations, crop growth durations and yields, and plant transfer factors used for this sensitivity analysis are shown in Tables 3-3 through 3-7. The following sections describe these parameter selections in greater detail.

3.3.1 Irrigation Rates and Durations

The BDOSE crop model uses irrigation rates and durations to evaluate the annual deposition of irrigation water and associated radiological contaminants to the plant surfaces of crops.

Table 3-3. Crop Irrigation Rates and Durations

Crop Type	Irrigation Rate (in/yr)*	Irrigation Duration, Uniform (Min, Max) (Months Per Year)†
Grain	10	5.3, 8
Fruit	10	4.7, 6.7
Vegetables	10	1.7, 8
Leafy green vegetables	10	2, 6.7
Fodder	10	4, 8
All other livestock feeds	10	5.3,8

*Data derived from USDA (2010).
†Data ranges derived values reported in Home and Garden Information Center (HGIC) (2009) and Beyeler, et al.(1999).
Complete reference information can be found in Chapter 6.

Table 3-4. Crop Growth Durations and Yields

Crop Type	Duration, Uniform (Min, Max) (day/yr)*	Yield Triangular(Min, Expected, Max) (kg/m^2)†
Grain	80, 120	0.28, 0.40, 0.52
Fruit	70, 100	2.2, 2.4, 2.6
Vegetables	25, 120	2.3, 2.4, 2.5
Leafy green vegetables	30,100	2.7, 2.9, 3.2
Fodder	30	0.7, 1.8, 2.0
All other livestock feeds	80, 120	0.28, 0.40, 0.52

*Values derived from HGIC (2009) and NUREG/CR–5512 (Beyeler, et al., 1999, Vol. 1, Table 6.12).
†Field data from NRC (Beyeler, et al.,1999, Vol. 3, Table 6.55) except fodder value is from Hamby (1991). Complete reference information can be found in Chapter 6.

Table 3-5. Plant Transfer Factors*				
Element (Radionuclide)	**Grain/Fodder/ Livestock Feeds**	**Fruit**	**Vegetables**	**Leafy Green Vegetables**
Carbon (C-14)	0	0	0	0
Selenium (Se-79)	2.50E−01	5.00E−02	5.00E−02	3.00E+00
Strontium (Sr-90)	2.10E−01	2.00E−01	5.00E−01	1.00E−02
Yttrium (Y-90)	1.00E−02	1.00E−02	1.00E−02	2.50E−02
Niobium (Nb-94)	2.50E−02	2.50E−02	2.50E−02	2.10E+02
Technetium (Tc-99)	7.30E−01	1.5	2.40E−01	4.00E−02
Iodine (I-129)	4.00E−02	4.00E−02	4.00E−02	4.60E−01
Cesium (Cs-137)	2.60E−02	2.20E−01	1.30E−01	1.50E−01
Lead (Pb-210)	4.70E−03	1.00E−02	6.00E−03	4.90E−02
Radium (Ra-226)	1.20E−03	6.10E−03	2.00E−03	4.90E−02
Thorium (Th-230)	3.40E−05	2.50E−04	3.30E−04	4.70E−04
Uranium (U-233, U-234, U-236, and U-238)	1.30E−03	4.00E−03	1.20E−02	3.20E−02
Neptunium (Np-237)	2.70E−03	1.00E−02	1.30E−02	6.00E−05
Plutonium (Pu-239, Pu-240, and Pu-242)	8.60E−06	4.50E−05	1.10E−03	6.00E−05
Americium (Am-241)	2.20E−05	2.50E−04	3.50E−04	4.70E−04
*Values from Staven, et al. (2003) are concentration ratios based on the dry weight of plant and soil materials				

Table 3-6. Crop Translocation Factors	
Crop Type	**Translocation Value***
Grain	0.1
Fruit	0.1
Vegetables	1.0
Leafy green vegetables	0.1
Fodder	1.0
All other livestock feeds	0.1
*Data from Beyeler, et al. (1999). Complete reference information can be found in Chapter 6.	

Table 3-3 lists the irrigation rates and durations used for this sensitivity analysis. The annual irrigation rates were based on state-level data collected in 2008 (USDA, 2010) as part of a separate farm and ranch survey for the 2007 USDA Agricultural Census. The annual irrigation rate was then derived for this analysis by dividing the reported volume or irrigation water applied by the reported area of cropland irrigated. The resulting annual irrigation rates were 0.828 ac-ft/ac for South Carolina and 0.870 ac-ft/ac for Georgia. These values were converted to 25.2 and 26.5 cm/yr and an approximate midpoint value rounded to 25.4 cm/yr was selected as representative of the region. This value represents a variety of different farms in these states and therefore the derived value is used for all crops evaluated in this sensitivity analysis. Constant values are used based in part on the available information in the source document and low expected variability among possible values. As only 25 percent of farms in Georgia and 16 percent of farms in South Carolina are irrigated (USDA, 2007a,b), the inclusion of irrigation in this sensitivity analysis is a conservative selection and generally consistent with a critical group style of analysis (i.e., selection of a hypothetical receptor for dose modeling that is based on local and regional characteristics and conceptually represents a subset of the local

Table 3-7. Agricultural Parameters and Modeling Values		
Parameter	**Value**	**References***
Deposition Velocity	0.001m/s	LaPlante and Poor (1997, Section 2.3.5.2)
Root Fraction	1.0	Conservative assumption
Crop Irrigation Interception Fraction	0.1 to 0.6 (Uniform)	Beyeler, et al. (1999)
Crop Air Deposition Fraction	0.1 to 0.6 (Uniform)	Values for irrigation interception fraction are used in absence of specific data for air deposition.
Crop Dry-to-Wet Ratios	0.91 (Grain) 0.18 (Fruit) 0.20 (Leafy Green Vegetables) 0.195 (Vegetables) 0.22 (Fodder) 0.91 (All Other Livestock Feeds)	Beyeler, et al. (1999, Vol. 3, Table 6.77)—Grain Lee and Coffield (2007, Table 5-2)—All other crops
Crop Fraction Carbon	0.40 (Grain) 0.09 (Fruit) 0.09 (Leafy Green Vegetables) 0.09 (Vegetables) 0.40 (Fodder) 0.40 (All Other Livestock Feeds)	Beyeler, et al. (1999, Vol. 3, Table 6.36)
Leaf Surface Resuspension Factor	$1.0E-9\ m^{-1}$	Napier, et al. (2004, Table F.1)
Carbon Emission Rate	$12\ yr^{-1}$	NRC (1977)
*Complete reference information can be found in Chapter 6.		

population that would be expected to receive the higher doses from postulated radionuclide releases relative to the general population).

Irrigation duration by crop group in Table 3-3 is based on the growing period ranges for each crop group listed in Table 3-4 and an assumption based on information from a South Carolina planting guide that indicates there are two planting seasons per year (spring, fall) in central South Carolina (HGIC, 2009). Accounting for the total months of irrigation per year by multiplying the crop growing period by the number of plantings per year is appropriate based on the use of the irrigation duration parameter in the model to calculate a monthly irrigation deposition rate from the annual irrigation rate [Eq. (B–7)]. Conceptually, the model accounts for a higher short-term deposition rate based on the total volume of annual irrigation water being applied to crops during a period that is shorter than a year. The variation in the irrigation duration inputs is a reflection of different growing durations for specific crops within each crop group. Values for fodder are based on an assumption that fodder would grow throughout the season, would be irrigated for 4 to 8 months, and would be cut every 30 days. Uniform distributions are used because the crops considered in the exposure scenario are assumed to be equally likely to be grown locally. Based on the relationship of crop growth duration and irrigation duration, the sampling of these input distributions is correlated using an assumed coefficient of 1.0.

3.3.2 Crop Growth Durations and Yields

Crop growth durations are used in the model only to represent the amount of time that contaminants deposited on plant surfaces from irrigation and soil resuspension would be subjected to losses from radioactive decay and weathering. The initial radionuclide deposition rate used in calculating crop concentrations from crop surface deposition [Eq. (B–7)] is based on the annual irrigation rate and the months of irrigation (i.e., irrigation duration) as described in Section 3.3.1. Therefore, conceptually, radionuclides are added to plant surfaces based on a deposition rate calculated from the annual irrigation rate and the number of months that irrigation occurs per season, whereas the loss rates from plant surfaces are based on the amount of time individual plantings crops are exposed to weathering and decay (i.e., growing duration). Based on this implementation in the model, an inverse relationship exists between the growth duration and the calculated dose. The ranges of values used in the sensitivity analysis listed in Table 3-4 were derived from review of a home gardening planting guide for South Carolina that provided ranges of approximate days to harvest for 39 garden crops (HGIC, 2009) and generally applicable minimum values derived for NRC in NUREG/CR–5512 (Beyeler, et al., 1999). The ranges selected encompass the range of values reported in both source documents. Uniform distributions are used because the crops considered in the exposure scenario are assumed to be equally likely to be grown locally. Based on the relationship of crop growth duration and irrigation duration, the sampling of these input distributions is correlated using an assumed coefficient of 1.0.

Crop yield (or biomass) input parameters provide the amount of plant mass per unit area of cropland that can become contaminated from irrigated soils that are resuspended to air and deposited onto plant surfaces. Values selected for the sensitivity analysis for all crop types, except fodder, are general values (Beyeler, et al., 1999) compiled from available sources for use in NRC dose analyses. The yield values were derived from a review of USDA crop reports collected from 1994 to 1996 that included annual average yields and the fraction of crop area devoted to each crop. Mean and range information was provided in the source documentation so a triangular distribution is an appropriate distribution that could be derived from the source document. The values for fodder were obtained from an SRS compilation of site information and parameters (Hamby, 1991). That study conducted a survey of county extension agents in the area surrounding SRS and reported a single-yield value that represented the low end of the sampled range. The upper end of the range was from NRC Regulatory Guide 1.109 (NRC, 1977). Consistent with the needs of the model, all the selected yields are based on wet weight values.

3.3.3 Plant Transfer Factors

Plant transfer factors from Staven, et al. (2003) were used to describe the partitioning between contaminated soils and agricultural crops. These transfer factors are single-point values with no reported uncertainty or variability information. Data sources, including IAEA TRS–472 (2010) and Lee and Coffield (2008), were evaluated for use in this sensitivity analysis. In general, the TRS-472 (2010) and Lee and Coffield (2008) data sources, which include parameter distribution statistics, have mean values that generally agreed with Staven, et al. (2003). Initial scoping calculations performed using values from Lee and Coffield (2008) were performed, which incorporated sampling from parameter distributions. The scoping calculation results identified no strong correlation between plant transfer factor values and receptor doses. The input parameter review effort also found that Lee and Coffield (2008) had assumed vegetable consumption in the SRS area to be primarily root vegetables based on site-specific land and water use evaluations. Therefore, the plant transfer factors from that reference were not selected for the sensitivity analysis so a broader selection of crops could be evaluated. Based on the low correlation between plant transfer factors and receptor dose identified in the screening calculations, the simpler single-point values from Staven, et al. (2003) were used to reduce the overall complexity of the sensitivity analyses. The plant transfer factors are provided in Table 3-5. In future analyses, if biosphere input parameters are changed in a manner that would increase the contribution of the root uptake pathway to the all-pathway dose, then sampling the plant transfer factors may be warranted. Examples of such changes include decreasing the dose contribution from direct deposition to plant surfaces, increasing deposition and retention of radionuclides in soil (e.g., changes to irrigation or leaching inputs), and increasing applicable crop-related consumption rates and/or decreasing important noncrop consumption rates. The most recent values that include distribution statistics are given in IAEA TRS–472 (2010).

Translocation factors, which describe what fraction of activity deposited on a plant surface is transferred to edible portions of the plant, used for this sensitivity analysis are provided in Table 3-6. A review of recent literature identified little comprehensive data pertaining to translocation factors. As a consequence, these values are based on generic recommendations provided in Beyeler, et al. (1999).

In addition to the parameters previously addressed, several other parameters were required to model the uptake of radionuclides into agricultural crops. The values used for these parameters are presented in Table 3-7.

3.4 Animal Products

The BDOSE model calculates radionuclide transfer from the biosphere to consumed portions of animals (animal products) identified in BDOSE as beef, milk, poultry, eggs, game and fish. Interactions between livestock and contaminated environmental media in the model are represented by the consumption of potentially contaminated groundwater, the consumption of potentially contaminated feed grains or fodder, and the ingestion of contaminated soils. The extent to which these contaminants are incorporated into the animal products is controlled by (i) the animal consumption rate of contaminated feeds and water, (ii) the fraction of livestock feeds that are potentially contaminated, and (iii) the fraction of contaminants that are ingested and transferred into the edible portions of the animal.

Input parameters for modeling contaminant transport to animal products were based on the agricultural conditions in the region of interest. The agricultural conditions were previously discussed at the beginning of this chapter and were based on site-specific information provided in SRS documents (compiled and reported in Hamby, 1991) and regional agricultural information provided by the USDA Census of Agriculture and related reports (USDA, 2007c–i; 2010). This information indicates beef and milk production occur in the region with local farmers relying predominantly on forage for feed. Chickens raised for meat and egg production are also raised locally, although they are normally fed commercial feed rather than locally derived feed. Potential recreational wildlife resources exist on SRS but are generally not available for hunting based on the restricted access to the site. SRS reports (WSRC, 2006) public hunts of white-tailed deer and wild pigs are the only available public recreational use of SRS wildlife. From 1965 to 1996, 35,690 deer and 2,489 pigs were killed during organized public hunts. Consumption of contaminated meat from game hunting is assumed to displace and not add to the more common consumption of beef and poultry products and is, therefore, not explicitly modeled in the sensitivity analysis.

BDOSE parameter values applicable to modeling animal product pathways are shown in Tables 3-8, 3-9(a), and 3-9(b). The Table 3-8 livestock consumption rates and feed fractions come primarily from the site-specific information presented in Lee and Coffield (2007) and Hamby (1992). These values compare favorably to the more recent literature sources reviewed for this sensitivity analysis.

The animal transfer factors used for this sensitivity analysis were developed through a comparison of the most recent site-specific information contained in Lee and Coffield (2008) and the data published in TRS–472 (IAEA, 2010). TRS–472 (IAEA, 2010) does not include data for all of the radionuclides of interest, but those included compare favorably with the site-specific data used in the sensitivity analyses and presented in Table 3-9(a). Of note is the assumption that beef values were used for game due to the lack of data from the literature on specific game transfer factors. Very little updated research exists for the poultry and egg animal transfer factors, so the generally accepted single-point values from Staven, et al. (2003) presented in Table 3-9(b) were used for this analysis.

Table 3-8. Livestock Consumption Rates and Feed Fractions*

Livestock	Water Consumption Rates (L/Day) Triangular (Min, Expected, Max)	Soil Consumption Rates (kg/Day)	Feed Consumption Rates (Wet kg/Day) Triangular (Min, Expected, Max)	Fraction of Feed That Is Contaminated (Grain/Fodder)
Beef	28, 28, 50	0.43	6, 36, 50	0.25/0.75
Milk	50, 50, 60	0.97	11, 52, 52	0.44/0.56
Poultry	0.3†	0.01	0.1†	0.000/0.00
Egg	0.3†	0.01	0.1†	0.00/0.00
Game	28, 28, 50	0.43	6, 36, 50	0.00/1.00

*Data from Lee and Coffield (2007) and Hamby (1992). Complete reference information can be found in Chapter 6.
†Single point value used

Table 3-9(a). Animal Transfer Factors*

Element (Radionuclide)	Beef and Game Triangular (Min, Expected, Max) (day/kg)	Milk Triangular (Min, Expected, Max) (day/L)	Fish Bioaccumulation Factor Triangular (Min, Expected, Max) (L/kg)
Carbon (C-14)	0†	0†	3.00E+00, 5.0E+04, 5.0E+04‡
Selenium (Se-79)	1.50E−02, 1.50E−02, 1.00E−01	4.00E−03, 4.00E−03, 4.50E−02	1.7E+02, 1.7E+02, 2.00E+02
Strontium (Sr-90)	3.00E−04, 8.00E−03, 1.00E−02	8.00E−04, 2.80E−03, 2.80E−03	3.00E+01, 6.00E+01, 5.01E+02
Yttrium (Y-90)	3.00E−04, 1.00E−03, 8.00E-03	1.00E−05, 2.00E−05, 2.00E−03	2.50E+01, 3.00E+01, 3.00E+01
Niobium (Nb-94)	3.00E−07, 2.90E−04, 2.80E−01	4.10E−07, 3.20E−05, 2.06E−02	2.00E+02, 3.00E+02, 3.00E+04
Technetium (Tc-99)	1.00E-04, 6.32E-03, 4.00E-01	2.30E−05, 1.87E−03, 2.50E−02	1.50E+01, 2.00E+01, 2.00E+01

Table 3-9(a). Animal Transfer Factors* (continued)			
Element (Radionuclide)	**Beef and Game Triangular (Min Expected, Max) (day/kg)**	**Milk Triangular (Min, Expected, Max) (day/L)**	**Fish Bioaccumulation Factor Triangular (Min, Expected, Max) (L/kg)**
Iodine (I-129)	4.00E−02, 2.90E−03, 4.00E−02	9.00E−03, 6.00E−03, 1.20E−02	4.00E+01, 1.50E+01, 5.00E+02
Cesium (Cs-137)	5.00E−02, 4.00E−03, 5.00E−02	7.90E−03, 7.00E−03, 1.20E−02	3.00E+03, 2.00E+03, 4.70E+03
Lead (Pb-210)	4.00E−04, 3.00E−04, 8.00E−04	2.60E−04, 2.50E−04, 3.00E−04	3.00E+02, 1.00E+02, 3.00E+02
Radium (Ra-226)	9.00E−04, 2.50E−04, 1.00E−03	1.30E−03, 4.50E−04, 1.30E−03	5.00E+01, 5.00E+01, 7.00E+01
Thorium (Th-230)	4.00E−05, 6.00E−06, 2.00E−04	5.00E−06, 5.00E−06, 5.15E−06	1.00E+02, 3.00E+01, 1.00E+02
Uranium (U-233, U-234, U-236, and U-238)	3.00E−04, 2.00E−04, 8.00E−04	4.00E−04, 4.00E−04, 6.18E−04	1.00E+01, 2.00, 5.00E+01
Neptunium (Np-237)	1.00E−03, 5.50E−05, 1.00E−03	5.00E−06, 5.00E−06, 1.00E−05	2.10E+01, 1.00E+01, 2.50E+02
Plutonium (Pu-239, Pu-240, and Pu-242)	1.00E−05, 5.00E−07, 1.00E−04	1.10E−06, 1.00E−07, 2.00E−06	3.00E+01, 3.50, 4.70E+03
Americium (Am-241)	4.00E−05, 3.50E−06, 2.00E−04	1.50E−06, 4.00E−07, 5.00E−06	3.00E+01, 2.10E+01, 2.40E+03

*Data from Lee and Coffield (2008). Complete reference information can be found in Chapter 6.
†H-3 and C-14 transfer to animal products other than fish is addressed by a separate model in BDOSE that does not use a transfer factor (Section B.3.6.2); therefore, values for H-3 and C-14 are set to zero
‡For H-3, the value selected is the maximum of a limited range reported in Lee and Coffield (2008). For C-14, the range encompasses commonly used values found in Lee and Coffield (2008); the minimum value is a preliminary value based on a site specific analysis that accounts for effect of environmental carbon on fish uptake (Hinton, et al., 2009).

Table 3-9(b). Animal Transfer Factors*		
Element (Radionuclide)	**Poultry (day/kg)[1]**	**Egg (day/kg)[1]**
Carbon (C-14)	0†	0†
Selenium (Se-79)	9.00E+00	9.00E+00
Strontium (Sr-90)	8.00E−02	2.00E−01
Yttrium (Y-90)	1.00E−02	2.00E−03
Niobium (Nb-94)	3.00E−04	1.00E−03
Technetium (Tc-99)	3.00E−02	3.00E+00
Iodine (I-129)	5.00E−02	4.40E+00
Cesium (Cs-137)	3.00E+00	4.00E−01
Lead (Pb-210)	8.00E−01	1.00E+00
Radium (Ra-226)	3.00E−02	3.10E−01
Thorium (Th-230)	6.00E−03	4.00E−03
Uranium (U-233, U-234, U-236, and U-238)	1.00E+00	1.00E+00
Neptunium (Np-237)	6.00E−03	4.00E−03

Table 3-9(b). Animal Transfer Factors* (continued)		
Element (Radionuclide)	Poultry (day/kg)[1]	Egg (day/kg)[1]
Plutonium (Pu-239, Pu-240, and Pu-242)	3.00E−03	5.00E−04
Americium (Am-241)	6.00E−03	4.00E−03
*Data from Staven, et al. (2003). Complete reference information can be found in Chapter 6. †C-14 transfer to animal products other than fish is addressed by a separate model in BDOSE that does not use a transfer factor (Section B.3.6.2); therefore, values for C-14 are set to zero		

3.5 Receptor

The receptor evaluated for this analysis is a resident who lives in the vicinity of SRS, whose behaviors and habits are consistent with regional practices. These behaviors include the ingestion of locally grown crops, animal products, and groundwater; direct exposure to potentially contaminated soil, water, and air; and inhalation of air containing radionuclide contaminants. The aforementioned local and regional agricultural conditions provide the basis for modeled exposure pathways and the associated crops and animal products that would be consumed. The receptor is assumed to engage in aquatic recreational activities such as fishing, swimming, and boating, with the associated consumption of fish and external exposure to contaminated surface water.

3.5.1 Consumption Rate

Values used to describe the receptor consumption rate distributions for crops and animal products are presented in Tables 3-10, 3-11, and 3-12. While the most reliable data on human food consumption practices come from population surveys, local consumption surveys are rare and no such surveys of the population in the region surrounding SRS were identified.

Consumption rates previously used for BDOSE calculations from Beyeler, et al. (1999) were applicable to consumption of homegrown foods. Because the receptor evaluated in this sensitivity analysis is assumed to consume food that could be either homegrown or locally

Table 3-10. Receptor Consumption Rate Distributions for Crop Ingestion				
Cumulative Probability*	Grain (kg/yr)	Fruit (kg/yr)	Leafy Green Vegetables (kg/yr)	Vegetable (kg/yr)
0	0	0	0	0
0.01	0	0	0	0
0.05	18	0	0	0
0.1	28	0	0	0
0.25	45	0	10	6
0.5	71	46	27	22
0.75	104	123	55	43
0.9	142	221	88	75
0.95	170	280	109	97
0.99	249	446	187	157
1	1,892	1,808	440	251
*Values derived from EPA (1997). Complete reference information can be found in Chapter 6.				

Table 3-11. Receptor Consumption Rate Distributions for Animal Product Ingestion				
Cumulative Probability*	**Beef (kg/yr)**	**Milk (L/yr)**	**Poultry (kg/yr)**	**Eggs (kg/yr)**
0	0	0	0	0
0.01	0	0	0	0
0.05	0	3	0	0
0.1	2	8	1	0
0.25	8	25	3	0
0.5	18	69	9	0
0.75	30	132	21	26
0.9	45	213	36	53
0.95	59	278	47	70
0.99	83	450	72	104
1	166	1,131	103	318
*Values derived from EPA (1997). Complete reference information can be found in Chapter 6.				

Table 3-12. Other Receptor Consumption Rates		
Consumed Item	**Consumption Rate**	**Reference***
Water consumption rate (provided as a cumulative fraction)	0.00, 24 L/yr 0.10, 24 L/yr 0.25, 153 L/yr 0.50, 336 L/yr 0.75, 556 L/yr 0.90, 812 L/yr 0.95, 1023 L/yr 1.00, 1023 L/yr	EPA, 2004, Appendix E*
Fish consumption rate	2.2, 9, 21 kg/yr (triangular distribution: min, mean, max)	Lee and Coffield (2008), which cited Hamby (1992)
Game consumption rate	0 kg/yr	Game consumption is assumed to be represented by beef and poultry
Soil consumption rate	0.0, 0.0182, 0.0365 kg/yr (triangular distribution: min, mean, max)	Beyeler, et al. (1999)
*Complete reference information can be found in Chapter 6.		

produced and because the BDOSE model includes an input parameter for the fraction of locally derived food, consumption rates that apply to normal total food intake of various foods were considered to be more applicable than the previously used values.

The best available information on normal human food intakes identified for the sensitivity analysis calculations was obtained from the results of national food consumption surveys that the U.S. Environmental Protection Agency (EPA) compiled and analyzed in its Exposure Factors Handbook (EPA, 1997). That reference evaluated and compiled consumption data from a variety of studies; however, most of the data came from either the USDA Nationwide Food

Consumption Survey (NFCS) or the USDA Continuing Survey of Food Intakes by Individuals (CSFII). The most recent survey data reported for food groups that matched the foods included in this analysis and also included distribution statistics originated from the 1989 to 1992 CSFII. CSFII surveyed 15,000 individuals of all ages in the 48 conterminous states with a 48 percent response rate. The survey included a personal interview and a 2-day dietary record. EPA-reported data from that survey include individual average per capita daily intakes per unit body weight (i.e., g/kg-day) stratified by age and percentile of the population for various foods.

Parameters derived from the CSFII data for this analysis included consumption rate distributions for grain, fruit, leafy green vegetables (reported as exposed vegetables), vegetables (reported as root vegetables), beef, milk (reported as total dairy), poultry, and eggs. Consistent with the information in the source document, the per capita values were divided by the reported percentage consuming to convert the values to consumer only values that represent only the individuals who responded to the surveys. This was done so values would more accurately reflect the intake of an individual person rather than a population adjusted value. The reported intakes were also scaled by the 70 kg body weight of an average individual (EPA, 1997) and multiplied by the number of days per year to derive annual values consistent with the input parameter values for BDOSE. To represent an adult receptor for this analysis, consumption rates for the age group 20 to 39 years was selected. While this is a subset of all adult ages, the rates from ages 40 to 69 years were similar to the selected group, and selecting a single age group was preferred to preserve the original data and reported statistical information. The resulting consumption rate cumulative probability distributions are provided in Tables 3-10 and 3-11. While it is recognized that food consumption behaviors are influenced by regional conditions and some regional variability is to be expected, because statistical distributions of intakes are sampled in this analysis, these intake values are expected to encompass the general food consumption behaviors of the population in the region surrounding SRS.

Annual consumption rates for other items that could not be obtained in the desired form from the aforementioned EPA reported CSFII data included drinking water, fish, game, and soil. These consumption rates are provided in Table 3-12.

For drinking water consumption, this analysis uses detailed national survey data from a later CSFII (from 1994 to 1998) for tapwater consumption that EPA compiled and analyzed in a separate report (EPA, 2004). Using values for tapwater consumption is preferable because it applies to the water obtained from local sources rather from other sources such as purchased drinks. The resulting parameter distribution is a truncated cumulative probability distribution truncated at the 10th and 95th percentile values. The 50th percentile of this distribution equates to 0.91 L/d and the 90th percentile value is about 2 L/d while the 95th percentile value equates to 2.8 L/d. For comparison, a commonly used value for dose assessments is a constant 2 L/d and this distribution encompasses that value. The fish consumption rate distribution was obtained from an SRS analysis of parameters for dose modeling at SRS (Hamby, 1992). The value is based on an earlier (1977 to 1978) USDA NFCS study (USDA, 1983) of food consumption in southern states. While the information is somewhat dated, usable survey information on fish consumption is limited and this was the best available regional information that could be identified.

3.5.2 Fraction of Food Produced Locally

As the consumption rates apply to total food intake, the fraction of food that is produced locally adjusts the total food intake to account for that portion of food that has the potential to become contaminated by the modeled radioactive contaminants. The BDOSE model provides control of these fractions for each food product that is modeled. Information on the fraction of foods obtained from local sources is limited and ideally obtained from surveys of the local population. Because no such studies were identified, these inputs were derived from limited available information.

Regionally applicable values for the fraction of food produced locally were derived using data from studies of regional practices (EPA, 1997). For crops, the following information was considered. First, the minimum fraction is bounded by zero because it is reasonable to assume the population in the region includes households that do not obtain any food from local sources. For an expected value, the following information from EPA (1997) was considered. The fraction of food intake that was homegrown for individual gardeners was reported as 10 percent for all fruit and 17 percent for all vegetables. The fraction of homes in the south that have vegetable gardens was reported as 33 percent. Weighting the fraction of food intake that was homegrown by the percentage of home gardeners in the south results in the fraction of food intake produced from gardening in homes in the south. The resulting values are 3 percent for fruit and 6 percent for vegetables. Because home gardening is not the only source of locally grown produce, these values only provide insight into the possible values, but it suggests the actual values are quite low. Therefore, a value of 10 percent is assumed to account for some additional sources of locally derived crops. Because NRC has previously used a value of 25 percent of food locally derived (Hoffman, et al., 1992), that value was considered as a possible maximum value. Because information in the EPA data (EPA, 1997, Table 13-71) shows the fraction of food intake that is homegrown for specific subgroups of the population, these unweighted fractions also represent maximum values for these subgroups. For the all vegetables category, the highest reported fraction is for households who farm with a value of 31 percent of food being homegrown. Therefore, because a range and central value can be derived, a triangular distribution for locally grown vegetables is created with a minimum of zero, an expected value of 10 percent, and a maximum of 31 percent.

A similar approach is used for the remaining food products; however, based on limited data for establishing the expected values, the value of 10 percent is used for all food products as an assumed representative value. The resulting suite of receptor dietary fraction triangular distributions is shown in Table 3-13. Differences in the reported maximum values in the table

Table 3-13. Fraction of Receptor Diet Obtained That Is Locally Grown

Consumed Item	Dietary Fraction Triangular (Min, Expected, Max)*
Grain	0.0, 0.10, 0.52
Fruit	0.0, 0.10, 0.16
Leafy Green Vegetables	0.0, 0.10, 0.31
Vegetables	0.0, 0.10, 0.31
Beef	0.0, 0.10, 0.49
Milk	0.0, 0.10, 0.25
Poultry	0.0, 0.10, 0.16
Eggs	0.0, 0.10, 0.21
Fish	0.0, 0.10, 0.32
Game	0.0, 0.10, 0.73

*Values derived from EPA (1997, Tables 13-1 and 13-71). Complete reference information can be found in Chapter 6.

reflect differences in the values reported for specific population subgroups (i.e., households that garden, households that farm, households that hunt) in the EPA data (EPA, 1997, Table 13-71). Overall, these locally derived food fractions are used in the model to compute the receptor consumption rates for locally grown (i.e., contaminated) food items as the product of the receptor (total) consumption rates (Tables 3-10, 3-11, and 3-12) and the fraction of diet that is locally grown (Table 3-13).

3.5.3 Inhalation Exposure Pathway Parameters

In addition to consumption pathways, a receptor can receive exposure through the inhalation pathway. Parameters that describe the receptor inhalation pathway include the receptor inhalation rate, the air carbon content, and the soil resuspension factor. The values and distributions used to describe the receptor are presented in Table 3-14.

3.5.3.1 Inhalation Rate

The inhalation rate is used in the BDOSE model to calculate the intake of airborne radioactive material that enters the body from breathing. BDOSE uses a simple inhalation exposure model [Eq. (B–15)] that incorporates a fixed (i.e., not defined as an input parameter) 1-year exposure time to calculate the dose from resuspended soil particulates. If the model is executed with a

Table 3-14. Receptor Inhalation Exposure Pathway Parameters

Parameter	Units	Value	Reference*
Soil resuspension factor (RF)	m^{-1}	1E−10, 1E−10, 1E−7 Logtriangular (min, expected, max)	IAEA 1616 (2009); Sehmel (1980) density based on Napier, et al. (2004) GENII Version 2 user manual
Air carbon content	kg m^{-3}	0.00018	Equilibrium concentration of stable carbon in air Yu, et al. (2001, Appendix L)
Inhalation rates	$m^3\ yr^{-1}$	0.000 645 0.001 645 0.011 810 0.051 952 0.101 1,072 0.201 1,248 0.301 1,360 0.401 1,471 0.501 1,571 0.601 1,701 0.701 1,843 0.801 2,008 0.901 2,230 0.951 2,435 0.981 2,685 0.999 3,237 1 3,456	Annual effective inhalation rate derived as the product of a constant moderate physical activity breathing rate (EPA, 1997, Table 5-23) and the cumulative distribution of annual hours spent outdoors (i.e., Surface Exposure Time in Table 3-15) (Beyeler, et al. (1999, Table 6.13).

*Complete reference information can be found in Chapter 6.

typical annual inhalation rate and an outdoor resuspension factor, the model would reflect an exposure scenario where all of the receptor's annual time is spent outdoors exposed to resuspended soil. Because such an approach would be overly conservative, for the sensitivity analysis the annual inhalation rate input parameter is adjusted to account for only the total annual volume of air inhaled annually while the receptor is outdoors. The distribution of inhalation rates in Table 3-14 was therefore revised from prior BDOSE calculations by selecting a constant adult breathing rate of 1.6 m^3/hr applicable to a moderate physical activity level (EPA, 1997, Table 5-23). Assuming moderate physical activity (reported values range from rest, sedentary, light, moderate, and heavy) is considered reasonably conservative when applied to a long time period (i.e., an annual exposure). This constant inhalation rate is then multiplied by the annual time the receptor is assumed to spend outdoors (adopted from the External Exposure Time input shown in Table 3-15) to generate an effective annual outdoor inhalation rate (shortened to inhalation rate in Table 3-14). Because the External Exposure Time parameter is represented by a distribution of exposure times, and a constant hourly inhalation rate is assumed, the resulting distribution of effective annual inhalation rates follows the same distribution as the External Exposure Time input parameter, which is the distribution selected for the sensitivity analysis. This approach assumes the indoor inhalation exposures to resuspended soil would be significantly attenuated relative to outdoor exposures (based on building structure, ventilation, and distance from source considerations) such that the indoor exposures do not need to be considered in the model. A more refined approach for future analysis could involve (i) developing more inclusive activity-time-weighted effective breathing rates and similarly adjusted effective resuspension factors for use with the current model or (ii) making changes to the model to account for various inhalation exposure environments and receptor activity levels.

3.5.3.2 Air Carbon Content

The air carbon content is used to evaluate exposure from C-14, which is assumed to be in equilibrium with atmospheric carbon. A value for equilibrium concentration of stable carbon in air from Yu, et al. (2001) was used for this analysis.

3.5.3.3 Soil Resuspension Factor

The soil resuspension factor is used in the model to convert the concentration of radionuclides in surface soil to an airborne concentration of radionuclides as an approximation of the complex processes involved in resuspension of contaminated surface soil to air. The resuspension factor is defined as the ratio of airborne contaminant concentration per unit air volume divided by the contaminant surface concentration per unit area (Sehmel, 1980). Prior dose assessments of SRS have not reported site-specific resuspension factor values (Lee and Coffield, 2008; Centers for Disease Control, 2006; Hamby, 1991, 1992). Comprehensive literature reviews of resuspension studies include Sehmel (1980) and more recently IAEA (2009). These references indicate much of the research on resuspension factors has been conducted for sites located in arid climate conditions, and reported measurements vary widely from 1×10^{-2} to 1×10^{-10} m^{-1}. Some of the reported high values represent short-term resuspension events that would not be representative of long-term chronic (annual) exposure conditions. Also, use of values based on studies conducted under arid conditions for the subtropical SRS conditions would be expected to overestimate air concentrations. None of the reported values in the studies reviewed were measured at South Carolina or Georgia locations; however, the IAEA report included values measured in nonarid sites such as Kentucky and New York. Values reported for nonarid locations in the two references were reviewed, and values ranged predominantly from 1×10^{-10} to 1×10^{-7} m^{-1}. Based on the results of these studies, a logtriangular distribution with minimum, mean and maximum values of 1 × 10^{-10}, 1 × 10^{-10} and 1 × 10^{-7} m^{-1} have been selected to represent expected soil resuspension in the region of interest.

3.5.4 External Exposure Pathway Parameters

Parameters that describe the direct exposure pathway and their selected values are also presented in Table 3-15. These include the exposure times for external radiation fields, airborne radioactive materials, boating, and swimming. Additionally, the shielding factor for external radiation exposure is provided in Table 3-15.

3.5.4.1 Outdoor Air External Exposure Time

The outdoor air external exposure times were based on generally applicable values from available sources. The external exposure time distribution from Beyeler, et al. (1999) is based on information from the National Human Activity Patterns Survey analysis by Tsang and Klepis (1996), which EPA (1997) characterized as the largest and most current human activity survey available. The survey included more than 9,000 respondents that provided 24-hour diaries from 1992 to 1994. The distribution represents the variability in hours per year members of the general U.S. population spent outdoors.

Table 3-15. Receptor External Exposure Pathway Parameters

Parameter	Units	Value	Reference*
Surface exposure time	hr/yr	0 403 0.001 403 0.011 506 0.051 595 0.101 670 0.201 780 0.301 850 0.401 919 0.501 982 0.601 1,063 0.701 1,152 0.801 1,255 0.901 1,394 0.951 1,522 0.981 1,678 0.999 2,023 1 2,160	Cumulative distribution of annual hours spent outdoors from Beyeler, et al. (1999, Table 6.13)
Surface shielding factor		1	Conservative assumption
Outdoor air exposure time	hr/yr	Same as surface exposure time	Beyeler, et al. (1999, Table 6.13)
Swimming exposure time	hr/yr	8.9, 8.9, 21 triangular (min, expected, max)	Lee and Coffield (2007, Table 4-1)
Boating exposure time	hr/yr	9.1, 21, 21 triangular (min, expected, max)	Lee and Coffield (2007, Table 4-1)

*Complete reference information can be found in Chapter 6.

3.5.4.2 Swimming and Boating Exposure Times

The swimming and boating exposure times were reported for SRS by Lee and Coffield (2007) and were based on a regional survey conducted by Hamby (1991). The expected value for swimming of 8.9 hours per year is slightly less than the value of 12 hours per year that would be calculated using the EPA-recommended (EPA, 1997) swimming activity, based on survey data from Tsang and Klepis (1996).

4 DESCRIPTION OF SENSITIVITY ANALYSIS METHODS

A sensitivity analysis has been performed to identify key parameters in the biosphere dose assessment model, BDOSE. Using Latin Hyper Cube Monte Carlo sampling, 5,000 realizations were run for the groundwater exposure scenario described in Chapters 2 and 3 to support the analyses in Chapter 5. The number of realizations used to perform this analysis was based on an observational convergence of correlation value using differing sample sizes and on statistical guidance Iman and Conover (1982) provided. Correlations between TEDE estimates for each radionuclide and sampled model parameters were then computed to identify those sampled parameters that have the greatest influence on each TEDE distribution. This chapter presents the derivation of numerical thresholds to differentiate correlations of high magnitude from low or random correlations.

In this sensitivity analysis, parameters were ranked based on the magnitude of a correlation coefficient between each sampled input parameter and the model output. The model output selected was the TEDE distribution for each radionuclide. In the following discussion, these definitions were used:

Sample	—	set of values of a stochastic variable
Sample size	—	number of elements in the sample
x_j	—	stochastic input parameter j
x_{ij}	—	i^{th} sampled value of stochastic parameter x_j
$\mathbf{x}_j=\{x_{ij}, i=1, 2, \ldots, N\}$	—	random sample of stochastic parameter x_j of sample size N

If F_j is the cumulative distribution function (CDF) of the stochastic input parameter x_j, then the *rank mapping* or *rank transformation* of the sample $\mathbf{x}_j=\{x_{ij}, i=1, 2, \ldots, N\}$ is the set $\{p_{ij}, i=1, 2, \ldots, N\}$ with entries computed as

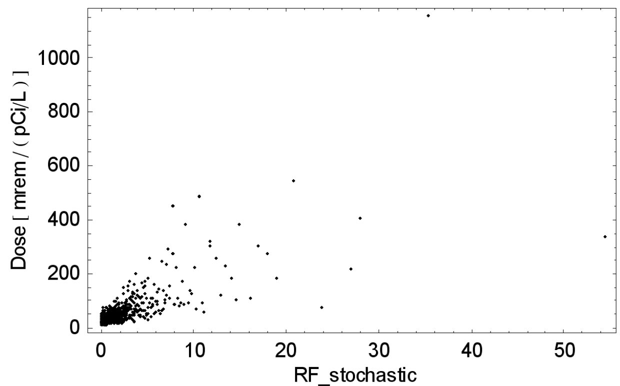
$$p_{ij} = F_j(x_{ij}) \tag{4-1}$$

If the CDF is not known, the rank mapping can be approximately derived by sorting the sample $\mathbf{x}_j$ in ascending order and equating the rank of a value x_{ij} to its sorted position divided by N.

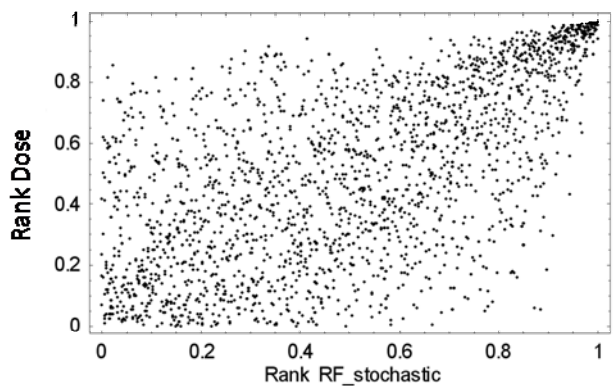
The *standardized transformation* (Hald, 1952) of the sample $\mathbf{x}_j$ is the set $\mathbf{u}_j=\{u_{ij}, i=1, 2, \ldots, N\}$ with entries

$$u_{ij} = \sqrt{2}\,\mathrm{erf}^{-1}\left[2F_j(x_{ij})-1\right] \tag{4-2}$$

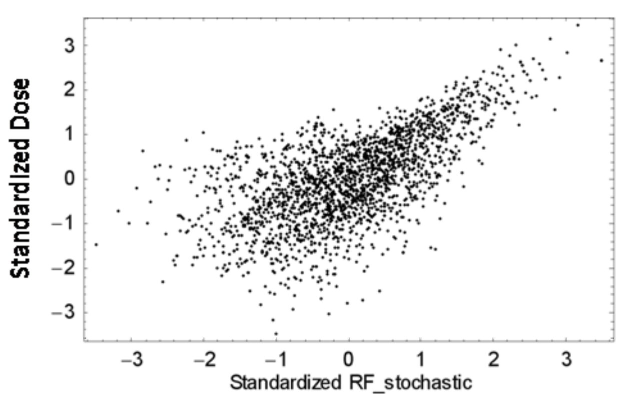
The symbol erf is the error function, and erf^{-1}, its inverse. Under this transformation, the sample $\mathbf{u}_j$ follows a *standard normal distribution* (zero mean and unit standard deviation). Mapping the sample $\mathbf{x}_j$ into the sample $\mathbf{u}_j$ is referred to as *standardization*. Standardization is useful to accentuate correlations in scatter plots. Figure 4-1 shows example scatter plots (dose versus a stochastic input parameter) with three kinds of data mappings. Figure 4-1(a) presents raw data; Figure 4-1(b), rank data; and Figure 4-1(c), standardized data. Clearly, the standardization allows for more immediate correlation visualization.



(a) Raw Data



(b) Rank Data



(c) Standardized Data

Figure 4-1. Calculated Dose Versus a Stochastic Input Parameter of the BDOSE Model (RF_stochastic); (a) Raw Data, (b) Rank Transformed Data, and (c) Standardized Data

The criterion to differentiate high from low magnitudes of a correlation coefficient is defined in this analysis based on the identification of outliers. If x_o is a member of a sample of the stochastic variable x_j with K-elements and x_o satisfies

$$x_o > F_j^{-1}\left([K-1]/K \right) \quad \text{or} \quad x_o < F_j^{-1}(1/K) \tag{4-3}$$

then x_o is considered an *outlier* of the x_j distribution. Thus, for example, if x is a variate that follows a standard normal distribution [for a normal distribution, $F(x) = 0.5\left(1 + erf\left[x/\sqrt{2}\right]\right)$], and 10 values of the variate are randomly sampled, the sample is expected to range between –1.282 and 1.282. The values −1.282 and 1.282 are the 0.1 and 0.9 quantiles of the standard normal distribution [i.e., –1.282 = $F^{-1}(0.1)$ and 1.282 = $F^{-1}(0.9)$]. Values outside of the range [−1.282, 1.282] would be considered outliers. If 1,000 values were sampled, the sample would be expected to range between −3.09 and 3.09 [−3.09 = $F^{-1}(0.001)$ and 3.09 = $F^{-1}(0.999)$]. In this case, values outside of the range [−3.09, 3.09] would be considered outliers. In general for distributions with infinite tails, as the sample size increases, the magnitude that an observation must have to be considered an outlier also increases.

Equation (4-3) was used as a basis to distinguish high magnitude correlations from low magnitude correlations as a function of the number of compared input parameters (K = number of compared input parameters). The approach is detailed in the next paragraphs.

Correlation Coefficient

The correlation coefficient between samples **x** and **z** is defined as follows. Let the size of samples **x** and **z** represented by N, and m_x and m_z denote the respective means of the samples. If the vectors $\mathbf{m}_x$ and $\mathbf{m}_z$ are constructed with N entries as $\mathbf{m}_x = \{m_x, m_x, \ldots, m_x\}$ and $\mathbf{m}_z = \{m_z, m_z, \ldots, m_z\}$, then the correlation coefficient between the samples **x** and **z**, corr(**x**, **z**), is defined as

$$\text{corr}(\mathbf{x},\mathbf{z}) = r = \frac{(\mathbf{x}-\mathbf{m}_x)\cdot(\mathbf{z}-\mathbf{m}_z)}{\|\mathbf{x}-\mathbf{m}_x\|\,\|\mathbf{z}-\mathbf{m}_z\|} \tag{4-4}$$

where• and || || are the dot product and Euclidean norm operators, respectively. To define a criterion to distinguish between high and low values of the correlation coefficient, it is convenient to transform the correlation coefficient as (Pensado, 2008)

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}} \tag{4-5}$$

If the variables $\boldsymbol{x}$ and $\boldsymbol{z}$ are independent, the statistic t follows a Student's t-distribution with N−2 degrees of freedom (Hald, 1952). In this analysis, the sample size N is the number of realizations, which is typically on the order of at least hundreds in performance assessments.

With such large values of N, t tends to a standard normal distribution (Hald, 1952). In the limit when N is large, the cumulative distribution function for t, $F(t)$, becomes

$$F(t) = \frac{1}{2}\left[1 + erf\left(\frac{t}{\sqrt{2}}\right)\right] \tag{4-6}$$

and the inverse is

$$F^{-1}(p) = \sqrt{2}\, erf^{-1}(2p-1) \tag{4-7}$$

In this analysis, correlation coefficients between standardized stochastic input parameters, Eq. (4-2), and concentration-to-dose conversion factors per realization (per radionuclide) were computed to identify the parameters driving the dose associated with a particular radionuclide. A common approach to rank parameters according to the correlation coefficient is to sort the parameters by decreasing magnitude of the correlation and select the top parameters. A more objective approach to comparatively distinguish influential parameters has been developed (Pensado, 2008). In that approach, the set $\{t_j, j=1, \ldots, K\}$ [K = number of input compared parameters; t_j computed according to Eq. (4-5) for each stochastic input parameter] is compared to a standard normal distribution and the parameters with outlier values of t_j are identified as influential to the dose. For the nonoutlier parameters, the correlation is deemed weak (i.e., it is not clear whether they truly influence the dose) (Pensado, 2008). The ranking approach is described in more detail with an example.

Figure 4-2 is a graphical example of the approach to identify influential parameters. In the analyses conducted for this report, plots such as Figure 4-2 are not included (i.e., for each radionuclide and input parameter) for the sake of brevity. The following example is intended to demonstrate that nonrandom correlations between an input parameter and the calculated dose were considered to satisfy $|r| > 0.05$ (N = 2,000 and K = 109). In the example, sensitivity coefficients t_j were computed for the 109 stochastic input parameters considered for the groundwater exposure scenario model runs. Correlations between input parameters and the Cm-248 dose were computed. Figure 4-2(a) shows the comparison of the discrete cumulative distribution of the set of 109 t_j values and a standard normal distribution. Each point represents an input parameter. Figure 4-2(b) is the cumulative distribution function with the outliers excluded, to allow for better visual comparison to the standard normal distribution. This region between the dotted lines in Figure 4-2(a) and (c) defines the “random” region (i.e., it encloses the parameters that are not clearly correlated to the Cm-248 dose). According to the outlier definition in Eq. (4-3), and using the inverse function $F^{-1}(p)$ in Eq. (4-7) with p=1/109 and p=108/109, the random region is enclosed between $t = \sqrt{2}\,\mathrm{erf}^{-1}\left[2(1/109) - 1\right] = -2.36$ and $t = \sqrt{2}\,\mathrm{erf}^{-1}\left[2(108/109) - 1\right] = 2.36$. From Eq. (4-5)

$$r = \frac{t}{\sqrt{t^2 + N - 2}} \tag{4-8}$$

From substitution of the boundaries $t = \pm 2.36$ and N = 2,000 (number of realizations considered in this example) into Eq. (4-8), it follows that a correlation, r, can be dismissed as random, in this example, if $|r| \leq 0.05$. On the other hand, significant parameters (for the case N = 2,000 and K = number of stochastic parameters = 109) satisfy $|r| > 0.05$. Figure 4-2(c) displays the cumulative distribution function of the set of correlation values and the random region (region between the dotted lines).

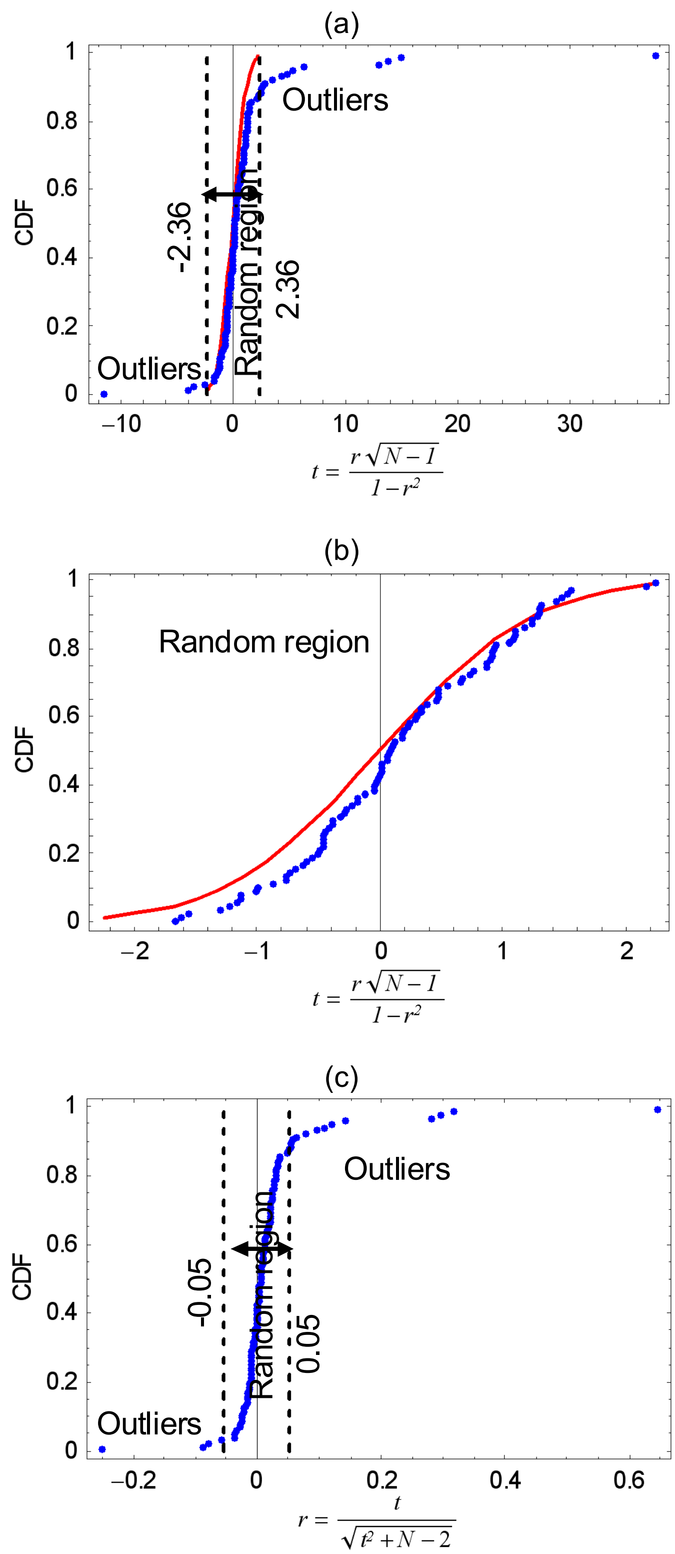


Figure 4-2. Graphical Approach To Identify Random and Influential Parameters (Outliers). Each Point Represents a Correlation Statistic for a Stochastic Input Parameter.

5 SENSITIVITY ANALYSIS RESULTS

5.1 Introduction

Understanding the effects of parameter uncertainty on calculated dose and the identification of model input parameters that have the most significant influence on dose estimates is an important aspect of a biosphere analysis. Because the BDOSE biosphere model has a large number of input parameters, this information can be used to focus attention and resources on those items that are most relevant to the dose analysis. This focus improves program efficiency and builds confidence in model results.

5.2 Propagation of Parameter Uncertainty

A sensitivity analysis has been performed using the biosphere model, BDOSE 2.0, to model the environment of interest as described in Chapters 2 and 3. The goal of this analysis is to identify parameter uncertainties (or variabilities) that most significantly affect calculated doses and to provide insight into which pathways and radionuclides may play a key role in a total dose assessment.

Using the GoldSim integrated Monte Carlo and Latin Hypercube Sampling (LHS) methods in conjunction with the sensitivity analysis described in Chapter 4, 109 parameter distributions were stochastically sampled to evaluate exposure values for a receptor. To determine an adequate sample size necessary for this sensitivity analysis, several factors were evaluated. The first was the minimum sample size necessary to evaluate a stable expected value (mean dose result) using LHS. Following recommendations by Iman and Conover (1982) for LHS sampling, an estimated 100 realizations would be required as a minimum to ensure a stable mean dose estimate. In addition to meeting the minimum sampling recommendations for LHS analysis, considerations were also given to the numerical stability of parameter rank correlation values, as well the observed stability of the expected dose results. Based on results observed when varying sample sizes and the aforementioned considerations, a sample size of 5,000 realizations was determined to be sufficient to provide numerical stability for both the expected dose results and the parameter rank correlation values.

The results of the BDOSE calculations performed for this sensitivity analysis are presented in two parts. First, summary statistics and graphical representations are presented to provide basic descriptive information about the model output. Second, results of the sensitivity analysis describe input parameter correlations to the calculated radionuclide dose results. These results are provided as a set of tables listing the parameters correlated to radionuclide-specific annual TEDE results (mrem/yr per unit groundwater concentration).

5.3 Dose Results

BDOSE runs were executed for the groundwater scenario described in Chapters 2 and 3. This modeling analysis was focused on the biosphere model and therefore assumed groundwater used by the receptor and surrounding community contained a 1-pCi/L concentration of each radionuclide. The initial analysis of model results involved computing descriptive statistics on the model output—the calculated annual radionuclide-specific TEDE distributions. The results are shown in Table 5-1 and Figure 5-1. The statistics in Table 5-1 are provided to assist in describing these TEDE distributions. Additionally, annual individual TEDE values are presented graphically as box-whisker plots in Figure 5-1. In this plot the 25th and 75th percentiles (represented by the box), the median (the vertical line in the box), and the minimum and maximum values (the whiskers) are annotated. In this figure, radionuclides are ordered by decreasing median TEDE values on a log scale. This arrangement highlights the range of dose results, over many orders of magnitude, when a unit groundwater concentration is run in the model for all radionuclides.

In Table 5-1, the calculated annual TEDE mean, standard deviation, median, geometric mean, and geometric standard deviation are provided for each radionuclide. Considering the standard deviation as a measure of uncertainty, most radionuclides have uncertainties that are about an order of magnitude or less of the evaluated mean annual TEDE values. In Figure 5-1, the full effect of sampled input parameter uncertainty is shown by presenting the entire span of annual TEDE values, from minimum to maximum values. The figure provides insights to the statistical distribution for TEDE values that varies by radionuclide.

Figure 5-1 also provides insight into which radionuclides have relatively high dose potentials for the same level of concentration. This does not imply that radionuclides with relatively low TEDE values will not contribute to potentially significant dose, or that radionuclides with high TEDE values will contribute to high doses, because the dose to the receptor in a total system performance assessment calculation will be dependent on the magnitude of radionuclide concentrations in the groundwater that accumulate in the accessible environment. However, if reliable concentration estimates are known, the annual TEDE values reported here can be used as factors for conversion of groundwater radionuclide concentrations into annual TEDE values.

In addition to the plots provided in Figure 5-1 depicting TEDE distributions for individual radionuclides, plots were generated that depict pathway contributions to the TEDE for individual radionuclides. These plots, presented in Appendix A, provided information to identify pathways that contribute most to a radionuclide dose and were evaluated along with the correlation results to identify those parameters or parameter groups that are likely to significantly affect radionuclide dose results.

5.4 Parameter Correlations

Using the sensitivity analysis methods described in Chapter 4, parameter correlation results showing the relationship between the standardized sampled input parameter distributions and the standardized TEDE distribution for each radionuclide were evaluated for the 20 radionuclides identified in Table 2-1 for the groundwater scenario. The results of these correlation analyses are summarized in Tables 5-2 through 5-17, with correlations shown only for those parameters that satisfied the statistical criterion described in Chapter 4 and were relevant to the individual radionuclide TEDE values (or provide insight into the relative correlation strength of other parameters). In a few instances, parameters with low borderline correlations that did not meet the statistical criterion but were related to the group of parameters that met the criterion were included in the table to be inclusive of borderline yet potentially relevant results. These table entries were marked to identify their status.

For the elements uranium and plutonium, the radionuclides U-234, U236, and U-238, and Pu-239, Pu-240, and Pu-242 were evaluated individually during the sensitivity analysis. However, the results of the sensitivity analysis showed the dose results for these radionuclides were each similarly controlled by the same elemental attributes. Thus, for simplicity, average parameter correlations for these radionuclides are presented in two consolidated tables for these radioisotopes of uranium and plutonium.

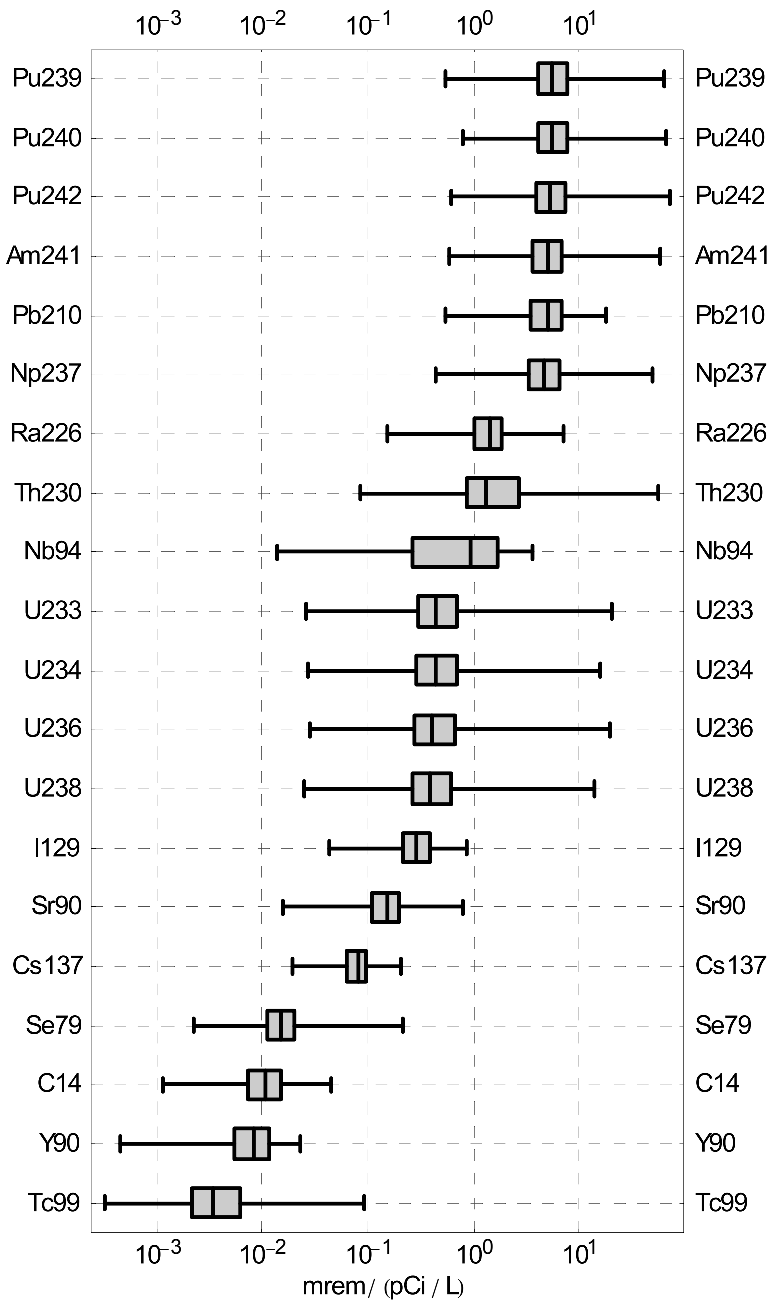


Figure 5-1. Annual TEDE Distributions for the Groundwater Scenario (1 pCi/L) for Each Radionuclide Evaluated

Table 5-1. Summary Statistics for the Groundwater Scenario Model Results by Radionuclide: Annual Total Effective Dose Equivalent (mrem/yr per pCi/L)*					
Radionuclide	Arithmetic Mean	Standard Deviation	Median	Geometric Mean	Geometric Standard Deviation
C-14	1.16E-02	5.83E-03	1.07E-02	1.01E-02	1.72E+00
Se-79	1.69E-02	9.65E-03	1.50E-02	1.49E-02	1.63E+00
Sr-90	1.57E-01	6.59E-02	1.50E-01	1.42E-01	1.58E+00
Y-90	8.68E-03	4.42E-03	8.30E-03	7.34E-03	1.91E+00
Nb-94	1.03E+00	8.02E-01	9.23E-01	6.00E-01	3.56E+00
Tc-99	5.45E-03	6.07E-03	3.38E-03	3.79E-03	2.23E+00
I-129	3.04E-01	1.21E-01	2.93E-01	2.78E-01	1.55E+00
Cs-137	8.13E-02	2.48E-02	7.93E-02	7.75E-02	1.38E+00
Pb-210	5.17E+00	2.29E+00	4.96E+00	4.61E+00	1.66E+00
Ra-226	1.47E+00	6.17E-01	1.40E+00	1.33E+00	1.59E+00
Th-230	2.59E+00	3.67E+00	1.34E+00	1.60E+00	2.44E+00
U-233	7.45E-01	1.11E+00	4.38E-01	4.83E-01	2.29E+00
U-234	7.22E-01	1.01E+00	4.29E-01	4.78E-01	2.26E+00
U-236	6.87E-01	1.01E+00	4.10E-01	4.52E-01	2.25E+00
U-238	6.63E-01	9.96E-01	3.84E-01	4.29E-01	2.28E+00
Np-237	5.12E+00	2.79E+00	4.75E+00	4.51E+00	1.68E+00
Pu-239	6.84E+00	4.94E+00	5.59E+00	5.77E+00	1.74E+00
Pu-240	6.80E+00	4.91E+00	5.57E+00	5.76E+00	1.74E+00
Pu-242	6.55E+00	4.94E+00	5.34E+00	5.50E+00	1.75E+00
Am-241	5.94E+00	4.15E+00	5.03E+00	5.06E+00	1.72E+00
* Calculated assuming a groundwater concentration of 1 pCi/L for each radionuclide					

Table 5-2. Sampled Input Parameter Distributions That Correlated With the C-14 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	Common Parameter Name	BDOSE Parameter Name
0.597	Fish bioaccumulation factor for C-14	Stoch_Fish_trans[C14][L/kg]
0.381	Fraction of fish that is locally produced	RES_Fish_Fract_Local
0.288	Fish consumption rate	RES_Fish_consumption[kg/yr]
0.110	Water consumption rate	RES_water_consump_rate[L/yr]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-3. Sampled Input Parameter Distributions That Correlated With the Se-79 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	Common Parameter Name	BDOSE Parameter Name
0.630	Soil distribution coefficient for Se-79	KD6[L/kg]
0.345	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.176	Milk transfer factor for Se-79	Stoch_milk_trans[Se79][day/L]
0.155	Grain consumption rate	RES_Grain_consum_rate[kg/yr]
0.124	Fraction of grain that is locally produced	RES_Grain_Fract_Local

Table 5-3. Sampled Input Parameter Distributions That Correlated With the Se-79 Total Effective Dose Equivalent Distribution* (continued)		
Correlation Coefficient	**Common Parameter Name**	**BDOSE Parameter Name**
0.120	Beef transfer factor for Se-79	Stoch_beef_trans[Se79][day/kg]
0.103	Milk consumption rate	RES_Milk_consumption[l/yr]
0.084	Beef feed consumption rate	Beef_feed_consump_rate[kg/day]
0.079	Fodder irrigation interception fraction	Fod_irr_intercept_fract
0.071	Milk feed consumption rate	Milk_feed_consump_rate[kg/day]
-0.059	Livestock fodder irrigation duration	Fod_irrigation_duration[mon/yr]
0.048	Fraction of beef that is locally produced	RES_Beef_Fract_Local
0.042	Egg consumption rate	RES_egg_consumption[kg/yr]
0.039	Beef consumption rate	RES_Beef_consumption[kg/yr]†
*Results are based on analysis of standardized data for input parameter and dose distributions. †This parameter did not meet the statistical criterion for inclusion but was applicable to other parameters included in the table and therefore was included as a borderline entry.		

Table 5-4. Sampled Input Parameter Distributions That Correlated With the Sr-90 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	**Common Parameter Name**	**BDOSE Parameter Name**
0.606	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.199	Soil distribution coefficient for Sr-90	KD7[L/kg]
0.114	Grain consumption rate	RES_Grain_consum_rate[kg/yr]
0.088	Leafy green vegetable consumption rate	RES_LGV_consum_rate[kg/yr]
0.075	Fraction of grain that is locally produced	RES_Grain_Fract_Local
0.058	Fraction of leafy green vegetable that is locally produced	RES_LGV_Fract_Local
0.049	Beef transfer factor for Sr-90	Stoch_beef_trans[Sr90][day/kg]
0.049	Grain irrigation interception fraction	Grain_irr_intercept_fract
0.043	Beef consumption rate	RES_Beef_consumption[kg/yr]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-5. Sampled Input Parameter Distributions That Correlated With the Y-90 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	**Common Parameter Name**	**BDOSE Parameter Name**
0.664	Drinking water consumption rate	RES_water_consump_rate[L/yr]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-6. Sampled Input Parameter Distributions That Correlated With the Nb-94 Total Effective Dose Equivalent Distribution*		
SRC	**Common Parameter Name**	**BDOSE Parameter Name**
0.926403	Soil distribution coefficient for Nb-94	KD9[L/kg]
0.181281	External exposure surface exposure time	RES_farmer_Surface_exp_time[hr]
-0.04336	External exposure air exposure time	RES_farmer_air_exp_time[hr]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-7. Sampled Input Parameter Distributions That Correlated With the Tc-99 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	**Common Parameter Name**	**BDOSE Parameter Name**
0.599	Soil distribution coefficient for Tc-99	KD10[L/kg]
0.485	Beef transfer factor for Tc-99	Stoch_beef_trans[Tc99][day/kg]
0.195	Beef feed consumption rate	Beef_feed_consump_rate[kg/day]
0.191	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.141	Beef consumption rate	RES_Beef_consumption[kg/yr]
0.105	Fraction of beef that is locally produced	RES_Beef_Fract_Local
0.077	Milk transfer factor for Tc-99	Stoch_milk_trans[Tc99][day/L]
0.046	Fodder irrigation interception fraction	Fod_irr_intercept_fract
0.044	Milk consumption rate	RES_Milk_consumption[l/yr]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-8. Sampled Input Parameter Distributions That Correlated With the I-129 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	**Common Parameter Name**	**BDOSE Parameter Name**
0.628	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.102	Fodder irrigation interception fraction	Fod_irr_intercept_fract
0.072	Grain consumption rate	RES_Grain_consum_rate[kg/yr]
0.064	Soil distribution coefficient for I-129	KD11[L/kg]
0.061	Beef consumption rate	RES_Beef_consumption[kg/yr]
0.060	Milk consumption rate	RES_Milk_consumption[l/yr]
0.058	Grain irrigation interception fraction	Grain_irr_intercept_fract
0.056	Leafy green vegetable consumption rate	RES_LGV_consum_rate[kg/yr]
0.053	Beef feed consumption rate	Beef_feed_consump_rate[kg/day]
-0.052	Fodder irrigation duration	Fod_irrigation_duration[mon/yr]
0.048	Beef transfer factor for I-129	Stoch_beef_trans[I129][day/kg]
0.045	Fraction of beef that is locally produced	RES_Beef_Fract_Local
0.045	Fraction of leafy green vegetables that is locally produced	RES_LGV_Fract_Local
0.044	Fraction of grain that is locally produced	RES_Grain_Fract_Local
-0.040	Leafy green vegetable growth duration	LGV_Growth_Duration[day]
-0.040	Leafy green vegetable irrigation duration	LGV_irrigation_duration[mon/yr]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-9. Sampled Input Parameter Distributions That Correlated With the Cs-137 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	**Common Parameter Name**	**BDOSE Parameter Name**
0.553	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.200	Fraction of fish that is locally produced	RES_Fish_Fract_Local
0.160	Fish bioaccumulation factor for Cs-137	Stoch_Fish_trans[Cs137][L/kg]
0.152	Fish consumption rate	RES_Fish_consumption[kg/yr]
0.094	Fodder irrigation interception fraction	Fod_irr_intercept_fract
0.084	Beef feed consumption rate	Beef_feed_consump_rate[kg/day]

Table 5-9. Sampled Input Parameter Distributions that Correlated With the Cs-137 Total Effective Dose Equivalent Distribution* (continued)		
Correlation Coefficient	**Common Parameter Name**	**BDOSE Parameter Name**
0.080	Beef consumption rate	RES_Beef_consumption[kg/yr]
0.079	Milk consumption rate	RES_Milk_consumption[l/yr]
0.070	Beef transfer factor for Cs-137	Stoch_beef_trans[Cs137][day/kg]
0.070	Grain consumption rate	RES_Grain_consum_rate[kg/yr]
-0.052	Fodder irrigation duration	Fod_irrigation_duration[mon/yr]
0.051	Fraction of beef that is locally produced	RES_Beef_Fract_Local
0.048	Grain irrigation interception fraction	Grain_irr_intercept_fract
0.045	Fraction of leafy green vegetables that is locally produced	RES_LGV_Fract_Local
0.040	Leafy green vegetable consumption rate	RES_LGV_consum_rate[kg/yr]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-10. Sampled Input Parameter Distributions That Correlated With the Pb-210 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	**Common Parameter Name**	**BDOSE Parameter Name**
0.640	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.087	Grain consumption rate	RES_Grain_consum_rate[kg/yr]
0.061	Grain irrigation interception fraction	Grain_irr_intercept_fract
0.060	Leafy green vegetable consumption rate	RES_LGV_consum_rate[kg/yr]
0.050	Fraction of grain that is locally produced	RES_Grain_Fract_Local
0.050	Fraction of leafy green vegetables that is locally produced	RES_LGV_Fract_Local
-0.038	Leafy green vegetable growth duration	LGV_Growth_Duration[day]†
-0.038	Leafy green vegetable irrigation duration	LGV_irrigation_duration[mon/yr]†
*Results are based on analysis of standardized data for input parameter and dose distributions. †These parameters did not meet the statistical criterion for inclusion but were applicable to other parameters included in the table and therefore were included as borderline entries.		

Table 5-11. Sampled Input Parameter Distributions That Correlated With the Ra-226 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	**Common Parameter Name**	**BDOSE Parameter Name**
0.597	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.141	Soil distribution coefficient for Ra-226	KD18[L/kg]
0.138	Grain consumption rate	RES_Grain_consum_rate[kg/yr]
0.096	Soil resuspension factor	RF[1/m]
0.091	Fraction of grain that is locally produced	RES_Grain_Fract_Local
0.083	Leafy green vegetable consumption rate	RES_LGV_consum_rate[kg/yr]
0.058	Fraction of leafy green vegetables that is locally produced	RES_LGV_Fract_Local
0.048	Grain irrigation interception fraction	Grain_irr_intercept_fract
0.041	Fruit yield	Fruit_yield[kg/m^2]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-12. Sampled Input Parameter Distributions That Correlated With the Th-230 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	Common Parameter Name	BDOSE Parameter Name
0.745292	Soil resuspension factor	RF[1/m]
0.297157	Soil distribution coefficient for Th-230	KD23[L/kg]
0.165714	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.040836	Beef feed grain irrigation duration	Beef_Gr_irrigation_duration[mon/yr]
0.040823	Beef feed grain growth duration	Beef_Gr_Growth_Duration[day]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-13. Sampled Input Parameter Distributions That Correlated With the U-233 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	Common Parameter Name	BDOSE Parameter Name
0.555	Soil distribution coefficient for U-233	KD27[L/kg]
0.493	Soil resuspension factor	RF[1/m]
0.277	Drinking water consumption rate	RES_water_consump_rate[L/yr]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-14. Sampled Input Parameter Distributions That Correlated With the U-234, U-236, and U-238 Total Effective Dose Equivalent Distributions*		
Correlation Coefficient	Common Parameter Name	BDOSE Parameter Name
0.539	Soil distribution coefficient for uranium	KD31[L/kg]
0.504	Soil resuspension factor	RF[1/m]
0.277	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.049	Grain consumption rate	RES_Grain_consum_rate[kg/yr]
0.042	Beef feed grain irrigation duration	Beef_Gr_irrigation_duration[mon/yr]
0.042	Beef feed grain growth duration	Beef_Gr_Growth_Duration[day]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-15. Sampled Input Parameter Distributions That Correlated With the Np-237 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	Common Parameter Name	BDOSE Parameter Name
0.525	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.354	Soil resuspension factor	RF[1/m]
0.176	Soil distribution coefficient for Np-237	KD32[L/kg]
0.065	Grain consumption rate	RES_Grain_consum_rate[kg/yr]
0.047	Grain irrigation interception fraction	Grain_irr_intercept_fract
0.044	Fruit yield	Fruit_yield[kg/m^2]
0.040	Fraction of grain that is locally produced	RES_Grain_Fract_Local
0.039	Leafy Green Vegetable consumption rate	RES_LGV_consum_rate[kg/yr]†
*Results are based on analysis of standardized data for input parameter and dose distributions. †This parameter did not meet the statistical criterion for inclusion but was applicable to other parameters included in the table and therefore was included as a borderline entry.		

Table 5-16. Sampled Input Parameter Distributions That Correlated With the Pu-239, Pu-240, and Pu-242 Total Effective Dose Equivalent Distributions*		
Correlation Coefficient	**Common Parameter Name**	**BDOSE Parameter Name**
0.623	Soil resuspension factor	RF[1/m]
0.342	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.184	Fish bioaccumulation factor for plutonium	Stoch_Fish_trans[Pu240][L/kg]
0.101	Soil distribution coefficient for plutonium	KD35[L/kg]
0.061	Fraction of fish that is locally produced	RES_Fish_Fract_Local
0.044	Grain consumption rate	RES_Grain_consum_rate[kg/yr]
0.042	Beef feed grain irrigation duration	Beef_Gr_irrigation_duration[mon/yr]
0.042	Beef feed grain growth duration	Beef_Gr_Growth_Duration[day]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

Table 5-17. Sampled Input Parameter Distributions That Correlated With the Am-241 Total Effective Dose Equivalent Distribution*		
Correlation Coefficient	**Common Parameter Name**	**BDOSE Parameter Name**
0.571	Soil resuspension factor	RF[1/m]
0.398	Drinking water consumption rate	RES_water_consump_rate[L/yr]
0.144	Soil distribution coefficient for Am-241	KD39[L/kg]
0.106	Fish bioaccumulation factor for Am-241	Stoch_Fish_trans[Am241][L/kg]
0.045	Fraction of fish that is locally produced	RES_Fish_Fract_Local
0.044	Grain consumption rate	RES_Grain_consum_rate[kg/yr]
0.041	Beef feed grain irrigation duration	Beef_Gr_irrigation_duration[mon/yr]
0.041	Beef feed grain growth duration	Beef_Gr_Growth_Duration[day]
*Results are based on analysis of standardized data for input parameter and dose distributions.		

The parameter correlations presented in Tables 5-2 though 5-17 and information provided in Appendix A were evaluated to identify meaningful relationships that provide insights into the relative importance of exposure pathways and parameters to the calculated dose. Considering the pathway-specific dose results presented in Appendix A, the drinking water ingestion pathway is the largest contributor to the calculated dose for most of the radionuclides considered. For the majority of radionuclides evaluated for which drinking water was the predominant pathway, the second contributing pathway to drinking water contributes a median dose that is approximately an order of magnitude lower than the median drinking water dose. Therefore, for most radionuclides the non-drinking-water pathways make small contributions to the total dose for most realizations. Se-79, Tc-99, Cs-137, Th-230, and the isotopes of plutonium (Figures A–2, A–6, A–8, A–11, A–17, A–18, and A–19, respectively) all have results that show secondary non-drinking-water pathways (e.g., fish, beef, grain, air inhalation) contributing a much greater proportion to the total dose relative to most of the other radionuclide results yet still less than 50 percent of the total dose in all cases (with drinking water constituting at least 50 percent or more of the dose for these radionuclides).

Results for only 2 of the 20 radionuclides evaluated (C-14, Nb-94) (Figures A–1 and A–5) show a pathway other than drinking water as the largest contributor to the calculated dose. Fish ingestion is the primary contributing pathway to the C-14 dose results, and direct exposure from the ground contamination is the primary contributing pathway to the Nb-94 dose results. Those results are explained by a wide range of values sampled for the fish bioaccumulation factor for C-14 that significantly affect the magnitude of the calculated fish pathway doses. The calculated Nb-94 dose is predominantly from direct exposure because that radionuclide is a strong gamma emitter with low inhalation and ingestion dose coefficients (thereby the direct exposure from ground contamination pathway is the primary route of exposure).

The parameter correlation results presented in Tables 5-2 through 5-17 were evaluated considering both (i) the pathway-specific dose results presented in Appendix A and (ii) how each of the correlated input parameters are used in the BDOSE model (Appendix B). This evaluation was informative for (i) evaluating the validity of the correlation results (i.e., consistency with the information presented in Appendix A) and (ii) identifying the input parameters and pathways that are clearly influencing the model results. Because many of the biosphere pathways in the model involve input parameters that are radionuclide-dependent and the magnitude of these inputs varies by radionuclide (Chapter 3), both the number of pathways and the number of input parameters that are influential are expected to vary by radionuclide. Because the all-pathway dose is the sum of all pathway-specific doses, the analysis of results focuses on those pathways that contribute the most to the all-pathway dose (hereafter referred to as primary pathways). In this discussion of results, the primary pathways for a specific radionuclide were identified as those pathways shown in the Appendix A figures that involve the influential input parameters shown in the correlation results tables provided in this section. Primary pathways selected using this approach emphasize discussion of a small number of pathways that constitute the largest proportion of the total (all-pathway) dose.

For the 20 radionuclides included in the sensitivity analysis, the primary exposure pathways identified in the results ranged from only one to many. This variation in results is influenced by the physical properties of the radionuclide that affect the mobility of the radionuclide in the modeled biosphere and affect both the magnitude and route of exposure (and dose) to the receptor. Pathway results are briefly summarized here and then described in greater detail for specific radionuclides or groups of radionuclides in the paragraphs that follow. The simplest primary pathway results were identified for Y-90 and Nb-94 and involved only one primary pathway for each radionuclide (Tables 5-5 and 5-6; Figures A–4 and A–5). The results for C-14, Tc-99, Pb-210, Th-230, and the isotopes of uranium (U-233, U-234, U-236, U-238) were generally limited to two primary pathways. For these radionuclides, drinking water was the largest contributor to the all-pathway dose followed by other contributing primary pathways that differed for each radionuclide. Results for Se-79, Sr-90, and I-129 involved three primary pathways that comprise drinking water, crop ingestion, and animal product ingestion. Ra-226 and Np-237 results also involved three pathways including drinking water, inhalation, and crop ingestion primary pathways. Results for Am-241 and three isotopes of plutonium (Pu-239, Pu-240, Pu-242) exhibited diverse pathway contributions including drinking water, aquatic food (fish), inhalation, and crop ingestion. Results for Cs-137 showed similarly diverse pathway contributions including drinking water, aquatic food (fish), crop ingestion, and animal product ingestion.

Results for Y-90 show drinking water was identified as the primary pathway because the water ingestion dose was well above (approximately a factor of 100 times larger) any of the other pathway doses for that radionuclide (Figure A–4) and the water consumption rate was the only input parameter that correlated with the all-pathway dose results for that radionuclide (Table 5-5). When modeled as a separate source radionuclide in groundwater from its parent, Sr-90, as done here, the short half life of Y-90 is expected to limit its persistence in soil and therefore reduce the soil-based environmental pathway contributions to the total dose results. Under actual conditions in the environment, Y-90 would be present as a decay product of Sr-90 in the same pathways where Sr-90 exists. A similarly limited result was found for Nb-94, where the primary pathway was direct exposure from ground contamination because the dose result was well above (approximately 100 times larger) any of the other pathway doses for that radionuclide (Figure A–5) and the two input parameters that correlated with results were the soil distribution coefficient (involved in soil sorption/leaching calculations) and the ground surface exposure time (involved in calculating the receptor exposure) (Table 5-6). This can be explained by the properties of Nb-94 as a soil sorbing [relatively high soil distribution coefficient value; Table 3-2(a)] gamma emitter with relatively low inhalation and ingestion dose coefficients.

The C-14 results involved drinking water and fish pathways (Figure A–1). Influential parameters included the fish bioaccumulation factor, the fraction of fish locally obtained, and consumption rates (Table 5-2). The influence of the fish bioaccumulation factor is expected to be the result of the wide range of values sampled based on available reported values (Section 3.4). The differences in the models used for carbon relative to most other radionuclides and the associated use of different (and constant) values for most of the input parameters for C-14 modeling in this analysis limited the number of parameters that correlated significantly with model output in the sensitivity analysis results.

Tc-99 results involved drinking water and livestock product consumption including beef and milk (Figure A–6). Influential parameters included the soil distribution coefficient, animal product transfer coefficients, livestock feed consumption, food and water product consumption rates, the fraction of food that is locally derived, and the fodder interception fraction (Table 5-7). These influential parameters suggest a combination of soil retention and feed crop interception of irrigation deposition to plant surfaces are influencing Tc-99 transport to livestock the receptor consumes.

Pb-210 results involved drinking water and crop ingestion pathways for grain and leafy green vegetables (Figure A–9). Influential input parameters included consumption rates, the crop interception fractions, and the fractions of locally derived foods (Table 5-10). These influential input parameters suggest biosphere processes, such as direct deposition from irrigation to plant surfaces that are consumed by the receptor, are significant contributors to the Pb-210 all-pathway dose, although water consumption is the most influential contributor at approximately a factor of 10 higher pathway dose than the next contributing pathway (grain).

The results for Th-230 and the isotopes of uranium involved drinking water and inhalation as the primary exposure pathways (Figures A–11, and A–12 through A–15). Influential input parameters included the soil resuspension factor, soil distribution coefficient, and the water consumption rate (Tables 5-12 and 5-13). Three of the uranium isotopes showed low correlations for grain input parameters that were not identified for U-233 and therefore were considered potentially borderline results. As a result, the biosphere processes that contribute most to all-pathway dose include Drinking contaminated water and irrigation deposition and retention of Th-230 and uranium in soil followed by soil resuspension to air that is inhaled by the receptor. The relatively high soil sorption (distribution coefficient) yet low values for plant transfer factors for Th-230 would have reduced the uptake to plants and livestock feed and therefore reduced the contribution from crop and livestock pathways. The relatively high inhalation dose coefficient for the isotopes of uranium combined with the highly variable resuspension factor could explain the influence of the inhalation pathway in the results. The relatively high correlation of the resuspension factor to the all pathway dose (Table 5-13) is consistent with the wide range in the sampled input distribution. The resuspension factor distribution was derived from the best available data (a large compilation of field study results) (Section 3.5.3.3); however, no site-specific or directly applicable measurements were located for this analysis. Given the subtropical environment surrounding SRS, actual values for resuspension may be lower and potentially less important than indicated in the results of this analysis.

The all-pathway dose for Se-79 involving consumption of water, grain, milk, and beef (Figure A–2) included influential input parameters such as the soil distribution coefficient, animal product transfer factors, consumption rates, fraction of locally derived food, livestock feed consumption rates, the fodder interception fraction, and irrigation duration (Table 5-3). These influential input parameters suggest biosphere processes, such as irrigation deposition to soil, soil retention, transfer from soil to crops and from irrigation deposition to livestock fodder, contribute significantly to the Se-79 all-pathway dose. These results are consistent with the large sampled range for the soil distribution coefficient [Table 3-2(a)] and relative high values for grain, beef, and milk transfer factors [Tables 3-5 and 3-9(a)].

The all-pathway dose for Sr-90 involving consumption of water, grain, leafy green vegetables, and beef (Figure A–3) included influential input parameters such as consumption rates, soil distribution coefficient, fractions of locally derived foods, beef transfer factor, and grain interception fraction (Table 5-4). These influential parameters suggest biosphere processes, such as irrigation deposition to soil, soil retention, animal product transfer, and crop interception, contribute significantly to the Sr-90 all pathway dose, although water consumption is the most influential contributor at approximately a factor of 10 higher pathway dose than the next contributing pathway (grain).

Regarding the results for I-129, the all-pathway dose involving water, grain, leafy green vegetables, milk, and beef consumption (Figure A–7) included a number of influential input parameters such as consumption rates, crop interception fractions, distribution coefficient, livestock feed consumption, fodder irrigation duration, beef transfer, the fraction of locally derived food products, vegetable growing, and irrigation durations (Table 5-8). These influential parameters suggest biosphere processes, such as drinking contaminated water, irrigation deposition and crop interception as well as root uptake for food and feed products and subsequent human consumption of crop and livestock food products are contributing significantly to the I-129 all-pathway dose, although water consumption is the most influential contributor at approximately a factor of 10 higher pathway dose than the next most significant contributing pathway (grain).

Radionuclides Ra-226 and Np-237 involved drinking water, inhalation, and crop ingestion primary pathways (Figures A–10 and A–16). Correlation results for Ra-226 and Np-237 showed similar influential parameters; the pathway-specific dose results were generally consistent, but the inhalation pathway was a more influential contributor to the Np-237 all-pathway dose relative to the Ra-226 results (Np-237 has a higher inhalation dose coefficient). The influential input parameters include consumption rates, soil resuspension factor, distribution coefficient, interception fraction, the fraction of locally derived food, and the yield for fruit (Tables 5-11 and 5-14). These influential parameters suggest biosphere processes, such as irrigation deposition to soil, soil retention, resuspension of soil to air that is inhaled by the receptor, and crop interception and consumption, contribute significantly to the all-pathway doses from Ra-226 and Np-237, although drinking water consumption is the most influential contributor at approximately a factor of 10 higher pathway dose than the next most significant contributing pathway (grain).

Results for Am-241 and the isotopes of plutonium (Pu-239, Pu-240, Pu-242) exhibited diverse pathway contributions including drinking water, aquatic food (fish), inhalation, and crop ingestion (Figures A–17 through A–20). Correlation results for these radionuclides selected similar influential input parameters including the soil resuspension factor, consumption rates, distribution coefficient, and the fish bioaccumulation factor (Tables 5-15 and 5-16). Low correlations were identified for a few beef input parameters that were considered spurious based on the low pathway contribution for beef ingestion in Figures A–17 through A–20. The influential parameters suggest biosphere processes, such as bioaccumulation in fish that is consumed by the receptor, irrigation deposition, retention of radionuclides in soil and to crops, resuspension of radionuclides from soil to air that is inhaled by the receptor, contribute significantly to the all-pathway dose from Am-241 and the isotopes of plutonium that were modeled, although drinking water remains the most influential contributor. While plant-concentration-related input parameters were not identified specifically in the correlation results, direct deposition is expected to be the means of transfer to crops based on the low magnitudes of plant transfer factors for Am-241 and the isotopes of plutonium shown in Table 3-5. The results are consistent with the relatively high and wide ranging values for fish bioaccumulation [Table 3-9(a)] for these radionuclides, the high and wide ranging values for soil distribution coefficients [Table 3-2(a)], and high inhalation dose coefficients combined with a wide range of sampled values for the resuspension factor.

Results for Cs-137 also show diverse pathway contributions to the calculated dose including drinking water, aquatic food (fish), crop ingestion, and animal product ingestion (Figure A–8). Correlation results selected influential input parameters including consumption rates, the fraction of locally derived food, fish bioaccumulation factor, crop interception fractions, beef transfer, and fodder irrigation duration (Table 5-9). The influential parameters suggest biosphere processes, such as drinking contaminated water, fish bioaccumulation, and irrigation deposition and interception by crop surfaces, are most important, followed by livestock consumption of feed, and transfer of radionuclides to food products that are consumed by the receptor. Considering the pathway-specific dose results in Figure A–8, the fish ingestion dose is comparable in magnitude to the drinking water dose, while crop and animal product pathways are approximately a factor of 10 lower in magnitude than the drinking water and fish doses. These results are consistent with the high value and wide range for the sampled fish bioaccumulation factor for Cs-137 [Table 3-9(a)] as well as relatively high values for plant and animal product transfer coefficients [Tables 3-5 and 3-9(a)].

Considering the sensitivity analysis results, the drinking water pathway was the predominant contributor to calculated doses for most of the radionuclides included in the analysis. Other important contributing pathways included grain, beef, and milk consumption. Limited sets of radionuclides showed fish consumption and inhalation pathways to be influential contributors to the all-pathway dose. In addition to the general pathways, some input parameters were consistently found to be influential contributors to the calculated all-pathway dose results. These parameters include consumption rates (particularly water and grain followed by beef, milk, and leafy green vegetables), soil distribution coefficients, the fraction of locally obtained food products, animal product transfer factors, and the crop interception fractions. Plant transfer factors were absent from results because they were not sampled for this analysis based on the results of early screening calculations. Input parameter changes for the calculations and results presented in this report may have changed the influence of the plant transfer factors relative to the initial screening calculations that suggested low importance of these factors (Section 2.3). Limited resources did not allow the code changes required to sample these inputs for the calculations and results presented in this report. Sampling the plant transfer factor inputs is recommended for future calculations.

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APPENDIX A

PATHWAY CONTRIBUTIONS TO TOTAL EFFECTIVE DOSE EQUIVALENTS

Figures A–1 through A–20 present data collected and evaluated from the BDOSE sensitivity analysis for a 1 pCi/L contaminated groundwater scenario. Parameter values and distributions, as well as model sampling and sample size, are the same as those presented in the attached report.

Pathway contributions to individual radionuclide doses are provided as box-whisker plots, where the 25th and 75th percentiles form the boundary of the box, the vertical line within the box is the median, and the minimum and maximum values are the extent of the whiskers. In these figures, the pathways have been arranged in order of decreasing median values. These figures have been provided on a log scale to present values that span many orders of magnitude. However, several pathways include parameter distributions, which when sampled can result in a zero dose consequence for some realizations. The inclusion of a zero valued result cannot be presented on a log scale, so a lower limit set to the lowest non-zero result has been used to truncate the lower bound of pathway dose contributions. In practice, this truncation has typically resulted in truncations occurring at values below 10^{-13} mrem. Thus, because of the typically low values for these truncations, there are no significant consequences from the truncation.

These figures have been provided to enhance reader insight about which pathways and subsequently which modeling parameters may significantly affect doses for individual radionuclides.

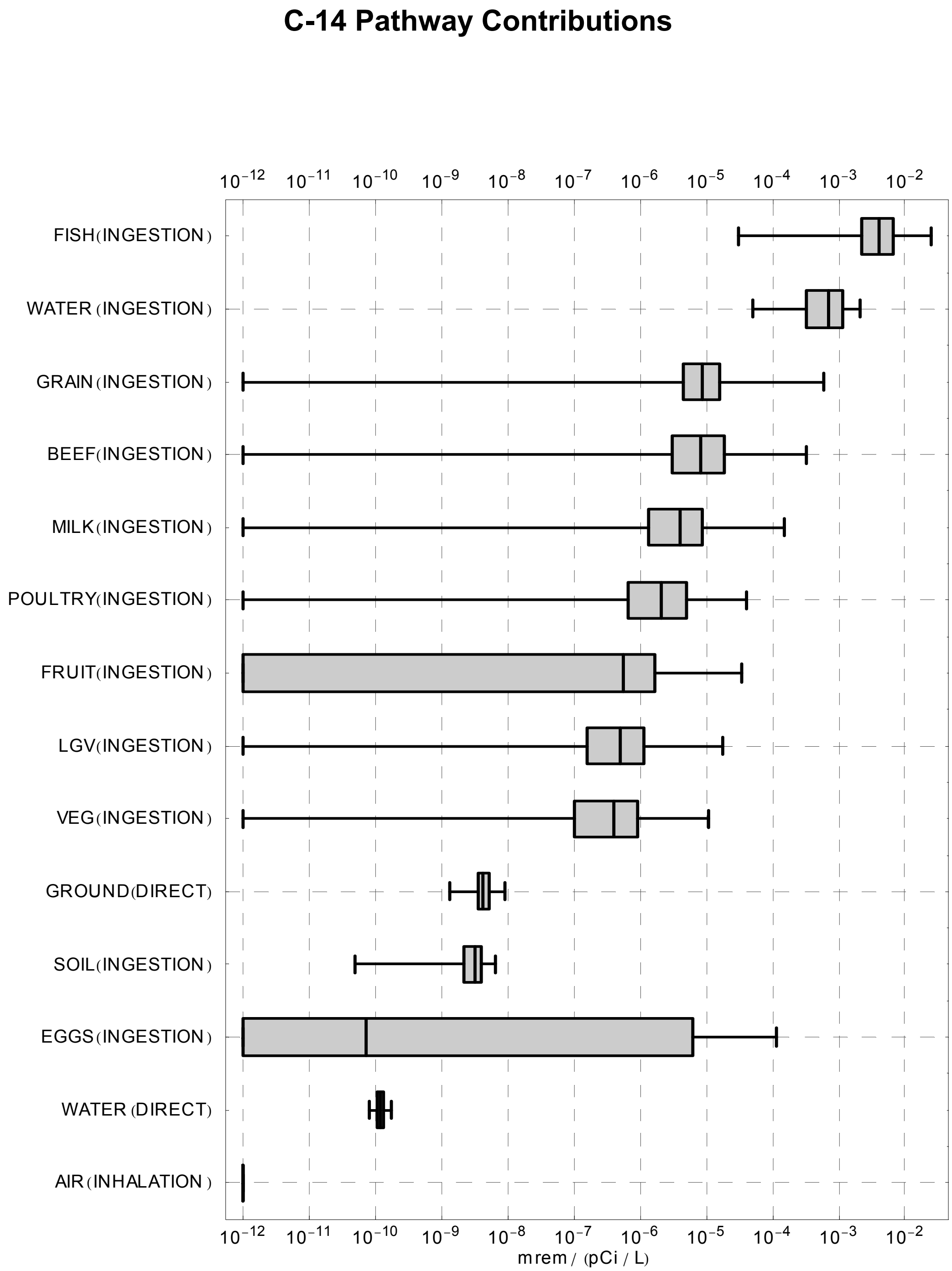

Figure A–1. Annual Dose Distributions for C-14 for Significant Contributing Pathways

Se-79 Pathway Contributions

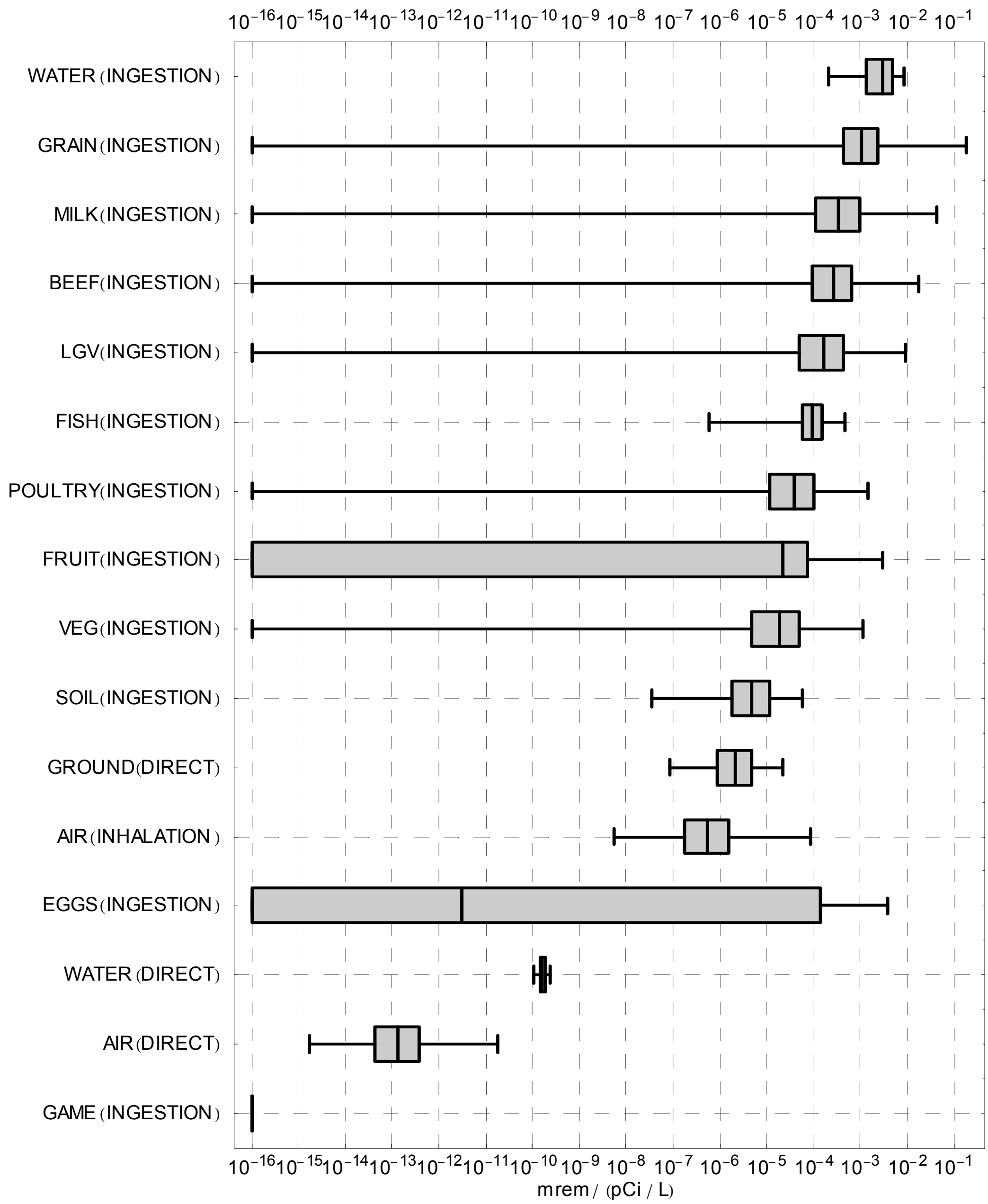

Figure A–2. Annual Dose Distributions for Se-79 for Significant Contributing Pathways

Sr-90 Pathway Contributions

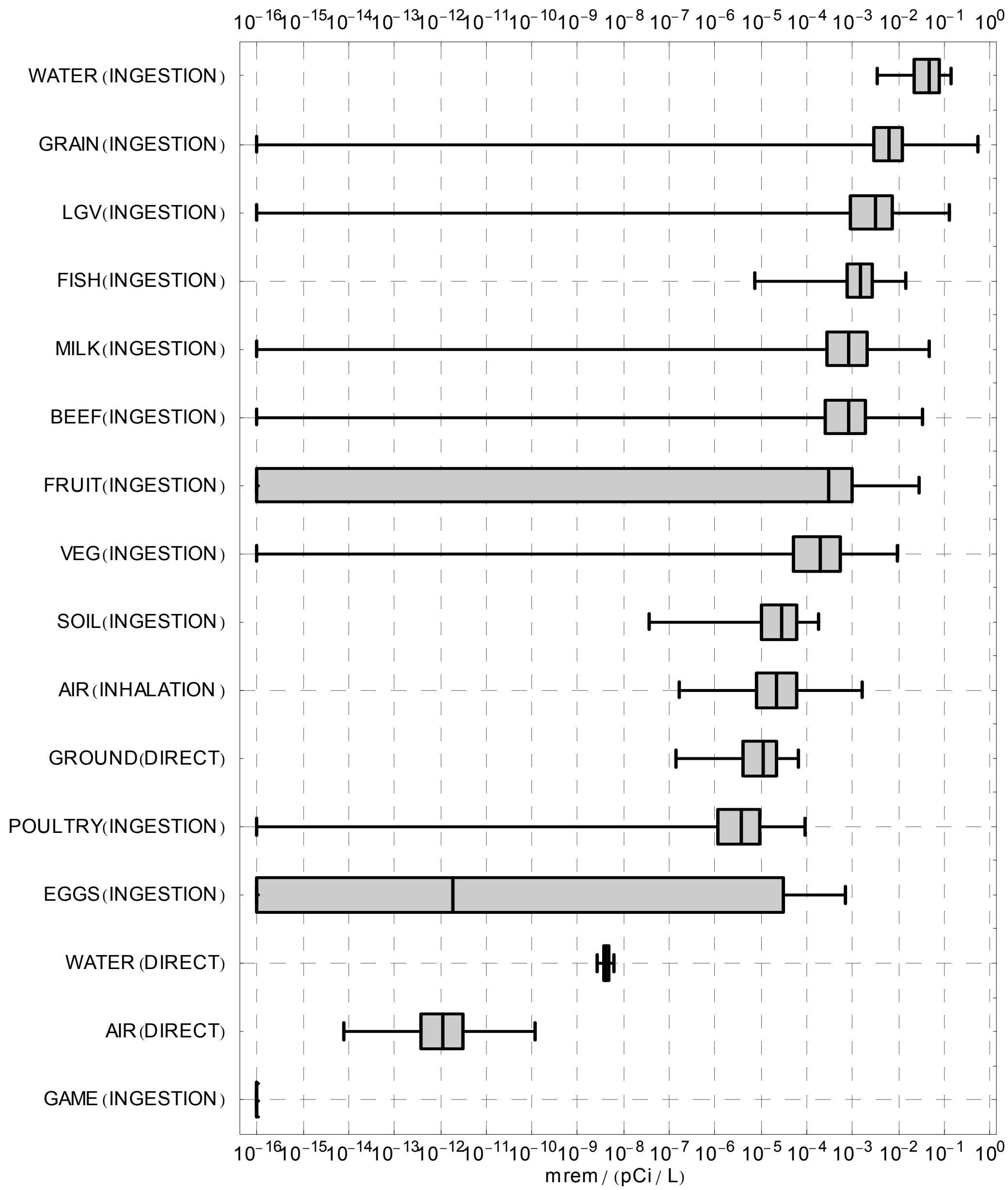

Figure A–3. Annual Dose Distributions for Sr-90 for Significant Contributing Pathways

Y-90 Pathway Contributions

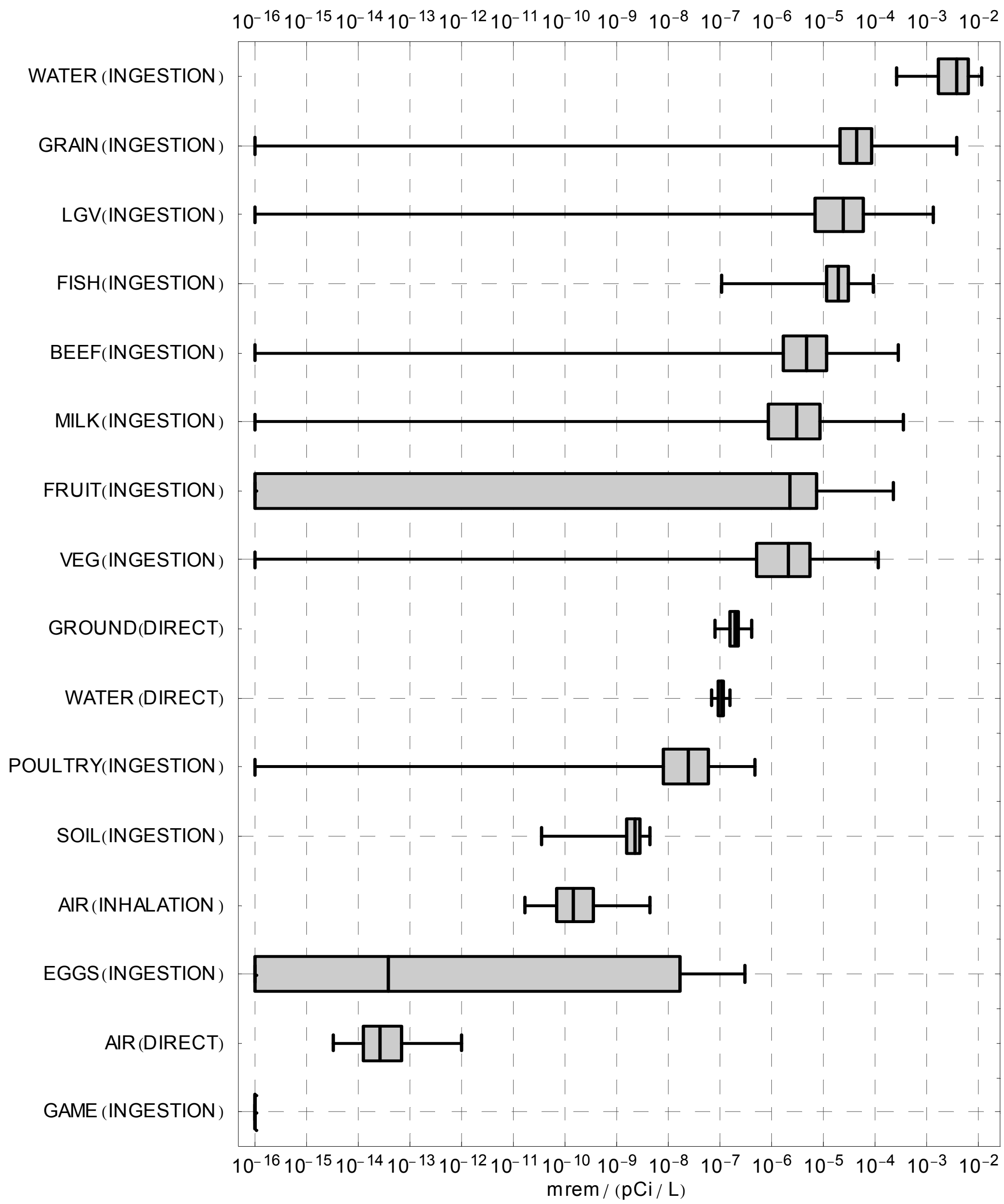

Figure A–4. Annual Dose Distributions for Y-90 for Significant Contributing Pathways

Nb-94 Pathway Contributions

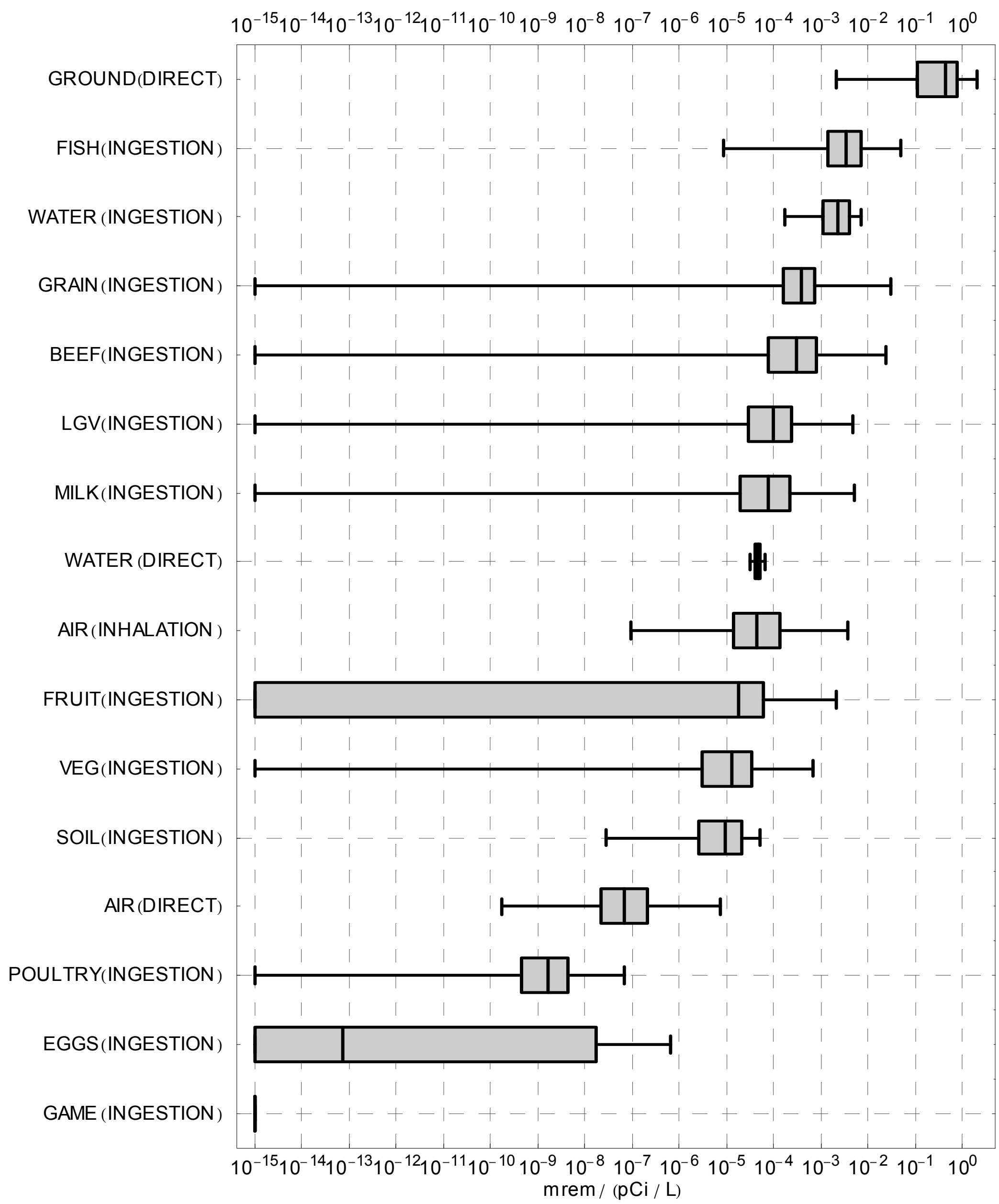

Figure A–5. Annual Dose Distributions for Nb-94 for Significant Contributing Pathways

Tc-99 Pathway Contributions

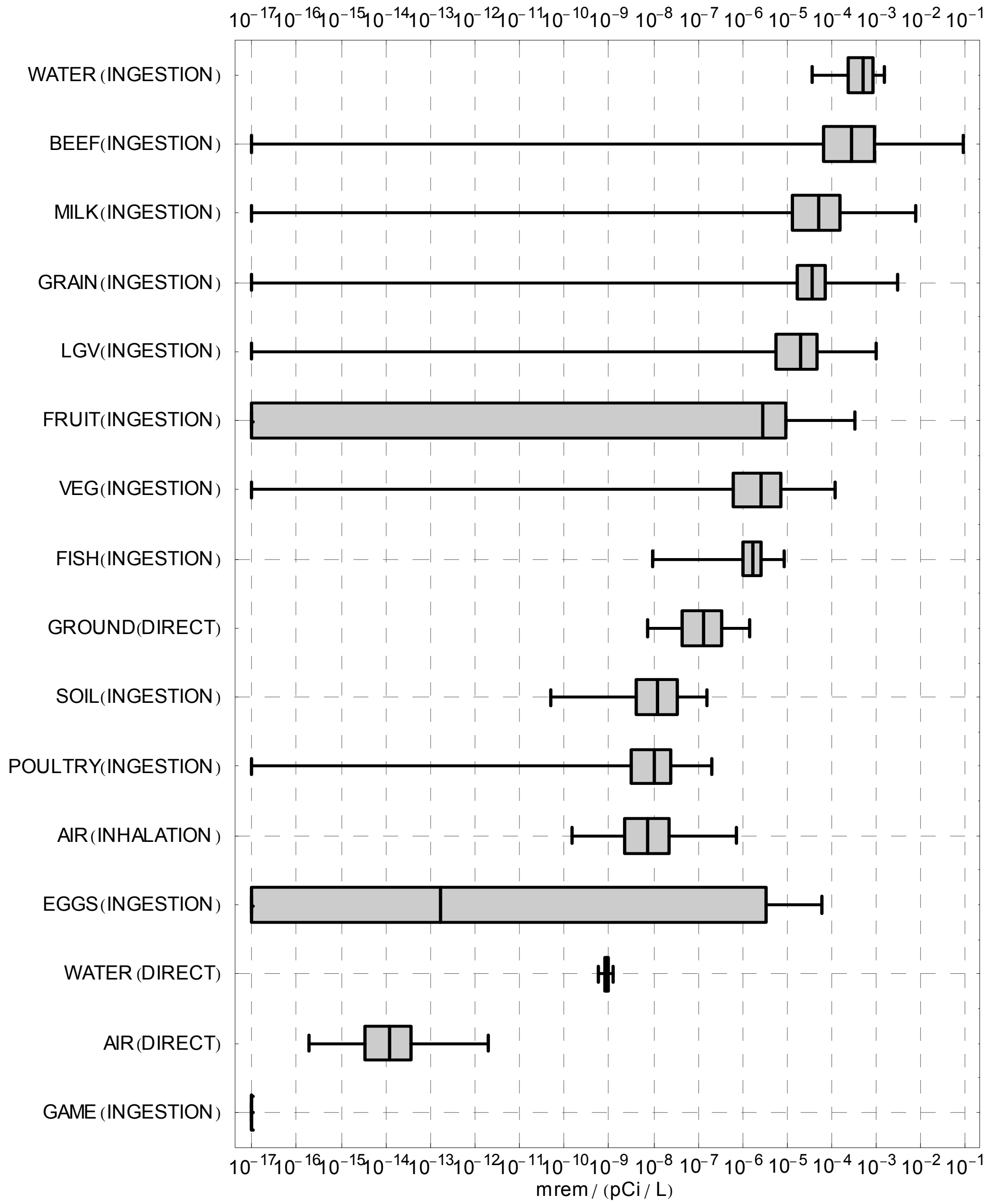

Figure A–6. Annual Dose Distributions for Tc-99 for Significant Contributing Pathways

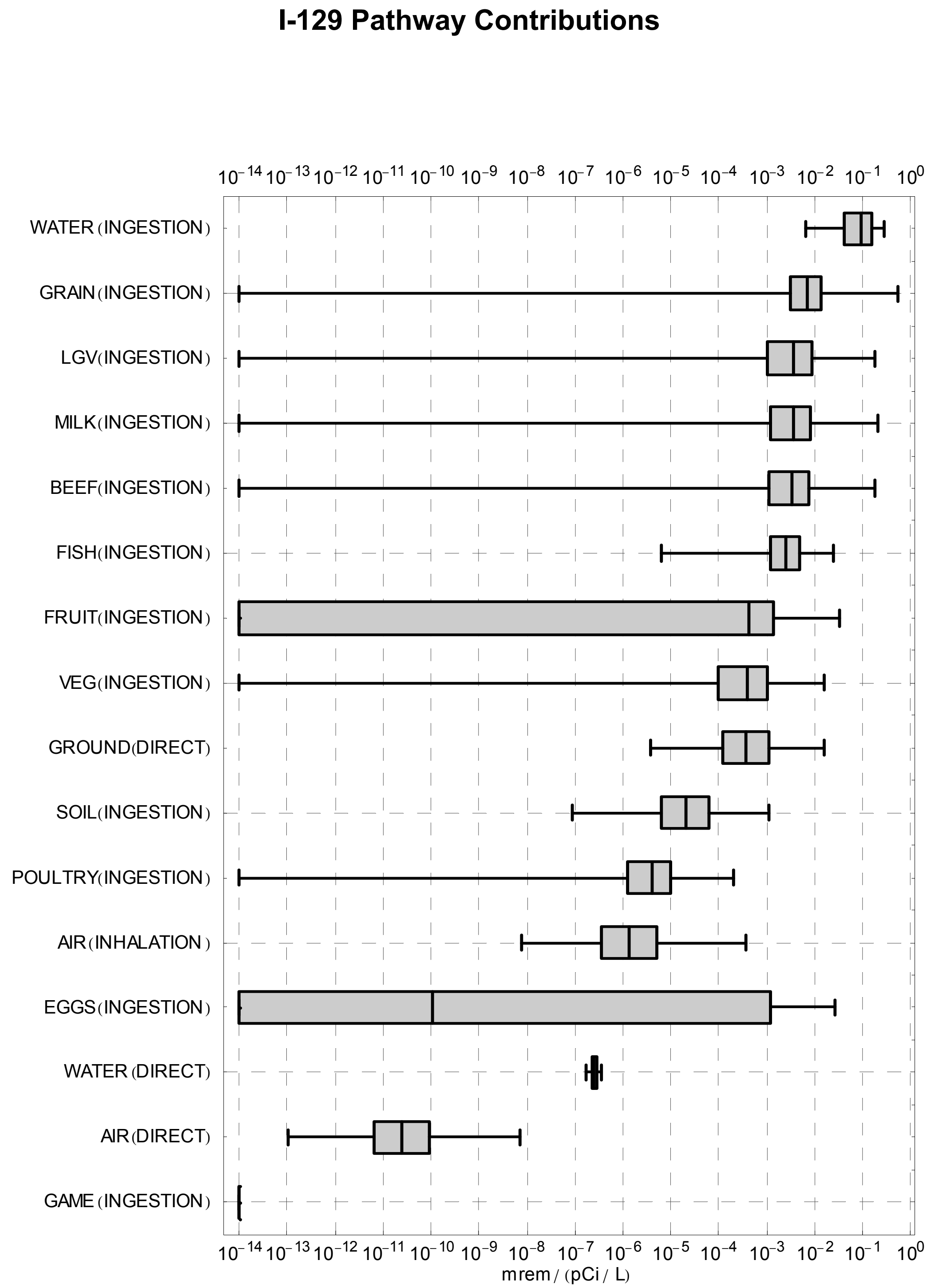

Figure A–7. Annual Dose Distributions for I-129 for Significant Contributing Pathways

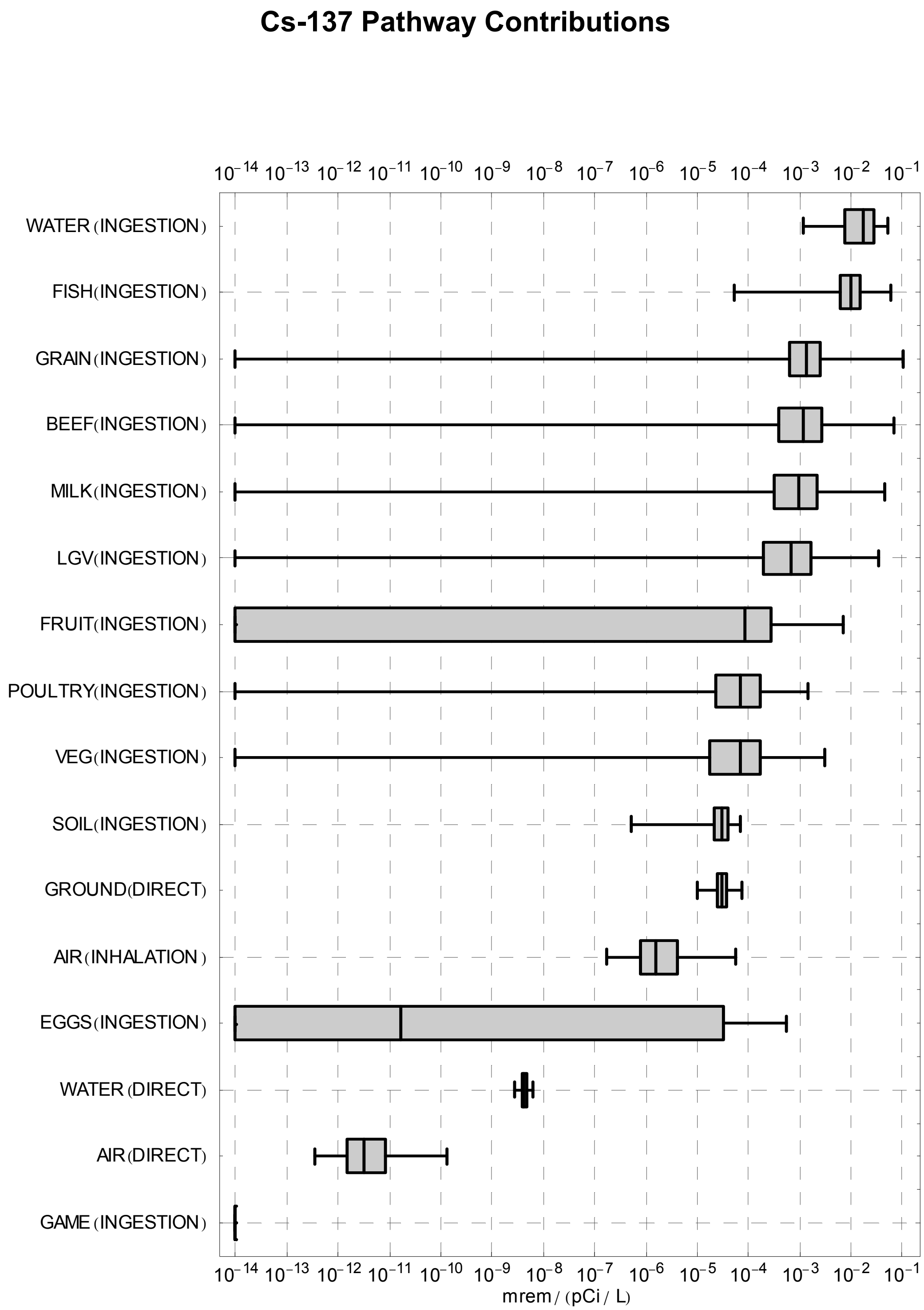

Figure A–8. Annual Dose Distributions for Cs-137 for Significant Contributing Pathways

Pb-210 Pathway Contributions

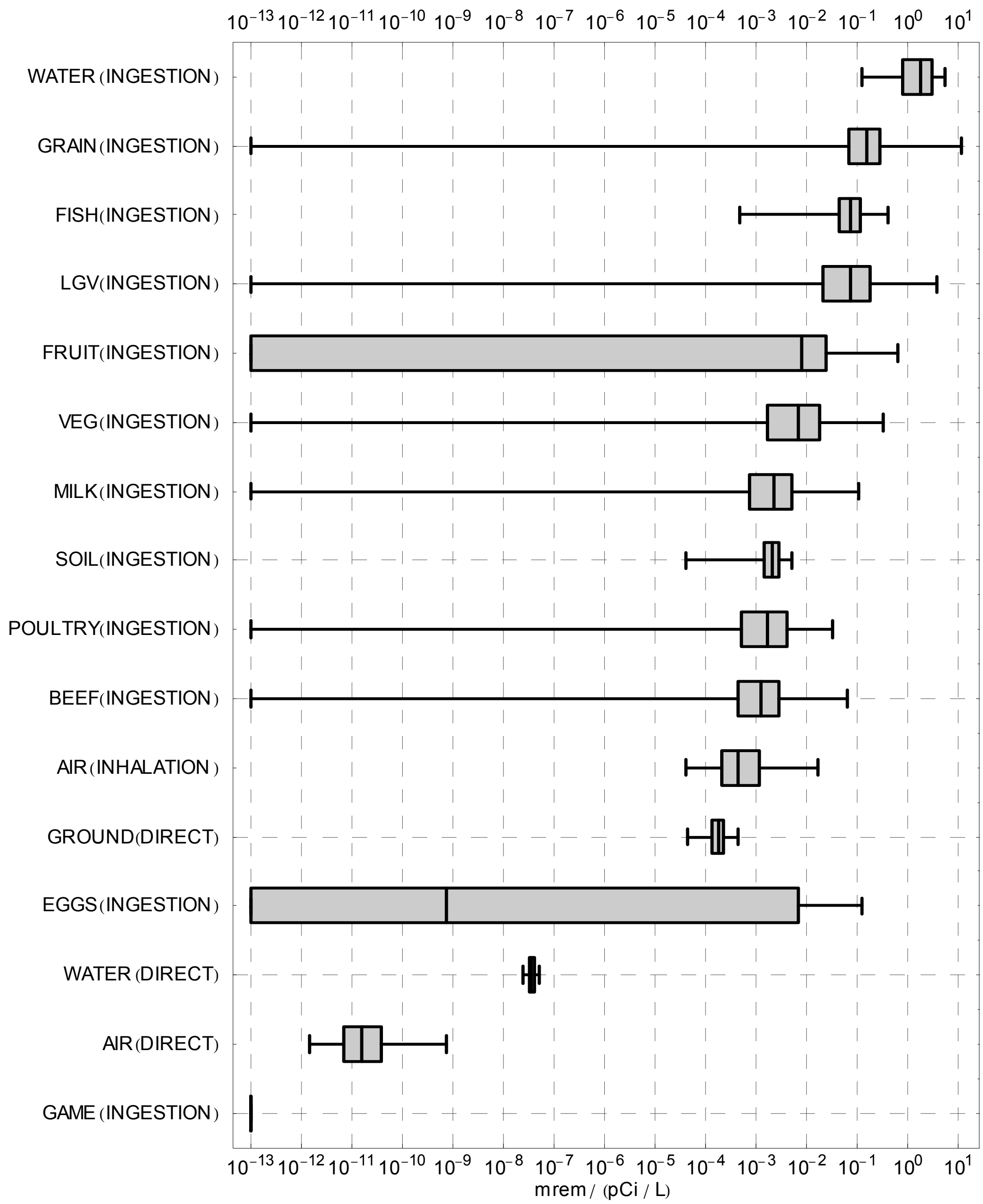

Figure A–9. Annual Dose Distributions for Pb-210 for Significant Contributing Pathways

Ra-226 Pathway Contributions

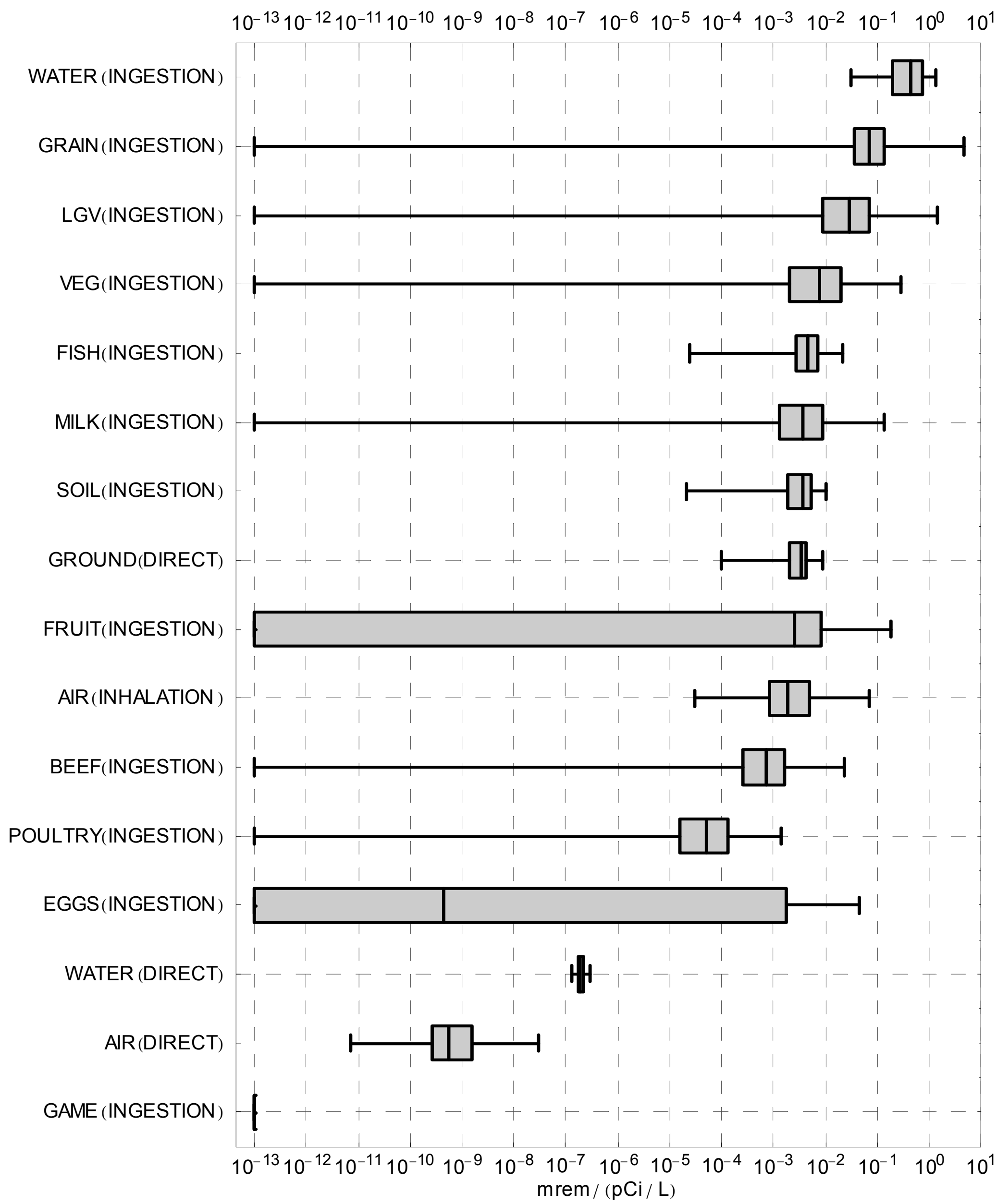

Figure A–10. Annual Dose Distributions for Ra-226 for Significant Contributing Pathways

Th-230 Pathway Contributions

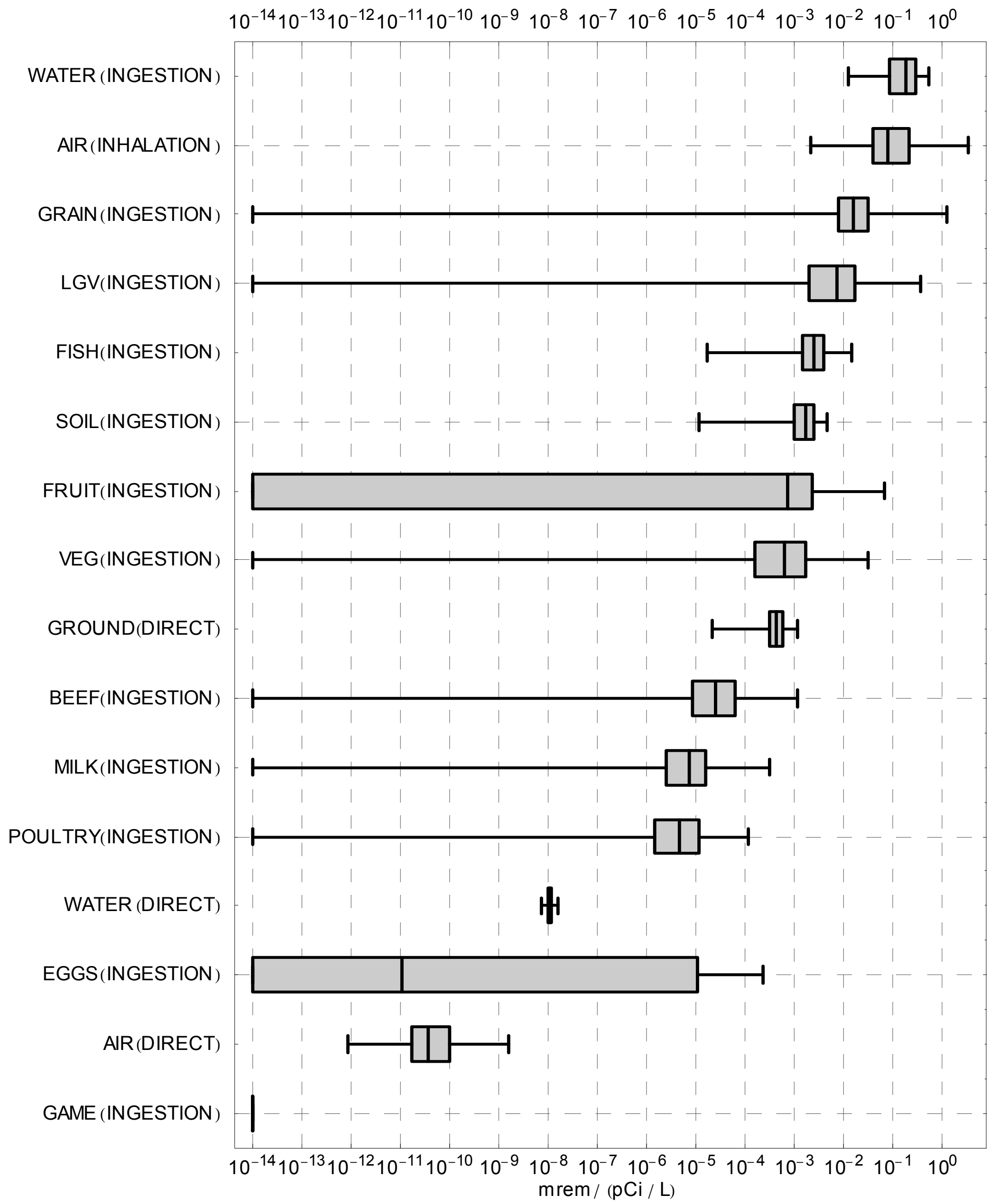

Figure A–11. Annual Dose Distributions for Th-230 for Significant Contributing Pathways

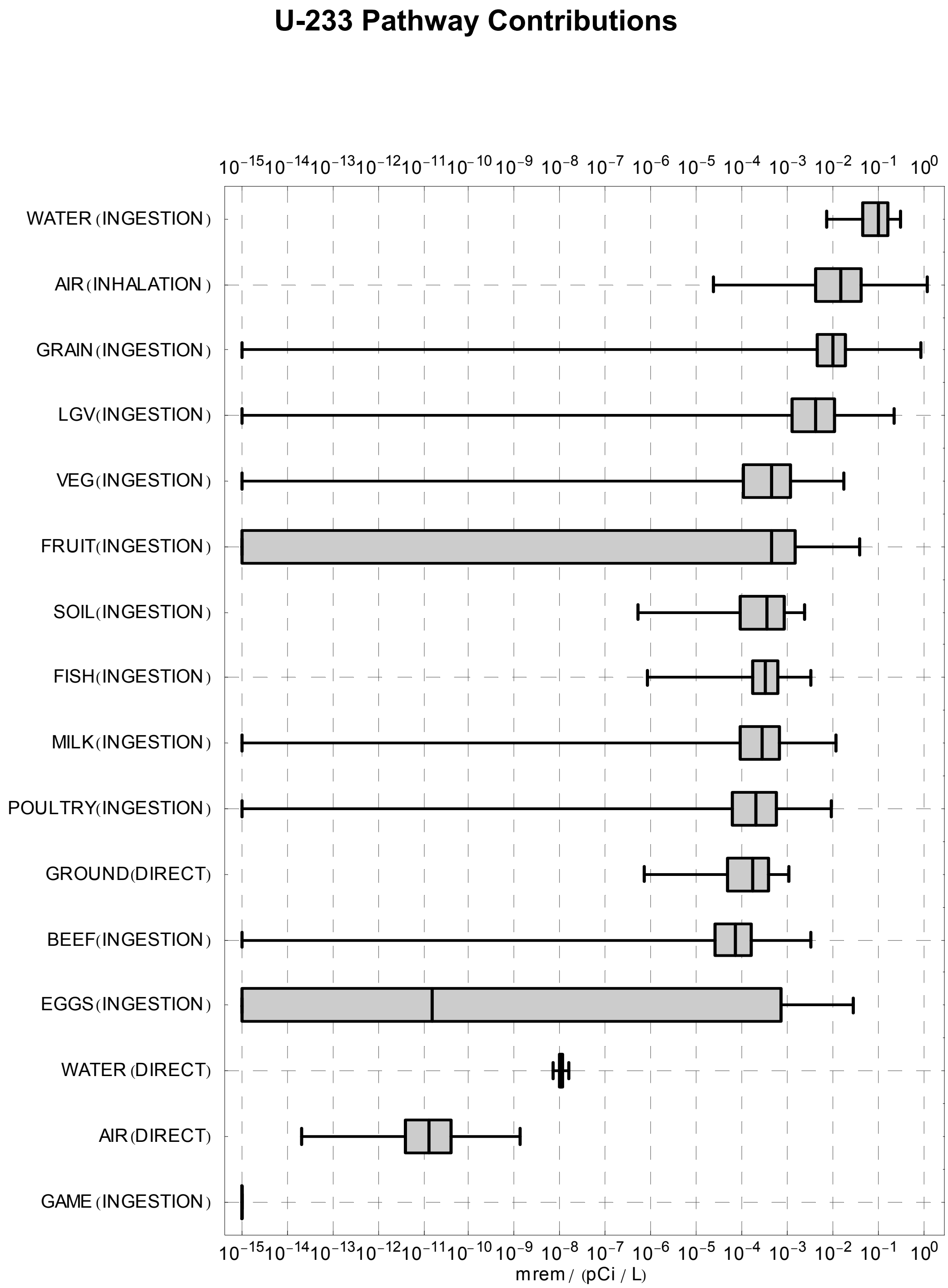

Figure A–12. Annual Dose Distributions for U-233 for Significant Contributing Pathways

U-234 Pathway Contributions

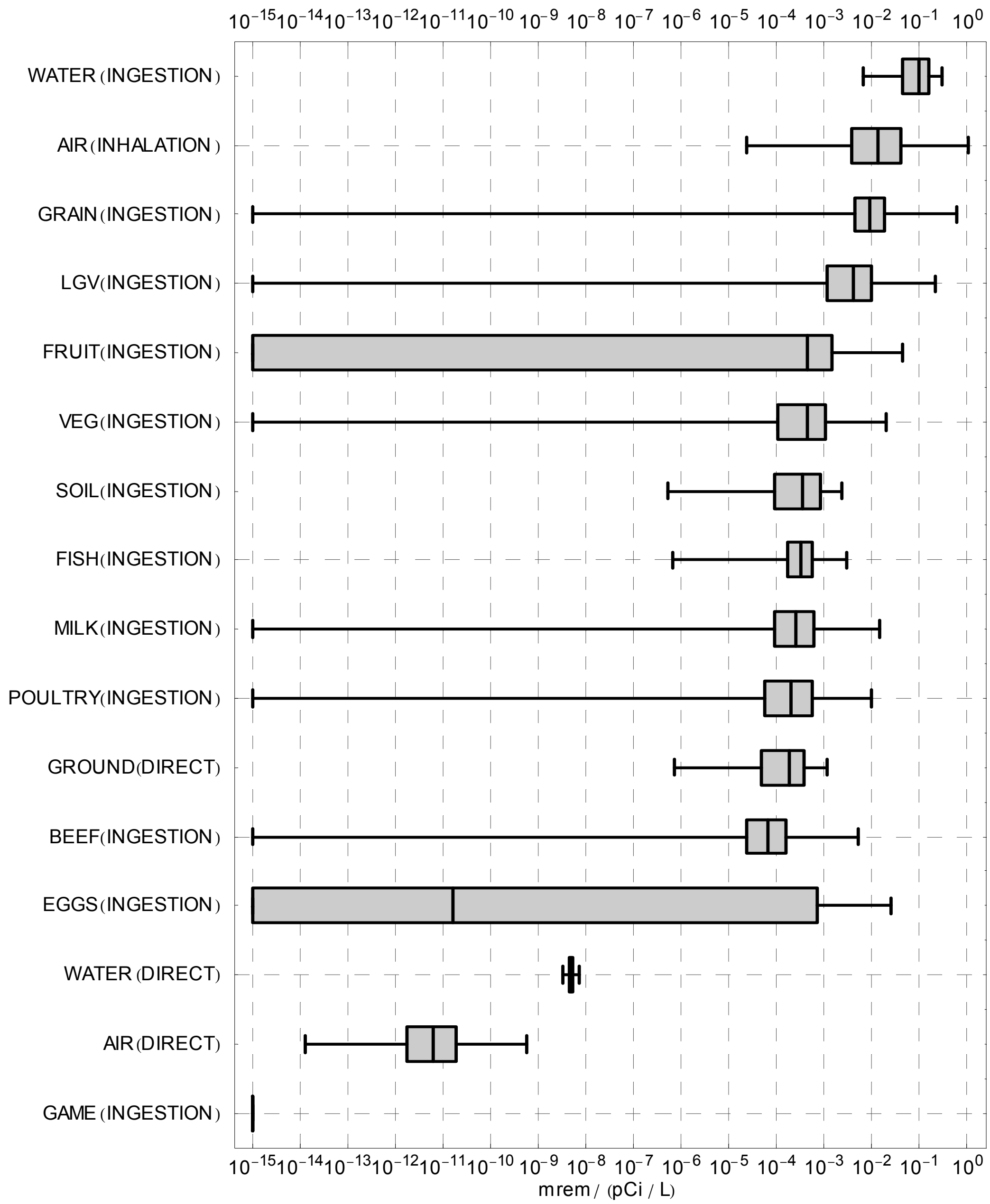

Figure A–13. Annual Dose Distributions for U-234 for Significant Contributing Pathways

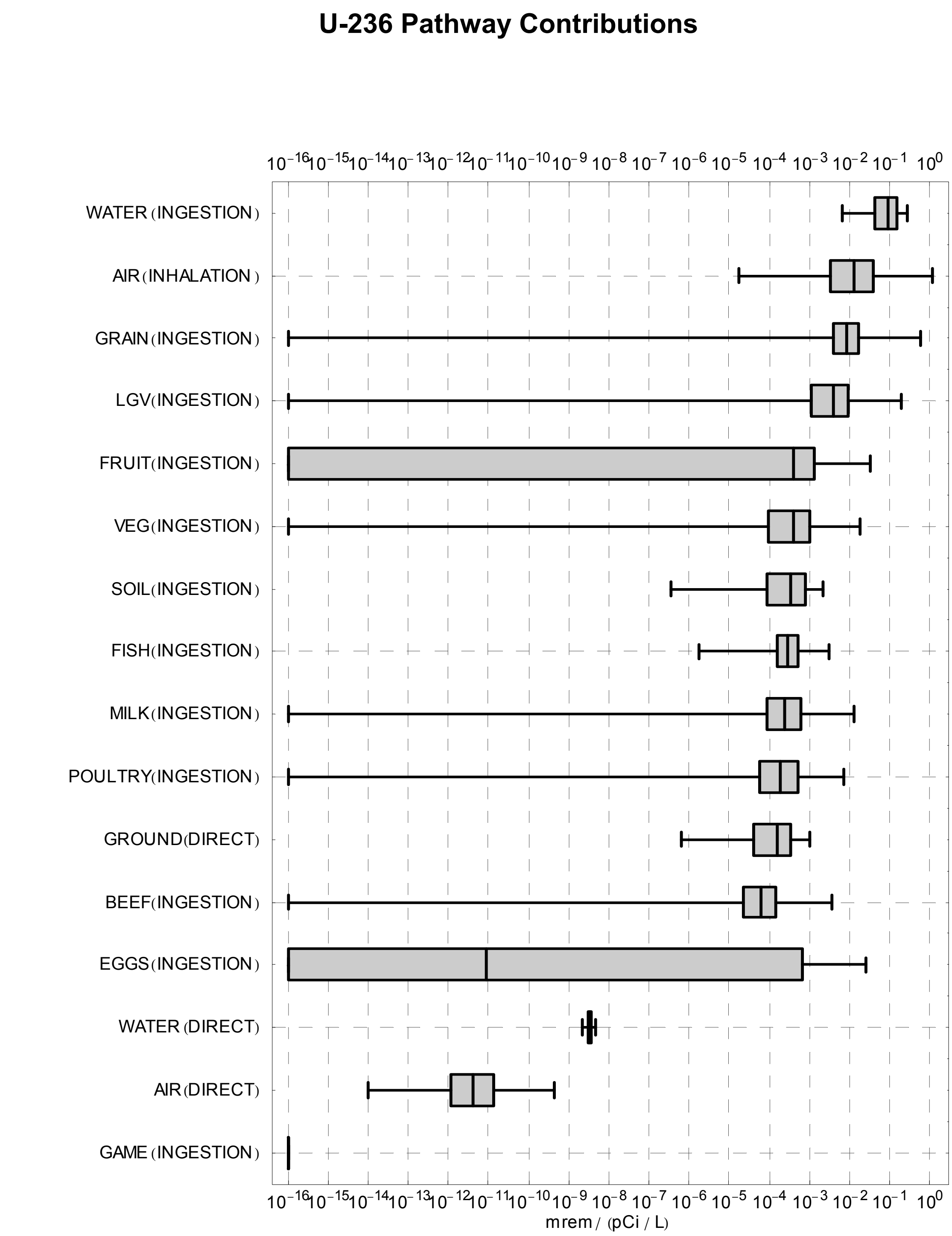

Figure A–14. Annual Dose Distributions for U-236 for Significant Contributing Pathways

U-238 Pathway Contributions

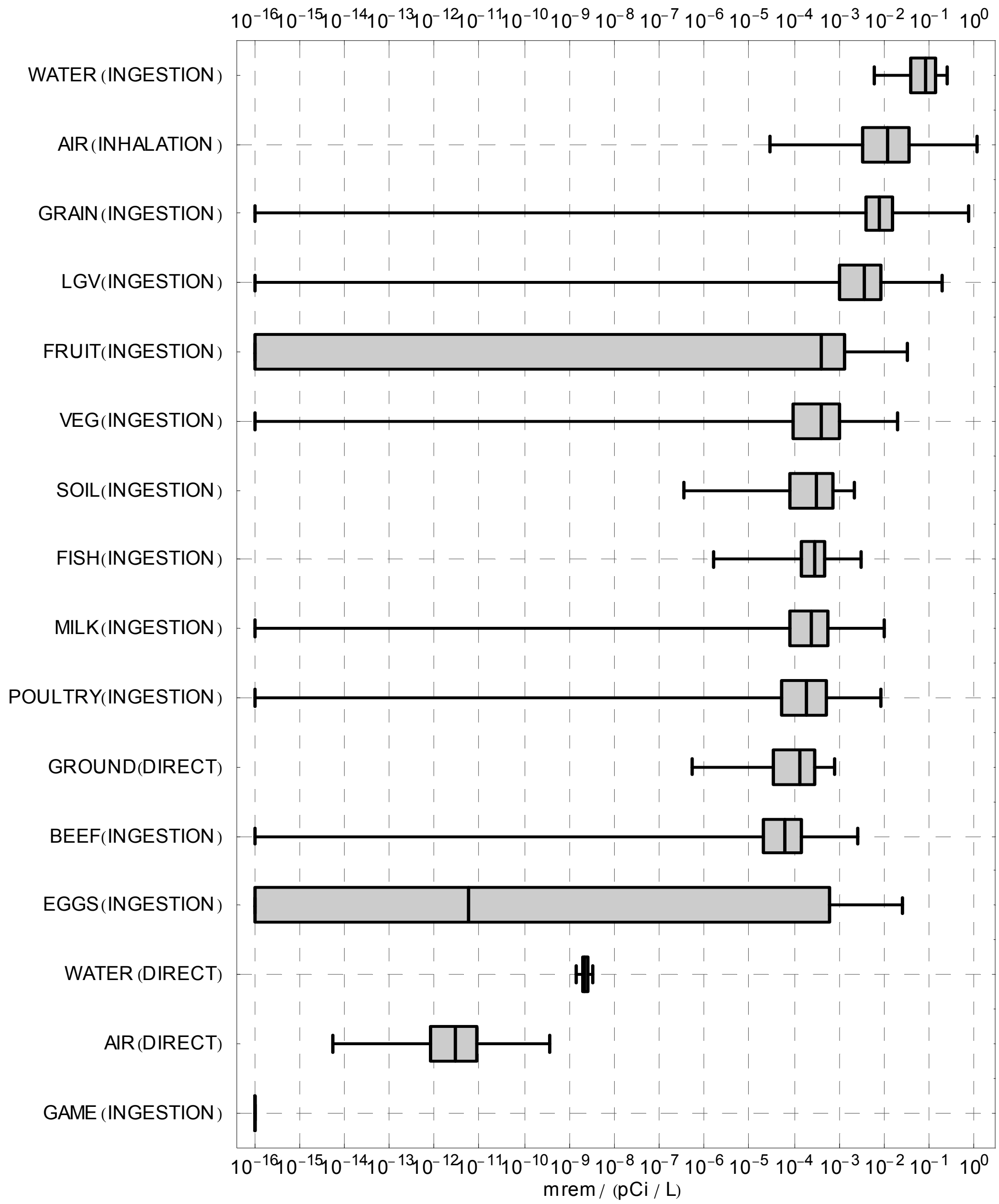

Figure A–15. Annual Dose Distributions for U-238 for Significant Contributing Pathways

Np-237 Pathway Contributions

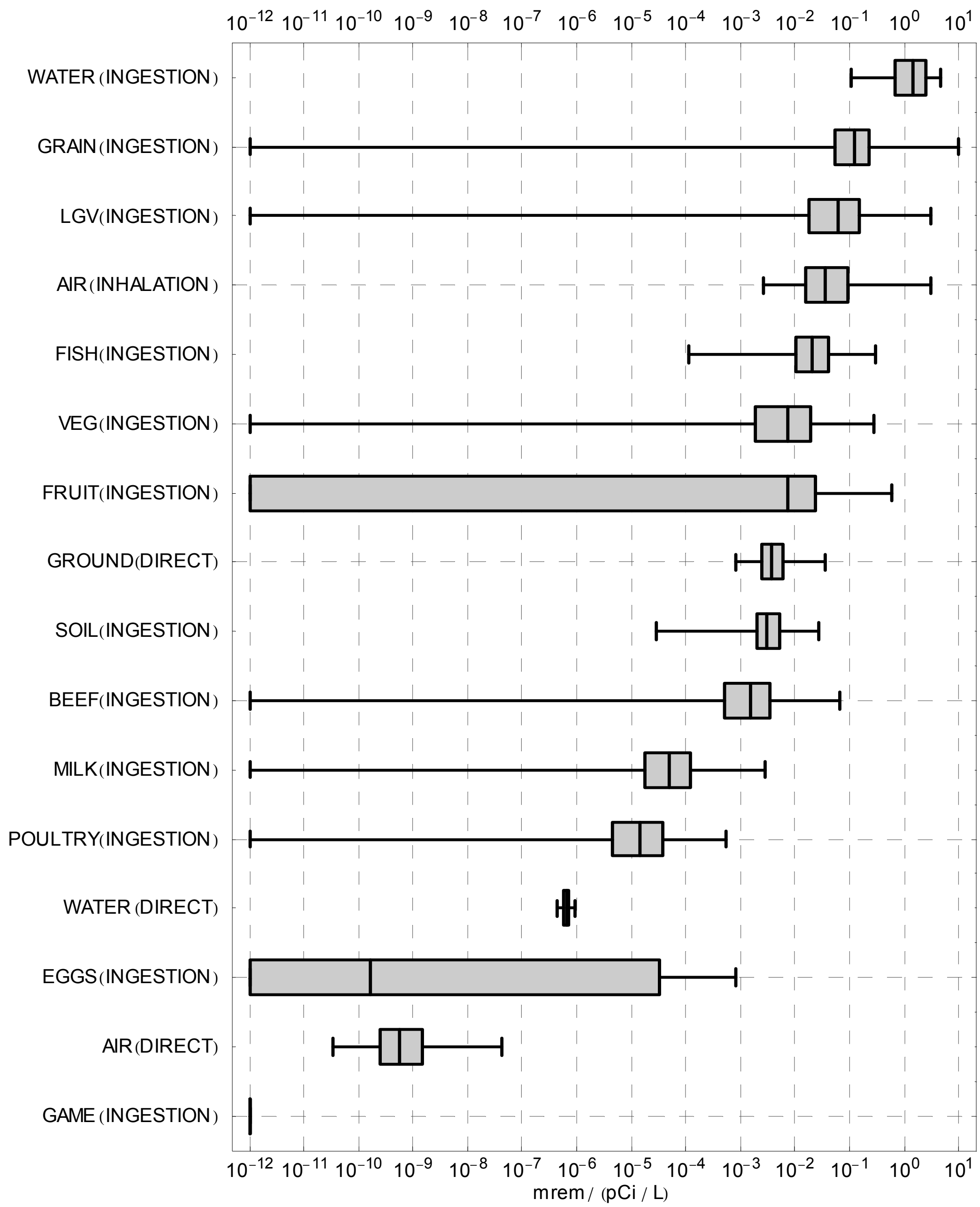

Figure A–16. Annual Dose Distributions for Np-237 for Significant Contributing Pathways

Pu-239 Pathway Contributions

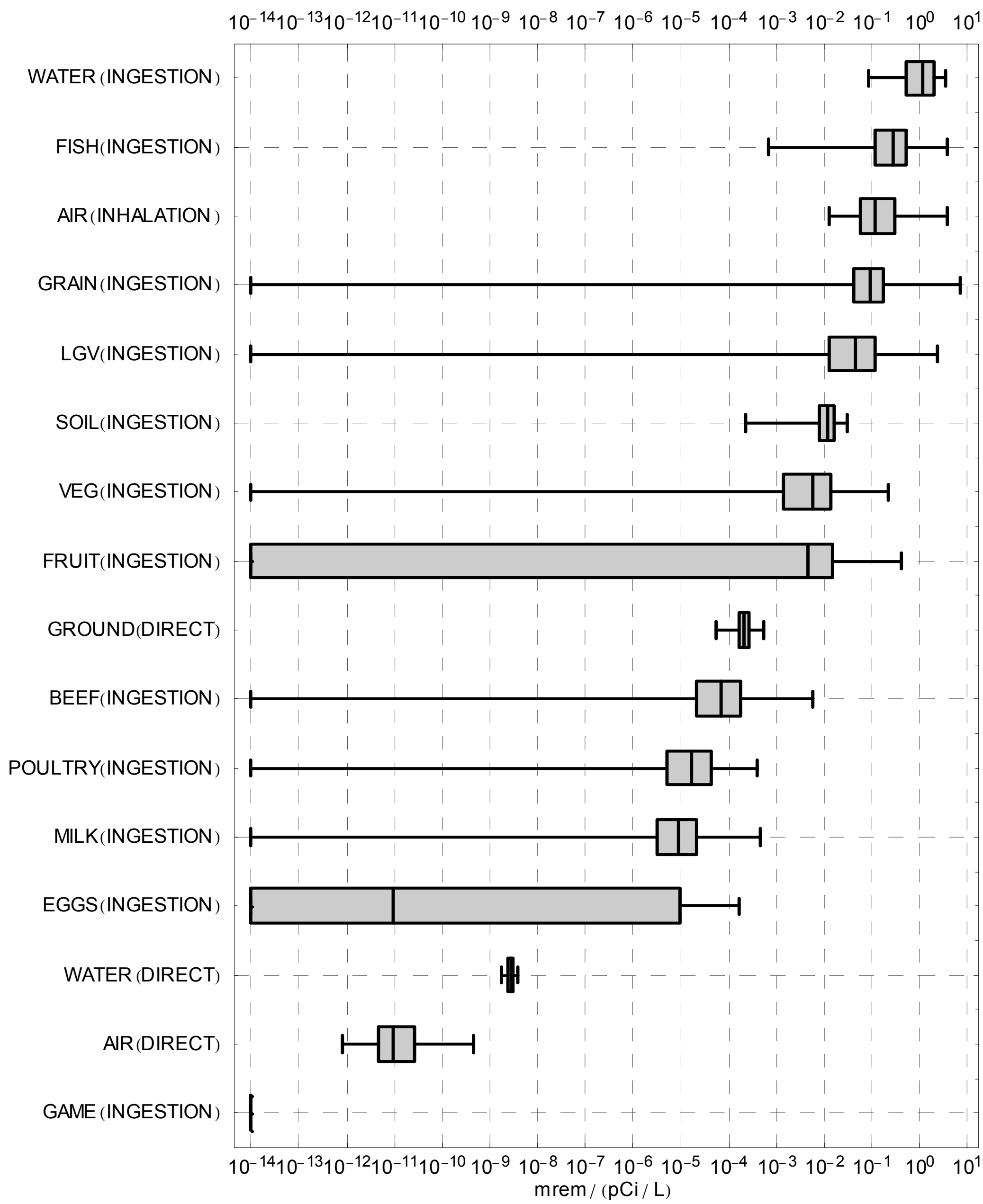

Figure A–17. Annual Dose Distributions for Pu-239 for Significant Contributing Pathways

Pu-240 Pathway Contributions

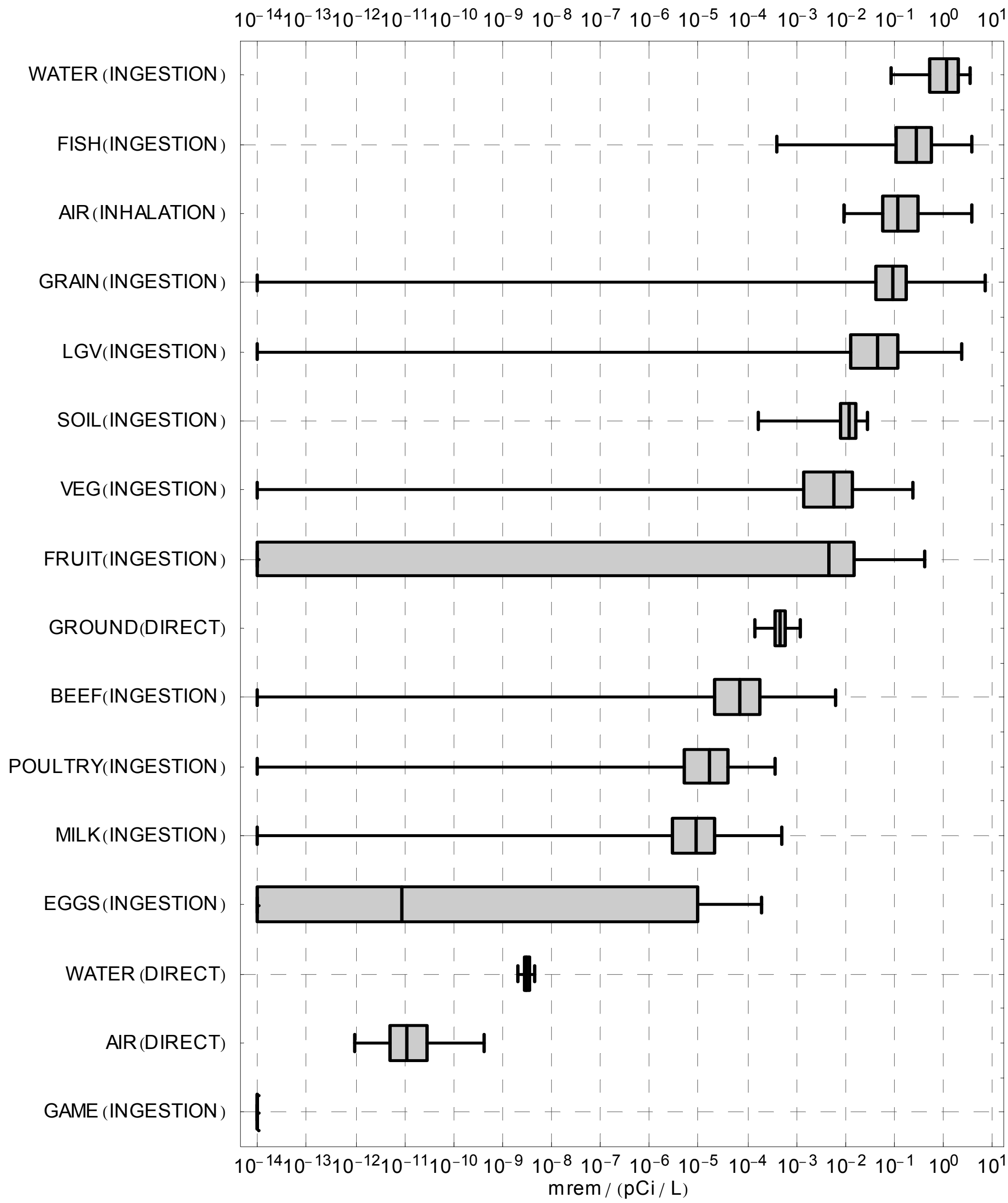

Figure A–18. Annual Dose Distributions for Pu-240 for Significant Contributing Pathways

Pu-242 Pathway Contributions

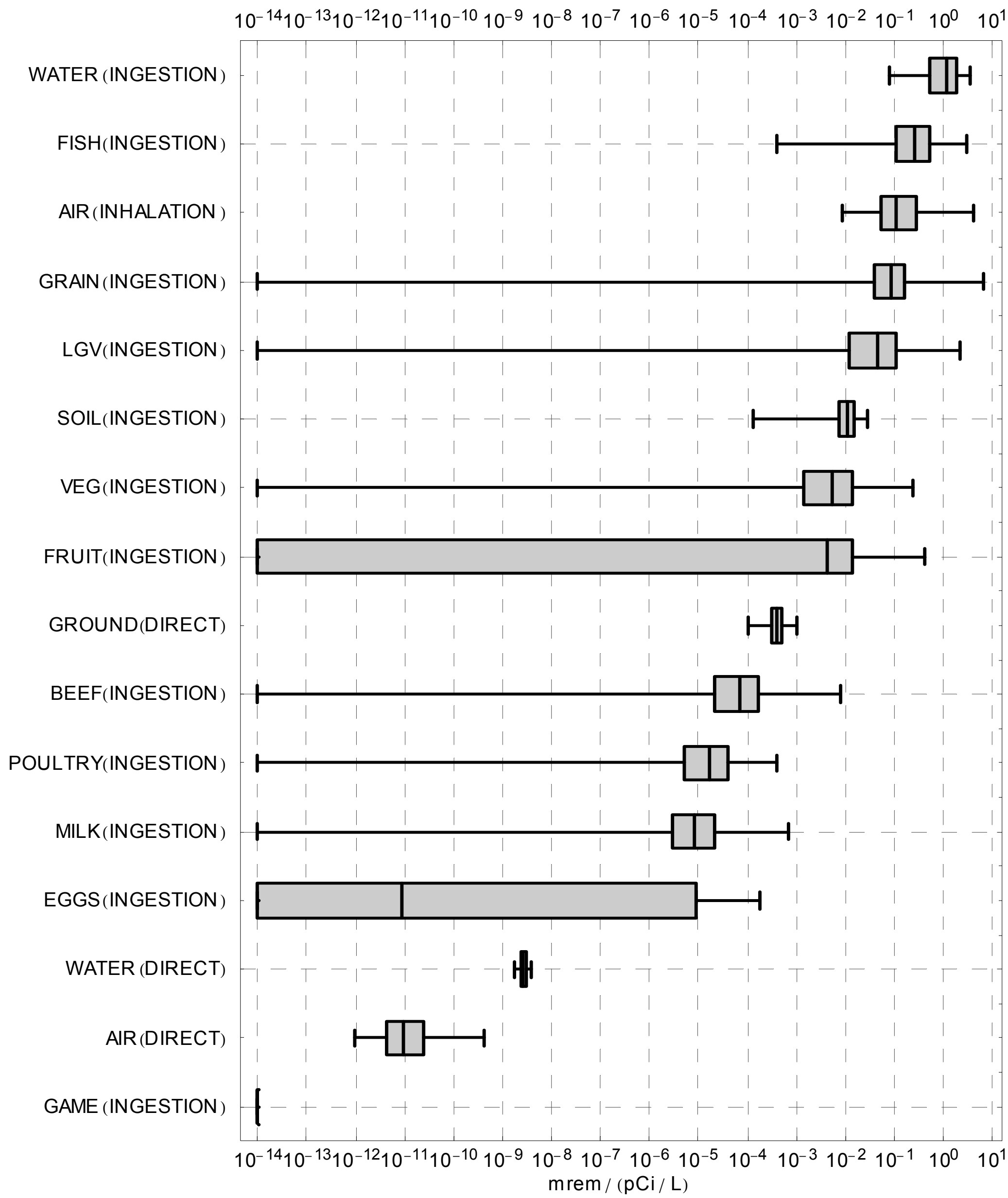

Figure A–19. Annual Dose Distributions for Pu-242 for Significant Contributing Pathways

Am-241 Pathway Contributions

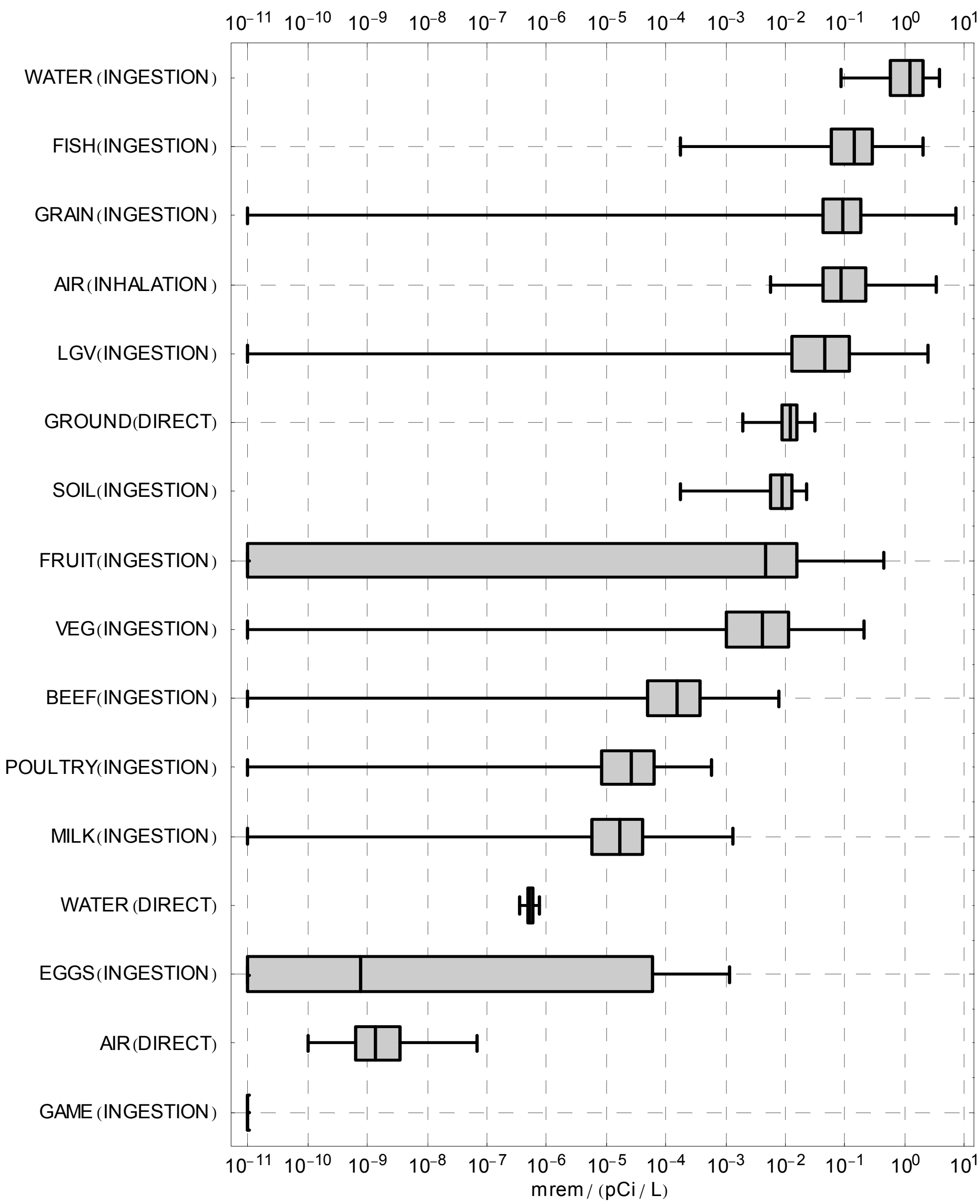

Figure A–20. Annual Dose Distributions for Am-241 for Significant Contributing Pathways

APPENDIX B

BDOSE MODELING DESCRIPTION

BDOSE^{TM} Version 2.0 (Mancillas, 2008), hereafter referred to as BDOSE, was developed to support the U.S. Department of Energy (DOE) consultations with the U.S. Nuclear Regulatory Commission (NRC) on non-high-level waste determinations. BDOSE is conceptually similar to existing dose assessment codes (e.g., GENII, Napier, et al., 2004) in that it evaluates a dose to a receptor, where the dose is the combined exposure from multiple pathways for some set of radionuclides. Scenario analyses can include the evaluation of doses via multiple pathways including inhalation, ingestion, and direct exposure; thus, a total effective dose equivalent (TEDE) to a receptor can be evaluated.

A unique capability of BDOSE is an integrated ability to stochastically evaluate and graphically represent the effects of parameter uncertainty and variability on estimated dose. These capabilities are derived from the GoldSim™ modeling environment, in which BDOSE was developed. The GoldSim modeling environment supports stochastic sampling of parameters from several commonly defined or user-defined statistical distributions. Additionally to propagate uncertainties, GoldSim allows for Monte Carlo execution of a model with simple random sampling or Latin Hyper Cube sampling, with or without stratified sampling or correlated sampling [see GoldSim User Manual (GoldSim Technology Group, LLC, 2003)]. BDOSE was designed to be a modular GoldSim model readily incorporated into other GoldSim™ models or performance assessment evaluations. Within the scope of this sensitivity analysis, a brief description of BDOSE is provided.

B.1 Radionuclides

BDOSE was developed to evaluate non-high-level waste determinations, thus it was designed to evaluate dose significant radionuclides typical of the Ronald W. Reagan National Defense Authorization Act of 2005 (NDAA) sites. These radionuclides tend to be those which are at least moderately long lived (half life greater than a year) and, through the action of groundwater transport, can develop a significant presence in a receptor environment. Table B–1 lists the radionuclides BDOSE evaluated. Note that in addition to moderately long-lived radionuclides, this list also includes a few short-lived radionuclides (i.e., Y-90 and Ba-137m), which are progeny of other considered radionuclides.

Table B–1. Radionuclides List for BDOSE

H-3	C-14	Co-60	Ni-59	Ni-63
Se-79	Sr-90	Y-90	Nb-94	Tc-99
I-129	Cs-137	Ba-137m	Eu-152	Eu-154
Eu-155	Pb-210	Ra-226	Ra-228	Ac-227
Th-228	Th-229	Th-230	Th-232	Pa-231
U-232	U-233	U-234	U-235	U-236
U-238	Np-237	Pu-238	Pu-239	Pu-240
Pu-241	Pu-242	Pu-244	Am-241	Am-242m
Am-243	Cm-242	Cm-243	Cm-244	Cm-245
Cm-246	Cm-247	Cm-248	Cf-249	

B.2 Pathways

In BDOSE, the evaluation of environmental accumulation and distribution of contaminants is centered on a water-dependent scenario, originating with a contaminated groundwater source. Conceptually this begins with irrigation of soil with contaminated groundwater and soil accumulating contaminants from the irrigation water. Crops are then grown in contaminated soils and irrigated with contaminated waters, thus accumulating contaminants simultaneously from both the soil and water. Animals then ingest and accumulate contaminants from contaminated soil, feeds, and waters. A human receptor is then exposed to accumulated contaminants via multiple exposure pathways:

- Ingestion of contaminated groundwater
- Ingestion of contaminated soil
- Ingestion of crops irrigated with contaminated groundwater and grown in contaminated soil
- Ingestion of animal products raised with contaminated feed, contaminated drinking water, and contaminated soils
- Ingestion of fish (or other aquatic animals) raised in contaminated waters
- Inhalation of resuspended contaminants and radioactive gases
- External exposure from contaminated soil
- External exposure from contaminated waters (via swimming and boating)
- External exposure from resuspended contaminants and radioactive gases

In BDOSE, parameters that determine the degree of exposure the receptor receives through these pathways can be placed into one of two categories, environmental and behavioral. Environmental factors affect the rate of contaminant accumulation and the amount of contaminants found in each of the components of the biosphere, including

- Contaminated waters (groundwater, ponds, and streams)
- Crops (grain, fruit, leafy green vegetables, vegetables, animal feeds, and fodder)
- Animal products (beef, milk, poultry, eggs, game animals, and fish)

Behavioral parameters generally define the amount to which the receptor imbibes or is exposed to environmental contaminants. In BDOSE these parameters are receptor annual consumption rates, annual inhalation volumes, and annual exposure times.

B.3 Environmental Components and Parameters

Individual components of the biosphere accumulate radionuclide contaminants from differing mechanisms and pathways. The following descriptions briefly present how these components are evaluated in BDOSE.

B.3.1 Contaminant Source

The principal source of radionuclides (in BDOSE) in the receptor environment is groundwater. Radionuclide contaminants are transported from a source location via groundwater transport to an underground aquifer. Contaminants are then introduced to the biosphere via a well. This water can then be directly consumed, used for irrigation, or introduced into local surface waters.

B.3.1.1 Surface Waters

Groundwater can migrate to surface waters such as ponds, streams, or rivers. Simple dilution of water bodies is used, and instantaneous mixing of the water is assumed to occur. The user specifies boating, swimming, or fishing in each of the three water types (groundwater, pond, or stream) independently. Groundwater concentration is maintained as a possible selection solely to allow the user to enter known water concentrations, and no further dilution is applied.

B.3.1.1.1 Stream or River

Using simple dilution, the stream or river concentration in the water is determined by (NRC, 1977)

$$C_{sr,i}(t) = GW_i(t) \times DF \qquad \text{(B–1)}$$

where

$C_{sr,i}(t)$ — concentration in the stream or river of radionuclide *i* at time *t* [Bq/L]
$GW_i(t)$ — groundwater concentration of radionuclide *i* at time *t* [Bq/L]
DF — dilution factor

The stream or river dilution factor, *DF*, is calculated as follows

$$DF = \frac{IVFR}{IVFR + SVFR} \qquad \text{(B–2)}$$

DF — dilution factor (unitless)
$IVFR$ — infiltration volume flow rate (m^3/d)
$SVFR$ — stream volume flow rate (m^3/d)

B.3.1.1.2 Pond

For a pond, simple dilution is applied with the dilution factor determined as the ratio of the contaminated zone area and the area of the watershed (Yu, et al., 2001).

$$C_{pond,i}(t) = C_{gw,i}(t)\frac{CZ}{PA} \tag{B–3}$$

where

$C_{pond,i}(t)$	—	concentration in pond water of radionuclide *i* at time *t* [Bq/L]
$C_{gw,i}(t)$	—	concentration in groundwater of radionuclide *i* at time *t* [Bq/L]
CZ	—	area of contaminated zone [m^2]
PA	—	area of pond [m^2]

The concentration in the pond is calculated assuming no buildup of contaminants.

B.3.2 Soil

In BDOSE, two separate soil types are evaluated, with each soil type characterizing a different contamination scenario. A resident soil (simply referred to as “soil” in BDOSE) is characteristic of a scenario in which contaminants from irrigation water gradually accumulate in the soil. An intruder soil is characteristic of a scenario in which contaminants from waste excavations are directly deposited onto the soil.

B.3.2.1 Resident Soil

The evaluation of the buildup of contaminants in the resident soil is a complicated analysis, which for brevity will not be presented in detail here. Within the scope of this discussion (sensitivity analysis), it is sufficient to present the parameters that affect the long-term accumulation of contaminants in the soil from irrigation. These parameters are those that define

- Irrigation rate
- Precipitation rate
- Evapotranspiration rate
- Soil erosion loss rate
- Deep percolation losses
- Soil density
- Soil water content
- Soil plow depth
- Soil-liquid partition coefficients for radionuclides

A detailed description of how BDOSE evaluates contaminant buildup from irrigation with contaminated groundwater can be found in Simpkins, et al. (2008).

B.3.2.2 Intruder Soil

The intruder soil conceptual model is a simple model. Conceptually, waste materials are introduced into the environment as a *pile* of excavated materials, which includes some fraction of waste material. The waste concentration of the *pile* is a function of the source waste concentration, the volume of waste intersected during the excavation process, and the total excavated volume. The *pile* is then evenly distributed into agricultural soils through plowing. The agricultural soil contaminated by the pile is the *intruder soil* and its concentration is a function of the *pile* concentration, the distribution area, and the plow depth of the soil. In BDOSE the excavated material can originate from one of two scenarios, drilling or excavation.

In the drilling scenario

$$Pile_{d,j}(t) = C_{waste,j}(t) \times p(d / 2)^2 \times W_t \times \frac{W_t}{BD} \tag{B–4a}$$

where

$Pile_{d,j}(t)$—	concentration of radionuclide i at time t [Bq/m^2] in the drill-cutting pile
$C_{waste,j}(t)$—	concentration of radionuclide i at time t [Bq/m^2] in the subterranean source
d —	diameter of drill [m]
W_t —	thickness of the waste [m]
BD —	depth of the borehole [m]

and where the volume of the excavated material is

$$V_{drill} = \pi(d / 2)^2 \times BD \tag{B–4b}$$

d —	diameter of drill [m]
BD —	depth of the borehole [m]

In the excavation scenario

$$Pile_{e,j}(t) = C_{waste,j}(t) \times \frac{V_{source,e}}{V_{excavation}} \tag{B–4c}$$

where

V_{drill}	—	volume of excavated material [m^3[
$Pile_{e,j}(t)$	—	concentration of radionuclide i at time t [Bq/m^2] in the excavation pile
$C_{waste,j}(t)$	—	concentration of radionuclide i at time t [Bq/m^2] in the subterranean source
V_{source}	—	volume of source material intersected by the excavation [m^3]
$V_{excavation}$	—	total volume of the excavation [m^3]

The concentration in the intruder soil is

$$C_{int-ssoil,i}(t) = \frac{Pile_{s,i}(t) \times V_s}{A \times PD} \tag{B–5}$$

where

$C_{int\text{-}ssoil,i}(t)$	—	concentration in the surface soil for radionuclide i at time t [Bq/m^2]
$Pile_{s,j}\ (t)$	—	concentration of radionuclide i at time t [Bq/m^2] in the pile from scenario s (drilling or excavation)
V_s	—	volume of pile [m^3] from scenario s (drilling or excavation)
A	—	area that contaminated waste is spread over [m^2]
PD	—	plot depth [m^2]

Further details can be found in Simpkins, et al. (2008).

B.3.3 Air

In BDOSE, contaminated soil particles are assumed to become airborne by soil disturbances, primarily wind. The rate of resuspension is assumed to be uniform across the soil surface and results in a uniform distribution within the air. Using the surface soil concentration, the concentration in the air is determined by applying a resuspension factor as follows

$$C_{air,i}(t) = C_{soil,i}(t)\ RF \tag{B–6}$$

where

$C_{air,i}(t)$	—	air concentration of radionuclide i at time t [Bq/m^3]
$C_{soil,i}(t)$	—	concentration in surface soil of radionuclide i at time t [Bq/m^2]
RF	—	resuspension factor [1/m]

For C-14, emission losses from the soil are not assumed to result in a potential air pathway, although the emission is modeled as a removal mechanism.

B.3.4 Crops

Using the concentration in the air and surface soil, the concentration in the vegetation is determined. The radionuclide concentrations in crops result from depositions on the plant surfaces, sorption of water, and uptake through the roots. The dominant pathway for radionuclide accumulation in crops is through deposition on the plant surface from soil resuspended in the air (Prohl, 2009). (Thus it is expected that soil concentration, resuspension factor, and deposition velocity are key factors that determine dose through the crop ingestion pathway.) BDOSE evaluates multiple crop types. Receptor crops include leafy green vegetables, vegetables, fruits, and grains. Animal feeds include fodder and individual animal feeds. The concentration in crop type p is

$$C_{p,i}(t) = [ID_i(t)\frac{12}{M_p}r_{i,p} + C_{soil,i}(t)RFv_{d,i}r_{d,p}CF]\frac{TV_p}{B_p}\left[\frac{1-e^{-(\lambda_w+\lambda_i)T_{g,p}}}{\lambda_w+\lambda_i}\right] + \frac{C_{soil,i}(t)f_{rz,p}BV_{p,i}f_p}{P} \tag{B–7}$$

where

$C_{p,i}(t)$	—	concentration in crop type p of radionuclide i [Bq/kg]
$ID_i(t)$	—	irrigation deposition rate of radionuclide i for year t [Bq/m^2/y]

M_p — irrigation duration for plant type p [months]
$r_{i,p}$ — irrigation interception fraction for plant type p [unitless]
$C_{soil,i}(t)$ — concentration in surface soil of radionuclide i at time t [Bq/m^2]
$v_{d,i}$ — deposition velocity [m/s]
$r_{d,p}$ — deposition interception fraction for plant type p [unitless]
RF — resuspension factor [1/m]
CF — seconds per year [3.15×10^7 s/yr]
TV_p — translocation factor for plant type p [unitless]
B_p — biomass for plant type p [kg/m^2]
λ_w — weathering constant [1/yr]
λ_i — radionuclide decay constant for radionuclide i [1/yr]
$T_{g,p}$ — growing period for plant type p
$f_{rz,p}$ — fraction of roots in surface soil for plant type p [unitless]
$BV_{p,i}$ — soil-to-plant transfer factor for plant type p and radionuclide i (element) [unitless]
f_p — dry-to-wet ratio for plant type p [unitless]
P — surface soil density [kg/m^2]

The first and second terms include the contribution from irrigated water and contaminated air (via resuspended soil) interacting with the plant surface. The final term includes the contribution from root uptake. More details on the various factors can be found in Baes, et al. (1984).

B.3.5 Animal Products

Animals that forage on contaminated grass and ingest contaminated water are used to produce contaminated animal products. In BDOSE, a numerical description provided in Napier, et al. (2004) is used to determine the contaminant concentration in animal products.

$$C_{j,i}(t) = F_j \left[\left[\sum_{w=1}^{N} C_{w,i}(t) f_{w,j} U_{w,j} \right] + \frac{C_{soil,i}(t) f_{s,j} U_{s,j}}{P} + \left[\sum_{p=1}^{M} C_{p,i}(t) f_p \right. \right. \quad \text{(B–8)}$$

where

$C_{j,i}(t)$ — concentration in animal j products at time t for radionuclide I [Bq/kg]
F_j — transfer factor for animal j [d/kg]
$C_{w,i}(t)$ — concentration in water at time t for radionuclide i [Bq/L]
w — water type [index]
$f_{w,j}$ — fraction of water consumed by animal j that is contaminated [unitless]
$U_{w,j}$ — daily animal j water-consumption rates [kg/d]
$C_{soil,i}(t)$ — concentration in surface soil of radionuclide i at time t [Bq/m2]
$f_{s,j}$ — fraction of soil consumed by animal j that is contaminated [unitless]
$U_{s,j}$ — daily animal j soil-consumption rates [kg/d]

P	—	surface soil density [kg/m^2]
$C_{p,i}(t)$	—	concentration in plant type p at time t [Bq/kg]
$f_{p,j}$	—	fraction of plant type p consumed by animal j that is contaminated [unitless]
$U_{p,j}$	—	daily beef plant-consumption rates [kg/d]
p	—	plant type [index]
N	—	number of water types [includes groundwater, surface water, and pond water]
M	—	number of plant types

The summations are included within the equation because animals can consume both water and food from different sources. The possible water sources include pond, river or stream, and groundwater. The possible plant food sources include grain and fodder.

This same equation applies to all types of animals and animal products: beef, poultry, game, milk, and eggs. Usage amounts and transfer factors are different for each of the animal product types.

In BDOSE, fish are evaluated using a model that is different from the other animal product calculations. For fish, the radionuclide concentration in the water is assumed to be in equilibrium with the concentration within the muscle of the fish, such that

$$C_{f,i}(t) = C_{w,i}(t) \times BF_{f,i} \quad \text{(B–9)}$$

where

$C_{f,i}(t)$	—	concentration in the fish muscle of radionuclide i at time t [Bq/kg]
$C_{w,i}(t)$	—	water concentration (stream/river or pond) of radionuclide i at time t [Bq/L]
$BF_{f,i}$	—	chemical-specific bioaccumulation factor of fish for radionuclide i [L/kg]

The bioaccumulation factor assumes equilibrium is established between the concentration in the water and the concentration in the fish. The radionuclide specific bioaccumulation factors also apply to C-14.

B.3.6 Special Radionuclides

Tritium and C-14 are handled differently due to their behavior in the environment. The concentration of tritium and C-14 in the environmental media is assumed to have the same concentration as the contaminated media to which it is exposed (i.e., the tritium concentration in the plant water is assumed to be directly proportional to the tritium concentration in water within the air). These models are often referred to as specific activity models.

B.3.6.1 Tritium

Tritium is assumed to be of the form tritium oxide (HTO), and the concentration of the HTO in the water within the air is assumed to be the same as the concentration of HTO in the water in the soil. Once the tritium air concentration is known, the concentration in the vegetation is assumed to be directly proportional to the concentration of HTO in water in the air. This is often referenced as a specific activity model (NRC, 1977)

$$C_{p,trit}(t) = \frac{C_{air,trit}(t) F_{p,trit} RF_{trit,p}}{H} \tag{B–10}$$

where

$C_{p,trit}(t)$	—	concentration of tritium in the plant at time t [Bq/kg]
$C_{air,trit}(t)$	—	concentration of tritium in the air at time t [Bq/m^3]
$F_{p,trit}$	—	fraction of plant type p that is fresh matter [unitless]
$RF_{trit,p}$	—	reduction factor for tritium in plant type p [unitless]
H	—	annual average absolute humidity [kg/m^3]

The concentration of tritium in the animal product m is (Napier, et al., 2004)

$$C_{h,m}(t) = f_{h,m} \left[\frac{\sum_{w=1}^{M} C_{w,h}(t) U_{w,m} d_{w,m} + \sum_{p=1}^{N} C_{h,p}(t) U_{a,p} d_{a,p}}{U_{w,m} + \sum_{p=1}^{N} f_{h,p} U_{a,p}} \right] \tag{B–11}$$

where

$C_{h,m}(t)$	—	tritium concentration in animal product m at time t [Bq/kg or Bq/L]
$f_{h,m}$	—	fraction of hydrogen in animal product m [unitless]
M	—	number of different types of water consumed by animal m
$C_{w,h}(t)$	—	tritium concentration in water [Bq/L]
$U_{w,m}$	—	usage amount of water for animal m [kg/yr]
$d_{w,m}$	—	fraction of water from contaminated source [unitless]
N	—	number of different types of crops consumed by animal m
$C_{h,p}(t)$	—	tritium concentration in plant type p at time t [Bq/kg]
$U_{a,p}$	—	usage amount of plant type p from animal m [kg/yr]
$d_{a,p}$	—	fraction of plant type p from contaminated source [unitless]
$f_{h,p}$	—	fraction of plant that is fresh matter [unitless]
p	—	plant type [index]
w	—	water type [index]

B.3.6.2 C-14

The C-14 model is similar to the tritium model. The concentration of C-14 in vegetation is calculated assuming an uptake factor from the soil and an average fraction of the soil that is carbon, which is assumed to be C-14. The concentration in the vegetation is calculated from the irrigation contribution (Napier, et al., 2004)

$$C_{c,p}(t) = \frac{0.1 f_{c,p}}{0.01 P} C_{soil,c}(t) \tag{B–12}$$

where

$C_{c,p}$	—	carbon concentration in plant type p from irrigation [Bq/kg]
$C_{soil,c}(t)$	—	carbon concentration in the soil at start of Bq/m^2
$f_{c,p}$	—	fraction of plant type p that is carbon [unitless]
0.1	—	assumed 10 percent uptake from soil
0.01	—	average fraction of soil that is carbon
P	—	surface soil density [kg/m^2]

The concentration of C-14 in animal products (with the exception of fish) is (Napier, et al., 2004)

$$C_{c,m}(t) = f_{c,m} \frac{\sum_{p=1}^{N} C_{c,p}(t) U_{m,p} + \sum_{w=1}^{M} C_{c,w}(t) U_w}{\sum_{p=1}^{N} U_{m,p} f_{c,p} + U_w f_{cw}} \tag{B–13}$$

where

$C_{c,m}(t)$	—	concentration of carbon in animal product m at time t [Bq/kg]
$C_{c,p}(t)$	—	concentration carbon in plant type p at time t [Bq/kg]
$C_{c,w}(t)$	—	concentration carbon in water source w at time t [Bq/L]
$f_{c,m}$	—	fraction of carbon in animal product m [unitless]
$f_{c,p}$	—	fraction of carbon in plant type p [unitless]
f_{cw}	—	fraction of carbon in water [unitless]
U_w	—	water consumption rate [kg/yr]
$U_{m,p}$	—	plant consumption rate [kg/yr]
N	—	number of plant types
M	—	number of different types of water consumed by animal m
p	—	plant type [index]
w	—	water type [index]

The radionuclide concentration in fish is calculated using a simple bioaccumulation factor model that multiplies the radionuclide concentration of the habitat water by a fish bioaccumulation factor that is an input parameter. The habitat water used in this calculation is selectable as groundwater, stream water, or pond water (groundwater was used for the sensitivity analysis).

B.4 Behavioral Parameters

The dose a receptor receives from exposure to environmental contaminants is a function of both the radionuclide concentration in the environment and the behavior of the receptor. The following describes how receptor behaviors are incorporated into the BDOSE dose assessment.

B.4.1 Ingestion Pathways

When any type of contaminated food or water is ingested, the dose is calculated in the same way regardless of food type because the dose is dependent on the quantity of the radionuclide that enters the body. Therefore, one generic equation can be used to calculate dose from ingesting water, vegetables, meat, milk, and soil

$$D_f(t) = C_f(t) I_f L_f DC_{ing} \tag{B–14}$$

where

$D_f(t)$	—	dose from pathway *f* [Sv] for year *t*
f	—	ingestion pathway (e.g., vegetables, meat, milk, soil)
$C_f(t)$	—	concentration in food, soil, or water [Bq/L or Bq/kg] in year *t*
I_f	—	ingestion rate [L/yr of kg/yr]
L_f	—	fraction of ingested foods that are locally grown and are contaminated
DC_{ing}	—	dose coefficient for ingestion [Sv/Bq]

B.4.2 Inhalation Pathways

Receptor annual inhalation volume, effective resuspension factors and inhalation dose conversion factors are used to evaluate inhalation doses to receptors. The inhalation dose in 1 year is calculated from the air concentration according to

$$D_{inh}(t) = C_a(t) I_a DC_{inh} 1\ yr \tag{B–15}$$

where

$D_{inh}(t)$	—	dose from inhalation for year *t* [Sv]
$C_a(t)$	—	concentration in air for year *t* [Bq/m^3]
I_a	—	inhalation rate [m^3/yr]
DC_{inh}	—	dose coefficient for inhalation [Sv/Bq]
1 yr	—	time period of exposure

B.4.3 Direct Exposure Pathways

The annual external dose received from submersion in the contaminated air is

$$D_s(t) = C_a(t) SF \times DC_s 1yr\ CF \tag{B–16}$$

where

D_s	—	dose from shine for year *t* [Sv]
$C_a(t)$	—	concentration in air for year *t* [Bq/m^3]
SF	—	shielding factor [unitless]
DC_s	—	dose coefficient for exposure submersion in air [Sv-m^3/Bq/s]
1 yr	—	exposure time
CF	—	seconds to years [3.15×10^7 s/yr]

The shielding factor accounts for the reduction in external dose provided by housing.

The annual external dose received from the ground is

$$D_g(t) = C_{soil}(t) SF \times DC_{gs} 1yrCF \tag{B–17}$$

where

$D_g(t)$	—	dose from ground shine for year t [Sv]
$C_{soil}(t)$	—	concentration in soil at time t (Bq/m^2]
SF	—	shielding factor [unitless]
DC_{gs}	—	dose coefficient for exposure to contaminated ground surface [Sv-m^2/Bq/s]
1 yr	—	exposure time
CF	—	seconds per year [3.15×10^7 s/yr]

The annual dose from being submersed in contaminated water while swimming and boating is

$$D_{ws} = C_{sw} \times DC_{subwater} T_{swim} CF + C_{sw} \times DC_{subwater} T_{boat} CF / 2 \qquad \text{(B–18)}$$

where

D_{ws}	—	dose from submersion for water [Sv]
C_{sw}	—	concentration in surface water [Bq/L]
$DC_{subwater}$	—	dose coefficient for submersion in water [Sv-m^3/Bq/s]
T_{swim}	—	time swimming [hrs/yr]
T_{boat}	—	time boating [hrs/yr]
CF	—	3.6×10^6 [sL/hr m^3]

B.5 Scenarios

Using BDOSE, multiple receptor scenarios are simultaneously defined and evaluated, with differing receptor descriptions determining the radiological dose to each receptor. Within BDOSE these receptors are the

- Resident
- Recreationalist
- Chronic intruder
- Acute intruder

The resident and recreationalist are similar, in that they are exposed to the same environmental elements (soil, water, air …), with their differences arising from differing exposure pathways, exposure times, and consumption rates. For example, a recreationalist (by definition) may not eat locally grown (contaminated) fruits, spend only a small fraction of the year in the contaminated environment, and consume only a small fraction of an annual diet from contaminated foods and water. For more detail, see Simpkins, et al. (2008). In contrast, a resident can be expected have a diet largely composed of locally grown (contaminated) food and water, and have exposure times consistent with a person who spends most of their time in the area.

Unlike the resident and recreationalist, (in BDOSE) the chronic intruder is exposed to a different environment. This intruder environment differs from the resident and recreationalist environment, in that the principle source of radionuclide contamination in the soil is not from irrigation. In the chronic intruder scenario, the soil is contaminated through the excavation and deposition of waste material directly into the environment, with the annual dose estimated for the year the source material was introduced into the environment. The chronic intruder can include exposure to any of the dose pathways, with or without the inclusion of contaminated groundwater. For more detail, see Simpkins, et al. (2008). For this sensitivity analysis, the chronic intruder environmental contaminants are introduced solely through excavation and deposition of source materials.

The acute intruder is a simplified analysis for a worker who performed the excavation of source material at a facility when institutional controls are no longer enforced. Pathways include, inhalation of resuspended contaminants, ingestion of contaminants, and direct exposure to contaminants in an earthen pile. For more detail, see Simpkins, et al. (2008).

B.6 References

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