DESCRIPTION OF METHODOLOGY FOR BIOSPHERE DOSE MODEL BDOSE

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ABSTRACT

The Ronald W. Reagan National Defense Authorization Act of 2005 requires the U.S. Nuclear Regulatory Commission (NRC) to consult with the U.S. Department of Energy (DOE) 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 in 10 CFR Part 61, Subpart C, can be met. A probabilistic dose model has been developed in the GoldSim [registered trademark of GoldSim Technology Group, LLC (2003)] probabilistic simulation environment to be used as a tool by the NRC and the Center for Nuclear Waste Regulatory Analyses to review non-high-level waste and waste-incidental-to-reprocessing determinations for compliance with the appropriate performance objectives. The model considers unit inputs of groundwater concentrations and estimates dose for the following receptors: resident farmer, resident gardener, and recreationist. Acute and chronic intruder scenarios are also considered, using inputs of actual waste concentrations with units of activity per unit volume. Exposure pathways include external exposure from surface, air, and water; internal exposure from inhalation of air; and internal exposure from ingestion of drinking water, vegetables/fruits, milk, beef, game, fish, and soil. This document describes the equations used within the GoldSim model and documents the default parameters.

Reference:

GoldSim Technology Group, LLC. “User’s Guide: GoldSim Contaminant Transport Module.” Issaquah, Washington: GoldSim Technology Group, LLC. 2003.

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QUALITY OF DATA ANALYSIS AND CODE DEVELOPMENT

DATA: No CNWRA-generated data are referenced in this report. Data from other sources are included with references to their source. Sources of these non-CNWRA data should be consulted for determining levels of quality assurance.

ANALYSES AND CODES: The report describes the BDOSE code. The BDOSE Version 1.0 was developed following the procedures in Geosciences and Engineering Division Technical Operating Procedure (TOP–018), Development and Control of Scientific and Engineering Software. Code development activities are recorded in a software requirements description and is available in Simpkins and Mancillas (2007) and a Scientific Notebook 833E.

Reference

Simpkins, A. and J. Mancillas. “Software Requirements Description and Software Development Plan for Biosphere Model to Estimate Radiological Dose in the GoldSim Environment.” San Antonio, Texas: CNWRA. 2007.

1 INTRODUCTION

The Ronald W. Reagan National Defense Authorization Act of 2005 requires the U.S. Nuclear Regulatory Commission (NRC) to consult with the U.S. Department of Energy (DOE) 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 in 10 CFR Part 61, Subpart, C, can be met.

A biosphere dose model (BDOSE) has been developed in the GoldSim [registered trademark of GoldSim Technology Group, LLC (2003)] probabilistic simulation environment to be used as a tool for NRC and the Center for Nuclear Waste Regulatory Analyses (CNWRA) to review non-high-level waste and waste-incidental-to-reprocessing determinations for compliance with the appropriate performance objectives. The model considers inputs of groundwater concentrations to predict probabilistic dose for the following receptors: resident farmer, resident gardener, and recreationist. Acute and chronic intruder scenarios are also considered, using inputs of actual waste concentrations. Exposure pathways include direct exposure from surface, air, and water; internal exposure from inhalation of air; and internal exposure from ingestion of drinking water, vegetables/fruits, milk, beef, game, fish, and soil.

This report describes the equations that are implemented within the BDOSE model and includes justification for default parameters and their associated distributions that have been included in the model. A short description of how BDOSE was implemented in GoldSim has also been included. Once a GoldSim license is installed on a computer, the user can open BDOSE by simply double-clicking on the model. Within the model, information on the various parameters is included as well as discussions on some of the equations.

2 METHODOLOGY

Given radionuclide concentrations in the groundwater or an underground storage area, the model calculates the probabilistic dose to adult receptors for different scenarios for a period of up to 10,000 years. The following scenarios are considered: (i) resident farmer, (ii) resident gardener, (iii) recreationist, (iv) chronic intruder, and (v) acute intruder. The initial concentration used for the first three scenarios is in the groundwater; for discussion purposes, these are referred to as water-dependent scenarios. For the chronic and acute intruder, the source term is the inventory of the underground disposal area and herein is referred to as intruder scenarios.

Table 2-1 shows the biosphere exposure pathways that are considered for each scenario. Table 2-2 shows the radionuclides that are used for the analysis and their half-lives. These are highly radioactive or key radionuclides identified in previous non-high-level waste and waste-incidental-to-reprocessing determinations from Hanford Site, West Valley Decommissioning Project, Savannah River Site, and Idaho National Laboratory. Some radionuclide decay chain members are not included in this list due to a short half-life that merely serves as a conduit for a longer lived progeny in the chain. Weldy and Peckenpaugh (2001), Mohanty, et al. (2002), DOE (2002), and Baum, et al. (2002) were consulted in developing Table 2-2.

Table 2-1. Receptors and Pathways Used for Model Development					
Pathways	**Resident Farmer**	**Resident Gardener (Subset of Farmer)**	**Recreationist**	**Acute Intruder**	**Chronic Intruder**
Ingestion					
Ingestion of Drinking Water	X	X			X
Ingestion of Vegetation	X	X			X
Ingestion of Milk	X				X
Ingestion of Beef	X				X
Ingestion of Game	X		X		
Ingestion of Poultry	X				X
Ingestion of Eggs	X				X
Ingestion of Fish	X	X	X		X
Ingestion of Soil	X	X	X	X	X
Inhalation	X	X	X	X	X
External					
Surface	X	X	X	X	X
Submersion in Air	X	X	X	X	X
Submersion in Water			X		

Table 2-2. Radionuclides To Be Used as Input to the Model						
Species ID*	**Half-Life†**	**Progeny**	**INL‡**	**SRS§**	**Hanford Site**	**WVDP‖**
H3	12.32 yr		X	X		
C14	5715 yr		X	X		X
Co60	5.271 yr		X	X	X	
Ni59	7.6E4 yr		X	X		
Ni63	101 yr		X	X	X	
Se79	2.9E5 yr			X		
Sr90	28.78 yr	Y90	X	X	X	X
Y90	2.67 d		X	X	X	
Nb94	2.0E4 yr		X	X		
Tc99	2.13E5 yr		X	X	X	X
I129	1.57E7 yr		X	X		X
Cs137	30.07 yr	Ba137m	X	X	X	X
Ba137m	2.552 min		X	X	X	
Eu152	13.54 yr				X	
Eu154	8.593 yr				X	
Eu155	4.75 yr				X	
Pb210	22.3 yr					X
Ra226	1599 yr	Pb210				X
Ra228	5.76 yr	Th228				X

Table 2-2. Radionuclides To Be Used as Input to the Model (continued)						
Species ID*	**Half-Life†**	**Progeny**	**INL‡**	**SRS§**	**Hanford**	**WVDP‖**
Ac227	21.772 yr		decay chain member			
Th228	1.912 yr				X	
Th229	7.3E3 yr		decay chain member			
Th230	7.54E4 yr	Ra226			X	
Th232	1.40E10 yr	Ra228			X	
Pa231	3.28E4 yr	Ac227	decay chain member			
U232	69.8 yr	Th228				X
U233	1.592E5 yr	Th229			X	X
U234	2.46E5 yr	Th230			X	X
U235	7.04E8 yr	Pa231			X	
U236	2.342E7 yr	Th232			X	
U238	4.47E9 yr	U234			X	X
Np237	2.14E6 yr	U233	X	X	X	X
Pu238	87.7 yr	U234	X	X	X	X
Pu239	2.410E4 yr	U235	X	X	X	X
Pu240	6.56E3 yr	U236	X	X	X	X
Pu241	14.4 yr	Am241	X	X	X	X
Pu242	3.75E5 yr	U238	X	X		X
Pu244	8.0E7 yr	Pu240		X		X
Am241	432.7 yr	Np237	X	X	X	X
Am242m	141 yr	Pu238		X		
Am243	7.37E3 yr	Pu239		X		
Cm242	162.8 d	Pu238	X		X	
Cm243	29.1 yr	Pu239			X	
Cm244	18.1 yr	Pu240		X	X	
Cm245	8.5E3 yr	Pu241		X		
Cm246	4.76E3 yr	Pu242		X		
Cm247	1.56E7 yr	Am243		X		
Cm248	3.48E5 yr	Pu244		X		
Cf249	351 yr	Cm245		X		

*ID = identification
†Knolls Atomic Power Laboratory, Inc. (KAPL). "Chart of the Nuclides." 16th Edition. Schenectady, New York: Lockheed Martin Distribution Services. 2002.
‡INL = Idaho National Laboratory
§SRS = Savannah River Site
‖WVDP = West Valley Decommissioning Project

2.1 Methodology Overview

For the water-dependent scenarios, soil becomes contaminated via irrigation with contaminated water. The contaminated soil and air are assumed to interchange contaminants. Direct exposure from and incidental ingestion of the contaminated soil is an exposure pathway for the receptor. Inhalation and submersion doses result from the receptor being surrounded by contaminated air and will result in an internal and external exposure pathway for the receptor.

Various plants grown on contaminated soil can be contaminated through irrigation, deposition, and soil uptake. Ingestion of plants, as well as contaminated water, provides a means of internal exposure to the receptor. Milk cows, beef cows, poultry, and game also ingest contaminated plant products and water, thus transferring contaminants to humans who consume the resulting food products (e.g., milk, beef).

Water-dependent scenarios also include recreation exposures from boating, swimming, or ingesting fish. Contaminated water enters a pond or stream and serves as a submersion exposure scenario for boating and swimming. Fish accumulate radionuclides within their tissue and, once ingested, expose individuals.

For the intruder scenarios, the source is assumed to be the inventory of the waste. The intruder is assumed to drill directly into the waste or excavate into the waste, and the contaminated materials are brought to the surface and distributed over the surface soil. The acute intruder is exposed to the waste during the actual drilling of the waste. After waste is exhumed to the surface, it is assumed to be evenly distributed over some area. The chronic intruder is similar to the resident farmer except the drill cuttings have been evenly distributed over the soil, thus contaminating the soil.

Figures 2-1 and 2-2 show the various pathways and how they are propagated through the biosphere model. Groundwater and waste concentrations are determined externally and must be entered by the user. Once the time-dependent concentrations in various exposure media (e.g., air, soil, milk) have been determined, pathway-specific doses are determined using Federal Guidance Reports 11 and 12 (EPA, 1993, 1988) or ICRP Publication 72 (International Commission on Radiological Protection, 1996) dose coefficients. Methods are consistent with GENII 1.485 (Napier, et al., 1988) where possible. RESRAD code documentation (Yu, et al., 2001) and GENII code documentation (Napier, 2006) were also consulted.

The model uses the GoldSim radionuclide transport model that accounts for decay and ingrowth of radioactive progeny. This model predicts the concentration in a material at the future time of interest. Details on the decay and ingrowth model for GoldSim can be found in GoldSim Technology Group, LLC (2003).

2.2 Water-Dependent Scenarios

Water-dependent scenarios include those originating with a groundwater contamination source. Receptors include the resident farmer, resident gardener, and recreationist. The resident gardener includes a subset of the pathway used for the resident farmer. The manner in which the contamination originates is irrigation with contaminated groundwater. Crops grown on the area that is irrigated with contaminated water become contaminated, as do any livestock or game that forage on the contaminated land. Ingestion of contaminated groundwater by individuals or livestock offers another pathway of exposure. Individuals are also directly exposed by standing on contaminated ground surface and being immersed in and inhaling contaminated air. A majority of the exposure pathways begin with the deposition from irrigation water to the surface soil.

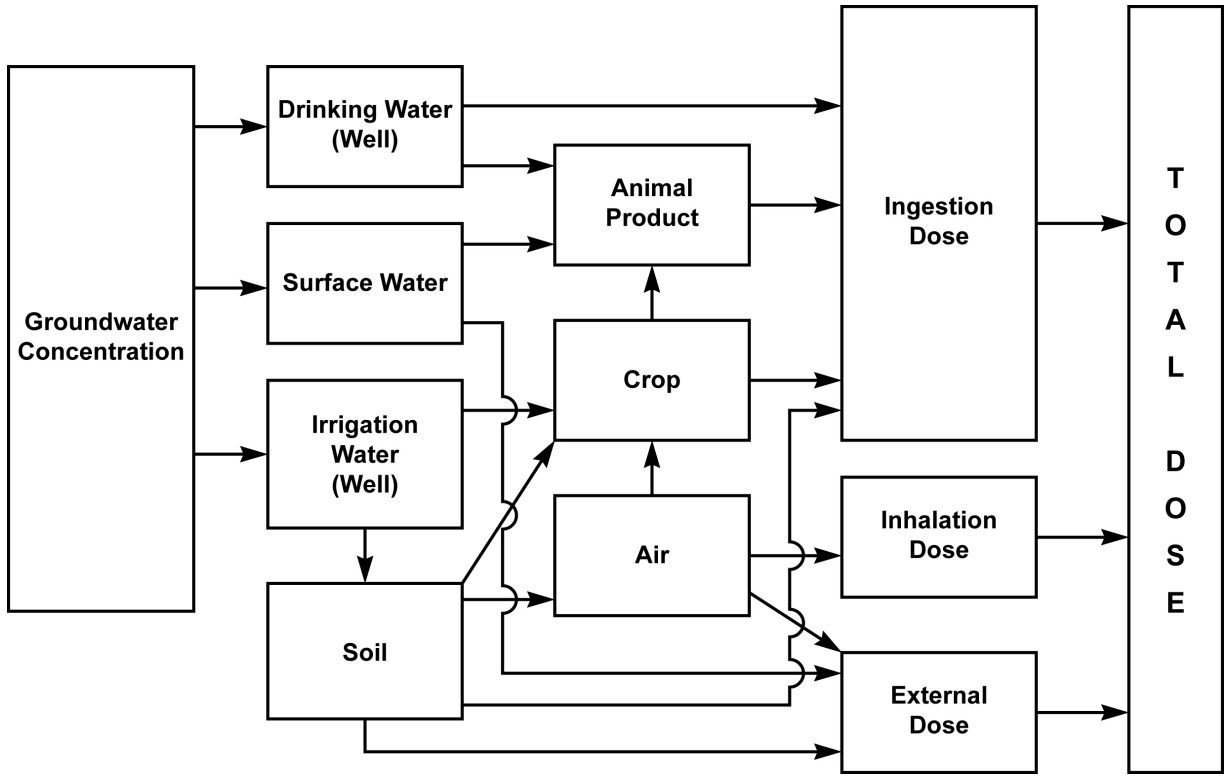

Figure 2-1. Groundwater-Dependent Pathways

2.2.1 Surface Soil Concentration

Surface soil can become contaminated when irrigated with water from a well that contains contaminated water. Time-dependent groundwater concentrations are calculated within the GoldSim radionuclide model by simulating decay and ingrowth of the radionuclides (GoldSim Technology Group, LLC, 2003). Chains considered are shown in Table 2-2. The irrigation deposition rate for each radionuclide on the surface of the soil is

$$ID_i = C_{gw,i} \times IR \times 1{,}000 \tag{2-1}$$

where

ID_i — irrigation deposition rate of radionuclide i [Bq/m^2/y]
$C_{gw,i}$ — concentration of radionuclide i in water used for irrigation [Bq/L]
IR — irrigation rate [m/yr]
1,000 — conversion factor for L/m^3

Once the irrigation deposition rate is determined, the concentration in the soil can be calculated. Contaminants can be lost from the soil by leaching into deeper soils, erosion, or radioactive

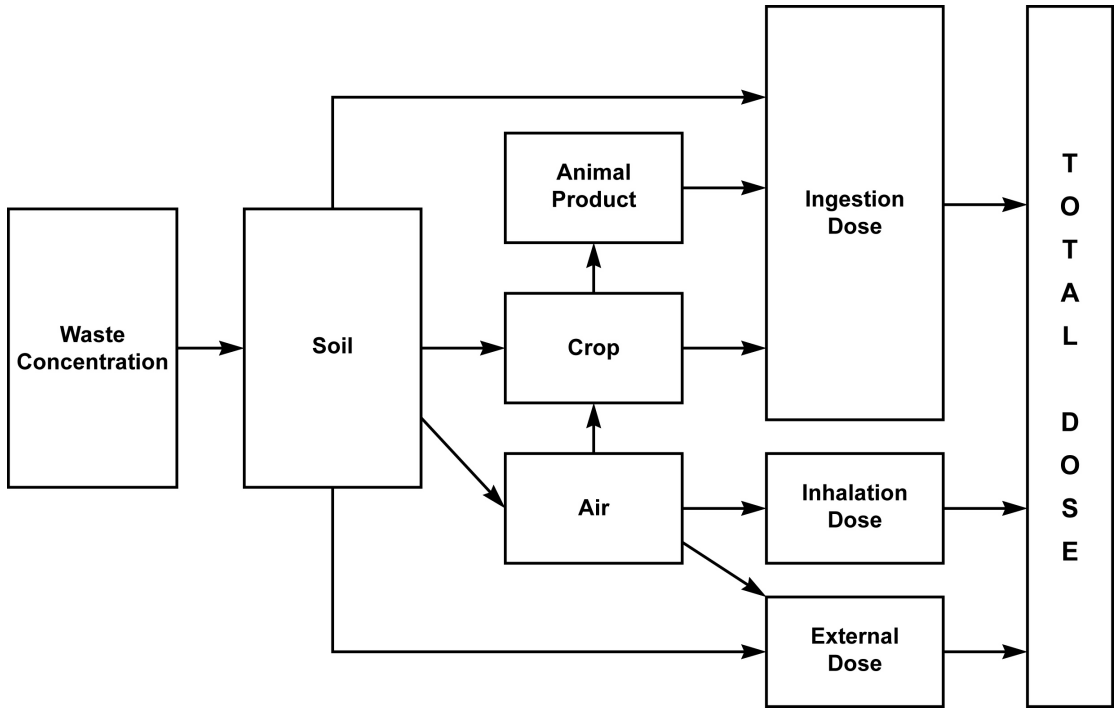

Figure 2-2. Waste-Dependent Pathways

decay. Radionuclide concentration in the surface soil is calculated using the following equation (Napier, et al., 2004)

$$C_{\text{soil},i} = ID_i(t)\left[\frac{1-e^{-(\lambda_i+\lambda_{l,i}+\lambda_e)t_e}}{\lambda_i+\lambda_{l,i}+\lambda_e}\right] \tag{2-2}$$

where

$C_{\text{soil},i}(t)$ — concentration in surface soil of radionuclide i at time t [Bq/m^2]
ID_i — irrigation deposition rate of radionuclide i [Bq/m^2/y]
λ_i — radionuclide decay constant for radionuclide i [1/yr]
$\lambda_{l,i}$ — radionuclide-specific leaching loss rate {see Eq. (2-3) [1/yr]}
λ_e — erosion loss rate {see Eq. (2-4) [1/yr]}
t_e — equilibrium soil time [yr]

The equilibrium soil time varies based on which soil model the user selects, and it accounts for the radionuclide buildup in the soil.

The leaching loss rate is calculated by using an equation from Baes, et al. (1984)

$$\lambda_{l,i} = \frac{PR + IR - ER}{d\theta\left[1 + \frac{\rho}{\theta} K_{d,i}\right]} \tag{2-3}$$

where

$\lambda_{l,i}$	—	leaching loss rate of radionuclide *i* [1/yr]
PR	—	precipitation rate [m/yr]
IR	—	irrigation rate [m/yr]
ER	—	evapotranspiration rate [m/yr]
d	—	soil depth [m]
θ	—	volumetric water content of soil [unitless]
ρ	—	density of the soil [kg/m^3]
$K_{d,i}$	—	soil–liquid partition coefficient of radionuclide *i* [m^3 liquid/kg solid]

The soil-liquid partition coefficients are chemical specific and also vary by soil type. The loss due to erosion is calculated as

$$\lambda_e = \frac{ER}{d\rho} \tag{2-4}$$

where

λ_e	—	erosion loss rate [1/yr]
ER	—	erosion rate [kg/m^2/yr]
d	—	soil depth [m]
ρ	—	density of the soil [kg/m^3]

The soil depth in the previous two equations refers to surface soil depth that typically corresponds to the root zone. Calculations for accumulation in vegetation are discussed in Section 2.2.5.

Seven soil models are included in the biosphere model with different degrees of conservatism. Details of each are shown in the model within text boxes for the user to read, and a summary is shown in Table 2-3.

2.2.2 Air Concentration

Contaminated soil particles become airborne by disturbances of the soil, primarily by 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

$$C_{\text{air},i}(t) = C_{\text{soil},i}(t)\ RF \tag{2-5}$$

Table 2-3. Different Soil Models Available Within BDOSE	
Soil Model	**Description**
1	Complete transfer of contaminants from irrigation water to soil with no accumulation, decay, erosion, or leaching.
2	Includes erosion, leaching, and decay, but only applied for a given year.
3	Includes erosion, leaching, and decay.
4	Includes erosion, leaching, and decay. Based on continued irrigation of the soil to achieve equilibrium soil concentration value.
5	GoldSim cell element used to evaluate buildup using physical descriptions of soil (K_D, density, water content, etc.) and includes ingrowth.
6	Individual radionuclide erosion and leaching with buildup to equilibrium value and includes ingrowth.
7	Soil concentration set to constant value of 1 pCi/m^2.

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]

2.2.3 Surface Water Concentration

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 to allow the user to enter known water concentrations.

2.2.3.1 Stream or River

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

$$C_{sr,i}(t) = \frac{GW_i(t)}{FR} \tag{2-6}$$

where

$C_{sr,i}(t)$ — concentration in the stream or river of radionuclide i at time t [Bq/L]
$GW_i(t)$ — groundwater flux of radionuclide i at time t [Bq/s]
FR — annual average surface water flow rate [L/s]

2.2.3.2 Pond

For a pond, simple dilution is applied with the dilution factor determined as the ratio of the annual volume of water that percolates into the contaminated zone to the inflow of water into the pond (Yu, et al., 2001) assuming uniform depth of the pond

$$C_{\text{pond},i}(t) = C_{gw,i}(t)\frac{CZ}{PA} \tag{2-7}$$

where

$C_{\text{pond},i}(t)$	—	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.

2.2.4 Concentration in Fish

The radionuclide concentration in the water is assumed to be in equilibrium with the concentration within the muscle of the fish such that

$$C_{f,i}(t) = C_{w,i}(t) \times BF_{f,i} \tag{2-8}$$

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.

2.2.5 Concentration in Vegetation

Using the concentration in the air and surface soil, the concentration in the vegetation is determined. The concentration in vegetation includes the contribution from deposition on the plant surface and uptake from the roots. Deposition on the plant surface occurs from the air and from the irrigated water and is dependent on the growing period of the plant. The plant types include leafy vegetables, vegetables, fruit, fodder, and grain. The concentration in plant type *p*

$$C_{p,i}(t) = [ID_i(t)\frac{12}{M_p}r_{i,p} + C_{\text{soil},i}(t)RFv_{d,i}r_{d,p}CF]\frac{TV_p}{B_p}\left[\frac{1-e^{-(\lambda_w+\lambda_i)T_{g,p}}}{\lambda_w+\lambda_i}\right] + \frac{C_{\text{soil},i}(t)f_{rz,p}BV_{p,i}f_p}{P} \tag{2-9}$$

where

$C_{p,i}(t)$	—	concentration in plant 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).

2.2.6 Concentration in Animal Products

Cattle that forage on contaminated grass and ingest contaminated water produce contaminated beef and milk products. Concentration in beef is determined by Napier (2004)

$$C_{beef,i}(t) = F_b\left[\left[\sum_{w=1}^{N} C_{w,i}(t) f_{w,b} U_{w,b}\right] + C_{soil,i}(t) f_{s,b} U_{s,b} + \left[\sum_{p=1}^{M} C_{p,i}(t) f_{p,b} U_{p,b}\right]\right] \quad (2\text{-}10)$$

where

$C_{beef,i}(t)$	—	concentration in beef at time *t* for radionuclide *i* [Bq/kg]
F_b	—	transfer factor for beef [d/kg]
$C_{w,i}(t)$	—	concentration in water at time *t* for radionuclide *i* [Bq/L]
w	—	water type [unitless]
$f_{w,b}$	—	fraction of water consumed by beef cows that is contaminated [unitless]
$U_{w,b}$	—	daily beef cow water-consumption rates [kg/d]
$C_{soil,i}(t)$	—	concentration in surface soil of radionuclide *i* at time *t* [Bq/m^2]
$f_{s,b}$	—	fraction of soil consumed by beef cows that is contaminated [unitless]
$U_{s,b}$	—	daily beef cow soil-consumption rates [kg/d]
$C_{p,i}(t)$	—	concentration in plant type *p* at time *t* [Bq/kg]
$f_{p,b}$	—	fraction of plant type *p* consumed by beef cows that is contaminated [unitless]
$U_{p,b}$	—	daily beef cow plant-consumption rates [kg/d]
p	—	plant type [unitless]

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 the cow consumes 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.

2.2.7 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.

2.2.7.1 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)

$$C_{p,trit}(t) = \frac{C_{\text{air},trit}(t) F_{p,trit} RF_{trit,p}}{H} \tag{2-11}$$

where

$C_{p,trit}(t)$	—	concentration of tritium in the plant at time t [Bq/kg]
$C_{\text{air},trit}(t)$	—	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 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)

$$C_{h,m}(t) = f_{h,m}\left[\frac{\sum_{w=1}^{M} C_{w,h}(t) U_{w,m} d_{w,m} + \sum_{p=1}^{N} C_{h,p}(t) U_{a,p} d_{a,p}}{U_{w,m} + \sum_{p=1}^{N} f_{h,p} U_{a,p}}\right] \tag{2-12}$$

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]
$C_{w,h}(t)$ — 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 for 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]

2.2.7.2 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)

$$C_{c,p}(t) = \frac{0.1 f_{c,p}}{0.01 P} C_{\text{soil},c}(t) \tag{2-13}$$

where

$C_{c,p}$ — carbon concentration in plant type *p* from irrigation [Bq/kg]
$C_{\text{soil},c}(t)$ — carbon concentration in the soil at start of Bq/m^2
$f_{c,p}$ — fraction of plant type *p* that is carbon [unitless]

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

$$C_{c,m}(t) = f_{c,m} \frac{\sum_{p=1}^{N} C_{c,p}(t) U_{m,p} + \sum_{w=1}^{M} C_{cw,p}(t) U_w}{\sum_{p=1}^{N} U_{m,p} f_{c,p} + U_w f_{cw}} \tag{2-14}$$

where

$C_{c,m}(t)$ — concentration of carbon in animal product *m* at time *t* [Bq/kg]
$f_{c,m}$ — 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

2.3 Intruder Scenarios

Intruder scenarios include acute and chronic exposure resulting from drilling a well or excavating directly into the waste form. The acute intruder is exposed during the actual excavating or drilling of the well, and the exposure pathways include direct exposure from submersion and ground surface as well as inhalation of contaminated air. Incidental ingestion of soil is also included. The chronic intruder is assumed to farm on the waste site once the contaminated waste has been brought to the surface and distributed across the soil.

2.3.1 Concentration in the Surface Soil

The concentration in the soil is determined by evenly distributing the drill cuttings over a defined area. The amount of waste that is exhumed to the surface is

$$W_v = \pi(d/2)^2 \times W_t \tag{2-15}$$

where

W_v — volume of waste [m^3]
d — diameter of drill [m]
W_t — thickness of the waste [m]

The user enters the volume of waste exhumed during excavation activities as well as the total excavation volume. The concentration in the soil is then determined by spreading this volume of contamination over the lot size. The concentration in the surface soil is

$$C_{int-\text{ssoil},i}(t) = \frac{W_v C_{\text{waste},i}(t)}{A} \tag{2-16}$$

where

$C_{int\text{-ssoil},i}$ — concentration in the surface soil for radionuclide i [Bq/m^2]
A — area that contaminated waste is spread over [m^2]
$C_{\text{waste},i}(t)$ — concentration in the waste [Bq/m^3]

Once the surface soil concentrations are determined, then vegetable and animal concentrations can be determined as in Section 2.2. For the chronic exposure, the person farms and grows livestock on the contaminated area. Intake of contaminated forage must be adjusted to account for feeding on noncontaminated ground.

2.3.2 Concentration in the Soil Volume

For the chronic intruder, the contamination is assumed to be plowed into the ground for farming. For the acute intruder, the waste is assumed to be evenly distributed over a user-defined area with an assumed thickness of 1 cm [0.4 in]. For these reasons, the volumetric soil

concentration is used to estimate the dose to the externally exposed individual. This volumetric soil concentration is

$$C_{int-v\text{soil},i}(t) = \frac{W_v C_{\text{waste},i}(t)}{Ad} \tag{2-17}$$

where

$C_{int\text{-}v\text{soil},i}$	—	concentration in the soil for radionuclide *i* [Bq/m^3]
$C_{\text{waste},i}(t)$	—	concentration in the waste [Bq/m^3]
d	—	depth which the contaminated waste is being mixed into the soil [*m*]

2.3.3 Dilution of Waste With Soil

The waste will potentially be diluted by two methods: mixing with soil when waste is exhumed to the surface during well drilling/excavation or mixing with clean soil when drill cuttings are plowed.

The dilution factor for the well drilling/excavation is

$$D_{\text{drill}} = \frac{V_w}{V_s} \tag{2-18}$$

where

D_{drill}	—	dilution due to drilling [unitless]
V_w	—	volume of the waste [m^3]
V_s	—	volume of the soil including the waste [m^3]

The second dilution could occur by plowing the contaminated drill cuttings into the clean soil

$$D_{\text{plow}} = \begin{cases} 1 \text{ when } \dfrac{V_s}{A} \geq d_p \\ \dfrac{Ad_p}{V_s} \text{when } \dfrac{V_s}{A} < d_p \end{cases} \tag{2-19}$$

where

D_{plow}	—	dilution due to plowing [unitless]
V_s	—	volume of waste [m^3]
A	—	spread area [m^2]
d_p	—	plow depth [m]

Dilution is not considered for the acute intruder, because the intruder is exposed to the newly deposited soil that is not tilled into clean soil.

2.4 Dose Calculations

Once the concentrations are estimated in the various environmental media, radionuclide-specific doses are calculated. The inhalation dose in 1 year is calculated from the air concentration according to

$$D_{inh}(t) = C_a(t) I_a DC_{inh} 1 \text{ yr} \tag{2-20}$$

where

$D_{inh}(t)$	—	dose from inhalation for year t [Sv]
$C_a(t)$	—	concentration in air at 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

The external dose received in 1 year for submersion in the contaminated air is

$$D_s(t) = C_a(t) SF \times DC_s 1 \text{ yr } CF \tag{2-21}$$

where

D_s	—	dose from shine for year t [Sv]
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 external dose received from the ground is

$$D_g(t) = C_{\text{soil}}(t) SF \times DC_{\text{gs}} 1 \text{ yr } CF \tag{2-22}$$

where

$D_g(t)$	—	dose from ground shine for year t [Sv]
$C_{\text{soil}}(t)$	—	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]

For the intruder scenarios, different dose coefficients are applied based on the depth in which the contamination is assumed to be distributed. For the acute intruder, the waste is assumed to lie on top of the soil, and the 1-cm dose coefficients are used. For the chronic intruder, tilling is assumed to mix the waste with the soil, and the 15-cm dose coefficients are used. Equation (2-22) is modified to

$$D_g = C_{v\text{soil}}(t) SF \times DC_{v_{gs}} 1 \text{ yr } CF \tag{2-23}$$

where

SF	—	shielding factor [unitless]
$C_{vsoil}(t)$	—	volumetric soil concentration at time t [Bq/m$_3$]
$DC_{v_{gs}}$	—	dose coefficient for exposure to a contaminated volume of soil [Sv-m^3/Bq/s]
1 yr	—	exposure time
CF	—	seconds per year [3.15 × 10^7 s/yr]

Once 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 ingestion of water, vegetables, meat, milk, and soil

$$D_f(t) = C_f(t) I_f DC_{ing} \tag{2-24}$$

where

$D_f(t)$	—	dose from pathway f [Sv] in year t
f	—	ingestion pathway (e.g., vegetables, meat, milk)
$C_f(t)$	—	concentration in food/water product [Bq/L or Bq/kg] in year t
I_f	—	ingestion rate [L/yr of kg/yr]
DC_{ing}	—	dose coefficient for ingestion [Sv/Bq]

Dose for the recreation scenario includes dose from being submersed in contaminated water while swimming and boating. This dose is calculated as

$$D_{ws} = C_{sw} \times DC_{subwater} T_{swim} CF + C_{sw} \times DC_{subwater} T_{boat} CF / 2 \tag{2-25}$$

where

D_{ws}	—	dose from submersion in 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]

Users can select the internal dose coefficients from Federal Guidance Report 11 (EPA, 1988), International Commission on Radiological Protection Publication 72 (1996), or manually enter other user-justified coefficients. Caution should be used when changing the dose coefficients, however, because summing over the different pathways could produce a total dose for which different methods were used to estimate the internal and external pathways. External dose coefficients are taken from U.S. Environmental Protection Agency (EPA) (1993). Currently, external dose coefficients consistent with applicable methods used in International Commission on Radiological Protection 72 are not available and therefore are not available for use with BDOSE.

Once the doses from the various pathways have been calculated, the doses are summed according to the receptors as shown in Table 1 in the Appendix of this report. Certain pathways can be turned off by entering zero for the usage rates or exposure times or modifying the pathways under Receptor Definitions with the Controls Section.

2.5 Model Limitations and Assumptions

Complex agricultural systems are modeled assuming steady-state conditions in the environmental media. Homogeneity is also assumed throughout the model. Holdup time prior to consumption is not considered, but is expected to minimally affect resulting doses due to the long half-lives of most of the radionuclides. No crop rotation is assumed. Other assumptions are also discussed within their respective sections.

Game are assumed to forage on irrigated grass and can ingest irrigated grain. Default transfer factors included in the model are the same as the beef transfer factors and are assumed to be representative of deer. The user should change the transfer factors and other game parameters if another type of animal is assumed.

Default input parameters and distributions have been included for all input parameters and are documented in the Appendix to this report. Default input parameters are typically averages for the United States, and the user should use site-specific parameters and distributions when possible.

2.6 GoldSim Implementation

The biosphere dose model was developed using GoldSim Version 9.5 (GoldSim Technology Group, LLC, 2003). The model may be saved in player mode to run using GoldSim Player. GoldSim is a personal computer-based program that runs in the Microsoft® Windows™ operating system. A Pentium or higher CPU with at least 128 Mb RAM is recommended. Users must install GoldSim on their computer to run BDOSE.

The model described in this report is implemented in the GoldSim modeling environment. The model, BDOSE, has been designed to present biosphere calculations in a structured format using GoldSim modeling elements, where parameters and calculations have been compartmentalized along principal component boundaries: source calculations, radionuclide remobilization and accumulation with the biosphere, dose coefficients, receptor pathways for radionuclide imbibment, and receptor dose consequences (results). Within these principal compartments, calculations (or results) have been ordered in a hierarchical manner, with composite calculations presented in upper tiers and fundamental calculations performed in lower tiers. In addition, meaningful names have been used to describe parameters and calculations. In whole, the name, color coding, and organization of the model were performed to establish a transparent and easy-to-use biosphere model.

GoldSim tracks contaminants in the soil, air, and water on a mass basis, and specific activities are applied when necessary. The user can change any and all parameters; however, some are recommended not to be changed, and these have been labeled accordingly within the model.

The primary input is the groundwater concentration for the resident pathways and the waste concentration for the intruder pathways. Input parameters can be stochastically sampled using

the features of GoldSim. Different types of distributions include uniform, log-uniform, normal, lognormal, triangular, logtriangular, cumulative, discrete, poisson, beta, gamma, weibull, binomial, boolean, and student's test. For a description of these distributions, see the GoldSim Manual (GoldSim Technology Group, LLC, 2003). When executing the model, the user specifies the number of realizations, and the execution time increases with additional realizations. The model has no special graphics requirements. GoldSim, however, offers the capability for graphic display of output and intermediate outputs as functions of time. GoldSim offers data-generating capability for graphic display or for exporting the data in text format to be used in graphical software such as Microsoft Excel® (Microsoft Corporation, 2000).

3 SUMMARY AND CONCLUSIONS

A model has been developed that estimates dose to receptors for different scenarios using the GoldSim programming environment. The model stochastically samples various input parameters (thus providing stochastic output) and has the flexibility to change inputs to appropriately address the different types of waste sites that exist.

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APPENDIX

DEFAULT INPUT PARAMETER SET

The default input parameter set is presented in the following tables. Table 1 is organized by the parameter group (first column) of similar or related parameters. This is followed by columns for the BDOSE parameter name, units, the distribution type and parameter values, and a remarks column to include the reference for the parameter and any additional explanation if necessary. Tables 2–5 provide the large vectors of parameters noted in Table 1 for internal and external dose coefficients, soil partition coefficients, and transfer factors. All references cited in the tables are found in the references section at the end of the appendix. The BDOSE parameter name is the explicitly used name in the code that takes advantage of the search feature of the GoldSim modeling environment. When this name is typed as written into the search window of the BDOSE model, the user can go directly to that parameter within the model for further parameter description or editing to a site-specific value or distribution.

Table 1. Input Parameter Values for BDOSE Version 1.0				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
Dose Coefficients	DCF_INH_Adult72 DCF_INH_FG11 DCF_ING_FG11 DCF_ING_ICRP72	Sv/Bq	constant See Tables 2 and 3	Internal dose coefficients for inhalation and ingestion intake include user-selectable data sets of maximum values from Federal Guidance Report No. 11 (EPA, 1988) or International Commission on Radiological Protection Publication 72 (International Commission on Radiological Protection, 1996). External dose coefficients are from Federal Guidance Report No. 12 (EPA, 1993).
	DCF_water_immersion DCF_air_submersion	Sv m^3/Bq yr		
	DCF_soil_surface	Sv m^2/Bq yr		
	DCF_soil_depth_1cm DCF_soil_depth_15cm	Sv m^3/Bq yr		
Source	GW_manual_input	pCi/L	constant 1	Value for each radionuclide groundwater concentration specified by user or linked to an existing model.
	Intruder_manual_input	pCi/m^3	constant 100	Value for each radionuclide waste concentration specified by user or linked to an existing model.
	Institution_control_period	yr	constant 100	Value from 10 CFR Part 61 Performance Objectives.
	Waste_thickness	m	constant 0.3	Default value is placeholder applicable to thin layer of subsurface contamination. Value should be adjusted to match site conditions.
	Well_diameter		constant 0.15	Value from DOE–Idaho (2003, Section 5.2) assuming a 6-in-diameter residential water well. Site-specific drilling and excavation practices should be used.
	Bore_hole_depth		constant 122	Value from DOE–Idaho (2003, Section 5.2) assuming a 122-m [400-ft] deep residential water well. Site-specific drilling and excavation practices should be used.
Inhalation and External Exposure Inputs	RES_INH_rate_air_farmer RES_INH_rate_air_gardener REC_INH_rate_air INT_INH_rate_air	m^3/yr	constant 8400	U.S. Nuclear Regulatory Commission (NRC) (1999, Section 6.3, Table 6.29) weighted average breathing rate of 23 m^3/day.
	RF	m^{-1}	constant 4.4×10^{-10}	Resuspension factor in LaPlante and Poor (1997, Section 2.3.5.2).
	SF_air_RES SF_air_REC SF_air_INT SF_gs_REC	unitless	constant 1	Shielding factor in NRC (1999, Section 6.4.1).

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	SF_gs_RES SF_gs_INT	unitless		
	RES_farmer_air_exp_time RES_gardener_air_exp_time RES_farmer_surface_exp_time RES_gardener_surface_exp_time INT_air_exp_time INT_surface_exp_time REC_air_exp_time REC_surface_exp_time	hr	discrete (mean, 965) 0.00, 403 0.001, 403 0.011, 506 0.051, 595 0.101, 670 0.201, 780 0.301, 850 0.501, 982 0.601, 1063 0.701, 1152 0.801, 1255 0.901, 1394 0.951, 1522 0.981, 1678 0.999, 2023 1.00, 2160	NRC (1999, Table 6.13) distribution values for outdoor activities in hours annually.
	RES_Swimming REC_Swimming INT_Swimming RES_Boating REC_Boating INT_Boating		constant 12	U.S. Environmental Protection Agency (EPA) (1997a, Table 15-176, Summary). The values should be based on local practices at each site.
Acute Exposure Inputs	Driller_INT_Acute_soil_ING	kg	constant 7.3×10^{-4}	Value from U.S. Department of Energy (DOE)–Idaho (2003, Section 5.2) assuming 40 g/yr ingestion rate while working and 160 hours to drill and develop the irrigation well. Site-specific drilling and excavation practices should be used.
	Excavator_INT_Acute_soil_ING			Value from DOE–Idaho (2003, Section 5.3) assuming 40 g/yr ingestion rate while working and 160 hours to excavate. Site-specific drilling and excavation practices should be used.

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	Driller_INT_Acute_INH_vol	m^3	constant 150	Value from DOE–Idaho (2003, Section 5.2) assuming 8,400 m^3/yr breathing rate while working and 160 hours to drill and develop the irrigation well. Site-specific drilling and excavation practices should be used.
	Excavator_INT_Acute_INH_vol			Value from DOE–Idaho (2003, Section 5.3) assuming 8,400 m^3/yr breathing rate while working and 160 hours to excavate. Site-specific drilling and excavation practices should be used.
	Total_Excavation_Volume		constant 600	Value from DOE–Idaho (2003, Section 5.3) assuming a 20 × 10 × 3-m excavation. Site-specific drilling and excavation practices should be used.
	Source_Excavation_Volume_acute		constant 1	Value is a site-specific input used to define the volume of waste that could be contacted while the worker is excavating the Total_Excavation_Volume. The default value is selected as 1 to remind the user to input a value based on the site being analyzed.
	RF_acute_Drilling RF_acute_Excavation	m^{-1}	constant 4.4×10^{-10}	Resuspension factor in LaPlante and Poor (1997, Section 2.3.5.2).
	Acute_SF_AS Acute_SF_GS	unitless	constant 1	Shielding factor in NRC (1999, Section 6.4.1).
	Driller_Acute_occupancy_time Excavator_Acute_occupancy_time	yr	constant 0.018	Value from DOE–Idaho (2003, Section 5.2) assuming 160 hours to drill and develop the irrigation well. Site-specific drilling and excavation practices should be used.
	Well_diameter_Acute	m	constant 0.56	Value from DOE–Idaho (2003, Section 5.2) assuming a 22-in diameter irrigation well. Site-specific drilling and excavation practices should be used.
Soil Model Parameters	Source_Excavation_Volume Source_Excavation_Volume_acute	m^3	constant 1	Value is a site-specific input used to define the volume of waste that could be contacted while excavating the Total_Excavation_Volume and spread on the construction site. The default value is selected as 1 to remind the user to input a value based on the site being analyzed.
	soil_RN_KD	L/kg	constant See Table 4	Mean values for sand selected from Sheppard and Thibault (1990).

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	Vol_water_in_soil	unitless	constant 0.32	Geometric mean for all soils combined at field capacity from Baes and Sharp (1983). Based on measurements of 154 pasture and cropland soils.
	Soil_density	kg/m^3	constant 1510	Simple computed value based on sandy soil porosity (0.43), practical mean particle density (2.65 g/cm3), and Eq. 6.57 from NRC (1999).
	Soil_Plow_depth	m	constant 0.15	Commonly assumed value for plow depth.
	Intruder_spread_area	m^2	constant 100	Assumed value applicable to small farm.
	Soil_spread_depth	m	constant 0.15	Value is based on assumption that soil is spread by plow to plow depth of 0.15 m.
	water_density	kg/m^3	constant 1000	Kennedy and Strenge (1992, Appendix D).
	Irrigation_rate	m/yr	constant 0.58	Average irrigation rate for irrigation of farm and ranch land in Idaho reported in NRC (1999). This value is approximately 2 acre-ft/acre and is applicable to an arid region growing common crops such as potatoes. For site-specific analyses, more refined crop and site or regional values can be used. This value should match values in model for crop irrigation rates.
	Precipitation_rate		constant 0.84	Approximate midpoint of range of average precipitation rates from weather stations across the United States (33 in/yr) from Figure 6.24 in NRC (1999). Site-specific analyses should be based on local precipitation data.
	Evaporation_rate		constant 0.42	Value set at half the precipitation rate. Site-specific analyses should be based on local evapotranspiration data.
	Soil_Erosion_rate	kg/m^2yr	constant 1.05	National average annual cropland soil erosion value for 2003 of 4.7 tons/acre (U.S. Department of Agriculture, 2003). Site-specific analyses should be based on local soil erosion data.

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
Fraction of Diet from Local Contaminated Food	RES_Grain_Fract_Local RES_Fruit_Fract_Local RES_LGV_Fract_Local RES_Veg_Fract_Local RES_Beef_fract_Local RES_Milk_fract_Local RES_Poultry_fract_Local RES_egg_fract_Local RES_Fish_fract_Local RES_Game_fract_Local	unitless	constant 1.0	Value set to 1.0 because the default food consumption rates are applicable to locally produced food. If consumption rates are changed to values representing all food intake then the input parameters for fraction of diet from local contaminated food should be changed accordingly.
Transfer Coefficients	Grain_transfer_factors Fruit_transfer_factors LGV_transfer_factors Veg_transfer_factors	unitless	constant See Table 5	Values obtained from Staven, et al. (2003). This reference is a compendium of recommended constant values (mostly geometric means) based on consideration of a hierarchy of available sources emphasizing more recent publications first including International Atomic Energy Agency (1994), Kennedy and Strenge (1992), National Council on Radiation Protection and Measurements (1996), and Coughtrey and Thorne (1983). For crop categories containing multiple crops (e.g., leafy vegetables, root vegetables) weighted averages were computed based on national consumption rates (therefore, commonly consumed crops are emphasized). Plant values are based on dry weight. Animal values are based on wet weight.
	Beef_transfer_coefficients	d/kg		
	Milk_transfer_coefficients	d/L		
	Poultry_transfer_coefficients	d/kg		
	Egg_transfer_coefficients			

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	Game_transfer_coefficients	d/kg		
	Beef_Gr_transfer_factors	unitless		
	Milk_Gr_transfer_factors			
	Poultry_Gr_transfer_factors			
	Egg_Gr_transfer_factors			
	Fod_transfer_factors			
	Fish_accumulation_factor	L/kg		
Livestock and Game Feed Consumption Rates	Beef_soil_consumption_rate	kg/d	constant 0.43	Dry matter and water intake values for livestock are from the International Atomic Energy Agency (1994) compilation of transfer factors. No information was provided for game so values for beef cattle were used. Soil consumption values are based on the reported 6% of feed intake for grazing cattle. No information was provided for poultry or egg-laying hens in the primary reference, so the value of 10% of dry matter intake from NRC (1999) was used.
	Milk_soil_consumption_rate		constant 0.97	
	Poultry_soil_consumption_rate		constant 0.01	
	Egg_soil_consumption_rate		constant 0.01	
	Game_soil_consumption_rate		constant 0.43	
	Beef_feed_consump_rate		constant 7.2	
	Milk_feed_consump_rate		constant 16.1	
	Poultry_feed_consump_rate		constant 0.1	
	Egg_feed_consump_rate		constant 0.1	
	Game_feed_consump_rate		constant 7.2	
	Beef_water_consumption_rate	L/d	constant 60	

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	Milk_water_consumption_rate	L/d	constant 100	
	Poultry_water_consumption_rate		constant 0.3	
	Egg_water_consumption_rate		constant 0.3	
	Game_water_consumption_rate		constant 60	
Fraction of Livestock Soil Consumption that is Contaminated	Beef_soil_fraction Beef_soil_fraction_INT Milk_soil_fraction Milk_soil_fraction_INT Poultry_soil_fraction Poultry_soil_fraction_INT Egg_soil_fraction Egg_soil_fraction_INT Game_soil_fraction Game_soil_fraction_INT	unitless	constant 1.0	Default assumption is that all soil consumed by livestock is contaminated. This assumption is consistent with the approach used in NRC (1999). Site-specific conditions can include spatial heterogeneity of contamination, so actual value for a specific site could be lower.
Livestock Feed Type Partitioning	Beef_grain_Fraction Beef_grain_Fraction_INT		constant 0.25	Beef cattle portion of diet of 25% of intake as grain feed is based on value provided in NRC (1999, Section 6.4.6.3).
	Milk_grain_Fraction Milk_grain_fraction_INT		constant 0.1	Milk cow portion of diet of 10% of intake as grain feed is based on value provided in NRC (1999, Section 6.4.6.3).
	Poultry_grain_Fraction Poultry_grain_Fraction_INT Egg_grain_Fraction Egg_grain_fraction_INT		constant 0.75	Poultry and hen portion of diet of 75% of intake as grain feed is based on value provided in NRC (1999, Section 6.4.6.3).
	Game_fraction_Beef_grain Game_fraction_Beef_grain_INT		constant 0.0	Value assigned to no grain consumption for game (game assumed to forage on leafy plants).

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	Beef_fodder_Fraction Beef_fodder_Fraction_INT	unitless	constant 0.75	Beef cattle portion of diet of 75% of intake as fodder feed (model does not distinguish fresh from cut) is based on value provided in NRC (1999, Section 6.4.6.3).
	Milk_fodder_Fraction Milk_fodder_Fraction_INT		constant 0.9	Milk cow portion of diet of 90% of intake as fodder feed (model does not distinguish fresh from cut) is based on value provided in NRC (1999, Section 6.4.6.3).
	Poultry_fodder_Fraction Egg_fodder_fraction Egg_fodder_fraction_INT		constant 0.25	Poultry and hen portion of diet of 25% of intake as grain feed (model does not distinguish fresh from cut) is based on value provided in NRC (1999, Section 6.4.6.3).
	Game_fraction_fodder Game_fraction_fodder_INT		constant 1.0	Value assigned to 100% fodder consumption for game (game assumed to forage on leafy plants).
	Beef_feed_clean_fraction Beef_feed_clean_fraction_INT Milk_feed_clean_fraction Milk_feed_clean_fraction_INT Egg_feed_clean_fraction Egg_feed_clean_fraction_INT Poultry_feed_clean_fraction Poultry_feed_clean_fraction_INT Game_feed_clean_fraction Game_feed_clean_fraction_INT		constant 0	Value assigned to assume zero uncontaminated feed consumption.
Crop Interception Fraction (Irrigation)	Grain_irr_intercept_fract Fruit_irr_intercept_fract LGV_irr_intercept_fract Veg_irr_intercept_fract Beef_Gr_irr_intercept_fract Milk_Gr_irr_intercept_fract Poultry_Gr_irr_intercept_fract Egg_Gr_irr_intercept_fract Fod_Gr_irr_intercept_fract		uniform 0.10, 0.60	Values from NRC (1999) based on consideration of experimentally derived values by Hoffman, et al. (1992). Range encompasses value from NRC (1977) of 0.25. The same distribution is applied to all types of crops, but the model is capable of accepting individual values if available.

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
Crop Interception Fraction (Air)	Grain_air_deposition_fract Fruit_air_deposition_fract LGV_air_deposition_fract Veg_air_deposition_fraction Beef_Gr_air_deposition_fraction Milk_Gr_air_deposition_fraction Poultry_Gr_air_deposit_fract Egg_Gr_air_deposition_fract Fod_air_deposition_fract	unitless	uniform 0.10, 0.60	Values for water interception are used in absence of specific data for air deposition.
Irrigation Water Source Partitioning	LSW_fraction_GW LSW_fraction_Pond LSW_fraction_SoR Beef_Gr_fraction_GW Beef_Gr_fraction_Pond Beef_Gr_fraction_SoR Milk_Gr_fraction_GW Milk_Gr_fraction_Pond Milk_Gr_fraction_SoR Poultry_Gr_fraction_GW Poultry_Gr_fraction_Pond Poultry_Gr_fraction_SoR Egg_Gr_fraction_GW Egg_Gr_fraction_Pond Egg_Gr_fraction_SoR Fod_fraction_GW Fod_fraction_Pond Fod_fraction_SoR IRW_fraction_GW IRW_fraction_Pond IRW_fraction_Pond Game_water_fraction_GW Game_water_fraction_Pond Game_water_fraction_SoR		constant	Values for all irrigation sources are set to use groundwater as the source of water. User can change individual use values to reflect other configurations of sources for specific water uses. Game use of groundwater implies animals drink from groundwater that has seeped to ground surface so it is accessible to animals.

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
Crop Irrigation Rate	Grain_irrigation_rate Fruit_irrigation_rate LGV_irrigation_rate Veg_irrigation_rate Beef_Gr_irrigation_rate Milk_Gr_irrigation_rate Poultry_Gr_irrigation_rate Egg_Gr_irrigation_rate Fod_irrigation_rate	in/yr	constant 22.7	Average irrigation rate for farm and ranch land in Idaho reported in NRC (1999). This value is approximately 2 acre-ft/acre and is applicable to an arid region growing common crops such as potatoes. For site-specific analyses, more refined crop and site or regional values can be used.
Crop Irrigation Duration	Grain_irrigation_duration Fruit_irrigation_duration LGV_irrigation_duration Veg_irrigation_duration Beef_Gr_irrigation_duration Milk_Gr_irrigation_duration Poultry_Gr_irr_duration Egg_Gr_irrigation_duration Fod_irrigation_duration	mo/yr	constant 6.0	Assumed representative value for length of the growing season for all crops (i.e., the duration irrigation). For site-specific analyses, more refined crop and site or regional values can be used.
Crop Growing Duration	Grain_Growth_Duration Fruit_Growth_Duration	days	constant 90	Minimum growing periods for various crop groups obtained from Table 6.30 in NRC (1999) except value for forage was obtained from Table 6.12 in Kennedy and Strenge (1992) because no value was identified for forage in NRC (1999).
	LGV_Growth_Duration		constant 45	
	Veg_Growth_Duration Beef_Gr_Growth_Duration Milk_Gr_Growth_Duration Poultry_Gr_Growth_Duration Egg_Gr_Growth_Duration		constant 90	
	Fod_Growth_Duration		constant 30	

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
Fraction of Roots in Contaminated Soil	Grain_root_fraction Fruit_root_fraction LGV_root_fraction Veg_root_fraction Beef_Gr_root_fraction Milk_Gr_root_fraction Poultry_Gr_root_fraction Egg_Gr_root_fraction Fod_root_fraction	unitless	constant 1.0	Default setup assumes all roots are within the contaminated plow layer. Use of lower values when justified by available site information will decrease plant uptake proportionally in the model.
Plant Translocation Factors	Grain_translocation_factor Fruit_translocation_factor		constant 0.1	Values from NRC (1999) represent the fraction of activity deposited on plant surface that is transferred to edible portions.
	LGV_translocation_factor		constant 1.0	
	Veg_translocation_factor Beef_Gr_translocation_factor Milk_Gr_translocation_factor Poultry_Gr_translocation_factor Egg_Gr_translocation_factor		constant 0.1	
	Fod_translocation_factor		constant 1.0	
Human Consumption Rates	RES_water_consumption REC_water_consumption INT_water_consumption	L/yr	constant 730.5	Generally accepted default value of 2 L/d from various sources including NRC (1999).

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	RES_Grain_consum_rate REC_Grain_consum_rate INT_Grain_consum_rate	kg/yr	discrete (mean, 14) 0.00, 1.41 0.01, 1.41 0.05, 2.22 0.10, 3.22 0.25, 4.83 0.50, 8.20 0.75, 15.80 0.90, 31.78 0.95, 44.01 0.99, 84.78 1.00, 99.47	Human consumption rates are from national average compilations in NRC (1999, Vol. 3, Section 6.2). Then the user can evaluate these parameter values and change to site-specific constant or distribution values. Note: Distributions are ingestion rates of homegrown foods.
	RES_Fruit_consum_rate REC_Fruit_consum_rate INT_Fruit_consum_rate		discrete (mean, 53) 0.00, 1.93 0.01, 1.93 0.05, 3.64 0.10, 5.08 0.25, 9.48 0.50, 20.48 0.75, 45.36 0.90, 125.96 0.95, 190.05 0.99, 460.84 1.00, 673.57	

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	RES_LGV_consum_rate REC_LGV_consum_rate INT_LGV_consum_rate	kg/yr	discrete (mean, 21) 0.00, 1.04 0.01, 1.04 0.05, 1.71 0.10, 2.04 0.25, 5.90 0.50, 11.68 0.75, 24.58 0.90, 46.27 0.95, 66.03 0.99, 135.52 1.00, 222.95	
	RES_Veg_consum_rate REC_Veg_consum_rate INT_Veg_consum_rate		discrete (mean, 45) 0.00, 2.23 0.01, 2.23 0.05, 4.15 0.10, 5.95 0.25, 11.27 0.50, 26.64 0.75, 55.57 0.90, 77.07 0.95, 145.57 0.99, 301.49 1.00, 384.03	
	RES_Soil_consum_rate REC_Soil_consum_rate INT_Soil_consum_rate		triangular 0 1.83×10^{-2} 3.65×10^{-2}	

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	RES_Beef_consumption REC_Beef_consumption INT_Beef_consumption	kg/yr	discrete (mean, 40) 0.00, 2.42 0.01, 2.42 0.05, 7.03 0.10, 8.20 0.25, 13.26 0.50, 28.79 0.75, 48.41 0.90, 76.75 0.95, 105.71 0.99, 220.06 1.00, 222.75	
	RES_Milk_consumption REC_Milk_consumption INT_Milk_consumption	L/yr	discrete (mean, 233) 0.00, 6.59 0.01, 6.59 0.05, 6.86 0.10, 7.67 0.25, 58.63 0.50, 148.56 0.75, 294.81 0.90, 554.94 0.95, 721.00 0.99, 1210.78 1.00, 1210.78	

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	RES_poultry_consumption REC_Poultry_consumption INT_Poultry_consumption	kg/yr	discrete (mean, 25) 0.00, 3.85 0.01, 3.85 0.05, 4.18 0.10, 5.94 0.25, 9.57 0.50, 19.85 0.75, 38.22 0.90, 50.83 0.95, 58.52 0.99, 72.81 1.00, 72.81	
	RES_egg_consumption REC_egg_consumption INT_egg_consumption		discrete (mean, 19) 0.00, 2.80 0.01, 2.80 0.05, 4.50 0.10, 5.30 0.25, 8.23 0.50, 12.36 0.75, 21.35 0.90, 35.90 0.95, 47.35 0.99, 120.71 1.00, 120.71	

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	RES_Fish_consumption REC_Fish_consumption INT_Fish_consumption	kg/yr	discrete (mean, 21) 0.00, 1.85 0.01, 1.85 0.05, 1.92 0.10, 2.84 0.25, 3.68 0.50, 7.77 0.75, 16.14 0.90, 39.08 0.95, 79.05 0.99, 112.82 1.00, 852.06	
	RES_game_consumption REC_game_consumption INT_game_consumption		constant 4.34	The game consumption rate is the maximum mean daily intake for meats/game from EPA (1997b, Table 11-21) of 11.9 g/d to give a constant value of 4.34 kg/yr. Site-specific values using local hunting practices and consumption should be used when possible.
Crop Yield	Grain_yield	kg/m^2	triangular 0.28 0.40 0.52	NRC (1999, Vol. 3, Table 6.55) crop yield for edible crops.
	Fruit_yield		triangular 2.2 2.4 2.6	
	LGV_yield		triangular 2.7 2.9 3.2	
	Veg_yield		triangular 2.3 2.4 2.5	

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	Beef_Gr_yield Milk_Gr_yield Poultry_Gr_yield Egg_Gr_yield	kg/m^2	normal 0.5781 0.0777	NRC (1999, Vol. 3, Table 6.62) crop yield for grain crops.
	Fod_yield		constant 0.5	NRC (1999, Vol. 3, Table 6.56) crop yield for forage crops.
Dry to Wet Conversion Factor	Grain_dry_to_wet	unitless	constant 0.91	NRC (1999, Vol. 3, Table 6.77) values for wet-to-dry-weight conversion factors.
	Fruit_dry_to_wet		constant 0.18	
	LGV_dry_to_wet		constant 0.2	
	Veg_dry_to_wet		constant 0.25	
	Beef_Gr_dry_to_wet Milk_Gr_dry_to_wet Poultry_Gr_dry_to_wet Egg_Gr_dry_to_wet		constant 0.91	NRC (1999, Vol. 3, Table 6.82) values for wet-to-dry-weight conversion factors, with 0.91 used to represent an average of the various grain types.
	Fod_dry_to_wet		constant 0.22	NRC (1999, Vol. 3, Table 6.80) values for wet-to-dry-weight conversion factors with 0.22 used to represent an average of the various fodder types.
Tritium and Carbon Model Inputs	Relative_Humidity	kg/m^3	constant 0.008	NRC (1999, Vol. 3, Table 6.30) value for absolute humidity.
	Milk_density		constant 1032	CRC (1980, p. F–3).
	Carbon_emission_constant	yr^{-1}	constant 12	Yu, et al. (2001, Appendix L, Table L.2).
	Grain_reduction_factor Fruit_reduction_factor	unitless	constant 0.8	Napier, et al. (2004, Table 9.3).
	LGV_reduction_factor		constant 0.9	

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	Veg_reduction_factor Beef_Gr_reduction_factor Milk_Gr_reduction_factor Poultry_Gr_reduction_factor Egg_Gr_reduction_factor	unitless	constant 0.8	
	Fod_reduction_factor		constant 0.9	
	Beef_Hydrogen_fraction		constant 0.1	NRC (1999, Vol. 3, Table 6.30).
	Milk_Hydrogen_fraction		constant 0.11	
	Poultry_Hydrogen_fraction		constant 0.1	
	Egg_Hydrogen_fraction		constant 0.11	
	Game_Hydrogen_fraction		constant 0.1	
	Game_carbon_fraction		constant 0.36	NRC (1999, Vol. 3, Table 6.36).
	Water_carbon_fraction		constant 2×10^{-5}	Yu, et al. (2001, Appendix L).
	Air_carbon_content	kg/m^3	constant 1.8×10^{-4}	
	Soil_carbon_content	unitless	constant 0.03	NRC (1999, Vol. 3, Table 6.30).
	Grain_fract_carbon		constant 0.4	NRC (1999, Vol. 3, Table 6.34).
	Fruit_fract_carbon LGV_fract_carbon Veg_fract_carbon		constant 0.09	

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	Beef_Gr_fract_carbon Milk_Gr_fract_carbon Poultry_Gr_fract_carbon Egg_Gr_fract_carbon Fod_fract_carbon	unitless	constant 0.4	
	Beef_carbon_fraction		constant 0.36	NRC (1999, Vol. 3, Table 6.36).
	Milk_carbon_fraction		constant 0.06	
	Poultry_carbon_fraction		constant 0.18	
	Egg_carbon_fraction		constant 0.16	
	Grain_frac_fresh_matter		constant 0.117	Napier, et al. (2004, Table 9.3).
	Fruit_frac_fresh_matter		constant 0.853	
	LGV_frac_fresh_matter		constant 0.906	
	Veg_frac_fresh_matter		constant 0.824	
	Beef_Gr_frac_fresh_matter Milk_Gr_frac_fresh_matter Poultry_Gr_frac_fresh_matter Egg_Gr_frac_fresh_matter		constant 0.117	
	Fod_frac_fresh_matter		constant 0.8	
Miscellaneous	Deposition_velocity	m/s	constant 0.001	LaPlante and Poor (1997, Section 2.3.5.2).
	Weathering_constant	yr^{-1}	18.07	NRC (1977) value from 14-day weathering half-life.
	Leaf_surface_RF	m^{-1}	constant 1×10^{-9}	Napier, et al. (2004, Table F.1).

Table 1. Input Parameter Values for BDOSE Version 1.0 (continued)				
Parameter Group	**BDOSE Parameter Name**	**Units**	**Distribution Type and Parameter Value(s)**	**Remarks**
	Stream_vol_flow_rate Infiltration_vol_flow_rate	m^3/day	constant 10	Note: Placeholder input values—site-specific parameter values depending on local topography and site location should be used.
	Pond_area Infiltration_area	m^2	constant 1	

Table 2. BDOSE Ingestion and Inhalation Dose Coefficients (Sv/Bq)				
Radionuclide	**ICRP* Publication 72†**		**Federal Guidance Report No. 11‡**	
	Ingestion	**Inhalation**	**Ingestion**	**Inhalation**
H3	1.80E-11	2.60E-10	1.73E-11	1.73E-11
C14	5.80E-10	5.80E-09	5.64E-10	5.64E-10
Ni59	6.30E-11	4.40E-10	5.67E-11	7.31E-10
Co60	3.40E-09	3.10E-08	7.28E-09	5.91E-8
Ni63	1.50E-10	1.30E-09	1.56E-10	1.70E-09
Se79	2.90E-09	6.80E-09	2.35E-09	2.66E-09
Sr90	2.80E-08	1.60E-07	3.85E-08	3.51E-07
Y90	2.70E-09	1.50E-09	2.91E-09	2.28E-09
Nb94	1.70E-09	4.90E-08	1.93E-09	1.12E-07
Tc99	6.40E-10	1.30E-08	3.95E-10	2.25E-09
I129	1.10E-07	3.60E-08	7.46E-08	4.69E-08
Cs137	1.30E-08	3.90E-08	1.35E-08	8.63E-09
Ba137m	none	none	none	none
Eu152	1.40E-09	none	1.75E-09	5.97E-08
Eu154	2.00E-09	none	2.58E-09	7.73E-08
Eu155	3.20E-10	none	4.13E-10	1.12E-08
Pb210	6.90E-07	5.60E-06	1.45E-06	3.67E-06
Ra226	2.80E-07	9.50E-06	3.58E-07	2.32E-06
Ra228	6.90E-07	1.60E-05	3.88E-07	1.29E-06
Ac227	1.10E-06	5.50E-04	3.80E-06	1.81E-03
Th228	7.20E-08	4.00E-05	1.07E-07	9.23E-05
Th229	4.90E-07	2.40E-04	9.54E-07	5.80E-04
Th230	2.10E-07	1.00E-04	1.48E-07	8.80E-05
Th232	2.30E-07	1.10E-04	7.38E-07	4.43E-04
Pa231	7.10E-07	1.40E-04	2.86E-06	3.47E-04
U232	3.30E-07	3.70E-05	3.54E-07	1.78E-04
U233	5.10E-08	9.60E-06	7.81E-08	3.66E-05
U234	4.90E-08	9.40E-06	7.66E-08	3.58E-05
U235	4.70E-08	8.50E-06	7.19E-08	3.32E-05
U236	4.70E-08	8.70E-06	7.26E-08	3.39E-05
U238	4.50E-08	8.00E-06	6.88E-08	3.20E-05
Np237	1.10E-07	5.00E-05	1.20E-06	1.46E-04
Pu238	2.30E-07	1.10E-04	8.65E-07	1.06E-04
Pu239	2.50E-07	1.20E-04	9.56E-07	1.16E-04
Pu240	2.50E-07	1.20E-04	9.56E-07	1.16E-04
Pu241	4.80E-09	2.30E-06	1.85E-08	2.23E-06
Pu242	2.40E-07	1.10E-04	9.08E-07	1.11E-04
Pu244	2.40E-07	1.10E-04	8.97E-07	1.09E-04

Table 2. BDOSE Ingestion and Inhalation Dose Coefficients (Sv/Bq) (continued)				
Radionuclide	**ICRP* Publication 72†**		**Federal Guidance Report No. 11‡**	
	Ingestion	**Inhalation**	**Ingestion**	**Inhalation**
Am241	2.00E-07	9.60E-05	9.84E-07	1.20E-04
Am242m	1.90E-09	9.20E-05	9.50E-07	1.15E-04
Am243	2.00E-07	9.60E-05	9.79E-07	1.19E-04
Cm242	1.20E-08	5.90E-06	3.10E-08	4.67E-06
Cm243	1.50E-07	6.90E-05	6.79E-07	8.30E-05
Cm244	1.20E-07	5.70E-05	5.45E-07	6.70E-05
Cm245	2.10E-07	9.90E-05	1.01E-06	1.23E-04
Cm246	2.10E-07	9.80E-05	1.00E-06	1.22E-04
Cm247	1.90E-07	9.00E-05	9.24E-07	1.12E-04
Cm248	7.70E-07	3.60E-04	3.68E-06	4.47E-04
Cf249	3.50E-07	7.00E-05	1.28E-06	1.56E-04

*International Commission on Radiological Protection (ICRP)
†International Commission on Radiological Protection (1996)
‡U.S. Environmental Protection Agency (EPA) (1988)

Table 3. Dose Coefficients for External Exposure to Radionuclides in Air, Water, and Soil From Federal Guidance Report No. 12*					
Radionuclide	**Air Submersion (Sv m^3/Bq yr)**	**Water Submersion (Sv m^3/Bq yr)**	**Soil Surface (Sv m^2/Bq yr)**	**Soil Contaminated to Depth of 1 cm (Sv m^3/Bq yr)**	**Soil Contaminated to Depth of 15 cm (Sv m^3/Bq yr)**
H3	1.04E-11	0.00e+00	0.00e+00	0.00e+00	0.00e+00
C14	7.06E-12	1.38E-14	5.08E-13	1.36E-15	2.27E-15
Ni59	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Co60	3.97E-06	8.64E-09	7.41E-08	4.79E-10	2.29E-09
Ni63	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Se79	9.56E-12	1.87E-14	6.53E-13	1.82E-15	3.14E-15
Sr90	2.38E-10	4.60E-13	8.96E-12	4.13E-14	1.17E-13
Y90	6.00E-09	1.14E-11	1.68E-10	1.01E-12	3.78E-12
Nb94	2.43E-06	5.27E-09	4.83E-08	3.11E-10	1.43E-09
Tc99	5.11E-11	9.90E-14	2.46E-12	9.21E-15	2.11E-14
I129	1.20E-08	2.81E-11	8.14E-10	1.88E-12	2.19E-12
Cs137	2.44E-10	4.70E-13	8.99E-12	4.23E-14	1.24E-13
Ba137m	9.08E-07	1.97E-09	1.85E-08	1.19E-10	5.39E-10
Eu152	1.78E-06	3.88E-09	3.47E-08	2.22E-10	1.02E-09
Eu154	1.94E-06	4.19E-09	3.75E-08	2.40E-10	1.11E-09
Eu155	2.13E-06	1.77E-10	1.86E-09	1.06E-11	3.07E-11
Pb210	1.78E-09	4.13E-12	7.83E-11	2.61E-13	4.13E-13
Ra226	9.94E-09	2.19E-11	2.03E-10	1.31E-12	5.20E-12
Ra228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ac227	1.84E-10	4.10E-13	4.95E-12	2.43E-14	8.26E-14
Th228	2.90E-09	6.46E-12	7.42E-11	3.85E-13	1.32E-12
Th229	1.21E-07	2.70E-10	2.70E-09	1.61E-11	5.36E-11
Th230	5.49E-10	1.24E-12	2.37E-11	7.35E-14	2.02E-13
Th232	2.75E-10	6.28E-13	1.74E-11	7.25E-12	8.77E-14
Pa231	5.43E-08	1.19E-10	1.28E-09	5.93E-14	3.03E-11
U232	4.48E-10	1.02E-12	3.19E-11	5.93E-14	1.50E-13
U233	5.14E-10	1.15E-12	2.26E-11	6.81E-14	2.28E-13
U234	2.41E-10	5.52E-13	2.36E-11	3.19E-14	6.75E-14
U235	2.27E-07	5.01E-10	4.67E-09	2.99E-11	1.18E-10
U236	1.58E-10	3.66E-13	2.05E-11	2.06E-14	3.60E-14
U238	1.08E-10	2.51E-13	1.74E-11	1.39E-14	1.74E-14
Np237	3.25E-08	7.32E-11	9.06E-10	4.35E-12	1.31E-11
Pu238	1.54E-10	3.60E-13	2.64E-11	2.00E-14	2.55E-14
Pu239	1.34E-10	3.03E-13	1.16E-11	1.77E-14	4.79E-14
Pu240	1.50E-10	3.50E-13	2.53E-11	1.96E-14	2.47E-14

Table 3. Dose Coefficients for External Exposure to Radionuclides in Air, Water, and Soil From Federal Guidance Report No. 12* (continued)					
Radionuclide	**Air Submersion (Sv m^3/Bq yr)**	**Water Submersion (Sv m^3/Bq yr)**	**Soil Surface (Sv m^2/Bq yr)**	**Soil Contaminated to Depth of 1 cm (Sv m^3/Bq yr)**	**Soil Contaminated to Depth of 15 cm (Sv m^3/Bq yr)**
Pu241	2.29E−12	5.11E−15	6.09E−14	3.03E−16	9.93E−16
Pu242	1.27E−10	2.95E−13	2.10E−11	1.65E−14	2.16E−14
Pu244	9.37E−11	2.19E−13	1.76E−11	1.21E−14	1.27E−14
Am241	2.58E−08	5.93E−11	8.68E−10	3.63E−12	7.38E−12
Am242m	1.94E−08	2.30E−12	9.52E−11	1.35E−13	2.84E−13
Am243	6.87E−08	1.56E−10	1.69E−09	9.33E−12	2.40E−11
Cm242	1.80E−10	4.19E−13	3.02E−11	2.39E−14	2.86E−14
Cm243	1.79E−10	4.10E−10	3.94E−09	2.46E−11	9.52E−11
Cm244	1.55E−10	3.63E−13	2.77E−11	2.06E−14	2.13E−14
Cm245	1.25E−07	2.79E−10	2.74E−09	1.65E−11	5.68E−11
Cm246	1.41E−10	3.31E−13	2.48E−11	1.88E−14	1.96E−14
Cm247	4.73E−07	1.03E−09	9.78E−09	6.31E−11	2.78E−10
Cm248	1.07E−10	2.51E−13	1.89E−11	1.43E−14	1.48E−14
Cf249	4.98E−07	1.09E−09	1.03E−08	3.91E−12	1.74E−11
*U.S. Environmental Protection Agency (EPA) (1993)					

Table 4. Geometric Mean Soil Partition Coefficients (L/kg) by Element and Soil Type*				
Element	**Sand**	**Loam**	**Clay**	**Organic**
H	0.06	20	30	75
C	5	20	1	70
Co	60	1,300	550	1,000
Ni	400	300	650	1,100
Se	150	500	740	1,800
Sr	15	20	110	150
Y	170	720	1,000	2,600
Nb	160	550	900	2,000
Tc	0.1	0.1	1	1
I	1	5	1	25
Cs	280	4,600	1,900	270
Ba†	52	—	—	—
Eu†	240	—	—	—
Pb	270	16,000	550	22,000
Ra	500	36,000	91,000	2,400
Ac	450	1,500	2,400	5,400
Th	3,200	3,300	5,800	89,000
Pa	550	1,800	2,700	6,600
U	35	15	1,600	410
Np	5	25	55	1,200
Pu	550	1,200	5,100	1,900
Am	1,900	9,600	8,400	11,200
Cm	4,000	18,000	6,000	6,000
Cf†	510	—	—	—

*Sheppard and Thibault (1990)
†Default values from U.S. Nuclear Regulatory Commission (NRC) (1999)

Table 5. Transfer Factors for Animal and Plant-Based Food Products*									
	Poultry (d/kg Wet Weight)	Eggs (d/kg Wet Weight)	Beef (d/kg Wet Weight)	Milk (d/L Wet Weight)	Fish (L/kg Wet Weight)	Fruit (Dry Weight)	Grain (Dry Weight)	Leafy Vegetables (Dry Weight)	Root Vegetables (Dry Weight)
Co	2.0e+00	1.0E−01	1.0E−02	3.0E−04	3.0e+02	7.0E−03	3.7E−03	2.3E−01	6.7E−02
Ni	1.0E−03	1.0E−01	5.0E−03	1.6E−02	1.0e+02	6.0E−02	3.0E−02	2.8E−01	6.0E−02
Se	9.0E+00	9.0E+00	1.5E−02	4.0E−03	1.7E+02	5.0E−02	2.5E−01	2.5E−01	5.0E−02
Sr	8.0E+02	2.0E−01	8.0E−03	2.8E−03	6.0E+01	2.0E−01	2.1E−01	3.0E+00	5.0E−01
Y	1.0E−02	2.0E−03	1.0E−03	2.0E−05	3.0E+01	1.0E−02	1.0E−02	1.0E−02	1.0E−02
Nb	3.0E−04	1.0E−03	3.0E−07	4.1E−07	3.0E+02	2.5E−02	2.5E−02	2.5E−02	2.5E−02
Tc	3.0E−02	3.0E+00	1.0E−04	1.4E−04	2.0E+01	1.5E+00	7.3E−01	2.1E+02	2.4E−01
I	5.0E−02	4.4E+00	4.0E−02	9.0E−03	4.0E+01	4.0E−02	4.0E−02	4.0E−02	4.0E−02
Cs	3.0E+00	4.0E−01	5.0E−02	7.9E−03	2.0E+03	2.2E−01	2.6E−02	4.6E−01	1.3E−01
Ba	9.0E−03	9.0E−01	2.0E−04	4.8E−04	4.0E+00	1.5E−02	1.5E−02	1.5E−01	1.5E−02
Eu	2.0E−03	4.0E−05	2.0E−05	3.0E−05	3.0E+01	2.0E−02	2.0E−02	2.0E−02	2.0E−02
Pb	8.0E−01	1.0E+00	4.0E−04	2.6E−04	3.0E+02	1.0E−02	4.7E−03	1.0E−02	6.0E−03
Ra	3.0E−02	3.1E−01	9.0E−04	1.3E−03	5.0E+01	6.1E−03	1.2E−03	4.9E−02	2.0E−03
Ac	6.0E−03	4.0E−03	4.0E−04	2.0E−05	2.5E+01	2.5E−04	2.2E−05	4.7E−04	3.5E−04
Th	6.0E−03	4.0E−03	4.0E−05	5.0E−06	1.0E+02	2.5E−04	3.4E−05	1.8E−03	3.3E−04
Pa	6.0E−03	4.0E−03	4.0E−05	5.0E−06	1.0E+01	2.5E−04	2.2E−05	4.7E−04	3.5E−04
U	1.0E+00	1.0E+00	3.0E−04	4.0E−04	1.0E+01	4.0E−03	1.3E−03	8.3E−04	1.2E−02
Np	6.0E−03	4.0E−03	1.0E−03	5.0E−06	2.1E+01	1.0E−02	2.7E−03	3.2E−02	1.3E−02
Pu	3.0E−03	5.0E−04	1.0E−05	1.1E−06	3.0E+01	4.5E−05	8.6E−06	6.0E−05	1.1E−03
Am	6.0E−03	4.0E−03	4.0E−05	1.5E−06	3.0E+01	2.5E−04	2.2E−05	4.7E−04	3.5E−04
Cm	6.0E−03	4.0E−03	4.0E−05	2.0E−05	3.0E+01	1.5E−05	2.1E−05	7.7E−04	4.3E−04
Cf	6.0E−03	4.0E−03	4.0E−05	1.5E−06	2.5E+01	2.5E−04	2.2E−05	4.7E−04	3.5E−04

*Staven, et al. (2003)

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