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Savannah River National Laboratory™
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EXECUTIVE SUMMARY

This report provides a detailed description of the methodology developed to perform dose calculations for E-Area Low Level Waste Facility Performance Assessments and Savannah River Site Composite Analyses. Chapters 2 – 8 give a complete set of equations to be used to calculate dose for individual exposure pathways. The first set of dose scenarios assume that a member of the public establishes residence near the waste site and uses contaminated groundwater or contaminated surface water for personal consumption and to irrigate a garden and pasture where produce and farm animals are raised. Products from the garden and farm animals are used for personal consumption. This scenario applies to both E-Area Performance Assessments and Savannah River Site Composite Analyses. General dose exposure pathways for the resident farmer scenario are:

1. Ingestion pathways described in Chapter 2,
2. Inhalation pathways described in Chapter 3,
3. External exposure pathways described in Chapter 4, and
4. Recreational pathways described in Chapter 5 (Composite Analysis only).

Doses from all of the above pathways are directly related to the contaminant concentration in the water.

Additional dose scenarios considered for E-Area Performance Assessment assume that an inadvertent intruder encroaches on the waste disposal site after loss of institutional control. General dose exposure pathways considered for the inadvertent intruder are:

1. Ingestion pathways described in Chapter 6,
2. Inhalation pathways described in Chapter 7, and
3. External exposure pathways described in Chapter 8.

Doses from all of the intruder pathways are directly related to the contaminant concentration in the buried waste.

Special dose considerations related to human consumption of meat and dairy, and treatment of tritium in dose calculations are discussed in Chapter 9.

Chapter 10 describes an Excel database named "*Radionuclide, Element and Dose Parameter Data Package"* that has been created to provide a system for maintaining the data required to perform radionuclide transport and dose calculations. This data includes:

- Isotope physical parameters and radioactive decay data needed for both transport and dose calculations,
- Isotope-specific dose coefficients and soil shielding factors associated with exposure pathways,
- Radionuclide drinking water concentration limits either published by the Environmental Protection Agency or derived from internal dose coefficients to meet the groundwater protection requirements in Department of Energy Order 435.1,
- Element-specific bio-transfer factors used in dose calculations,
- Dose equations and values of physical parameters and human factors used in dose calculations, and
- Key physical constants used in dose calculations.

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LIST OF ABBREVIATIONS

AMU	Atomic Mass Unit
CA	Composite Analysis
CFR	Code of Federal Regulations
DCF	Dose Conversion Factor
DOE	Department of Energy
DRF	Dose Release Factor
EDE	Effective Dose Equivalent
ELLWF	E-Area Low Level Waste Facility
EPA	Environmental Protection Agency
HPCFS	High Performance Computing File System
IAEA	International Atomic Energy Agency
ICRP	International Committee on Radiological Protection
LLW	Low Level Waste
MCL	Maximum Concentration Limit
MEI	Maximally Exposed Individual
MOP	Member of Public
NBS	National Bureau of Standards
NDAA	National Defense Authorization Act
NESHAP	National Emission Standards for Hazardous Air Pollutants
NIST	National Institute of Standards
NRC	Nuclear Regulatory Commission
PA	Performance Assessment
POA	Point of Assessment
SRNL	Savannah River National Laboratory
SRR	Savannah River Remediation
SRS	Savannah River Site
WSRC	Westinghouse Savannah River Company

1.0 Introduction

The Savannah River Site (SRS) disposes of solid low-level radioactive waste in on-site engineered disposal units within the E-Area Low-Level Waste Facility (ELLWF). The SRS must demonstrate that this disposal meets the requirements of Department of Energy (DOE) Order 435.1 (DOE, 2001) by completing a Performance Assessment (PA). The PA is used to provide DOE with a reasonable expectation that low-level waste (LLW) disposal will meet the radiological performance objectives for long-term protection of the public established in DOE Manual 435.1-1, *Radioactive Waste Management Manual*. DOE Order 435.1 also requires a Composite Analysis (CA) to assess the cumulative impact to future members of the public from residual radioactive material projected to remain on the site after all DOE operations have ceased. These analyses consider the fate and transport of disposed material in the environment and the potential dose to an individual residing on or intruding onto the disposal facility following site closure and loss of institutional control. In order to perform these analyses, scenarios describing expected human behavior at the disposal site in the future are postulated and dose equations appropriate to these scenarios developed. In addition to a set of dose equations, isotope-specific physics and dose parameters, and some element specific data are required.

The primary purpose of this report is to present a derivation of dose equations that can be used in the PA and CA all-pathways analysis and in the PA intruder analysis. The report also describes a single source, designated as the *Radionuclide, Element and Dose Parameter Data Package* that contains the most recent radionuclide and element specific data and associated dose parameters required for ELLWF PA and SRS CA calculations of disposal limits and doses. This data package is intended to provide a framework that not only contains the most recent data available at the time of issue but that can also be used to update the data as new information becomes available. The contents of the data package were checked through an extensive independent verification process that checked all of the numerical values in the package and the decay chains. The data package has been created in an Excel workbook for both ease of use and ready distribution. This work is part of an on-going maintenance program to periodically review and update existing PA and CA work as new data become available.

The methodology described in this report builds on the dose calculation methods used in the current ELLWF PA (WSRC, 2008) and SRS CA (SRNL, 2010). The dose calculation methodology described herein is similar to dose methodology used by Savannah River Remediation (SRR) in the preparation of the Saltstone Disposal Facility PA, H Tank Farm PA and F Tank Farm PA (SRR, 2014). Though similar in many respects, SRR dose calculation methodology is designed to accommodate the unique features of these three SRS disposal facilities and different regulatory framework under the *Ronald W. Reagan National Defense Authorization Act (NDAA) for Fiscal Year 2005,* Section 3116 (NDAA, 3116). A number of differences in approach between the two programs are noted in this report.

1.1 Performance Measures

For PAs, the radiological dose to human receptors is determined from an all-pathways analysis, an inadvertent intruder analysis, an air-pathway analysis, and analysis of Radon flux from the disposal facility. Although the all-pathways performance objective includes all exposure pathways and transport pathways, the air pathway is evaluated separately in the ELLWF PA. For the ELLWF PA, the all-pathways analysis includes only groundwater transport pathways because receptors for the groundwater and air pathways will likely be at different locations and maximum doses from the two pathways will occur at different times. This groundwater only all-pathways analysis determines the cumulative dose to a human who resides near the waste disposal site after site closure and loss of institutional control. The human is assumed to engage in residential and farming activities that use groundwater contaminated by

the leaching of radioactive material from the disposed waste. Dose pathways through ingestion, inhalation, and external exposure to the contaminated groundwater are considered. For the all-pathways PA analysis, the performance measure of relevance is specified in DOE M 435.1-1.IV.P. (1) (DOE 1999a) to be 25 mrem/yr effective dose equivalent (EDE) to representative members of the public, excluding dose from radon and its progeny in air. The PA inadvertent intruder analysis determines the cumulative dose to a human who engages in activities on top of the waste disposal site after site closure and loss of institutional control that result in exposure from contaminated soil. Dose pathways through the ingestion, inhalation, and external exposure to the soil are considered. For the PA inadvertent intruder, the applicable performance measures are found in DOE M 435.1-1.IV.P. (2). (h), (DOE 1999a) to be 100 mrem/yr EDE and 500 mrem/yr EDE for chronic and acute exposure scenarios, respectively.

The CA performs analyses similar to those used in the PA all-pathways analysis with the exception that it considers all sources of contamination at the SRS and assumes that the resident farmer uses contaminated surface water from streams and rivers located on or adjacent to the SRS. For the CA it is also assumed that the resident will engage in recreational activities using the surface water. The applicable CA performance measure is a dose limit of 100 mrem/yr EDE and a dose constraint of 30 mrem/yr EDE. If CA results show that dose to the public will exceed the dose constraint, a monitoring program or remedial action must be taken to ensure that the dose limit will not be exceeded.

Dose pathways not considered by the methodology developed in this report are: airborne releases, Radon emission, and compliance with Environmental Protection Agency (EPA) drinking water protection standards. While calculation methods to determine these doses are not developed, the database includes parameters required by these calculations. Requirements for these doses are briefly discussed here and the dose parameters are described in Chapter 10. Airborne releases must meet National Emission Standards for Hazardous Air Pollutants (NESHAP) requirements. The performance measure for the PA air pathway is 10 mrem/yr EDE excluding doses from radon and its progeny. Air transport of volatile radionuclides to the ground surface is simulated using the CAP-88 model (EPA 2006) to calculate a dose from inhalation of the contaminated air. Radon fluxes for each disposal unit are calculated and compared to an average flux of 20 $pCi/m^2/s$ which is the upper limit specified in the performance objective. The format and content guide for DOE 435.1 (DOE 1999b) states "DOE M 435.1-1 does not specify the level of protection for water resources that should be used in a performance assessment for a specific low-level waste disposal facility. Rather, a site-specific approach, in accordance with a hierarchical set of criteria should be followed." At SRS, protection of groundwater resources is addressed by comparing the groundwater concentrations calculated at compliance points with the EPA Safe Drinking Water Act maximum concentration limits (MCLs) for beta-gamma and alpha-emitting radionuclides, and for Radium and Uranium (EPA 2000; EPA 2001). MCLs for applicable radionuclides are provided in the database as described in Chapter 10.

1.2 All-Pathways and Intruder Dose Scenarios and Report Outline

In the PA and CA dose scenarios, it is assumed that the representative Member of the Public (MOP) serving as a human dose receptor is a resident farmer who uses water from a contaminated source for human and animal consumption, irrigation of a garden, and irrigation of a pasture where farm animals are raised. Products from the garden and farm animals are used for human consumption. The contaminated water may either be groundwater (PA) from a well that is typically assumed to be 100 m down gradient from the boundary of the waste disposal facility or surface water (CA) drawn from the Savannah River. The contamination is leached out of the ELLWF (PA and CA) or other source of residual radionuclides (CA only) and transported through the vadose zone to the groundwater aquifer where it is transported to the point of access by a MOP. An additional recreation scenario is assumed for the CA MOP.

The dose exposure pathways for the resident farmer scenario developed in Chapters 2 – 4 are:

1. Ingestion pathways to a MOP described in Chapter 2,
2. Inhalation pathways to a MOP described in Chapter 3,
3. External exposure pathways to a MOP described in Chapter 4, and
4. Recreational pathways to a MOP described in Chapter 5 (CA only).

Doses from these pathways are directly related to the concentration of contaminants in the groundwater (PA) or surface water (CA). In addition to the resident farmer, the CA also includes recreational exposure pathways to a MOP at the mouth of local streams as described in Chapter 5. For recreational use, the contamination in the groundwater is diluted by fresh water in the streams and river.

In contrast to doses to a MOP, doses to an inadvertent intruder are directly related to the concentration of contaminants in the waste disposal facility itself. The dose exposure pathways for an inadvertent intruder who encroaches onto the waste disposal site after loss of institutional control developed in Chapters 6 – 8 are:

1. Ingestion pathways to an inadvertent intruder described in Chapter 6,
2. Inhalation pathways to an inadvertent intruder described in Chapter 7, and
3. External exposure pathways to an inadvertent intruder described in Chapter 8.

The intruder scenarios can be divided into acute scenarios that result in doses over short time durations and chronic scenarios that result in doses over extended periods of time. The three acute intruder scenarios considered are:

1. The basement construction scenario which assumes that the intruder builds a home on the disposal site, with the basement extending into the waste zone. Intrusion into the waste over the 1,000 year period of assessment is precluded when the thickness of clean cover material over the waste is greater than the depth of a typical basement (3 meters or ~10 feet) or when the integrity of engineered barriers such as reinforced concrete over the waste prevents it. This initial thickness will be reduced over time through erosion of soil-like material and degradation of impenetrable barriers.

2. The well drilling scenario which assumes that the intruder drills a well directly into the waste disposal unit. This scenario is excluded from consideration over the 1,000 year assessment period if drilling into the waste is precluded by the inability of typical site-specific drilling techniques from penetrating an engineered barrier such as reinforced concrete.

3. The discovery scenario which assumes that after active institutional control ceases, an intruder attempts to excavate a basement for a home on the disposal site but stops prior to excavating into the waste and moves elsewhere because of the unusual nature of the materials being excavated. A difference in the basement construction scenario and discovery scenario is the time at which they occur. The discovery scenario can occur at any time after loss of institutional control whereas the basement construction scenario cannot occur until the thickness of the overlying cover material is eroded to a depth less than that of a typical basement (3 meters or 10 feet).

The three chronic intruder scenarios considered are:

1. The agriculture scenario which assumes that the intruder comes onto the site and establishes a permanent homestead. Waste in the disposal facility is assumed to be

accessed when an intruder constructs a home directly on top of a disposal facility and the basement of the home extends into the waste itself. Waste exhumed from the disposal facility is assumed to be mixed with native soil in the intruder's vegetable garden. Intrusion into the waste is assumed to be precluded when the thickness of clean cover material over the waste is greater than the depth of a typical basement (3 meters or ~10 feet) or when the integrity of engineered barriers such as reinforced concrete prevents it.

2. The post-drilling scenario which assumes that an intruder who resides permanently near the disposal facility drills through the disposal facility while constructing a well for a domestic water supply. Contaminated waste material brought to the surface during drilling operations, which is assumed to be indistinguishable from native soil, is mixed with native soil in the intruder's vegetable garden. This scenario is excluded from consideration over the 1,000 year assessment period if drilling into the waste is precluded by the inability of typical site-specific drilling techniques from penetrating an engineered barrier such as reinforced concrete.

3. The residential scenario which assumes that an intruder lives in a home with a basement located directly above the disposal facility. It is further assumed that the basement does not extend into the waste disposal zone because this eventuality is included in the agricultural scenario. The resident is shielded from exposure to radionuclides in the waste by the concrete floor slab and the soil remaining between the basement and the disposal facility. The exposure pathway for this scenario is therefore external exposure to photon-emitting radionuclides in the disposal facility while residing in a home located on top of the facility. Because the intruder does not excavate into the waste it is assumed that there is no significant inhalation or ingestion exposure.

The following thought process was used in the selection of intruder scenarios in the current ELLWF PA (WSRC, 2008). Because the final ELLWF closure cap will contain an erosion barrier and is designed to be thicker than a standard ten-feet-deep basement, an acute intruder basement construction scenario is assumed to be unrealistic. Because basement construction is the source of radionuclides for the intruder garden, the chronic agriculture scenario is not considered by the ELLWF PA intruder analysis. Although a basement excavated into the waste zone is not evaluated, a home with a basement built on top of (or a small distance above) the waste zone leading to external exposure is feasible and included in the PA. The chronic post drilling intruder scenario is analyzed in the ELLWF PA for trench units but not for the reinforced concrete vaults which remain intact and impervious to standard well drilling equipment during the 1,000 year period of performance. In the current PA, chronic intruder scenarios were judged to be more restrictive than the corresponding acute scenarios and therefore acute scenarios were not analyzed. However because more recent PA's have included them, acute scenarios will be considered in the next ELLWF PA revision. For completeness, the full set of intruder pathways is described in Chapters 6-8.

The inadvertent intruder analysis does not include direct ingestion of contaminated groundwater or the use of contaminated groundwater for crop irrigation. The reason for this is found in the "*Format and Content Guide for U.S. Department of Energy Low-Level Waste Disposal Facility Performance Assessments and Composite Analyses"*, December 7, 1977. Page B-34 of this reference states:

"The purpose of the inadvertent intruder analysis is to provide a surrogate for the determination of LLW that is acceptable for near-surface disposal. The inadvertent intruder analysis does not have the purpose of protecting future members of the public. As a result, the ingestion of contaminated water need not be considered as part of the inadvertent intruder

analysis, because the protection of water resources is considered explicitly as one of the performance criteria for the performance assessment."

This approach is a point of difference between the DOE and Nuclear Regulatory Commission (NRC). The NRC position is that ingestion of contaminated groundwater should be considered as part of the inadvertent intruder analysis. However, the NRC chronic dose objective is 500 mrem/yr as compared to the DOE chronic dose objective of 100 mrem/yr (a margin of 400 mrem/yr). Thus, the DOE position is that water ingestion is already covered by the Groundwater Protection Requirement (interpreted by SRS to be 4 mrem/yr for beta-gamma in drinking water) and the 25 mrem/yr all-pathways performance objective. Because of NRC involvement in Tank Farm Closure and Saltstone Disposal Facility PA's, SRR included the water ingestion pathway for the intruder (SRR, 2014).

In Chapters 6 – 8 relatively simple models to calculate a dose to an intruder are presented. The intruder dose calculations can be more detailed by considering erosion over time of soil-like material used to cover the waste and degradation of engineered barriers such as grout and concrete. Cover material above the waste can be represented as distinct layers with a specific thickness, erosion rate, and degradation time for each layer. The intruder dose may also consider that only a portion of a home is likely to be placed directly over the waste disposal area reducing the amount of waste accessed. Koffman (2006) describes an intruder dose model that includes these features. These factors will influence the depth to the waste, soil shielding factors, and amount of waste accessed but do not change the fundamental dose calculation methods presented in this report.

Table 1-1 presents some general notation used in the dose calculations and gives abbreviated names used to identify general dose pathways in the development presented in Chapters 2 – 8. Other notation used in the dose equations, for example, to identify specific dose pathways such as ingestion of vegetables, is defined as required in the Chapters. Table 1-2 gives an overview of the dose pathways considered in development of dose equations in this report. Note that in Table 1-1 and elsewhere in this document m^3 is used as the unit of liquid volume while liters are typically used when performing PA and CA calculations.

Table 1-1. General Notation used in Dose Calculations.

Symbol	Description	Representative Units
$C_{w,i}$	Concentration of contaminant species *i* in water	pCi/m^3
$C_{rw,i}$	Concentration of contaminant species *i* in river or stream	pCi/m^3
$C_{wz,i}$	Concentration of contaminant species *i* in waste zone	pCi/m^3
$D_{p,i}$	Annual dose through pathway *p* from contaminant species *i*	mrem/yr
$EC_{p,i}$	Effective dose coefficient for contaminant *i* in dose pathway *p*	mrem/pCi
F	Fraction	-
Q	Animal consumption rate	kg/yr or m^3/yr
T	Bio-transfer factor	Various by media
U	Human consumption rate	kg/yr or m^3/yr
t	Time	yr
λ_i	Radioactive decay constant for contaminant species *i*	1/yr
Ing	Ingestion pathway	-
Inh	Inhalation pathway	-
Ext	External exposure to radiation pathway	-

Table 1-2. Dose Pathways.

Human Receptor	Scenario	General Exposure Pathway	Specific Exposure Pathway	Chapter
Member of Public (PA)	Resident Farmer (Groundwater 100 m Well)	Ingestion	Drinking Water	2
			Garden Vegetables	
			Meat	
			Milk	
			Garden Soil (Dust)	
		Inhalation	Garden Soil (Dust)	3
			Irrigation Water	
			Shower Water	
		External Exposure	Garden Soil	4
			Shower Water	
Member of Public (CA)	Resident Farmer (Surface Water, Savannah River)	Ingestion	Drinking Water	2
			Garden Vegetables	
			Meat	
			Milk	
			Garden Soil (Dust)	
		Inhalation	Garden Soil (Dust)	3
			Irrigation Water	
			Shower Water	
		External Exposure	Garden Soil	4
			Shower Water	
Member of Public (CA)	Recreation (Surface Water, SRS Stream or Savannah River)	Ingestion	Dermal Adsorption of H^3	5
			Fish	
		Inhalation	Swimming Water	5
		External Exposure	Swimming Water	5
			Boating Water	
			Shore Soil	
Acute Intruder (PA)	Basement Construction	Ingestion	Waste Material	6
		Inhalation	Waste Material	7
		External Exposure	Waste Material	8
	Well Drilling	Ingestion	Waste Material	6
		Inhalation	Waste Material	7
		External Exposure	Waste Material	8
	Discovery	External Exposure	Waste Material	8
Chronic Intruder (PA)	Agriculture	Ingestion	Garden Vegetables	6
			Garden Soil (Dust)	
		Inhalation	Garden Soil (Dust)	7
			Dust in Home	
		External Exposure	Garden Soil	8
			Home	
	Post Drilling	Ingestion	Garden Vegetables	6
			Garden Soil (Dust)	
		Inhalation	Garden Soil (Dust)	7
		External Exposure	Garden Soil	8
	Residential	External Exposure	Home Residence	8

1.3 Lumped Parameter Transport Model

To determine the dose to an individual from exposure to contaminated material it is necessary to determine the concentration of contaminant in the material. Before considering specific dose pathways, a general lumped parameter model of contaminant transport is derived which will be used in Chapter 2 to calculate radionuclide concentrations in irrigated soil (taking into account soil-water partitioning and flux of contaminants into and out of the root zone) which is required by several of the dose pathways (see Section 2.2.2, *Contaminant Uptake by Crop Root*). To derive a lumped parameter model of contaminant transport, consider the porous material with volume V and surface area A_s illustrated in Figure 1-1 containing water and solid phases (neglecting the gas phase as described below) with contaminated water flowing through the material.

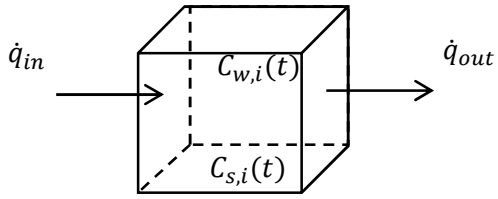

Figure 1-1. Volume of contaminated material.

Within the volume, the concentration of contaminant species i in the water phase is $C_{w,i}(t)$ and $C_{s,i}(t)$ in the solid phase. Aqueous concentrations are typically specified per unit volume of liquid whereas solid phase concentrations are typically specified per unit mass of solid. Volumetric fluxes (volume/area/time) of contaminated water flowing into and out of the surface are $\dot{q}_{in}$ and $\dot{q}_{out}$, respectively, with corresponding contaminant concentrations $\{c_{w,i}(t)\}_{in}$ and $\{c_{w,i}(t)\}_{out}$. Taking a lumped parameter approach, the rates of change of contaminant concentration in the liquid and solid phases within the material volume are given by the equations:

$$\alpha_w\, V \frac{dC_{w,i}(t)}{dt} = \dot{q}_{in}\alpha_w\, A_s \{c_{w,i}(t)\}_{in} - \dot{q}_{out}\, \alpha_w\, A_s \{c_{w,i}(t)\}_{out} + \alpha_w\, V\ \dot{r}_{w,i}(t) - F_{ws,i} \qquad (1.1\text{-}1)$$

$$(\alpha_s\, \hat{\rho}_s\, V)\, \frac{dC_{s,i}(t)}{dt} = (\alpha_s\, \hat{\rho}_s\, V)\, \dot{r}_{s,i}(t) + F_{ws,i} \qquad (1.1\text{-}2)$$

Where[1]:

$C_{w,i}(t)$ .....Concentration of contaminant *i* in water phase (mol/m^3)
$C_{s,i}(t)$ .....Concentration of contaminant *i* in solid phase (mol/kg)
$\hat{\rho}_s$ .....Solid material density (kg/m^3)
α_w, α_s .....Water and solid volume fractions (-)
$\dot{r}_{w,i}(t)$ .....Reaction rate of contaminant *i* in water phase (mol/m^3-yr)
$\dot{r}_{s,i}(t)$ .....Reaction rate of contaminant *i* in solid phase (mol/kg-yr)
$F_{ws,i}$ .....Rate of transfer of species *i* from water phase to solid phase (mol/yr)

The reaction rates could represent a chemical reaction of species i or radioactive decay and ingrowth. Taking ϕ to be solid porosity, $\theta_w = S\,\phi$, where θ_w is moisture content and S is water saturation. The

[1] Concentrations are given in moles but mass or Curies could be used as well.

solid fraction is $\alpha_s = 1 - \phi$. When water saturation is less than one, a gas phase is also present. However; this gas phase represents a small mass of material and is neglected so that $\alpha_w = \theta_w$.

Using the lumped parameter approach, it is assumed that the material volume is well mixed and the concentration of contaminant in the outlet stream is the same as the concentration within the liquid volume:

$$\{c_{w,i}(t)\}_{out} = C_{w,i}(t) \tag{1.1-3}$$

It is also assumed that the contaminant concentration in the solid phase is in equilibrium with the concentration in the liquid phase and that this equilibrium can be represented by a linear K_d dependence as shown below in Eq. (1.1-4) where $K_{d,i}$ is a constant for each species i.

$$C_{s,i}(t) = K_{d,i}\, C_{w,i}(t) \tag{1.1-4}$$

Where:

$K_{d,i}$.....Solid-liquid equilibrium constant for contaminant i (m^3/kg)

An additional simplification is made by assuming that reaction rates in the water and solid phases follow first order kinetics with rate constants $\lambda_{w,i}$ and $\lambda_{s,i}$, respectively, giving the equations:

$$\dot{r}_{w,i}(t) = \lambda_{w,i}\, C_{w,i}(t) \tag{1.1-5}$$

$$\dot{r}_{s,i}(t) = \lambda_{s,i}\, C_{s,i}(t) = \lambda_{s,i}\, K_{d,i}\, C_{w,i}(t) \tag{1.1-6}$$

Introducing the assumptions made in Eq. (1.1-3) – Eq. (1.1-6) into Eq. (1.1-1) and Eq. (1.1-2) and adding the resulting equations gives:

$$\begin{aligned}\left[\left(\theta_w + \alpha_s\, \hat{\rho}_s\, K_{d,i}\right) V\right] \frac{dC_{w,i}(t)}{dt} = {} & \theta_w\, A_s \left[\dot{q}_{in} \{c_{w,i}(t)\}_{in} - \dot{q}_{out}\, C_{w,i}(t)\right] \\ & + \left[\theta_w\, \lambda_{w,i} + \alpha_s\, \hat{\rho}_s\, \lambda_{s,i}\, K_{d,i}\right] V\, C_{w,i}(t)\end{aligned} \tag{1.1-7}$$

The final problem preventing the integration of Eq. (1.1-7) is that, in general, the contaminant concentration in the inlet stream varies with time. To avoid this complication it is assumed that Eq. (1.1-7) can be time averaged such that the inlet concentration is represented by a constant value $\hat{c}_{w,i}$ over the integration time interval. With this assumption, Eq. (1.1-7) can be written as:

$$\begin{aligned}\left[\left(\theta_w + \alpha_s\, \hat{\rho}_s\, K_{d,i}\right) V\right] \frac{dC_{w,i}(t)}{dt} + \left\{\dot{q}_{out}\, \theta_w\, A_s - \left[\theta_w\, \lambda_{w,i} + \alpha_s\, \hat{\rho}_s\, \lambda_{s,i}\, K_{d,i}\right] V\right\} C_{w,i}(t) \\ = \dot{q}_{in}\, \hat{c}_{w,i}\, \theta_w\, A_s\end{aligned} \tag{1.1-8}$$

In deriving Eq. (1.1-8), it has been assumed that different reactions can occur on the solid surface and in the bulk liquid. For radioactive decay alone, these reactions will be the same with decay constant λ_i and Eq. (1.1-8) reduces to:

$$(R_i\,\theta_w\,V)\frac{dC_{w,i}(t)}{dt} + \{\dot{q}_{out}\,\theta_w\,A_s + R_i\,\theta_w V\,\lambda_i\}\,C_{w,i}(t) = \dot{q}_{in}\,\theta_w\,A_s\,\hat{c}_{w,i} \quad (1.1\text{-}9)$$

In Eq. (1.1-9), R_i is the retardation factor for transport of contaminant species *i*:

$$R_i = 1 + \frac{\hat{\rho}_s\,(1-\phi)\,K_{d,i}}{\theta_w} = 1 + \frac{\rho_s\,K_{d,i}}{\theta_w} \quad (1.1\text{-}10)$$

In Eq. (1.1-10), the product of solid density and porosity is replaced with the solid bulk density ρ_s. Eq. (1.1-9) can now be integrated. To simplify the notation, the equation is rewritten as:

$$\frac{dC_{w,i}(t)}{dt} + \beta_i\,C_{w,i}(t) = S_i \quad (1.1\text{-}11)$$

Where:

$$\beta_i = \lambda_i + \frac{\dot{q}_{out}\,A_s}{R_i\,V} \quad \text{and} \quad S_i = \frac{\dot{q}_{in}\,A_s}{R_i\,V}\,\hat{c}_{w,i} \quad (1.1\text{-}12)$$

In Eq. (1.1-12), the β_i term is a time constant with units of inverse time and S_i is a constant production rate or source term for the contaminant with units of mass, moles, or Curies per unit volume per time. Integrating Eq. (1.1-11) from time = 0 to time = t gives:

$$C_{w,i}(t) = C_{w,i}(0)\,e^{-\beta_i t} + \frac{S_i}{\beta_i}\left(1 - e^{-\beta_i t}\right) \quad (1.1\text{-}13)$$

Making the assumption that the environment is initially clean, Eq. (1.1-13) reduces to:

$$C_{w,i}(t) = \frac{S_i}{\beta_i}\left(1 - e^{-\beta_i t}\right) \quad (1.1\text{-}14)$$

In the following presentation of dose equations, Eq. (1.1-14) will be applied to calculate contaminant concentrations in irrigated soil, plant leaves and plant roots. The basic assumptions made to derive this model include:

1. The initial assumption of a lumped parameter system which is a simplistic model treating the material as if it can be described by a set of properties averaged over the entire volume.
2. The use of a constant K_d representing equilibrium between contaminant concentrations in the liquid and solid phases.
3. The assumption of first order kinetics and identical solid and liquid reaction mechanisms which is applicable for radioactive decay but limiting for chemical reactions.
4. Neglecting time variation in the inlet stream concentration over the integration time interval.

1.4 General Form of Dose Equations

As will be shown by the derivations presented in Chapters 2 – 8, the equations for dose to a human receptor from any specific pathway are all of the general form:

$$D_{p,i} = EC_{p,i}\, Exp_{w,i}\, C_{w,i} \qquad (1.2\text{-}1)$$

Where:

$D_{p,i}$ ..... Annual dose from exposure to contaminant *i* through pathway *p* (mrem/yr)
$EC_{p,i}$ ..... Effective dose coefficient for exposure to contaminant *i* through pathway *p* (mrem/pCi)
$Exp_{w,i}$ ..... Equivalent direct exposure to source material *w* (m^3/yr)
$C_{w,i}$ ..... Concentration of contaminant *i* in source material *w* (pCi/m^3)

As Eq. (1.2-1) shows, the dose to an individual from contaminant *i* through a specific pathway is the product of the effective dose coefficient, the source concentration, and an exposure term. The exposure term represents the equivalent amount of source material to which the dose recipient is exposed. For example, the specific pathway considered might be ingestion of milk from cows that have consumed contaminated water and eaten grass contaminated by irrigation with the water. The grass is itself contaminated by absorbing radioactive material through the leaves and roots. While, as in the example cited, the path of contaminants from the dose source, in this case ground or surface water, to humans may be circuitous the result is an exposure term representing the equivalent amount of contaminated water that the dose recipient has ingested. This representation of the dose calculation in Eq. (1.2-1) will be used in Chapters 2 – 8 to summarize results. A complete listing of all the terms used in dose equations described in Chapters 2 – 8 along with their definitions and units is provided in Chapter 11.

1.5 Terminology

The terms “Typical Person” and “Reference Person” are introduced in the following sections where values of dose parameters related to human behavior are provided. SRS has defined the concept of the "Typical Person" as a hypothetical person that is typical of the entire population group established at the 50th percentile (median) of national usage data. See Stone and Jannik (2013) for more information. Typical Person usage parameters are used in ELLWF PA and SRS CA best-estimate, deterministic calculations of limits and doses. DOE Order 458.1 defines the "Reference Person" as a hypothetical aggregation of human (male and female) physical and physiological characteristics arrived at by international consensus for the purpose of standardizing radiation dose calculations. At SRS, the Reference Person, who is at the 95th percentile of national usage data, is used as a replacement for the Maximally Exposed Individual (MEI). In the ELLWF PA the Reference Person at the 95th percentile is used in sensitivity calculations, and in the CA it is used to define the upper end of parameter distributions for uncertainty analysis.

1.6 Quality Assurance

Requirements for performing reviews of technical reports and the extent of review are established in manual E7 2.60. Savannah River National Laboratory (SRNL) documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2 (WSRC, 2004).

2.0 Ingestion Dose to Resident Farmer MOP

Figure 2-1 shows a schematic diagram of sources of dose to a member of the public through ingestion pathways originating from the use of contaminated ground or surface water. The MOP is assumed to be a resident farmer who either uses well water drawn from contaminated groundwater or contaminated surface water (Savannah River) for both direct consumption and to raise a garden and farm animals that provide milk and meat which is also consumed. In the case of groundwater use, the well is typically assumed to be 100 m down gradient from the boundary of the contamination source (PA only). In the case of surface water use (CA only), the water is assumed to be drawn from points of assessment (POAs) that fall into two general categories: 1) POAs in the Savannah River as a source of drinking water, irrigation water and recreation water, and 2) POAs at the mouths of SRS surface streams entering the Savannah River as a source of recreation water only.

Contaminated water drawn from the Savannah River for use by the MOP is more dilute and therefore has a lower concentration than contaminated water found at the mouth of SRS surface streams. Therefore, applying the correct contaminated water concentration of radionuclides in dose equations involves knowing the location of the POA from which the water originated. It is assumed that the concentration of contaminants in the groundwater is known as a function of time and that the stream and/or river dilution factor is known as well. In general, dilution could vary with time but typically a constant annual average river or stream flow is used. See SRNL, 2010 for more discussion on CA POAs.

The following mechanisms of contaminant transfer from water to the human receptor through ingestion are considered in this model:

1. Direct consumption of contaminated water.
2. Consumption of garden produce contaminated by the use of water for irrigation.
3. Consumption of milk from dairy cattle that drink contaminated water and consume pasture grass irrigated with contaminated water.
4. Consumption of meat from farm animals that drink contaminated water and consume pasture grass irrigated with contaminated water.
5. Inadvertent consumption of dust from garden soil contaminated by the use of water for irrigation.

Produce or vegetable contamination occurs through two routes. One is absorption of contaminated water used for garden irrigation through the plant leaves. The second route is absorption of contaminants from soil through the plant roots where the soil has been contaminated by water through irrigation. Farm animals that provide milk and meat for human consumption are similarly exposed to contaminants by their direct ingestion of the water and by ingestion of plants exposed to contaminated water by irrigation. Like garden produce, pasture grass consumed by the animals is contaminated by absorption through both the leaves and roots from irrigation of the pasture using contaminated water.

As the above discussion and Figure 2-1 illustrate, many factors must be considered to determine the amount of contamination ultimately consumed by a MOP. It is assumed that the concentration of contaminants in the water is known as a function of time. Ingestion dose to a human receptor depends on the amount of contaminated water, produce, milk, meat and soil consumed and on the accumulation of contaminants in the ingested produce, milk, meat and soil. In the next section, we present a general model that accounts for ingestion of contaminants by the pathways shown in Figure 2-1. Table 1-1 presents some general notation used in the equations.

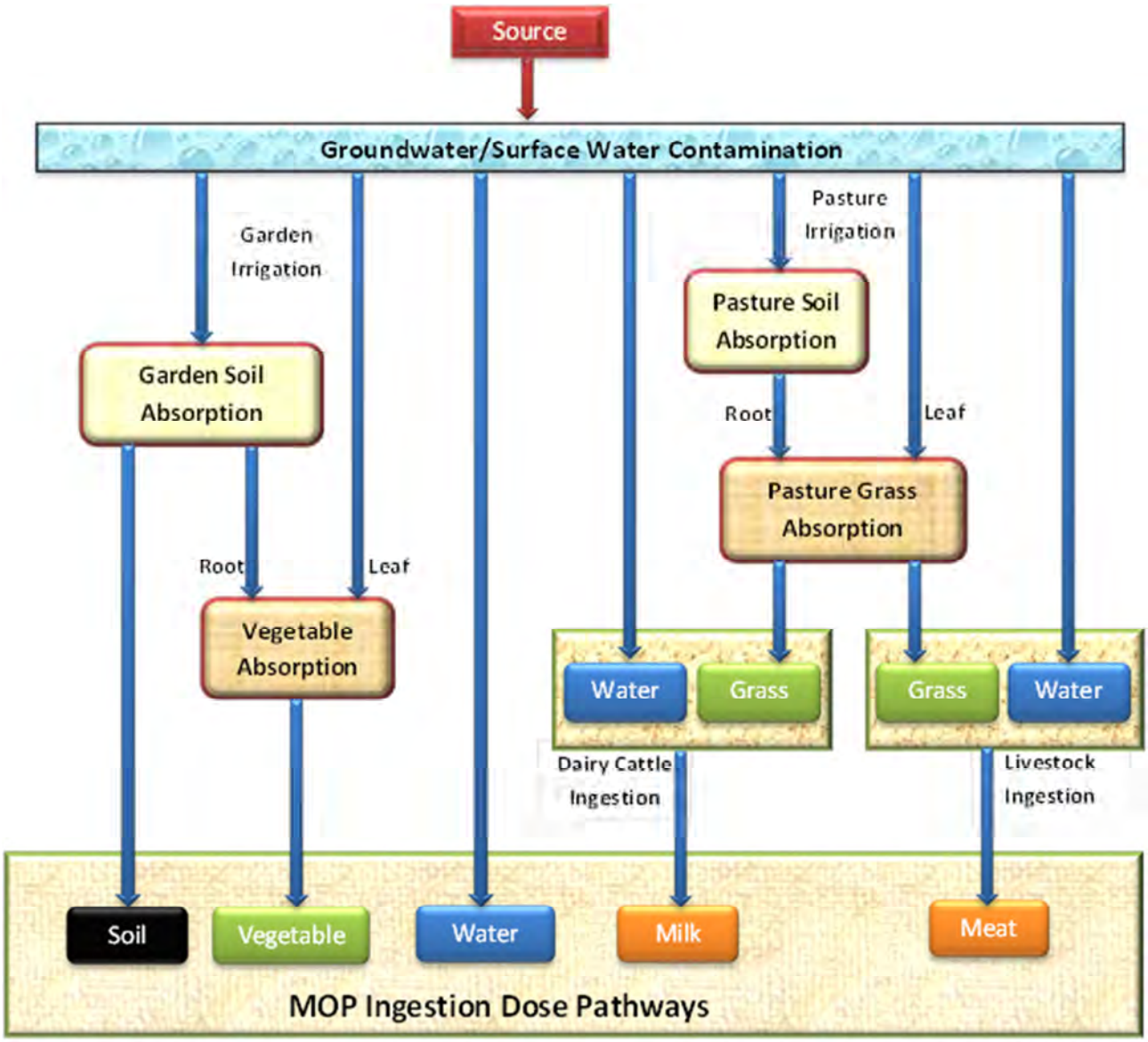

Figure 2-1. Ingestion dose pathways to residential MOP.

2.1 Ingestion Dose Methodology

The general methodology for calculating the ingestion dose to a MOP from a delivery pathway for contamination is the same for any pathway. Effective ingestion dose coefficients are available for 888 radionuclides to convert the radionuclide ingestion over a year of time into an effective annual dose. Radionuclide ingestion is calculated by summing the ingestion from each pathway shown in Figure 2-1. Total ingestion dose to an individual is calculated by summing the doses from individual radionuclides. This calculation can be expressed in equation form as:

$$D_{ing,Total} = \sum_{i=1}^{N} D_{ing,i} = \sum_{i=1}^{N} \left\{ EC_{ing,i} \sum_{j=1}^{J} Ing_{j,i} \right\} \quad (2.1\text{-}1)$$

Where:

$D_{ing,Total}$ ..... Total annual average dose from ingestion of all radionuclides through all pathways (mrem/yr)
$D_{ing,i}$ ..... Annual average dose from ingestion of radionuclide *i* (mrem/yr)
N ..... Number of radionuclides included in the dose calculation
$EC_{ing,i}$ ..... Effective dose coefficient for ingestion of radionuclide *i* (mrem/pCi)
$Ing_{j,i}$ ..... Annual average ingestion of radionuclide *i* through pathway *j* (pCi/yr)
J ..... Number of ingestion pathways included in the dose calculation

Annual average human consumption rates of various food sources are known as a function of factors such as age, gender and geographical region. From this data, food consumption rates for a Typical and Reference Person can be determined for each particular application. The ingestion of radionuclide *i* through pathway *j* is then the product of the concentration of radionuclide in the pathway material and the consumption rate. Applying this to Eq. (2.1-1) gives the basic relationship:

$$D_{ing,Total} = \sum_{i=1}^{N} \left\{ EC_{ing,i} \sum_{j=1}^{J} \left(U_j \, C_{j,i} \right) \right\} \quad (2.1\text{-}2)$$

Where:

U_j ..... Annual average human rate of consumption through ingestion pathway *j* (kg/yr or m^3/yr)
$C_{j,i}$ ..... Concentration of radionuclide *i* in pathway *j* (pCi/kg or pCi/m^3)

Other factors can be introduced into the dose calculation. For example, it may be postulated that only some fraction of the food consumed by individuals (and farm animals) is locally grown contaminated foodstuff. Similarly, it can be assumed that on average, there is a time lag between harvesting the food and human consumption which allows some decay of the radionuclides. More generally, Eq. (2.1-2) would then be written as:

$$D_{ing,Total} = \sum_{i=1}^{N} \left\{ EC_{ing,i} \sum_{j=1}^{J} \left(F_j \, U_j \, C_{j,i} \, e^{-t_{hold,j} \lambda_i} \right) \right\} \quad (2.1\text{-}3)$$

Where:

F_j.....Fraction of contaminated food consumed through pathway *j* (-)
$t_{hold,j}$.....Holdup time between harvesting and consumption through pathway *j* (yr)
λ_i.....Decay constant for radionuclide *i* (1/yr)

In Eq. (2.1-3), the summation over index *j* is over the five human consumption pathways shown in Figure 2-1. The ingestion rate of radionuclide *i* through pathway *j* is:

$$Ing_{j,i} = F_j\, U_j\, C_{j,i}\, e^{-t_{hold,j}\,\lambda_i} \tag{2.1-4}$$

The dose to a MOP from ingestion of radionuclide *i* through pathway *j* can then be calculated as:

$$D_{ing,j,i} = EC_{ing,i}\, Ing_{j,i} \tag{2.1-5}$$

The general terms "food" or material have been used to describe the human ingestion pathways and it is understood that these include inadvertent ingestion of contaminated soil as well as intentional ingestion of foodstuff. To apply Eq. (2.1-3) and determine the dose to an individual from the consumption of contaminated material it is necessary to determine the concentration of contaminant in the material. Before considering the specific consumption pathways, the lumped parameter model of contaminant transport derived in Chapter 1 is first used to calculate radionuclide concentrations in soil and produce. As shown in Figure 2-1, these concentrations are required in several of the ingestion pathways.

2.2 Uptake by Crop Leaf and Root

The development of the lumped parameter transport model in Section 1.1 tried to be somewhat general. However, from here on the development of dose equations is limited to considering radionuclide contamination and the determination of dose to a MOP from the ingestion of radionuclides. Before considering the dose equations in detail, the lumped parameter model is first applied to calculate contaminant concentrations in plants. This is treated separately because it is one of the more complicated aspects of the dose calculations and, as shown in Figure 2-1, is used in multiple pathways. The source of contamination is assumed to be from the use of contaminated water for crop irrigation.

2.2.1 Contaminant Uptake by Crop Leaf

Let the material in Figure 1-1 represent the plant leaves in an irrigated garden or pasture. Contaminated irrigation water flows into this system and some fraction of the water is retained on and absorbed by the plant leaves. Therefore, there is no flow out of the plant system (i.e. water that is not retained simply bypasses the leaf) and no retardation effect applies. Because plant consumption is typically measured by mass and not volume, the production rate in Eq. (1.1-12) is converted to a mass basis by replacing the system volume per unit area (V/A_s) with the crop yield in mass per unit area (kg/m^2). The rate of contaminant addition to irrigated garden or pasture crop leaf is then:

$$S_i = \frac{I_R\, F_r}{Y}\, C_{w,i} \tag{2.2-1}$$

Where:

S_i .....Rate of contaminant *i* addition to crop leaf (pCi/kg-yr)
I_R .....Crop irrigation rate (m/yr)
F_r .....Fraction of irrigation water deposited on leaf that is retained (-)
Y .....Crop yield (kg/m^2)
$C_{w,i}$ .....Concentration of contaminant *i* in water (pCi/m^3)

For leafy vegetables and pasture grass, weathering decay is assumed to occur which removes some of the plant material from the consumption pathway. Weathering is assumed to be a linear decay rate similar to radioactive decay and is added to the rate of radionuclide decay. The decay constant in Eq. (1.1-12) is then:

$$\beta_i \equiv \lambda_e = \lambda_w + \lambda_i \tag{2.2-2}$$

Where:

λ_e .....Weathering and radiological decay constant (1/yr)
λ_w .....Weathering decay constant (1/yr)
λ_i.....Radiological decay constant for species *i* (1/yr)

Inserting Eq. (2.2-1) and (2.2-2) into Eq. (1.1-14) gives an equation for the concentration of radionuclide *i* in the plant leaf as:

$$C_{Leaf,i}(t_{irr}) = R_{Leaf,i}\, C_{w,i} \tag{2.2-3a}$$

$$R_{Leaf,i} \equiv \frac{I_R\, F_r}{\lambda_e\, Y}\left(1 - e^{-\lambda_e\, t_{irr}}\right) \tag{2.2-3b}$$

Where:

$C_{Leaf,i}$ .....Concentration of radionuclide *i* in plant leaf (pCi/kg)
$R_{Leaf,i}$.....Retention of contaminated water in plant leaf for species *i* (m^3/kg)
t_{irr} .....Time crop is exposed to irrigation (yr)

The irrigation rate used above is not an annual average value but is the actual rate of water addition to the plants while irrigation is taking place. The fraction of time the soil is irrigated is not included in Eq. (2.2-1) when calculating radionuclide accumulation in the leaves. The irrigation time is accounted for in Eq. (2.2-3) by integrating the contaminant concentration over the time of irrigation.

The above derivation has been kept general and as shown in Figure 2-1, both human consumption of garden produce and the consumption by farm animals of fodder from grass grown in a pasture must be considered. Specific parameters such as irrigation rate, irrigation time and crop yield may be different for the two agricultural settings. Therefore it is necessary to distinguish between the two types of crops and the notation can become cumbersome. Nevertheless, for convenience, separate equations are written for garden and pasture crop leaf contamination using the subscripts *g* and *p* to indicate garden produce and pasture grass, respectively.

For garden produce leaf:

$$C_{Leaf,g,i}(t_{irr,g}) = R_{Leaf,g,i}\, C_{w,i} \tag{2.2-4a}$$

$$R_{Leaf,g,i} \equiv \frac{I_{R,g}\, F_r}{\lambda_e\, Y_g}\left(1 - e^{-\lambda_e\, t_{irr,g}}\right) \tag{2.2-4b}$$

For pasture grass leaf:

$$C_{Leaf,p,i}(t_{irr,p}) = R_{Leaf,p,i}\, C_{w,i} \tag{2.2-5a}$$

$$R_{Leaf,p,i} \equiv \frac{I_{R,p}\, F_r}{\lambda_e\, Y_p}\left(1 - e^{-\lambda_e\, t_{irr,p}}\right) \tag{2.2-5b}$$

The only difference between the two equations is the use of individual irrigation rates ($I_{R,g}$ and $I_{R,p}$), irrigation times ($t_{irr,g}$ and $t_{irr,p}$), and crop yields (Y_g and Y_p).

2.2.2 Contaminant Uptake by Crop Root

Plants also absorb contaminants through their root systems. To evaluate this case, let the material shown in Figure 1-1 represent the soil layer in an irrigated vegetable garden or pasture where the root system is present. The volume occupied by the roots themselves is neglected. In this case, contaminated irrigation water flows through the soil along with water from precipitation reduced by loss to evaporation. The flux of contaminated water into the system from irrigation is:

$$\theta_w\, \dot{q}_{in} = F_R\, I_R \tag{2.2-6a}$$

While the net flux of water out of the system is:

$$\theta_w\, \dot{q}_{out} = F_R\, I_R + P - E \tag{2.2-6b}$$

Where:

F_R .....Fraction of time soil is irrigated (-)
P .....Annual average precipitation rate (m/yr)
E .....Annual average evapotranspiration rate (m/yr)

Root uptake takes place over a longer time period than the irrigation time. Therefore, in contrast to the leaf where contaminant accumulation only occurs during irrigation, the annual average irrigation rate is used in the calculation of root contaminant concentration. The terms defined in Eq. (1.1-12) can then be written as:

$$\beta_i \equiv \lambda_{B,i} = \lambda_i + \lambda_{L,i} \quad \text{and} \quad S_i = \lambda_{R,i}\, C_{w,i} \tag{2.2-7}$$

From the definition given in Eq. (1.1-12), the time constants in Eq. (2.2-7) are:

$$\lambda_{L,i} = \frac{F_R\, I_R + P - E}{R_i\, \theta_w\, d_t} \quad \text{and} \quad \lambda_{R,i} = \frac{F_R\, I_R}{R_i\, \theta_w\, d_t} \tag{2.2-8}$$

Where:

$\lambda_{L,i}$ .....Time constant for leaching of contaminant *i* from irrigated soil (1/yr)
$\lambda_{R,i}$ .....Time constant for retention of contaminant *i* in irrigated soil (1/yr)
d_t .....Depth of tilling (V/A_s) for gardening or agriculture (m)

Inserting the results derived above into Eq. (1.1-14) gives the following expression for contamination in agricultural soil water:

$$C_{sw,i}(t_b) = \frac{\lambda_{R,i}}{\lambda_{B,i}} \left(1 - e^{-\lambda_{B,i}\, t_b}\right) C_{w,i} \tag{2.2-9}$$

Where:

$C_{sw,i}$ .....Concentration of contaminant *i* in soil water (pCi/m^3)
t_b .....Characteristic time for radionuclide buildup in the soil (yr)

The time constant $\lambda_{B,i}$ that appears in Eq. (2.2-9) is defined in Eq. (2.2-7) and represents the combined effects of radionuclide decay and leaching to remove material from the soil. The subscript *B* originated from the association with the β_i parameter and should not be confused with "buildup" of material in the soil.

Soil water represents the moisture located in the root zone as distinguished from the water used for irrigation. The concentration of radionuclide *i* in soil water, $C_{sw,i}$, is different from that in water, $C_{w,i}$, used in irrigation based on soil-water partitioning and flux of contaminants into and out of the root zone as described above. From Eq. (1.1-4), the corresponding concentration in the soil (pCi/kg) is:

$$C_{s,i}(t_b) = K_{d,i} \frac{\lambda_{R,i}}{\lambda_{B,i}} \left(1 - e^{-\lambda_{B,i}\, t_b}\right) C_{w,i} = R_{Soil,i}\, C_{w,i} \tag{2.2-10a}$$

$$R_{Soil,i} \equiv K_{d,i} \frac{\lambda_{R,i}}{\lambda_{B,i}} \left(1 - e^{-\lambda_{B,i}\, t_b}\right) \tag{2.2-10b}$$

Where:

$R_{Soil,i}$ .....Retention of contaminated water in soil for species *i* (m^3/kg)

Radionuclide buildup in the soil is typically assumed to occur over a period of many years. While the radionuclide buildup occurs over several years, the model accounts for leaching of radionuclides from the soil which will, in particular, reduce the concentration of the more mobile species.

Bio-transfer factors have been compiled that relate contaminant concentrations measured in dry agricultural soils to the corresponding concentrations measured in plants. Therefore, the soil concentration is related to the root uptake by multiplying by the soil to plant bio-transfer factor. In equation form:

$$C_{Root,i}(t_b) = T_{StoV,i}\, C_{s,i}(t_b) = R_{Root,i}\, C_{w,i} \tag{2.2-11a}$$

$$R_{Root,i} \equiv T_{StoV,i}\, R_{Soil,i} = T_{StoV,i}\, K_{d,i}\, \frac{\lambda_{R,i}}{\lambda_{B,i}} \left(1 - e^{-\lambda_{B,i}\, t_b}\right) \quad (2.2\text{-}11b)$$

Where:

$T_{StoV,i}$ ..... Bio-transfer factor equal to the ratio of the concentration of contaminant *i* in dry soil to the concentration in the vegetation (-)

$R_{Root,i}$ ..... Retention of contaminated water in plant through root uptake for species *i* (m^3/kg)

Bio-transfer factors are given for elements so isotopes of the same element would have the same transfer factor.

The above derivation has been kept general and specific factors such as irrigation rate and irrigation time may be different for a garden or a pasture. As with leaf uptake, it is convenient for later use to write separate equations for the two types of crops. It is assumed that soil in the garden and pasture are the same material. Then the only difference between the two agriculture locations is the irrigation rate and irrigation time which occur in the time constants defined in Eq. (2.2-8). Therefore, the following equations apply.

For garden produce roots:

$$C_{Root,g,i}(t_b) = T_{StoV,i}\, R_{Soil,g,i}\, C_{gw,i} = R_{Root,g,i}\, C_{w,i} \quad (2.2\text{-}12a)$$

$$R_{Root,g,i} \equiv T_{StoV,i}\, R_{Soil,g,i} = T_{StoV,i}\, K_{d,i}\, \frac{\lambda_{R,g,i}}{\lambda_{B,g,i}} \left(1 - e^{-\lambda_{B,g,i}\, t_b}\right) \quad (2.2\text{-}12b)$$

Time constants in Eq. (2.2-12b) are:

$$\lambda_{B,g,i} = \lambda_i + \frac{F_{R,g}\, I_{R,g} + P - E}{R_i\, \theta_w\, d_t} \quad \text{and} \quad \lambda_{R,g,i} = \frac{F_{R,g}\, I_{R,g}}{R_i\, \theta_w\, d_t} \quad (2.2\text{-}12c)$$

For pasture grass roots:

$$C_{Root,p,i}(t_b) = T_{StoV,i}\, R_{Soil,p,i}\, C_{gw,i} = R_{Root,p,i}\, C_{w,i} \quad (2.2\text{-}13a)$$

$$R_{Root,p,i} \equiv T_{StoV,i}\, R_{Soil,p,i} = T_{StoV,i}\, K_{d,i}\, \frac{\lambda_{R,p,i}}{\lambda_{B,p,i}} \left(1 - e^{-\lambda_{B,p,i}\, t_b}\right) \quad (2.2\text{-}13b)$$

Time constants in Eq. (2.2-13b) are:

$$\lambda_{B,p,i} = \lambda_i + \frac{F_{R,p}\, I_{R,p} + P - E}{R_i\, \theta_w\, d_t} \quad \text{and} \quad \lambda_{R,p,i} = \frac{F_{R,p}\, I_{R,p}}{R_i\, \theta_w\, d_t} \quad (2.2\text{-}13c)$$

2.3 Human Uptake through Ingestion

Using the equations derived in the previous section, equations to calculate human uptake of contamination can be developed in a relatively straight forward manner for each ingestion pathway.

2.3.1 Ingestion of Water

Ingestion of water through drinking is the only exposure pathway directly from the contaminated groundwater or surface water to human use. Applying Eq. (2.1-4), uptake of radionuclide *i* by a MOP through the ingestion of contaminated water is calculated as:

$$Ing_{w,i} = F_w\ U_w\ C_{w,i}\ e^{-t_{hold,w}\,\lambda_i} \tag{2.3-1}$$

Where:

$Ing_{w,i}$ ..... Uptake of radionuclide *i* by MOP through the consumption of contaminated drinking water (pCi/yr)
F_w ..... Fraction of drinking water obtained from local contaminated water (-)
U_w ..... Human consumption rate of drinking water (m^3/yr)
$C_{w,i}$ ..... Concentration of radionuclide *i* in drinking water (pCi/m^3)
$t_{hold,w}$ ..... Holdup time between obtaining contaminated water and ingestion (yr)
λ_i ..... Decay constant for radionuclide *i* (1/yr)

It would typically be assumed that there is no holdup time for drinking water.

2.3.2 Ingestion of Produce

The radionuclide uptake by a MOP from the ingestion of contaminated produce (including leafy and non-leafy vegetables) is calculated assuming two pathways for plant contamination: (1) direct deposition of contaminated irrigation water on plant leaves and (2) root uptake of contaminated irrigation water from the soil. Applying Eq. (2.1-4), uptake of radionuclide *i* by a MOP through the ingestion of contaminated garden produce is calculated as:

$$Ing_{g,i} = F_g\ U_g\ C_{g,i}\ e^{-t_{hold,g}\,\lambda_i} \tag{2.3-2}$$

Where:

$Ing_{g,i}$ ..... Uptake of radionuclide *i* by MOP through the consumption of contaminated garden produce (pCi/yr)
F_g ..... Fraction of produce obtained from a local garden irrigated using contaminated water (-)
U_g ..... Human consumption rate of garden produce (kg/yr)
$C_{g,i}$ ..... Concentration of radionuclide *i* in irrigated garden produce (pCi/kg)
$t_{hold,g}$ ..... Holdup time between harvesting produce and ingestion (yr)

Using Eq. (2.2-4) and Eq. (2.2-12), the total concentration of radionuclide *i* in irrigated garden produce is:

$$C_{g,i} = C_{Leaf,g,i}(t_{irr,g}) + C_{Root,g,i}(t_b) = (F_L\, F_W\, R_{Leaf,g,i} + R_{Root,g,i})C_{w,i} \quad (2.3\text{-}3)$$

Two additional fractions in Eq. (2.3-3) are:

F_L .....Fraction of produce that is leafy (-)
F_W .....Fraction of contamination retained on leaf after washing (-)

The fraction F_W is included on the assumption that leafy vegetables are typically washed before human consumption and that this washing removes some of the contamination disregarding the fact that the wash water would itself be contaminated.

Combining Eq. (2.3-3) with Eq. (2.3-2) gives:

$$Ing_{g,i} = F_g\, U_g\, (F_L\, F_W\, R_{Leaf,g,i} + R_{Root,g,i})\, C_{w,i}\, e^{-t_{hold,g}\,\lambda_i} \quad (2.3\text{-}4)$$

The dose calculation methodology employed in DOE 435.1 PA's for the all-pathways performance objective is based in part on prior standards developed in the NRC Regulatory Guide 1.109 (NRC, 1977). A comparison of the vegetable dose equation derived above with the equivalent equation in NRC Reg. Guide 1.109 is provided in Appendix A.

2.3.3 Ingestion of Dust

While working in a garden, a MOP will inadvertently consume some small quantity of airborne contaminated garden soil. Applying Eq. (2.1-4), uptake of radionuclide *i* by a MOP through the ingestion of contaminated soil is calculated as:

$$Ing_{s,i} = F_s\, U_s\, C_{s,i}\, e^{-t_{hold,s}\,\lambda_i} \quad (2.3\text{-}5)$$

Where:

$Ing_{s,i}$ .....Uptake of radionuclide *i* by MOP through the inadvertent ingestion of contaminated soil (pCi/yr)
F_s.....Fraction of ingested soil from garden, fraction of year spent in garden (-)
U_s.....Human inadvertent ingestion rate of soil (kg/yr)
$C_{s,i}$ .....Concentration of radionuclide *i* in irrigated soil (pCi/kg)
$t_{hold,s}$.....Holdup time between exposure to contaminated soil and ingestion (yr)

The holdup time for soil ingestion while working in an irrigated garden would be zero but this factor is included in the soil dose equation to make it consistent with the other dose equations. Equation (2.2-10) provides an expression for the concentration of contaminant species in irrigated soil. Applying this to garden soil, as was done in deriving Eq. (2.2-12), gives:

$$Ing_{s,i} = F_s\, U_s\, R_{Soil,g,i}\, C_{w,i}\, e^{-t_{hold,s}\,\lambda_i} \quad (2.3\text{-}6)$$

$$R_{Soil,g,i} \equiv K_{d,i}\, \frac{\lambda_{R,g,i}}{\lambda_{B,g,i}}\, (1 - e^{-\lambda_{B,g,i}\, t_b}) \quad (2.3\text{-}7)$$

Where:

$R_{Soil,g,i}$ ..... Retention of contaminated water in garden soil root zone for species *i* (m^3/kg)
$\lambda_{R,g,i}$ ..... Time constant for retention of radionuclide *i* in garden soil (1/yr)
$\lambda_{B,g,i}$ ..... Time constant for removal of radionuclide *i* from garden soil (1/yr)

2.3.4 Ingestion of Milk

Applying Eq. (2.1-4), the uptake of radionuclide *i* by a MOP through the ingestion of contaminated milk is calculated as:

$$Ing_{milk,i} = F_{milk}\, U_{milk}\, C_{milk,i}\, e^{-t_{hold,milk}\,\lambda_i} \tag{2.3-8}$$

Where:

$Ing_{milk,i}$ ..... Uptake of radionuclide *i* by MOP through the consumption of milk from dairy cattle that have consumed contaminated water (pCi/yr)
F_{milk} ..... Fraction of milk obtained from dairy cattle using local contaminated water (-)
U_{milk} ..... Human consumption rate of milk (m^3/yr)
$C_{milk,i}$ ..... Concentration of radionuclide *i* in milk (pCi/m^3)
$t_{hold,milk}$ ..... Holdup time between obtaining contaminated milk and human ingestion (yr)

As shown below in Section 2.3.4.3, element specific bio-transfer factors are available that relate the rate of contaminant consumption by dairy cattle to the concentration in milk. Therefore, the calculation of the dose to humans from ingestion of milk reduces to determining the ingestion rate of contaminant by dairy cattle from drinking contaminated water and consuming plants irrigated with contaminated water. These calculations are analogous to those performed above for human consumption.

2.3.4.1 Ingestion of Water by Dairy Cattle

Water ingestion by dairy cattle is analogous to water ingestion by humans except for a different rate of consumption. Applying Eq. (2.1-4), uptake of radionuclide *i* by dairy cattle through the ingestion of contaminated water is calculated as:

$$Ing_{w,milk,i} = F_{w,milk}\, Q_{w,milk}\, C_{w,i}\, e^{-t_{hold,milk,w}\,\lambda_i} \tag{2.3-9}$$

Where:

$Ing_{w,milk,i}$ ..... Uptake of radionuclide *i* by dairy cattle through the consumption of contaminated drinking water (pCi/yr)
$F_{w,milk}$ ..... Fraction of dairy cattle drinking water from local contaminated water (-)
$Q_{w,milk}$ ..... Dairy cattle consumption rate of drinking water (m^3/yr)
$C_{w,i}$ ..... Concentration of radionuclide *i* in drinking water (pCi/m^3)
$t_{hold,milk,w}$ ..... Holdup time between obtaining contaminated water and ingestion by dairy cattle (yr)

It would typically be assumed that there is no holdup time for dairy cattle drinking contaminated water.

2.3.4.2 Ingestion of Fodder by Dairy Cattle

The radionuclide uptake by dairy cattle from ingestion of contaminated feed (pasture grass or stored fodder) is calculated assuming two pathways for plant contamination: (1) direct deposition of contaminated irrigation water on plant leaves and (2) root uptake of contaminated irrigation water in the soil. The analysis also considers that for some part of the year the dairy cattle graze on pasture grass while for the remainder of the year the cattle consume stored fodder harvested from the pasture. The difference between the two feedings is that fodder storage allows some time for radionuclide decay. Introducing these factors into Eq. (2.1-4), the uptake of radionuclide *i* by dairy cattle through the ingestion of contaminated pasture grass is calculated as:

$$Ing_{p,milk,i} = F_{p,milk}\, Q_{p,milk} \left[F_{on,milk} + \left(1 - F_{on,milk}\right) e^{-t_{hold,fod}\,\lambda_i}\right] C_{p,i} \tag{2.3-10}$$

Where:

$Ing_{p,milk,i}$ ..... Uptake of radionuclide *i* by dairy cattle through the consumption of contaminated feed (pCi/yr)
$F_{p,milk}$ ..... Fraction of dairy cattle feed from local pasture irrigated using contaminated water (-)
$F_{on,milk}$ ..... Fraction of year dairy cattle graze on pasture (-)
$Q_{p,milk}$ ..... Dairy cattle consumption rate of fodder (kg/yr)
$C_{p,i}$ ..... Concentration of radionuclide *i* in fodder (pCi/kg)
$t_{hold,fod}$ ..... Holdup time between harvesting fodder and dairy cattle ingestion (yr)

Using Eq. (2.2-5) and Eq. (2.2-13), the total concentration of radionuclide *i* in the fodder is:

$$C_{p,i} = C_{Leaf,p,i}\left(t_{irr,p}\right) + C_{Root,p,i}(t_b) = \left(R_{Leaf,p,i} + R_{Root,p,i}\right) C_{w,i} \tag{2.3-11}$$

Equation (2.3-11) assumes that dairy cattle eat only grassy plants and that the plants are not washed. Combining Eq. (2.3-10) and Eq. (2.3-11) gives:

$$\begin{aligned} Ing_{p,milk,i} = {} & F_{p,milk}\, Q_{p,milk}\left(R_{Leaf,p,i} + R_{Root,p,i}\right)\left[F_{on,milk}\right. \\ & \left. + \left(1 - F_{on,milk}\right) e^{-t_{hold,fod}\,\lambda_i}\right] C_{w,i} \end{aligned} \tag{2.3-12}$$

2.3.4.3 Contaminant Concentration in Milk

Equations (2.3-9) and (2.3-12) can be combined to obtain the total ingestion rate of contaminant radionuclides by dairy cattle (pCi/yr) as:

$$\begin{aligned} Ing_{Total,milk,i} = {} & \left\{F_{w,milk}\, Q_{w,milk}\right. \\ & + F_{p,milk}\, Q_{p,milk}\left(R_{Leaf,p,i} + R_{Root,p,i}\right)\left[F_{on,milk}\right. \\ & \left.\left. + \left(1 - F_{on,milk}\right) e^{-t_{hold,fod}\,\lambda_i}\right]\right\} C_{w,i} \end{aligned} \tag{2.3-13}$$

To simplify Eq. (2.3-13), it has been assumed that there is no holdup time for water consumption by dairy cattle. Finally, the bio-transfer factor from feed to milk is applied to calculate the concentration of radionuclide *i* in milk (pCi/m^3) which is used in Eq. (2.3-8):

$$C_{milk,i} = T_{FtoMilk,i}\, Ing_{Total,milk,i} \tag{2.3-14}$$

Where:

$T_{FtoMilk,i}$ ..... Bio-transfer factor relating consumption of radionuclide *i* by dairy cattle to the concentration in milk (yr/m^3)

Bio-transfer factors are given for elements so isotopes of the same element would have the same transfer factor.

2.3.5 Ingestion of Meat

Applying Eq. (2.1-4), uptake of radionuclide *i* by a MOP through the ingestion of contaminated meat is calculated as:

$$Ing_{meat,i} = F_{meat}\, U_{meat}\, C_{meat,i}\, e^{-t_{hold,meat}\,\lambda_i} \tag{2.3-15}$$

Where:

$Ing_{meat,i}$ ..... Uptake of radionuclide *i* by MOP through the consumption of meat from livestock that have consumed contaminated water (pCi/yr)
F_{meat} ..... Fraction of meat obtained from livestock using local contaminated water (-)
U_{meat} ..... Human consumption of meat (kg/yr)
$C_{meat,i}$ ..... Concentration of radionuclide *i* in meat (pCi/kg)
$t_{hold,meat}$ ..... Holdup time between obtaining contaminated meat and human ingestion (yr)

As shown below in Section 2.3.5.3, element specific bio-transfer factors have been published that relate the rate of contaminant consumption by livestock to the concentration in meat. Then, as for dairy cattle, the calculation of the dose to humans from ingestion of meat reduces to determining the ingestion rate of contaminant by livestock from drinking contaminated water and consuming plants irrigated with contaminated water. These calculations are exactly analogous to those performed in the previous section for dairy cattle.

2.3.5.1 Ingestion of Water by Livestock

Water ingestion by livestock is analogous to water ingestion by humans and dairy cattle except for a different rate of consumption. Applying Eq. (2.1-4), uptake of radionuclide *i* by meat producing animals through the ingestion of contaminated water is calculated as:

$$Ing_{w,meat,i} = F_{w,meat}\, Q_{w,meat}\, C_{w,i}\, e^{-t_{hold,meat,w}\,\lambda_i} \tag{2.3-16}$$

Where:

$Ing_{w,meat,i}$ ..... Uptake of radionuclide *i* by livestock through the consumption of contaminated drinking water (pCi/yr)
$F_{w,meat}$ ..... Fraction of livestock drinking water from local contaminated water (-)
$Q_{w,meat}$ ..... Livestock rate of drinking water consumption (m^3/yr)
$C_{w,i}$ ..... Concentration of radionuclide *i* in drinking water (pCi/m^3)
$t_{hold,meat,w}$ ..... Holdup time between obtaining contaminated water and livestock ingestion (yr)

It would typically be assumed that there is no holdup time for livestock drinking contaminated water.

2.3.5.2 Ingestion of Fodder by Livestock

The radionuclide uptake by livestock from ingestion of contaminated feed (pasture grass or stored fodder) is calculated assuming two pathways for plant contamination: (1) direct deposition of contaminated irrigation water on plant leaves and (2) root uptake of contaminated irrigation water in the soil. The analysis also considers that for some part of the year the livestock graze on pasture grass while for the remainder of the year the livestock consume stored fodder harvested from the pasture. The difference between the two feedings is that fodder storage allows some time for radionuclide decay. Introducing these factors into Eq. (2.1-4), the uptake of radionuclide *i* by livestock through the ingestion of contaminated pasture grass is calculated as:

$$Ing_{p,meat,i} = F_{p,meat}\, Q_{p,meat} \left[F_{on,meat} + \left(1 - F_{on,meat}\right) e^{-t_{hold,fod}\,\lambda_i}\right] C_{p,i} \qquad (2.3\text{-}17)$$

Where:

$Ing_{p,meat,i}$ ..... Uptake of radionuclide *i* by livestock through the consumption of contaminated fodder (pCi/yr)
$F_{p,meat}$ ..... Fraction of livestock feed from local pasture irrigated using contaminated water (-)
$F_{on,meat}$ ..... Fraction of year livestock graze on pasture (-)
$Q_{p,meat}$ ..... Livestock consumption rate of fodder (kg/yr)
$C_{p,i}$ ..... Concentration of radionuclide *i* in fodder (pCi/kg)
$t_{hold,fod}$ ..... Holdup time between fodder harvest and livestock ingestion (yr)

It is assumed that a resident farmer uses the same pasture to graze dairy cattle and livestock. Therefore, Eq. (2.3-11) applies for livestock as well as dairy cattle:

$$C_{p,i} = C_{Leaf,p,i}\left(t_{irr,p}\right) + C_{Root,p,i}(t_b) = \left(R_{Leaf,p,i} + R_{Root,p,i}\right) C_{w,i} \qquad (2.3\text{-}11)$$

Combining Eq. (2.3-11) with Eq. (2.3-17) gives:

$$Ing_{p,meat,i} = F_{p,meat}\, Q_{p,meat} \left(R_{Leaf,p,i} + R_{Root,p,i}\right)\left[F_{on,meat} + \left(1 - F_{on,meat}\right) e^{-t_{hold,fod}\,\lambda_i}\right] C_{w,i} \qquad (2.3\text{-}18)$$

2.3.5.3 Contaminant Concentration in Meat

Equations (2.3-16) and (2.3-18) can be combined to obtain the total ingestion rate of contaminant radionuclides by livestock (pCi/yr) as:

$$Ing_{Total,meat,i} = \{F_{w,meat}\, Q_{w,meat} + F_{p,meat}\, Q_{p,meat}\, (R_{Leaf,p,i} + R_{Root,p,i})\, [F_{on,meat} + (1 - F_{on,meat})\, e^{-t_{hold,fod}\,\lambda_i}]\}\, C_{w,i} \quad (2.3\text{-}19)$$

To simplify Eq. (2.3-19), it is again assumed that there is no holdup time for water consumption by livestock. Finally, the bio-transfer factor from feed to meat is applied to calculate the concentration of radionuclide *i* in meat (pCi/kg) which is used in Eq. (2.3-15):

$$C_{meat,i} = T_{FtoMeat,i}\, Ing_{Total,meat,i} \quad (2.3\text{-}20)$$

Where:

$T_{FtoMeat,i}$ ..... Bio-transfer factor relating consumption of radionuclide *i* by livestock to the concentration in meat (yr/kg)

Bio-transfer factors are given for elements so isotopes of the same element would have the same transfer factor.

2.4 Ingestion Dose Equation Summary

Applying Eq. (1.2-1) to summarize the ingestion dose equations with dose coefficient $EC_{ing,i}$ (mrem/pCi) and water source concentration $C_{w,i}$ (pCi/m^3) gives the results shown in Eq. (2.4-1) and Table 2-1. The ingestion dose equations for each pathway can all be written in the general form:

$$D_{ing,j,i} = EC_{ing,i}\, \{F_j\, U_j\, T_{j,i}\, R_{j,i}\, e^{-t_{hold,j}\,\lambda_i}\}\, C_{w,i} \quad (2.4\text{-}1)$$

Where:

$D_{ing,j,i}$ ..... Annual average dose from ingestion of radionuclide *i* through ingestion pathway *j* (mrem/yr)
i ..... Radionuclide index
j ..... Ingestion pathway index
F_j ..... Fraction of consumption from contaminated source through ingestion pathway *j* (-)
U_j ..... Human consumption rate (kg/yr, m^3/yr)
$T_{j,i}$ ..... Bio-transfer factor (yr/m^3, yr/kg, m^3/kg)
$R_{j,i}$ ..... Retention factor for radionuclide *i* in ingestion pathway *j* (m^3/kg, m^3/yr)
$t_{hold,j}$ ..... Holdup time (yr)

The term in brackets in Eq. (2.4-1) is the exposure term shown in Table 2-1 for each of the five ingestion dose pathways.

Table 2-1. Summary of Ingestion Dose Equations.

Ingestion Pathway	Exposure	Units
Water	$F_w\ U_w\ e^{-t_{hold,w}\,\lambda_i}$	m^3/yr
Garden Produce	$F_g\ U_g\ R_{g,i}\ e^{-t_{hold,g}\,\lambda_i}$	m^3/yr
	$R_{g,i} = F_L\ F_W\ R_{Leaf,g,i} + R_{Root,g,i}$	m^3/kg
	$R_{Leaf,g,i} = \frac{I_{R,g}\ F_r}{\lambda_e\ Y_g}\left(1 - e^{-\lambda_e\ t_{irr.g}}\right)$	m^3/kg
	$R_{Root,g,i} = T_{StoV,i}\ K_{d,i}\ \frac{\lambda_{R,g,i}}{\lambda_{B,g,i}}\left(1 - e^{-\lambda_{B,g,i}\ t_b}\right)$	m^3/kg
	$\lambda_{B,g,i} = \lambda_i + \left(F_{R,g}\ I_{R,g} + P - E\right)/(R_i\ \theta_w\ d_t)$	1/yr
	$\lambda_{R,g,i} = \left(F_{R,g}\ I_{R,g}\right)/(R_i\ \theta_w\ d_t)$	1/yr
	$\lambda_e = \lambda_w + \lambda_i$	1/yr
	$R_i = 1 + \rho_s\ K_{d,i}/\theta_w$	-
Garden Soil	$F_s\ U_s\ R_{Soil,g,i}\ e^{-t_{hold,s}\,\lambda_i}$	m^3/yr
	$R_{Soil,g,i} = K_{d,i}\ \frac{\lambda_{R,g,i}}{\lambda_{B,g,i}}\left(1 - e^{-\lambda_{B,g,i}\ t_b}\right)$	m^3/kg
Milk	$F_{milk}\ U_{milk}\ T_{FtoMilk,i}\ R_{Milk,i}\ e^{-t_{hold,milk}\,\lambda_i}$	m^3/yr
	$R_{Milk,i} = F_{w,milk}\ Q_{w,milk} + F_{p,milk}\ Q_{p,milk}\left(R_{Leaf,p,i} + R_{Root,p,i}\right)\left[F_{on,milk} + \left(1 - F_{on,milk}\right)e^{-t_{hold,fod}\,\lambda_i}\right]$	m^3/yr
	$R_{Leaf,p,i} = \frac{I_{R,p}\ F_r}{\lambda_e\ Y_p}\left(1 - e^{-\lambda_e\ t_{irr.p}}\right)$	m^3/kg
	$R_{Root,p,i} = T_{StoV,i}\ K_{d,i}\ \frac{\lambda_{R,p,i}}{\lambda_{B,p,i}}\left(1 - e^{-\lambda_{B,p,i}\ t_b}\right)$	m^3/kg
	$\lambda_{B,p,i} = \lambda_i + \left(F_{R,p}\ I_{R,p} + P - E\right)/(R_i\ \theta_w\ d_t)$	1/yr
	$\lambda_{R,p,i} = \left(F_{R,p}\ I_{R,p}\right)/(R_i\ \theta_w\ d_t)$	1/yr
Meat	$F_{meat}\ U_{meat}\ T_{FtoMeat,i}\ R_{Meat,i}\ e^{-t_{hold,meat}\,\lambda_i}$	m^3/yr
	$R_{Meat,i} = F_{w,meat}\ Q_{w,meat} + F_{p,meat}\ Q_{p,meat}\left(R_{Leaf,p,i} + R_{Root,p,i}\right)\left[F_{on,meat} + \left(1 - F_{on,meat}\right)e^{-t_{hold,fod}\,\lambda_i}\right]$	m^3/kg

Table 2-2 demonstrates that the ingestion dose equations are dimensionally consistent. For ingestion of water, leafy vegetables, and soil, the equivalent bio-transfer factors in Eq. (2.4-1) are one because the contamination is directly consumed. The factor $R_{j,i}$ determines the amount of contaminated water retained in the ingestion pathway. The retention factor for water ingestion is one.

Table 2-2. Dimensions of Terms in Ingestion Dose Equations.

Pathway	Water	Produce	Soil	Milk	Meat
U_j	m^3/yr	kg/yr	kg/yr	m^3/yr	kg/yr
$T_{j,i}$	1	1	1	yr/m^3	yr/kg
$R_{j,i}$	1	m^3/kg	m^3/kg	m^3/yr	m^3/yr
$U_j\ T_{j,i}\ R_{j,i}$	m^3/yr	m^3/yr	m^3/yr	m^3/yr	m^3/yr

2.5 Ingestion Dose Parameters

The development in the preceding sections has introduced a large number of parameters into the dose calculations which must be specified. For immediate reference, values for these parameters are tabulated below in Tables 2-3 through 2-7. Calculation parameters that depend on the radionuclide or element such as half-lives or bio-transfer factors are not listed in this report but are provided in the companion Excel database as described in Chapter 10. The dose parameters listed in Tables 2-3 through 2-7 are also included in the database along with references. The hierarchy of references used to obtain the dose parameter values is given in Figure 10-15 where the database is discussed.

Table 2-3. Human Consumption Parameters.

Parameter	Description	Typical Person	Reference Person	Units
U_w	Consumption of drinking water	0.3	0.8	m^3/yr
U_g	Consumption of garden produce	100	320	kg/yr
U_s	Inadvertent consumption of soil	0.0365 (100 mg/d)		kg/yr
U_{milk}	Consumption of milk	0.069	0.260	m^3/yr
U_{meat}	Consumption of meat	32	81	kg/yr
F_s	Fraction of year spent in garden	0.01		-
F_w	Fraction of drinking water that is contaminated	1		-
F_g	Fraction of produce from local garden	0.308	1	-
F_{milk}	Fraction of milk from local source	0.254	1	-
F_{meat}	Fraction of meat from local source	0.319	1	-
$t_{hold,g}$	Time from harvesting produce to consumption	0.0164 (6 d/yr)	0.0027 (1 d/yr)	yr
$t_{hold,w}$	Time from obtaining water to consumption	0		yr
$t_{hold,s}$	Time from exposure to garden dust to consumption	0		yr
$t_{hold,milk}$	Time from obtaining milk to consumption	0.0082 (3d/yr)		yr
$t_{hold,meat}$	Time from obtaining meat to consumption	0.0164 (6 d/yr)		yr

Table 2-4. Animal Consumption Parameters.

Parameter	Description	Nominal Value	Units
$Q_{w,milk}$	Consumption of water by dairy cattle	18.263	m^3/yr
$Q_{p,milk}$	Consumption of fodder by dairy cattle	18,993	kg/yr
$Q_{w,meat}$	Consumption of water by livestock	10.227	m^3/yr
$Q_{p,meat}$	Consumption of fodder by livestock	13,149	kg/yr
$F_{w,milk}$	Fraction of water from local well consumed by dairy cattle	1	-
$F_{p,milk}$	Fraction of fodder from pasture irrigated with local well water consumed by dairy cattle	0.56	-
$F_{on,milk}$	Fraction of time dairy cattle graze on pasture	1	-
$F_{w,meat}$	Fraction of water from local well consumed by livestock	1	-
$F_{p,meat}$	Fraction of fodder from pasture irrigated with local well water consumed by livestock	0.75	-
$F_{on,meat}$	Fraction of time livestock graze on pasture	1	-
$t_{hold,milk,w}$	Time between watering and consumption by dairy cattle	0	yr
$t_{hold,meat,w}$	Time between watering and consumption by livestock	0	yr
$t_{hold,fod}$	Time between harvesting fodder and consumption by dairy cattle and livestock	0.246 (90 d/yr)	yr

Table 2-5. Other Ingestion Dose Parameters.

Parameter	Description	Nominal Value	Units
F_r	Fractional retention of irrigation water on leaf surface	0.25	-
F_L	Fraction of produce that is leafy vegetables	0.23	-
F_W	Fractional retention of contaminant on leaf after washing	0.50	-
$F_{R,g}$	Fraction of year garden is irrigated	0.192 (70 d/yr)	-
$F_{R,p}$	Fraction of year pasture is irrigated	0.082 (30 d/yr)	-

Table 2-6. Physical Ingestion Dose Parameters.

Parameter	Description	Nominal Value	Units
λ_w	Leaf weathering removal constant	18.1	1/yr
Y_g	Yield of garden produce	2.2	kg/m^2
Y_p	Yield of pasture grass (fodder)	0.7	kg/m^2
P	Annual average precipitation rate	1.232	m/yr
E	Annual average evapotranspiration rate	0.828	m/yr
$I_{R,g}$	Irrigation rate of garden	1.315	m/yr
$I_{R,p}$	Irrigation rate of pasture	1.315	m/yr
$t_{irr,g}$	Garden irrigation time, (same value as $F_{R,g}$)	0.192	yr
$t_{irr,p}$	Pasture irrigation time, (same value as $F_{R,p}$)	0.082	yr
t_b	Time for buildup of contaminants in soil	25	yr
ρ_s	Bulk soil density	1,650[1,2]	kg/m^3
ϕ	Soil porosity	0.38[1,2]	-
θ_w	Soil water content	0.26[2]	-
d_t	Soil tilling depth	0.15	m

[1] Phifer, M.A., M.A. Millings, G.P. Flach, 2006, "Hydraulic Property Data Package for the E-Area and Z-Area Vadose Zone Soils, Cementitious Materials, and Waste Zones", WSRC-STI-2006-00198, Washington Savannah River Company, Aiken, SC, Table 5-9, Sand.

[2] Phifer, M.A. and K.L. Dixon, 2009, "Material Property, Infiltration and Saturation Estimates and Distributions for the Composite Analysis", SRNL-STI-2009-00316, Savannah River National Laboratory, Aiken, SC, Table 1, Vadose Zone Sandy Soil. ($\theta_w = S\,\phi$; soil water saturation, *S*, given as 0.683 in Phifer and Dixon, 2009.)

Table 2-7. Radionuclide Specific Ingestion Dose Parameters.

Parameter	Description	Units
λ_i	Decay constant for radionuclide *i*	1/yr
$K_{d,i}$	Soil adsorption coefficient for radionuclide *i*	m^3/kg
$T_{StoV,i}$	Bio-transfer factor for radionuclide *i* from soil to vegetable	-
$T_{FtoMeat,i}$	Bio-transfer factor for radionuclide *i* from livestock feed to meat	yr/kg
$T_{FtoMilk,i}$	Bio-transfer factor for radionuclide *i* from dairy cattle feed to milk	yr/m^3

3.0 Inhalation Dose to Resident Farmer MOP

Figure 3-1 shows a schematic diagram of sources of dose to a member of the public from the inhalation of contaminated groundwater or surface water and inhalation of contaminated soil. The MOP is assumed to be a resident farmer who uses water drawn from the contaminated source to irrigate a garden. For groundwater, the well is typically assumed to be 100 m down gradient from the boundary of an ELLWF disposal unit (PA only). For surface water, the water is assumed to be drawn from the mouth of an SRS stream or the Savannah River (see discussion of CA POAs in Section 2.0). The following mechanisms of contaminant transfer from water inhalation to the human receptor are considered in this model:

1. Inhalation of contaminated water during garden irrigation.
2. Inhalation of dust that has been contaminated by the use of water for garden irrigation.
3. Inhalation of contaminated water during showering.

As Figure 3-1 illustrates, determining the amount of contaminant inhaled by a MOP is less complicated than the ingestion pathways shown in Figure 2-1. It is assumed that the concentration of contaminants in the water is known as a function of time. Dose to a human receptor depends on the amount of contaminated water inhaled during garden irrigation and showering and on the accumulation of contaminants in inhaled soil. Accumulation of contaminants in the soil has already been treated when considering ingestion pathways in Chapter 2.

In addition to the three inhalation pathways shown in Figure 3-1, inhalation of contaminated water during swimming and boating could also be included. Swimming and boating are considered to be recreational activities that would take place in the Savannah River or mouth of an SRS stream contaminated by groundwater. Because they will be summed up under the recreation scenario these inhalation pathways have not been included here but are treated separately in Chapter 5. In the next section, we present a model that accounts for inhalation of contaminants by the pathways shown in Figure 3-1. Table 1-1 presents some general notation used in the equations.

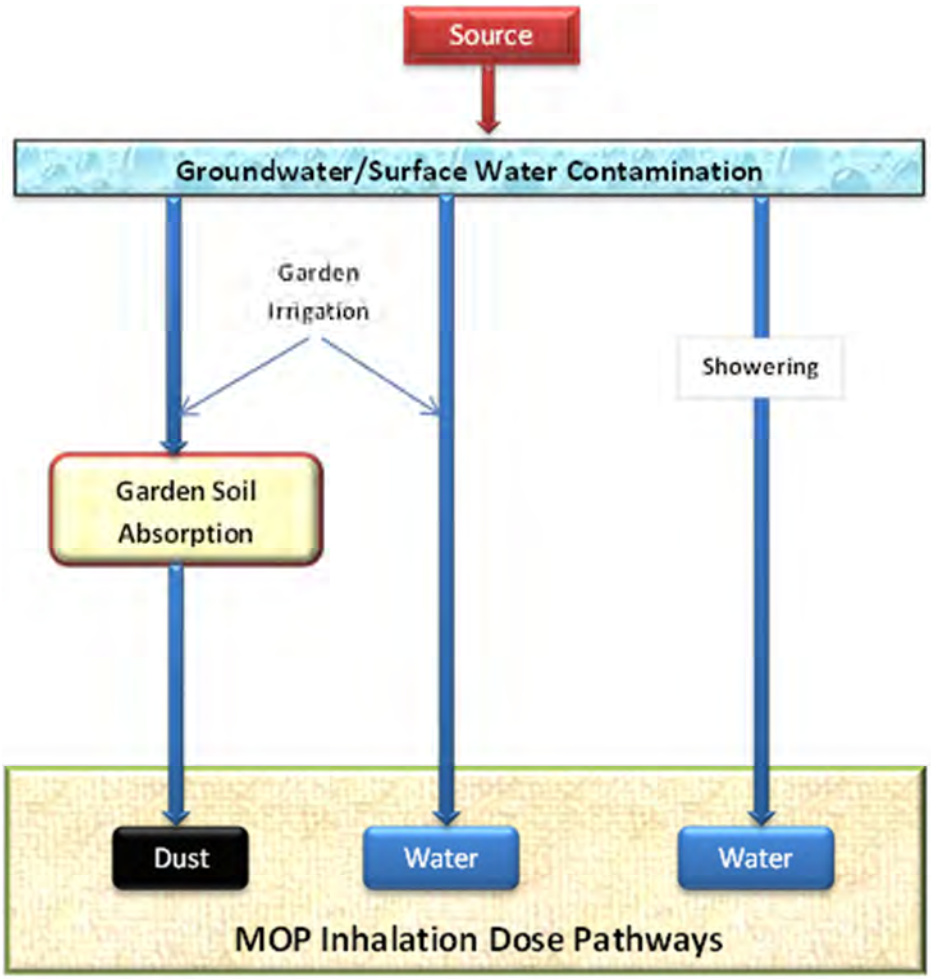

Figure 3-1. Inhalation dose pathways to residential MOP.

3.1 Inhalation Dose Methodology

The general methodology for calculating the dose to a MOP from an inhalation delivery pathway for contamination is the same for each contributing pathway. Effective inhalation dose coefficients are available for the same 888 radionuclides that have effective ingestion dose coefficients. These coefficients are used to convert the amount of radionuclide inhaled over a year of time into an effective annual dose. Radionuclide inhalation is calculated by summing the contribution from each pathway shown in Figure 3-1. Total inhalation dose to an individual is calculated by summing the doses from individual radionuclides. This calculation can be expressed in equation form as:

$$D_{inh,Total} = \sum_{i=1}^{N} D_{inh,i} = \sum_{i=1}^{N} \left\{ EC_{inh,i} \sum_{k=1}^{K} Inh_{k,i} \right\} \quad (3.1\text{-}1)$$

Where:

$D_{inh,Total}$ ..... Total annual average dose from inhalation of all radionuclides through all pathways (mrem/yr)
$D_{inh,i}$ ..... Annual average dose from inhalation of radionuclide *i* (mrem/yr)
N ..... Number of radionuclides included in the dose calculation
$EC_{inh,i}$ ..... Effective dose coefficient for inhalation of radionuclide *i* (mrem/pCi)
$Inh_{k,i}$ ..... Annual average inhalation of radionuclide *i* through pathway *k* (pCi/yr)
K ..... Number of inhalation pathways included in the dose calculation

Annual average human inhalation rates of air are known as a function of factors such as age and gender. From this data, inhalation rates for a Typical or Reference person can be determined for a specific application. The inhalation of radionuclide *i* through pathway *k* is then the product of the concentration of radionuclide in the pathway material and the inhalation rate. Applying this to Eq. (3.1-1) gives:

$$D_{inh,Total} = \sum_{i=1}^{N} \left\{ EC_{inh,i} \sum_{k=1}^{K} \left(F_k \, U_k \, C_{k,i} \right) \right\} \quad (3.1\text{-}2)$$

Where:

F_k ..... Fraction of year individual is exposed to contamination through pathway *k* (-)
U_k ..... Annual average rate of inhalation through pathway *k* (m^3/yr)
$C_{k,i}$ ..... Concentration of radionuclide *i* in pathway *k* (pCi/m^3)

In Eq. (3.1-2), the summation over index *j* is over the three human inhalation pathways shown in Figure 3-1. The inhalation rate of radionuclide *i* through pathway *k* is:

$$Inh_{k,i} = F_k \, U_k \, C_{k,i} \quad (3.1\text{-}3)$$

The dose to a MOP from inhalation of radionuclide *i* through pathway *k* can then be calculated as:

$$D_{inh,k,i} = EC_{inh,i}\, Inh_{k,i} \quad (3.1\text{-}4)$$

To apply Eq. (3.1-2) and determine the dose to an individual from the inhalation of contaminated material it is necessary to determine the concentration of contaminant in the material. The concentration of contaminant in irrigated soil has been determined in Section 2.2.2 as shown by Eq. (2.2-10).

3.2 Human Uptake through Inhalation

Using the equations derived in the previous section, equations to calculate human uptake of contamination can be developed in a relatively straight forward manner for each inhalation pathway.

3.2.1 Inhalation of Irrigation Water

Inhalation of contaminated water during garden irrigation is the first inhalation exposure pathway considered. Applying a modified version of Eq. (3.1-3), uptake of radionuclide *i* by a MOP through the inhalation of contaminated water is calculated as:

$$Inh_{gw,i} = \frac{F_s\, F_{ar}\, MC_{air,g}\, U_{air}}{\rho_w}\, C_{w,i} \quad (3.2\text{-}1)$$

Where:

$Inh_{gw,i}$ ..... Uptake of radionuclide *i* by MOP through the inhalation of contaminated irrigation water in garden (pCi/yr)
F_s ..... Fraction of year spent in garden (-)
F_{ar} ..... Airborne release fraction (-)
$MC_{air,g}$ ..... Moisture content of ambient air in garden (kg/m^3)
U_{air} ..... Annual human inhalation rate of air (m^3/yr)
$C_{w,i}$ ..... Concentration of radionuclide *i* in contaminated water (pCi/m^3)
ρ_w ..... Density of water (kg/m^3)

The airborne release fraction represents the fraction of the ambient air moisture content that comes from airborne irrigation water.

3.2.2 Inhalation of Shower Water

Inhalation of contaminated water during showering is the second inhalation exposure pathway considered. This exposure pathway is identical to the inhalation of irrigation water except that different moisture content in the air is assumed to apply under shower conditions. Applying a slightly modified version of Eq. (3.2-1), uptake of radionuclide *i* by a MOP through the inhalation of contaminated water during showering is calculated as:

$$Inh_{sw,i} = \frac{F_{sh}\, F_{ar}\, MC_{air,sh}\, U_{air}}{\rho_w}\, C_{w,i} \quad (3.2\text{-}2)$$

Where:

$Inh_{sw,i}$ ..... Uptake of radionuclide *i* by MOP through the inhalation of contaminated shower water (pCi/yr)
F_{sh} ..... Fraction of year spent in shower (-)
F_{ar} ..... Airborne release fraction (-)

$MC_{air,sh}$ .....Moisture content of air in shower (kg/m^3)
U_{air} .....Annual human inhalation rate of air (m^3/yr)
$C_{w,i}$ .....Concentration of radionuclide *i* in contaminated water (pCi/m^3)
ρ_w .....Density of water (kg/m^3)

3.2.3 Inhalation of Garden Dust

While working in a garden, a MOP will inadvertently inhale some small quantity of contaminated garden soil. Applying Eq. (3.1-3), uptake of radionuclide *i* by a MOP through the inhalation of contaminated garden soil is calculated as:

$$Inh_{s,i} = F_s\, U_{air}\, L_{soil}\, C_{s,i} \tag{3.2-3}$$

Where:

$Inh_{s,i}$.....Uptake of radionuclide *i* by MOP through the inhalation of contaminated garden soil (pCi/yr)
F_s.....Fraction of year spent in garden (-)
U_{air}.....Annual human inhalation rate of air (m^3/yr)
L_{soil} .....Loading of soil in garden air (kg/m^3)
$C_{s,i}$ .....Concentration of radionuclide *i* in irrigated garden soil (pCi/kg)

Equation (2.2-10) provides an expression for the concentration of contaminant species in soil irrigated with contaminated water. Applying this to garden soil, as was done in deriving Eq. (2.2-10), gives:

$$Inh_{s,i} = F_s\, U_{air}\, L_{soil}\, R_{Soil,g,i}\, C_{w,i} \tag{3.2-4}$$

$$R_{Soil,g,i} = K_{d,i}\, \frac{\lambda_{R,g,i}}{\lambda_{B,g,i}} \left(1 - e^{-\lambda_{B,g,i}\, t_b}\right) \tag{3.2-5}$$

Where:

$R_{Soil,g,i}$.....Retention of contaminated water in garden soil for species *i* (m^3/kg)
$\lambda_{R,g,i}$ .....Time constant for retention of radionuclide *i* in garden soil (1/yr)
$\lambda_{B,g,i}$ .....Time constant for removal of radionuclide *i* from garden soil (1/yr)

3.3 Inhalation Dose Equation Summary

Applying Eq. (1.2-1) to summarize the inhalation dose equations with dose coefficient $EC_{inh,i}$ (mrem/pCi) and water source concentration $C_{w,i}$ (pCi/m^3) gives the results shown in Eq. (3.3-1) and Table 3-1. The inhalation dose equations for each pathway can all be written in the general form:

$$D_{inh,k,i} = EC_{inh,i} \left\{F_k \, R_{k,i} \, U_{air}\right\} C_{w,i} \tag{3.3-1}$$

Where:

$D_{inh,k,i}$ ..... Annual average dose from inhalation of radionuclide *i* through inhalation pathway *k* (mrem/yr)
i ..... Radionuclide index
k ..... Inhalation pathway index
F_k ..... Fraction of year individual is exposed to contamination through inhalation pathway *k* (-)
$R_{k,i}$ ..... Retention factor for radionuclide *i* in inhalation pathway *k* (-)
U_{air} ..... Human air inhalation rate (m^3/yr)

In Eq. (3.3-1), the term in brackets is the exposure term shown in Table 3-1. The factor $R_{k,i}$ in Eq. (3.3-1) determines the amount of contaminated water retained in the particular inhalation pathway. Values of parameters used in the inhalation dose equations are provided in Tables 3-2 through 3-4.

Table 3-1. Summary of Inhalation Dose Equations.

Inhalation Pathway	Exposure	Units
Irrigation Water	$F_s \, F_{ar} \dfrac{MC_{air,g}}{\rho_w} \, U_{air}$	m^3/yr
Shower Water	$F_{sh} \, F_{ar} \dfrac{MC_{air,sh}}{\rho_w} \, U_{air}$	m^3/yr
Garden Soil	$F_s \, L_{soil} \, K_{d,i} \dfrac{\lambda_{R,g,i}}{\lambda_{B,g,i}} \left(1 - e^{-\lambda_{B,g,i} \, t_b}\right) U_{air}$	m^3/yr

3.4 Inhalation Dose Parameters

The development in the preceding section introduced a few new parameters into the dose calculations which must be specified. For immediate reference, nominal values for all parameters used in the inhalation dose equations are tabulated below in Tables 3-2 through 3-4. The hierarchy of references used to obtain the dose parameter values is given in Figure 10-15 where the database is discussed.

Table 3-2. Human Behavior Inhalation Dose Parameters.

Parameter	Description	Typical Person	Reference Person	Units
U_{air}	Air inhalation rate	5,000	6,400	m^3/yr
F_s	Fraction of year spent in garden	0.010	0.01	-
F_{sh}	Fraction of year spent in shower	0.007 (10 min/day)	0.007 (10 min/day)	-

Table 3-3. Physical Inhalation Dose Parameters.

Parameter	Description	Nominal Value	Units
F_{ar}	Airborne fraction of contaminated water	1.0E-04	-
$MC_{air,g}$	Moisture content of ambient air	0.010	kg/m^3
$MC_{air,sh}$	Moisture content of shower air	0.041	kg/m^3
L_{soil}	Loading of soil in ambient air	1.0E-07	kg/m^3
ρ_w	Density of water	1,000	kg/m^3
t_b	Time for buildup of contaminants in soil	25	yr

Table 3-4. Radionuclide Specific Inhalation Dose Parameters.

Parameter	Description	Units
$K_{d,i}$	Soil adsorption coefficient	m^3/kg
$\lambda_{R,g,i}$	Time constant for radionuclide *i* retention in garden soil (Eq. 2.2-12c)	1/yr
$\lambda_{B,g,i}$	Time constant for radionuclide *i* removal from garden soil (Eq. 2.2-12c)	1/yr

4.0 External Exposure Dose to Resident Farmer MOP

Figure 4-1 shows a schematic diagram of sources of dose to a member of the public from external exposure to contaminated groundwater or surface water used for irrigation and showering. The MOP is assumed to be a resident farmer who uses water drawn from the contaminated source to irrigate a garden and to shower. The groundwater source is typically assumed to be a well 100 m down gradient from the boundary of an ELLWF disposal unit (PA only). The surface water source is assumed to be POAs in the Savannah River or mouth of an SRS stream contaminated by groundwater seepage (see discussion on CA POAs on page 10). The following mechanisms of external exposure of contaminants to the human receptor are considered in this model:

1. Exposure to soil contaminated by water during garden irrigation.
2. Exposure to contaminated water during showering.

It is assumed that the concentration of contaminants in the water is known as a function of time. External dose to a human receptor depends on the time of exposure and contamination level in water used for showering and on the accumulation of contaminants in garden soil. Accumulation of contaminants in the soil has already been treated when considering ingestion pathways in Chapter 2.

In addition to the two external exposure pathways shown in Figure 4-1, exposure to contaminated water during swimming and boating could also be included. Swimming and boating are considered to be recreational activities that would only take place in a stream contaminated by groundwater. The concentration of contaminants in the stream would be significantly diluted and these exposure pathways are treated separately in Chapter 5. In the next section, we present a model that accounts for external exposure to contaminants by the two pathways shown in Figure 4-1. Table 1-1 presents the general notation used in the dose equations.

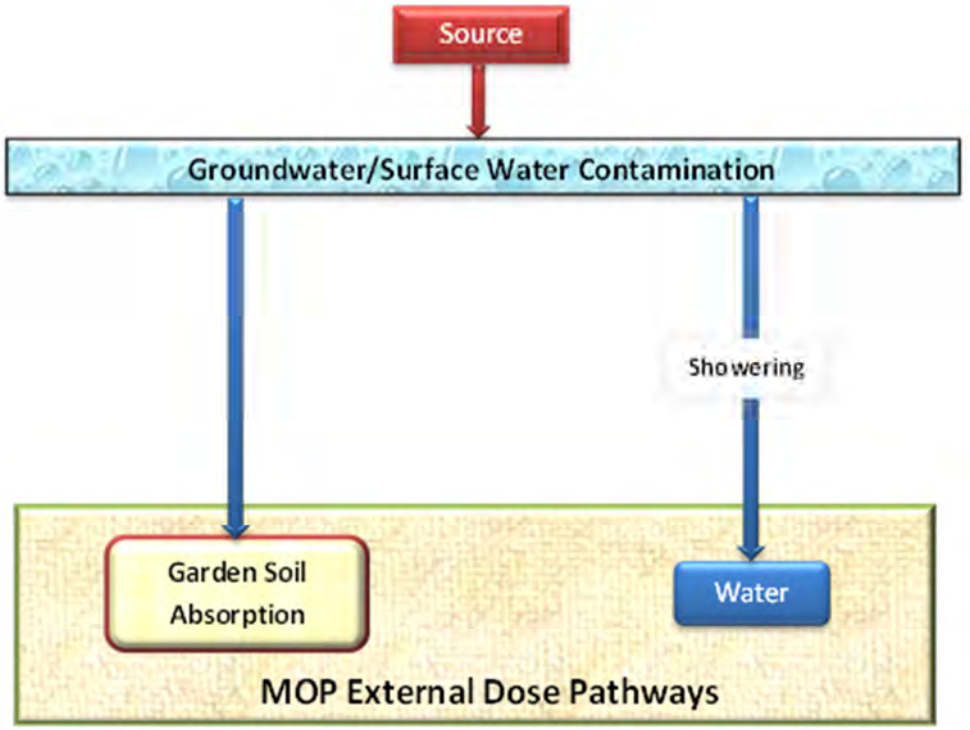

Figure 4-1. External exposure dose pathways to residential MOP.

4.1 External Exposure Dose Methodology

The general methodology for calculating the dose to a MOP from an external exposure delivery pathway for contamination is the same for each pathway. Effective dose coefficients for external exposure are available for 1252 radionuclides. These coefficients are used to convert the radionuclide exposure over a year of time into an effective annual dose. Radionuclide exposure is calculated by summing the contribution from each pathway shown in Figure 4-1. Total dose to an individual from external exposure is calculated by summing the doses from individual radionuclides. This calculation can be expressed in equation form as:

$$D_{ext,Total} = \sum_{i=1}^{N} D_{ext,i} = \sum_{i=1}^{N} \left\{ \sum_{m=1}^{M} EC_{ext,m,i}\, Ext_{m,i} \right\} \quad (4.1\text{-}1)$$

Where:

$D_{ext,Total}$ ..... Total annual average dose from external exposure to all radionuclides through all pathways (mrem/yr)
$D_{ext,i}$ ..... Annual average dose from external exposure to radionuclide *i* (mrem/yr)
N ..... Number of radionuclides included in the dose calculation
$EC_{ext,m,i}$ ..... Effective dose coefficient for external exposure to radionuclide *i* through pathway *m* (mrem/yr)/(pCi/m^3)
$Ext_{m,i}$ ..... Annual average exposure to radionuclide *i* through pathway *m* (pCi/m^3)
M ..... Number of external exposure pathways included in the dose calculation

In Eq. (4.1-1), the summation over index *m* is over the two external exposure pathways shown in Figure 4-1. For external exposure pathways, specific dose coefficients apply depending on the pathway. The "*Radionuclide, Element and Dose Parameter Data Package"* described in Chapter 10 provides external dose coefficients for the following cases:

$EC_{ext,WS,i}$ ..... Water submersion
$EC_{ext,AI,i}$ ..... Air immersion
$EC_{ext,GS,i}$ ..... Ground shine
$EC_{ext,1cm,i}$ ..... Soil contaminated to a depth of 1 cm
$EC_{ext,5cm,i}$ ..... Soil contaminated to a depth of 5 cm
$EC_{ext,15cm,i}$ ..... Soil contaminated to a depth of 15 cm
$EC_{ext,\infty,i}$ ..... Soil contaminated to an infinite depth

In addition, the database provides shielding factors that can be applied to the infinite depth soil contamination dose coefficients to account for shielding by clean soil with a thickness of 0, 1, 5, 15, 30, 45 or 100 cm.

In general, exposure to radionuclide *i* through pathway *m* is calculated as:

$$Ext_{m,i} = F_m\, C_{m,i} \quad (4.1\text{-}2)$$

Where:

F_m .....Fraction of time individual is exposed to external contamination through pathway *m* (-)
$C_{m,i}$ .....Concentration of radionuclide *i* in pathway *m* (pCi/m^3)

The dose to a MOP from external exposure to radionuclide *i* through pathway *m* can then be calculated as:

$$D_{ext,m,i} = EC_{ext,m,i}\ Ext_{m,i} \quad (4.1\text{-}3)$$

To apply Eq. (4.1-3) and determine the dose to an individual from the exposure to contaminated material it is necessary to determine the concentration of contaminant in the material. The concentration of contaminant in irrigated soil has been determined in Section 2.2.2 as shown by Eq. (2.2-10).

4.2 Human Uptake through External Exposure

Using the equations derived in the previous section, equations to calculate human uptake of radiation dose from external exposure can be developed in a relatively straight forward manner for each pathway.

4.2.1 External Exposure to Shower Water

Exposure to contaminated water during showering is the first external exposure pathway considered. The external dose factor for submersion in water is used to estimate the external dose from showering. Because showering does not involve total submersion in contaminated water, a geometry factor is included to account for partial submersion during showering. This factor can be set to one for a conservative estimate of the external dose.

Exposure to radionuclide *i* by a MOP through external contact with contaminated water during showering is calculated as:

$$Ext_{sw,i} = F_{sh}\ G_{sh}\ C_{w,i} \quad (4.2\text{-}1)$$

Where:

$Ext_{sw,i}$ .....External exposure to radionuclide *i* by MOP through the contact with contaminated shower water (pCi/m^3)
F_{sh} .....Fraction of year spent in shower (-)
G_{sh} .....Geometry factor for immersion in shower water (-)
$C_{w,i}$ .....Concentration of radionuclide *i* in water (pCi/m^3)

4.2.2 External Exposure to Garden Soil

While working in a garden, a MOP will be exposed to radionuclides in the contaminated garden soil. The external dose factor for exposure to soil contaminated to a depth of 15 cm is used to calculate the external dose from exposure to garden soil. Applying Eq. (4.1-3), the exposure to radionuclide *i* by a MOP through contaminated soil is calculated as:

$$Ext_{s,i} = F_s\ C_{s,i}\ \rho_s \quad (4.2\text{-}2)$$

Where:

$Ext_{s,i}$ .....External exposure to radionuclide *i* by MOP through contaminated garden soil (pCi/m^3)
F_s.....Fraction of time spent in garden (-)
$C_{s,i}$ .....Concentration of radionuclide *i* in garden soil (pCi/kg)
ρ_s .....Soil bulk density (kg/m^3)

Equation (2.2-10) provides an expression for the concentration of contaminant species *i* in soil irrigated with contaminated water. Applying this to garden soil, as was done in deriving Eq. (2.2-12), gives:

$$Ext_{s,i} = F_s\, \rho_s\, R_{Soil,g,i}\, C_{w,i} \tag{4.2-3}$$

$$R_{Soil,g,i} = K_{d,i}\, \frac{\lambda_{R,g,i}}{\lambda_{B,g,i}} \left(1 - e^{-\lambda_{B,g,i}\, t_b}\right) \tag{4.2-4}$$

4.3 External Exposure Dose Equation Summary

Applying Eq. (1.2-1) to summarize the external exposure dose equations with water source concentration $C_{w,i}$ (pCi/m^3) gives the results shown in Eq. (4.3-1) and Table 4-1. The external exposure dose equations for each pathway can be written in the general form:

$$D_{ext,m,i} = EC_{ext,m,i} \left\{F_m\, R_{m,i}\right\} C_{w,i} \tag{4.3-1}$$

Where:

$D_{ext,m,i}$ .....Annual average dose from external exposure to radionuclide *i* through pathway *m* (mrem/yr)
i .....Radionuclide index
m .....External exposure pathway index
F_m .....Fraction of time spent in external exposure pathway *m* (-)
$R_{m,i}$.....Retention factor for radionuclide *i* in external exposure pathway *m* (-)

In Eq. (4.3-1), the term in brackets is the exposure term shown in Table 4-1. The factor $R_{m,i}$ in Eq. (4.3-1) determines the amount of contaminated water retained in the particular pathway. For external exposure, different effective dose coefficients apply for the two pathways. The depth of soil in the garden is assumed to be 15 cm. Values of parameters used in the direct exposure dose equations are provided in Tables 4-2 through 4-4.

Table 4-1. Summary of Direct Exposure Dose Equations.

External Exposure Pathway	Dose Coefficient (mrem/yr)/(pCi/m^3)	Exposure	Units
Shower Water	$EC_{ext,WS,i}$	$F_{sh}\, G_{sh}$	-
Garden Soil	$EC_{ext,15cm,i}$	$F_s\, \rho_s\, K_{d,i}\, \frac{\lambda_{R,g,i}}{\lambda_{B,g,i}} \left(1 - e^{-\lambda_{B,g,i}\, t_b}\right)$	-

4.4 External Exposure Dose Parameters

The only new parameter introduced in the development of external dose pathways is the showering geometry factor. For immediate reference, the values for all parameters used to calculate external dose are tabulated below in Tables 4-2 through 4-4. The hierarchy of references used to obtain the dose parameter values is given in Figure 10-15 where the database is discussed.

Table 4-2. Human Behavior Direct Exposure Dose Parameters.

Parameter	Description	Typical Person	Reference Person	Units
F_s	Fraction of year spent in garden	0.01	0.01	-
F_{sh}	Fraction of year spent in shower	0.007 (10 min/day)	0.007 (10 min/day)	-

Table 4-3. Physical Direct Exposure Dose Parameters.

Parameter	Description	Nominal Value	Units
G_{sh}	Geometry factor for showering	1	-
ρ_s	Bulk soil density	1,650	kg/m^3
t_b	Time for buildup of contaminants in soil	25	yr

Table 4-4. Radionuclide Specific Direct Exposure Dose Parameters.

Parameter	Description	Units
$K_{d,i}$	Soil adsorption coefficient	m^3/kg
$\lambda_{R,g,i}$	Time constant for radionuclide *i* retention in garden soil (Eq. 2.2-12c)	1/yr
$\lambda_{B,g,i}$	Time constant for radionuclide *i* removal from garden soil (Eq. 2.2-12c)	1/yr

5.0 Recreational Dose to MOP

Dose pathways developed in Chapters 2 – 4 apply for either exposure to a MOP from contaminated ground water (PA) or Savannah River surface water (CA). The recreational doses considered in this Chapter are distinct in that they apply only for exposure to contaminated surface water (Savannah River at mouth of SRS site streams) and have only been used in calculating a CA dose.

Figure 5-1 shows a schematic diagram of sources of dose to a MOP caused by exposure to contaminated water from recreational activities. The MOP is assumed to engage in recreational activity in the Savannah River at the mouth of SRS site streams contaminated by groundwater seepage. The distance of the seep line from the source of contamination, which determines the travel time of the contaminant from the source to the receptor, will depend on the geography of the site being analyzed. Similarly, the dilution of the groundwater in the stream will depend on the stream and groundwater flow rates. The following mechanisms of exposure of contaminant to the human receptor are considered in this model:

1. Exposure (partial immersion) to contaminated river water while swimming.
2. Exposure (partial immersion) to contaminated river water while boating.
3. External exposure to shine from radionuclides adsorbed onto river bank soil.
4. Inhalation of contaminated water while swimming.
5. Internal exposure from dermal absorption of tritium while swimming.
6. Consumption of fish exposed to contaminated river water.

In addition to exposure pathways shown in Figure 5-1, inadvertent ingestion of water during boating and swimming and water inhalation during boating could also have been included in the dose calculation. However, the dose from the small ingestion of river water likely to occur during recreational activities will be negligible and is therefore not considered. Similarly, inhalation of water during boating was judged to be negligible.

It is assumed that the concentration of contaminants in the groundwater is known as a function of time and that the stream and/or river dilution factor is known. In general, dilution could vary with time but typically a constant annual average river or stream flow is used. External dose to a human receptor depends on the time of exposure and contamination level in the water used for recreational purposes. In the next section, we present a model that accounts for recreational exposure to contaminants by the pathways shown in Figure 5-1. Table 1-1 presents the general notation used in the dose equations.

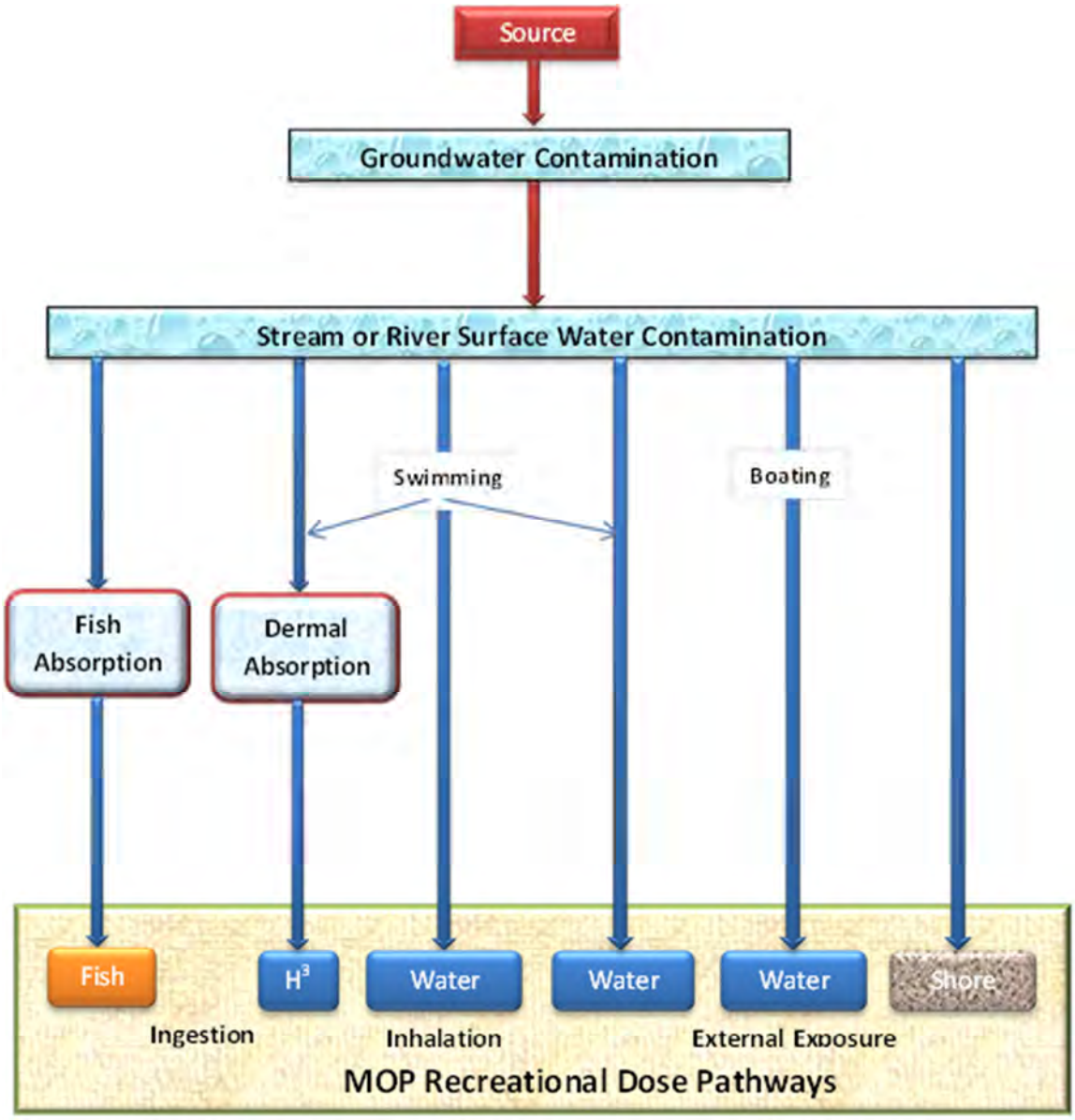

Figure 5-1. Recreational dose pathways to MOP.

5.1 Recreational Dose Methodology

The recreational exposure pathways have all been considered previously in slightly different forms. Water immersion was already considered in determining external doses in Chapter 4 for different pathways than those considered here. As noted previously, ingestion and inhalation dose coefficients are available for 888 radionuclides and effective dose coefficients for external exposure are available for 1252 radionuclides. These coefficients are used to convert the radionuclide exposure over a year of time into an effective annual dose. Radionuclide exposure is calculated by summing the contribution from each pathway shown in Figure 5-1. Total dose to an individual from external exposure is calculated by summing the doses from individual radionuclides over all pathways. This calculation can be expressed in its most general form as:

$$D_{rec,Total} = \sum_{i=1}^{N} D_{rec,i} = \sum_{i=1}^{N} \left\{ EC_{ing,i} \sum_{j=1}^{J} Ing_{j,i} + EC_{inh,i} \sum_{k=1}^{K} Inh_{k,i} + EC_{ext,i} \sum_{m=1}^{M} Ext_{m,i} \right\} \quad (5.1\text{-}1)$$

Where:

$D_{rec,Total}$ ..... Total annual average dose from recreational exposure to all radionuclides through all pathways (mrem/yr)
$D_{rec,i}$ ..... Annual average dose from recreational exposure to radionuclide *i* (mrem/yr)
N ..... Number of radionuclides included in the dose calculation
$EC_{ing,i}$ ..... Effective dose coefficient for ingestion of radionuclide *i* (mrem/pCi)
$Ing_{j,i}$ ..... Annual average ingestion of radionuclide *i* through pathway *j* (pCi/yr)
J ..... Number of ingestion pathways included in the dose calculation
$EC_{inh,i}$ ..... Effective dose coefficient for inhalation of radionuclide *i* (mrem/pCi)
$Inh_{k,i}$ ..... Annual average inhalation of radionuclide *i* through pathway *k* (pCi/yr)
K ..... Number of inhalation pathways included in the dose calculation
$EC_{ext,i}$ ..... Effective dose coefficient for external exposure to radionuclide *i* (mrem/yr)/(pCi/m^3)
$Ext_{m,i}$ ..... Annual average exposure to radionuclide *i* through pathway *m* (pCi/m^3)
M ..... Number of external exposure pathways included in the dose calculation

Exposure to radionuclide *i* through ingestion pathway *j* can be expressed as shown in Eq. (2.1-4). For recreational exposure the holdup time is assumed to be zero giving the slightly simplified ingestion rate:

$$Ing_{j,i} = F_j \, U_j \, C_{j,i} \quad (5.1\text{-}2)$$

Where:

F_j ..... Fraction of food from contaminated source consumed through pathway *j* (-)

U_j .....Annual average human rate of consumption through ingestion pathway *j* (kg/yr or m^3/yr)
$C_{j,i}$ .....Concentration of radionuclide *i* in pathway *j* (pCi/kg or pCi/m^3)

Exposure to radionuclide *i* through inhalation pathway *k* can be expressed as shown in Eq. (3.1-3) reproduced below as Eq. (5.1-3):

$$Inh_{k,i} = F_k\ U_k\ C_{k,i} \tag{5.1-3}$$

Where:

F_k .....Fraction of year individual is exposed to contamination through pathway *k* (-)
U_k .....Annual average rate of inhalation through pathway *k* (m^3/yr)
$C_{k,i}$ .....Concentration of radionuclide *i* in pathway *k* (pCi/m^3)

Similarly, external exposure to radionuclide *i* through pathway *m* can be expressed as in Eq. (4.1-2) reproduced below as Eq. (5.1-4):

$$Ext_{m,i} = F_m\ C_{m,i} \tag{5.1-4}$$

Where:

F_m .....Fraction of year individual is exposed to external contamination through pathway *m* (-)
$C_{m,i}$ .....Concentration of radionuclide *i* in pathway *m* (pCi/m^3)

The dose to a MOP from exposure to radionuclide *i* through recreational activities can then, in general, be calculated as:

$$D_{rec,i} = EC_{ing,i} \sum_{j=1}^{J} F_j\ U_j\ C_{j,i} + EC_{inh,i} \sum_{k=1}^{K} F_k\ U_k\ C_{k,i} + EC_{ext,i} \sum_{m=1}^{M} F_m\ C_{m,i} \tag{5.1-5}$$

To apply Eq. (5.1-5) and determine the dose to an individual from the exposure to contaminated materials it is necessary to determine the concentration of contaminant in the materials.

5.2 Human Uptake through Recreational Activity

To apply the equations derived in the previous section, equations to calculate human uptake of contamination through recreational activities can be developed in a relatively straight forward manner for each pathway.

5.2.1 Inhalation of Water while Swimming

Inhalation of contaminated water during swimming is the only inhalation exposure pathway considered. This exposure pathway is identical to the inhalation of irrigation water considered in Chapter 3 except for a different exposure time. Applying a slightly modified version of Eq. (3.2-1), the uptake of radionuclide *i* by a MOP through the inhalation of contaminated water during swimming is calculated as:

$$Inh_{swim,i} = \frac{F_{swim}\, F_{ar}\, MC_{air,g}}{\rho_w} U_{air}\, C_{rw,i} \quad (5.2\text{-}1)$$

Where:

$Inh_{swim,i}$ ..... Uptake of radionuclide *i* by MOP through the inhalation of contaminated water while swimming (pCi/yr)
F_{swim} ..... Fraction of year spent swimming (-)
F_{ar} ..... Airborne release fraction (-)
$MC_{air,g}$ ..... Moisture content of ambient air (kg/m^3)
U_{air} ..... Annual human inhalation rate of air (m^3/yr)
$C_{rw,i}$ ..... Concentration of radionuclide *i* in river or stream water (pCi/m^3)
ρ_w ..... Density of water (kg/m^3)

5.2.2 External Exposure to Water while Swimming

Exposure to contaminated water while swimming is the first external exposure pathway considered for recreational activities. The external dose factor for submersion in water is used to estimate the external dose from swimming. Because swimming does not involve total submersion in contaminated water at all times, a geometry factor is included to account for partial submersion during swimming. This factor can be set to one for a conservative estimate of the external dose.

Exposure to radionuclide *i* by a MOP through external contact with contaminated water during swimming is calculated as:

$$Ext_{swim,i} = F_{swim}\, G_{swim}\, C_{rw,i} \quad (5.2\text{-}4)$$

Where:

$Ext_{swim,i}$ ..... Exposure of radionuclide *i* by MOP through the external contact with contaminated river water during swimming (pCi/m^3)
F_{swim} ..... Fraction of year spent swimming (-)
G_{swim} ..... Geometry factor for water immersion during swimming (-)
$C_{rw,i}$ ..... Concentration of radionuclide *i* in river or stream water (pCi/m^3)

5.2.3 Dermal Adsorption of H^3 while Swimming

Exposure to contaminated stream water during swimming may result in adsorption of tritium through the skin. While it is actually water that is absorbed through the skin, it is assumed that tritium is the only radionuclide that can pass through the skin. Adsorption through the skin is considered an ingestion dose pathway. Exposure to tritium by a MOP through dermal adsorption from contact with contaminated water during swimming is calculated as:

$$Ing_{derm,H^3} = F_{swim}\, DA_w\, C_{rw,H^3} \quad (5.2\text{-}5)$$

Where:

Ing_{derm,H^3} ..... Exposure of tritium by MOP through the external contact with contaminated river water during swimming (pCi/yr)
F_{swim} ..... Fraction of year spent swimming (-)
DA_w ..... Dermal absorption rate of water (m^3/yr)
C_{rw,H^3} ..... Concentration of tritium in river or stream water (pCi/m^3)

5.2.4 External Exposure to Water while Boating

Exposure to contaminated river water during boating is another external exposure pathway considered for recreational activities. The external dose factor for submersion in water is again used to estimate the external dose from boating. The only difference between swimming and boating exposure is the geometry factor applied for each case and the time spent in each activity. The geometry factor can be set to one for a conservative estimate of the external dose.

Exposure to radionuclide *i* by a MOP through external contact with contaminated water during boating is calculated as:

$$Ext_{boat,i} = F_{boat}\, G_{boat}\, C_{rw,i} \tag{5.2-6}$$

Where:

$Ext_{boat,i}$ ..... Exposure to radionuclide *i* by a MOP through the external contact with contaminated river water during boating (pCi/m^3)
F_{boat} ..... Fraction of year spent boating (-)
G_{boat} ..... Geometry factor for water immersion during boating (-)
$C_{rw,i}$ ..... Concentration of radionuclide *i* in river water (pCi/m^3)

5.2.5 External Exposure to Contaminated Soil on Shore

Exposure to contaminated soil during time spent on a river or stream shore is the last external exposure pathway considered for recreational activities. It is assumed that the shore consists of saturated sandy soil and that contaminated water is flowing through the soil. As shown by Chapter 2 Eq. (2.2-10a), the concentration of contamination in the shore soil (pCi/kg) is calculated using the equation:

$$C_{shore,i}(t_b) = K_{d,i}\, \frac{\lambda_{R,i}}{\lambda_{B,i}} \left(1 - e^{-\lambda_{B,i}\, t_b}\right) C_{rw,i} \tag{5.2-7}$$

Assuming saturated conditions and that water flow into and out of the shore soil (width w_{shore}) is equal to saturated hydraulic conductivity (K_{sat}), the time constants in Eq. (5.2-7) become:

$$\lambda_{B,i} = \lambda_i + \lambda_{L,i} \quad \text{with} \quad \lambda_{L,i} = \lambda_{R,i} = \frac{K_{sat}}{R_i\, w_{shore}} \tag{5.2-8}$$

Equating flow to saturated conductivity is equivalent to assuming a relative permeability of one for the shore soil and assuming that the hydraulic gradient across the soil is also one. For saturated conditions ($\theta_w = 1$), the retardation factor in Eq. (5.2-8) reduces to:

$$R_i = 1 + \rho_s\, K_{d,i} \tag{5.2-9}$$

External exposure to a MOP from contaminated soil on a river or stream bank is calculated as:

$$Ext_{shore,i} = F_{shore}\, G_{shore}\, \rho_s\, C_{shore,i} \tag{5.2-10}$$

Where:

$Ext_{shore,i}$ ..... Exposure of radionuclide *i* by MOP through the external contact with contaminated soil on a river or stream shore (pCi/m^3)
F_{shore} ..... Fraction of year spent on shore (-)
G_{shore} ..... Geometry factor for shore exposure (-)
ρ_s ..... Bulk soil density (kg/m^3)
$C_{shore,i}$ ..... Concentration of radionuclide *i* in shore soil (pCi/kg)

5.2.6 Ingestion of Fish

The recreational ingestion pathway considered for a MOP is the consumption of fish exposed to contaminated river water. In the SRS CA [SRNL-STI-2009-00512] and SRR Tank Farm PAs and Saltstone PA [SRR-CWDA-2013-00058] it is assumed that contaminated fish used for human consumption are only obtained from recreational activity in the Savannah River.

Applying Eq. (2.1-4), uptake of radionuclide *i* by a MOP through the ingestion of contaminated fish is calculated as:

$$Ing_{fish,i} = F_{fish}\, U_{fish}\, C_{fish,i}\, e^{-t_{hold,fish}\,\lambda_i} \quad (5.2\text{-}11)$$

Where:

$Ing_{fish,i}$ ..... Uptake of radionuclide *i* by MOP through the consumption of fish exposed to contaminated water (pCi/yr)
F_{fish} ..... Fraction of fish consumed that are obtained from local contaminated water (-)
U_{fish} ..... Human consumption of fish (kg/yr)
$C_{fish,i}$ ..... Concentration of radionuclide *i* in fish (pCi/kg)
$t_{hold,fish}$ ..... Holdup time between obtaining fish and ingestion (yr)

Element specific bio-transfer factors have been published that account for the fraction of radionuclide *i* in water that is transferred to fish meat. Therefore, these transfer factors are used to determine the concentration of contaminants in fish as:

$$C_{fish,i} = T_{WtoFish,i}\, C_{rw,i} \quad (5.2\text{-}12)$$

Where:

$T_{WtoFish,i}$ ..... Bio-transfer factor relating concentration of radionuclide *i* in water to the concentration in fish (m^3/kg)

Combining Eq. (5.2-12) with Eq. (5.2-11) gives:

$$Ing_{fish,i} = F_{fish}\, U_{fish}\, T_{WtoFish,i}\, C_{rw,i}\, e^{-t_{hold,fish}\,\lambda_i} \quad (5.2\text{-}13)$$

5.3 Recreational Dose Equation Summary

The recreational exposure rates derived in Section 5.2 all include the contaminant concentration in the stream or river water $C_{rw,i}$. Assuming that the stream or river is uncontaminated before mixing with the groundwater, the contaminant concentration in the stream or river water is related to the groundwater concentration by the expression:

$$C_{rw,i} = C_{gw,i} \frac{q_{gw}}{q_{gw} + q_{sw}} = \phi_w C_{gw,i} \quad (5.3\text{-}1)$$

Where:

q_{gw} .....Groundwater discharge rate into the stream or river (m^3/yr)
q_{sw} .....Stream or river flow rate (m^3/yr)
ϕ_w.....Ratio of flow rates defined by Eq. (5.3-1)

In the most general case, both the groundwater and stream or river flow rates would be functions of time. Factoring out the common term of $C_{rw,i}$, the radionuclide exposures derived in Section 5.2 can be rewritten as the equivalent exposures to contaminated stream or river water. In practice, two or more dilution steps may be involved where the groundwater first seeps into nearby streams which then flow into the river. The SRS CA considers recreational activities such as boating and swimming as taking place at the mouths of site streams entering the Savannah River and in the river at the 301 Highway Bridge located downstream from the site.

Applying Eq. (1.2-1) to summarize the recreational dose equations with water source concentration $C_{rw,i}$ (pCi/m^3) gives the results shown in Eq. (5.3-2) and Table 5-1. The recreational exposure dose equations for each pathway can be written in the general form:

$$D_{rec,n,i} = EC_{n,i} \{F_n R_{n,i}\} C_{rw,i} \quad (5.3\text{-}2)$$

Where:

$D_{rec,n,i}$ .....Annual average dose from recreational exposure to radionuclide *i* through pathway *n* (mrem/yr)
i .....Radionuclide index
n.....Recreational exposure pathway index
F_n .....Fraction of time spent in recreational exposure pathway *n* (-)
$R_{n,i}$.....Retention factor for radionuclide *i* in recreational exposure pathway *n* (-)

In Eq. (5.3-2), the term in brackets is the exposure term shown in Table 5-1. The factor $R_{n,i}$ in Eq. (4.3-1) determines the amount of contaminated water retained in the particular pathway. As shown in Eq. (5.1-5), for recreational exposure, different effective dose coefficients apply for the different pathways. Values of parameters used in the recreational exposure dose equations are provided in Tables 5-2 through 5-4.

Table 5-1. Summary of Recreational Dose Equations.

Recreational Pathway	Dose Coefficient	Units	Exposure	Units
Fish Ingestion	$EC_{ing,i}$	mrem/pCi	$F_{fish}\ U_{fish}\ T_{WtoFish,i}\ e^{-t_{hold,fish}\,\lambda_i}$	m^3/yr
Swimming Inhalation	$EC_{inh,i}$	mrem/pCi	$F_{swim}\ \frac{F_{ar}\ MC_{air}}{\rho_w}\ U_{air}$	m^3/yr
Tritium Dermal Adsorption	EC_{ing,H^3}	mrem/pCi	$F_{swim}\ DA_w$	m^3/yr
Swimming External Exposure	$EC_{ext,WS,i}$	(mrem/yr)/ (pCi/m^3)	$F_{swim}\ G_{swim}$	-
Boating External Exposure	$EC_{ext,WS,i}$	(mrem/yr)/ (pCi/m^3)	$F_{boat}\ G_{boat}$	-
Shore External Exposure	$EC_{ext,\infty,i}$	(mrem/yr)/ (pCi/m^3)	$F_{shore}\ G_{shore}\ \rho_s\ K_{d,i}\ \frac{\lambda_{R,i}}{\lambda_{B,i}}\left(1-e^{-\lambda_{B,i}\,t_b}\right)$	-

5.4 Recreational Dose Parameters

Several new parameters are introduced in the development of recreational dose pathways. For immediate reference, nominal values for all parameters used to determine the recreational dose are tabulated below in Tables 5-2 through 5-4. The hierarchy of references used to obtain the dose parameter values is given in Figure 10-15 where the database is discussed.

Table 5-2. Human Recreational Dose Parameters.

Parameter	Description	Typical Person	Reference Person	Units
U_{air}	Air inhalation rate	5,000	6,400	m^3/yr
F_{swim}	Fraction of year swimming	0.0008 (7 hr/yr)	0.0016 (14 hr/yr)	-
F_{boat}	Fraction of year boating	0.00251 (22 hr/yr)	0.00502 (44 hr/yr)	-
F_{shore}	Fraction of year on river (stream) shore	0.00114 (10 hr/yr)	0.00228 (20 hr/yr)	-
U_{fish}	Consumption of fish	3.7	24	kg/yr
F_{fish}	Fraction of fish from local source	1		-

Table 5-3. Physical Recreational Dose Parameters.

Parameter	Description	Nominal Value	Units
G_{swim}	Geometry factor for swimming	1.0	-
G_{boat}	Geometry factor for boating	0.5	-
G_{shore}	Geometry factor for shore	0.2	-
DA_w	Dermal absorption rate of water	0.307 (35 ml/hr)	m^3/yr
$t_{hold,fish}$	Time between obtaining fish and consumption	0.0055 (2 d/yr)	yr
t_b	Time for buildup of contaminants in soil	25	yr
F_{ar}	Airborne fraction of contaminated water	1.0E-04	-
$MC_{air,g}$	Moisture content of ambient air	0.01	kg/m^3
ρ_s	Bulk soil density	1,650	kg/m^3
ρ_w	Density of water	1,000	kg/m^3
w_{shore}	Width of shore	river/stream geography dependent	m

Table 5-4. Radionuclide Specific Recreational Dose Parameters.

Parameter	Description	Units
$K_{d,i}$	Soil adsorption coefficient for radionuclide *i*	m^3/kg
$T_{WtoFish,i}$	Bio-transfer factor for radionuclide *i* from water to fish	m^3/kg
λ_i	Time constant for radionuclide *i* decay	1/yr
$\lambda_{R,g,i}$	Time constant for radionuclide *i* retention in shore soil (Eq. 5.2-8)	1/yr
$\lambda_{B,g,i}$	Time constant for radionuclide *i* removal from shore soil (Eq. 5.2-8)	1/yr

6.0 Inadvertent Intruder Ingestion Dose

As described in the introduction, the inadvertent intruder is exposed to ingestion dose pathways involving exhumed waste (indistinguishable from soil), or waste remaining in the exposed disposal facility on which the intruder's home is located. As previously discussed, the inadvertent intruder scenario does not include direct ingestion of contaminated groundwater or the use of contaminated groundwater for crop irrigation (see page 3). Therefore, the ingestion pathways assumed to occur for an intruder are:

1. Ingestion of vegetables grown in contaminated garden soil.
2. Ingestion of dust originating from contaminated garden soil.
3. Ingestion of dust originating from the waste zone.

Pathways 1 and 2 apply to the chronic intruder agriculture and post drilling scenarios. Pathway 3 applies to the acute intruder basement construction and well drilling scenarios. Figure 6-1 shows a schematic diagram of the sources of dose to an inadvertent intruder through these ingestion pathways.

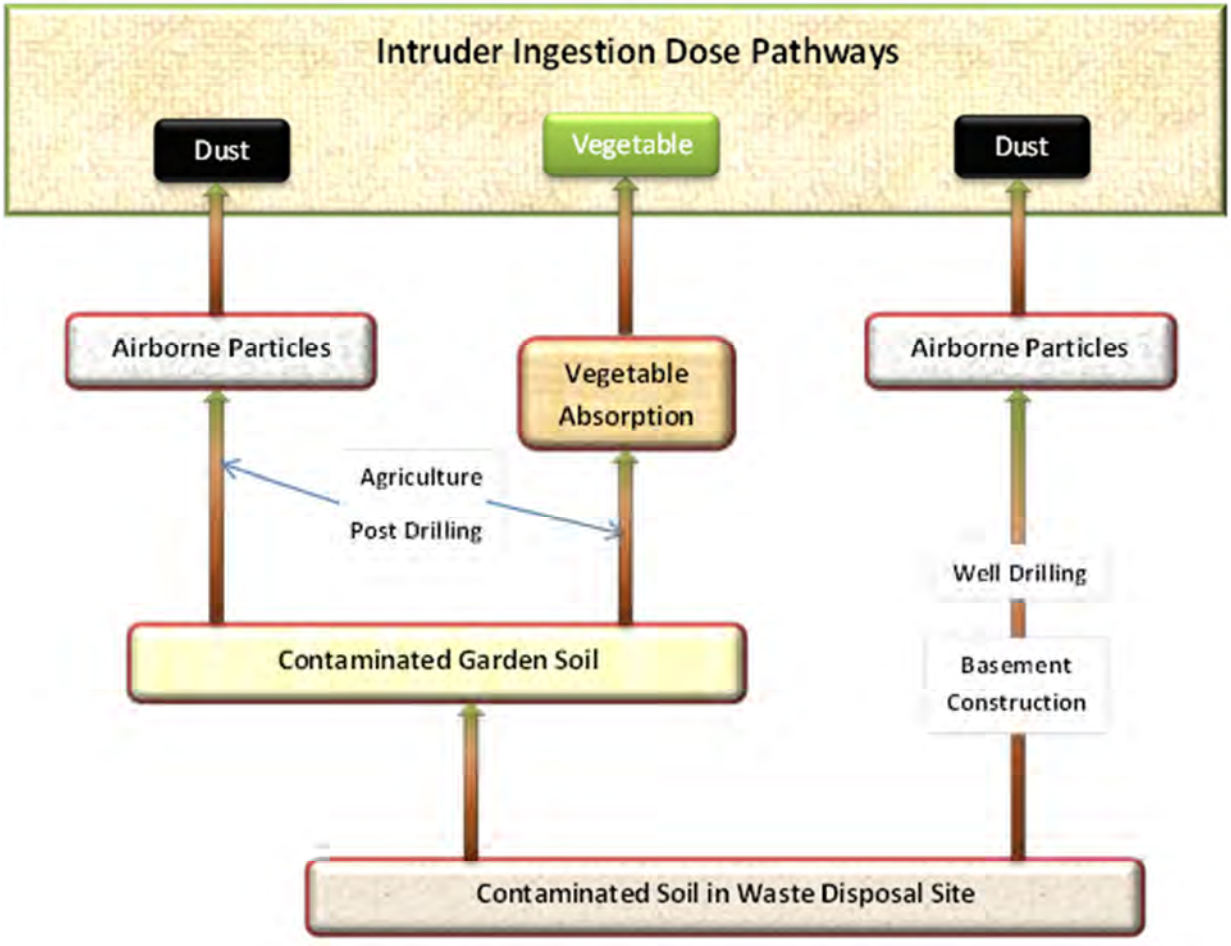

Figure 6-1. Ingestion dose pathways to inadvertent intruder.

6.1 Intruder Ingestion Dose Methodology

The methodology to calculate an intruder ingestion dose is basically the same as that for the ingestion dose to a resident farmer MOP developed in Section 2.1. However, for the intruder dose, any time between exposure and ingestion is neglected and the ingestion doses are not summed over all possible pathways because, as shown in Figure 6-1, the pathways used depend on the intruder scenario. Therefore, in this case, the dose from each individual pathway is calculated as:

$$D_{ing,j} = \sum_{i=1}^{N} D_{ing,j,i} = \sum_{i=1}^{N} \{EC_{ing,i}\ Ing_{j,i}\} \quad (6.1\text{-}1)$$

Where:

$D_{ing,j}$ ..... Annual average dose from ingestion through pathway *j* (mrem/yr)
$D_{ing,j,i}$ ..... Annual average dose from ingestion of radionuclide *i* through pathway *j* (mrem/yr)
N ..... Number of radionuclides included in the dose calculation
$EC_{ing,i}$ ..... Effective dose coefficient for ingestion of radionuclide *i* (mrem/pCi)
$Ing_{j,i}$ ..... Annual average ingestion of radionuclide *i* through pathway *j* (pCi/yr)

Similar to Eq. (2.1-4), the ingestion rate of radionuclide *i* through pathway *j* is given by:

$$Ing_{j,i} = F_j\ U_j\ C_{j,i} \quad (6.1\text{-}2)$$

Where:

F_j ..... Fraction of contaminated material consumed through ingestion pathway *j* (-)
U_j ..... Annual average human rate of consumption through ingestion pathway *j* (kg/yr or m^3/yr)
$C_{j,i}$ ..... Concentration of radionuclide *i* in pathway *j* (pCi/kg or pCi/m^3)

The dose to an intruder from ingestion of radionuclide *i* through pathway *j* is then calculated as:

$$D_{ing,j,i} = EC_{ing,i}\ Ing_{j,i} \quad (6.1\text{-}3)$$

6.2 Intruder Uptake through Ingestion

Using the equations derived in the previous section, equations to calculate uptake of contamination by an inadvertent intruder can be developed in a relatively straight forward manner for each ingestion pathway.

6.2.1 Ingestion of Produce

Radionuclide uptake to a chronic intruder from the ingestion of produce is calculated assuming that plant contamination only occurs through the uptake of contamination by plant roots in the garden soil. The

uptake of radionuclide *i* by an intruder through the ingestion of contaminated garden produce is calculated as:

$$Ing_{ag,i} = F_g\ U_g\ C_{ag,i} \tag{6.2-1}$$

Where:

$Ing_{ag,i}$ ..... Uptake of radionuclide *i* by intruder through the consumption of contaminated garden produce (pCi/yr)
F_g ..... Fraction of produce obtained from garden (-)
U_g ..... Human consumption rate of garden produce (kg/yr)
$C_{ag,i}$ ..... Concentration of radionuclide *i* in garden produce (pCi/kg)

Without considering effects from irrigation, the concentration of radionuclide *i* in garden produce is, in general, given by:

$$C_{ag,i} = T_{StoV,i} \frac{F_{gd,ap}}{\rho_s} C_{wz,i} \tag{6.2-2}$$

Where:

$T_{StoV,i}$ ..... Bio-transfer factor equal to the ratio of the concentration of contaminant *i* in the soil to the concentration in the vegetation (-)
$F_{gd,ap}$ ..... Scenario dependent dilution factor from mixing exhumed waste with native soil in garden during intruder agriculture ($F_{gd,ag}$) or post drilling ($F_{gd,pd}$) activity (-)
ρ_s ..... Bulk solid density (kg/m^3)
$C_{wz,i}$ ..... Concentration of radionuclide *i* in waste zone (pCi/m^3)

Combining Eq. (6.2-1) with Eq. (6.2-2) gives the following general equation for either intruder agriculture or post drilling activity:

$$Ing_{ag,i} = F_g\ U_g\ T_{StoV,i} \frac{F_{gd,ap}}{\rho_s} C_{wz,i} \tag{6.2-3}$$

6.2.2 Ingestion of Dust in Garden

The soil ingestion dose pathway for a chronic intruder working in the garden is consumption of airborne contaminated garden soil. The uptake of radionuclide *i* by an intruder through the ingestion of contaminated soil during gardening is calculated as:

$$Ing_{gd,i} = F_s\ U_s \frac{F_{gd,ap}}{\rho_s} C_{wz,i} \tag{6.2-4}$$

Where:

$Ing_{gd,i}$ ..... Uptake of radionuclide *i* by intruder through the ingestion of contaminated soil during gardening (pCi/yr)
F_s ..... Fraction of year spent gardening (-)
U_s ..... Annual average human ingestion rate of soil (kg/yr)

$F_{gd,ap}$ .....Scenario dependent dilution factor from mixing exhumed waste with native soil in garden during intruder agriculture ($F_{gd,ag}$) or post drilling ($F_{gd,pd}$) activity (-)
ρ_s .....Bulk soil density (kg/m^3)
$C_{wz,i}$ .....Concentration of radionuclide *i* in waste zone (pCi/m^3)

6.2.3 Ingestion of Dust during Construction or Drilling

The acute intruder soil ingestion dose pathway is the inadvertent consumption of airborne contaminated soil during basement construction or well drilling activity. The uptake of radionuclide *i* by an intruder through the ingestion of contaminated soil during construction activity is calculated as:

$$Ing_{cd,i} = F_{cd}\, U_{s,cd}\, \frac{F_{dil,cd}}{\rho_s} C_{wz,i} \tag{6.2-5}$$

Where:

$Ing_{cd,i}$ .....Uptake of radionuclide *i* by intruder through ingestion of contaminated soil during basement construction ($Ing_{bc,i}$) or well drilling ($Ing_{wd,i}$) (pCi/yr)
F_{cd} .....Scenario dependent fraction of year spent in basement construction (F_{bc}) or well drilling (F_{wd}) (-)
$U_{s,cd}$ .....Scenario dependent annual human ingestion rate of soil during basement construction ($U_{s,bc}$) or well drilling ($U_{s,wd}$) (kg/yr)
$F_{dil,cd}$ .....Scenario dependent dilution factor from mixing contaminated soil from exhumed waste with clean soil during basement construction ($F_{dil,bc}$) or well drilling ($F_{dil,wd}$) (-)
ρ_s .....Bulk soil density (kg/m^3)
$C_{wz,i}$ .....Average concentration of radionuclide *i* in waste zone (pCi/m^3)

The parameter $F_{dil,cd}$ is equal to volume of contaminated soil exhumed divided by the total amount of soil exhumed and would be estimated based on the geometry of the basement excavation or drilling site. For basement construction a simple estimate of the dilution factor would be:

$$F_{dil,bc} = max(0, 1 - d_{wz}/d_b) \tag{6.2-6}$$

Where:

d_b.....Depth of basement (m) (assumed to be 3 m)
d_{wz} .....Depth from ground surface to top of waste zone (m)

Equation (6.2-6) assumes that the basement area lies entirely over the waste material. Because the basement construction scenario presupposes that the digging penetrates into the waste zone, a dilution factor of one can be used to obtain a conservative estimate of the dose. For the well drilling scenario a simple estimate of the dilution factor would be:

$$F_{dil,wd} = h_{wz}/d_{gw} \tag{6.2-7}$$

Where:

h_{wz}.....Height of waste zone (m)
d_{gw} .....Depth of groundwater aquifer from surface (m)

Equation (6.2-7) assumes that the well is drilled from the surface to the aquifer and that it completely penetrates the waste zone. Equation (6.2-7) also assumes that the exhumed waste material is solely in the waste zone. A more exact version of the dilution factor for the well drilling scenario could be constructed by considering contamination that has leached out of the waste zone into the soil layer below the waste zone and above the aquifer. Equation (6.2-5) would use the average contaminant concentration in the waste zone and the soil below the waste zone and Eq. (6.2-7) would use the distance from the top of the waste zone to the aquifer in place of h_{wz}.

6.3 Intruder Ingestion Dose Equation Summary

Applying Eq. (1.2-1) to summarize the ingestion dose equations with dose coefficient $EC_{ing,i}$ (mrem/pCi) and waste source concentration $C_{wz,i}$ (pCi/m^3) gives the results shown in Eq. (6.3-1) and Table 6-1. The ingestion dose equations for each pathway can all be written in the general form:

$$D_{ing,j,i} = EC_{ing,i} \left\{ F_j \, T_{j,i} \, R_{j,i} \, U_j \right\} C_{wz,i} \tag{6.3-1}$$

Where:

$D_{ing,j,i}$ ..... Annual average dose from ingestion of radionuclide *i* through ingestion pathway *j* (mrem/yr)
i ..... Radionuclide index
j ..... Ingestion pathway index
F_j ..... Fraction of consumption through ingestion pathway *j* (-)
$T_{j,i}$ ..... Bio-transfer factor (yr/m^3, yr/kg, m^3/kg)
U_j ..... Human consumption rate (kg/yr, m^3/yr)
$R_{j,i}$ ..... Retention factor for radionuclide *i* in pathway *j* (m^3/kg, m^3/yr)

In Eq. (6.3-1), the term in brackets is the exposure term shown in Table 6-1. For ingestion of water, leafy vegetables, and soil, the equivalent bio-transfer factors are one because the contamination is directly consumed. The factor $R_{j,i}$ determines the amount of contaminated waste retained in the particular ingestion pathway. The retention factor is one for ingestion of undiluted waste. In applying these equations, it is assumed that the buried waste is indistinguishable from native soil and that the contamination is homogeneously mixed within the waste zone material. Therefore, the contaminant concentration in the waste zone is the average radionuclide concentration at the time the dose is evaluated.

Table 6-1. Summary of Intruder Ingestion Dose Equations.

Ingestion Pathway	Scenario	Exposure	Units
Vegetable	Agriculture	$F_g\, T_{StoV,i} \frac{F_{gd,ag}}{\rho_s} U_g$	m^3/yr
	Post Drilling	$F_g\, T_{StoV,i} \frac{F_{gd,pd}}{\rho_s} U_g$	m^3/yr
Garden Soil	Agriculture	$F_s \frac{F_{gd,ag}}{\rho_s} U_s$	m^3/yr
	Post Drilling	$F_s \frac{F_{gd,pd}}{\rho_s} U_s$	m^3/yr
Waste Soil	Well Drilling	$F_{wd} \frac{F_{dil,wd}}{\rho_s} U_{s,wd}$	m^3/yr
	Basement Construction	$F_{bc} \frac{F_{dil,bc}}{\rho_s} U_{s,bc}$	m^3/yr

6.4 Intruder Ingestion Dose Parameters

For immediate reference, nominal values of parameters introduced in calculation of ingestion doses for the intruder scenarios are given below in Table 6-2 through Table 6-4. The hierarchy of references used to obtain the dose parameter values is given in Figure 10-15 where the database is discussed.

Table 6-2. Human Behavior Intruder Ingestion Dose Parameters.

Parameter	Description	Nominal Value		Units
U_g	Consumption of garden produce	100 (Typical)	320 (Reference)	kg/yr
U_s	Inadvertent consumption of soil	0.0365 (100 mg/d)		kg/yr
$U_{s,bc}$	Human ingestion rate of soil during construction activity	0.0402 (110 mg/d)		kg/yr
$U_{s,wd}$	Human ingestion rate of soil during well drilling activity	0.0365 (100 mg/d)		kg/yr
F_g	Fraction of produce from local garden	0.308 (Typical)	1 (Reference)	-
F_s	Fraction of year spent in garden	0.01		-
F_{bc}	Fraction of year spent constructing basement	0.0183 (160 hr/yr)		-
F_{wd}	Fraction of year spent drilling well	0.0034 (30 hr/yr)		-

Table 6-3. Physical Intruder Ingestion Dose Parameters.

Parameter	Description	Nominal Value	Units
$F_{gd,ag}$	Dilution factor for mixing waste with garden soil for agriculture scenario	0.20	-
$F_{gd,pd}$	Dilution factor for mixing waste with garden soil for post drilling scenario	0.02	-
$F_{dil,bc}$	Dilution factor for mixing contaminated and clean soil during basement construction	calculated	-
$F_{dil,wd}$	Dilution factor for mixing contaminated and clean soil in drill cuttings	calculated	-
ρ_s	Bulk soil density	1,650	kg/m^3

Table 6-4. Radionuclide Specific Intruder Ingestion Dose Parameters.

Parameter	Description	Units
$T_{StoV,i}$	Bio-transfer factor for radionuclide *i* from soil to vegetable	-

7.0 Inadvertent Intruder Inhalation Dose

As described in the introduction, the inadvertent intruder is exposed to inhalation dose pathways involving exhumed waste or waste remaining in the exposed disposal facility on which the intruder's home is located. The inhalation pathways assumed to occur are:

1. Inhalation of dust originating from contaminated garden soil while working in a garden.
2. Inhalation of dust originating from contaminated garden soil while residing in a home.
3. Inhalation of dust originating from the waste zone.

Pathways 1 and 2 apply to the chronic intruder agriculture scenario. Pathway 1 is also applied to the chronic intruder post drilling scenario. Pathway 3 applies to the acute intruder basement construction and well drilling scenarios. Figure 7-1 shows a schematic diagram of the sources of dose to an inadvertent intruder through the inhalation pathways.

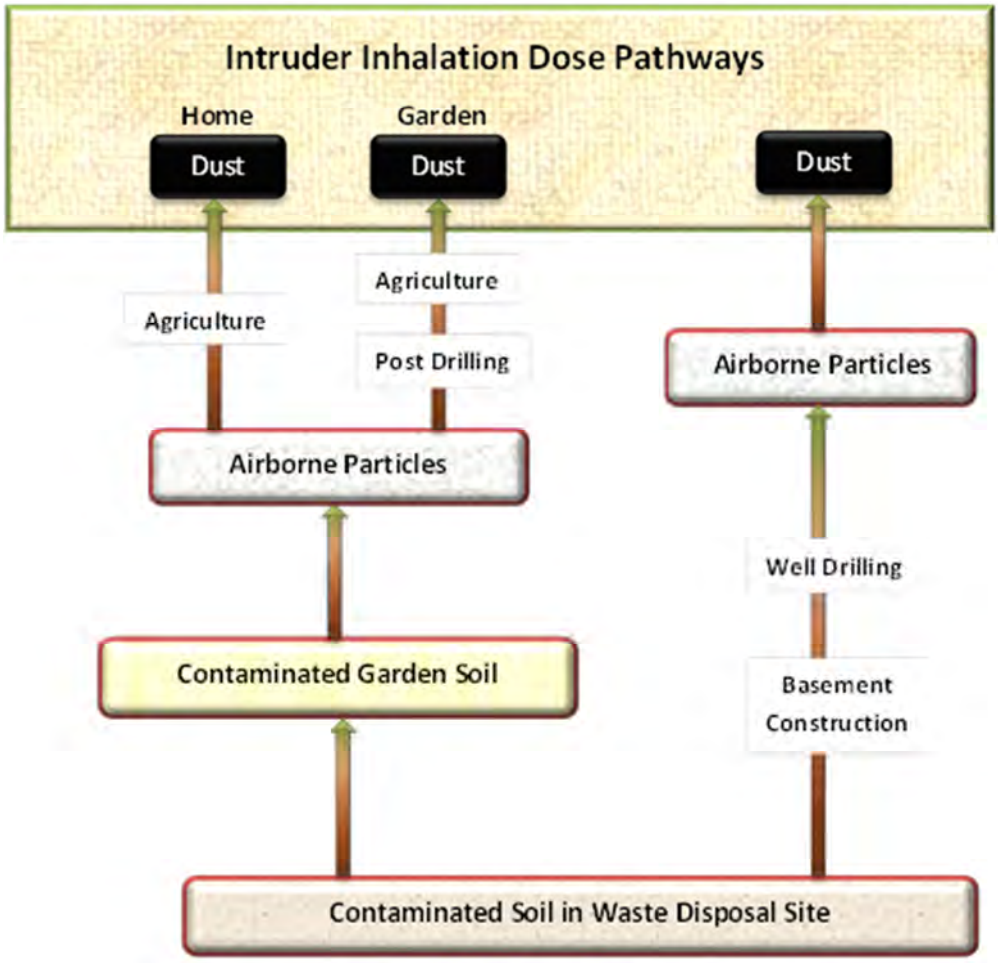

Figure 7-1. Inhalation dose pathways to inadvertent intruder.

7.1 Intruder Inhalation Dose Methodology

The methodology to calculate an intruder inhalation dose is basically the same as that for the inhalation dose to a resident farmer MOP developed in Section 3.1. As with the ingestion dose, intruder inhalation doses are not summed over all possible pathways because, as shown in Figure 7-1, the pathways used depend on the intruder scenario. Therefore, in this case, the dose from each individual pathway is calculated as:

$$D_{inh,k} = \sum_{i=1}^{N} D_{inh,k,i} = \sum_{i=1}^{N} \{EC_{inh,i}\ Inh_{k,i}\} \quad (7.1\text{-}1)$$

Where:

$D_{inh,k}$ ..... Annual average dose from inhalation through pathway *k* (mrem/yr)
$D_{inh,k,i}$ ..... Annual average dose from inhalation of radionuclide *i* through pathway *k* (mrem/yr)
N ..... Number of radionuclides included in the dose calculation
$EC_{inh,i}$ ..... Effective dose coefficient for inhalation of radionuclide *i* (mrem/pCi)
$Inh_{k,i}$ ..... Annual average inhalation of radionuclide *i* through pathway *k* (pCi/yr)

Similar to Eq. (3.1-3), the annual average inhalation rate of radionuclide *i* through pathway *k* is:

$$Inh_{k,i} = F_k\ U_k\ C_{k,i} \quad (7.1\text{-}2)$$

Where:

F_k ..... Fraction of year individual is exposed to contamination through pathway *k* (-)
U_k ..... Annual average rate of inhalation through pathway *k* (m^3/yr)
$C_{k,i}$ ..... Concentration of radionuclide *i* in pathway *k* (pCi/m^3)

The dose to an intruder from inhalation of radionuclide *i* through pathway *k* can then be calculated as:

$$D_{inh,k,i} = EC_{inh,i}\ Inh_{k,i} \quad (7.1\text{-}3)$$

To apply Eq. (7.1-2) and determine the dose to an individual from the inhalation of contaminated material it is necessary to determine the concentration of contaminant in the material.

7.2 Intruder Uptake through Inhalation

Using the equations derived in the previous section, equations to calculate human uptake of contamination can be developed in a relatively straight forward manner for each inhalation pathway.

7.2.1 Inhalation of Dust in Garden

The garden dust inhalation dose pathway is the inadvertent inhalation of airborne contaminated garden soil. The uptake of radionuclide *i* by an intruder through the inhalation of contaminated soil is, in general, calculated as:

$$Inh_{gd,i} = F_s\, U_{air}\, L_{soil}\, \frac{F_{gd,ap}}{\rho_s}\, C_{wz,i} \qquad (7.2\text{-}1)$$

Where:

$Inh_{gd,i}$ ..... Uptake of radionuclide *i* by intruder through the inhalation of contaminated soil during gardening (pCi/yr)
F_s ..... Fraction of year spent in garden (-)
U_{air} ..... Annual human inhalation rate of air (m^3/yr)
L_{soil} ..... Loading of soil in ambient garden air (kg/m^3)
$F_{gd,ap}$ ..... Scenario dependent dilution factor from mixing exhumed waste with native soil in garden for agriculture ($F_{gd,ag}$) or post drilling ($F_{gd,pd}$) activity (-)
ρ_s ..... Bulk soil density (kg/m^3)
$C_{wz,i}$ ..... Concentration of radionuclide *i* in waste zone (pCi/m^3)

7.2.2 Inhalation of Dust in Home

The home inhalation dose pathway during intruder agriculture is the inadvertent inhalation of airborne contaminated soil while residing in the home. It is assumed that contaminated soil from the waste zone is mixed with native soil to form garden soil in developing the source term for this pathway. Similar to Eq. (7.2-1), the uptake of radionuclide *i* by an intruder through the inhalation of contaminated soil in the home is, in general, calculated as:

$$Inh_{res,i} = F_{res}\, U_{air}\, L_{soil,res}\, \frac{F_{gd,ag}}{\rho_s}\, C_{wz,i} \qquad (7.2\text{-}2)$$

Where:

$Inh_{res,i}$ ..... Uptake of radionuclide *i* by intruder through the inhalation of contaminated soil while residing in the home (pCi/yr)
F_{res} ..... Fraction of year spent in home (-)
U_{air} ..... Annual human inhalation rate of air (m^3/yr)
$L_{soil,res}$ ..... Mass loading of soil in home air (kg/m^3)
$F_{gd,ag}$ ..... Dilution factor from mixing exhumed waste with native soil in garden from agriculture activity (-)
ρ_s ..... Bulk soil density (kg/m^3)
$C_{wz,i}$ ..... Concentration of radionuclide *i* in waste zone (pCi/m^3)

7.2.3 Inhalation of Dust during Construction or Drilling

The inhalation dose pathway during basement construction (designated with subscript *bc*) and well drilling (designated with subscript *wd*) is the inadvertent inhalation of airborne contaminated soil. The uptake of radionuclide *i* by an intruder through the inhalation of contaminated soil during basement construction or well drilling is, in general, calculated as:

$$Inh_{cd,i} = F_{cd}\, U_{air,cd}\, L_{soil,cd}\, \frac{1}{\rho_s} C_{wz,i} \qquad (7.2\text{-}3)$$

Where:

$Inh_{cd,i}$ ..... Uptake of radionuclide *i* by intruder through the inhalation of contaminated soil during basement construction ($Inh_{bc,i}$) or well drilling ($Inh_{wd,i}$) (pCi/yr)

F_{cd} ..... Scenario dependent fraction of year spent in basement construction (F_{bc}) or well drilling (F_{wd}) (-)

$U_{air,cd}$ ..... Scenario dependent annual human inhalation rate of air during basement construction ($U_{air,bc}$) or well drilling ($U_{air,wd}$) (m^3/yr)

$L_{soil,cd}$ ..... Loading of soil in air during basement construction ($L_{soil,bc}$) or well drilling ($L_{soil,wd}$) (kg/m^3)

ρ_s ..... Soil density (kg/m^3)

$C_{wz,i}$ ..... Concentration of radionuclide *i* in waste zone (pCi/m^3)

7.3 Intruder Inhalation Dose Equation Summary

Applying Eq. (1.2-1) to summarize the intruder inhalation dose equations with dose coefficient $EC_{inh,i}$ (mrem/pCi) and water source concentration $C_{wz,i}$ (pCi/m^3) gives the results shown in Eq. (7.3-1) and Table 7-1. The intruder inhalation dose equations for each pathway can all be written in the general form:

$$D_{inh,k,i} = EC_{inh,i} \left\{F_k \; R_{k,i} \; U_{air}\right\} C_{wz,i} \tag{7.3-1}$$

Where:

$D_{inh,k,i}$ ..... Annual average dose from ingestion of radionuclide *i* through inhalation pathway *j* (mrem/yr)
i ..... Radionuclide index
k ..... Inhalation pathway index
F_k ..... Fraction of year individual is exposed to contamination through pathway *k* (-)
$R_{k,i}$ ..... Retention factor for radionuclide *i* in inhalation pathway *k* (-)
U_{air} ..... Scenario specific human air inhalation rate (m^3/yr)

In Eq. (7.3-1), the term in brackets is the exposure term shown in Table 7-1. The factor $R_{k,i}$ in Eq. (7.3-1) determines the amount of contaminated waste retained in the particular inhalation pathway. In applying these equations, it is assumed that the buried waste is indistinguishable from native soil and that the contamination is homogeneously mixed within the waste zone. Therefore, the concentration in the waste zone is the average radionuclide concentration at the time the dose is evaluated. In all cases, the Effective Dose Coefficient is $EC_{inh,i}$ (mrem/pCi). Values of parameters used in the inhalation dose equations are provided in Tables 7-2 and 7-3.

Table 7-1. Summary of Intruder Inhalation Dose Equations.

Inhalation Pathway	Scenario	Exposure	Units
Garden Soil	Agriculture	$F_s \frac{F_{gd,ag} \, L_{soil}}{\rho_s} U_{air}$	m^3/yr
	Post Drilling	$F_s \frac{F_{gd,pd} \, L_{soil}}{\rho_s} U_{air}$	m^3/yr
Home Soil	Agriculture	$F_{res} \frac{F_{gd,ag} \, L_{soil,res}}{\rho_s} U_{air}$	m^3/yr
Waste Soil	Well Drilling	$F_{wd} \frac{L_{soil,wd}}{\rho_s} U_{air,wd}$	m^3/yr
	Basement Construction	$F_{bc} \frac{L_{soil,bc}}{\rho_s} U_{air,bc}$	m^3/yr

7.4 Intruder Inhalation Dose Parameters

For immediate reference, nominal values of parameters introduced in calculation of inhalation doses for the intruder scenarios are given below in Table 7-2 and Table 7-3. The hierarchy of references used to obtain the dose parameter values is given in Figure 10-15 where the database is discussed.

Table 7-2. Human Behavior Intruder Inhalation Dose Parameters.

Parameter	Description	Nominal Value		Units
U_{air}	Air inhalation rate	5,000 (Typical)	6,400 (Reference)	m^3/yr
$U_{air,bc}$	Human inhalation rate during construction activity	11,400		m^3/yr
$U_{air,wd}$	Human inhalation rate during drilling activity	8,400		m^3/yr
F_s	Fraction of year spent in garden	0.01		-
F_{bc}	Fraction of year spent constructing basement	0.0183 (160 hr/yr)		-
F_{wd}	Fraction of year spent in well drilling	0.0034 (30 hr/yr)		-
F_{res}	Fraction of year spent residing in home	0.7		-

Table 7-3. Physical Intruder Inhalation Dose Parameters.

Parameter	Description	Nominal Value	Units
$F_{gd,ag}$	Dilution factor for mixing waste with garden soil for agricultural scenario	0.20	-
$F_{gd,pd}$	Dilution factor for mixing waste with garden soil for post drilling scenario	0.02	-
$L_{soil,res}$	Loading of soil in home air	1.0E-08	kg/m^3
L_{soil}	Loading of soil in ambient air	1.0E-07	kg/m^3
$L_{soil,bc}$	Loading of soil in air during construction activity	6.0E-07	kg/m^3
$L_{soil,wd}$	Loading of soil in air during drilling activity	1.0E-07	kg/m^3
ρ_s	Bulk soil density	1,650	kg/m^3

8.0 Inadvertent Intruder External Exposure Dose

As described in the introduction, the inadvertent intruder receives an external dose from direct exposure to contaminated soil. The external exposure pathways assumed to occur are:

1. Exposure to contaminated soil in a garden.
2. Exposure to contaminated soil from the waste zone.
3. Exposure while residing in a home located above the waste disposal site.

Pathway 1 applies to the chronic intruder agriculture and post drilling scenarios. Pathway 2 applies to the acute intruder well drilling, basement construction, and discovery scenarios. Pathway 3 applies to the chronic intruder agriculture and residential scenarios. Figure 8-1 shows a schematic diagram of the sources of dose to an inadvertent intruder through the inhalation pathways. While Figure 8-1 shows soil shielding affecting all of the acute dose pathways, soil shielding typically only impacts the discovery scenario.

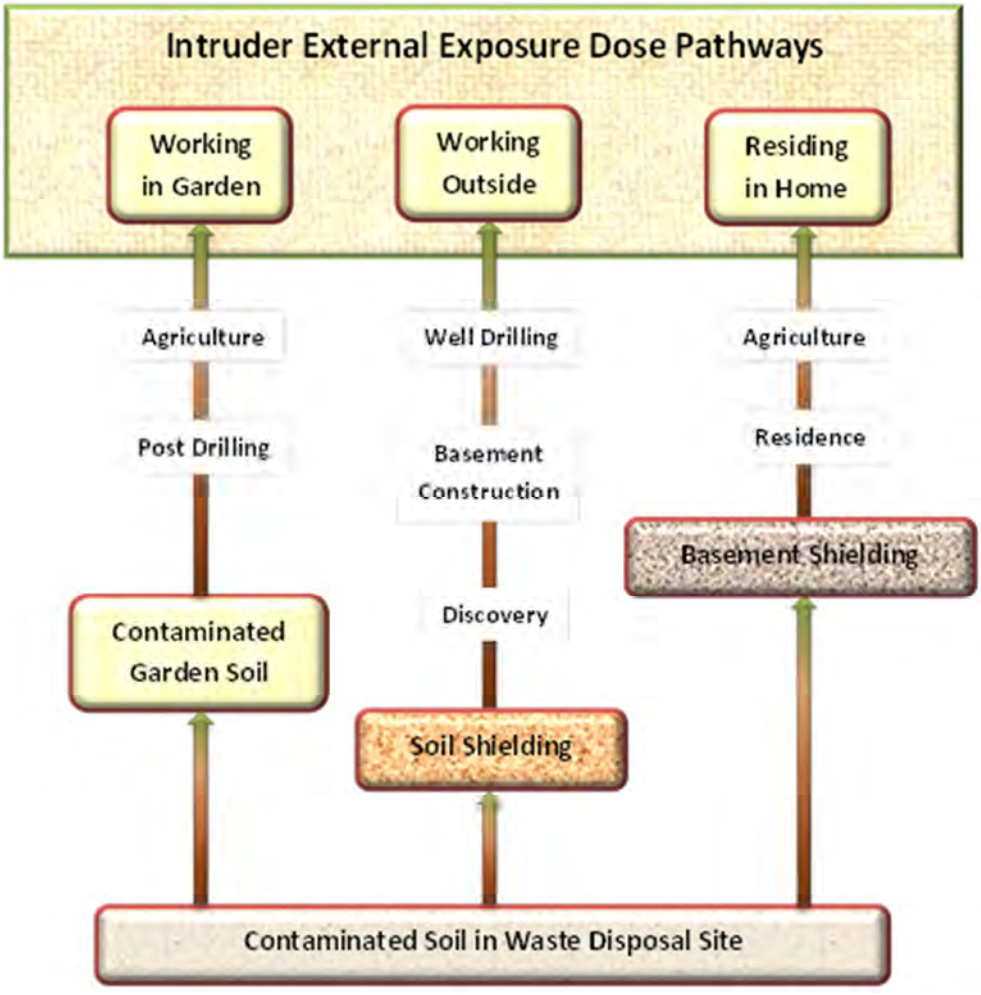

Figure 8-1. External exposure dose pathways to inadvertent intruder.

8.1 Intruder External Exposure Dose Methodology

The methodology to calculate an intruder dose from external exposure is basically the same as that for the external exposure dose to a resident farmer MOP developed in Section 4.1. As illustrated in Figure 8-1, the dose pathways used depend on the intruder scenario. Therefore, as was done in the other intruder dose calculations, the intruder external exposure doses are not summed over all possible pathways to give a total dose. Instead the dose from each individual pathway is calculated as:

$$D_{ext,m} = \sum_{i=1}^{N} D_{ext,m,i} = \sum_{i=1}^{N} \{EC_{ext,m,i}\ Ext_{m,i}\} \quad (8.1\text{-}1)$$

Where:

$D_{ext,m}$ ..... Annual average dose from external exposure through pathway *m* (mrem/yr)
$D_{ext,m,i}$ ..... Annual average dose from external exposure to radionuclide *i* through pathway *m* (mrem/yr)
N ..... Number of radionuclides included in the dose calculation
$EC_{ext,m,i}$ ..... Effective dose coefficient for external exposure to radionuclide *i* through pathway *m* (mrem/yr)/(pCi/m^3)
$Ext_{m,i}$ ..... Annual average exposure to radionuclide *i* through pathway *m* (pCi/m^3)

In general, as shown in Eq. (4.1-2), exposure to radionuclide *i* through pathway *m* is calculated as:

$$Ext_{m,i} = F_m\ C_{m,i} \quad (8.1\text{-}2)$$

Where:

F_m ..... Fraction of time individual is externally exposed to contamination through pathway *m* (-)
$C_{m,i}$ ..... Concentration of radionuclide *i* in external pathway *m* (pCi/m^3)

The dose to a MOP from external exposure to radionuclide *i* through pathway *m* can then be calculated as:

$$D_{ext,m,i} = EC_{ext,m,i}\ Ext_{m,i} \quad (8.1\text{-}3)$$

To apply Eq. (8.1-3) and determine the dose to an individual from the exposure to contaminated material it is necessary to determine the concentration of contaminant in the material.

8.2 Intruder Uptake through External Exposure

Using the equations derived in the previous section, equations to calculate human uptake of radiation dose from external exposure can be developed in a relatively straight forward manner for each pathway.

8.2.1 External Exposure to Garden Soil

Exposure to radionuclide *i* from external contact with contaminated garden soil for either the chronic intruder agriculture or post drilling scenario is calculated as:

$$Ext_{ag,i} = F_s \, F_{gd} \, C_{wz,i} \tag{8.2-1}$$

Where:

$Ext_{ag,i}$ ..... External exposure of radionuclide *i* by intruder through exposure to contaminated garden soil (pCi/m^3)
F_s ..... Fraction of year spent in garden (-)
F_{gd} ..... Scenario dependent dilution factor from mixing exhumed waste with native soil in garden (-)
$C_{wz,i}$ ..... Concentration of radionuclide *i* in waste zone (pCi/m^3)

8.2.2 External Exposure to Contaminated Soil

Exposure to radionuclide *i* by an intruder through external contact with contaminated soil in the waste zone during acute intruder activities can, in the most general case, be calculated as:

$$Ext_{cd,i} = \phi(\delta)_{shield,i} \, F_{cd} \, F_{dil,cd} \, C_{wz,i} \tag{8.2-2}$$

Where:

$Ext_{cd,i}$ ..... External exposure to radionuclide *i* by intruder through the contact with contaminated soil during acute intruder activity (pCi/m^3)
$\phi(\delta)_{shield,i}$ ..... Soil shielding fraction for radionuclide *i* for clean soil depth δ cm (-)
F_{cd} ..... Scenario dependent fraction of year spent in acute intruder activity (-)
$F_{dil,cd}$ ..... Scenario dependent dilution factor for mixing of contaminated and clean soil (-)
$C_{wz,i}$ ..... Concentration of radionuclide *i* in waste zone (pCi/m^3)

As described in the introduction, if physically possible, intruder basement construction is assumed to penetrate into the waste zone or else is not considered. Therefore, for basement construction there is no soil shielding and the clean soil depth is zero. When the clean soil depth is zero:

$$\phi(0)_{shield,i} = 1 \tag{8.2-3}$$

The well drilling scenario assumes exposure to well cuttings containing waste material that have been brought to the surface and mixed with clean soil. Therefore, again for this scenario, the soil shielding fraction is set to 1.0 by using $\delta = 0$. The discovery scenario assumes that the intruder will start basement

excavation but will stop when unusual material such as a geo-membrane or liner is encountered. In this case, soil shielding will apply with δ equal to the remaining distance to the waste zone.

8.2.3 External Exposure in Home

Exposure to radionuclide i from contaminated soil in the waste disposal site for both the intruder agriculture and residence scenarios are, in general, calculated as:

$$Ext_{res,i} = \phi(\delta)_{shield,i}\, F_{res}\, F_{shield}\, C_{wz,i} \tag{8.2-4}$$

Where:

$Ext_{res,i}$ ..... External exposure of radionuclide i by intruder through exposure from contaminated soil during residence in home (pCi/m^3)
$\phi(\delta)_{shield,i}$ ..... Soil shielding fraction for radionuclide i for clean soil depth δ cm (-)
F_{res} ..... Fraction of year spent in home (-)
F_{shield} ..... Shielding fraction in home from basement concrete (-)
$C_{wz,i}$ ..... Concentration of radionuclide i in waste zone (pCi/m^3)

As described in the introduction, if physically possible, the intruder agricultural scenario is assumed to penetrate into the waste zone or is else not considered. Therefore, for the chronic agriculture scenario, there is no soil shielding and the clean soil depth is zero. When the agricultural scenario does not apply, the chronic residential scenario is used which assumes that the intruder resides in a home above the waste disposal site. Typically this scenario is further simplified by assuming that the only shielding between the resident and the waste is from the concrete basement. However, if desired, the additional soil shielding could also be accounted for using Eq. (8.2-4) with δ equal to the distance between the basement and the waste zone.

8.3 Intruder External Exposure Dose Equation Summary

Applying Eq. (1.2-1) to summarize the intruder external exposure dose equations with source concentration $C_{wz,i}$ (pCi/m^3) gives the results shown in Eq. (8.3-1) and Table 8-1. The external exposure dose equations for each pathway can be written in the general form:

$$D_{ext,m,i} = EC_{ext,m,i} \left\{F_m \, R_{m,i}\right\} C_{wz,i} \tag{8.3-1}$$

Where:

$D_{ext,m,i}$ ..... Annual average dose from external exposure to radionuclide *i* through pathway *m* (mrem/yr)
i ..... Radionuclide index
m ..... External exposure pathway index
F_m ..... Fraction of year spent in external exposure pathway *m* (-)
$R_{m,i}$ ..... Retention factor for radionuclide *i* in external exposure pathway *m* (-)

In Eq. (8.3-1), the term in brackets is the exposure term shown in Table 8-1. The factor $R_{m,i}$ in Eq. (8.3-1) determines the amount of contaminated waste retained in the exposure particular pathway. For external exposure, different effective dose coefficients apply for exhumed (garden) soil and soil in the waste zone. The depths of soil in the garden and the drill cuttings pile are assumed to be 15 cm. Values of parameters used in the direct exposure dose equations are provided in Tables 8-2 and 8-3.

Table 8-1. Summary of Intruder External Exposure Dose Equations.

External Exposure Pathway	Scenario	Dose Coefficient (mrem/yr)/(pCi/m^3)	Exposure	Units
Garden Soil	Agriculture	$EC_{ext,15cm,i}$	$F_s \, F_{gd,ag}$	-
	Post Drilling	$EC_{ext,15cm,i}$	$F_s \, F_{gd,pd}$	-
Soil in Waste Zone	Basement Construction	$EC_{ext,\infty,i}$	$F_{bc} \, F_{dil,bc}$	-
	Well Drilling	$EC_{ext,\infty,i}$	$F_{wd} \, F_{dil,wd}$	-
	Discovery	$EC_{ext,\infty,i}$	$\phi(\delta)_{shield,i} \, F_{dis}$	-
Residing in Home	Agriculture	$EC_{ext,\infty,i}$	$F_{shield} \, F_{res}$	-
	Residential	$EC_{ext,\infty,i}$	$\phi(\delta)_{shield,i} \, F_{shield} \, F_{res}$	-

In applying these equations, it is assumed that the buried waste is indistinguishable from native soil and that the contamination is homogeneously mixed within the waste zone. Therefore, the concentration in the waste zone is the average radionuclide concentration at the time the dose is evaluated.

8.4 Intruder External Exposure Dose Parameters

For immediate reference, nominal values of parameters introduced in calculation of external exposure doses for the intruder scenarios are given below in Tables 8-2 and 8-3. The hierarchy of references used to obtain the dose parameter values is given in Figure 10-15 where the database is discussed.

Table 8-2. Human Behavior Intruder External Exposure Dose Parameters.

Parameter	Description	Nominal Value	Units
F_s	Fraction of year spent in garden	0.01	-
F_{bc}	Fraction of year spent constructing basement	0.0183 (160 hr/yr)	-
F_{wd}	Fraction of year spent in well drilling	0.0034 (30 hr/yr)	-
F_{dis}	Fraction of year spent in site discovery	0.0091 (80 hr/yr)	-
F_{res}	Fraction of year spent residing in home	0.5	-

Table 8-3. Physical Intruder External Exposure Dose Parameters.

Parameter	Description	Nominal Value	Units
$F_{gd,ag}$	Dilution factor for mixing waste with garden soil for agricultural scenario	0.20	-
$F_{gd,pd}$	Dilution factor for mixing waste with garden soil for post drilling scenario	0.02	-
$F_{dil,bc}$	Dilution factor for mixing contaminated and clean soil during basement construction	calculated	-
$F_{dil,wd}$	Dilution factor for mixing contaminated and clean soil in drill cuttings	calculated	-
F_{shield}	Shielding factor in home from basement concrete	0.7	-

9.0 Additional Dose Considerations

In this chapter, the following items related to the implementation of the dose calculations described in the previous chapters are discussed:

1. Inclusion of chicken and egg with meat and dairy consumption rates.
2. Special treatment of tritium.

9.1 Human Consumption of Meat and Dairy

Human consumption rates for meat and dairy products used in the dose calculations were obtained from Stone and Jannik (2013). As described in that reference, meat ingestion includes all meats such as beef, chicken and pork and dairy consumption includes milk and eggs. International Atomic Energy Agency (IAEA) Publication 472 (IAEA, 2010) does provide separate coefficients for the bio-transfer of elements to beef, pork, poultry, cow's milk and eggs. Therefore, while the number of elements with reported transfer coefficients are more complete for beef and cow's milk than for the other food sources, in principle, dose coefficients could be created for each food source separately. For example, bio-transfer coefficients for poultry and eggs could be used where available and the values for beef and milk used as default values in cases where specific transfer coefficients are not available. Bio-transfer coefficients for poultry and eggs tend to be much larger than those for beef and milk, respectively, indicating a greater accumulation of radionuclides in poultry and eggs per unit weight. These larger bio-transfer coefficients are partially offset by the significantly smaller consumption of contaminated water and feed by chickens compared to cattle and lower human consumption rates.

Of the 888 radionuclides in the latest database that have ingestion dose coefficients, 515 radionuclides have calculated effective dose conversion factors for poultry consumption greater than the effective dose conversion factors for beef consumption and 514 radionuclides have effective dose conversion factors for egg consumption greater than the effective dose conversion factors for milk consumption. However, many of these 500 or so radionuclides with higher dose conversion factors for poultry and eggs do not contribute significantly to human dose. Of the 162 radionuclides screened for inclusion in the 2008 E-Area PA, only 46 have effective dose conversion factors that are higher for poultry and eggs than the corresponding factors for beef and milk. These 46 radionuclides are listed below in Table 9-1.

Table 9-1. E-Area PA Radionuclides with High Poultry or Egg Dose Conversion Factors.

Ac-228	Bi-212	Co-60	Np-233	Pb-212	Si-32
Am-237	Bi-213	Co-60m	Np-239	Pb-214	Ta-180
Am-241	Bi-214	Fe-60	Pa-234	Po-210	Te-123
Am-243	Cd-113	Ga-68	Pb-202	Pu-243	Th-226
Am-245	Cf-249	In-115	Pb-205	Ru-97	Th-231
Am-246m	Cf-250	Ir-192	Pb-209	Sb-126m	U-240
Au-194	Cf-251	La-137	Pb-210	Sc-44	
Be-10	Cf-252	La-138	Pb-211	Se-79	

As shown in Table 9-1, the 46 radionuclides with higher beef and egg dose conversion factors do not include key radionuclides that typically contribute most to dose such as C-14, Sr-90, Tc-99, I-129, Ra-226 and Np-237. No Pu isotopes appear in the list and the only uranium present is U-240. Radionuclides appearing in the list that might have some significant dose contribution are Am-241, Co-60, Pb-210 and the isotopes of Californium. Based on this analysis, it is concluded that combining poultry with beef consumption and combining eggs with milk consumption is overall a conservative approach.

9.2 Treatment of Tritium in Dose Calculations

As noted by Lee and Coffield (2008) in a footnote to Table 5-3 of their report, the all-pathways dose calculation in the ELLWF PA assumes that the concentration of H-3 in plants is equal to the concentration in the groundwater. Assuming that plants are largely water and that the water in plants is groundwater leads to the conclusion that the H-3 concentration in plants is equal to the concentration in groundwater. This assumption is made despite the fact that there is a published bio-transfer factor for tritium uptake from soil through plant roots so tritium could be treated the same as other elements using the dose equations derived in Chapter 2. Tritium may warrant special treatment because tritiated water can readily exchange tritium with hydrogen in normal water in the environment. The published bio-transfer factors are more appropriate for the transfer of radionuclides in solid form.

Appendix L in the RESRAD 6 User's Guide (Yu et al., 2001) describes special models for both H-3 and C-14 uptake that account for the unique behavior of these radionuclides in the environment. The H-3 concentration in water exposed to contaminated soil is calculated using the equation:

$$C_{sw,H^3} = \frac{\rho_s}{\theta_w \, R_{H^3}} \, C_{s,H^3} \qquad (9.2\text{-}1)$$

Where:

C_{sw,H^3} .....Tritium concentration in water exposed to contaminated soil (pCi/m^3)
C_{s,H^3} .....Tritium concentration in contaminated soil (pCi/kg)
R_{H^3} .....Retardation factor for H-3 in contamination zone
(for $K_{d,H^3} = 0$ $R_{H^3} = 1$)

The tritium concentration in plants grown in the contaminated soil is then calculated as the soil water concentration multiplied by 0.8 which is the assumed mass fraction of water in plants. Similar expressions are derived for tritium uptake through meat and milk ingestion. The RESRAD calculation does not appear to directly account for irrigation with contaminated water and may be more applicable to an intruder analysis where the soil contamination is known. Another set of expressions is derived for C-14 uptake in plants after arguing that using the bio-transfer factor, as was done in Chapter 2, is not appropriate for carbon because plants absorb most of their carbon from the atmosphere as carbon dioxide.

10.0 Radionuclide, Element and Dose Parameter Data Package

A database named "*Radionuclide, Element and Dose Parameter Data Package"*, Version 1.0, has been created as an Excel workbook that provides a system for maintaining, updating and archiving the following data required for ELLWF PA and SRS CA calculations:

- Isotope specific physical parameters and radioactive decay data needed for both transport and dose calculations.
- Isotope-specific dose coefficients and soil shielding factors associated with exposure pathways.
- Radionuclide drinking water concentration limits either published by the EPA or derived from internal dose coefficients to meet the groundwater protection requirements in DOE 435.1 (DOE, 2001).
- Element-specific bio-transfer factors used in dose calculations.
- Physical parameters and human usage/uptake factors used in dose calculations.
- Key physical constants used in the dose calculations

The workbook is divided into nine worksheets containing the actual data and additional worksheets providing diagrams of radionuclide decay chains. Features of the database are described in the following sections.

10.1 Data Package Structure

Figure 10-1 shows the Contents worksheet in the database which gives the organization of the data, the number of radionuclides to which each data set applies, and associated data sources including updated and prior references. The columns shaded in grey list data sources used in the most recent ELLWF PA (WSRC, 2008) and SRS CA (SRNL, 2010). Most of the data sources have changed since publication of the 2008 ELLWF PA. The updated data are compliant with DOE Order 458.1 (DOE, 2011a) and the DOE Derived Concentration Technical Standard (DOE, 2011b).

10.1.1 Configuration Control of Data

Values for all parameters, factors, rates, limits and coefficients listed in this report and Version 1.0 of the "*Radionuclide, Element and Dose Parameter Data Package"* used in the dose calculations described in Chapters 2-8 are all current as of the date of publication of this report. Data used in dose calculations are periodically updated through site specific studies or publication of new national or international consensus reference values such as published by the DOE, EPA and IAEA. Personnel in the Environmental Sciences and Biotechnology group at SRL are responsible for maintaining current dose parameters for use in site PAs and CAs. When these parameters are revised, new values are published in SRNL reports. The "*Radionuclide, Element and Dose Parameter Data Package"* and associated text files will be revised as new information is published. Such updates to the database will be tracked by change log within the database resulting in minor version changes. To avoid frequent revisions to this report, the data included in this document will not be updated to reflect minor revisions in the database. Periodically, accumulated changes will be captured in a revision of this report and a new major version of the accompanying database and associated text files. The database should be consulted to obtain the latest approved data.

The "*Radionuclide, Element and Dose Parameter Data Package"* is maintained on the SRNL High Performance Computing Files System (HPCFS) server with Read and Write access restricted to the database custodian and Read-Only access for all others. Periodic backups are performed as part of regular maintenance of the HPCFS. A data management plan is being prepared to document these controls.

SRNL Radionuclide, Element, and Dose Parameters Data Package							
Initially Compiled - October 2013, Last Updated - March 2015							
Table	**Worksheet**	**Data[a,b]**	**Radionuclides**	**Updated References**	**2010 SRS CA References[f]**	**2008 ELLWF PA References[f]**	**Notes**
	ICRP Table A.1	ICRP table and List of elements	1252	ICRP Publication 107 (ICRP, 2008)			Table from ICRP Publication 107. Data for 11 radionuclides with branching fractions that summed to significantly less than 1.0 were modified based on information in Nuclear Wallet Cards 8th edition, 2011.
1	**Rad Data**	Radionuclide Half-lives, Atomic Mass Units, Specific Activities, and Decay Constants	1252	ICRP Publication 107	2005 Nuclear Wallet Cards (Tuli, 2005)	2005 Nuclear Wallet Cards (Tuli, 2005)	
2	**Rad Decay Data**	Radionuclide Decay Modes, Daughters, Branching Fractions, gross alpha fraction, and beta-gamma fraction	1252	ICRP Publication 107	2005 Nuclear Wallet Cards	2005 Nuclear Wallet Cards	
3	**Dose Coefficients**	**Internal Dose Coefficients**					
		Water Ingestion	888[a]	SRNL-STI-2013-00115 (Stone and Jannik, 2013)	ICRP-72 1995/NCRP 1996	FGR 11 (EPA, 1988)	Based on DOE-STD-1196-2011 reference person (888 radionuclides with half-lives ≥ 10 minutes are included in the DOE Standard)
		Air Inhalation	888[a]	SRNL-STI-2013-00115	ICRP-72 1995/NCRP 1996	FGR 11	Based on DOE-STD-1196-2011 reference person (888 radionuclides with half-lives ≥ 10 minutes are included in the DOE Standard)
		External Exposure Dose Coefficients					
		Water Submersion	1252	DCFPAK 3.02 (Eckerman and Leggett)	EPA 1993	FGR 12 (EPA, 1993)	Identical to values in Federal Guidance Report 12 (EPA-402-R-93-081)
		Air Immersion	1252	DCFPAK 3.02	NA	FGR 12	Differs from values in DOE-STD-1196-2011 for: Ar-37 and Rn-210, 212, 215, 216, 217, 218, 219, 220, 222
		Ground Shine	1252	DCFPAK 3.02	EPA 1993	FGR 12	
		Soil Contamination Dose Coefficients					
		1 cm Depth	1252	DCFPAK 3.02	NA	FGR12	
		5 cm Depth	1252	DCFPAK 3.02	NA	FGR12	
		15 cm Depth	1252	DCFPAK 3.02	EPA 1993	FGR 12	
		Infinite Depth	1252	DCFPAK 3.02	NA	FGR 12	
		Atmospheric Dose Release Factors					
		Site Boundary	15	WSRC-STI-2006-00262[h] (Lee, 2006)	NA	WSRC-STI-2006-00262 (Lee, 2006)	Impact of 1 curie released to the atmosphere from the ELLWF at the Site boundary (Institutional Control Period)
		Facility Boundary	15	WSRC-STI-2006-00262[h] (Lee, 2006)	NA	WSRC-STI-2006-00262 (Lee, 2006)	Impact of 1 curie released to the atmosphere from each type of ELLWF disposal unit (ET, ST, CIG, LAWV, ILV, NRCDA-1 and NRCDA-2) at the facility (100-m) boundary (post-Institutional Control Period)
4	**Water Limits**	**Drinking Water Concentration Limits**					
		gross alpha (15 pCi/L)	160/1252	40-CFR-141 Section 66	40-CFR-141.66	40-CFR-141.15&16	Excluding uranium and radon but including Ra-226
		uranium (30 µg/L)	15/1252	40-CFR-141 Section 66	40-CFR-141.66	40-CFR-141.15&16	Combined uranium isotopes (this MCL is sometimes interpreted to applied to natural uranium only (i.e. U-234, U-235, and U-238))
		radium (5 pCi/L)	2/1252	40-CFR-141 Section 66	40-CFR-141.66	40-CFR-141.15&16	Combined Ra-226 and Ra-228
		beta-gamma (4 mrem/year) (listed in hierarchical order of beta-gamma MCL use)	2	40-CFR-141 Section 66	40-CFR-141.66	40-CFR-141.15&16	H-3 and Sr-90 Concentration causing 4 mrem/year dose on the basis of 2 liters/day drinking water intake and the NBS Handbook 69 (August 1963)
			179 (including H-3 and Sr-90)	EPA-570/9-76-003 Appendix IV	40-CFR-141.66 (DCFs from ICRP-72)	EPA-816-F-00-002, Appendix I	Concentration causing 4 mrem/year dose on the basis of 2 liters/day drinking water intake and the NBS Handbook 69 (August 1963). For multiple radionuclides the sum-of-fractions must be < 1.
			838/888	SRNL-STI-2013-00115 based on DOE-STD-1196-2011 (DOE, 2011)	40-CFR-141.66 (DCFs from ICRP-72)	WSRC-STI-2006-00162 (Cook, 2007)	MCL for reference person based on Derived Concentration Standard[g] for water ingestion (i.e. 100 mrem/year) proportioned to arrive at the 4 mrem/year derived concentration limit.
5	**Shielding**	Kocher Shielding Factors	490	SRNL-STI-2014-00227 and WSRC-TR-2004-00295	NA	Intruder Application KocherShielding.xls	Values from Excel workbook KocherShielding.xls referenced by Lee (2004) and Koffman (2006).
6	**Bio-Transfer**	Soil-to-Vegetable	1252	SRNL-STI-2010-00447, Table 2 (Jannik et al., 2010)	Lee and Coffield, 2008 (NCRP-1996)	Baes et al. 1984, Sheppard 1991 and NRC 1977	Element specific, 100 elements
		Feed-to-Milk	1206	SRNL-STI-2010-00447, Table 3	Lee and Coffield, 2008 (NCRP-1996)	Baes et al., 1984	Element specific, 94 elements
		Feed-to-Meat	1213	SRNL-STI-2010-00447, Table 4	Lee and Coffield, 2008 (NCRP-1996)	Baes et al., 1984	Element specific, 94 elements
		Water-to-Fish	1183	SRNL-STI-2010-00447, Table 5	Lee and Coffield, 2008 (NCRP-1996)	NA	Element specific, 91 elements
7	**Dose Equations & Parameters**	Human Usage Factors	NA	SRNL-STI-2010-00447, Tables 10 & 11, updated by SRNL-STI-2013-00115, Table 11	Taylor et al., 2008/Jannik and Dixon, 2006	Yu et al., 2001	Median (best estimate) and 95% confidence (sensitivity) values
		Physical Parameters	NA	SRNL-STI-2010-00447, Table 1	Jannik and Dixon, 2006/Phifer and Dixon, 2009	Hamby, 1991 and Yu et al., 2001	
8	**Constants**	Key Physical Constants and Conversion Factors	NA	NIST and Various	Various	Various	
Decay Chain Diagrams	**Full Chains**	Full Decay Chains[c]	1252	ICRP Publication 107	2005 Nuclear Wallet Cards	2005 Nuclear Wallet Cards	Spontaneous fission excluded from decay chains
	0.5 Year Chains	Decay Chains (half-lives > 0.5 years)[d]	1252	ICRP Publication 107	2005 Nuclear Wallet Cards	2005 Nuclear Wallet Cards	Spontaneous fission excluded from decay chains
	1 Year Chains	Decay Chains (half-lives > 1 year)[d]	1252	ICRP Publication 107	2005 Nuclear Wallet Cards	2005 Nuclear Wallet Cards	Spontaneous fission excluded from decay chains
	3 Year Chains	Decay Chains (half-lives > 3 years)[d]	1252	ICRP Publication 107	2005 Nuclear Wallet Cards	2005 Nuclear Wallet Cards	Spontaneous fission excluded from decay chains
	5 Year Chains	Decay Chains (half-lives > 5 years)[d]	1252	ICRP Publication 107	2005 Nuclear Wallet Cards	2005 Nuclear Wallet Cards	Spontaneous fission excluded from decay chains
	Copy of Full Chains						Used as starting point to create shorter chains

Figure 10-1. SRNL *Radionuclide, Element and Dose Parameter Data Package* "Contents" worksheet.

10.2 ICRP Table A.1

Physical and decay data for radionuclides was primarily obtained from Table A.1 in International Committee on Radiation Protection (ICRP) Publication 107 (ICRP, 2008). A copy of this table was extracted directly from the publication into the workbook and modified as described below. The ICRP-107 table lists elements in order of increasing atomic number and for each element lists radioisotopes and their corresponding decay products in order of increasing atomic mass. Data for 1252 radionuclides is provided in the reference. Figure 10-2 shows an excerpt from the worksheet listing the uranium isotopes

(U-227 through U-242). The ICRP convention of grouping the data by element and then radionuclide was followed for the data tables in the rest of the data package.

ICRP Publication 107 Table A.1a

Z	Element	Nuclid	Half-life or Branching fraction	Units	Decay mode	Emitted energy (MeV/nt) Alpha	Electron	Photon	Total
92	Uranium	U-227	1.1000E+00	m	A	6.9984	0.096	0.1199	7.2143
		Th-223	1.0000E+00						
		U-228	9.1000E+00	m	ECA	6.6046	0.0231	0.0056	6.6333
		Th-224	9.7500E-01						
		Pa-228	2.5000E-02						
		U-230	2.0800E+01	d	A	5.9681	0.0216	0.0032	5.9929
		Th-226	1.0000E+00						
		U-231	4.2000E+00	d	ECA	0.0002	0.0847	0.0896	0.1745
		Pa-231	1.0000E+00						
		Th-227	4.0000E-05						
		U-232	6.8900E+01	y	A	5.3948	0.0164	0.0023	5.4135
		Th-228	1.0000E+00						
		U-233	1.5920E+05	y	A	4.9013	0.0059	0.0013	4.9085
		Th-229	1.0000E+00						
		U-234	2.4550E+05	y	A	4.843	0.0137	0.002	4.8587
		Th-230	1.0000E+00						
		U-235	7.0400E+08	y	A	4.4693	0.053	0.1669	4.6891
		Th-231	1.0000E+00						
		U-235m	2.6000E+01	m	IT	–	<E-04	<E-04	<E-04
		U-235	1.0000E+00						
		U-236	2.3420E+07	y	A	4.5592	0.0114	0.0018	4.5723
		Th-232	1.0000E+00						
		U-237	6.7500E+00	d	B-	–	0.1991	0.1442	0.3433
		Np-237	1.0000E+00						
		U-238	4.4680E+09	y	ASF	4.2584	0.0092	0.0014	4.2691
		Th-234	1.0000E+00						
		SF	5.4500E-07						
		U-239	2.3450E+01	m	B-	–	0.4108	0.0519	0.4626
		Np-239	1.0000E+00						
		U-240	1.4100E+01	h	B-	–	0.1276	0.0099	0.1374
		Np-240m	1.0000E+00						
		U-242	1.6800E+01	m	B-	–	0.3859	0.0413	0.4272
		Np-242	1.0000E+00						

Figure 10-2. Listing of uranium nuclides extracted from "ICRP Table A.1" worksheet.

The copy of the ICRP table in the Excel worksheet is a slightly compressed version of the listing in Publication 107 with radioisotopes and their first decay products listed in the third column and half-lives and decay branching fractions both listed in the fourth column. For purposes of subsequent data manipulation, it was easy to distinguish between parent isotopes and the daughters because only parent isotopes have units for half-life in the fifth column and decay mode specifications in the sixth column.

In addition to a copy of the ICRP publication table, this worksheet contains some additional information not shown in Figure 10-2 including a list of the 97 elements that appear in the table, element symbols, full names, the number of radionuclide isotopes listed for each element and a list of the 246 stable isotopes that appear in the ICRP table.

10.2.1 Branching Fraction Adjustments

Subsequent analysis of the as published ICRP-107 table revealed that the branching fractions for 124 of the parent nuclides did not sum to unity. This resulted from the use of at most five significant figures in reporting any branching fraction. For example, for As-79 the table gives a branching fraction of 0.97188 for decay to Se-79m and a branching fraction of 0.028121 for decay to Se-79. Each fraction is given to

five significant figures but the sum of these branching fractions is 1.000001 which is not physically possible.

In all, 82 branching fractions summed to greater than one with a maximum discrepancy of 9.5E-05 and 42 branching fractions summed to less than one with a maximum discrepancy of 0.03 for At-219. The discrepancies in branching fractions that summed to greater than one were relatively small while some of the branching fractions that summed to less than one were significantly in error. To correct this problem, information from the *Nuclear Wallet Cards* (8th edition) (Tuli, 2011) was used to correct decay chains for the 11 nuclides with the largest discrepancies in branching fractions that summed to less than one. These modifications to the original ICRP-107 table are clearly indicated in the workbook by highlighting the modified cells in blue. An example of one such correction is shown in Figure 10-3 where the addition of Ra-223 to the Ac-223 decay chain has been made.

After correcting decay chains for the 11 nuclides with the largest discrepancies, 31 branching fractions remained that summed to less than one with a maximum discrepancy of 3.0E-05. This reduced absolute discrepancies in the remaining 113 nuclides with branching fractions that did not sum exactly to one to less than 1.0E-4. These small discrepancies were removed using the simple expedient of reducing or increasing the largest branching fraction for the nuclide to make the sum of branching fractions exactly equal to one.

ICRP Publication 107 Table A.1a

			Half-life or			Emitted	energy	(MeV/nt)	
Z	Element	Nuclid	Branching fraction	Units	Decay mode	Alpha	Electron	Photon	Total
89	Actinium	Ac-223	2.1000E+00	m	ECA	6.6721	0.0254	0.019	6.7165
		Fr-219	9.9000E-01						
		Ra-223	1.0000E-02						
		Ac-224	2.7800E+00	h	ECA	0.5662	0.049	0.2325	0.8477
		Ra-224	9.0900E-01						
		Fr-220	9.1000E-02						
		Ac-225	1.0000E+01	d	A	5.892	0.0248	0.0171	5.9338
		Fr-221	1.0000E+00						
		Ac-226	2.9370E+01	h	B-ECA	0.0003	0.2914	0.1327	0.4245
		Th-226	8.3000E-01						
		Ra-226	1.7000E-01						
		Fr-222	6.0000E-05						
		Ac-227	2.1772E+01	y	B-A	0.0693	0.015	0.0011	0.0853
		Th-227	9.8620E-01						
		Fr-223	1.3800E-02						
		Ac-228	6.1500E+00	h	B-	–	0.4495	0.8671	1.3166
		Th-228	1.0000E+00						
		Ac-230	1.2200E+02	s	B-	–	0.9229	0.544	1.4668
		Th-230	1.0000E+00						
		Ac-231	7.5000E+00	m	B-	–	0.6361	0.419	1.055
		Th-231	1.0000E+00						
		Ac-232	1.1900E+02	s	B-	–	0.9707	1.1528	2.1235
		Th-232	1.0000E+00						
		Ac-233	1.4500E+02	s	B-	–	0.8355	0.4993	1.3348
		Th-233	1.0000E+00						

Figure 10-3. Illustration of adjustments made to "ICRP-107 Table A.1".

10.3 Rad Data: Isotope Physical Parameters

The "**Rad Data**" worksheet lists the 1252 radionuclides included in the ICRP-107 table giving the isotopic atomic weight, atomic mass (AMU), half-life, and the time units in which the half-life is reported. The half-life data and time units were extracted directly from the "**ICRP Table A.1**" worksheet. Some atomic mass units contained in the ICRP-07.ndx file (part of the installable ICRP-07 software package on the CD provided with the publication) were found to be in error. These were corrected by using the values obtained from Magill and Galy (2005).

In addition to the data extracted from the ICRP-107 publication, this worksheet contains the following parameters for each radionuclide that were calculated from the basic data: half-life in years, specific activity in Ci/g, specific activity in Ci/mol, and radionuclide decay constant in inverse years. Figure 10-4 shows an excerpt from the "**Rad Data**" worksheet.

Table 1			ICRP Publication 107 Radionuclide Data								
Select			Data Extracted from ICRP Publication 107				Calculated from ICRP Publication 107 Data				
Z	Element	Nuclid	Atomic Wt.	AMU[a]	Half-life	Units[b]	Half-Life (yr)	Sp. Act. (Ci/g)[c]	Sp. Act. (Ci/mol)	Decay Constant (yr^{-1})	Decay Constant (day^{-1})
1	Hydrogen	H-3	3	3.016049278	1.2320E+01	y	1.2320E+01	9.6210E+03	2.9018E+04	5.6262E-02	1.5404E-04
4	Beryllium	Be-7	7	7.01692983	5.3220E+01	d	1.4571E-01	3.4965E+05	2.4535E+06	4.7571E+00	1.3024E-02
		Be-10	10	10.0135338	1.5100E+06	y	1.5100E+06	2.3643E-02	2.3675E-01	4.5904E-07	1.2568E-09
6	Carbon	C-10	10	10.0168532	1.9255E+01	s	6.1015E-07	5.8492E+10	5.8591E+11	1.1360E+06	3.1103E+03
		C-11	11	11.0114336	2.0390E+01	m	3.8767E-05	8.3746E+08	9.2216E+09	1.7880E+04	4.8952E+01
		C-14	14	14.00324199	5.7000E+03	y	5.7000E+03	4.4789E+00	6.2719E+01	1.2160E-04	3.3294E-07
7	Nitrogen	N-13	13	13.00573861	9.9650E+00	m	1.8946E-05	1.4508E+09	1.8869E+10	3.6585E+04	1.0016E+02
		N-16	16	16.0061017	7.1300E+00	s	2.2594E-07	9.8855E+10	1.5823E+12	3.0679E+06	8.3994E+03
8	Oxygen	O-14	14	14.00859625	7.0606E+01	s	2.2374E-06	1.1406E+10	1.5978E+11	3.0980E+05	8.4820E+02
		O-15	15	15.0030656	1.2224E+02	s	3.8736E-06	6.1515E+09	9.2291E+10	1.7894E+05	4.8992E+02
		O-19	19	19.00358	2.6464E+01	s	8.3859E-07	2.2433E+10	4.2630E+11	8.2656E+05	2.2630E+03

Figure 10-4. Upper portion of data table in "Rad Data" worksheet.

In the upper left hand corner of the worksheet a button labeled **Select** is provided. The user can quickly select an element from the list by entering an identifier in the cell to the right of the button representing the first unique characters in the symbol for the element and clicking on the **Select** button. For example, if the user enters "u" in the cell and clicks on **Select** the uranium isotopes are displayed as shown in Figure 10-5. However, if the user enters "n" the data for N, Ne, Na, Ni, Nb, Nd and Np will be listed. The full list can be displayed by leaving the cell blank and clicking on **Select**. The select feature has been included on most of the worksheet tables.

Table 1			ICRP Publication 107 Radionuclide Data								
Select	u		Data Extracted from ICRP Publication 107				Calculated from ICRP Publication 107 Data				
Z	Element	Nuclid	Atomic Wt.	AMU[a]	Half-life	Units[b]	Half-Life (yr)	Sp. Act. (Ci/g)[c]	Sp. Act. (Ci/mol)	Decay Constant (yr^{-1})	Decay Constant (day^{-1})
92	Uranium	U-227	227	227.031156	1.1000E+00	m	2.0914E-06	7.5291E+08	1.7093E+11	3.3143E+05	9.0739E+02
		U-228	228	228.031374	9.1000E+00	m	1.7302E-05	9.0612E+07	2.0662E+10	4.0062E+04	1.0968E+02
		U-230	230	230.03394	2.0800E+01	d	5.6947E-02	2.7290E+04	6.2777E+06	1.2172E+01	3.3324E-02
		U-231	231	231.036294	4.2000E+00	d	1.1499E-02	1.3456E+05	3.1089E+07	6.0279E+01	1.6504E-01
		U-232	232	232.0371562	6.8900E+01	y	6.8900E+01	2.2361E+01	5.1886E+03	1.0060E-02	2.7543E-05
		U-233	233	233.0396352	1.5920E+05	y	1.5920E+05	9.6360E-03	2.2456E+00	4.3539E-06	1.1920E-08
		U-234	234	234.0409521	2.4550E+05	y	2.4550E+05	6.2220E-03	1.4562E+00	2.8234E-06	7.7301E-09
		U-235	235	235.0439299	7.0400E+08	y	7.0400E+08	2.1605E-06	5.0781E-04	9.8458E-10	2.6956E-12
		U-235m	235	235.0439299	2.6000E+01	m	4.9433E-05	3.0768E+07	7.2319E+09	1.4022E+04	3.8390E+01
		U-236	236	236.045568	2.3420E+07	y	2.3420E+07	6.4668E-05	1.5265E-02	2.9596E-08	8.1030E-11
		U-237	237	237.0487302	6.7500E+00	d	1.8480E-02	8.1606E+04	1.9344E+07	3.7507E+01	1.0269E-01
		U-238	238	238.0507882	4.4680E+09	y	4.4680E+09	3.3612E-07	8.0012E-05	1.5514E-10	4.2474E-13
		U-239	239	239.0542933	2.3450E+01	m	4.4585E-05	3.3542E+07	8.0183E+09	1.5547E+04	4.2564E+01
		U-240	240	240.056592	1.4100E+01	h	1.6085E-03	9.2585E+05	2.2226E+08	4.3093E+02	1.1798E+00
		U-242	242	242.06293	1.6800E+01	m	3.1942E-05	4.6237E+07	1.1192E+10	2.1700E+04	5.9413E+01

Figure 10-5. Selection in data table in "Rad Data" worksheet.

10.3.1 Half-Lives

Half-lives used for the current 2008 ELLWF PA and the SRS CA were obtained from the *Nuclear Wallet Cards 7th edition* (Tuli, 2005). These data are part of Brookhaven National Laboratory's compendium of nuclear data and are widely accepted. However, the latest dose parameters approved by DOE were based on nuclear data given in ICRP Publication 107 (ICRP, 2008). Therefore, for consistency, this source was used to obtain nuclide half-lives.

10.3.2 Decay Constants

Decay constants (λ) are the fraction of a given nuclide which decays in a year. Decay constants used in the current 2008 ELLWF PA and the SRS CA were derived from the half-lives given by Tuli (2005). Because future revisions to the PA and CA will use half-life data from ICRP (2008), decay constants derived from the ICRP data are provided in the data package. Decay constants are given in units of both years^{-1} and days^{-1} and are calculated from the half-life using the following standard equation:

$$\lambda = ln(2)/t_{1/2} \tag{10.1}$$

Where $t_{1/2}$ is the half-life in years or days.

10.3.3 Specific Activity

The specific activity (λ_N) of a nuclide is a ratio between its physical amount in mass or moles and its radioactivity in Curies or Becquerels. Specific activity data used in the 2008 ELLWF PA and the SRS CA were derived from the half-lives given in Tuli (2005). However, because future revisions to the PA and CA will use specific activity data derived from half-lives obtained from ICRP (2008), new specific activity data derived from the ICRP (2008) half-lives and atomic masses are given in the data package. Specific activities are given in units of Curies/gram (λ_N) and Curies/mole ($\hat{\lambda}_N$) and are calculated from half-lives and atomic weights using the following standard equations:

$$\lambda_N\left(\frac{Ci}{g}\right) = \frac{N_A\,\lambda(yr^{-1})}{AMU}\left(\frac{1\ Ci}{3.7\times10^{10}dps}\right)\left(\frac{1yr}{365.25\ d\times24\ hr/d\times3600\ s/hr}\right) \tag{10.2}$$

$$\hat{\lambda}_N(Ci/mol) = AMU \bullet \lambda_N(Ci/g) \tag{10.3}$$

In equations (10.2) and (10.3), N_A is Avogadro's number (atoms/mol) and AMU is the atomic mass units of the radionuclide (g/mol).

10.4 Rad Decay Data

The "**Rad Decay Data**" worksheet gives decay chain data for each of the 1252 radionuclides listed in the ICRP-107 table. Decay chain data consists of daughter nuclides, decay modes, and decay fractions. ICRP-107 lists at most five daughter nuclides for any parent. Only one nuclide (Es-254m) has more than three decay modes. The section of the "**Rad Decay Data**" table for plutonium isotopes is show in Figure 10-6 as an example of the data presented. Branching fractions that have been increased to make the total sum to one are highlighted in blue. Branching fractions that have been decreased to make the total sum to one are highlighted in green. The two columns on the right hand side of the table show gross-alpha and beta-gamma fractions calculated for the nuclide as discussed below in Section 10.4.3.

Table 2			ICRP Publication 107 Radionuclide Decay Dat										
Select	pu		(This table was created from the modified ICRP-107 data in worksheet ICRP Table A.1. The data is further adj										
Z	Element	Nuclid	Decay mode 1[a]	Daughter 1[b]	Fraction 1[c]	Decay Mode 2[a]	Daughter 2[b]	Fraction 2[c]	Decay Mode 3[a]	Daughter 3[b]	Fraction 3[c]	147 Gross Alpha[d]	1167 Beta-Gamma[e]
94	Plutonium	Pu-232	EC	Np-232	0.77	A	U-228	0.23	na	na	na	0.23	0.77
		Pu-234	EC	Np-234	0.94	A	U-230	0.06	na	na	na	0.06	0.94
		Pu-235	EC	Np-235	0.999971	A	U-231	0.000027	na	na	na	0	1
		Pu-236	A	U-232	0.99999999863	SF	SF	0.00000000137	na	na	na	1	0
		Pu-237	EC	Np-237	0.999958	A	U-233	0.000042	na	na	na	0	1
		Pu-238	A	U-234	0.99999999815	SF	SF	1.85E-09	na	na	na	1	0
		Pu-239	A	U-235m	0.9994	A	U-235	0.0006	na	na	na	1	0
		Pu-240	A	U-236	0.9999999425	SF	SF	5.75E-08	na	na	na	1	0
		Pu-241	B-	Am-241	0.9999755	A	U-237	0.0000245	na	na	na	0	1
		Pu-242	A	U-238	0.99999446	SF	SF	0.00000554	na	na	na	1	0
		Pu-243	B-	Am-243	1	na	na	na	na	na	na	0	1
		Pu-244	A	U-240	0.99879	SF	SF	0.00121	na	na	na	0.99879	0.00121
		Pu-245	B-	Am-245	1	na	na	na	na	na	na	0	1
		Pu-246	B-	Am-246m	1	na	na	na	na	na	na	0	1

Figure 10-6. Portion of data table for plutonium isotopes in "Rad Decay Data" worksheet.

10.4.1 Decay Modes

Decay modes are the processes by which radioactive decay occurs. Decay modes used in recent 2008 ELLWF PA and the SRS CA modeling were taken from Tuli (2005). These decay modes are widely accepted; however, the latest concentration standards and dose coefficients approved by DOE use the data provided in ICRP-107. Therefore, for consistency, the ICRP-107 data has been used in the database. The radioactive decay modes in the ICRP-107 table are: alpha, beta, internal (also called isomeric) transition and electron capture and/or positron emission. Spontaneous fission is also noted, but because it can result in many different daughter nuclides and because most (but not all) branching fractions to spontaneous fission are small, has not been considered in PA/CA modeling (see Branching Fractions Section 10.4.2 below for further discussion). Additionally, some nuclides decay in minor fractions by ejecting other nuclides. This happens almost universally in extremely small fractions and these decay modes are not included in ICRP-107.

While decay modes are listed in the ICRP-107 table, they cannot clearly be related to the corresponding daughter. Therefore, decay modes were assigned to each daughter nuclide according to the decay mechanisms:

$$\alpha\ decay\text{:}\ {}^{A}_{Z}N \rightarrow {}^{A-4}_{Z}N + \alpha$$
$$\beta\ decay\text{:}\ {}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N + \beta^{-}$$
$$electron\ capture\text{:}\ {}^{A}_{Z}N + e^{-} \rightarrow {}^{A}_{Z-1}N$$
$$isomeric\ transition\text{:}\ {}^{A}_{Z}N \rightarrow {}^{A}_{Z}N + \gamma$$

10.4.2 Branching Fractions

Branching fractions are the fractions of the total decay that produces a specific daughter. Branching fractions used in 2008 ELLWF PA and SRS CA modeling were derived from decay modes given in the *Nuclear Wallet Cards 7th edition* published by Brookhaven National Laboratory (Tuli, 2005). While widely accepted, this source is not complete for all branching fractions because the decay modes given do not distinguish between fractions going to metastable or ground states of the same nuclide.

In addition to being used to produce the approved dose concentration standards and internal dose coefficients given in the new DOE Standard: *Derived Concentration Technical Standard* (DOE, 2011b) ICRP-107 gives true branching fractions that distinguish both ground state and metastable daughters. Therefore, ICRP-107, with the adjustments described in Section 10.2.1, was used as the reference source for branching fractions listed in the database.

Some of the actinide nuclides have spontaneous fission as one of their decay modes, and in a few nuclides it can be a significant fraction (e.g., 0.74 for Cm-250). Spontaneous fission has not been included in previous PA or CA analyses because the number of different daughter nuclides is excessive and, for some nuclides, not readily available. Therefore, other than to note that spontaneous fission is a decay mode and to what extent it takes place for the various nuclides, the table does not include detailed information about the daughters. However, it appears that the effective dose coefficients for nuclides with spontaneous fission may account for spontaneous fission decay.

10.4.3 Gross Alpha and Beta-Gamma Fractions

To calculate groundwater protection doses to a MOP resulting from concentrations of radionuclides in groundwater, the radionuclides are grouped into categories of those contributing to an alpha dose, a beta-gamma dose, a uranium dose, or a radium dose. As part of the determination of which category each radionuclide belongs to, an alpha decay fraction and beta-gamma decay fraction were determined for each

radionuclide based on the decay mode and branching fraction. The alpha fraction was calculated as the sum of the branching fractions for alpha decay modes (Pu-239 is the only nuclide with two alpha decay modes). The beta-gamma fraction was calculated by subtracting the alpha fraction from one. In equation form, where b_i is the branching fraction for decay mode *i*:

$$f_\alpha = \sum_{i=1}^{\substack{decay \\ modes}} b_i \, (f_\alpha)_i \quad \text{and } f_{\beta-\gamma} = 1 - f_\alpha \tag{10.4}$$

Because spontaneous fission products typically decay further through beta or gamma emissions, spontaneous fission decay fractions have been included in the beta-gamma fraction.

As noted in Section 10.2.1, decay modes for 11 nuclides with total branching fractions significantly less than one were adjusted using the information in *Nuclear Wallet Cards 8th edition* (Tuli, 2011). In addition, as described in Section 10.2.1, minor adjustments were made to branching fractions for another 113 nuclides so that they summed identically to one. Because the gross-alpha and beta-gamma fraction are only used to determine groundwater protection limits, alpha decay fractions less than 0.001 were rounded to zero and alpha decay fractions greater than 0.999 were rounded to one before applying equation (10.4). Following this approach, 85 nuclides have total gross-alpha branching fractions equal to one, 1105 nuclides have total beta-gamma branching fractions equal to one, and the remaining 62 nuclides have both alpha and beta-gamma branching fractions.

10.5 Effective Dose Coefficients

Effective dose coefficients are used to calculate the radioactive dose received from radionuclides to the concentration of the nuclide in the environment. Effective dose coefficients were historically referred to as Dose Conversion Factors (DCFs) in earlier DOE (DOE, 1999a) and EPA (EPA, 1976) references. Both terms are used interchangeably in this data package report. DCFs have been published for both internal exposure and external exposure. Internal exposure DCFs have been published for ingestion of water and inhalation of air. Ingestion DCFs relate dose received to the amount of nuclide ingested, and inhalation DCFs relate dose to the amount of nuclide inhaled. External exposure DCFs are also available to determine the effective whole body dose from submersion in contaminated water, immersion in air, and from ground shine. Both types of DCFs take into account the elemental chemistry and biochemistry of the nuclide in the body, mode of decay, and energy of the decay. Hence the note at the end of Section 10.4.2 that fission product decay has been factored into the DCFs and does not need to be accounted for separately.

In 2011, DOE issued new guidance (DOE, 2011b) for internal dose factors. Effective dose coefficients are provided for the 888 nuclides in ICRP-107 publication having a half-life ≥ 10 min, excluding noble gases. The coefficients are based on the bio-kinetic models in EPA Federal Guidance Report #12 (Eckerman and Ryman, 1993). The new DCFs give information for a reference person, who is a composite average of both sexes and all age groups living in the United States. These DCFs were analyzed by Stone and Jannik (2013) and values recommended for use in SRS PAs and CAs determined. Dose coefficients in the "*Radionuclide, Element and Dose Parameter Data Package"* have been taken directly from Stone and Jannik (2013) and are provided in the "**Dose Coefficients**" worksheet. A portion of this worksheet containing the internal and external exposure dose factors is shown in Figure 10-7 below.

Table 3			Internal Exposure Dose Coefficients[a]				21	External Exposure Effective Dose Coefficients[b]					
Select			Water Ingestion		Air Inhalation			Water Submersion		Air Immersion		Ground Shine	
Z	Element	Nuclid	Sv/Bq	mrem/pCi	Sv/Bq	mrem/pCi		Sv/s per Bq/m^3	mrem/yr per pCi/m^3	Sv/s per Bq/m^3	mrem/yr per pCi/m^3	Sv/s per Bq/m^2	mrem/yr per pCi/m^2
1	Hydrogen	H-3	2.10E-11	7.77E-08	1.93E-11	7.14E-08		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	Beryllium	Be-7	3.48E-11	1.29E-07	6.40E-11	2.37E-07		4.81E-18	5.62E-07	2.21E-15	2.58E-04	4.76E-17	5.56E-06
		Be-10	1.56E-09	5.77E-06	3.66E-08	1.35E-04		1.55E-19	1.81E-08	1.39E-16	1.62E-05	3.44E-18	4.02E-07
6	Carbon	C-10	na	na	na	na		1.71E-16	2.00E-05	7.90E-14	9.22E-03	1.76E-15	2.06E-04
		C-11	3.10E-11	1.15E-07	2.56E-12	9.47E-09		9.90E-17	1.16E-05	4.56E-14	5.32E-03	1.00E-15	1.17E-04
		C-14	6.33E-10	2.34E-06	6.70E-12	2.48E-08		2.89E-21	3.37E-10	2.60E-18	3.04E-07	1.28E-20	1.49E-09
7	Nitrogen	N-13	na	na	na	na		9.91E-17	1.16E-05	4.57E-14	5.34E-03	1.03E-15	1.20E-04
		N-16	na	na	na	na		5.63E-16	6.57E-05	2.59E-13	3.02E-02	3.44E-15	4.02E-04
8	Oxygen	O-14	na	na	na	na		3.52E-16	4.11E-05	1.63E-13	1.90E-02	3.03E-15	3.54E-04
		O-15	na	na	na	na		9.95E-17	1.16E-05	4.60E-14	5.37E-03	1.07E-15	1.25E-04
		O-19	na	na	na	na		9.83E-17	1.15E-05	4.60E-14	5.37E-03	1.03E-15	1.20E-04
9	Fluorine	F-17	na	na	na	na		9.95E-17	1.16E-05	4.60E-14	5.37E-03	1.07E-15	1.25E-04
		F-18	6.24E-11	2.31E-07	6.64E-11	2.46E-07		9.58E-17	1.12E-05	4.41E-14	5.15E-03	9.49E-16	1.11E-04
10	Neon	Ne-19	na	na	na	na		9.98E-17	1.17E-05	4.63E-14	5.41E-03	1.09E-15	1.27E-04
		Ne-24	na	na	na	na		5.33E-17	6.22E-06	2.48E-14	2.90E-03	6.15E-16	7.18E-05
11	Sodium	Na-22	3.88E-09	1.44E-05	3.15E-08	1.17E-04		2.20E-16	2.57E-05	1.02E-13	1.19E-02	2.05E-15	2.39E-04
		Na-24	5.46E-10	2.02E-06	5.83E-10	2.16E-06		4.51E-16	5.27E-05	2.08E-13	2.43E-02	3.59E-15	4.19E-04
12	Magnesium	Mg-27	na	na	na	na		8.98E-17	1.05E-05	4.16E-14	4.86E-03	9.25E-16	1.08E-04
		Mg-28	2.82E-09	1.04E-05	1.50E-09	5.55E-06		1.38E-16	1.61E-05	6.38E-14	7.45E-03	1.26E-15	1.47E-04

Figure 10-7. Upper portion of table containing internal and external dose conversion factors in "Dose Coefficients" worksheet.

Water ingestion and air inhalation DCFs are given in the left-hand columns of the worksheet in units of Sv/Bq and mrem/pCi. Water ingestion DCFs are identical to the values that appear in DOE 2011b. In a few cases, more than one DCF is given for a nuclide in the reference. For H^3 the recommended DCF is that for tritiated water (H^3-OH), for sulfur, mercury and polonium nuclides, the recommended DCFs are those for inorganic forms.

Inhalation DCFs in the original source (DOE, 2011b) are given for all nuclides for three lung absorption types (fast, medium and slow) and, in a few instances, for vapor (isotopes of H, Ni, Ru, Te and Hg) or gas (isotopes of H, C, S, I and Hg) forms. Table 4 in DOE 2011b provides recommended default absorption types that should be used when no further information is available. These recommended types were adopted by Stone and Jannik (2013) and are reproduced in the "**Dose Coefficients**" worksheet. The user will see that columns D-O of worksheet "**Dose Coefficients**" are hidden. These columns contain a full listing of the ingestion and inhalation DCFs given in the DOE standard (DOE, 2011b) and indicate which adsorption type was selected. While this additional information may be useful and, in some instances, it may even be appropriate to use other DCF values, these columns are hidden so the worksheet only displays the DCFs recommended for use in PAs and CAs.

External DCFs in the "**Dose Coefficients**" worksheet, shown in Figure 10-7, relate dose received by a reference person to nuclide concentrations in air and water surrounding an individual and to contamination on ground surfaces around the individual. DCFs for all 1252 nuclides in the ICRP-107 Publication were obtained from data files provided with the DCFPACK 3.0 software (Eckerman and Leggett, 2013). Values of DCFs from exposure to soil contamination at various depths were also obtained from the DCFPACK 3.0 files. These values are given for contamination in soil to depths of 1 cm, 5 cm, and 15 cm, and to an infinite depth. A portion of the Dose Coefficients worksheet containing the soil contamination dose coefficients is shown in Figure 10-8, below.

Table 3			Soil Contamination Effective Dose Coefficients[b]							
Select			1 cm Depth		5 cm Depth		15 cm Depth		Infinite Depth	
Z	Element	Nuclid	Sv/s per Bq/m^3	mrem/yr per pCi/m^3	Sv/s per Bq/m^3	mrem/yr per pCi/m^3	Sv/s per Bq/m^3	mrem/yr per pCi/m^3	Sv/s per Bq/m^3	mrem/yr per pCi/m^3
1	Hydrogen	H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	Beryllium	Be-7	3.03E-19	3.54E-08	8.63E-19	1.01E-07	1.32E-18	1.54E-07	1.45E-18	1.69E-07
		Be-10	1.98E-21	2.31E-10	4.25E-21	4.96E-10	5.35E-21	6.25E-10	5.43E-21	6.34E-10
6	Carbon	C-10	1.07E-17	1.25E-06	3.03E-17	3.54E-06	4.70E-17	5.49E-06	5.24E-17	6.12E-06
		C-11	6.21E-18	7.25E-07	1.77E-17	2.07E-06	2.72E-17	3.18E-06	3.00E-17	3.50E-06
		C-14	3.47E-23	4.05E-12	5.54E-23	6.47E-12	5.92E-23	6.91E-12	5.92E-23	6.91E-12
7	Nitrogen	N-13	6.23E-18	7.27E-07	1.77E-17	2.07E-06	2.72E-17	3.18E-06	3.00E-17	3.50E-06
		N-16	2.28E-17	2.66E-06	6.73E-17	7.86E-06	1.19E-16	1.39E-05	1.73E-16	2.02E-05
8	Oxygen	O-14	1.91E-17	2.23E-06	5.56E-17	6.49E-06	9.11E-17	1.06E-05	1.12E-16	1.31E-05
		O-15	6.28E-18	7.33E-07	1.78E-17	2.08E-06	2.73E-17	3.19E-06	3.01E-17	3.51E-06
		O-19	5.87E-18	6.85E-07	1.64E-17	1.91E-06	2.59E-17	3.02E-06	3.04E-17	3.55E-06
9	Fluorine	F-17	6.28E-18	7.33E-07	1.78E-17	2.08E-06	2.73E-17	3.19E-06	3.01E-17	3.51E-06
		F-18	6.01E-18	7.02E-07	1.71E-17	2.00E-06	2.64E-17	3.08E-06	2.91E-17	3.40E-06
10	Neon	Ne-19	6.33E-18	7.39E-07	1.79E-17	2.09E-06	2.74E-17	3.20E-06	3.02E-17	3.53E-06
		Ne-24	3.38E-18	3.95E-07	9.50E-18	1.11E-06	1.46E-17	1.70E-06	1.61E-17	1.88E-06
11	Sodium	Na-22	1.31E-17	1.53E-06	3.76E-17	4.39E-06	5.97E-17	6.97E-06	6.90E-17	8.06E-06
		Na-24	2.31E-17	2.70E-06	6.79E-17	7.93E-06	1.14E-16	1.33E-05	1.46E-16	1.70E-05
12	Magnesium	Mg-27	5.41E-18	6.32E-07	1.54E-17	1.80E-06	2.44E-17	2.85E-06	2.81E-17	3.28E-06
		Mg-28	8.01E-18	9.35E-07	2.31E-17	2.70E-06	3.70E-17	4.32E-06	4.37E-17	5.10E-06

Figure 10-8. Upper portion of table containing soil contamination dose coefficients in "Dose Coefficients" worksheet.

Dose Release Factors (DRF's, mrem/Ci) have been calculated by Lee (2006) for the 15 volatile radionuclides used in the air pathways analysis at SRS. These DRF's represent the impact at the facility and site boundary of releasing one curie of each volatile radionuclide to the atmosphere from the ELLWF disposal units. The DRF's were used by Hiergesell and Taylor (2011) in the most recent analysis of the Air Pathway dose from the ELLWF. The DRF values have been included in the "**Dose Coefficients**" worksheet as shown in Figure 10-9. The DRF values have not been updated from those provided in the original reference (Lee, 2006).

The DRF's calculated by Lee (2006) will need to be updated using the latest Site meteorological data (current data found in CAP88 version 4.0, and MAXDOSE-SR 2013) and updated dose coefficients and human uptake factors (Stone and Jannik 2013, and Eckerman and Legget 2013, for external DCFs) before the next PA revision. To show compliance with NESHAPs, the CAP88 PC code would need to be used, unchanged and unmodified. However, nearly all of the input parameters used in CAP88 will be different from the updated values provided by Stone and Jannik (2013). To determine the actual Air Pathway dose, the MAXDOSE-SR code would be used, which contains all of the factors from Stone and Jannik (2013).

Atmospheric Dose-Release Factors[c]											
Gas Data[d]				Site Boundary DRF	E-Area Waste Disposal Facility[e] DRF at 100 m Boundary (mrem/Ci)						
Nuclide	Gas Species	Mol. Wt. (g/mol)	D_g (m^2/yr)[f]	Total (mrem/Ci)	NR26E	NR7E	CIG	LAW	ILV	Slit Trench	Engineered Trench
C-14	CO_2	46	762.6	1.1E-04	7.0E-02	3.5E-01	5.9E-02	5.9E-02	3.5E-01	5.9E-02	5.9E-02
Cl-36	HCl	37	850.3	2.3E-04	1.1E-01	5.6E-01	9.3E-02	9.3E-02	5.6E-01	9.3E-02	9.3E-02
H-3	H_3OH	20	1156.5	2.2E-06	1.5E-03	7.3E-03	1.2E-03	1.2E-03	7.3E-03	1.2E-03	1.2E-03
I-129	HI	130	453.6	4.9E-02	1.0E+02	5.2E+02	8.6E+01	8.6E+01	5.2E+02	8.6E+01	8.6E+01
S-35	S	35	874.3	2.8E-05	9.3E-03	4.6E-02	7.7E-03	7.7E-03	4.6E-02	7.7E-03	7.7E-03
Sb-124	$SbCl_3$	229	341.8	2.0E-03	6.8E-01	3.4E+00	5.7E-01	5.7E-01	3.4E+00	5.7E-01	5.7E-01
Sb-125	$SbCl_3$	230	341.0	6.5E-03	2.0E+00	1.0E+01	1.7E+00	1.7E+00	1.0E+01	1.7E+00	1.7E+00
Se-75	H_2Se	77	589.4	1.1E-03	3.7E-01	1.8E+00	3.1E-01	3.1E-01	1.8E+00	3.1E-01	3.1E-01
Se-79	H_2Se	81	574.7	6.3E-04	2.2E-01	1.1E+00	1.8E-01	1.8E-01	1.1E+00	1.8E-01	1.8E-01

Figure 10-9. Upper portion of table containing atmospheric dose release factors in "Dose Coefficients" worksheet.

10.6 Water Limits: Drinking Water Concentration Limits

The maximum concentration of radionuclides in drinking water must be such that the DOE established dose limit of 100 mrem/yr to a MOP is not exceeded. Additionally, concentration standards based on the EPA drinking water limits must also be met as summarized below. A brief description of the origin and application of drinking water standards is given in Table 10-1.

For alpha emitting radionuclides (including Ra-226 but excluding Ra-228), the limit in drinking water is a concentration of 15 pCi/L. A separate radium limit of 5 pCi/L is established for combined Ra-226 and Ra-228. For uranium isotopes, the EPA concentration limit is 30 μg/L. The uranium limit has been converted into equivalent units of pCi/L for each uranium isotope in the data base. Parent radionuclides of both radium and uranium will lead to the production of these two elements. For dose modeling purposes, inventory limits based on uranium and radium doses are established for the parent nuclides.

For beta or photon emitters (β–γ) the EPA limits the annual dose for safe drinking water to 4 mrem/yr. Ordinarily, concentration limits calculated from the DOE 100 mrem/yr dose standards or from the DCFs would be used to determine concentration limits corresponding to the 4 mrem/yr dose limit from beta or photon emitters. However, the EPA has specifically set concentration limits for 179 nuclides in 40 CFR Part 141 (see also EPA, 1976). In general, because the EPA calculated concentration limits are intended to obtain a drinking water dose limit of 4 mrem/yr, they should be considered the limiting concentrations. In most cases, the EPA concentration limits are more conservative than limits derived from dose conversion factors. In a few cases (e.g., Cs-135, Cs-136 and Cs-137) the limits calculated using the new DCFs would be more conservative. Nevertheless, the EPA derived concentration limits are applied for the 179 nuclides for which they are available. Beta-gamma limits are not applied to uranium.

Table 10-1. EPA Groundwater Protection Performance Objectives - Maximum Concentration Limits

Data	Reference	Radionuclides	Notes
gross alpha (15 pCi/L)	40 CFR Part 141 Section 66	160	Excluding uranium and radon but including Ra-226.
uranium (30 mg/L)	40 CFR Part 141 Section 66	15	Combined uranium isotopes. This MCL is sometimes interpreted to apply to natural uranium only (U-234, U-235, and U-238).
radium (5 pCi/L)	40 CFR Part 141 Section 66	2	Combined Ra-226 and Ra-228.
beta-gamma (4 mrem/yr) (listed in hierarchical order of beta-gamma MCL use)	40 CFR Part 141 Section 66	2 (H-3 and Sr-90)	Concentration causing 4 mrem/yr dose on the basis of 2 liters per day drinking water intake and the NBS Handbook 69 (NBS, 1963). For multiple radionuclides the sum-of-fractions must be less than one.
	EPA-570/9-76-003 Appendix IV	179 (including H-3 and Sr-90)	Concentration causing a 4 mrem/yr dose on the basis of a 2 liters per day drinking water intake and the NBS Handbook 69 (NBS, 1963).
	SRNL-STI-2013-00115 based on DOE-STD-1196-2011	838	95% Reference Person Derived Concentration Standard[1] for water ingestion (100 mrem/yr) proportioned to arrive at the 4 mrem/year derived concentration limit.

[1] The 95% Reference Person Derived Concentration Standard for water ingestion (100 mrem/yr) in SRNL-STI-2013-00115 is based on an intake of 2.2 L/day water; whereas the EPA's 4 mrem/yr MCLs are based upon an intake of 2.0 L/day. In addition to the adjustment from 100 to 4 mrem/yr, a further adjustment to account for the difference in water intake could be made which results in an increase in the calculated MCL or derived concentration limits by a factor of 1.1.

As noted in Section 10.4.3, 62 nuclides have both alpha and beta-gamma decay paths that account for at least 0.1% of the total branching fraction. Of these 62 nuclides, 15 do not have water ingestion dose conversion factors so no derived beta-gamma MCL can be computed and they are counted as having alpha decay alone when determining dose. A number of possible methods were considered for handling the remaining 47 nuclides with both alpha and beta-gamma decay paths including:

1. Assigning all 47 nuclides to the alpha dose pathway because internal dose from alpha emissions is typically larger.
2. Assigning the entire dose from the nuclide to the pathway having the largest branching fraction. Using this method, 39 nuclides would be assigned to the beta-gamma pathway and 8 to the alpha pathway.
3. Calculating a modified MCL for each pathway based on the branching fractions and assigning the nuclide to the pathway having the lower MCL. The modified alpha and beta-gamma MCLs would be calculated as:

$$\overline{MCL}_{\alpha} = [15\ pCi/L]\left[\frac{1}{f_{\alpha}}\right] \tag{10.5}$$

$$\overline{MCL}_{\beta-\gamma} = \left[\frac{4\ mrem/yr}{(DCF\ mrem/pCi)\ (2\ L/d)(365.25\ d/yr)}\right]\left[\frac{1}{f_{\beta-\gamma}}\right] \tag{10.6}$$

Using this method, 32 nuclides would be assigned to the alpha pathway and 15 to the beta-gamma pathway.

4. Calculating derived MCLs as in Option #3 and applying them to both dose pathways.

Option #4 was selected because beta-gamma doses are typically limiting in PA and CA dose calculations and this option weighted the beta-gamma dose more heavily while still allowing some contribution to the alpha dose. It was recognized that weighting the dose by the branching fractions is not strictly correct because alpha and beta-gamma doses are related to the emission energy as well as the source strength. However, lacking additional information, this method was deemed acceptable. Calculations of derived MCLs and the selection of a dose pathway are included in the "**Water Limits**" spreadsheet. Using the modified MCLs in Equations (10.5) and (10.6) to determine concentration limits is equivalent to using the unmodified MCLs given in equations (10.7) and (10.8) and adjusting the nuclide concentration by multiplying by the alpha or beta-gamma branching fractions as shown in Equation (10.9).

$$MCL_{\alpha} = [15\ pCi/L] \tag{10.7}$$

$$MCL_{\beta-\gamma} = \left[\frac{4\ mrem/yr}{(DCF\ mrem/pCi)\ (2\ L/d)(365.25\ d/yr)}\right] \tag{10.8}$$

$$f_{limit} = \frac{C}{\overline{MCL}_{\beta-\gamma}} = \frac{f_{\beta-\gamma}\ C}{MCL_{\beta-\gamma}} \tag{10.9}$$

Figure 10-10 shows a small excerpt from the "**Water Limits**" worksheet. As described above, the EPA established limits have been converted into equivalent concentration limits. Along with the EPA limits, a derived $MCL_{\beta-\gamma}$, calculated using Equation (10.8), is provided for all beta-gamma emitting nuclides. The last column in the table gives recommended beta-gamma MCLs using the 179 EPA specified values where available and the derived MCLs in all other cases.

Table 4			EPA Drinking Water Concentration Limits				Derived MCL[e]	EPA & Derived MCL[g]
Select			gross-alpha[a] (15 pCi/L)	uranium[b] (30 µg/L)	radium[c] (5 pCi/L)	beta-gamma[d] (4 mrem/yr)	beta-gamma[f] (4 mrem/yr)	beta-gamma (4 mrem/yr)
Z	Element	Nuclid	pCi/L	pCi/L	pCi/L	pCi/L	pCi/L	pCi/L
1	Hydrogen	H-3	na	na	na	2.00E+04	7.05E+04	2.00E+04
4	Beryllium	Be-7	na	na	na	6.00E+03	4.25E+04	6.00E+03
		Be-10	na	na	na	na	9.49E+02	9.49E+02
6	Carbon	C-10	na	na	na	na	na	na
		C-11	na	na	na	na	4.77E+04	4.77E+04
		C-14	na	na	na	2.00E+03	2.34E+03	2.00E+03
7	Nitrogen	N-13	na	na	na	na	na	na
		N-16	na	na	na	na	na	na
8	Oxygen	O-14	na	na	na	na	na	na
		O-15	na	na	na	na	na	na
		O-19	na	na	na	na	na	na
9	Fluorine	F-17	na	na	na	na	na	na
		F-18	na	na	na	2.00E+03	2.37E+04	2.00E+03
10	Neon	Ne-19	na	na	na	na	na	na
		Ne-24	na	na	na	na	na	na
11	Sodium	Na-22	na	na	na	4.00E+02	3.81E+02	4.00E+02
		Na-24	na	na	na	6.00E+02	2.71E+03	6.00E+02
12	Magnesium	Mg-27	na	na	na	na	na	na
		Mg-28	na	na	na	na	5.25E+02	5.25E+02

Figure 10-10. Upper portion of data table in "Water Limits" worksheet.

DOE also specifies a maximum dose constraint of 25 mrem/yr to a member of the general public outside the buffer zone (generally 100 meters from the actual disposal unit boundary) surrounding any low level waste disposal facility. A limiting water concentration could be calculated for this case using the DOE concentration limit. However, this dose constraint applies for all exposure pathways and is not for drinking water alone.

10.7 Shielding

Dose conversion factors for 816 nuclides including the effect of soil shielding are provided in worksheet "**Shielding**". These represent DCFs for external exposure to contaminated soil with a layer of clean soil providing shielding between the source and recipient. These DCFs are required for the inadvertent intruder analyses where the intruder is assumed to reside or work above the contaminated soil. The tabulated DCFs are a combination of values calculated by Kocher in 1991 (Lee, 2004) and more recent values calculated by Verst and Vinson (2014). DCFs are given for soil shielding thicknesses of 0, 1, 5, 15, 30, 45 and 100 cm in units of (mrem/yr) per (pCi/m^3). Figure 10-11 shows a small portion of the "**Shielding**" data table. The calculated DCFs are given in the first block of data (columns D-J) in the spreadsheet.

DCFs for zero soil shielding should be identical to the DCFs for exposure to an infinite depth of contamination listed in the "**Dose Coefficients**" worksheet and described in Section 10.5. However, these values are not the same reflecting differences in both modeling and the radionuclide data used in the calculations. The most consistent way to apply the shielding data is to convert the DCFs into fractions relative to the shielding DCF at zero soil-shielding thickness and apply these fractions to the accepted dose coefficient for exposure to soil at an infinite depth. This approach has been used in Chapter 8. The second table in the "**Shielding**" worksheet gives the shielding fractions and the third table gives the fractions multiplied by the infinite depth dose coefficient.

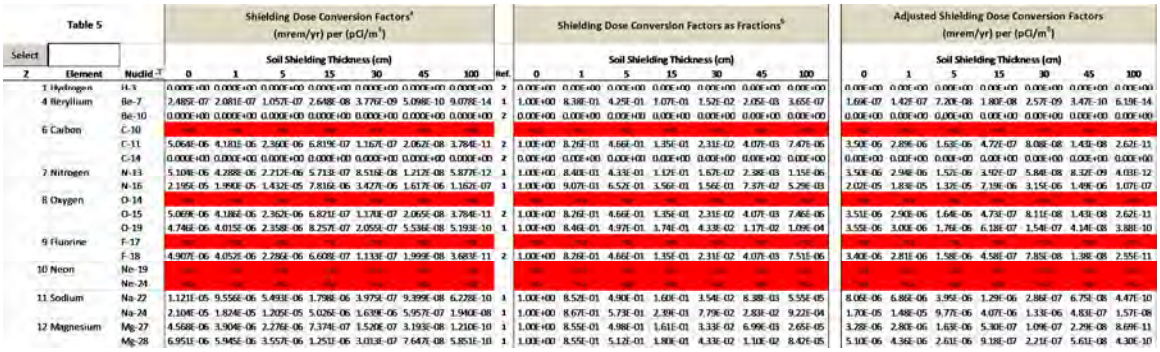

Table 5			Shielding Dose Conversion Factors[a] (mrem/yr) per (pCi/m³)								Shielding Dose Conversion Factors as Fractions[b]								Adjusted Shielding Dose Conversion Factors (mrem/yr) per (pCi/m³)							
Select			Soil Shielding Thickness (cm)								Soil Shielding Thickness (cm)								Soil Shielding Thickness (cm)							
Z	Element	Nuclid	0	1	5	15	30	45	100	Ref.	0	1	5	15	30	45	100		0	1	5	15	30	45	100	
1	Hydrogen	H-3	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
4	Beryllium	Be-7	2.48E-07	2.08E-07	1.05E-07	2.64E-08	3.77E-09	5.09E-10	9.07E-14	1	1.00E+00	8.38E-01	4.25E-01	1.07E-01	1.52E-02	2.05E-03	3.65E-07		1.69E-07	1.42E-07	7.20E-08	1.80E-08	2.57E-09	3.47E-10	6.19E-14	
		Be-10	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
6	Carbon	C-10																								
		C-11	5.06E-06	4.18E-06	2.36E-06	6.81E-07	1.16E-07	2.06E-08	3.78E-11	2	1.00E+00	8.26E-01	4.66E-01	1.35E-01	2.31E-02	4.07E-03	7.47E-06		3.50E-06	2.89E-06	1.63E-06	4.72E-07	8.08E-08	1.43E-08	2.62E-11	
		C-14	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
7	Nitrogen	N-13	5.10E-06	4.28E-06	2.21E-06	5.71E-07	8.51E-08	1.21E-08	5.87E-12	1	1.00E+00	8.40E-01	4.33E-01	1.12E-01	1.67E-02	2.38E-03	1.15E-06		3.50E-06	2.94E-06	1.52E-06	3.92E-07	5.84E-08	8.32E-09	4.03E-12	
		N-16	2.19E-05	1.99E-05	1.43E-05	7.81E-06	3.47E-06	1.61E-06	1.16E-07	1	1.00E+00	9.07E-01	6.52E-01	3.56E-01	1.56E-01	7.37E-02	5.29E-03		2.02E-05	1.83E-05	1.32E-05	7.19E-06	3.15E-06	1.49E-06	1.07E-07	
8	Oxygen	O-14																								
		O-15	5.06E-06	4.18E-06	2.36E-06	6.82E-07	1.17E-07	2.06E-08	3.78E-11	2	1.00E+00	8.26E-01	4.66E-01	1.35E-01	2.31E-02	4.07E-03	7.46E-06		3.51E-06	2.90E-06	1.64E-06	4.73E-07	8.11E-08	1.43E-08	2.62E-11	
		O-19	4.74E-06	4.01E-06	2.35E-06	8.25E-07	2.05E-07	5.53E-08	5.19E-10	1	1.00E+00	8.46E-01	4.97E-01	1.74E-01	4.33E-02	1.17E-02	1.09E-04		3.55E-06	3.00E-06	1.76E-06	6.18E-07	1.54E-07	4.14E-08	3.88E-10	
9	Fluorine	F-17																								
		F-18	4.90E-06	4.05E-06	2.28E-06	6.60E-07	1.13E-07	1.99E-08	3.68E-11	2	1.00E+00	8.26E-01	4.66E-01	1.35E-01	2.31E-02	4.07E-03	7.51E-06		3.40E-06	2.81E-06	1.58E-06	4.58E-07	7.85E-08	1.38E-08	2.55E-11	
10	Neon	Ne-19																								
		Ne-24																								
11	Sodium	Na-22	1.12E-05	9.55E-06	5.49E-06	1.79E-06	3.97E-07	9.39E-08	6.27E-10	1	1.00E+00	8.52E-01	4.90E-01	1.60E-01	3.54E-02	8.38E-03	5.55E-05		8.06E-06	6.86E-06	3.95E-06	1.29E-06	2.86E-07	6.75E-08	4.47E-10	
		Na-24	2.10E-05	1.82E-05	1.20E-05	5.02E-06	1.63E-06	5.95E-07	1.94E-08	1	1.00E+00	8.67E-01	5.73E-01	2.38E-01	7.79E-02	2.83E-02	9.22E-04		1.70E-05	1.48E-05	9.77E-06	4.07E-06	1.33E-06	4.83E-07	1.57E-08	
12	Magnesium	Mg-27	4.56E-06	3.90E-06	2.27E-06	7.37E-07	1.52E-07	3.19E-08	1.21E-10	1	1.00E+00	8.55E-01	4.98E-01	1.61E-01	3.33E-02	6.99E-03	2.65E-05		3.28E-06	2.80E-06	1.63E-06	5.30E-07	1.09E-07	2.29E-08	8.69E-11	
		Mg-28	6.95E-06	5.94E-06	3.55E-06	1.25E-06	3.01E-07	7.64E-08	5.85E-10	1	1.00E+00	8.55E-01	5.12E-01	1.80E-01	4.33E-02	1.10E-02	8.42E-05		5.10E-06	4.36E-06	2.61E-06	9.18E-07	2.21E-07	5.61E-08	4.30E-10	

Figure 10-11. Upper portion of data table in "Shielding" worksheet.

10.8 Bio-Transfer: Elemental Input

Element specific biological transfer factors used to calculate doses and disposal limits in the PA/CA process are included in the Rad Data Package. These data include transfer factors relating element concentrations in plants to soil, milk to feed, meat to feed and fish to water for 100 elements. These biological transfer factors (Jannik et al., 2010) are tabulated in worksheet "**Bio-Transfer**". Figure 10-12 shows the upper portion of this worksheet. These properties are chemical in nature and therefore depend only on the element and are not nuclide dependent. A separate database has been created for element K_d values used in transport modeling. Therefore, this data has not been included in the Rad Data Package. Transfer factors for poultry and eggs have been included in the table although, as discussed in Chapter 9, it is not intended to use them in dose calculations.

Table 6		Bio-Transfer and Bio-Accumulation Factors*				Data Extracted from IAEA-472 and PNNL-13421	
		Data Extracted from SRNL-STI-2010-00447					
Z	Element	Soil-to-Vegetable[a] (-)	Feed-to-Milk[b] (d/L)	Feed-to-Meat[c] (d/kg)	Water-to-Fish[d] (L/kg)	Feed-to-Poultry (d/kg)[e]	Feed-to-Eggs (d/kg)[e]
1	H	4.80E+00	1.50E-02	0.00E+00	1.00E+00	0.00E+00	0.00E+00
2	He	na	na	na	na	na	na
3	Li	7.80E-04	2.06E-02	1.00E-02	0.00E+00	0.00E+00	0.00E+00
4	Be	6.83E-04	8.30E-07	1.00E-03	1.00E+02	4.00E-01	2.00E-02
5	B	3.90E-01	1.55E-03	8.00E-04	0.00E+00	0.00E+00	0.00E+00
6	C	1.37E-01	1.20E-02	3.10E-02	3.00E+00	0.00E+00	0.00E+00
7	N	7.43E-03	2.50E-02	7.50E-02	2.00E+05	9.80E-02	2.60E-01
8	O	6.00E-01	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00
9	F	3.65E-03	1.00E-03	1.50E-01	1.00E+01	1.40E-02	2.70E+00
10	Ne	na	na	na	na	na	na
11	Na	5.85E-03	1.30E-02	1.50E-02	7.60E+01	7.00E+00	4.00E+00
12	Mg	1.28E-01	3.90E-03	2.00E-02	3.70E+01	3.00E-02	2.00E+00
13	Al	1.27E-04	2.06E-04	1.50E-03	5.10E+01	0.00E+00	0.00E+00
14	Si	2.65E-02	2.00E-05	4.00E-05	2.00E+01	8.00E-01	1.00E+00
15	P	1.95E-01	2.00E-02	5.50E-02	1.40E+05	1.90E-01	6.40E-01
16	S	2.93E-01	7.90E-03	2.00E-01	8.00E+02	2.30E+00	7.00E+00
17	Cl	3.49E+00	1.70E-02	1.70E-02	4.70E+01	3.00E-02	2.70E+00
18	Ar	na	na	na	na	na	na

Figure 10-12. Partial listing from data table in "Bio-Transfer" worksheet.

10.9 Dose Equations and Parameters

In addition to the tables of nuclide and element data in the worksheets described in the previous sections, other parameters used in dose calculations have also been included in the "*Radionuclide, Element and Dose Parameter Data Package"*. These dose parameters are entered in the "**Dose Equations and Parameters**" worksheet. These parameters include human usage factors such as a nominal drinking water ingestion rate, air inhalation rate, as well as other physical parameters. Parameters are organized in the table by exposure pathway as defined by the pertinent dose equation. Figure 10-13 shows the upper part of the "**Dose Equations and Parameters**" table containing the equations and dose parameters pertaining to the water ingestion exposure pathway. Definitions for each term and values for both the Typical Person and the Reference Person are listed along with references. For reference purposes, parameter values from the initial version of the database are provided in the Tables in Chapters 2-8. The database must be consulted to obtain the most recently published parameter values.

For the purpose of ELLWF PA and SRS CA calculations, SRS average human usage factors from Table 10 of Jannik et al. (2010), as updated by Table 11 in Stone and Jannik (2013) for a "Typical Person", are used in best-estimate, deterministic calculations of limits and doses. The logic for this decision is that PA and CA contaminant transport and dose calculations presuppose more highly exposed individuals located on or near the waste disposal site. Thus, use of average behavior patterns avoids compounding this conservatism. This is consistent with DOE 435.1-1 IV.P(2)(a) which states, "the assumption of average living habits and exposure conditions in representative critical groups of individuals projected to receive the highest dose is appropriate." SRS maximum human usage factors found in Table 11 of Jannik et al. (2010), as updated by Table 11 in Stone and Jannik (2013) for "Reference Person" intakes, are used in 95th percentile sensitivity calculations. Human usage factors for an inadvertent intruder and other physical parameters used in dose calculations (e.g. animal consumption rates of water and fodder) are also provided in this table. The primary sources for these parameters are the report by Stone and Jannik (2013) and the report by Jannik et al. (2010).

Dose equations in the database are consistent with those in this report. In some cases, the report uses a more general form of the equation. For example, uptake of radionuclide *i* by water ingestion (eqn. 2.3-1, p. 18) contains a decay term to account for the holdup time between obtaining contaminated water and ingestion. The water ingestion dose impact found in the database (eqn. 1-1 in Fig 10-13) ignores this hold up time as it is assumed to be zero.

Eqn.	Exposure Pathway and Terms	Dose Calculations and Definitions	Units	Typical Person[a]	Reference Person[b]	Reference or Comment
Dose calculations to a member of the public in Sections 1 through 14 use the water concentration:						
	$C_{w,i}$	concentration of radionuclide i in either groundwater (PA calc) or river/surface streams (CA calc)	pCi/L	☞	☞	from PA or CA contaminant transport calculations
1-1	**Water Ingestion**	$D_{ing,w,i} = EC_{ing,i}\, F_w\, U_w\, C_{w,i}$				
	$D_{ing,w,i}$	annual effective dose equivalent (EDE) to an individual from water ingestion for radionuclide i	mrem/yr	☞	☞	from water ingestion dose calculation (eqn 1-1)
	$EC_{ing,i}$	ingestion dose coefficient for radionuclide i	mrem/pCi	☞	☞	see "Dose Coefficients" worksheet
	F_w	fraction of drinking water from contaminated groundwater	unitless	1	1	
	U_w	water consumption rate	L/yr	300	800	Stone & Jannik, 2013

Figure 10-13. Partial listing from data table in "Dose Equations and Parameters" worksheet.

As shown in Figure 10-14, the right side of the table assigns the dose equations and associated parameters to the applicable performance objectives, environmental media and exposure scenarios where they are used. For example, the water ingestion dose equation and parameters are used to calculate dose in the following cases:

- Composite Analysis – dose to a hypothetical future member of the public from ingestion of river water (part of CA Residential scenario).
- Performance Assessment – dose to a hypothetical future member of the public from ingestion of groundwater (part of the PA All-Pathways scenario) as well as impacts to water resources (PA Groundwater Protection requirement).

The far right columns identify dose parameters as either human usage or physical. All columns in the table have been set up to be filtered. This allows the user to show just those aspects of the table that are of interest. For example, filtering on the "AP" column will reduce the sheet to show only those dose equations and parameters that are associated with the all-pathways performance calculation.

		Surface Water			Groundwater			Intruder-Chronic				Intruder-Acute				Parameters	
Eqn.	Exposure Pathway and Terms	CA SW	RES	REC	PA GW	GWP	AP	PA INT	AG	RES	PD	PA INT	BC	WD	DISC		PHYS	HUMAN
Dose calculations to a member of th																		
	$C_{w,i}$	✓	✓		✓	✓	✓											
1-1	Water Ingestion	✓	✓		✓	✓	✓											
	$D_{ing,w,i}$	✓	✓		✓	✓	✓											
	$EC_{ing,i}$	✓	✓		✓	✓	✓											
	F_w	✓	✓		✓											✓		✓
	U_w	✓	✓		✓	✓	✓									✓		✓

Figure 10-14. Applicable performance objectives, environmental media, exposure scenarios and parameter types in "Dose Equations and Parameters" worksheet.

The sources of values used for human usage factors and physical parameters continue to evolve as new data are published in national and international publications. The list of publications forms a hierarchy of references with the most recent references superseding (in full or part) earlier published data. Figure 10-15 below provides the hierarchy of references used for selecting the most recent values for human usage and physical parameters and is located at the bottom of the Dose Parameters and Equations worksheet.

Rank	Citation	Title	Document No.	Rev.	Date
1	Stone & Jannik, 2013	Site Specific Reference Person Parameters and Derived Concentration standards for the Savannah River Site	SRNL-STI-2013-00115	0	Mar-13
2	Jannik, 2013	Recommended Exposure Parameters for Acute Intruder Scenarios at the Portsmouth OH Disposal Facility	SRNL-L4310-2013-00016	0	6-Aug-13
3	Jannik et al., 2010	Land and Water Use Characteristics and Human Health Input Parameters for Use in Environmental Dosimetry and Risk Assessments at the Savannah River Site	SRNL-STI-2010-00447	0	6-Aug-10
4	Phifer et al., 2006	Hydraulic Property Data Package for the E-Area and Z-Area Soils, Cementitious Materials, and Waste Zones	WSRC-STI-2006-00198	0	Sep-06
5	Jannik & Dixon, 2006	LADTAP-PA: A Spreadsheet for Estimating Dose Resulting from E-Area Groundwater Contamination at the Savannah River Site	WSRC-STI-2006-00123	0	Aug-06
6	Lee, 2004	Inadvertent Intruder Analysis Input for Radiological Performance Assessments	WSRC-TR-2004-00295	0	22-Jul-04
7	---	All earlier and other references	---		

Figure 10-15. Hierarchy of References for Human Usage Factors and Physical Parameters in "Dose Equations and Parameters" worksheet.

10.10 Constants

Only a few constants used in the "*Radionuclide, Element and Dose Parameter Data Package"* including Avogadro's constant and the number of days in a year are listed in the "**Constants**" worksheet. The value for Avogadro's constant was taken from the National Institute of Standards (NIST) web site and is referenced to 2010 CODATA *Recommended Values of the Fundamental Physical Constants, Version 6*. The number of days in a year was set to 365.25 and is used in all spreadsheet calculations where this parameter appears. This value was chosen as the approximation to the days in a year that most commonly appears in related calculations. Other time factors (24 hrs/day, 60 min/hr and 60 sec/min) are used in some unit conversion calculations. Because these are standard values it was felt that there was no need to include them in the data package although, for convenience, the conversion from seconds to years is given. In addition to these constants, disintegrations per second per Curie and the factor to convert from Sv/Bq to mrem/pCi are also listed in the **Constants** worksheet.

10.11 Decay Chain Diagrams

Decay chains are a graphical representation of the progeny of a given radionuclide. Decay chains were previously based on nuclear data from Tuli (2005). Partial decay chains (including only nuclides with half-lives greater than 5 years, 3 years, and 1 year) have typically been made available to help modelers determine which nuclides to model in transport processes. Complete decay chains are needed for dose calculations. Decay chains shown in the "*Radionuclide, Element and Dose Parameter Data Package"* are derived from the data in ICRP-107. The main differences between these chains and past chains are the inclusion of new metastable states based on the improved branching fraction data from ICRP-107 and exclusion of radionuclides with half-lives greater than 1.0×10^{20} years.

For dose assessments, all nuclides anticipated to be present should be considered. Worksheet "**Full Chains**" in the Rad Data Package gives complete decay chains for all 1252 radionuclides in the ICRP-107 publication based on the decay steps listed in that reference and modified as described in Section 10.2.1. Figure 10-16 shows the full decay chain for Sr-81. The chain begins with the parent nuclide in the left most cell and proceeds along a row in the worksheet with branching indicated by the blue arrows. Radionuclides in the decay chain have the half-life displayed beside the name and branching fractions displayed below daughters. Stable isotopes that terminate the decay chain are italicized and shaded in green.

18	Sr-81 $t_{1/2}$ = 4.240E-05	Rb-81 $t_{1/2}$ = 5.220E-04	Kr-81m $t_{1/2}$ = 4.151E-07	Kr-81 $t_{1/2}$ = 2.290E+05	*Br-81*	
7		0.9985578	0.956909	0.999975	1	
				Br-81		
				0.000025		
			Kr-81 $t_{1/2}$ = 2.290E+05	*Br-81*		
			0.043091	1		
		Rb-81m $t_{1/2}$ = 5.799E-05	Rb-81 $t_{1/2}$ = 5.220E-04	Kr-81m $t_{1/2}$ = 4.151E-07	Kr-81 $t_{1/2}$ = 2.290E+05	*Br-81*
		0.0014422	0.97600045	0.956909	0.999975	1
					Br-81	
					0.000025	
				Kr-81 $t_{1/2}$ = 2.290E+05	*Br-81*	
				0.043091	1	
			Kr-81 $t_{1/2}$ = 2.290E+05	*Br-81*		
			0.023786	1		
			Kr-81m $t_{1/2}$ = 4.151E-07	Kr-81 $t_{1/2}$ = 2.290E+05	*Br-81*	
			0.00021355	0.999975	1	
				Br-81		
				0.000025		

Figure 10-16. Full decay chain diagram for Sr-81.

Abbreviated decay chains for nuclides with half-lives greater than 0.5 year, 1 year, 3 years, and 5 years are also provided in the database and may be used for transport modeling purposes. The 0.5 year cutoff is the shortest half-life that has been considered for parent nuclides in previous SRS PA/CA reports.

10.12 Workbook Macros

Some of the calculations needed to create tables and worksheets in the "*Radionuclide, Element and Dose Parameter Data Package"* were implemented in VBA macros contained in the workbook. Using macros and, in some cases, spreadsheet calculations avoided the need to manually manipulate the data. These macros may be useful when making future revisions to the database or for database maintenance so they were retained in the workbook. A brief listing of the workbook macros and a description of their primary functions is provided in this section. The macros typically call additional subroutines or functions which are not described.

alpha_beta

Builds a table of radionuclides that have both alpha and beta-gamma decay modes in the "**Water Limits**" worksheet.

auxiliary

Writes the following three files for use in limits and doses calculations:

Alpha_frac.txt – Alpha branching fractions for the 126 nuclides having alpha decay.

Betagamma_frac_mcl.txt – Beta/gamma branching fractions and mcl drinking water limits for the 824 nuclides having beta/gamma decay.

U-pCi_to_ug.txt – Molecular weights and half-lives for the 15 uranium nuclides in the database.

These files include data for all nuclides in the database. If a subset of nuclides is used, the user can extract a subset of the data from these files using a macro provided in the separate Excel workbook *Extract_Aux_Files.xlsm*.

beta_gamma_mcl

Calculates derived MCLs for radionuclides having beta-gamma decay, enters the values in the "**Water Limits**" worksheet, and creates the table of combined EPA and derived MCLs in that worksheet.

build_full_chains

Reads information from the "**ICRP Table A.1**", "**Rad Data**", and "**Rad Decay Data**" worksheets and uses it to construct full decay chain diagrams for all 1252 nuclides in worksheet "**Full Chains**". Chain construction is a graphical process that starts with the parent nuclide and its daughters and continues to search for subsequent daughter nuclides until the chains are exhausted. To create a full-chains diagram, the user first creates a blank worksheet named "**Full Chains**" and then runs the **build_full_chains** macro from the Macro menu that appears when selecting Macros from the View tab on the workbook ribbon.

check_branching

Checks total branching fractions for each nuclide in worksheet "**Rad Decay Data**", highlights nuclides with branching fractions that do not sum to one, and corrects the values by increasing or reducing the largest branching fraction.

decay_modes

Reads daughter nuclides and branching fractions from worksheet "**ICRP Table A.1**", determines the decay mode for each daughter using the method described in Section 10.4.1, and writes the results to worksheet "**Rad Decay Data**".

find _stable

Identifies stable isotopes in worksheet "**ICRP Table A.1**" and italicizes their names and shades the cell where they appear green.

gross_alpha

Determines which radionuclides have a gross-alpha MCL in worksheet "**Water Limits**".

half_life

Converts half-lives in worksheet "**Rad Data**" from the original units used in the ICRP-107 table to years.

Porflow_Input

The PORFLOW code (ACRI, 2004) is used by SRNL to perform radionuclide transport and decay calculations. This macro writes a set of standard PORFLOW input files that specify decay chains and parent and daughter half-lives for individual radionuclides. The input files can be built from any of the decay chain diagrams created with the macros described in the preceding two paragraphs. An example data file for Am-244 full chains (*Am-244.dat*) is shown below in Figure 10-16. The macro also writes the *MasterRad.out* file used for limits and doses calculations. The *MasterRad.out* file contains essentially the same information as the PORFLOW input in a different format.

```
DECAy half LIFE for C   is 1.1521789E-03 years ! Am-244
DECAy half LIFE for C2  is 1.8100000E+01 years ! Cm-244
DECAy half LIFE for C3  is 6.5640000E+03 years ! Pu-240
DECAy half LIFE for C4  is 2.3420000E+07 years ! U-236
DECAy half LIFE for C5  is 1.4050000E+10 years ! Th-232
DECAy half LIFE for C6  is 5.7500000E+00 years ! Ra-228
DECAy half LIFE for C7  is 7.0157426E-04 years ! Ac-228
DECAy half LIFE for C8  is 1.9116000E+00 years ! Th-228
DECAy half LIFE for C9  is 1.0020534E-02 years ! Ra-224
DECAy half LIFE for C10 is 1.7618577E-06 years ! Rn-220
DECAy half LIFE for C11 is 4.5947727E-09 years ! Po-216
DECAy half LIFE for C12 is 1.2137805E-03 years ! Pb-212
DECAy half LIFE for C13 is 1.1512282E-04 years ! Bi-212
DECAy half LIFE for C14 is 9.4747383E-15 years ! Po-212
DECAy half LIFE for C15 is 5.8046239E-06 years ! Tl-208


REGEneration of C2  from C   is 1.0000000E+00 ! Cm-244 from Am-244
REGEneration of C3  from C2  is 9.9999863E-01 ! Pu-240 from Cm-244
REGEneration of C4  from C3  is 9.9999994E-01 ! U-236  from Pu-240
REGEneration of C5  from C4  is 1.0000000E+00 ! Th-232 from U-236
REGEneration of C6  from C5  is 1.0000000E+00 ! Ra-228 from Th-232
REGEneration of C7  from C6  is 1.0000000E+00 ! Ac-228 from Ra-228
REGEneration of C8  from C7  is 1.0000000E+00 ! Th-228 from Ac-228
REGEneration of C9  from C8  is 1.0000000E+00 ! Ra-224 from Th-228
REGEneration of C10 from C9  is 1.0000000E+00 ! Rn-220 from Ra-224
REGEneration of C11 from C10 is 1.0000000E+00 ! Po-216 from Rn-220
REGEneration of C12 from C11 is 1.0000000E+00 ! Pb-212 from Po-216
REGEneration of C13 from C12 is 1.0000000E+00 ! Bi-212 from Pb-212
REGEneration of C14 from C13 is 6.4060000E-01 ! Po-212 from Bi-212
REGEneration of C15 from C13 is 3.5940000E-01 ! Tl-208 from Bi-212
```

Figure 10-17. PORFLOW input file for Am-244 full chains.

shielding

Converts soil shielding values from the original values in units of (rem/yr) per ($\mu Ci/m^3$) to fractions relative to the DCF at no shielding and writes the table of fractions in worksheet "**Shielding**".

shorter_chains

Starting with a copy of the full decay chains diagram this macro produces decay chains eliminating radionuclides having half-lives shorter than the specified cutoff value. Chain construction is a graphical

process that first passes along the chains removing radionuclides with half-lives less than the specified cutoff value followed by a second pass that combines common nuclides appearing at the same stage in the decay chain. To run this process, the database user must first copy the worksheet "**Copy of Full Chains**" to another sheet where the shorter chain will be created. This preserves a copy of the full decay chain diagrams without arrows for future use. To create a shorter decay chain with a cutoff of some chosen time in years, the user must edit macro **shorter_chains** and change the value of variable "cutoff" to equal the chosen cutoff time. The macro can then be run from the Macro menu and the copy of full chains will be converted into shorter chains at the specified cutoff. Shorter chains for 0.5, 1, 3 and 5 years are provided with the data package.

11.0 Dose Equation Nomenclature

11.1 Concentrations (pCi/kg)

$C_{ag,i}$ .....Concentration of radionuclide *i* in unirrigated garden produce
$C_{fish,i}$.....Concentration of radionuclide *i* in fish
$C_{g,i}$ .....Concentration of radionuclide *i* in irrigated garden produce
$C_{Leaf,i}$.....Concentration of radionuclide *i* in garden ($C_{Leaf,g,i}$) or pasture plant ($C_{Leaf,p,i}$) leaf
$C_{meat,i}$ .....Concentration of radionuclide *i* in meat
$C_{p,i}$ .....Concentration of radionuclide *i* in fodder
$C_{root,i}$ .....Concentration of radionuclide *i* in garden plant ($C_{root,g,i}$) or pasture grass ($C_{root,p,i}$) root
$C_{s,i}$ .....Concentration of radionuclide *i* in irrigated garden soil
$C_{shore,i}$ .....Concentration of radionuclide *i* in shore soil

11.2 Concentrations (pCi/m^3)

$C_{j,i}$ .....Concentration of radionuclide *i* in ingestion pathway *j* (pCi/kg or pCi/m^3)
$C_{k,i}$.....Concentration of radionuclide *i* in inhalation pathway *k*
$C_{m,i}$.....Concentration of radionuclide *i* in external exposure pathway *m*
$C_{milk,i}$ .....Concentration of radionuclide *i* in milk
$C_{rw,i}$ .....Concentration of radionuclide *i* in river or stream water
C_{rw,H^3} .....Concentration of tritium in river or stream water
$C_{sw,i}$.....Concentration of radionuclide *i* in soil (root zone) water
$C_{w,i}$ .....Concentration of radionuclide *i* in contaminated groundwater
$C_{wz,i}$ .....Concentration of radionuclide *i* in waste zone

11.3 Doses (mrem/yr)

$D_{ext,i}$ .....Annual average dose from external exposure to radionuclide *i*
$D_{ext,m}$.....Annual average dose from through external exposure pathway *m*
$D_{ext,m,i}$ .....Annual average dose from external exposure to radionuclide *i* through pathway *m*
$D_{ext,Total}$.....Total annual average dose from external exposure to all radionuclide through all pathways
$D_{ing,i}$ .....Annual average dose from ingestion of radionuclide *i*
$D_{ing,j}$.....Annual average dose through ingestion through pathway *j*
$D_{ing,j,i}$ .....Annual average dose from ingestion of radionuclide *i* through pathway *j*
$D_{ing,Total}$.....Total annual average ingestion dose from all radionuclides and pathways
$D_{inh,i}$ .....Annual average dose from inhalation of radionuclide *i*
$D_{inh,k}$ .....Annual average dose through inhalation pathway *k*
$D_{inh,k,i}$.....Annual average dose from inhalation of radionuclide *i* through pathway *k*
$D_{inh,Total}$.....Total annual average inhalation dose from all radionuclides and pathways
$D_{p,i}$ .....Annual dose from exposure to contaminant *i* through pathway *p*
$D_{rec,i}$ .....Annual average dose to MOP from recreational exposure to radionuclide *i*
$D_{rec,Total}$.....Total annual average dose to MOP from recreational exposure to all radionuclides

11.4 Effective Internal Exposure Dose Coefficients (mrem/pCi)

$EC_{ing,i}$ .....Effective dose coefficient from ingestion of radionuclide *i*
$EC_{inh,i}$ .....Effective dose coefficient from inhalation of radionuclide *i*
$EC_{p,i}$ .....Effective dose coefficient from exposure to contaminant *i* through pathway *p*

11.5 Effective External Exposure Dose Coefficients (mrem/yr)/(pCi/m^3)

$EC_{ext,i}$ .....Effective dose coefficient for exposure to radionuclide *i*
$EC_{ext,1cm,i}$ .....Effective dose coefficient for exposure to soil contaminated to a depth of 1 cm
$EC_{ext,5cm,i}$ .....Effective dose coefficient for exposure to soil contaminated to a depth of 5 cm
$EC_{ext,15cm,i}$ .....Effective dose coefficient for exposure to soil contaminated to a depth of 15 cm
$EC_{ext,\infty,i}$ .....Effective dose coefficient for exposure to soil contaminated to an infinite depth
$EC_{ext,AI,i}$.....Effective dose coefficient for exposure from immersion in air
$EC_{ext,GS,i}$ .....Effective dose coefficient for exposure from ground shine
$EC_{ext,m,i}$ .....Effective dose coefficient for exposure to radionuclide *i* through pathway *m*
$EC_{ext,WS,i}$ .....Effective dose coefficient for exposure from submersion in water

11.6 External Exposures (pCi/m^3)

$Ext_{ag,i}$.....Exposure to radionuclide *i* by intruder from contaminated soil during agriculture
$Ext_{cd,i}$ .....Exposure to radionuclide *i* by intruder through the contact with contaminated soil during acute intruder activity
$Ext_{boat,i}$.....Exposure to radionuclide *i* by MOP from contaminated river water during boating
$Ext_{m,i}$.....Exposure to radionuclide *i* through pathway *m*
$Ext_{res,i}$.....Exposure to radionuclide *i* by intruder from contaminated soil during residence in home
$Ext_{s,i}$ .....Exposure to radionuclide *i* by MOP from contaminated garden soil
$Ext_{shore,i}$ .....Exposure to radionuclide *i* by MOP from contaminated soil on a river or stream shore
$Ext_{sw,i}$.....Exposure to radionuclide *i* by MOP from contaminated shower water
$Ext_{swim,i}$.....Exposure of radionuclide *i* by MOP from contaminated river water during swimming

11.7 Fractions (dimensionless)

F_{ar} .....Airborne release fraction
F_{boat}.....Fraction of year spent boating
F_{bc}.....Fraction of year spent in basement construction (-)
$F_{dil,bc}$ .....Dilution factor for mixing contaminated soil from exhumed waste with clean soil during intruder basement construction
$F_{dil,wd}$ .....Dilution factor for mixing contaminated soil from exhumed waste with clean soil during intruder well drilling
F_{dis}.....Fraction of year spent in intruder site discovery (-)
F_{fish} .....Fraction of fish consumed exposed to contaminated water
F_g.....Fraction of produce obtained from a local garden
$F_{gd,ag}$ .....Dilution factor for mixing exhumed waste with native soil in garden during intruder agriculture activity

$F_{gd,pd}$ .....Dilution factor for mixing exhumed waste with native soil in garden during intruder post drilling activity
F_j .....Fraction of contaminated food consumed through pathway *j*
F_k .....Fraction of year individual is exposed to contamination through inhalation pathway *k*
F_L.....Fraction of produce that is leafy
F_m.....Fraction of time individual is exposed to contamination through external pathway *m*
F_{meat}.....Fraction of meat obtained from livestock using local contaminated water
F_{milk}.....Fraction of milk obtained from dairy cattle using local contaminated water
$F_{on,meat}$.....Fraction of year that livestock graze on pasture
$F_{on,milk}$ .....Fraction of year that dairy cattle graze on pasture
$F_{p,meat}$ .....Fraction of livestock feed from local pasture irrigated using contaminated water
$F_{p,milk}$ .....Fraction of dairy cattle feed from local pasture irrigated using contaminated water
F_R .....Fraction of time garden soil ($F_{R,g}$) or pasture soil ($F_{R,p}$) is irrigated
F_r .....Fraction of irrigation water deposited on crop leaf that is retained
F_{res} .....Fraction of year spent in home
F_s .....Fraction of year spent in garden also fraction of ingested soil from garden
F_{sh} .....Fraction of year spent in shower
F_{shield} .....Shielding fraction in home from basement concrete
F_{shore} .....Fraction of year spent on shore
F_{swim}.....Fraction of year spent swimming
F_W .....Fraction of contamination retained on leaf after washing
F_w .....Fraction of drinking water obtained from local contaminated water
F_{wd} .....Fraction of year spent in well drilling (-)
$F_{w,meat}$.....Fraction of livestock drinking water from local contaminated water
$F_{w,milk}$.....Fraction of dairy cattle drinking water from local contaminated water

11.8 Ingestion Uptake Rates (pCi/yr)

$Ing_{ag,i}$.....Uptake of radionuclide *i* by intruder through ingestion of contaminated garden produce
$Ing_{bc,i}$ .....Uptake of radionuclide *i* by intruder through ingestion of contaminated soil during basement construction
Ing_{derm,H^3} .....Uptake of tritium by MOP through contact with contaminated river water during swimming
$Ing_{gd,i}$.....Uptake of radionuclide *i* by intruder through ingestion of contaminated soil during gardening
$Ing_{fish,i}$ .....Uptake of radionuclide *i* by MOP through ingestion of fish exposed to contaminated stream water
$Ing_{g,i}$ .....Uptake of radionuclide *i* by MOP through ingestion of contaminated garden produce
$Ing_{j,i}$ .....Uptake of radionuclide *i* through ingestion pathway *j*
$Ing_{meat,i}$ .....Uptake of radionuclide *i* by MOP through ingestion of meat from livestock that have consumed contaminated water
$Ing_{milk,i}$ .....Uptake of radionuclide *i* by MOP through ingestion of milk from dairy cattle that have consumed contaminated water
$Ing_{p,meat,i}$.....Uptake of radionuclide *i* by livestock through ingestion of contaminated fodder

$Ing_{p,milk,i}$ .....Uptake of radionuclide *i* by dairy cattle through ingestion of contaminated feed
$Ing_{s,i}$ .....Uptake of radionuclide *i* by MOP through ingestion of contaminated soil during gardening
$Ing_{w,meat,i}$ .....Uptake of radionuclide *i* by livestock through ingestion of contaminated drinking water
$Ing_{w,milk,i}$ .....Uptake of radionuclide *i* by dairy cattle through the ingestion of contaminated drinking water
$Ing_{w,i}$ .....Uptake of radionuclide *i* by MOP through ingestion of contaminated drinking water
$Ing_{wd,i}$ .....Uptake of radionuclide *i* by intruder through ingestion of contaminated soil during well drilling

11.9 Inhalation Uptake Rates (pCi/yr)

$Inh_{bc,i}$ .....Uptake of radionuclide *i* by intruder through inhalation of contaminated soil during basement construction
$Inh_{gw,i}$ .....Uptake of radionuclide *i* by MOP through inhalation of contaminated irrigation water in garden
$Inh_{gd,i}$ .....Uptake of radionuclide *i* by intruder through inhalation of contaminated soil during gardening
$Inh_{k,i}$ .....Uptake of radionuclide *i* through inhalation pathway *k*
$Inh_{res,i}$ .....Uptake of radionuclide *i* by intruder through inhalation of contaminated soil while residing in home
$Inh_{s,i}$ .....Uptake of radionuclide *i* by MOP through inhalation of contaminated garden soil
$Inh_{sh,i}$ .....Uptake of radionuclide *i* by MOP through inhalation of contaminated shower water
$Inh_{swim,i}$ .....Uptake of radionuclide *i* by MOP through inhalation of contaminated water while swimming
$Inh_{wd,i}$ .....Uptake of radionuclide *i* by intruder through inhalation of contaminated soil during well drilling

11.10 Animal Consumption Rates

$Q_{p,meat}$ .....Livestock consumption of fodder (kg/yr)
$Q_{p,milk}$ .....Dairy cattle consumption of fodder (kg/yr)
$Q_{w,meat}$ .....Livestock consumption of drinking water (m^3/yr)
$Q_{w,milk}$ .....Dairy cattle consumption of drinking water (m^3/yr)

11.11 Bio-transfer Factors

$T_{FtoMeat,i}$ .....Factor relating consumption of radionuclide *i* by livestock to the concentration in meat, represents the nuclide fraction transferred from fodder to meat (yr/kg)
$T_{FtoMilk,i}$ .....Factor relating consumption of radionuclide *i* by dairy cattle to the concentration in milk, represents the nuclide fraction transferred from fodder to milk (yr/m^3)
$T_{StoV,i}$ .....Ratio of the concentration of contaminant *i* in dry soil to the concentration in vegetation, represents the nuclide fraction transferred from soil to vegetation (-)
$T_{WtoFish,i}$ .....Factor representing concentration of radionuclide *i* in fish meat to the concentration in water, represents nuclide fraction transferred from water to fish (m^3/kg)

11.12 Holdup Times (yr)

$t_{hold,fish}$ .....Time between obtaining contaminated fish and ingestion
$t_{hold,fod}$ .....Time between harvesting fodder and livestock or dairy cattle ingestion
$t_{hold,g}$ .....Time between harvesting garden produce and ingestion
$t_{hold,j}$ .....Time between harvesting and consumption through pathway *j*
$t_{hold,meat}$ .....Time between obtaining contaminated meat and human ingestion
$t_{hold,milk}$ .....Time between obtaining contaminated milk and human ingestion
$t_{hold,meat,w}$ .....Time between obtaining contaminated water and ingestion by livestock
$t_{hold,milk,w}$ .....Time between obtaining contaminated water and ingestion by dairy cattle
$t_{hold,s}$ .....Time between exposure to contaminated soil and ingestion
$t_{hold,w}$ .....Time between obtaining contaminated water and human ingestion

11.13 Human Consumption Rates

U_j .....Annual average consumption through ingestion pathway *j* (kg/yr or m^3/yr)
U_k .....Annual average inhalation through pathway *k* (m^3/yr)
U_{bc} .....Annual average soil ingestion during basement construction (kg/yr)
U_{wd} .....Annual average soil ingestion during well drilling (kg/yr)
U_{air} .....Annual average air inhalation (m^3/yr)
$U_{air,bc}$ .....Annual average air inhalation during construction activity (m^3/yr)
$U_{air,wd}$ .....Annual average air inhalation during drilling activity (m^3/yr)
U_{fish} .....Annual average fish consumption (kg/yr)
U_g .....Annual average garden produce consumption (kg/yr)
U_{meat} .....Annual average meat consumption (kg/yr)
U_{milk} .....Annual average milk consumption (m^3/yr)
U_s .....Annual average soil ingestion (kg/yr)
$U_{s,bc}$ .....Annual average soil ingestion during intruder basement construction (kg/yr)
$U_{s,wd}$ .....Annual average soil ingestion during intruder well drilling (kg/yr)
U_w .....Annual average drinking water consumption (m^3/yr)

11.14 Summation Indices

J .....Number of ingestion pathways included in the dose calculation
K .....Number of inhalation pathways included in the dose calculation
M .....Number of external exposure pathways included in the dose calculation
N .....Number of radionuclides included in the dose calculation

11.15 Other Symbols

A_s .....Surface area (m^2)
DA_w .....Dermal absorption rate of water (m^3/yr)
D_b .....Depth of basement (m) (assumed to be 3 m)
D_{gw}.....Depth of groundwater aquifer from surface (m)
d_t.....Depth of tilling (V/A_s) for gardening or agriculture (m)
d_{wz}.....Depth from ground surface to top of waste zone (m)
E.....Annual average evapotranspiration rate (m/yr)
$Exp_{w,i}$ .....Equivalent direct exposure to radionuclide *i* from source *w* (m^3/yr)
F_j .....Dimensionless factor for ingestion pathway *j*
F_k .....Dimensionless factor for inhalation pathway *k*
$F_{ws,i}$.....Rate of transfer of species *i* from water phase to solid phase (mol/yr)

G_{boat} .....Geometry factor for water immersion during boating (-)
G_{sh}.....Geometry factor for immersion in shower water (-)
G_{shore}.....Geometry factor for shore exposure (-)
G_{swim} .....Geometry factor for water immersion during swimming (-)
h_{wz}.....Waste zone height or thickness (m)
I_R .....Crop irrigation rate in garden ($I_{R,g}$) or pasture ($I_{R,p}$), actual irrigation rate not annual average (m/yr)
$K_{d,i}$ .....Solid-liquid equilibrium constant for contaminant *i* (m^3/kg)
K_{sat} .....Saturated hydraulic conductivity (m/yr)
L_{soil} .....Mass loading of soil in ambient garden air (kg/m^3)
$L_{soil,bc}$ .....Mass loading of soil in air during intruder basement construction (kg/m^3)
$L_{soil,res}$.....Mass loading of soil in home air (kg/m^3)
$L_{soil,wd}$ .....Mass loading of soil in air during intruder well drilling (kg/m^3)
$MC_{air,g}$.....Moisture content of ambient air in garden (kg/m^3)
$MC_{air,sh}$ .....Moisture content of air in shower (kg/m^3)
P.....Annual average precipitation rate (m/yr)
q_{gw}.....Groundwater discharge rate into the stream (m^3/yr)
q_{sw} .....Stream flow rate (m^3/yr)
$\dot{r}_{w,i}(t)$ .....Reaction rate of contaminant *i* in water phase (mol/m^3-yr)
$\dot{r}_{s,i}(t)$ .....Reaction rate of contaminant *i* in solid phase (mol/kg-yr)
R_i.....Retardation factor for transport of contaminant species *i* (-)
$R_{Leaf,i}$ .....Retention of contaminated irrigation water in garden plant ($R_{Leaf,g,i}$) or pasture grass ($R_{Leaf,p,i}$) through deposition on leaf for species *i* (m^3/kg)
$R_{Root,i}$ .....Retention of contaminated irrigation water in garden plant ($R_{Root,g,i}$) or pasture grass ($R_{Root,p,i}$) through root uptake for species *i* (m^3/kg)
$R_{Soil,i}$.....Retention of contaminated irrigation water in garden soil ($R_{Soil,g,i}$) and pasture soil ($R_{Soil,p,i}$) root zone for species *i* (m^3/kg)
S .....Soil water saturation (-)
S_i .....Rate of contaminant *i* addition to crop leaf (pCi/kg-yr)
t_b .....Characteristic time for radionuclide buildup in the soil (yr)
t_{irr}.....Time crop is exposed to irrigation (yr)
V.....Volume (m^3)
Y.....Crop yield for garden (Y_g) and pasture (Y_p) (kg/m^2)

11.16 Greek Letters

α_s .....Solid volume fraction (-)
α_w .....Water volume fraction (-)
β_i.....Time constant (1/yr)
$\lambda_{B,i}$ .....Time constant for removal of radionuclide *i* from garden soil ($\lambda_{B,g,i}$) or pasture soil ($\lambda_{B,p,i}$) by radioactive decay and leaching (1/yr)
λ_e.....Leaf weathering and radiological decay constant (1/yr)
λ_w.....Leaf weathering decay constant (1/yr)
λ_i .....Decay constant for radionuclide *i* (1/yr)
$\lambda_{L,i}$.....Leach rate time constant for removal of radionuclide *i* from soil (1/yr)
$\lambda_{R,i}$ .....Irrigation rate time constant for retention of radionuclide *i* in garden soil ($\lambda_{R,g,i}$) or pasture soil ($\lambda_{R,p,i}$) (1/yr)
$\phi(\delta)_{shield,i}$ .....Soil shielding fraction for radionuclide *i* for clean soil depth δ cm (-)

ϕ.....Soil porosity (-)
ϕ_w .....Ratio of flow rates defined by Eq. (5.3-2)
θ_w.....Soil moisture content (-)
ρ_s .....Bulk soil density (kg/m^3)
ρ_w .....Density of water (kg/m^3)

12.0 References

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13.0 Appendix A: Comparison of Vegetable Ingestion Dose Calculation to NRC 1.109

Dose calculation methodology employed in DOE 435.1 PA's for the all-pathways performance objective is based in part on prior standards developed in the NRC Regulatory Guide 1.109 (NRC, 1977). The intent of models assessing human health risks such as those contained in the NRC Reg. Guide is to predict concentrations in environmental source media and subsequent dose impacts from transfer and uptake of radionuclides. These NRC models rely on simple multiplicative chains of parameters based on the assumption of equilibrium conditions and average-condition parameter values. In the NRC model describing plant uptake of radionuclides through irrigation, a uniform soil concentration is assumed throughout a 15-cm deep root zone. Plant concentrations are calculated from the radionuclide content in the root-zone soil adjusted for radioactive decay. For relatively mobile nuclides with extremely long half-lives, such as Tc-99, inclusion of other removal processes such as leaching below the root zone, would be appropriate for assessing long-term dose impacts (Baes and Sharp, 1983). The following comparison of the NRC assessment model with the derivation considering first-order leaching effects contained in this report (see Sections 1.1 and 2.2) is discussed below.

In this Appendix, the expression used to calculate doses from the consumption of garden produce is compared to the equation given in NRC Reg. Guide. Combining Eq. (2.1-5) with Eq. (2.3-2) gives the following general expression for ingestion dose from consumption of garden produce:

$$D_{ing,g,i} = EC_{ing,i}\, Ing_{g,i} = EC_{ing,i}\, F_g\, U_g\, C_{g,i}\, e^{-t_{hold,g}\,\lambda_i} \tag{A-1}$$

From Eq. (2.3-3), the concentration of contamination in the produce is calculated as:

$$C_{g,i} = \left(F_L\, F_W\, R_{Leaf,g,i} + R_{Root,g,i}\right) C_{w,i} \tag{A-2}$$

Table 2-1 provides the following relations for the leaf and root retention factors:

$$R_{Leaf,g,i} = \frac{I_{R,g}\, F_r}{\lambda_e\, Y_g}\left(1 - e^{-\lambda_e\, t_{irr.g}}\right) \tag{A-3}$$

$$R_{Root,g,i} = T_{StoV,i}\, K_{d,i}\, \frac{\lambda_{R,g,i}}{\lambda_{B,g,i}}\left(1 - e^{-\lambda_{B,g,i}\, t_b}\right) \tag{A-4}$$

Combining Eq. (A-3) and Eq. (A-4) with Eq. (A-2) gives the expression:

$$C_{g,i} = C_{w,i}\left[F_L\, F_W\, \frac{I_{R,g}\, F_r}{\lambda_e\, Y_g}\left(1 - e^{-\lambda_e\, t_{irr.g}}\right) + T_{StoV,i}\, K_{d,i}\, \frac{\lambda_{R,g,i}}{\lambda_{B,g,i}}\left(1 - e^{-\lambda_{B,g,i}\, t_b}\right)\right] \tag{A-5}$$

Table 2-1 provides the following definition for the time constant for radionuclide retention in produce:

$$\lambda_{R,g,i} = \left(F_{R,g}\, I_{R,g}\right)/(R_i\, \theta_w\, d_t) \tag{A-6}$$

Substituting Eq. (A-6) into Eq. (A-5) and factoring out the common term $I_{R,g}$ that now occurs in both the leaf and root retention factors gives:

$$C_{g,i} = C_{w,i}\, I_{R,g}\left[F_L\, F_W\, \frac{F_r\left(1 - e^{-\lambda_e\, t_{irr.g}}\right)}{\lambda_e\, Y_g} + K_{d,i}\, \frac{F_{R,g}\, T_{StoV,i}\left(1 - e^{-\lambda_{B,g,i}\, t_b}\right)}{R_i\, \theta_w\, d_t\, \lambda_{B,g,i}}\right] \tag{A-7}$$

Table 2-1 also provides the following definitions of terms appearing in Eq. (A-7):

$$\lambda_{B,g,i} = \lambda_i + \lambda_{L,g,i} = \lambda_i + \left(F_{R,g}\, I_{R,g} + P - E\right)/(R_i\, \theta_w\, d_t) \quad \text{(A-8)}$$

$$\lambda_e = \lambda_w + \lambda_i \quad \text{(A-9)}$$

$$R_i\, \theta_w = \theta_w + \rho_s\, K_{d,i} \quad \text{(A-10)}$$

Using the notation adopted in this report, the equation in NRC 1.109 equivalent to Eq. (A-7) is:

$$C_{g,i} = C_{w,i}\, I_{R,g} \left[\frac{F_r \left(1 - e^{-\lambda_e\, t_{irr.g}}\right)}{\lambda_e\, Y_g} + \frac{F_{R,g}\, T_{StoV,i} \left(1 - e^{-\lambda_i\, t_b}\right)}{\rho_{ss}\, \lambda_i} \right] e^{-t_{hold,j}\, \lambda_i} \quad \text{(A-11)}$$

Equation (A-11) introduces the soil "areal density" ρ_{ss} defined to be $\rho_s\, d_t$. The NRC equation includes the holdup decay term in the calculation of produce concentrations whereas, to simplify notation in the current derivation, this term was not included in the concentration but carried separately. More importantly, the NRC equation does not account for the removal of radionuclides from garden soil through leaching. To examine the difference in the two equations, the factor $R_i \theta_w$ from Eq. (A-10) is substituted into Eq. (A-7) to give:

$$C_{g,i} = C_{w,i}\, I_{R,g} \left[F_L\, F_W \frac{F_r \left(1 - e^{-\lambda_e\, t_{irr.g}}\right)}{\lambda_e\, Y_g} + K_{d,i} \frac{F_{R,g}\, T_{StoV,i} \left(1 - e^{-\lambda_{B,g,i}\, t_b}\right)}{\left(\theta_w + \rho_s\, K_{d,i}\right) d_t\, \lambda_{B,g,i}} \right] \quad \text{(A-12)}$$

As $K_{d,i}$ becomes large, the approximation $\theta_w + \rho_s\, K_{d,i} \cong \rho_s\, K_{d,i}$ is valid. Then, including the holdup decay factor for comparison purposes, Eq. (A-12) reduces to:

$$C_{g,i} = C_{w,i}\, I_{R,g} \left[F_L\, F_W \frac{F_r \left(1 - e^{-\lambda_e\, t_{irr.g}}\right)}{\lambda_e\, Y_g} + \frac{F_{R,g}\, T_{StoV,i} \left(1 - e^{-\lambda_i\, t_b}\right)}{\rho_{ss}\, \lambda_i} \right] e^{-t_{hold,j}\, \lambda_i} \quad \text{(A-13)}$$

The only difference between the dose equation obtained through the current development in its limiting form for large $K_{d,i}$ and the NRC 1.109 version is the introduction of two additional factors, F_L (the fraction of total produce consumption consisting of leafy vegetables) and F_W (the fraction of contamination remaining on leafy vegetables after washing), in the current version. These factors appear to be reasonable additions to include in the dose calculation. Therefore, the above derivation demonstrates that the dose equation for produce consumption derived in the current work is equivalent to that in NRC 1.109 in the limit of large $K_{d,i}$. This is the expected result because the NRC 1.109 equation does not account for radionuclide leaching from soil which would apply in the case of large $K_{d,i}$.

Also note that combining Eq. (A-10) with Eq. (A-8) gives:

$$\lambda_{L,g,i} = \frac{\left(F_{R,g}\, I_{R,g} + P - E\right)}{\left(\theta_w + \rho_s\, K_{d,i}\right) d_t} \quad \text{(A-14)}$$

Equation (A-14) is exactly the leaching time constant proposed by Baes and Sharp (1983).

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