DOC-WMF

Final Report

RSP613.6 Safety Assessment Code Development and Application

Canadian Nuclear Safety Commission (CNSC)

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1.0 Introduction

Numerical codes can provide valuable insight into predicting radionuclide transport and total dose rates over time for various waste disposal options of radioactive waste. These codes can be used as part of a safety assessment of deep geological repositories, near-surface waste facilities and mine tailings and waste rock disposal facilities.

A code called DOC-WMF was developed based on the Scoping of Options and Analysing Risk (SOAR) model which was created by the US Nuclear Regulatory Commission (US NRC). The purpose of creating DOC-WMF was to develop a generic code to predict total dose rates for a variety of waste disposal options that overcomes the limitations of SOAR. The SOAR model was constructed within GoldSim, which is a user friendly simulation software, to provide a tool for assessing various waste disposal options. The resulting DOC-WMF model is a one-dimensional steady state flow code that predicts transport considering advection, dispersion, diffusion, sorption, solubility limits, ingrowth and decay. The predicted release to the biosphere is then used to calculate the dose rate to a receptor.

1.1 SOAR Overview

The SOAR model is modular and has five main components: The Waste Form Component; The Waste Package Component; The Near Field Component; The Far Field Component; and The Biosphere Component (see Figure 1.1). The modular format of SOAR allows for changes to one component without affecting others. Outputs from one component are inputted to others as required. For example, the Waste Form Component calculates the inventories and passes them to the Near Field Component for source-release calculations (see Figure 1.2).

Previously, the SOAR model was used to simulate the NWMO's Fifth Case Study (Osborne, 2015; NWMO, 2013a and b) and was found to show good comparison of results as well as being very robust. Some limitations were inherent in SOAR and are as follows:

- Only 16 radionuclides are incorporated (C-14, Cs-135, I-129, Np-237, Pu-238, Pu-239, Pu-240, Pu-242, Se-79, Tc-99, U-232, U-233, U-234, U-235, U-236, U-238).
- Ingestion of water is the only exposure pathway considered in the dose calculation.
- Only three legs (types of geology) are accounted for in the geosphere.
- Limited source release options
- Manner in which parameters are inputted is not necessarily site specific.
- Not able to add further radionuclides

Figure 1.1 – SOAR model configuration (taken from Markley et. al., 2011)

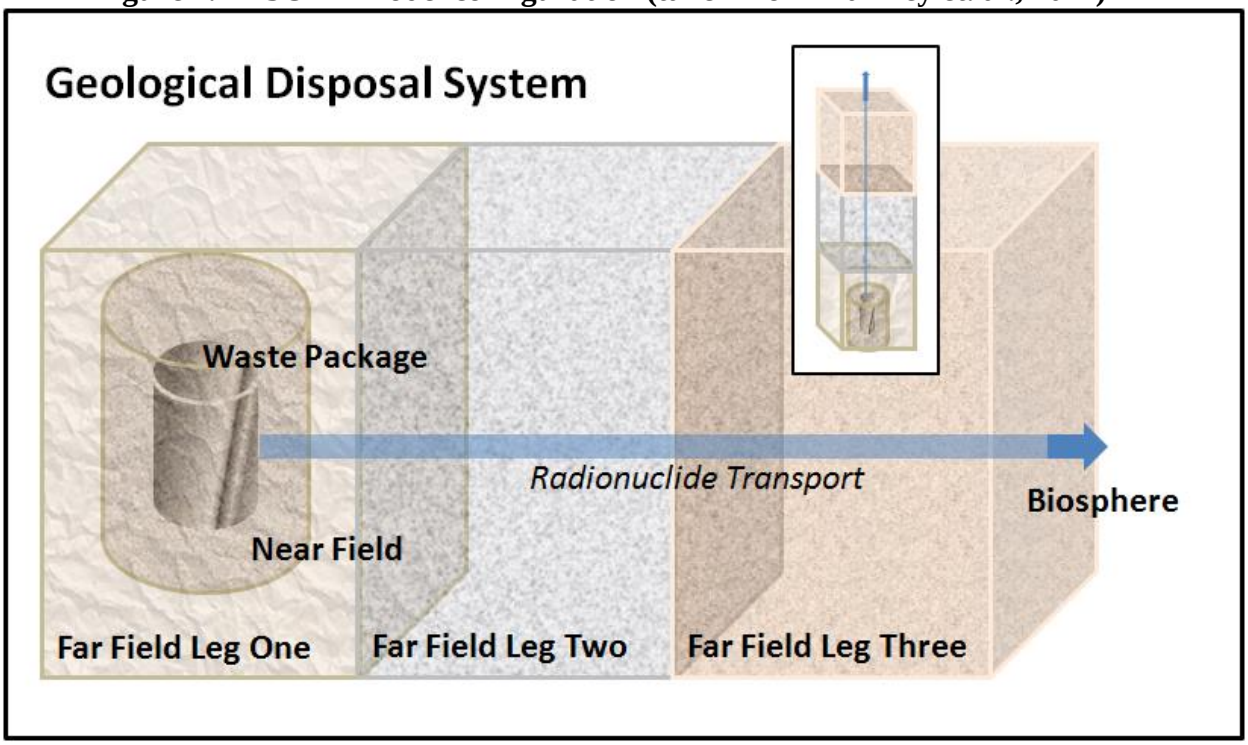
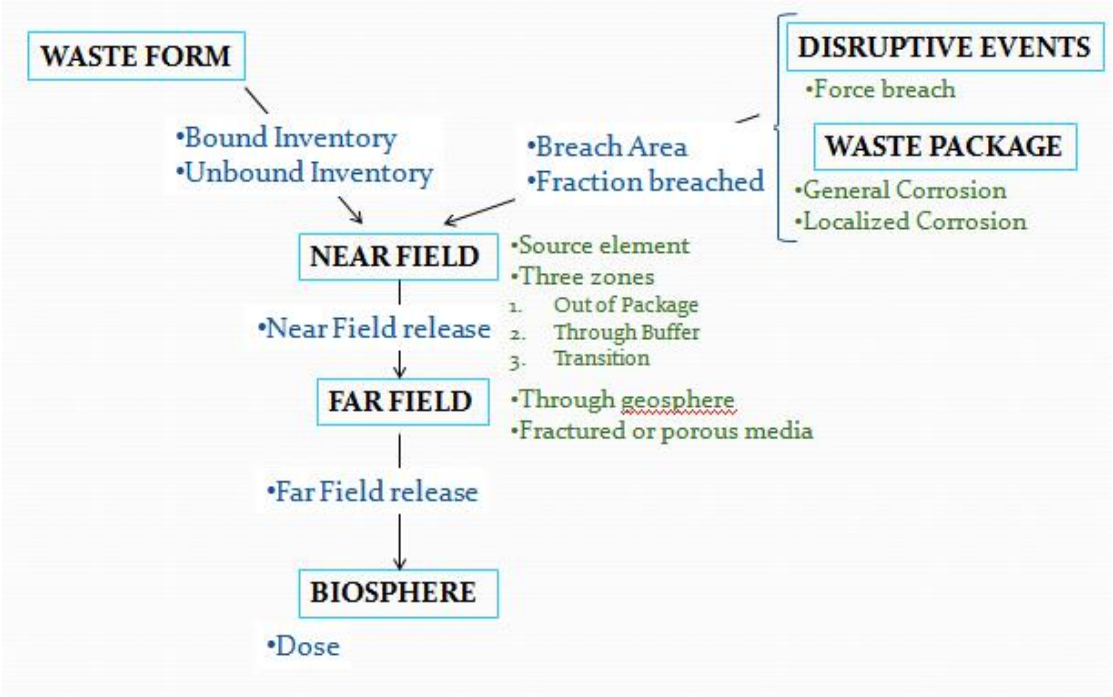


Figure 1.2 – SOAR model modules and interactions

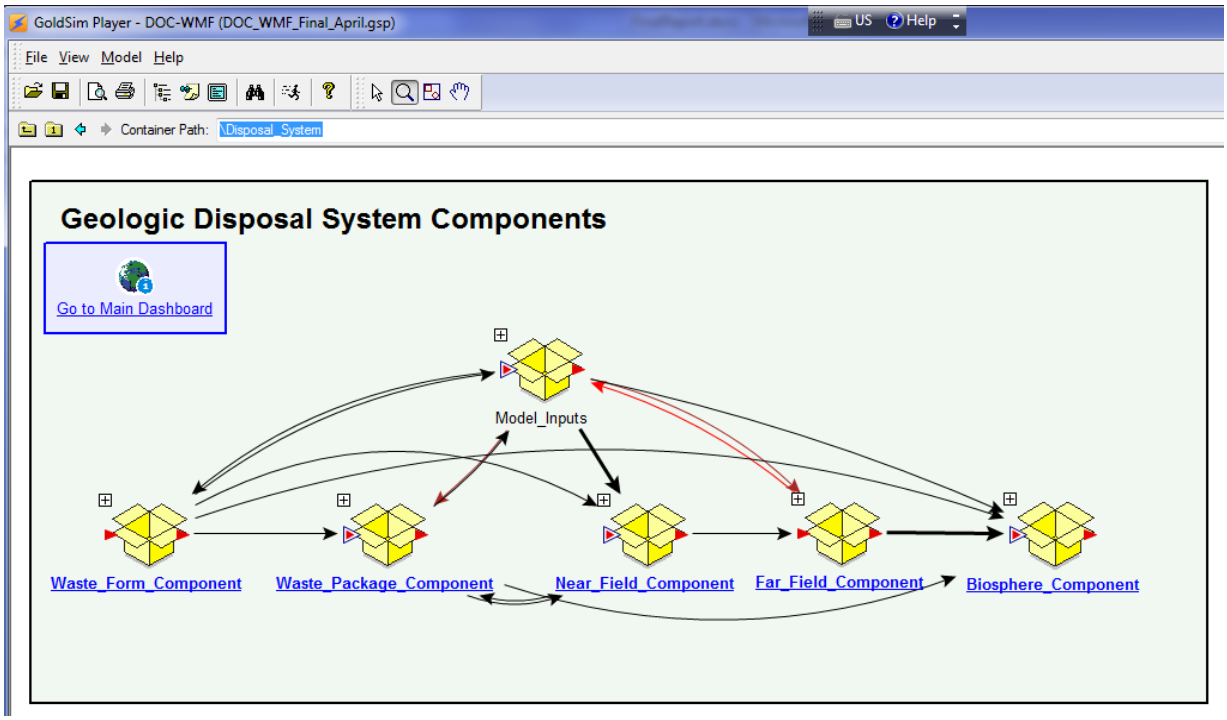


1.2 GoldSim

GoldSim is a commercially available simulation software package that has been used in many applications from Environmental Systems Modeling to Business Modeling. It has a user friendly interface where each element of the model is displayed by an icon in a Windows-type environment. To observe the properties associated with a GoldSim element, the user double clicks on the icon to display a property window containing all the required information of that element. GoldSim has numerous types of available elements to create the model such as Data and Stochastic which are Input Element types and Expressions and Selectors which are Function Element types. Spreadsheet elements are also available in which the user can import a scalar, vector or matrix from a specified Excel file and cell range(s). GoldSim visually displays the links between the various elements using arrows, providing a visual of the overall interactions within the model.

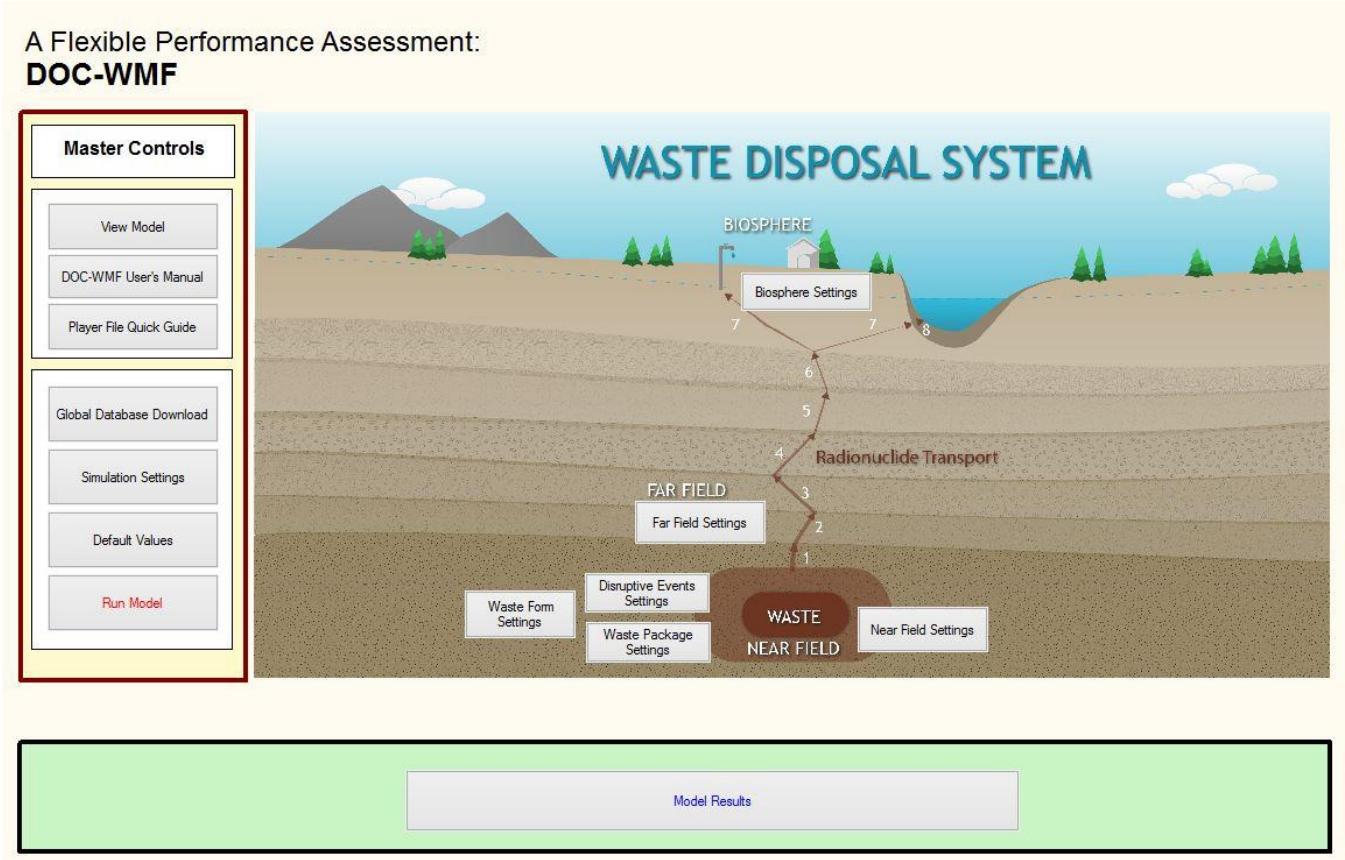
GoldSim also allows for organization of the model using containers. A model such as DOC-WMF contains hundreds of different GoldSim elements and if not organized in some manner would be difficult to manage. Containers provide a method by which elements can be sorted into subgroups. Containers can be placed within other containers providing for a hierarchy within the model. An example showing the use of these containers is presented in Figure 1.3. At this particular location within the model, there are six containers, one for each component (Waste Form, Waste Package, Near Field, Far Field and Biosphere) as well as one for the model inputs. It is possible to open containers to view the contents and move through the code. The GoldSim Container Path, which is like an address, to a specific location within the model is indicated in the menu bar towards the top of the screen. In this case the pathway is: \Disposal_System.

Figure 1.3 – GoldSim code showing organization using containers



Dashboards can be used for inputting parameters to make selections or for presenting results. The main dashboard of DOC-WMF is shown in Figure 1.4 and has various buttons that can be used to move around the model. Other dashboards contain input windows that the user inputs data and will be shown in the subsequent sections.

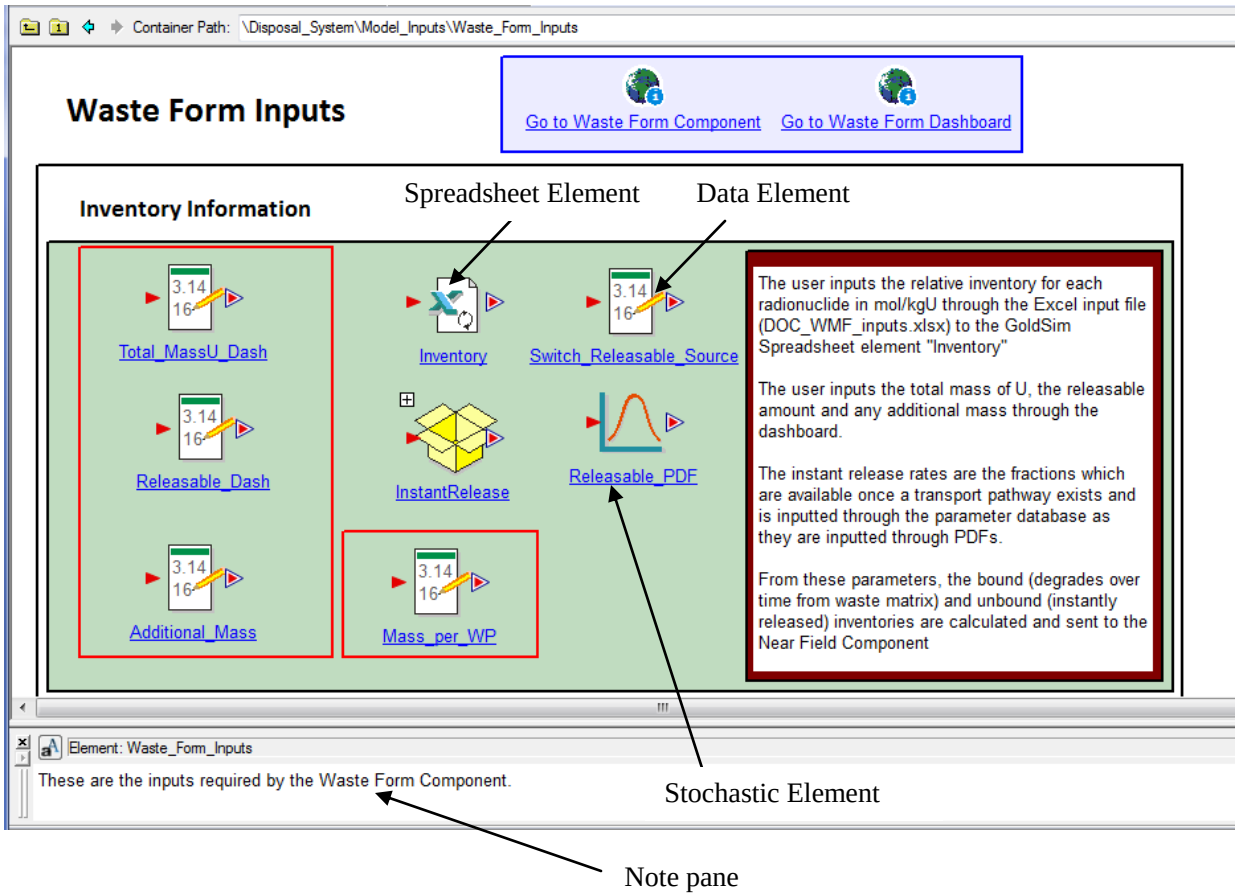
Figure 1.4 – Main dashboard from DOC-WMF



Several note options are available allowing for documentation throughout the code itself to provide explanations (See Figure 1.5 for example). There is a note pane at the bottom of the screen that contains information related to the selected GoldSim element. There are also text boxes providing explanations and comments throughout the code. These comments provide users with explanations throughout the code.

GoldSim allows for both deterministic and probabilistic modeling using the Monte Carlo Technique. The user has full control in specifying the time step, simulation time and the number of Monte Carlo simulations. For a deterministic simulation, the user can specify whether the mean or a specific percentile should be used to draw parameter values from those defined by a probability distribution function (PDF).

Figure 1.5 – Example GoldSim code from DOC-WMF



There are various manners in which the required parameters for the model can be inputted. GoldSim dashboards are used for selecting options and setting parameter values. Deterministic values can also be brought in through Excel files. Parameters defined by PDFs are brought in through parameter database. Finally, values can be hard coded directly into the GoldSim input elements.

A nice feature of GoldSim is that it keeps tracks of units for each element and makes conversions as required within equations. If an equation relating several elements does not result in the correct units, GoldSim will display an error and the model will not run. Having this feature reduces chances of errors when implementing new equations.

GoldSim has the main simulation software, as well as add-ons that are available. For the creation of DOC-WMF, the Contaminant Transport module was used and contains specialized elements and features specific to contaminant transport simulations. For any contaminant transport model, GoldSim creates a Species element which is required and may not be deleted. The Species element contains a list of the considered radionuclides and information such as molecular weight, half life and daughter products.

Another contaminant transport element is the GoldSim Source element that calculates the source release using inventory information, failure mode parameters, degradation of the bound waste form, solubility limits, decay and ingrowth. The Source element can consider both unbound inventory (that

which is released immediately when breach occurs) and bound inventory (that bound within the waste matrix that degrades over time).

Cell Pathways and Pipe Pathways are two different elements that can be used to model the transport of contaminants through the subsurface. GoldSim determines mass movement through the various transport elements such as Cell Pathways (used in the Near Field) and Pipe Pathways (used in Far Field) through the use of mass flux links. Advective and dispersive mass flux links are used to move the mass of contaminants as defined between the various elements.

A series of Cell Pathways are used to represent the transport through the buffer in the Near Field which is equivalent to a finite difference approximation. Pipe Pathways are used to model the transport through the geosphere or Far Field and uses a Laplace transform approach and can also be used to simulate transport through fractured media.

The SOAR model is used as the basis for the development of DOC-WMF. The next sections discuss the changes that were made in the creation of DOC-WMF. In some modules, such as the Biosphere Component, extensive changes were made to the model to allow for a biosphere component with more exposure pathways. Whereas, in the Waste Package module, very little changes were made and the functioning is essentially that of SOAR.

An overview of GoldSim is presented in the DOC-WMF User's Manual and further information can be found on the GoldSim website (goldsim.com) through their manuals, webinars and free on-line training.

1.3 DOC-WMF Overview

The DOC-WMF model was adapted from the SOAR model to make it more generic such that it can be applied to a variety of waste disposal options. The purpose was to overcome the limitations with SOAR that were previously described in Section 1.1. Changes were made within most modules and will be discussed fully in the following sections.

SOAR was originally developed in GoldSim version 10.1, and the first step in developing DOC-WMF was to upload it into a newer version of GoldSim, version 11.0. Since the initial creation of DOC-WMF, a newer version of GoldSim (version 12.0) has been released. Through investigation it is possible to directly load version 11.0 models into version 12.0 without any difficulties. The main change to this new version is to the graphics of GoldSim and the introduction of a new element not required within DOC-WMF. There would be no problem in the future to bring DOC-WMF into this version.

One organizational change is that the model inputs are stored together in one place in the model for ease of accessibility within the code itself. Various parameters are required to run a simulation and are inputted through various avenues, such as dashboards, a parameter database and from an Excel file. A series of dashboards, one for each module, were created for a user to indicate options and select parameters. The parameters inputted through these dashboards include variables such as quantity of waste, mode of failure, pathway options within the geosphere and ingestion/inhalation

rates for dose calculations. These are the types of parameters a user might want to alter to observe the effects on the final total dose. The parameters inputted through the dashboard have been assigned default values as well as minimum and maximum allowable values.

Data such as decay rates and dose coefficients that are deterministic but generally are not frequently altered are brought in through an excel file called "DOC_WMF_inputs.xlsx". Specialized GoldSim Spreadsheet elements are used to bring in data from this Excel file. The window and cell range of the parameter in this Excel file are specified and therefore it is imperative to not alter the positioning of the data. The values of the parameters in this Excel file can be changed as needed, then saved and at the beginning of the next GoldSim simulation these new values would be brought into the code.

Many of the parameters have values that are uncertain and defined through a PDF. These parameters are implemented using GoldSim stochastic elements and are brought in through a database called "DOC_WMF_inputs.mdb". This parameter database is set-up according to what is termed "Yucca Mountain database" in Microsoft Access. This database has been created and full explanation of how to change the distribution type and associated values of these stochastic parameters is covered in the User's Manual. The user also has the option of hard coding the parameter values directly into the GoldSim elements if required, which is also discussed in the User's Manual.

The model was also constructed where various options are available to the user and can be set through the dashboards. For example, the user can set options with regards to choice of source release from the waste disposal system, which failure methods to consider and sources of water to be used in the dose calculations.

Finally, the results from each module within the model, such as release from the Near Field or at various locations within the Far Field or the resulting total dose are displayed through charts or tables that can be viewed from a set of results dashboards. The user can copy the data from these tables and paste in excel if desired.

The subsequent sections describe the functioning of each component of the model. For the Waste Form Component, a larger list of radionuclides was incorporated. The Waste Package Component was combined with the Disruptive Component as they both provide the same outputs to the Near Field Component and provides for better organization. The Near Field Component was altered to allow a more source release options. The Far Field Component was adapted to allow for more changes in geology as well as provide the user with more options for release to the biosphere, including release to a surface water body. The Biosphere Component was adapted to calculate transfer from the contaminated water to other compartments such as soil and air which were then used to calculate the total dose to the receptor through various exposure pathways.

2.0 DOC-WMF Development

2.1 Waste Form Component

The Waste Form Component is the module where the various inventories are calculated and passed to the Near Field Component to calculate the source release. The DOC-WMF list of radionuclides was expanded to include those from the NWMO's Fifth Case Study (NWMO, 2013) and several others (see Table 2.1). The associated daughter products and stoichiometry for each radionuclide is specified in Table 2.2. The atomic weight, half-life, decay rate and specific activity of all considered radionuclides are presented in Table 2.3. Within the DOC-WMF model, this information for all radionuclides is within a specialized element called the Species Element and is located in Disposal_System\Model_Inputs\Common_Inputs.

In the event that additional radionuclides are required, the model has been coded with the ability to add in up to eight more species. All of the required coding for calculating the transport of these extra radionuclides and the dose rates is contained within the model. In the model's default state, these dummy or extra radionuclides are inactive in that they have no inventory or ingrowth and do not impact the model results. To activate these radionuclides requires adding inventory and the associated parameters. The exact procedure for activating one or more of these dummy radionuclides is covered in Appendix A of this report and is fully covered in the DOC-WMF User's Manual. The procedure to ignore or essentially deactivate a radionuclide included within the model is also covered in Appendix A of this report and the User's Manual.

Table 2.1 – Radionuclides included in DOC-WMF

Single	I-129, Cl-36, H-3, Pd-107, Tc-99, Se-79, Cs-134, Cs-135, Cs-137, Kr-85, Ir-192, Co-60, C-14, Sm-147, Sm-151, U-232
Neptunium Series	Am-241→Np-237= Pa-233→U-233→Th-229=Ra-225=Ac-225
Uranium Series	Pu-242→U-238→Th-234→*Pa-234m*→U-234→Th-230→Ra-226→Rn-222→Po-218→Pb-214→Bi-214→Po-214→Pb-210→Bi-210→Po-210
Actinium series	Pu-239→U-235=Th-231→Pa-231=Ac-227=Th-227=Ra-223
Thorium series	Pu-240→U-236→Th-232=Ra-228=Th-228=Ra-224
	Sr-90→Y-90
	Pu-238→U-234
	Zr-93→Nb93m

Note: Italics indicates not included

Table 2.2 – Radionuclides with daughter products and stoichiometry

Species	Description	Daughter 1	Daughter 2	Daughter 3
Ac-225	Actinium 225			
Ac-227	Actinium 227	Th-227 (0.9862)	Ra-223 (0.013799)	
Am-241	Americium 241	Pa-233 (1)		
Bi-210	Bismuth 210	Po-210 (1)		
Bi-214	Bismuth 214	Po-214 (0.99979)	Pb-210 (0.00021)	
C-14	Carbon 14			
Cl-36	Chlorine 36			
Co-60	Cobalt 60			
Cs-134	Caesium 134			
Cs-135	Caesium 135			
Cs-137	Caesium 137			
H-3	Hydrogen 3			
I-129	Iodine 129			
Ir-192	Iridium 192			
Kr-85	Krypton 85			
Nb93m	Niobium 93			
Np-237	Neptunium 237	U-233 (1)		
Pa-231	Protactinium 231	Ac-227 (1)		
Pa-233	Protactinium 233	Th-229 (1)		
Pb-210	Lead 210	Bi-210 (1)		
Pb-214	Lead 214	Bi-214 (1)		
Pd-107	Palladium 107			
Po-210	Polonium 210			
Po-214	Polonium 214	Pb-210 (1)		
Po-218	Polonium 218	Pb-214 (0.9998)	Bi-214 (0.0001998)	Po-214 ($2x10^{-7}$)
Pu-238	Plutonium 238	U-234 (1)		
Pu-239	Plutonium 239	U-235 (1)		
Pu-240	Plutonium 240	U-236 (1)		
Pu-242	Plutonium 242	U-238 (1)		
Ra-223	Radium 223			
Ra-224	Radium 224			
Ra-225	Radium 225	Ac-225 (1)		

Table 2.2 – Radionuclides with daughter products and stoichiometry (continued)

Species	Description	Daughter 1	Daughter 2	Daughter 3
Ra-226	Radium 226	Rn-222 (1)		
Ra-228	Radium 228	Th-228 (1)		
Rn-222	Radon 222	Po-218 (1)		
Se-79	Selenium 79			
Sm-147	Samarium 147			
Sm-151	Samarium 151			
Sr-90	Strontium 90	Y-90 (1)		
Tc-99	Technetium 99			
Th-227	Thorium 227	Ra-223 (1)		
Th-228	Thorium 228	Ra-224 (1)		
Th-229	Thorium 229	Ra-225 (1)		
Th-230	Thorium 230	Ra-226 (1)		
Th-231	Thorium 231	Pa-231 (1)		
Th-232	Thorium 232	Ra-228 (1)		
Th-234	Thorium 234	Th-230 (0.9984)		
U-232	Uranium 232			
U-233	Uranium 233	Th-229 (1)		
U-234	Uranium 234	Th-230 (1)		
U-235	Uranium 235	Th-231 (1)		
U-236	Uranium 236	Th-232 (1)		
U-238	Uranium 238	U-2341 (1)		
Y-90	Yttrium 90			
Zr-93	Zirconium 93	Nb93m (0.975)		

Table 2.3 – Parameter values for radionuclides

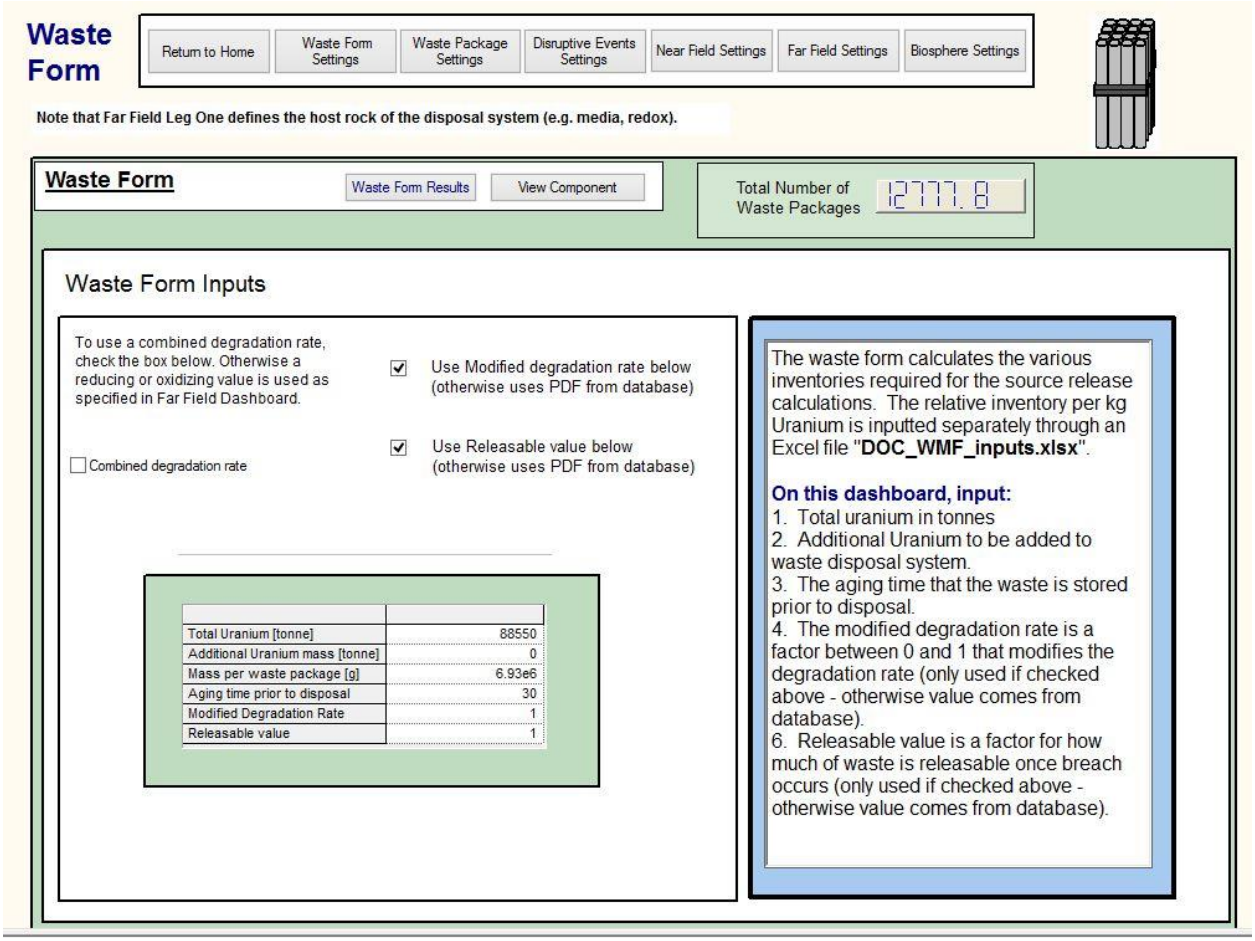
Species	Atomic Weight [g/mol]	Half-life	Decay Rate [1/yr]	Specific Activity [Bq/g]
Ac-225	225.023	10 d	25.3	2.147×10^{15}
Ac-227	227.028	21.772 yr	0.0318	2.6761×10^{12}
Am-241	241.057	432.4 yr	0.0016	1.2632×10^{11}
Bi-210	209.984	5.013 day	50.5	4.5896×10^{15}
Bi-214	213.999	19.9 min	1.83×10^{4}	1.6337×10^{18}
C-14	14.003	5707.8 yr	0.000121	1.6553×10^{11}
Cl-36	35.9683	3.01×10^{5} yr	2.3×10^{-6}	1.2208×10^{9}
Co-60	59.9338	5.2638 yr	0.132	4.1928×10^{13}
Cs-134	133.907	2.0648 yr	0.336	4.784×10^{13}
Cs-135	135	2.3×10^{6} yr	3.01×10^{-7}	4.26×10^{7}
Cs-137	136.907	30.093 yr	0.023	3.2106×10^{12}
H-3	3.01605	12.3351 yr	0.0562	3.5554×10^{14}
I-129	129	1.57×10^{7} yr	4.41×10^{-8}	6.531×10^{6}
Ir-192	191.963	73.827 day	3.43	3.409×10^{14}
Kr-85	84.9125	10.78133 yr	0.0643	1.4449×10^{13}
Nb93m	92.9064	16.13 yr	0.043	8.8266×10^{12}
Np-237	237	2.147×10^{6} yr	3.23×10^{-7}	2.5998×10^{7}
Pa-231	231.036	32,661 yr	2.12×10^{-5}	1.7529×10^{9}
Pa-233	233.04	26.967 d	9.39	7.6877×10^{14}
Pb-210	209.984	22.2 yr	0.0312	2.8375×10^{12}
Pb-214	214	26.8 min	1.36×10^{4}	1.213×10^{18}
Pd-107	106.905	6.5×10^{6} yr	1.07×10^{-7}	1.9035×10^{7}
Po-210	209.983	138.38 day	1.83	1.6627×10^{14}
Po-214	213.995	0.0001643 sec	1.33×10^{11}	1.1872×10^{25}
Po-218	218.009	3.1 min	1.18×10^{5}	1.0294×10^{19}
Pu-238	238	87.7 yr	0.00789	6.3274×10^{11}
Pu-239	239	24,131 yr	2.87×10^{-5}	2.2935×10^{9}
Pu-240	240	6563.9 yr	1.06×10^{-4}	8.3965×10^{9}
Pu-242	242	3.742×10^{5} yr	1.85×10^{-6}	1.4608×10^{8}
Ra-223	223.019	11.43 day	22.1	1.8953×10^{15}

Table 2.3 – Parameter values for radionuclides (continued)

Species	Atomic Weight [g/mol]	Half-life	Decay Rate [1/yr]	Specific Activity [Bq/g]
Ra-224	224.02	3.66 day	69.2	5.8924×10^{15}
Ra-225	225.024	14.9 day	17	1.4409×10^{15}
Ra-226	226.025	1601.3 yr	4.33×10^{-4}	3.6546×10^{10}
Ra-228	228.031	5.77 yr	0.12	1.0053×10^{13}
Rn-222	222.018	3.8235 day	66.2	5.6913×10^{15}
Se-79	79	295,000 yr	2.35×10^{-6}	5.6757×10^{8}
Sm-147	146.915	1.06×10^{11} yr	6.54×10^{-12}	849.38
Sm-151	150.92	90 yr	0.0077	9.7383×10^{11}
Sr-90	89.9077	28.82 yr	0.0241	5.1048×10^{12}
Tc-99	99	2.111×10^{5} yr	3.28×10^{-6}	6.3292×10^{8}
Th-227	227.028	18.68 day	13.6	1.1392×10^{15}
Th-228	228.029	1.9121 yr	0.363	3.0337×10^{13}
Th-229	229.032	7357 yr	9.42×10^{-5}	7.8501×10^{9}
Th-230	230.033	75,469 yr	9.18×10^{-6}	7.6193×10^{8}
Th-231	231.036	25.52 hr	238	1.9666×10^{16}
The-232	232.038	1.405×10^{10} yr	4.93×10^{-11}	4057.3
Th-234	234.044	24.1 day	10.5	8.5654×10^{14}
U-232	232	69.8 yr	0.0101	8.287×10^{11}
U-233	233	159,183 yr	4.35×10^{-6}	3.5663×10^{8}
U-234	234	245,750 yr	2.82×10^{-6}	2.3002×10^{8}
U-235	235	7.038×10^{8} yr	9.85×10^{-10}	7.9975×10^{4}
U-236	236	2.343×10^{7} yr	2.96×10^{-8}	2.3918×10^{6}
U-238	238	4.468×10^{9} yr	1.55×10^{-10}	1.2439×10^{4}
Y-90	89.9072	63.9 hr	95.1	2.0183×10^{16}
Zr-93	92.9065	1.53×10^{6} yr	4.53×10^{-7}	9.3054×10^{7}

The relative inventory for each radionuclide in [mol/kg U] is inputted through an excel file "DOC_WMF_inputs.xlsx". The user inputs the total mass of waste in [kg U] into the Waste Form dashboard (See Figure 2.1). This inputted total mass is multiplied by the relative inventory to obtain the initial moles of each radionuclide. The mass in grams of each radionuclide is then determined by multiplying by the molecular weight.

Figure 2.1 – Waste Form Dashboard



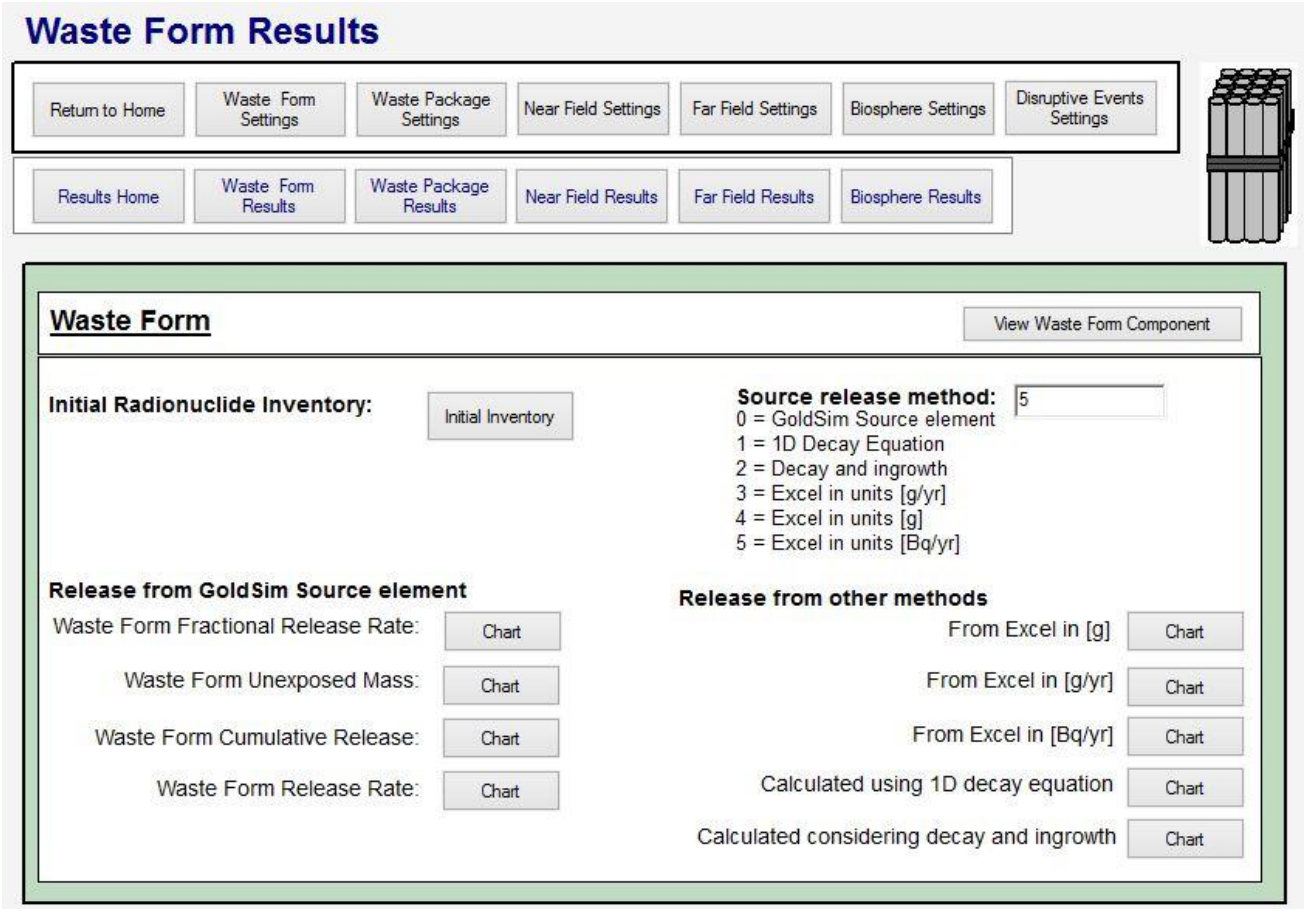
The user can input the age of the waste at the time of disposal and the model contains a waste aging sub model that is used to calculate the changes in inventory over time considering decay and ingrowth. The aging sub model returns an updated total inventory that is used to calculate the initial unbound and bound inventories.

Through the parameter database, a series of instant release fractions are inputted which are used to calculate the unbound inventory. This inventory is the amount of radionuclides that are available for transport immediately once breach occurs and a transport path out of the waste package is available. For each radionuclide, the unbound inventory is the total initial inventory multiplied by the instant release fraction. Those radionuclides with no instant release would be represented by zero mass in the unbound inventory.

The bound inventory would be the remaining mass of each radionuclide and represents the solid waste matrix that degrades over time, releasing the radionuclides according to a user-defined degradation rate in [1/yr]. The degradation rate is used to calculate a lifetime in [yr] which is passed to the Near Field for release calculations as will be discussed in Section 2.3 for the Near Field discussion.

The results from the waste form calculations are available on the Waste Form Results dashboard (see Figure 2.2). On this dashboard, the user can view such information as the chosen source release method and waste form release rate.

Figure 2.2 – Waste Form Results Dashboard



2.2 Waste Package Component

The Waste Package Component contains information with regards to the waste packages themselves in terms of material type, thickness and calculates the number of packages breached and breach area for each type of failure. Within DOC-WMF the Waste Package Component remains relatively unchanged from SOAR.

The waste package material type (copper, carbon steel, stainless steel or titanium), waste package thickness and internal water volume are set through the Waste Package Dashboard (see Figure 2.3). The model considers three possible failure modes: general corrosion; localized corrosion; and Disruptive Events. One, two or all failure modes can be considered as specified through the Waste Package Dashboard and Disruptive Events Dashboard (see Figure 2.4).

Figure 2.3 – Waste Package Dashboard

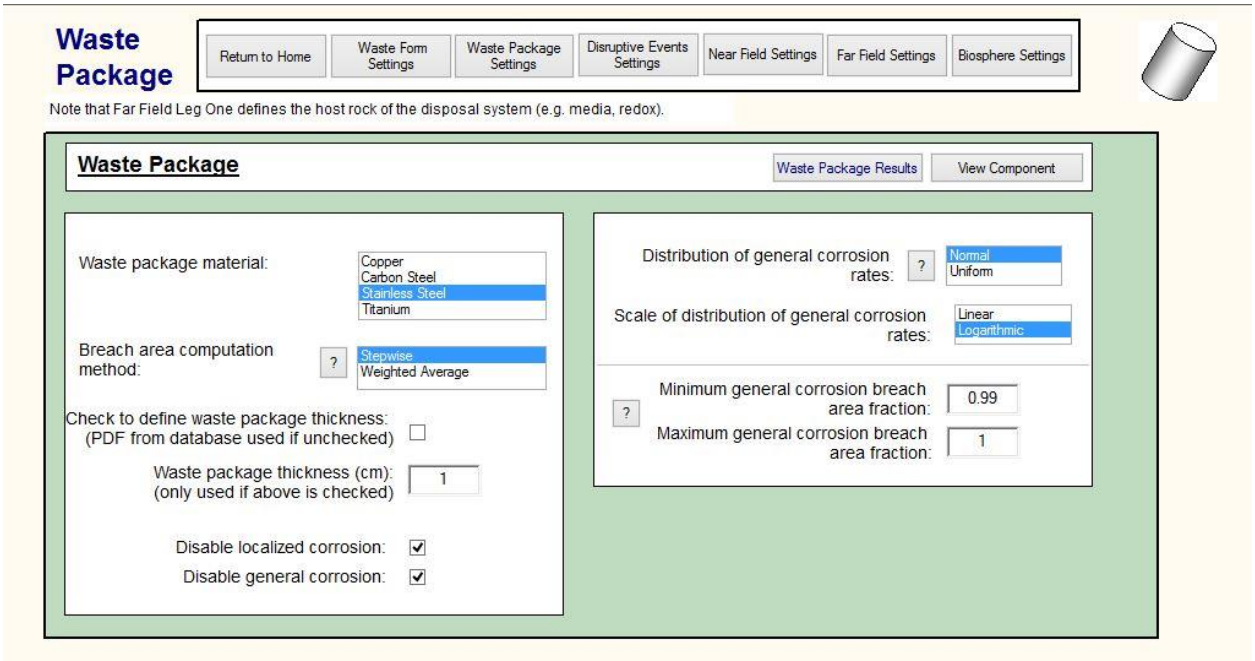
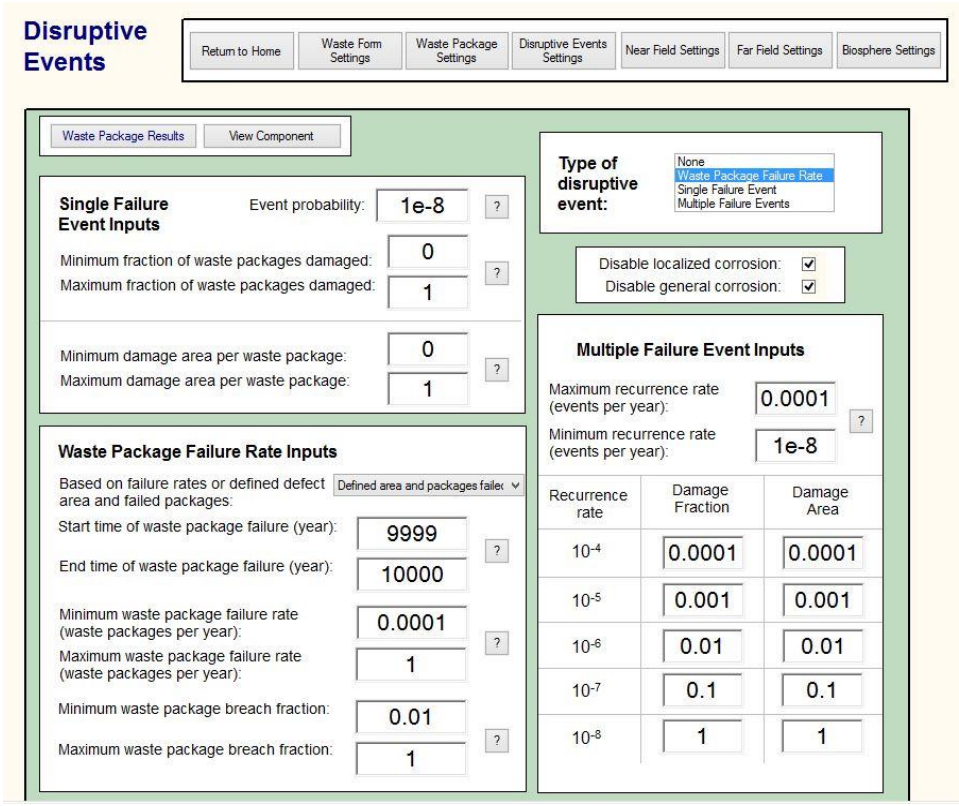


Figure 2.4 – Disruptive Events Dashboard



2.2.1 General Corrosion

General corrosion represents gradual corrosion that occurs in a slow and uniform manner over time. This type of corrosion assumes a slow thinning of the waste package material and assumes failure once the full thickness of the material has corroded. The following equation is used to represent general corrosion (Markley et al., 2011).

$$t_{gc} = \frac{L}{R_{gc}} \quad \textbf{2.1}$$

Where

t_{gc} = time to general corrosion failure
L = thickness of the waste package material
R_{gc} = specified corrosion rate [L/time]

The specified general corrosion rates are stochastic and the associated probability distribution functions (PDF) are inputted through the parameter database for each type of waste package material. The model selects the corrosion rate associated with the package material specified by the user on the waste package dashboard. The user can alter the waste package material through the dashboard to investigate the impact of the material type on the model results.

When conducting probabilistic modeling, the specified general corrosion rate would be the same for each waste package within a single realization. Each subsequent realization would choose a new general corrosion value based on the provided PDF that again would be used for all waste packages.

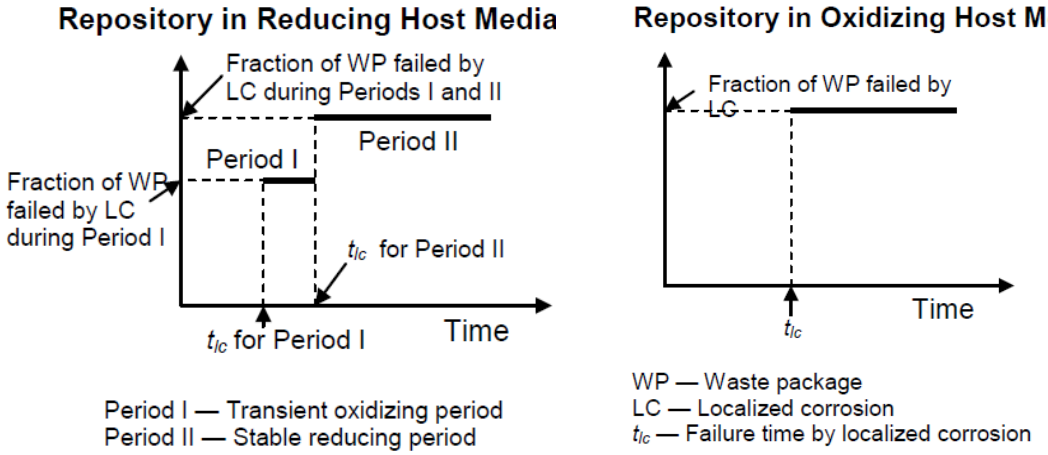
It is possible for the user to ignore general corrosion by clicking the box next to "Disable general corrosion" on the waste package dashboard. If general corrosion is disabled then the parameters associated with general corrosion, such as rates, are not required and will have no impact on the final model results.

2.2.2 Localized Corrosion

Localized corrosion occurs much quicker than general corrosion and in a step-wise manner. No specific model is used to determine failure times; instead PDFs are used (Markley et al, 2011). The required parameters for localized corrosion are REDOX dependent and have an associated PDF that are brought in through the parameter database. The repository environment, whether reducing or oxidizing, is assigned by the user through the Far Field dashboard.

For a reducing environment, it is assumed that initially the environment is oxidizing (Period I) due to presence of oxygen following repository construction. This relatively short period is in the tens to hundreds of years range and is followed by a transition to a reducing environment (Period II) (see Figure 2.5). The user inputs a PDF for failure time for each Period I and Period II and the fraction of waste packages affected within each period.

Figure 2.5 – Localized corrosion step functions (taken from Markley et al., 2011)



For a repository within an oxidizing environment, the user needs only provide a PDF for failure times and for the waste packages affected. As the environment does not change, only the one input for each is required.

Like general corrosion, localized corrosion can be disabled. If disabled, the associated parameters with localized corrosion do not need to be updated and will not have an effect on the model results.

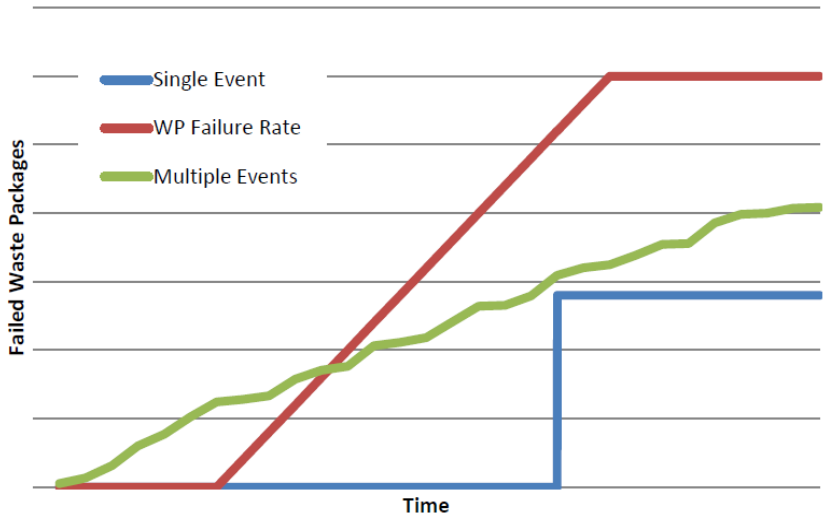
2.2.3 Disruptive Events

The Disruptive Events module has its own dashboard, which has remained relatively unchanged from the SOAR model. The Disruptive Events module provides the user with three additional failure modes: 1. Single failure event; 2. Multiple failure events; and 3. Defined waste package failure rate (see Figure 2.6). Only one of these disruptive event failure modes can be implemented per model simulation. Most of the required inputs are provided through the Disruptive Events dashboard. The Single Failure Event and Multiple Failure Events remain unchanged from SOAR.

2.2.3.1 Single Failure Event

For a Single Failure Event scenario, the user inputs the minimum and maximum of both the fraction of waste packages damaged and the extent of damage. Both parameters can range between 0 and 1 and are represented by a uniform PDF. The probability for an event to occur is also user defined. This method is valid for low recurrence rate events where the product of the total simulation time with the probability is less than 0.1 (Markley et al., 2011).

Figure 2.6 – Waste package failure curves for failure modes contained within the Disruptive Events module (taken from Markley et al., 2011)



2.2.3.2 Multiple Failure Events

The Multiple Failure Events scenario is a series of events that are assumed to occur randomly via a Poisson process (Markley et al., 2011). The user defines minimum and maximum for a series of recurrence rates that range from 10^{-4} and 10^{-8} 1/yr. For each order of magnitude the user defines the fraction of waste packages that are assumed to fail and the expected damage. Higher frequency events generally result in less damage than lower frequency events.

2.2.3.3 Waste Package Failure Rate

The Waste Package Failure Rate scenario allows the user to force breach at a specified time. There are two options available to the user, and is specified on the dashboard. The first method is that from SOAR and uses all the information that is inputted through the Disruptive Events dashboard under the Waste Package Failure Rate Inputs. Through the dashboard the user specifies the start time and end time of failure, the minimum and maximum waste package failure rate and the minimum and maximum waste package breach fraction. Uniform PDFs are created for the waste package failure rate and breach fraction from the inputted data. At a particular time step the number of waste packages breached and associated breach area are determined.

The second option for this failure mode was created for DOC-WMF. This option allows for the user to directly input the number of waste packages breached and the radius of the defect. This mode was used to define the failure within the NWMO's Fifth Case study. The failure scenario for this case study was that three packages were placed within the repository with undetected defects of 1 mm. Failure was assumed to occur at 10,000 years once enough water was present for a transport pathway to exist from the repository to the geosphere. To impose this scenario a start time of 9,999 years and

end time of 10,000 years was implemented. The radius of the defect and number of packages failed are defined by Stochastic elements and the associated PDFs are brought in through the parameter database.

2.2.4 Waste Package Outputs

The outputs from the Waste Package Component are sent to the Near Field Component. One output is the combined waste package breach area from general corrosion, localized corrosion and disruptive events. The value of the breach area is implemented as the diffusive area from the inside of the waste package to the outside through a Cell Pathway. The equations and description of the Cell Pathway will be further discussed in Section 2.3.

The combined waste package breach area from the various failure modes per failed waste package at each time step is required. Within the model, this breach area can be calculated through two different methods and is specified by the user on the dashboard. The first is a step-wise approach and at each time-step, the localized corrosion and general corrosion breach areas are examined and summed (Markley et al., 2011). This approach overestimates the breach area as only a few (not all) waste packages would be susceptible to both corrosion processes. If failure due to a disruptive event has also occurred at a particular time step, the larger breach area fraction of that from combined corrosive breach and disruptive breach is used.

The second approach uses a weighted average approach to calculate the fraction breached area based on that from localized corrosion, general corrosion and disruptive events (Markley et al., 2011).

$$WP_{BA} = \left(\frac{f_{GC}}{f_{Failed}} \cdot f_{GC,area} + \frac{f_{LC}}{f_{Failed}} \cdot f_{LC,area} + \frac{f_{DE}}{f_{Failed}} \cdot f_{DE,area}\right) \cdot A \qquad \textbf{2.2}$$

Where

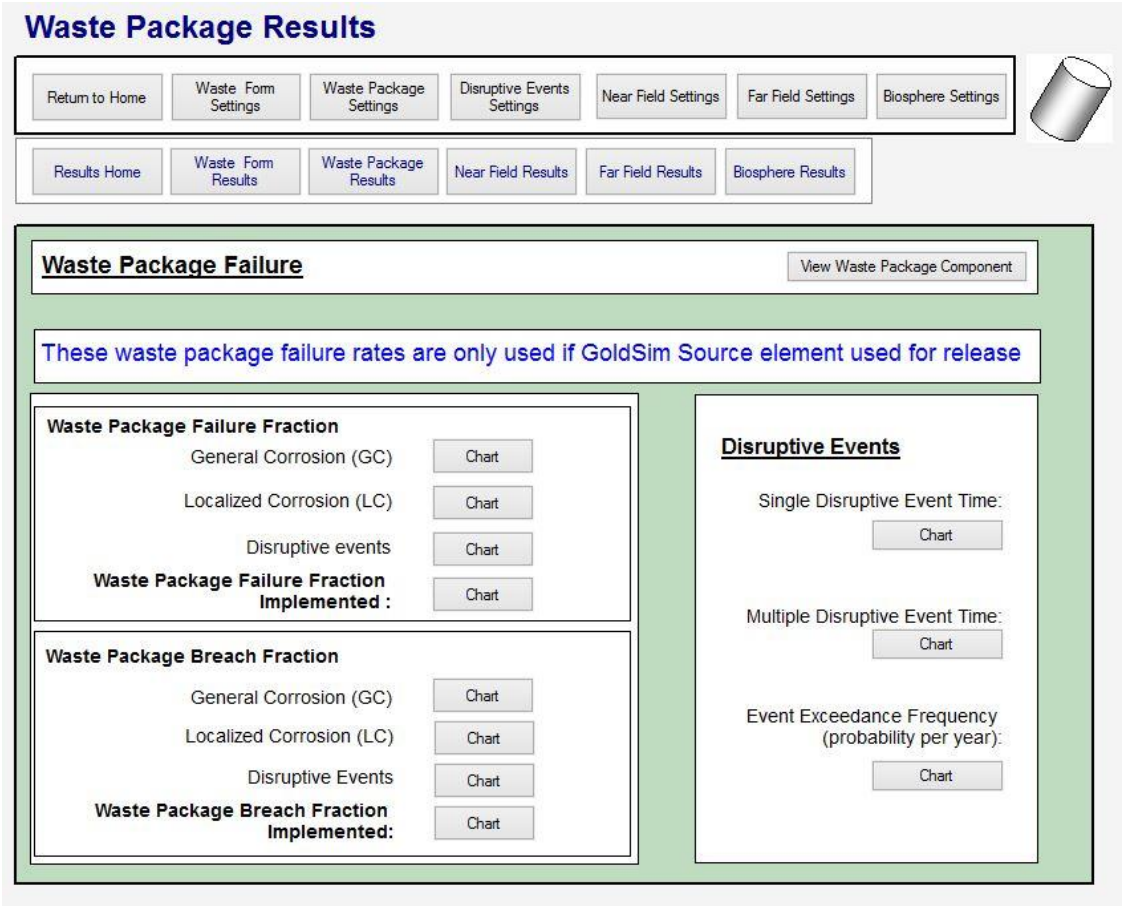
WP_{BA} = Fraction of waste packages breached using weighted average
f_{GC} = Fraction of waste packages failed by general corrosion
f_{LC} = Fraction of waste packages failed by localized corrosion
f_{DE} = Fraction of waste packages failed by disruptive events
f_{Failed} = Total fraction of waste packages failed
A = Total area of a waste package

This method weighs more of the breach area fraction to that with the most contribution. In other words, if most of the failure is due to localized corrosion, the resulting breach area fraction would be more highly impacted by that from localized corrosion.

The other output from the Waste Package Component is the fraction of waste packages breached. The value of waste packages breached from each failure mode are sent to the Source Element in the Near Field Component as will be discussed further in Section 2.3.

The Waste Package component results are presented on a dashboard as presented in Figure 2.7. The user can obtain results for waste package failure fraction and breach fraction for general corrosion, localized corrosion and disruptive events individually as well as combined results.

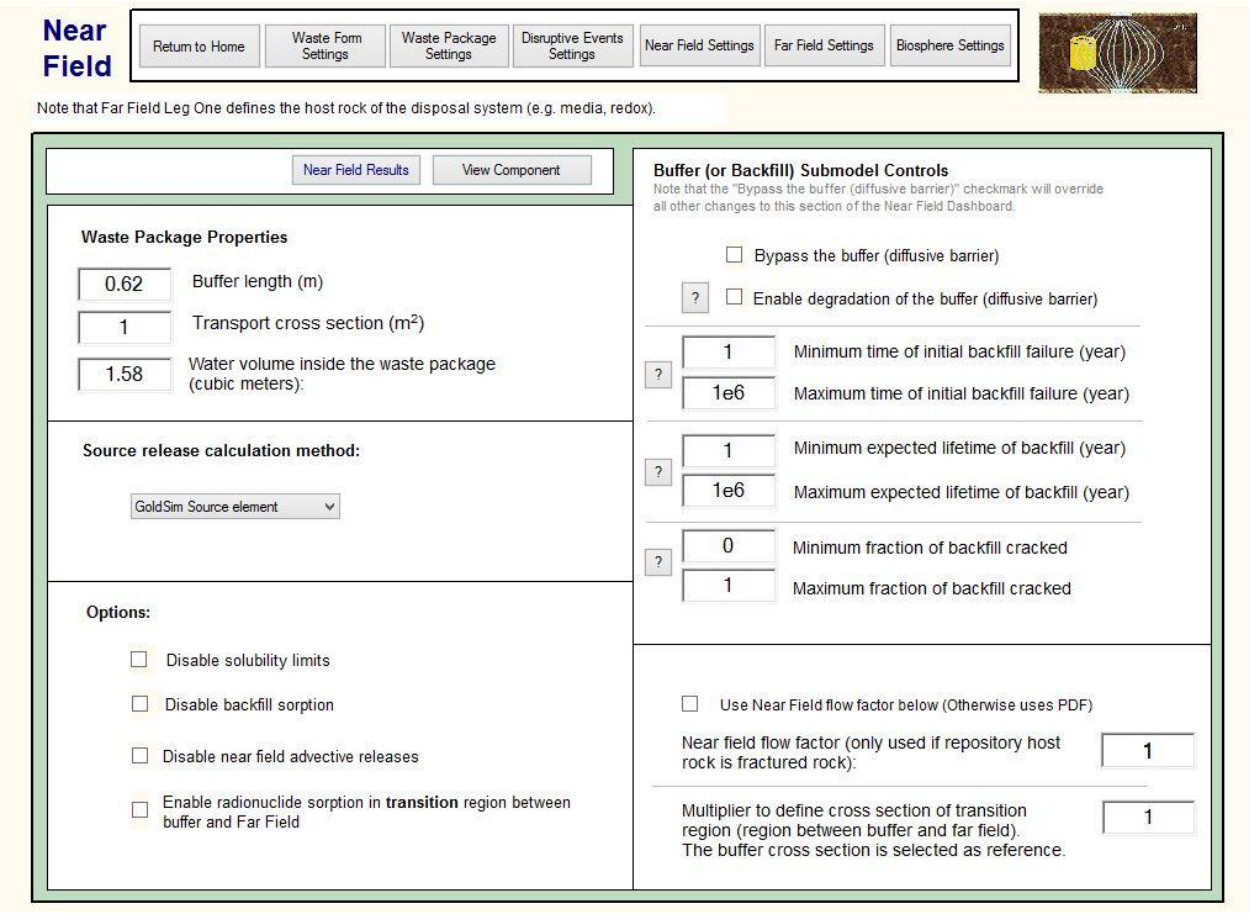
Figure 2.7 – Waste Package Results Dashboard



2.3 Near Field Component

The Near Field Component is the module where the release from the package, through buffer and release to the geosphere is predicted. Note that the terms buffer and backfill are used interchangeably in the model code itself. The Near Field Component is divided into three zones: zone 1, the release from the inside of the waste package to the surface; zone 2, travel through the buffer material; and zone 3, release to nearest fracture if assuming fractured media. In DOC-WMF, the source can either be represented by a GoldSim Source element as coded in SOAR, through a defined analytical solution, considering decay and ingrowth or user-defined through Excel. On the Near Field Component Dashboard, the user designates the source release method as well as general properties such as buffer length and water volume inside the waste package (see Figure 2.8) and options such as "Bypassing the buffer".

Figure 2.8 – Near Field Dashboard



2.3.1 Source Release Methods (Zone 1)

In DOC-WMF several options are available to assign or calculate the source release within Zone 1. The following sections discuss each of these options and the parameter requirements.

2.3.1.1 GoldSim Source element release

The GoldSim Source Element is a specialized element that uses the various inventories and degradation rate from the Waste Form Component and breach area and fraction of waste packages breached from the Waste Package Component as inputs. The Source Element allows the user to define the level of containment including number of packages, various inventories and failure modes. If the case to be modeled does not have packages, such as a landfill for example, the number of packages would be set equal to 1.

The Source element receives the bound and unbound inventories calculated in the Waste Form Component. The unbound inventory is available for release immediately once breach occurs and

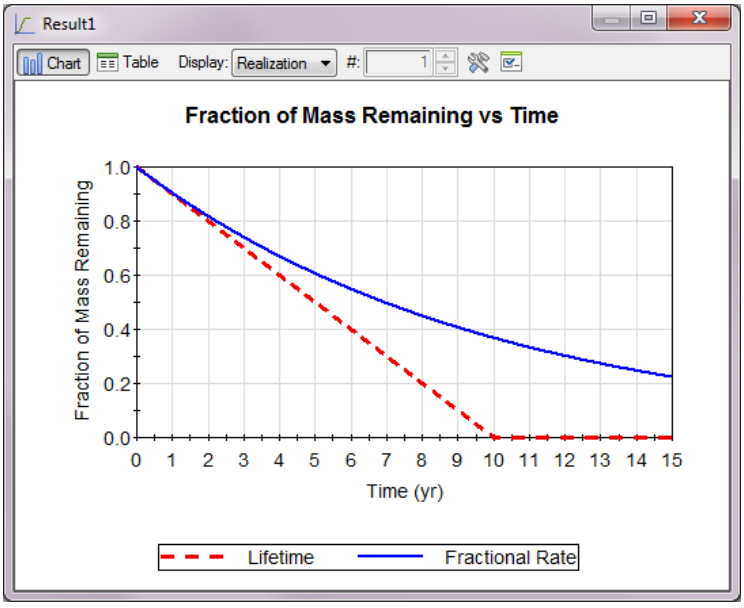
therefore does not require any further information within the Source element. For the bound inventory, parameters regarding the rate of degradation are required.

Within GoldSim, the bound waste form release can be set to degrade according to the Lifetime, a fractional degradation rate or congruent dissolution. The lifetime represents uniform degradation over time. The fractional degradation rate is the fraction of existing mass which degrades over time. The difference in how GoldSim accounts for a specified lifetime versus the fractional degradation rate is presented in Figure 2.9 for a specified lifetime of 10 years and fractional degradation rate of 0.1 1/yr. The lifetime represents a linear decrease in mass over the specified lifetime of 10 years and at the end of the lifetime all of the mass has been released. Whereas, for the fractional degradation rate the amount of mass remaining to be exposed declines exponentially and has not reached zero at the 10 year point.

In DOC-WMF (as in SOAR), the release form the bound waste form is defined through the Lifetime. The user inputs a degradation rate in 1/yr which is inversed to determine the lifetime in years. The lifetime represents the amount of time required to uniformly degrade the waste form completely. A higher value of lifetime results in a slower degradation of the waste matrix and longer time to release the contaminants.

The barrier failure information from the Waste Package Module is also incorporated into the Source Element by specifying the fraction of waste packages failed. The three failure modes, general corrosion, localized corrosion and disruptive events are included with their respective failure rates.

Figure 2.9 – Degradation of bound waste form through lifetime or degradation rate (taken from GoldSim (2014))



The following presents a summary of the equations used for the Source element as presented by GoldSim (2014). Within GoldSim, the Source element determines the exposure rate for the source release, e(n,t), as the sum of the release from both the bound ($e_{s,b}(n,t)$) and unbound ($e_{q,o}(n,t)$) inventories.

$$e(n,t) = \sum_{q=1}^{NI_q} e_{q,o}(n,t) + \sum_{s=1}^{NI_s} e_{s,b}(n,t) \quad \textbf{2.3}$$

Where

NI_q = Number of instant release or unbound inventories
NI_s = Number of bound inventories

The first term represents the rate at which mass becomes exposed for the unbound inventory and is calculated using the following equation.

$$e_{q,o}(n,t) = N \cdot I_q(n,t) \cdot c(t) \quad \textbf{2.4}$$

Where

N = Number of waste packages
$I_q(n,t)$ = Mass of species n per unfailed package in the instant release inventory [M]
c(t) = Barrier failure rate at time t [1/T]

Using the lifetime approach for bound matrix degradation, the exposure rate from the bound inventory is calculated using a convolution integral.

$$e_{s,b}(n,t) = N \cdot \int_0^t I_s(n,t) \cdot C\left(\tau\left(min\left(\frac{t-\tau}{T}\right), t\right)\right) d\tau \quad \textbf{2.5}$$

As the Source Element is a specialized type of container, other GoldSim elements can be contained within this Source Element. One requirement of the Source Element is that it requires an associated specialized Cell Pathway to be contained within the Source element container (Cell Pathways will be discussed in more detail in Section 2.3.2). This specialized Cell Pathway is referred to as an inventory cell and is intended to represent the release from one single package from the source. GoldSim then automatically scales the release to represent the presence of multiple packages. Initially this Cell Pathway has zero mass of contaminants and receives mass from the Source Element. This specialized Cell Pathway within DOC-WMF is what is considered to be Zone 1 of the Near Field Component which is the transport from inside the waste package to the surface. The breach area from the Waste Package Component is implemented as the diffusive area from this specialized Cell pathway to the first Cell Pathway within Zone 2, for the transport through the buffer.

2.3.1.2 One-Dimensional Decay equation for source release

The source release calculated using the one-dimensional decay equation is assigned through the following equation.

$$C_i = C_{0,i} \cdot e^{-k_i \cdot t} \quad \textbf{2.6}$$

Where

C_i = Concentration of contaminants released to Zone 2 at time t
$C_{0,i}$ = Initial total inventory of radionuclide i
k_i = Decay rate of radionuclide, i

Currently the model is set-up such that the release begins at the commencement of the simulation and then decays according to Equation 2.6. This differs from the GoldSim Source element in that barriers are not considered, and failure modes are ignored. As the release begins immediately, the dose rates from this method would generally be higher than those using the GoldSim Source method.

This source release method requires the total inventory from the Waste Form Component. However, failure information is not needed and therefore the Waste Package Component and associated parameters can be ignored if this method is chosen.

2.3.1.3 Source release considering decay and ingrowth

Another option is the using the initial inventory and determine the release based on decay as the analytical solution but also consider ingrowth. This source release method would be the same as the one-dimensional decay equation solution for radionuclides that have no ingrowth. However, would differ for those radionuclides that do have ingrowth.

Similar to the one-dimensional decay equation, the total inventory from the Waste Form Component is needed. However, this method does not require failure information and therefore can ignore the Waste Package Component and its associated parameters.

2.3.1.4 User-assigned source release

The final option for assigning the source release is that which is user-defined through the Excel input file called "DOC_WMF_inputs.xlsx". The user can input known source releases in [g], [g/yr] or [Bq/yr]. The user defines these source releases, which can vary over time, by adding in the appropriate source release values in the Excel file and this data would be brought in at the beginning of the simulation.

For this option, the source release is user provided and therefore the inventory information from the Waste Form Component and the failure information from the Waste Package Component are not required and have no effect on the model results.

2.3.2 Transport through Buffer (Zone 2)

For all of the source release methods, the release from Zone 1 is sent to Zone 2 for transport through the buffer material. For the GoldSim Source element release, the transfer from Zone 1 to Zone 2 is through a diffusive flux, with a diffusive area set equal to the breach area calculated in the Waste Package Component. For the other source release methods, the release is imposed as a boundary

condition at the beginning of the buffer material. An advective flux is also imposed if the buffer material has been set to degrade.

The transport through the buffer material is depicted by a series of ten GoldSim Cell Pathway elements. A Cell Pathway is a GoldSim element which is a mixing cell and can represent partitioning, solubility constraints, decay, ingrowth and mass transport. A series of connected Cell Pathways is mathematically represented by a finite difference approximation of the advection and dispersion transport equation. For a complete explanation of Cell Pathway computations see Appendix B in GoldSim (2014) (www.goldsim.com). A brief summary is as follows, with the mass balance equation used by GoldSim for a Cell pathway as shown.

$$m'_{is} = -m_{is} \cdot \lambda_s + \sum_{p=1}^{NP_s} m_{ip} \cdot \lambda_p \cdot f_{ps} \cdot R_{sp} \cdot \left(\frac{A_s}{A_p}\right) + \sum_{c=1}^{NF_i} f_{cs} + S_{is} \qquad \textbf{2.7}$$

Where

m'_{is} = Rate of increase of mass of species s in Cell i [M/T]
m_{is} = Mass of species s in Cell i [M]
λ_s = Decay rate for species s [T^{-1}]
NP_s = Number of direct parents for species s
f_{ps} = Fraction of parent p which decays into species s
R_{sp} = Stoichiometric ratio of moles of species s produced per mole of species p decayed
A_s = Molecular (or atomic) weight of species s [M/mol]
A_p = Molecular (or atomic) weight of species p [M/mol]
NF_i = Number of mass flux links from/to Cell i
f_{cs} = Influx rate of species s (into cell i) through mass flux link c [M/T]
S_{is} = Rate of direct input of species s to Cell i from "external" sources [M/T]

The first term on the right-hand side in the mass balance equation represents decay, the second term represents ingrowth, the third term represents mass transfer through mass flux links and the last term represents direct input to the cell.

The system of equations described by the mass balance equation is coupled through the ingrowth terms and through the mass terms. The flux types can be advective or diffusive and are presented in the following equations. For an advective flux from Cell i to Cell j for species s, the mass flux link, $f_{s,i\rightarrow j}$, is represented as:

$$f_{s,i\rightarrow j} = c_{ims} \cdot q + \sum_{t=1}^{NPT_{im}} PF_t \cdot c_{its} \cdot vm_t \cdot cp_{imt} \cdot q_c \qquad \textbf{2.8}$$

Where

q = Rate of advection (of the medium) for the mass flux link [L^3/T]
c_{ims} = Total dissolved, sorbed or precipitated concentration of species s in medium m within Cell i [M/L^3]
NPT_{im} = Number of solid media suspended in medium m within Cell i
NPT_{jn} = Number of solid media suspended in medium n within Cell j

PF_t = Boolean flag (0 or 1) which indicates whether advection of solid t suspended in the advecting fluid (m or n) is allowed for the mass flux link
c_{its} = Sorbed concentration of species s in solid medium t within Cell i [M/M]
vm_t = Advective velocity multiplier for solid particulate t
cp_{imt} = Concentration of suspended solid particulate t within fluid m in Cell i [M/L^3]

For cases in which the buffer is considered fully intact the flow rate is set equal to zero and this advective flux is ignored. For the case in which the buffer is degrading or has completely failed, advective fluxes are considered and the flow rate is equal to the flow rate within the first leg of the Far Field times the fraction of buffer that has failed.

The diffusive mass flux is governed by the concentration gradient. In the case of the intact buffer, this diffusive mass flux is the only considered.

$$DiffusiveMassRate = (DiffusiveConductance) \cdot (ConcentrationDifference)$$

If it is assumed that the contaminants are diffusing through a single fluid, then the Diffusive Conductance term (D) can be calculated using the following equation:

$$D = \frac{(A \cdot d \cdot t \cdot n \cdot r)}{L} \qquad \textbf{2.9}$$

Where

A = Mean cross-sectional area of the connection [L^2]
D = Diffusivity Conductance [L^3/T]
d = Diffusivity in the fluid [L^2/T]
n = Porosity of the porous medium
t = Tortuosity of the porous medium
r = Reduction factor that varies with saturation (1 if saturated)
L = Diffusive length [L]

The diffusive flux, $f_{s,i\rightarrow j}$, from pathway i to pathway j is computed using the following equation:

$$f_{s,i\rightarrow j} = D_s \cdot \left(c_{ims} - \frac{c_{jns}}{K_{nms}}\right) + \sum_{t=1}^{NPT_{im}} PF_t \cdot D_t\left(c_{its} \cdot cp_{imt} - c_{jts} \cdot cp_{jnt}\right) \qquad \textbf{2.10}$$

Where

D_s = Diffusive conductance for species s in the mass flux link [L^3/T]
c_{jns} = Dissolved concentration of species s in medium n within Cell j [M/L^3]
K_{nms} = Partition coefficient between fluid medium n (in Cell j) and fluid medium m (in Cell i) for species s [L^3 medium m/L^3 medium n]
D_t = Diffusive conductance for particulate t in the mass flux link [L^3/T]
c_{jts} = Sorbed concentration of species s associated with solid t within Cell j [M/M]

cp_{jmt} = Concentration of solid particulate t within fluid m in Cell j [M/L^3]

The first term in the equation accounts for diffusion of the dissolved species and the second term accounts for diffusion of particulates suspended in the fluid. From the above equations, a matrix equation was developed to solve the equations numerically using a backward difference approach. GoldSim used a customized version of the Iterative Methods Library IML++, version 1.2a, available from the National Institute of Standards web site http://math.nist.gov/iml++/.

As previously discussed, the buffer material can be assigned by the user to be intact, to degrade over time or to be bypassed and is set through the dashboard. If the buffer material is set to degrade, the associated parameters are inputted through the Near Field Dashboard. The velocity from the waste package and through the buffer material is a function of the flow rate in the first leg of the Far Field and the percent of buffer degraded. The model calculates the percent of buffer degraded at each time step based on parameters input through the dashboard. Uniform PDFs for each the backfill lifetime, failure time and fraction cracked are created from the maximum and minimum values input through the dashboard. If the simulation time is greater than the failure time, then the fraction failed is equal to $1 - exp\left(-\frac{time - failureTime}{expected\ lifetime}\right)$. This fraction is multiplied by the velocity of the first leg within the Far Field to determine the velocity within the buffer material.

If the buffer is assigned to be bypassed, then the model assigns a very high flow rate to this second zone to essentially ignore the buffer material and commence flow through the Far Field.

The parameters defined by a PDF and hence a GoldSim Stochastic element are brought in through the parameter database. These parameters include buffer diffusivities, buffer sorption and solubility limit parameters for each radionuclide element. Other parameters defined through stochastic elements are the backfill specific density, porosity, the dispersivity fraction of transition region and various fracture parameters.

It is also possible to set the buffer to degrade over time. In this case, the minimum and maximum of time of buffer failure, expected lifetime of buffer and fraction of buffer cracked are inputted through the dashboard.

2.3.3 Transition Zone from Buffer to Nearest Fracture (Zone 3)

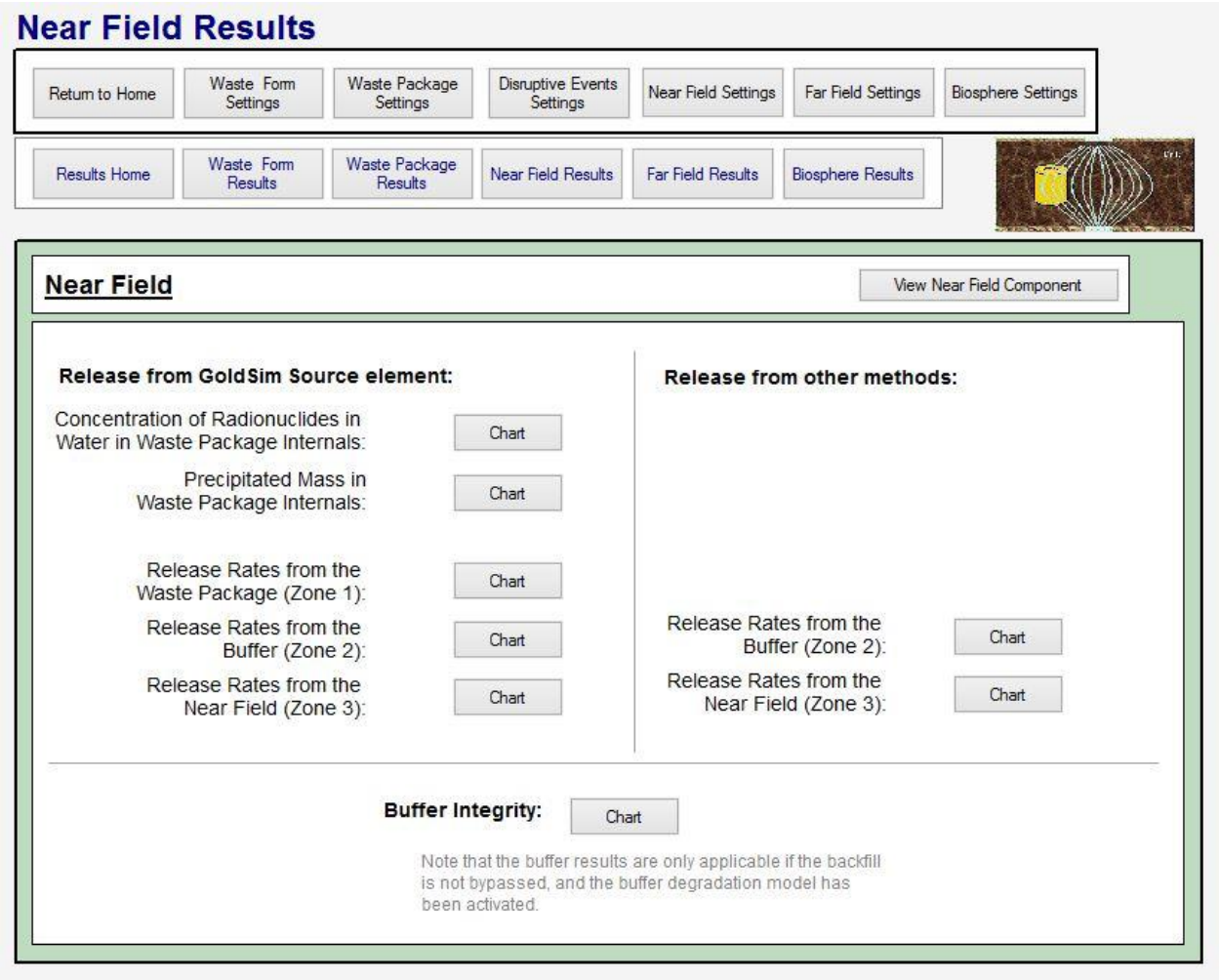
The release from the buffer is then transferred into Zone 3, which is specific to the case in which the first leg of the Far Field is designated as a fractured media. Zone 3 represents a transition zone from the buffer material to the nearest fracture. This zone remains unchanged from SOAR and is represented by a series of 10 Cell Pathways and the fracture is assumed to be kept at zero concentration. The effective distance to the nearest fracture affects the release rate to the Far Field. If the effective distance is large, this results in a release to the Far Field that is lower as there are fewer fractures that can receive the mass. On the other hand, if the effective distance to a fracture is smaller, representing a higher density of fractures, the release to the fractures is higher. In other words, the release to the Far Field is inversely proportional to the effective distance to the nearest fracture. In the case where the first leg of the Far Field is represented by a porous media, the effective distance to fracture is set to a very low number to essentially bypass this zone.

2.3.4 Near Field Component Summary

Various inputs are required for the Near Field Component. Through the dashboard, the user inputs the buffer length, the transport cross-section and the water volume inside the waste package. The user also has several options on the dashboard such as the ability to disable the use of solubility limits, disable the backfill sorption, enable sorption in the transition region for fractured media and/or disable near field advective releases. This provides a method for the user to easily ignore or consider these parameters to observe the effects on the dose rate, which would be beneficial during a sensitivity analysis.

Once the model is run, the Near Field results are available on a results dashboard as presented in Figure 2.10. The user can investigate results in regards to the releases from the waste package as well as from the buffer and from the Near Field. If the backfill or buffer degradation is utilized the results can also be observed on this dashboard.

Figure 2.10 – Near Field results dashboard



2.4 Far Field Component

The Far Field Component receives the release from the Near Field and computes the contaminant transport travel through the various layers of geosphere which can be represented as porous or fractured media. The transport within the Far Field is represented by a series of GoldSim Pipe Pathway elements. Each Pipe Pathway is referred to as a Leg and represents a homogeneous geological type or formation. The user can define the properties of the section including length, flow properties, sorption parameters and whether the flow is through fractured or porous media. Variations in geology are represented by a series of Pipe Pathways in which different properties can be defined.

A Pipe Pathway element in GoldSim behaves as a fluid conduit with one dimensional steady state flow where mass enters and travels through the pipe considering advection and dispersion, and then exits the other end (GoldSim Technology Group, 2014). The transport within a Pipe Pathway is solved using a Laplace transform approach for one-dimensional advection, longitudinal dispersion, retardation, decay and ingrowth and exchanges with immobile storage zones.

GoldSim analytically solves the transport equation to determine the mass flux exiting the pipe. A brief description of the equations used within GoldSim is presented in the following pages. For a more detailed discussion and further equations related to the Pipe Pathway representation, please refer to the GoldSim Contaminant Transport Module User's Guide (GoldSim Technology Group, 2014).

The objective within a Pipe Pathway in GoldSim is to compute the flux of each contaminant leaving the pathway over time, calculated using the following equation.

$$Flux_s = Q \cdot SV_s \cdot c_{m,s} - (A_m \cdot D_s + \alpha \cdot Q \cdot SV_s) \frac{\delta c_{m,s}}{\delta x}\Big|_{x=L} \qquad \textbf{2.11}$$

Where

$Flux_s$ = Flux of species s leaving the pathway [M/T]
Q = Volumetric flow rate of fluid in the pathway [L^3/T]
SV_s = Suspended solid velocity magnification factor for species s
$c_{m,s}$ = Mean mobile concentration of species s in available fraction of saturated pore space in mobile zone of pathway [M/L^3]
A_m = Cross-sectional area of the mobile zone [L^2]
D_s = Effective diffusivity of species s in the mobile zone = $n_{m,s} \cdot t_m \cdot d_{m,r} \cdot d_{m,s}$
$n_{m,s}$ = Available porosity of the porous medium in the mobile zone for species s
t_m = Tortuosity of the infill material
$d_{m,r}$ = Reference diffusivity for the reference fluid
$d_{m,s}$ = Relative diffusivity for species s in the reference fluid
α = Dispersivity of the pathway [L]

L = Length of the pathway [L]
x = Distance into the pathway [L]

To compute the flux of species leaving the pathway, the first step is to compute the concentration within the mobile zone of the pathway. The governing equation of the concentration within the mobile zone of the pipe is defined through the following equation, which is an expanded version of the one-dimensional advection-dispersion equation.

$$\frac{\delta c_{m,s}}{\delta t} = -\left[\left(\frac{Q \cdot SV_s}{n_{m,s} \cdot A_m \cdot R_{m,s}}\right)\frac{\delta c_{m,s}}{\delta x} - \left(\frac{A_m \cdot D_s + \alpha \cdot Q \cdot SV_s}{n_{m,s} \cdot A_m \cdot R_{m,w}}\right)\frac{\delta^2 c_{m,s}}{\delta x^2}\right] + \left[-c_{m,s} \cdot \lambda_s + \sum_{p=1}^{NP_s} c_{m,p} \cdot \lambda_p \cdot f_{ps} \cdot S_{ps} \cdot \left(\frac{AW_s}{AW_p}\right) \cdot \left(\frac{R_{m,p}}{R_{m,s}}\right) \cdot \left(\frac{n_{m,p} \cdot SF_p}{n_{m,s} \cdot SF_s}\right)\right] - \left[\frac{F_{st,s}}{n_{m,s} \cdot A_m \cdot R_{m,s}}\right] \quad \textbf{2.12}$$

Where

$R_{m,s}$ = Retardation factor for species s in the mobile zone
$R_{m,p}$ = Retardation factor for parent species p in the mobile zone
λ_s = Decay rate for species s [T^{-1}]
λ_p = Decay rate for parent species p [T^{-1}]
f_{ps} = Fraction of parent p which decays into species s
NP_s = Number of direct parents of species s
S_{ps} = Stoichiometric ratio of moles of species s produced per mole of species p which decays
AW_s = Molecular (or atomic) weight of species s [M/mole]
AW_p = Molecular (or atomic) weight of parent species p [M/mole]
$n_{m,p}$ = Available porosity of the porous medium in the mobile zone for species p
$c_{m,p}$ = Dissolved concentration of parent species p in mobile zone of pathway [M/L^3]
$F_{st,s}$ = Flux of species s from the mobile zone to storage zones per unit length of pathway [M/T/L]
SF_p = Suspended solid storage factor for species p
SF_s = Suspended solid storage factor for species s

$$SF_i = 1 + c_{ss} \cdot K_{ss,i} \quad \textbf{2.13}$$

Where

c_{ss} = Concentration of the suspended solid in the mobile zone [M/L^3]
$K_{ss,i}$ = Partition coefficient between the suspended solid and the reference fluid for species i [L^3/M]
SF_i = Ratio of mobile to dissolved mass in the mobile zone

For the above advection-dispersion equation, the first term represents the rate of change due to advective and dispersive fluxes, the second term represents rate of change due to decay and ingrowth and the third term represents changes due to exchanges with storage zones. The boundary conditions for this equation are:

- $c_{m,s} \rightarrow 0$ as $x \rightarrow \infty$
- at x = 0, a flux boundary condition is applied such that:

$$Q \cdot SV_s \cdot c_{m,s} - (A_m \cdot D_s + \alpha \cdot Q \cdot SV_s) \frac{\delta c_{m,s}}{\delta x}\Big|_{x=0} = \delta(t) M_{init,s} + F_{bc,s} + F_{paths,s} \qquad \textbf{2.14}$$

Where

$M_{init,s}$ = User-specified initial mass of species s applied to the pathways [M]
$F_{bc,s}$ = User-specified boundary flux for species s [M/T]
$F_{paths,s}$ = Flux of species s into pathway from other GoldSim pathways [M/T]
$\delta(t)$ = The Dirac delta function [T^{-1}]

The retardation, $R_{m,s}$, of species, s, sorbing to the medium, m, is the ratio of the total mass of species s to the mobile mass and calculated as follows.

$$R_{m,s} = \frac{P \cdot T \cdot (\rho_c \cdot K_{c,s} + n_{c,s}) + A_m \cdot (\rho_p \cdot K_{p,s} + n_{m,s} \cdot SF_s \cdot \theta)}{A_m \cdot n_{m,s} \cdot SF_s \cdot \theta} \qquad \textbf{2.15}$$

Where

P = Perimeter of the pathway [L]
T = Thickness of the coating [L]
ρ_c = Dry bulk density of the coating material [M/L^3]
ρ_p = Dry bulk density of the porous infill material [M/L^3]
$n_{c,s}$ = Available porosity of the coating material for species s
θ = Fluid saturation of the available pores in the mobile zone
$K_{c,s}$ = Partition coefficient for species s in the coating material [L^3/M]
$K_{p,s}$ = Partition coefficient for species s in the porous infill material [L^3/M]

This equation reduces to the standard retardation coefficient if the thickness of the coating is equal to zero and there are no suspended solids.

In the concentration equation (Equation 2.12), the $F_{st,s}$ parameter is the flux of species s into storage zones and is represented by the following equation.

$$F_{st,s} = F_{md,s} + F_{sd,s} \qquad \textbf{2.16}$$

The parameter $F_{md,s}$ is the total flux of species s into matrix diffusion zones per unit length of pathway [M/T/L] and is calculated through the following equation.

$$F_{md,s} = -\sum_{im=1}^{NMD} P \cdot f_{im} \cdot D_{im,s} \frac{\delta c_{im,s}}{\delta z}\Big|_{z=0} \qquad \textbf{2.17}$$

Where

f_{im} = Fraction of perimeter associated with matrix diffusion zone im
$D_{im,s}$ = Diffusivity of matrix diffusion zone im for species s
$c_{im,s}$ = Concentration of species s in matrix diffusion zone im of pathway [M/L^3]
NMD = Number of matrix diffusion zones
z = Distance in the matrix diffusion zone [L] (z-axis direction is orthogonal to flow direction, with z=0 representing the boundary between the mobile zone and the matrix diffusion zone)

The second term, $F_{sd,s}$, is calculated through the following equation.

$$F_{sd,s} = \beta \cdot SF_s \cdot Q \cdot \left(c_{m,s} - c_{sd,s}\right) \quad \textbf{2.18}$$

Where

β = Probability of an individual solute molecule moving from the mobile zone to the stagnant zone per length of distance traveled in the mobile zone [1/L]
$c_{sd,s}$ = Concentration of species s in stagnant dispersive zone of pathway [M/L^3]

The governing equation for the concentration in the matrix diffusion zone of the pipe pathway, $c_{im,s}$, is calculated through the following equation.

$$\frac{\delta c_{im,s}}{\delta t} = \left[\left(\frac{D_{im,s}}{n_{im,s}\cdot R_{im,s}}\right)\frac{\delta^2 c_{im,s}}{\delta z^2} + \left(\frac{D_{im,s}}{n_{im,s}\cdot A_m \cdot R_{im,s}}\right)\frac{\delta A_{im}}{\delta z}\frac{\delta c_{im,s}}{\delta z}\right] + \left[-c_{im,s}\cdot\lambda_s + \sum_{p=1}^{NP_s} c_{im,p}\cdot\lambda_p\cdot f_{ps}\cdot S_{ps}\cdot \left(\frac{AW_s}{AW_p}\right)\left(\frac{R_{im,p}}{R_{im,s}}\right)\left(\frac{n_{m,p}\cdot SF_p}{n_{m,s}\cdot SF_s}\right)\right] \quad \textbf{2.19}$$

Where

$D_{im,s}$ = Diffusivity of species s in matrix diffusion zone [L^2/T]
$n_{im,s}$ = Available porosity of the porous medium in the matrix diffusion zone for species s
A_{im} = Diffusive area of the matrix diffusion zone per unit length of mobile zone [L]
$R_{im,s}$ = Retardation factor for species s in the matrix diffusion zone
$R_{im,p}$ = Retardation factor for species p in the matrix diffusion zone
$c_{im,p}$ = Concentration of parent species p in mobile zone of pathway [M/L^3]

The first term in the above equation is the rate of change due to diffusive fluxes and the second term represents decay and ingrowth. The solutions for concentrations of each species in the decay chain are coupled with other species in the decay chain and must be solved as a coupled system of equations.

The GoldSim software allows for up to three diffusion zones in parallel. A "skin" zone is also allowed and if present exists in front of all matrix diffusion zones, in other words species must first diffuse through skin zone before reaching the diffusive zones. The above equation is applied individually to all diffusion zones and the skin zone. This feature is used in modeling the fractured media within DOC-WMF (as in SOAR). The Pipe Pathways in DOC-WMF are assigned one diffusion zone and no skin to represent a zone with fractures.

The inner boundary condition at z = 0 for the matrix diffusion zone is as follows.

$$c_{im,s} = c_{m,s} \qquad \text{at } z = 0$$

The outer boundary condition for the matrix diffusion zone.

$$\frac{\delta c_{im,s}}{\delta z} = 0 \qquad \text{at } z = T_{im}$$

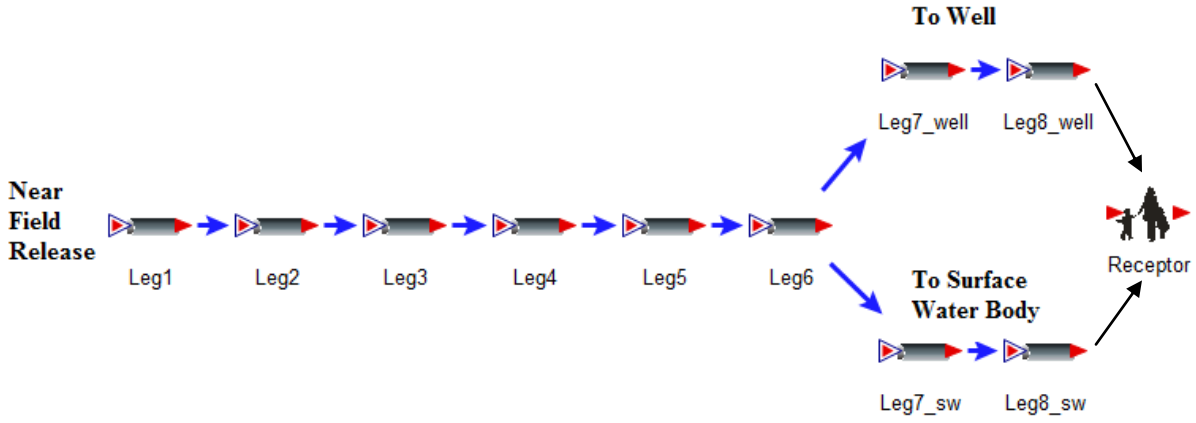
Where T_{im} is the thickness of the diffusion zone.

The method by which GoldSim solves the resulting set of Pipe Pathway equations is by using Laplace transforms. For a more detailed explanation of the Laplace transform solution, please refer to the GoldSim Contaminant Transport Module User's Guide, Appendix B (GoldSim Technology Group, 2014).

Within SOAR, the Far Field was represented by a series of three Pipe Pathways allowing for three zones of distinct geology. The release from the Near Field in [g] is imposed as the boundary condition on the first Pipe Pathway within the series. The initial condition imposed throughout the Far Field is zero contaminant concentration within all Pipe Pathways. The pathway considered in SOAR is from the repository to the biosphere which assumes release is to a well. The final Pipe Pathways in the series releases to a Cell Pathway which is representative of a constant flux boundary condition.

In DOC-WMF, more Pipe Pathways or legs, to a total of eight, have been included in series to allow for further alterations in geology (see Figure 2.11). In the same manner as SOAR, the Near Field release is imposed as the boundary condition at the beginning of the first Pipe Pathway. Also, the pathway has a release to a well in addition to a release to a surface water body, such as a lake or river. The amount of contaminants that would travel towards the well and to the surface water body would be dependent on the defined geology. The pathway with the higher flow rate would receive higher transport of contaminants as calculated by the model. Through the dashboard, the user is able to specify whether to consider the well pathway alone, the surface water pathway alone or both pathways.

Figure 2.11 – Schematic showing one pathway through geosphere



The final Pipe Pathways in well and surface water pathways are to a Cell Pathway. The Cell Pathway is a mixing cell with a defined volume and advective and diffusive mass flux links from the final Pipe Pathways within the series. To determine the concentrations within the groundwater (to well) and surface water, the mass in the pathway in [g/yr] from each final Pipe Pathway to the respective Cell Pathway is used and sent to the Biosphere Component for dose calculations.

In the event that a second pathway from the waste disposal site to the biosphere is required, an additional pathway was implemented within the code, with the same layout as the first. The user specifies the proportion of Near Field release to each pathway through the GoldSim dashboard. By default, all the Near Field release goes to Pathway 1 with a proportion equal to one and none to Pathway 2 with a proportion equal to zero. If ignored, the pathway has no effect on the final solution.

The dashboard for the Far Field is where the user inputs information for each leg of the two pathways, such as length, gradient, rock type with respect to defining sorption parameters and whether the unit is a porous or fractured media (See Figure 2.12). On the Far Field dashboard, the user has several options. The first is whether to assign the hydraulic conductivity for flow calculations based on the discrete value inputted through the dashboard or through a PDF brought in through the database. The user is also able to turn off sorption considerations within Far Field legs to observe the effects on the results through the dashboard.

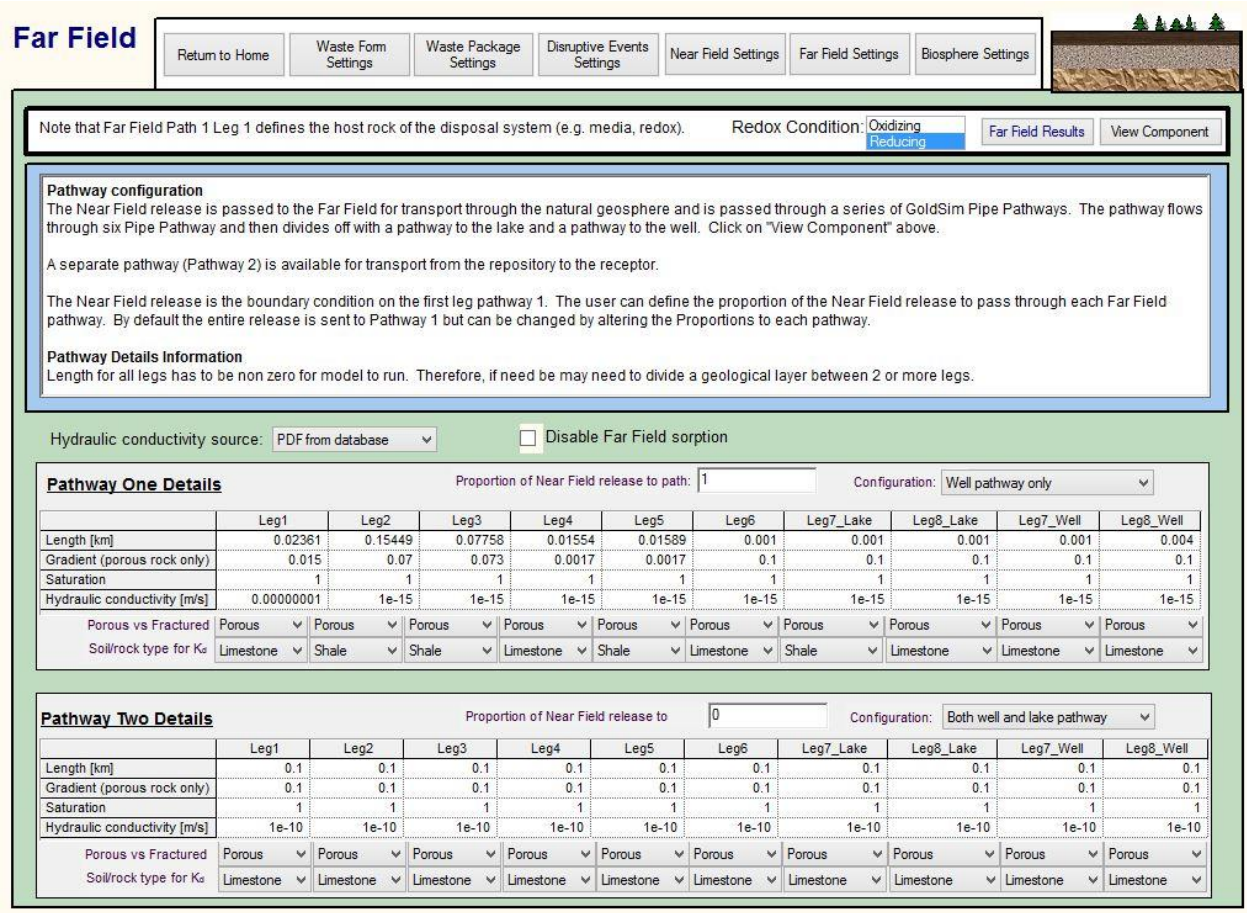
The stochastic parameters required within the Far Field with associated PDF, such as the hydraulic conductivity, density, tortuosity, porosity, fracture aperture, fracture separation and matrix perimeter are brought in through the parameter database. If the user has specified to utilize the hydraulic conductivity from the dashboard, then the hydraulic conductivity brought in through the database is ignored.

The dispersivity is assigned through a dispersivity fraction, which is represented by a PDF. This dispersivity fraction is the same for all legs in the Far Field. Within each Pipe Pathway, the dispersivity is the product of the dispersivity fraction and the length of the leg.

For porous media, the flow rate is computed from the provided gradient and hydraulic conductivity. The soil or rock medium of the leg is represented by a GoldSim Solid element called “Infill” represented by the provided density, porosity, tortuosity and associated sorption parameters. A GoldSim Fluid element called “Water” is used to assign the fluid properties such as the solubility limits and diffusion properties. For the case of the porous media, no diffusion zones or skin zone are considered in the pipe.

If the user specifies the Far Field leg as a fractured media then the hydraulic conductivity is calculated as a function of the fluid density and viscosity as well as the fracture aperture and fracture separation. The mobile area is reduced by a factor of fracture porosity. For this case, two solid mediums are present. The GoldSim Solid “FF_Lx_Infill” (where x represents the leg number) contains the same density and tortuosity as the porous media case, however, the porosity is set to zero as it is within the fracture. A second medium, represented by a GoldSim Solid element called “FF_Lx_Solid”, represents the diffusion zone into the rock. This solid element contains the density, porosity and tortuosity.

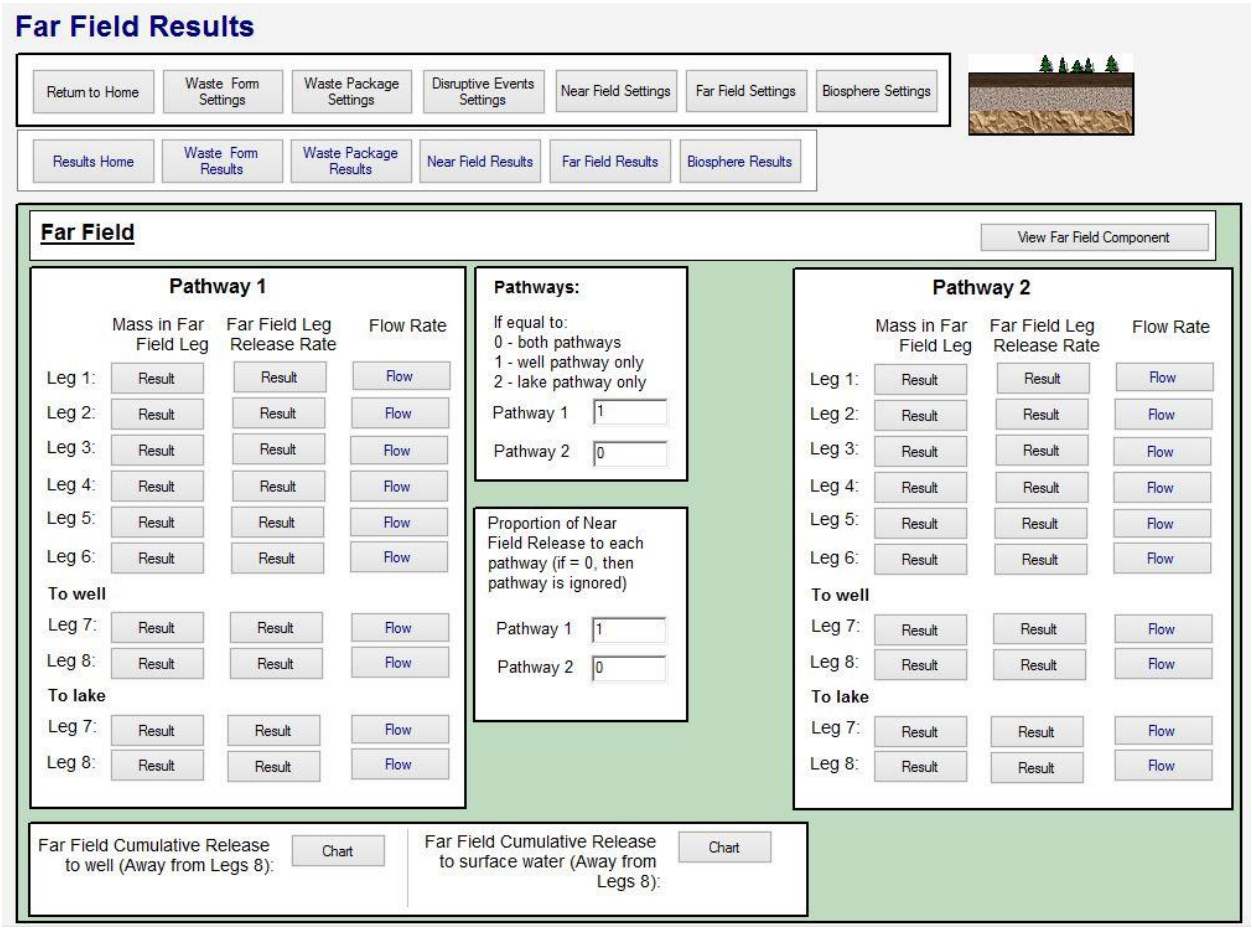
Figure 2.12 – Far Field dashboard



On the Far Field dashboard the user is able to designate whether the repository is placed within an oxidizing or reducing environment. The choice of Redox condition will impact the choice of degradation rate in the Waste Form and corrosion parameters used in the Waste Package.

The results of the Far Field can be accessed through the Far Field results dashboard (see Figure 2.13). In the middle of the dashboard, the pathway configurations and proportions to each pathway that were selected for the simulation are presented. The release rates and flow rates for each leg can be observed as well as the cumulative release to the well and surface water.

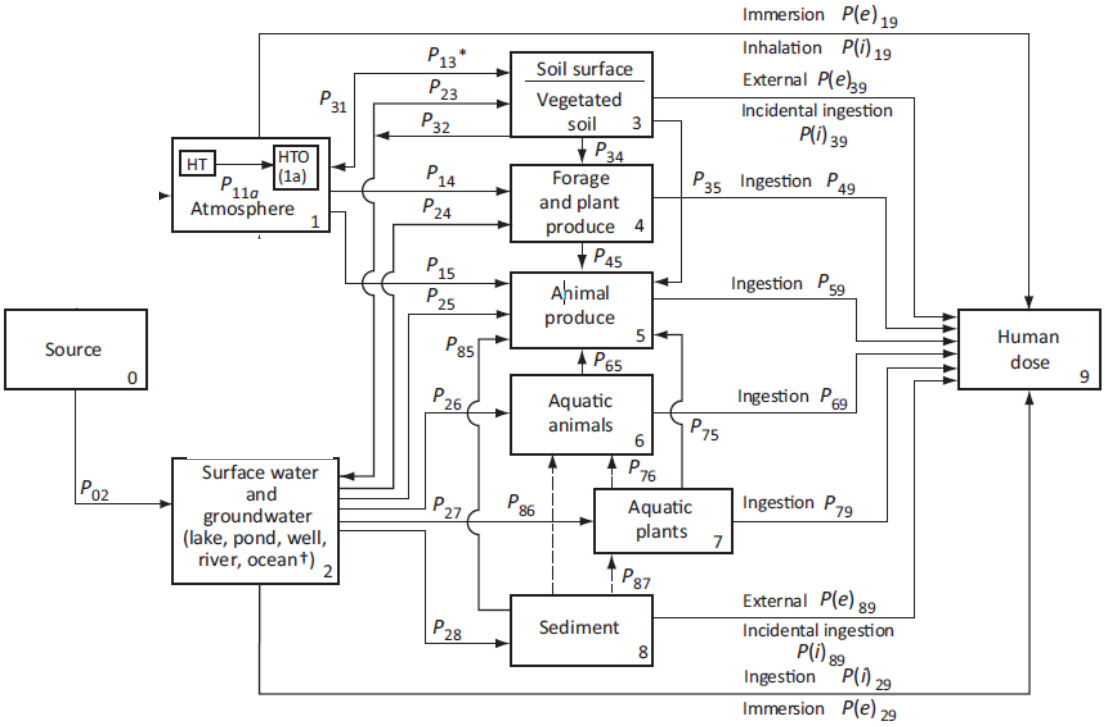
Figure 2.13 – Far Field results dashboard



2.5 Biosphere Component

The Biosphere Component within SOAR considers ingestion of water alone in the dose calculation. In DOC-WMF, the Biosphere Component was expanded to consider more exposure pathways as shown in Figure 2.14. The procedure followed to implement the expanded list of exposure pathways is that presented by N288.1-14, CSA N288.1-14 (2014) unless otherwise noted. The various compartments as shown on Figure 6.1 are assigned a number, for example surface and groundwater are assigned the number 2. The release in the model from the Far Field is to groundwater and surface water and requires determination of the transfer to the other compartments. The various pathways between compartments are illustrated by links and the transfer parameter P_{ij} represents the transfer from compartment i to j. The subsequent section presents the various equations for required transfer parameters.

Figure 2.14 – Biosphere transport pathways (taken from CSA Group, 2014)



To calculate the concentrations in each compartment initially requires concentrations in groundwater and surface water. The Biosphere Component received the release from the Far Field as the mass in the pathway between the final Pipe Pathway to the Cell Pathway in [g/yr]. The concentration in [Bq/m^3] is required in both the groundwater and surface water for dose calculations.

To calculate the groundwater concentration, $C_{2,gw}$, with units [Bq/m^3] the following equation was used. This concentration is used in the subsequent dose calculations.

$$C_{2,gw} = \frac{FFwell \cdot WCF \cdot SA}{Q} \qquad \textbf{2.20}$$

Where

FFwell = Predicted release from the Far Field module to a well [g/yr]
WCF = Well Capture Fraction is the fraction of contaminated groundwater that flows into the well
SA = Specific activity [Bq/g]
Q = Flow rate to the biosphere [m^3/yr]

The surface water release, $C_{0,sw}$ [Bq/s] is calculated from the Far Field release. The release is calculated from the mass released in the pathway to the Cell Pathway representing the lake as follows.

$$C_{0,sw} = FFlake \cdot SA \qquad \textbf{2.21}$$

Where

FFlake = the predicted release from the Far Field module to surface water [g/yr]

Once the contaminants release to the surface water body, dispersion will occur. To determine the surface water concentration, $C_{2,sw}$ in Bq/m^3, the surface water release is multiplied by the appropriate P_{02}, which is the transfer parameter accounting for dispersion. Various models for determining P_{02} are presented in section 2.5.1.1. Within DOC-WMF, the user will have the option to ignore dispersion (the most conservative approach) or consider dispersion in a large lake, small lake, river, river with banks or assign a known dispersion factor.

The groundwater and surface water concentrations, $C_{2,gw}$ and $C_{2,sw}$, represent Compartment 2 in Figure 2.14. To determine the concentrations within the other compartments, equations to calculate the various transfer parameters between i and j, P_{ij}, were used.

2.5.1 Transfer equations

The equations for the transfer between compartments as presented in N288.1-14, CSA N288.1-14 (2014) was used, unless otherwise noted. The concentrations in each compartment are calculated by multiplying the input concentration by the appropriate transfer parameter. For example to calculate C_j from C_i the following equation is used.

$$C_j = C_i \cdot P_{ij} \qquad \textbf{2.22}$$

Where P_{ij} is the transfer parameter from compartment i to j. Applying the various transfer parameters allows for determination of the impact through the various compartments to the receptor. The transfer parameters that were implemented in the model are presented in Table 2.4.

The equations used to calculate the various transfer parameters are presented in the following sections. All of these equations were coded within the biosphere component of DOC-WMF in order to calculate the doses to the receptor.

2.5.1.1 Surface Water Dispersion

The Far Field component of the model predicts the transport through the geosphere to a well and to surface water. The surface water release is to a lake or river and the radionuclides will disperse within the surface water body volume. Within DOC-WMF, several options are available through the Biosphere dashboard. The user can choose to ignore dispersion (the most conservative approach) or to have dispersion according to a model for large lake, small lake, river, river with banks and user-defined. The choice of ignoring dispersion would result in the highest dose rate, however would not be realistic. Those cases in which dispersion is considered, the transfer parameter P_{02} is calculated according to the equations presented in the following sections. The transfer parameter is multiplied by the surface water release, $C_{0,sw}$, to calculate the surface water concentration $C_{2,sw}$ used in the subsequent calculations.

Table 2.4 – Various compartments and transfer pathways

Transfer parameter	Compartments		Parameter Units
	From	To	
P_{02}	0 (release)	2 (water)	s/L
P_{23mass}	2 (water)	3 (soil)	L/kg
P_{23area}	2 (water)	3 (soil)	L/m^2
P_{23spw_HTO}	2 (water)	3 (soil)	Unitless
P_{3mass1}	3 (soil)	1 (air)	kg/m^3
P_{3spw1_HTO}	3 (soil)	1 (air)	L/m^3
P_{3mass4}	3 (soil)	4 (plant produce)	Unitless
P_{24}	2 (water)	4 (plant produce)	L/kg
P_{14}	1 (air)	4 (plant produce)	m^3/kg
P_{15}	1 (air)	5 (animal produce)	m^3/kg
P_{25}	2 (water)	5 (animal produce)	L/kg
P_{3mass5}	3 (soil)	5 (animal produce)	Unitless
P_{45}	4 (plant produce)	5 (animal produce)	Unitless
P_{26}	2 (water)	6 (aquatic animal)	L/kg
P_{65}	6 (aquatic animal)	5 (animal produce)	Unitless
P_{27}	2 (water)	7 (aquatic plant)	L/kg
P_{75}	7 (aquatic plant)	5 (animal produce)	Unitless
P_{85}	8 (sediment)	5 (animal produce)	Unitless
P_{28}	2 (water)	8 (sediment)	L/kg
$P(i)_{19}$	1 (air)	9 (receptor)	$(Sv/yr)/(Bq/m^3)$
$P(e)_{19}$	1 (air)	9 (receptor)	$(Sv/yr)/(Bq/m^3)$
$P(i)_{29}$	2 (water)	9 (receptor)	(Sv/yr)/(Bq/L)
$P(e)_{29}$	2 (surface water)	9 (receptor)	(Sv/yr)/(Bq/L)
$P(e)_{2w9}$	2 (groundwater)	9 (receptor)	(Sv/yr)/(Bq/L)
$P(i)_{3mass9}$	3 (soil)	9 (receptor)	(Sv/yr)/(Bq/kg)
$P(e)_{3area9}$	3 (soil)	9 (receptor)	$(Sv/yr)/(Bq/m^2)$
P_{49}	4 (plant produce)	9 (receptor)	(Sv/yr)/(Bq/kg)
P_{59}	5 (animal produce)	9 (receptor)	(Sv/yr)/(Bq/kg)
P_{69}	6 (aquatic animal)	9 (receptor)	(Sv/yr)/(Bq/kg)
$P(i)_{89}$	8 (sediment)	9 (receptor)	(Sv/yr)/(Bq/kg)
$P(e)_{89}$	8 (sediment)	9 (receptor)	(Sv/yr)/(Bq/kg)

2.5.1.1.1 Large Lake

The transfer parameter from the source (Compartment 0) to the receptor somewhere along the shoreline (Compartment 2) for a large lake (Area greater than 400 km^2) is represented by $P_{02,large\_lake}$ and has the units s/L. N288.1-14, CSA N288.1-14 (2014) uses the following equation by Gorman (1986).

$$P_{02,large\_lake} = \frac{\alpha \cdot \beta}{D_f \cdot Q_v} exp\left(-(\lambda_r + \lambda_s) \cdot \frac{x}{U_c}\right) \quad \textbf{2.23}$$

Where

α = Annual average fraction of time that the current direction is towards the point of interest [unitless]
β = Annual average effluent recirculation factor [unitless]
D_f = Annual average dilution ratio for steady-state currents [unitless]
Q_v = Annual average volumetric discharge rate of liquid effluent [L/s]
λ_r = Radioactive decay constant [1/s]
λ_s = Removal constant for sedimentation [1/s]
x = Distance between the source and the point of interest [m]
U_c = Annual average current speed in the direction towards the point of interest [m/s]

The dilution factor, D_f, is the ratio of the concentration at the source to the average annual concentration at the receptor location and is given by the following equation (in accordance with NCRP 123).

$$D_f = \left[\left(\frac{1000 \cdot d \cdot \beta \cdot \sqrt{\pi \cdot k}}{Q_v \cdot U_c^{0.17}}\right)^{\frac{1}{1.17}} \cdot x + D_0^{\frac{1}{1.17}}\right]^{1.17} \quad \textbf{2.24}$$

Where

d = Average water depth between the release point and the receptor [m]
k = Proportionality coefficient used to derive the lateral dispersion coefficient [unitless]
x = Distance between the source and the point of interest [m]
D_0 = Initial dilution at the point of discharge [unitless]

2.5.1.1.2 Small Lake

The equations to calculate the transfer parameter to account for dispersion within a small lake, $P_{02,small\_lake}$, were taken from IAEA, 2001. Atmospheric deposition to the lake is ignored as the water is the source of contamination. IAEA (2001) defines a small lake which is one with an area below 400 km^2. The transfer parameter for dispersion within a small lake is calculated using the following equation.

$$P_{02,small\_lake} = \frac{1-exp\left[-\left(\frac{U_c}{d}+\lambda_r\right)\cdot t\right]}{(U_c+\lambda_r\cdot d)\cdot A_l} \quad if\ \left(\frac{U_c}{d}+\lambda_r\right) > 10^{-8}\ s^{-1} \qquad \textbf{2.25}$$

$$P_{02,small\_lake} = \frac{1}{(U_c+\lambda_r\cdot d)\cdot A_l} \quad if\ \left(\frac{U_c}{d}+\lambda_r\right) < 10^{-8}\ s^{-1}$$

Where

A_l = Lake surface area [m^2]

2.5.1.1.3 River

The river dispersion model used by N288.1-14 CSA N288.1-14 (2014) was that given by NCRP 123 and is presented in the following equation.

$$P_{02,river} = \frac{1}{2\cdot\pi\cdot d\cdot\sqrt{k_x\cdot k_y}}\cdot exp\left(\frac{U_x\cdot x}{2\cdot k_x}-\lambda_s\cdot\frac{x}{U_x}\right)\cdot exp\left(-\lambda_r\cdot\frac{x}{U_x}\right)\cdot$$

$$K_0\left[\frac{U_x}{2\cdot k_x}\cdot\sqrt{x^2+\frac{k_x}{k_y}\cdot(y-y_0)^2}\right] \qquad \textbf{2.26}$$

Where

k_x = Longitudinal dispersion coefficient [m^2/s]
k_y = Lateral dispersion coefficient [m^2/s]
U_x = Current velocity [m/s]
K_0 = Modified Bessel function of the second kind
y = Offshore distance coordinate for the point (x,y) [m]
y_0 = Offshore distance to the plume centreline [m]

The concentration at the receptor point is calculated by multiplying the concentration by the transfer parameter P_{02} ($C_{2,sw} = C_{0,sw}\cdot P_{02}$). The above equation is valid for those cases where the riverbanks do not restrict the radionuclide spread within the river. If this is not the case, then the concentration within the river is modified, C_2', can be accounted for by using a mirror image technique using the following equation.

$$C_2' = C_2 + \sum_{n=1}^{\infty}(C_2[x,y_n] + C_2[x,y_n']) \qquad \textbf{2.27}$$

Where

$$y_n = n\cdot B - \left(y_0-\frac{B}{2}\right) + (-1)^n\cdot\left(y-\frac{B}{2}\right)$$

$$y_n' = -n \cdot B - \left(y_0 - \frac{B}{2}\right) + (-1)^n \cdot \left(y - \frac{B}{2}\right)$$

n = Number of reflection cycles (3 cycles is sufficient)
B = Average width of the river between the release point and the receptor [m]

2.5.1.1.4 User-defined dispersion

The final option for the user is to directly input the value of dispersion through the dashboard in the units of [(Bq/L)/(Bq/s)].

2.5.1.2 Soil Contamination

2.5.1.2.1 All radionuclides except tritium

Soil contamination occurs through irrigation with contaminated water. The user defines the source of irrigation water, whether groundwater or surface water, through the Biosphere Component dashboard (see Figure 2.14). The transfer parameter from the contaminated water to the soil, P_{23}, for all radionuclides except tritium is calculated through the following equations. P_{23area} is the transfer parameter on an area basis and has units [L/m^2] (giving Bq/m^2 in soil) and P_{23mass} is the transfer parameter on a mass basis and has units [L/kg *dw*] (giving Bq/kg *dw* in soil) (CSA, 2014).

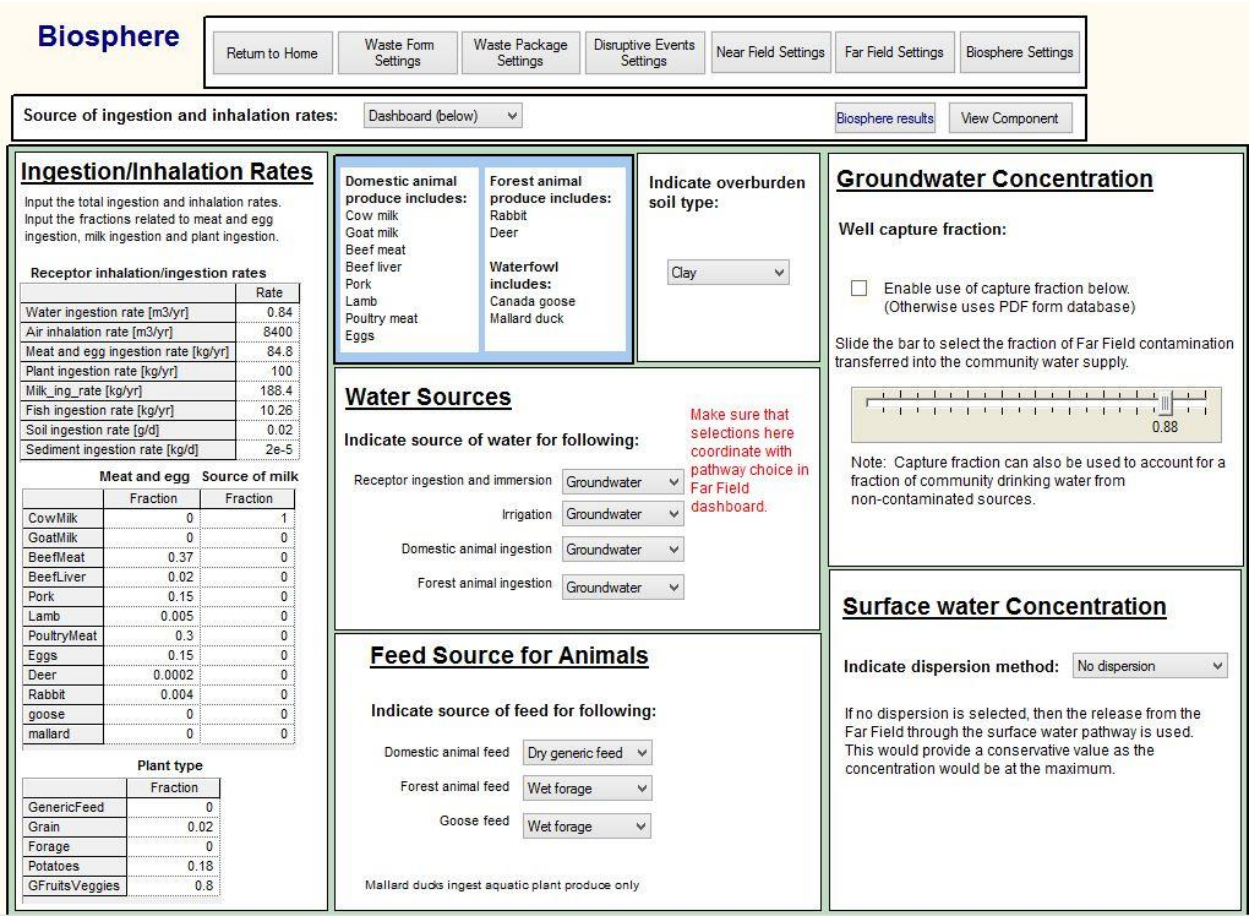
$$P_{23area} = \frac{L'}{\lambda_T} \cdot [1 - exp(-\lambda_T \cdot t)] \qquad \textbf{2.28}$$

$$P_{23mass} = \frac{L'}{\lambda_T \cdot \rho_b \cdot Z_{soil}} \cdot [1 - exp(-\lambda_T \cdot t)]$$

Where

L´ = the annual average irrigation rate [L/m^2·s]
λ_T = $\lambda_r + \lambda_{er} + \lambda_{vol} + \lambda_l + \lambda c$ [1/s]
Where
λ_r = radioactive decay constant [1/s]
λ_{er} = erosion rate constant [1/s]
λ_{vol} = volatilization rate constant [1/s]
λ_l = leaching rate constant [1/s]
λ_c = rate constant for losses due to crop removal [1/s]
t = duration of facility operation from commissioning to end of facility life [s]
ρ_b = soil dry bulk density [kg *dw*/m^3]
Z_{soil} = depth of the top mixed layer [m]

Figure 2.14 – Biosphere dashboard



The radioactive decay constants are well known for the various radionuclides and are presented in Table 2.3. CSA N288.1-14 (2014) used the following equation presented by Sheppard (1995) to calculate the erosion rate constant.

$$\lambda_{er} = \frac{ER \cdot (1 - f_{wat})}{\rho_b \cdot Z_{soil}} \qquad \textbf{2.29}$$

Where

ER = Soil erosion rate [kg dw/m^2·s]

f_{wat} = Fraction of radionuclide in soil in the water phase (i.e. not sorbed)

$$= \frac{\theta}{\theta + K_d \cdot \rho_b}$$

Where

θ = Volumetric water content of the soil [m^3_{water}/m^3_{soil}]

K_d = Soil partition coefficient of the radionuclide [m^3_{liquid}/kg_{soil}]

Volatilization losses (λ_v) are only relevant to those radionuclides that are volatile, such as tritium, radioidines, Cl, Rn-222 and C-14. Tritium is calculated through a separate equation as will be shown in the next section. See table B.1 in Appendix B for values of volatilization losses.

The leaching rate constant used by CSA N288.1-14 (2014) is from Baes and Sharp (1981) and is calculated as follows:

$$\lambda_l = \frac{q_{infil} \cdot f_{wat}}{\theta \cdot Z_{soil}} \quad \textbf{2.30}$$

Where

q_{infil} = Net infiltration rate of water through the soil [$m^3/m^2 \cdot s$] or [m/yr]

Wherever possible, site-specific infiltration rates should be used, however, a set of default values are provided in Table B.1.

Losses due to cropping cycle can be calculated through the following equation. In this equation the CSA N288.1-14 (2014) assumed a conservative loss of about 5% of the nutrient inventory of the crop.

$$\lambda_c = \frac{CR \cdot DW_p \cdot Y_c \cdot 0.05 \cdot cf}{hi \cdot Z_{soil} \cdot \rho_b} \quad \textbf{2.31}$$

Where

CR = Plant/soil concentration ratio $\left[\frac{\text{Bq}/\text{kg } dw \text{ plant}}{\text{Bq}/\text{kg } dw \text{ soil}}\right]$

DW_p = Dry/fresh weight ratio for plant products $\left[\frac{\text{kg } dw \text{ plant}}{\text{kg } fw \text{ plant}}\right]$

Y_c = Yield of consumable plant product per unit area $\left[\frac{\text{kg } fw \text{ plant}}{\text{m}^2 \text{ soil}}\right]$

cf = Cropping frequency [1/s]

hi = Harvest index (mass of consumable product divided by mass of total above-ground plant [total below-ground plant for root crops]) [unitless]

2.5.1.2.2 Tritium

The transfer to soil for tritium, P_{23spw_HTO} presented by CSA N288.1-14 (2014) has units L/L and is calculated through the following equation in which the irrigation water is diluted by precipitation water.

$$P_{23spw\_HTO} = \frac{L\prime}{1000 \cdot P} \quad \textbf{2.32}$$

Where

P = Long-term average precipitation rate [m/s]
1000 = Conversion factor

2.5.1.3 Air Contamination

The release of contamination to the environment is in the water phase through groundwater or surface water. Transfer from the water phase to air is from soil that is contaminated by irrigation and from surface water bodies.

2.5.1.3.1 Air contamination from soil

Contaminated water may be used for irrigation transferring contamination to soil. Volatilization from the contaminated soil can occur for select radionuclides, such as C-14, radioiodines, Cl, Rn and Se and is based on bulk soil concentration (CSA Group, 2014 and NWMO, 2013). The transfer from soil to the atmosphere for C-14, I, Cl and Se, P_{3mass1} [kg *dw*/m^3], is calculated using the following equation from Davis et al., 1993.

$$P_{3mass1} = Z_{soil} \cdot \rho_b \cdot \lambda_{vol} \cdot D_{res} \cdot C_{res} \quad \textbf{2.33}$$

Where

D_{res} = Dilution factor [s/m]
= $4.87 \cdot A_f^{1/8}$-3.56 (Davis et al., 1993)
Where
A_f = area of the irrigated field [m^2] (assume 10^6 m^2)
C_{res} = correction factor that accounts for the location of the receptor relative to the irrigated field [unitless]

For radon, the Rn-222 emission rate from soil is 2.7 x 10^{-9} (mol/m^2·s)/(mol/kg) as reported by Sheppard et al. (2005). From this value, the transfer of Rn-222 from the soil to air, P_{3mass1_Rn} [kg/m^3] can be calculated.

$$P_{3mass1\_Rn} = 2.7x10^{-9} \frac{mol/m^2 \cdot s}{mol/kg} \cdot D_{res} \quad \textbf{2.34}$$

Tritium in the form of tritiated water (HTO) is transferred to the atmosphere, P_{3spw1_HTO} [L/m^3] calculated through a separate equation as follows (CSA Group, 2014).

$$P_{3spw1\_HTO} = R_a \cdot H_a \cdot C_{res} \quad \textbf{2.35}$$

Where

H_a = Atmospheric absolute humidity [L/m^3]
R_a = Ratio of the concentration of tritium in air moisture at 1.5 m above ground to concentration of tritium in air moisture at ground level [unitless]

= 0.3 for $A_f \leq 10^2$ m^2
= $(\log_{10} A_f + 1)/10$ for $10^2 < A_f < 10^6$ m^2
= 0.7 for $A_f \geq 10^6$ m^2

2.5.1.3.2 Air contamination from surface water

Another pathway for contaminants to reach the atmosphere is through volatilization from contaminated surface water. NWMO (2013) presents equations to calculate the concentration of radionuclides in the air due to transfer from surface water. To calculate the concentration in air, $C_{air\_sw\_i}$, for radionuclide i [Bq/m^3], the following equation from NWMO (2013) was used.

$$C_{air\_sw\_i} = \lambda_{vol,i} \cdot C_{2,sw,i} \cdot z_L \cdot D_L \quad \textbf{2.36}$$

$\lambda_{vol,i}$ = Water-to-air loss rate constant for radionuclide i for surface water [1/yr]
z_L = Depth of lake [m]
D_L = Semi-empirical dispersion parameter over water [s/m]

The water-to-air loss rate constant for Rn-222 and I-129 are calculated through the following equations.

$$\lambda_{vol,Rn} = \frac{K_{water,Rn}}{z_L} \quad \textbf{2.37}$$

$$\lambda_{vol,I129} = \frac{I_{MLA}}{z_L \cdot D_L} \quad \textbf{2.38}$$

Where

$K_{water,Rn}$ = Radon transfer coefficient from fresh water to air = 6.7 x 10^{-6} (mol/m^2·s)/(mol/m^3) (Sheppard et al., 2002)
I_{MLA} = Iodine aquatic mass loading [unitless]

$$I_{MLA} = \frac{F_i \cdot k_v \cdot \sqrt{A_L}}{v_s \cdot z_A} \quad \textbf{2.39}$$

$$D_L = \frac{v_s}{v_{ref}} \cdot e^{5 \ln(\ln(A_L)) - 9} \text{ [s/m]} \quad \textbf{2.40}$$

Where

F_i = Correction factor to account for ice and lower temperatures
k_v = Iodine volatilization constant = 8.8x10^{-3} m/yr
A_L = Area of lake [m^2]
v_{ref} = Annual wind speed [m/s]
v_s = Wind speed at site – assumed same as reference [m/s]
z_a = Height of air compartment [m]

The water-to-air loss rate constant for C-14 is given in NWMO (2013) as 0.92 1/yr. Using these various water-to-air loss rate constants, the concentration in the air can be calculated. The dose to the receptor through air immersion and air inhalation will be calculated by multiplying by $P(e)_{19}$ and $P(i)_{19}$, respectively.

2.5.1.4 Plant produce Contamination

Plant produce can be contaminated through spray irrigation, air deposition or through root uptake (CSA Group, 2014).

2.5.1.4.1 Direct contamination by spray irrigation

The equation for contamination via spray irrigation assumes that for every irrigation event the leaves are fully wetted and hold a volume of water proportional to the leaf area (CSA, 2014). The equation for the transfer of irrigation water to plant produce, P_{24} [L/kg *fw*] for all radionuclides except tritium and C-14 is as follows.

$$P_{24} = \frac{LAI \cdot l_{wt} \cdot \eta_i \cdot tf \cdot hi \cdot [1 - exp(-\lambda_e \cdot t_e)]}{\lambda_e \cdot Y_c} \quad \textbf{2.41}$$

Where

LAI = Leaf area index (leaf area per unit ground surface; $\left[\frac{m^2}{m^2}\right]$)
l_{wt} = Volume of water retained per unit leaf area [L/m^2]
η_i = Frequency of irrigation events using contaminated water [1/s]
tf = Translocation factor from foliage to consumable product $\left[\frac{Bq/kg\ fw\ \text{consumable plant product}}{Bq/kg\ fw\ \text{total above-ground plant}}\right]$
t_e = Effective duration of the deposition [s]
λ_e = Effective removal constant from vegetation surfaces [1/s]
$= \lambda_r + \lambda_p$
Where
λ_p = physical removal processes such as wind, rain and plant growth [1/s]

For tritiated water (HTO), the transfer, P_{24_HTO} [L/kg *fw*], assumes that the plant moisture has the same activity as the irrigation water (CSA, 2014).

$$P_{24\_HTO} = 1 - DW_p \quad \textbf{2.42}$$

For organically bound tritium (OBT), the transfer, P_{24_OBT} [L/kg *fw*], is calculated with the following equation (CSA, 2014).

$$P_{24\_OBT} = DW_p \cdot ID_p \cdot WE_p \quad \textbf{2.43}$$

Where

ID_p = Isotopic discrimination factor for plant metabolism [unitless]
WE_p = Water equivalent of the plant dry matter [L water/kg *dw* plant] (the mass of water produced by combustion of a unit mass of dry matter)

For C-14, the transfer of irrigation water to plants P_{24_C14} [L/kg *fw*] is calculated through the following equation (CSA, 2014).

$$P_{24\_C14} = \frac{(1-f_{c\_air})\cdot L\prime\cdot f_v}{Y_c\cdot\left(\frac{TS}{hi}-1\right)\cdot cf} \quad \textbf{2.44}$$

Where

f_{c_air} = Fraction of stable carbon derived from air [unitless]
f_v = Fraction of the annual input of C-14 leaving the soil surface per annum [unitless]
TS = Ratio of the total plant yield to the total above-ground yield (total below-ground yield for root crops) [unitless]

2.5.1.4.2 Plant uptake from soil

The transfer parameter for root uptake from soil, P_{3mass4} [unitless], for all radionuclides except for tritium and C-14 can be calculated as follows (CSA, 2014).

$$P_{3mass4} = CR \cdot DW_p \quad \textbf{2.45}$$

The transfer of tritium and C-14 to plant produce is incorporated in the transfer from air to plants and therefore the transfer parameters for this pathway are set equal to zero (CSA, 2014).

$$P_{3mass4\_HTO} = P_{3mass4\_HT} = P_{3mass4\_OBT} = P_{3mass4\_C14} = 0 \quad \textbf{2.46}$$

2.5.1.4.3 Air deposition on plant produce

The transfer from air deposition /to plant produce, P_{14} [m^3/kg *fw*], for all radionuclides except tritium and C-14 can be calculated as follows (CSA, 2014).

$$P_{14} = \frac{v_g\cdot f_{int}\cdot tf\cdot hi\cdot[1-exp(-\lambda_e\cdot t_e)]}{\lambda_e\cdot Y_c} \quad \textbf{2.47}$$

Where

v_g = Deposition velocity [m/s]
f_{int} = Foliar interception fraction [unitless]

The transfer from air HTO (and soil HTO) to HTO in plant, P_{14_HTO} [m^3/kg *fw*] is calculated with the following equation (CSA, 2014).

$$P_{14\_HTO} = \frac{RF_p \cdot (1 - DW_p)}{H_a} \quad \textbf{2.48}$$

Where

RF_p = Reduction factor that accounts for the effect of soil water HTO concentrations that are lower than air moisture HTO concentrations [unitless]

The transfer parameter from air HTO to OBT in the plant produce, $P_{14\_HTO\_OBT}$ [m^3/kg *fw*] is given by the following equation (CSA, 2014).

$$P_{14\_HTO\_OBT} = \frac{RF_p \cdot DW_p \cdot ID_p \cdot WE_p}{H_a} \quad \textbf{2.49}$$

The equation for the transfer of C-14 from air to plant produce, P_{14_C14} [m^3/kg *fw*] is as follows (CSA, 2014).

$$P_{14\_C14} = \frac{f_{c\_air} \cdot X_{4\_C} \cdot DW_p}{X_{1\_C}} \quad \textbf{2.50}$$

Where

X_{4_C} = Mass of stable carbon per mass of plant [gC/kg *dw*]
X_{1_C} = Concentration of stable carbon in air [gC/m^3]

Default values of all the required parameters to calculate the various transfer to plant produce are presented in Table B.1 are for the CRL site.

2.5.1.5 Animal produce contamination

Animal produce are those products that are ingested such as milk, meat and eggs. In CSA N288.1-14 (2014), the animal produce that is considered is Cow's milk, Goat's milk, Beef meat, Beef liver, Pork, Lamb, Poultry meat, Eggs, Deer, Rabbit, Mallard ducks and Canadian Geese. The CSA N288.1-14 (2014) does not consider every radionuclide that is coded within DOC-WMF, resulting in some parameters not being defined for every radionuclide. For the NWMO's Fifth Case Study, the animal produce that was considered was Cow's milk, Beef meat and Poultry meat and considers further radionuclides providing further data. For completeness, all animal produce is contained within the model and the user has the capability of choosing which animal produce to consider through the dashboard. However, it must be recalled that for some of the animal produce, limited data for some parameters is available. If in the future these parameters become available they can be updated in the Excel Input file.

2.5.1.5.1 Water to animal produce

The ingestion of water will transfer contaminants to animal produce. By default, the source of water for domestic animals is contaminated well water and for forest animals and waterfowl it is surface water. The user has the ability to change the source of drinking water through the dashboard.

The transfer from ingestion of water to animal produce, P_{25} [L/kg *fw*], for all radionuclides except tritium and C-14, is calculated as follows (CSA, 2014).

$$P_{25} = k_{aw} \cdot Q_w \cdot F_{ing} \quad \textbf{2.51}$$

Where

k_{aw} = Fraction of water from contaminated sources [unitless]
Q_w = Water consumption of the animal [L/d]
F_{ing} = Fraction of animal's daily intake by ingestion that appears in each kg of produce [d/kg *fw*]

F_{ing} values are not fully represented in the Excel input file called DOC_WMF_inputs.xlsx for all radionuclides and animal produce types. As more data becomes available in the future it can be added to the Excel file easily. The transfer parameter can be calculated based on a dry feed diet or a wet feed diet. By default the model assumes that the domestic animals are on a dry generic feed diet and the forest animals and waterfowl are on a diet of wet forage. The user has the ability to change the diet if needed.

For tritiated water, the transfer of HTO through ingestion of water, P_{25_HTO} [L/kg *fw*], is calculated using the following equation (CSA, 2014).

$$P_{25\_HTO} = k_{aw} \cdot f_{w\_w} \cdot (1 - DW_a) \quad \textbf{2.52}$$

Where

f_{w_w} = Fraction of the animal water intake derived from direct ingestion of water [unitless]
DW_a = Dry/fresh weight ratio for animal products $\left[\frac{\text{kg } dw}{\text{kg } fw}\right]$

The formation of OBT due to animal ingesting HTO contaminated water, P_{25_OBT} [L/kg *fw*], is calculated as follows (CSA, 2014).

$$P_{25\_OBT} = P_{25\_HTO} \cdot f'_{OBT} \quad \textbf{2.53}$$

Where

f'_{OBT} = OBT/HTO ratio in the animal [unitless]

2.5.1.5.2 Air to animal produce

The transfer from air inhalation to animal produce, P_{15} [m^3/kg *fw*], is calculated with the following equation (CSA, 2014).

$$P_{15} = Q_a \cdot F_{inh} \quad \textbf{2.54}$$

Where

Q_a = Air inhalation rate of the animal [m^3/d]
F_{inh} = Fraction of animal's daily intake by inhalation that appears in each kg of produce [d/kg *fw*]
= $II \cdot F_{ing}$
Where
II = inhalation/ingestion absorption ratio [unitless]

The HTO transfer from air to animals, P_{15_HTO} [m^3/kg *fw*], is calculated with the following equation (CSA, 2014).

$$P_{15\_HTO} = \frac{f_{w\_sw} \cdot (1 - DW_a)}{H_a} \quad \textbf{2.55}$$

Where

f_{w_sw} = Fraction of the animal water intake derived from inhalation and skin absorption [unitless]

The transfer of OBT to animal produce through air inhalation, P_{15_OBT} [m^3/kg] is calculated with OBT/HTO ratios (f'_{OBT}) given by the metabolic model of Galerlu et al. (2007).

$$P_{15\_OBT} = P_{15\_HTO} \cdot f'_{OBT} \quad \textbf{2.56}$$

Animals take up very little C-14 via inhalation and therefore, $P_{15\_C14} = 0$.

2.5.1.5.3 Plant to animal produce

The transfer to animal produce through ingestion of feed for all radionuclides except tritium and C-14, P_{45} [unitless], is calculated with the following equation (CSA, 2014).

$$P_{45} = \frac{k_{af} \cdot Q_f \cdot F_{ing} \cdot exp(-\lambda_r \cdot t_h)}{DW_p} \quad \textbf{2.57}$$

Where

k_{af} Fraction of feed from contaminated sources [unitless]
Q_f Feed consumption by the animal [kg *dw*/d]

t_h Hold-up time between plant exposure to contamination and feeding [s]

The HTO transfer from feed to animal produce, P_{45_HTO} [unitless], is calculated as follows (CSA, 2014).

$$P_{45\_HTO} = \frac{k_{af}\cdot[(1-f_{OBT})\cdot f_{w\_pw}+0.5\cdot f_{w\_dw}]\cdot(1-DW_a)}{1-DW_p} \quad \textbf{2.58}$$

Where

f_{w_pw} = Fraction of the animal water intake derived from water in the plant feed [unitless]
f_{OBT} = Fraction of total tritium in the animal product in the form of OBT as a result of HTO ingestion [unitless]
f_{w_dw} = Fraction of the animal water intake that results from the metabolic decomposition of the organic matter in the feed [unitless]

The OBT transfer from feed to animal produce, P_{45_OBT} [unitless], is written in terms of the OBT concentration in the plant as follows (CSA, 2014).

$$P_{45\_OBT} = \frac{k_{af}\cdot[f_{OBT}\cdot f_{w\_pw}+0.5\cdot f_{w\_dw}]\cdot DW_a\cdot WE_a}{DW_p\cdot WE_p} \quad \textbf{2.59}$$

Where

WE_a = Water equivalent of the animal product dry matter [L water/kg *dw* produce]

Animals take in carbon mainly through their feed with very little coming through inhalation or water ingestion and the transfer from feed to produce, P_{45_C14} [unitless], is calculated as follows (CSA, 2014).

$$P_{45\_C14} = \frac{k_{af}\cdot X_{5\_C}}{X_{4\_C}\cdot DW_p} \quad \textbf{2.60}$$

Where

X_{5_C} = Stable carbon concentration in animal [gC/kg *fw*]

2.5.1.5.4 Aquatic plant to animal produce

The transfer parameter describing transfer from aquatic plant to wild waterfowl, P_{75} [unitless], is calculated in a similar manner to that describing transfer from feed to domestic animals (CSA, 2014).

$$P_{75} = \frac{k_{af}\cdot Q_f\cdot F_{ing}\cdot exp(-\lambda_r\cdot t_h)}{DW_{ap}} \quad \textbf{2.61}$$

Where

DW_{ap} = Dry weight of aquatic plant per total fresh weight $\left[\frac{\text{kg } dw}{\text{kg } fw}\right]$

The transfer of HTO from aquatic plants to wild waterfowl, P_{75_HTO} [unitless], is calculated as follows (CSA, 2014).

$$P_{75\_HTO} = \frac{k_{af} \cdot [(1-f_{OBT}) \cdot f_{w\_pw} + 0.5 \cdot f_{w\_dw}] \cdot (1-DW_a)}{1-DW_{ap}} \quad \textbf{2.62}$$

The transfer of OBT to wild waterfowl through the ingestion of aquatic plants, P_{75_OBT} [unitless], is calculated using the following equation (CSA, 2014).

$$P_{75\_OBT} = \frac{k_{af} \cdot [f_{OBT} \cdot f_{w\_pw} + 0.5 \cdot f_{w\_dw}] \cdot DW_a \cdot WE_a}{DW_{ap} \cdot WE_{ap}} \quad \textbf{2.63}$$

Where

WE_{ap} = Water equivalent of the aquatic plant dry matter [L/kg *dw*]

The transfer of C-14 between aquatic plants to wild waterfowl, P_{75_C14} [unitless], is calculated as follows (CSA, 2014).

$$P_{75\_C14} = \frac{k_{af} \cdot X_{5\_C}}{X_{7\_C} \cdot DW_{aa}} \quad \textbf{2.64}$$

Where

X_{7_C} = Stable carbon concentration in aquatic plants [gC/kg *dw*]

2.5.1.5.5 Aquatic animal to animal produce

The transfer parameter from aquatic animals, specifically freshwater fish to wild waterfowl, P_{65} [unitless] is calculated in a similar manner as the transfer from feed to domestic animals as follows (CSA, 2014).

$$P_{65} = \frac{k_{af} \cdot Q_f \cdot F_{ing} \cdot exp(-\lambda_r \cdot t_h)}{DW_{aa}} \quad \textbf{2.65}$$

Where

DW_{aa} = Fractional dry weight content of freshwater fish $\left[\frac{\text{kg } dw}{\text{kg } fw}\right]$

For transfer of HTO from fish to wild waterfowl the following equation was used (CSA, 2014).

$$P_{65\_HTO} = \frac{k_{af}\cdot[(1-f_{OBT})\cdot f_{w\_pw}+0.5\cdot f_{w\_dw}]\cdot(1-DW_a)}{1-DW_{aa}} \quad \textbf{2.66}$$

The transfer of OBT to wild waterfowl from the ingestion of fish was calculated as follows (CSA, 2014).

$$P_{65\_OBT} = \frac{k_{af}\cdot[f_{OBT}\cdot f_{w\_pw}+0.5\cdot f_{w\_dw}]\cdot DW_a\cdot WE_a}{DW_{aa}\cdot WE_{aa}} \quad \textbf{2.67}$$

Where

WE_{aa} = Water equivalent of the aquatic animal dry matter [L/kg *dw*]

The transfer of C-14 is calculated using the following equation (CSA, 2014).

$$P_{65\_C14} = \frac{k_{af}\cdot X_{5\_C}}{X_{6\_C}\cdot DW_{aa}} \quad \textbf{2.68}$$

Where

X_{6_C} = Stable carbon concentration in fish [gC/kg *dw*]

2.5.1.5.6 Soil to animal produce through incidental ingestion

Incidental soil ingestion transfers to animal produce through P_{3mass5} [unitless] is calculated through the following equation (CSA, 2014).

$$P_{3mass5} = \left(k_{af}\cdot Q_f\cdot f_{sl} + Q_s\right)\cdot F_{ing} \quad \textbf{2.69}$$

Where

f_{sl} = Soil load on feed as consumed $\left[\frac{\text{kg } dw \text{ soil}}{\text{kg } dw \text{ feed}}\right]$

Q_s = Soil consumption rate by animal from sources other than feed [kg *dw*/d]

Transfer of tritium and C-14 through soil ingestion to animal produce is negligible (CSA, 2014).

$$P_{3mass5\_HTO} = P_{3mass5\_OBT} = P_{3mass5\_C14} = 0 \quad \textbf{2.70}$$

2.5.1.5.7 Sediment to animal produce through incidental ingestion

Sediment is ingested incidentally by waterfowl and is quantified through the transfer parameter P_{85} [unitless] (CSA, 2014).

$$P_{85} = \left(k_{af} \cdot Q_f \cdot f_{sl}\right) \cdot F_{ing} \quad \textbf{2.71}$$

Sediment ingestion dose from tritium and C-14 is negligible (CSA, 2014).

$$P_{85\_HTO} = P_{85\_OBT} = P_{85\_C14} = 0 \quad \textbf{2.72}$$

2.5.1.6 Aquatic animal and aquatic plant contamination

The aquatic animals and plants that are considered in DOC-WMF are freshwater fish. The transfer from contaminated surface water to freshwater fish, P_{26} [L/kg *fw*] and freshwater plants, P_{27} [L/kg *fw*], are equated to bioaccumulation factors (BAF) (CSA, 2014).

$$P_{26/27} = BAF \quad \textbf{2.73}$$

The HTO transfer from surface water to fish and aquatic plants, P_{26_HTO} [L/kg *fw*] and P_{27_HTO} [L/kg *fw*], assumes that the specific activity between them is in equilibrium (CSA, 2014).

$$P_{26\_HTO} = 1 - DW_{aa} \quad \textbf{2.74}$$

$$P_{27\_HTO} = 1 - DW_{ap} \quad \textbf{2.75}$$

Where

$1\text{-}DW_{aa}$ = Fractional water content of aquatic animals [L/kg *fw*]
$1\text{-}DW_{ap}$ = Fractional water content of aquatic plants [L/kg *fw*]

The transfer of OBT from surface water to fish and aquatic plants, P_{26_OBT} [L/kg *fw*] and P_{27_OBT} [L/kg *fw*] is calculated as follows (CSA, 2014).

$$P_{26\_OBT} = DW_{aa} \cdot ID_{aa} \cdot WE_{aa} \quad \textbf{2.76}$$

$$P_{27\_OBT} = DW_{ap} \cdot ID_{ap} \cdot WE_{ap} \quad \textbf{2.77}$$

Where

ID_{ap} = Isotopic discrimination factor for aquatic plant metabolism [unitless]
ID_{aa} = Isotopic discrimination factor for aquatic animal metabolism [unitless]

The transfer of C-14 from surface water to fish, P_{26_C14} [L/kg *fw*], is calculated through a specific activity model (CSA, 2014).

$$P_{26\_C14} = \frac{M_{aa}}{M_w} \quad \textbf{2.78}$$

Where

M_{aa} = Mass of stable carbon in aquatic animals [gC/kg *fw*]
M_w = Mass of stable carbon in the dissolved inorganic phase in water [gC/L]

2.5.1.7 Sediment contamination

Sediment is contaminated through transfer from surface water, P_{28} [L/kg *dw*], and is calculated using the following equation (CSA, 2014).

$$P_{28} = \frac{X_8}{X_2} \quad \textbf{2.79}$$

Where

X_8 = Concentration in sediment [Bq/kg *dw*]
X_2 = Concentration in surface water [Bq/L]

2.5.1.8 Transfer to receptor

The various compartments: water; air; soil; plant; animal produce; aquatic animal; and aquatic plant are transferred to the receptor through ingestion, inhalation or immersion. The following sections present the equations used to calculate the transfer parameters from the various compartments to the receptor. For each transfer to receptor, dose coefficients are needed and are presented in Tables D.1 to D.6. The dose coefficients are brought into the model through a GoldSim Spreadsheet element from DOC_WMF_inputs.xlsx.

2.5.1.8.1 Air inhalation

The transfer to the receptor through inhalation of contaminated air, $P(i)_{19}$ [(Sv/yr)/(Bq/m^3)], is calculated through the following equation (CSA, 2014).

$$P(i)_{19} = I \cdot (DCF)_i \cdot (OF)_i \quad \textbf{2.80}$$

Where

I = Air inhalation rate [m^3/yr]
$(DCF)_i$ = Dose coefficient for inhalation [Sv/Bq]
$(OF)_i$ = Occupancy factor [unitless]

2.5.1.8.2 Air immersion

The transfer to the receptor through immersion in contaminated air, $P(e)_{19}$ [(Sv/yr)/(Bq/m^3)], is calculated as follows (CSA, 2014).

$$P(e)_{19} = f_0 \cdot [f_u + (1 - f_u) \cdot S_b](DCF)_a \quad \textbf{2.81}$$

Where

f_0 = Fraction of total time spent by the individual at the particular location (accounts for working and living at different locations) [unitless]
f_u = Time spent outdoors at a particular location as a fraction of total time spent at that location [unitless]
S_b = Building shielding factor, or fraction of the outdoor cloudshine dose that is received indoors [unitless]
$(DCF)_a$ = Effective dose coefficient for a semi-infinite cloud [(Sv/yr)/(Bq/m^3)]

2.5.1.8.3 Ingestion of water, plant produce, animal produce, fish and soil

The transfer through ingestion from various pathways, such as plant produce (P_{49}), animal produce (P_{59}) and freshwater fish (P_{69}) in [(Sv/yr)/(Bq/kg)] to the receptor is calculated as follows (CSA, 2014).

$$P_{49} = P_{59} = P_{69} = \rho_f \cdot g_f \cdot I_f \cdot (DCF)_f \quad \textbf{2.82}$$

The transfer through the ingestion of water, $P(i)_{29}$ [(Sv/yr)/(Bq/L)] is calculated using the following equation (CSA, 2014).

$$P(i)_{29} = \rho_w \cdot k''_w \cdot I_w \cdot (DCF)_f \quad \textbf{2.83}$$

The transfer to the receptor through incidental ingestion of soil, $P(i)_{3mass9}$ [(Sv/yr)/(Bq/kg)] is calculated as follows (CSA, 2014).

$$P(i)_{3mass9} = I_s \cdot EF_s \cdot (DCF)_f \quad \textbf{2.84}$$

Where

ρ_f = Modifying factor for food processing [unitless]
g_f = Fraction of plant, animal or fish from contaminated sources [unitless]
I_f = Intake rate of plant, animal or fish produce [kg *fw*/yr]
$(DCF)_f$ = Dose coefficient for intake by ingestion [Sv/Bq]
ρ_w = Removal factor to account for any water treatment [unitless]
k''_w = Fraction of drinking water that is contaminated [unitless]
I_w = Drinking water intake rate [L/yr]
I_s = Incidental intake of soil [kg *dw*/d]
EF_s = Number of days per year in which incidental soil ingestion can occur

2.5.1.8.4 Groundshine

The transfer from external dose to receptor from exposure to contaminated ground surface $P(e)_{3area9}$ [(Sv/yr)/(Bq/m^2)] is calculated as follows (CSA, 2014).

$$P(e)_{3area9} = f_0 \cdot f_r \cdot \left[f_u + (1 - f_u) \cdot S_g\right] \cdot (DCF)_g \quad \textbf{2.85}$$

Where

f_r = Dose reduction factor to account for non-uniformity of the ground surface [unitless]
S_g = Shielding factor for groundshine [unitless]
$(DCF)_g$ = Effective does coefficient for an infinite plane ground deposit [(Sv/yr)/(Bq/m^2)]

2.5.1.8.5 Water immersion

The transfer to receptor through immersion in contaminated water, $P(e)_{2w9}$ [(Sv/yr)/(Bq/L)], is calculated for groundwater as follows (CSA, 2014).

$$P(e)_{2w9} = (DCF)_w \cdot (D_c \cdot \rho \cdot OF'_w + \rho \cdot OF''_w) \quad \textbf{2.86}$$

For contaminated surface water, the transfer through immersion is an expanded form of the previous equation (CSA, 2014).

$$P(e)_{29} = (DCF)_w \cdot (OF_w + D_c \cdot \rho \cdot OF'_w + \rho \cdot OF''_w) \quad \textbf{2.87}$$

The calculation for the transfer of HTO to the receptor through water immersion in contaminated groundwater ($P(e)_{2w9\_HTO}$) and surface water ($P(e)_{29\_HTO}$) accounts for transfer through the receptor's skin (CSA, 2014).

$$P(e)_{2w9\_HTO} = S_a \cdot D_s \cdot (DCF)_f \cdot (\rho \cdot OF'_w + \rho \cdot OF''_w) \quad \textbf{2.88}$$

$$P(e)_{29\_HTO} = S_a \cdot D_s \cdot (DCF)_f \cdot (OF_w + \rho \cdot OF'_w + \rho \cdot OF''_w) \quad \textbf{2.89}$$

Where

$(DCF)_w$ = Dose coefficient for immersion in an infinite, uniformly contaminated water medium [(Sv/yr)/(Bq/L)]
D_c = Correction factor to account for finite size of bathtub [unitless]
ρ = Removal factor to account for processes such as sedimentation [unitless]
OF_w = Fraction of year spent swimming in surface water body [unitless]
OF'_w = Fraction of year spent taking baths [unitless]
OF''_w = Fraction of year spent in a swimming pool [unitless]
S_a = Skin surface area [m^2]
D_s = Diffusion rate for wetted skin [L/yr·m^2 skin surface area]

2.5.1.8.6 Incidental sediment ingestion

Transfer through incidental sediment ingestion to the receptor, $P(i)_{89}$ [(Sv/yr)/(Bq/kg)] is calculated through the following equation (CSA, 2014).

$$P(i)_{89} = EF_{sed} \cdot I_s \cdot (DCF)_f \cdot (DF)_s \quad \textbf{2.90}$$

Where

EF_{sed} = Number of days in year in which sediment ingestion can occur
I_s = Incidental intake of sediment [kg *dw*/d]
$(DF)_s$ = Dilution factor for shoreline deposits

2.5.1.8.7 Beachshine

The transfer to the receptor through the exposure to contaminated sediment, $P(e)_{89}$ [(Sv/yr)/(Bq/kg)], is calculated using the following equation (CSA, 2014).

$$P(e)_{89} = (OF)_s \cdot W \cdot (DCF)_s \cdot (DF)_s \quad \textbf{2.91}$$

Where

$(OF)_s$ = Shoreline occupancy factor [unitless]
W = Shore-width factor that describes the shoreline exposure geometry [unitless]
$(DCF)_s$ = Dose coefficient for a uniformly contaminated sediment [(Sv/yr)/(Bq/kg)]

The only source for beachshine dose coefficients was CSA N288.1-14 (2014), and therefore those radionuclides not considered in this reference currently have a value of zero, thereby neglecting the beachshine dose.

2.5.2 Dose calculations

The model predicts the releases to the biosphere to a well and to a lake or river. The concentration in the groundwater is calculated using Equation 2.20. The surface water concentration is calculated by multiplying the release in [Bq/s] (Equation 2.21) by the appropriate transfer parameter, P_{02} in [s/L], to account for dispersion. The concentration in the contaminated water is transferred through the various compartments or pathways to the receptor using the transfer parameters presented in Section 2.5.1.

The transfer pathways to the receptor are through air inhalation, air immersion, water immersion, ingestion of water, plant produce, animal produce and fish, incidental ingestion of soil and sediment and through groundshine and beachshine. The rates of inhalation and ingestion are user inputted through the dashboard or brought in as a PDF through the database. The dose equations for each of these pathways are presented in Table 2.5.

Table 2.5 – Dose calculations for various pathways

Pathway	From/to	Equation
Air inhalation	Irrigation water (2)→soil (3)→air (1)→receptor (9)	HTO: $C_{2,w} \cdot P_{23spw\_HTO} \cdot P_{3spw1\_HTO} \cdot P(i)_{19}$ Other: $C_{2,w} \cdot P_{23mass} \cdot P_{3mass1} \cdot P(i)_{19}$
	Surface water (2)→air (1)→receptor (9)	$C_{air\_sw\_i} \cdot P(i)_{19}$
Air immersion	Irrigation water (2)→soil (3)→air (1)→receptor (9)	HTO: $C_{2,w} \cdot P_{23spw\_HTO} \cdot P_{3spw1\_HTO} \cdot P(e)_{19}$ Other: $C_{2,w} \cdot P_{23mass} \cdot P_{3mass1} \cdot P(e)_{19}$
	Surface water (2)→air (1)→receptor (9)	$C_{air\_sw\_i} \cdot P(e)_{19}$
Water ingestion	Water (2)→ receptor (9) Surface water (2)→ receptor (9)	$C_{2,w} \cdot P(i)_{29}$ $C_{2,sw} \cdot P(i)_{29}$
Water immersion	Water (2)→ receptor (9) Surface water (2)→ receptor (9)	$C_{2,w} \cdot P(e)_{2w9}$ $C_{2,sw} \cdot P(e)_{29}$
Incidental soil ingestion	Water(2)→soil(3)→receptor(9)	$C_{2,w} \cdot P_{23mass} \cdot P(i)_{3mass9}$
Groundshine	Water(2)→soil(3)→receptor(9)	$C_{2,w} \cdot P_{23area} \cdot P(e)_{3area9}$
Incidental sediment ingestion	Surface water(2)→sediment(8)→receptor(9)	$C_{2,sw} \cdot P_{28} \cdot P(i)_{89}$
Beachshine	Surface water(2)→sediment(8)→receptor(9)	$C_{2,sw} \cdot P_{28} \cdot P(e)_{89}$

Table 2.5 – Dose calculations for various pathways (continued)

Pathway	From/to	Equation
Plant ingestion (sum of each component)	**Root uptake:** Irrigation water (2)→soil (3)→plant(4)→receptor (9)	$C_{2,w} \cdot P_{23mass} \cdot P_{3mass4} \cdot P_{49}$
	Irrigation: Irrigation water (2)→plant(4)→receptor(9)	$C_{2,w} \cdot P_{24} \cdot P_{49}$
	Air deposition: Irrigation water (2)→soil(3)→air(1)→plant(4)→receptor(9) Surface water (2)→air (1) →plant(4)→receptor (9)	HTO: $C_{2,w} \cdot P_{23spw\_HTO} \cdot P_{3spw1\_HTO} \cdot P_{14} \cdot P_{49}$ Other: $C_{2,w} \cdot P_{23mass} \cdot P_{3mass1} \cdot P_{14} \cdot P_{49}$ $C_{air\_sw\_i} \cdot P_{14} \cdot P_{49}$
Aquatic animal ingestion	Surface water (2)→fish(6)→receptor(9)	$C_{2,sw} \cdot P_{26} \cdot P_{69}$

Table 2.5 – Dose calculations for various pathways (continued)

Pathway	From/to	Equation
Domestic animal (meat, eggs and milk) ingestion (sum of each component)	**Water ingestion** Water (2)→animal(5)→receptor(9)	$C_{2,w} \cdot P_{25} \cdot P_{59}$
	Feed ingestion *Air deposition on plant* Irrigation water(2)→soil(3)→air(4)→animal(5)→receptor(9) Surface water (2)→air (1) →plant(4)→receptor (9) *Irrigation* Irrigation water (2)→plant(4)→animal(5)→receptor(9) *Root uptake* Irrigation water (2)→soil (3) →plant(4) →animal(5) →receptor (9)	 $C_{2,w} \cdot P_{23mass} \cdot P_{3mass1} \cdot P_{14} \cdot P_{45} \cdot P_{59}$ $C_{air\_sw\_i} \cdot P_{14} \cdot P_{45} \cdot P_{59}$ $C_{2,w} \cdot P_{24} \cdot P_{45} \cdot P_{59}$ $C_{2,w} \cdot P_{23mass} \cdot P_{3mass4} \cdot P_{45} \cdot P_{59}$
	Soil ingestion Irrigation water(2)→soil(3)→animal(5)→receptor(9)	$C_{2,w} \cdot P_{23mass} \cdot P_{35} \cdot P_{59}$
	Air inhalation Irrigation water (2)→soil (3)→air(1)→animal(5)→receptor(9) Surface water (2)→air (1) →animal(5)→receptor (9)	 HTO: $C_{2,w} \cdot P_{23spw\_HTO} \cdot P_{3spw1\_HTO} \cdot P_{15} \cdot P_{59}$ Other: $C_{2,w} \cdot P_{23mass} \cdot P_{31mass} \cdot P_{15} \cdot P_{59}$ $C_{air\_sw\_i} \cdot P_{15} \cdot P_{59}$

Table 2.5 – Dose calculations for various pathways (continued)

Pathway	From/to	Equation
Forest animal ingestion (sum of each component)	**Water ingestion** Water (2)→animal(5)→receptor(9)	$C_{2,sw} \cdot P_{25} \cdot P_{59}$
	Feed ingestion *Air deposition on plant* Irrigation water(2)→soil(3)→air(1) →plant(4) →animal(5) →receptor(9)	HTO: $C_{2,w} \cdot P_{23spw\_HTO} \cdot P_{3spw1\_HTO} \cdot P_{14} \cdot P_{45} \cdot P_{59}$ Other: $C_{2,w} \cdot P_{23mass} \cdot P_{3mass1} \cdot P_{14} \cdot P_{45} \cdot P_{59}$
	Surface water(2)→air(1) →plant(4) →animal(5) →receptor(9)	$C_{air\_sw\_i} \cdot P_{14} \cdot P_{45} \cdot P_{59}$
	Irrigation Irrigation water (2)→plant(4)→animal(5)→receptor(9)	$C_{2,w} \cdot P_{24} \cdot P_{45} \cdot P_{59}$
	Root uptake Irrigation water (2)→soil (3) →plant(4) →animal(5) →receptor (9)	$C_{2,w} \cdot P_{23mass} \cdot P_{3mass4} \cdot P_{45} \cdot P_{59}$
	Soil ingestion Irrigation water(2)→soil(3)→animal(5)→receptor(9)	$C_{2,w} \cdot P_{23mass} \cdot P_{35} \cdot P_{59}$
	Air inhalation Irrigation water (2)→soil (3)→air(1)→animal(5)→receptor(9)	HTO: $C_{2,w} \cdot P_{23spw\_HTO} \cdot P_{3spw1\_HTO} \cdot P_{15} \cdot P_{59}$ Other: $C_{2,w} \cdot P_{23mass} \cdot P_{31mass} \cdot P_{15} \cdot P_{59}$
	Surface water (2)→air (1) →animal(5)→receptor (9)	$C_{air\_sw\_i} \cdot P_{15} \cdot P_{59}$

Table 2.5 – Dose calculations for various pathways (continued)

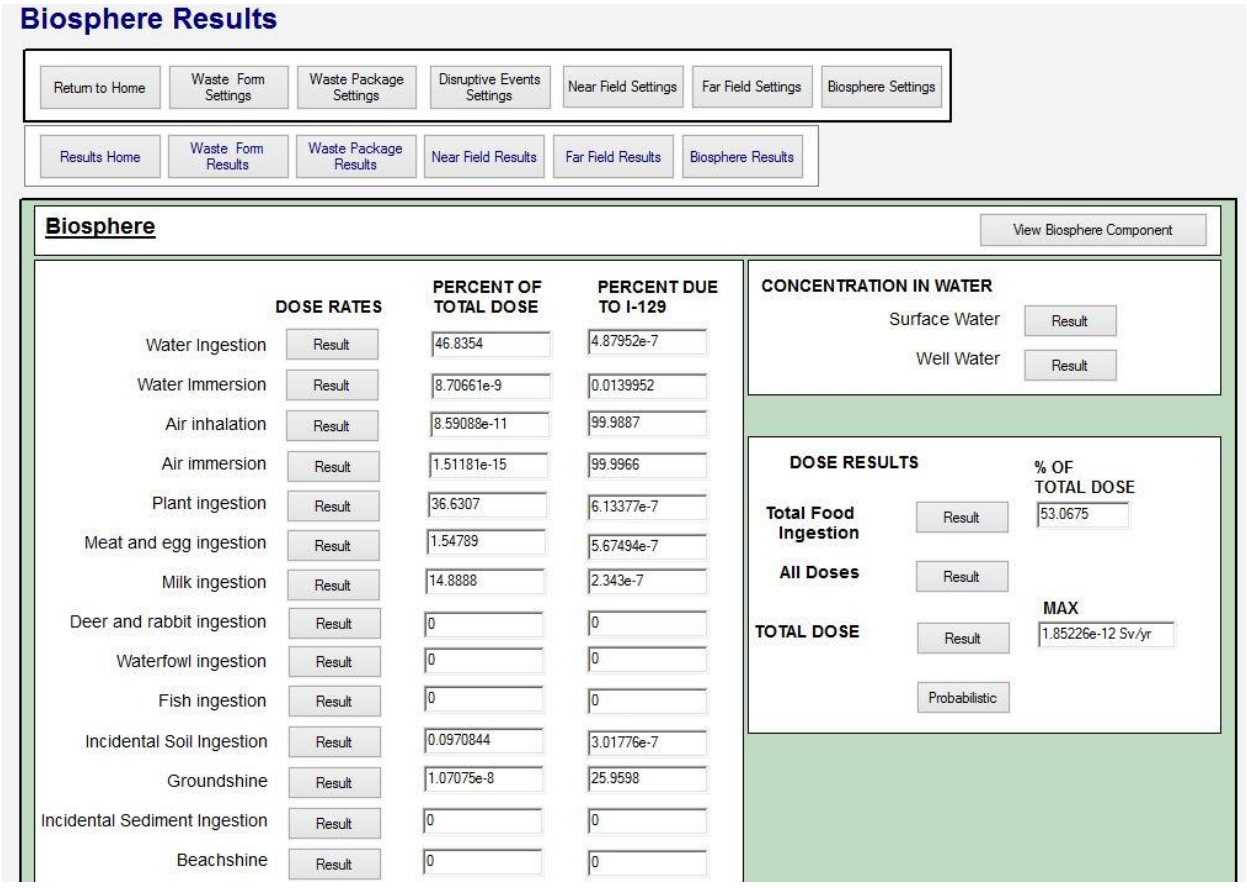
Pathway	From/to	Equation
Waterfowl ingestion (sum of each component)	**Water ingestion** water (2)→animal(5)→receptor(9)	$C_{2,w} \cdot P_{25} \cdot P_{59}$
	Fish ingestion Surface water(2)→fish ingestion(6)→animal(5)→receptor(9)	$C_{2,sw} \cdot P_{26} \cdot P_{65} \cdot P_{59}$
	Aquatic plant ingestion Surface water(2)→aquatic plant(7)→animal(5)→receptor(9)	$C_{2,sw} \cdot P_{27} \cdot P_{75} \cdot P_{59}$
	Soil ingestion Irrigation water(2)→soil(3)→animal(5)→receptor(9)	$C_{2,w} \cdot P_{23mass} \cdot P_{35} \cdot P_{59}$
	Feed ingestion *Air deposition on plant* Irrigation water(2)→soil(3)→air(1) →plant(4) →animal(5) →receptor(9) Surface water(2)→air(1) →plant(4) →animal(5) →receptor(9) *Irrigation* Irrigation water (2)→plant(4)→animal(5)→receptor(9) *Root uptake* Irrigation water (2)→soil (3) →plant(4) →animal(5) →receptor (9)	HTO: $C_{2,w} \cdot P_{23spw\_HTO} \cdot P_{3spw1\_HTO} \cdot P_{14} \cdot P_{45} \cdot P_{59}$ Other: $C_{2,w} \cdot P_{23mass} \cdot P_{3mass1} \cdot P_{14} \cdot P_{45} \cdot P_{59}$ $C_{air\_sw\_i} \cdot P_{14} \cdot P_{45} \cdot P_{59}$ $C_{2,w} \cdot P_{24} \cdot P_{45} \cdot P_{59}$ $C_{2,w} \cdot P_{23mass} \cdot P_{3mass4} \cdot P_{45} \cdot P_{59}$
	Sediment ingestion Surface water(2)→sediment(8)→animal(5)→receptor(9)	$C_{2,sw} \cdot P_{28} \cdot P_{85} \cdot P_{59}$
	Air inhalation Irrigation water (2)→soil (3)→air(1)→animal(5)→receptor(9) Surface water (2)→air (1) →animal(5)→receptor (9)	HTO: $C_{2,w} \cdot P_{23spw\_HTO} \cdot P_{3spw1\_HTO} \cdot P_{15} \cdot P_{59}$ Other: $C_{2,w} \cdot P_{23mass} \cdot P_{31mass} \cdot P_{15} \cdot P_{59}$ $C_{air\_sw\_i} \cdot P_{15} \cdot P_{59}$

For most radionuclides, a good representation of data is available to transfer through the various compartments and to the receptor. However, some data was not obtainable through the literature review for certain radionuclides (See Appendix B). As this missing data becomes available, the values can be added to the model.

One notable area where information was lacking is for Ir-192. Very little information regarding any transfer of this radionuclide was found and through discussion and literature review have found that little research has been conducted on this species. Therefore, even though this radionuclide is on the species list, it is essentially not included in the dose calculation as no transfer parameters were able to be calculated due to lack of data.

The results of the dose calculations through the various exposure pathways and total dose rates can be viewed through the Biosphere results dashboard (see Figure 2.15). The percent contribution of each pathway to the total dose rate is presented on the dashboard, as well as the percentage of each pathway as a result of I-129. By clicking on the Result button next to each exposure pathway, the dose rates for each radionuclide are presented in tabular or chart form. These tables of values can be copy and pasted into Excel for further analyses. The maximum total dose rate is also presented on the dashboard.

Figure 2.15 – Biosphere Results Dashboard



3.0 Verification

DOC-WMF is a model constructed using several modules as described in the previous sections. The verification of DOC-WMF was conducted by investigating three of these modules individually. The transport through the Far Field and Near Field Modules was compared against analytical solutions. For the Biosphere Component, the CSA presented tables of transfer parameters calculated using default parameter values. Within DOC-WMF the transfer parameters were calculated using the default values and compared against those presented in CSA N288.1-14. Also, CSA presented example dose calculations which were also used for comparison.

3.1 Far Field Verification

Within DOC-WMF, the Far Field is represented by a series of Pipe Pathways which represent a one-dimensional advection and dispersion equation considering solubility limits, decay, ingrowth and sorption. The Pipe Pathways within GoldSim are solved using a Laplace Transform approach. To verify the series of Pipe Pathways used in the Far Field, the model results were compared against well known analytical solutions for various scenarios.

3.1.1 Scenario 1

The first scenario that was considered was the one-dimensional transport equation that assumes no sorption, no decay, an initial condition of no contamination and a defined constant concentration (C_0) at the beginning of the system. The exact analytical solution to this problem, used for comparison to DOC-WMF is known as the Ogata-Banks equation (Ogata and Banks, 1961).

$$C(x,t) = \frac{C_0}{2}\left(erfc\left[\frac{x-v\cdot t}{2\cdot(D\cdot t)^{0.5}}\right] + exp\left(\frac{v\cdot x}{D}\right)\cdot erfc\left(\frac{x+v\cdot t}{2\cdot(D\cdot t)^{0.5}}\right)\right) \qquad \textbf{3.1}$$

Where

C(x,t) = Concentration at time t [yr] and location x [m]
v = Velocity [m/yr]
D = Hydrodynamic dispersion [m^2/yr]

The parameters for this first scenario are presented in Table 3.1 and the Ogata-Banks equation was used to solve for the concentration at select values x over time. The concentrations calculated from the analytical solution were used for comparison purposes to the DOC-WMF

model results in the Far Field. A good match between DOC-WMF and analytical solution results would indicate that the model is making the correct predictions.

To incorporate this scenario into DOC-WMF requires inputting the parameters from Table 3.1 into DOC-WMF. As this first scenario assumes no sorption, the "Disable Far Field Sorption" box was checked on the Far Field dashboard and the "Disable solubility limits" box was checked on the Near Field Settings dashboard to ignore solubility limits. The GoldSim software provides a setting in which the model can be run neglecting decay which was activated for this scenario. The remaining parameters were inputted into the model.

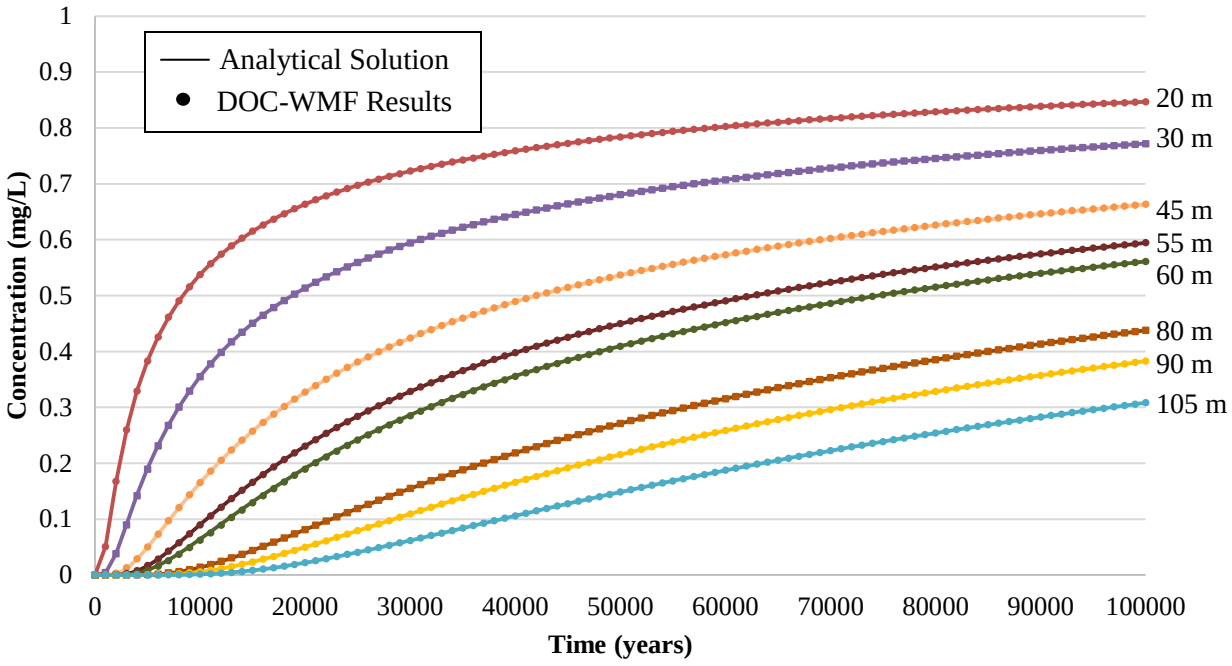
Hydrodynamic dispersion is included in GoldSim in two ways: through dispersivity; and diffusivity. To investigate both of these parameters, the hydrodynamic dispersion were each examined separately and compared against the analytical solution. Initially the hydrodynamic dispersion was assumed due to diffusion alone (see Table 3.1 for parameters) and dispersivity was set to 0.

Table 3.1 – Parameter values used in verification scenarios

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
C_0	1 mg/L	1 mg/L	1 mg/L	1 mg/L	1 mg/L
V	10^{-5} m/yr	10^{-5} m/yr	0.1 m/yr	0.1 m/yr	0.1 m/yr
Dispersivity	0	3000 m	3000 m	150 m	30 m
Flow rate	10^{-4} m^3/yr	10^{-4} m^3/yr	1 m^3/yr	1 m^3/yr	1 m^3/yr
A	100 m^2	100 m^2	100 m^2	100 m^2	100 m^2
Diffusion	5.24 x 10^{-2} m^2/yr	0	5.24 x 10^{-2} m^2/yr	15 m^2/yr	0
Porosity	0.1	0.1	0.1	0.1	0.1
K_d	0	0	0	5x10^{-5} m^3/kg	0
Decay rate	0	0	0	0	5700 years 2.3 x 10^6years

The results from the model (represented by markers) and the analytical solution (represented by lines) were compared at 8 different locations and are presented in Figure 3.1. By visual examination, the model results compare well to the analytical solution results.

Figure 3.1 – Model and analytical solution considering no sorption or decay (Scenario 1)



Another check is that a plot of the model values versus the analytical solution values should result in a one-to-one line with regressed slope of 1 and intercept equal to zero. The regressed slopes, intercepts and correlation factors are presented in Table 3.2. In all cases, the slope was equal to 1.0, the intercept was small and the correlation factor was equal to 1.0, showing good correlation between DOC-WMF and analytical solution.

T-tests were conducted on the regressed values of the slope and intercept for each leg. The null hypotheses were that the slope is not significantly different from 1 and the intercept is not significantly different from 0. To test these null hypotheses, t-values were calculated and compared against the critical values. If the calculated t-value was less than the critical t-value, then the null hypothesis could not be rejected, indicating good fit between model and analytical solution results. The t-values were calculated by the following equations.

$$t_{slope} = \frac{|m-m_0|}{s_m} = \frac{|m-1|}{s_m}; \quad t_{intercept} = \frac{|b-b_0|}{s_b} = \frac{|b-0|}{s_b} \qquad \textbf{3.2}$$

Where

s_m = Standard deviation of the regressed slope
m = Regressed value of the slope
b = Regressed value of the intercept
s_b = Standard deviation of the regressed intercept

The critical t-value for a significance level of 0.05 with 99 degrees of freedom is 1.984. The calculated t-values for the slope and intercept of all legs for the first scenario are presented in Table 3.2. In all cases, the calculated t-values are below the critical t-value indicating that the null hypotheses should not be rejected.

The concentrations calculated from the Ogata-Banks (1961) equation and the DOC-WMF model predictions compare well. This indicates that for this scenario, the DOC-WMF model is making good predictions.

Table 3.2 – Regressed line parameters and T-test results for Scenario 1

Leg	Slope	Intercept	R^2	Max Residual	T-test (slope)	T-test (intercept)
1	1.0	-2.3E-06	1.0	0.0000515	0.004	0.017
2	1.0	-0.00053	1.0	0.001163	0.57	0.69
3	1.0	0.000339	1.0	0.001559	0.088	0.58
4	1.0	-0.000086	1.0	0.000686	0.58	0.22
5	1.0	-0.00144	1.0	0.002001	0.92	1.36
6	1.0	0.000134	1.0	0.000411	0.17	0.81
7	1.0	0.000015	1.0	0.000229	0.38	0.11
8	1.0	0.0000931	1.0	0.000207	0.32	1.1

3.1.2 Scenario 2

The second scenario assumes no sorption or decay as in the first scenario and uses the Ogata-Banks again to generate the analytical solution results for comparison against the DOC-WMF results. The difference between this scenario and Scenario 1 is that the hydrodynamic dispersion is incorporated through dispersivity alone within DOC-WMF. The hydrodynamic dispersion used within the analytical solution is the product of this dispersivity and the velocity. The plot showing the model (markers) and analytical solution (lines) results is presented in Figure 7.2. Visually, the model results and analytical solution results compare well.

For each leg, the model results were compared against the analytical solution by regressing a line though the data. The values of the slope, intercept and correlation factor are presented in Table 3.3 and show that for all legs the slope is equal to 1 and the intercept is small, with correlation factors equal to 1. T-tests were conducted on the slope and intercept and in all cases the t-values were less than critical t-values. All results for this second scenario indicate good comparison between model and analytical solution results.

The concentrations calculated using the Ogata-Banks equation and those predicted by DOC-WMF using the dispersivity alone were found to compare well showing that the model is again making good predictions.

Figure 3.2 – Model and analytical solution considering no sorption or decay (Scenario 2)

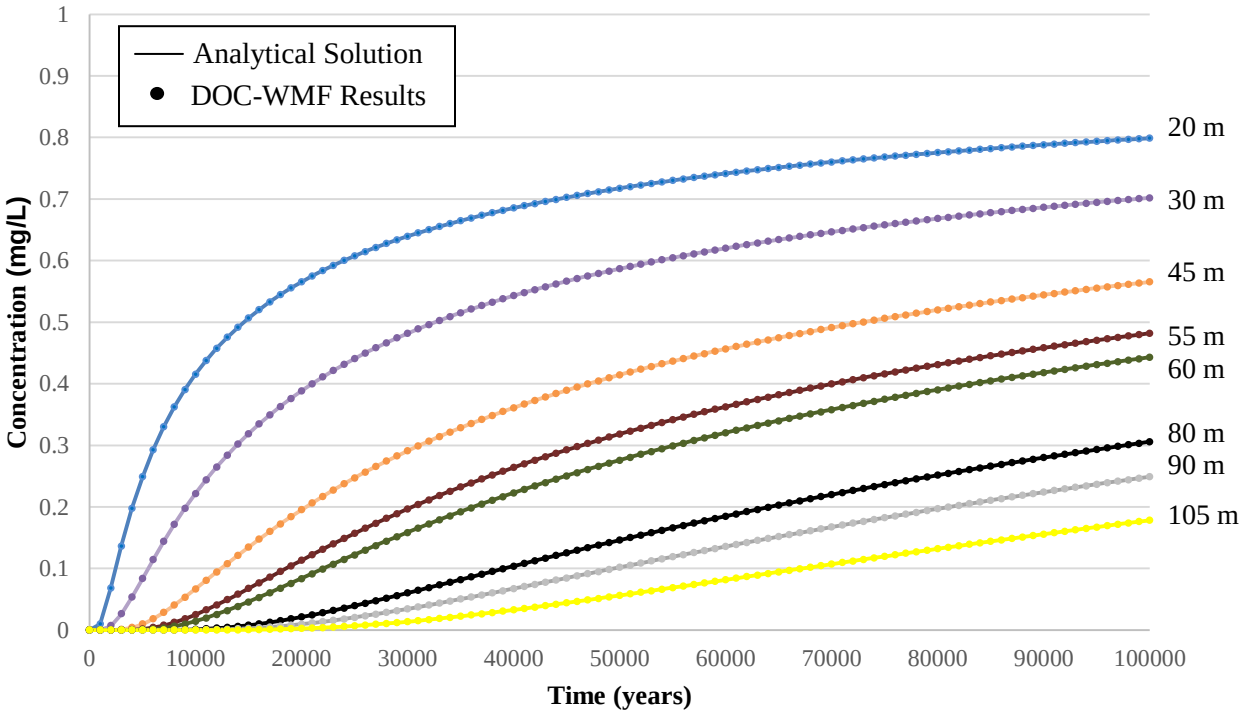


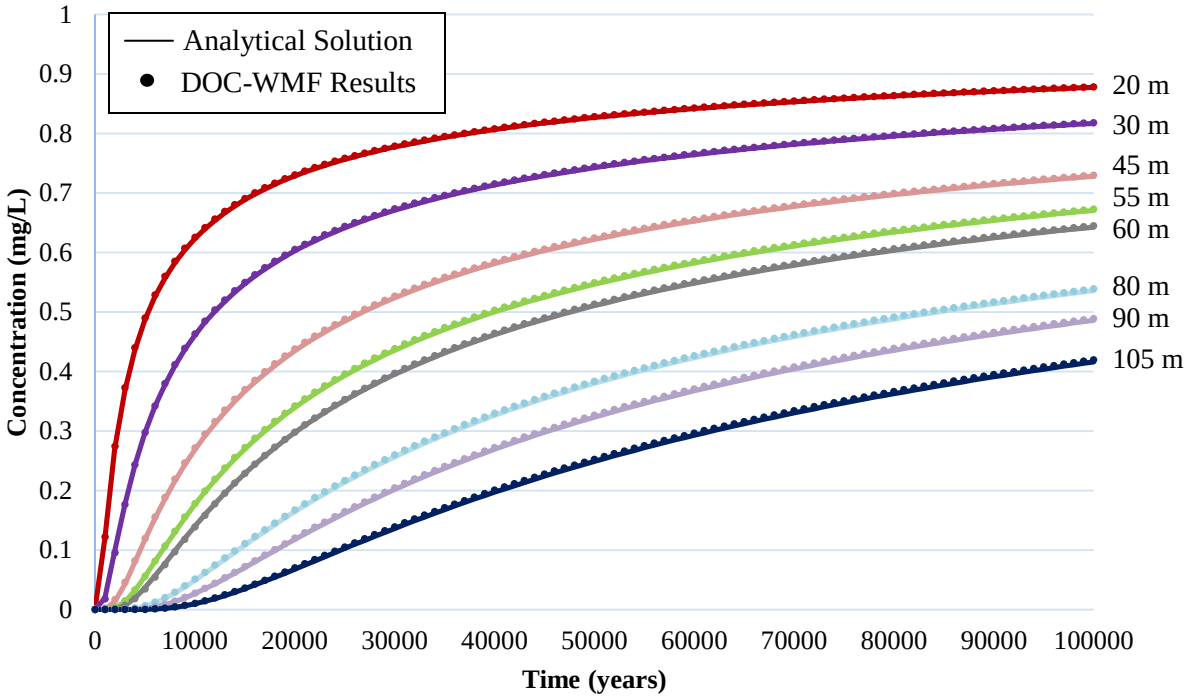
Table 3.3 – Regressed line parameters and T-test results for Scenario 2

Leg	Slope	Intercept	R^2	Max Residual	T-test (slope)	T-test (intercept)
1	1.0	-5.8×10^{-6}	1.0	5.0×10^{-5}	0.13	0.057
2	1.0	-2.3×10^{-4}	1.0	1.3×10^{-3}	0.49	0.52
3	1.0	1.4×10^{-4}	1.0	5.5×10^{-4}	0.60	0.64
4	1.0	-1.1×10^{-4}	1.0	3.4×10^{-4}	0.68	0.78
5	1.0	4.3×10^{-4}	1.0	6.9×10^{-4}	0.27	1.12
6	1.0	-4.7×10^{-5}	1.0	1.3×10^{-4}	0.66	0.73
7	1.0	-5.0×10^{-5}	1.0	1.0×10^{-4}	0.69	1.01
8	1.0	-3.7×10^{-5}	1.0	6.5×10^{-5}	0.65	1.05

3.1.3 Scenario 3

The third scenario still assumes no sorption or decay as in the first two scenarios and again uses the Ogata-Banks (1961) equation for comparison purposes. The difference between this scenario and the first two is how the hydrodynamic dispersion was incorporated into DOC-WMF. For this scenario the hydrodynamic dispersion was incorporated through both diffusivity and dispersivity. The parameters for this scenario are in Table 3.1 and the results are presented in Figure 3.3. By visual examination, the model results compare well with those from the analytical solution.

Figure 3.3 – Model and analytical solution considering no sorption or decay (Scenario 3)



As for Scenarios 1 and 2, linear regression was conducted on the model versus analytical results for all legs. The regressed values of slope, intercept and correlation factor are presented in Table 3.4. For all legs, the slope is equal to 1.0 with a very small intercept and a correlation factor equal to 1.0. T-tests were conducted on the slope and intercept and the results are shown in Table 3.4. The t-value for the intercept on the third leg is just above the critical value, however all other values are below the critical t-value. The overall results show that the model results compare well with the analytical solution for this scenario.

Table 3.4 – Regressed line parameters and T-test results for Scenario 3

Leg	Slope	Intercept	R^2	Max Residual	T-test (slope)	T-test (intercept)
1	1.0	0.0038	1.0	0.004	0.89	1.44
2	1.0	0.00037	1.0	0.003	0.46	0.13
3	1.0	0.0032	1.0	0.004	0.38	2.02
4	1.0	0.0017	1.0	0.003	0.64	1.18
5	1.0	-0.00079	1.0	0.003	1.7	0.49
6	1.0	0.0021	1.0	0.004	0.88	1.57
7	1.0	0.0013	1.0	0.004	1.6	1.25
8	1.0	0.0014	1.0	0.004	1.72	1.29

The concentrations calculated by the Ogata-Banks (1961) analytical solution were found to compare well to DOC-WMF predictions. This indicates that for this scenario, that DOC-WMF is making good predictions.

3.1.4 Scenario 4

The initial three scenarios all examined the advection and diffusion properties of the transport equation while neglecting sorption and decay. This fourth scenario incorporates sorption according to an adaptation of the Ogata-Banks (1961) equation, considering the same initial and boundary conditions. The sorption has the effect of decreasing the values of the velocity and dispersion. This equation assumes that the second term in equation 3.1 is negligible and therefore the parameters used in the scenario had to satisfy this criterion.

$$C(x,t) = \frac{C_0}{2} \cdot erfc\left[\frac{R_f \cdot x - v \cdot t}{2 \cdot \left(\alpha \cdot v \cdot t \cdot R_f\right)^{0.5}}\right] = \frac{C_0}{2} \cdot erfc\left[\frac{R_f \cdot x - v \cdot t}{2 \cdot \left(D \cdot t \cdot R_f\right)^{0.5}}\right] \qquad \textbf{3.3}$$

Where

$$R_f = 1 + \left(\frac{1-n}{n}\right)\rho \cdot K_d \qquad \textbf{3.4}$$

ρ = Density [kg/m$^{3]}$
K_d = Sorption parameter [m^3/kg]
α = Dispersivity [m]

Note that if R_f is equal to one, indicating no sorption, then the first term of the original Ogata-Banks equation (3.1) is recovered.

The parameters used for this fourth scenario are presented in Table 3.1. The model and analytical solution results were plotted against time and are presented in Figure 3.4. Visual examination shows slight variation between the results. The statistics for the regressed lines between model and analytical solution results are presented in Table 3.5. For all legs, the slope is equal to 1.0, the intercept is small and the correlation factor is equal to 1.0. The t-test results are also presented in Table 3.5 and for all legs the calculated t-values for slope and intercept are below the critical T-value.

It should be recalled that in the derivation of equation 3.4, the second term of the Ogata-Banks equation was neglected. By neglecting this term, the analytical solution may not be perfect but provides a reasonably close representation. This would explain the slight visual differences between the analytical solution and the DOC-WMF results. DOC-WMF uses a Laplace transform approach to obtain the exact analytical solution for the Pipe Pathway elements used in the Far Field. The DOC-WMF solution is more precise than equation 3.4. Nevertheless the difference is small but it is compared against equation 3.4 to make sure there are no big differences. In the comparison of DOC-WMF and the analytical solution some differences are observed, but the breakout curves occur at approximately the same time and level to the same concentration. The statistical analyses comparing the two results also indicated a satisfactory fit between the analytical solution and DOC-WMF, indicating that DOC-WMF is functioning well.

Figure 3.4 – Model and analytical solution considering no sorption or decay (Scenario 4)

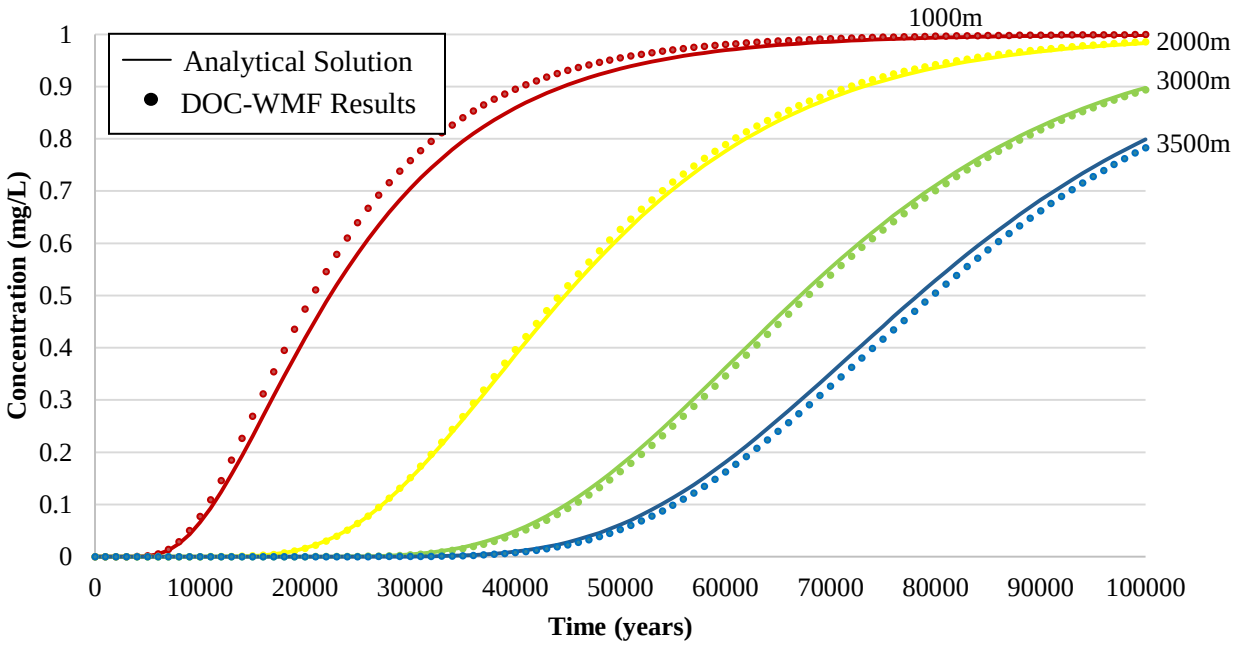


Table 3.5 – Regressed line parameters and T-test results for Scenario 4

Leg	Slope	Intercept	R^2	Max Residual	T-test (slope)	T-test (intercept)
1	1.0	-2.6×10^{-2}	1.0	0.059	0.15	0.54
2	0.99	-1.9×10^{-3}	1.0	0.014	0.65	0.27
3	1.0	4.1×10^{-3}	1.0	0.015	0.58	0.62
4	1.0	4.3×10^{-3}	1.0	0.025	1.32	0.55

3.1.5 Scenario 5

The final scenario (Scenario 5) to be examined within the Far Field component accounted for decay but not sorption. The following analytical equation, that has the same boundary and initial conditions as the Ogata-Banks (1961) equation, was used for comparison purposes (Bear, 1979).

$$C(x,t) = \frac{C_0}{2} \cdot exp\left\{\left(\frac{x}{2 \cdot \alpha}\right) \cdot \left[1 - \left(1 + \frac{4 \cdot \lambda_r \cdot \alpha}{v}\right)^{0.5}\right]\right\} \cdot erfc\left[\frac{x - v \cdot t \cdot \left(1 + {}^{4 \cdot \lambda_r \cdot \alpha}/_{v}\right)^{0.5}}{2 \cdot (\alpha \cdot v \cdot t)^{0.5}}\right] \quad \textbf{3.5}$$

This equation is adapted from Equation 3.1 assuming that the second term in Equation 3.1 is negligible. As the second term of the Ogata Banks equation is neglected in the derivation of equation 3.5, some differences may be present between DOC-WMF and this equation as was found in the sorption scenario.

The model was run for two decay rates: 5700 years; and 2,300,000 years and using parameters provided in Table 3.1. The model results along with analytical solution are presented in Figures 3.5. In all cases, the model solution is slightly greater than the analytical solution. This difference is thought to be due to the assumption in development of Equation 3.5 that assumes that the second term in Equation 3.1 is negligible. The statistics comparing the model and analytical solution results are presented in Table 3.6. In all cases, the slope is greater than 0.96 and the intercept is less than 0.06 with a correlation factor equal to 0.99. The t-test results also indicate that the null hypotheses should not be rejected indicating good comparison.

The analytical solution results differ slightly from DOC-WMF due to the derivation of the analytical solution. The breakout time and maximum concentration are the same between DOC-WMF and the analytical solution. The statistical analysis comparing the DOC-WMF model to the analytical solution showed a good comparison.

Figure 3.5 – Model and analytical solution considering decay (Scenario 5)

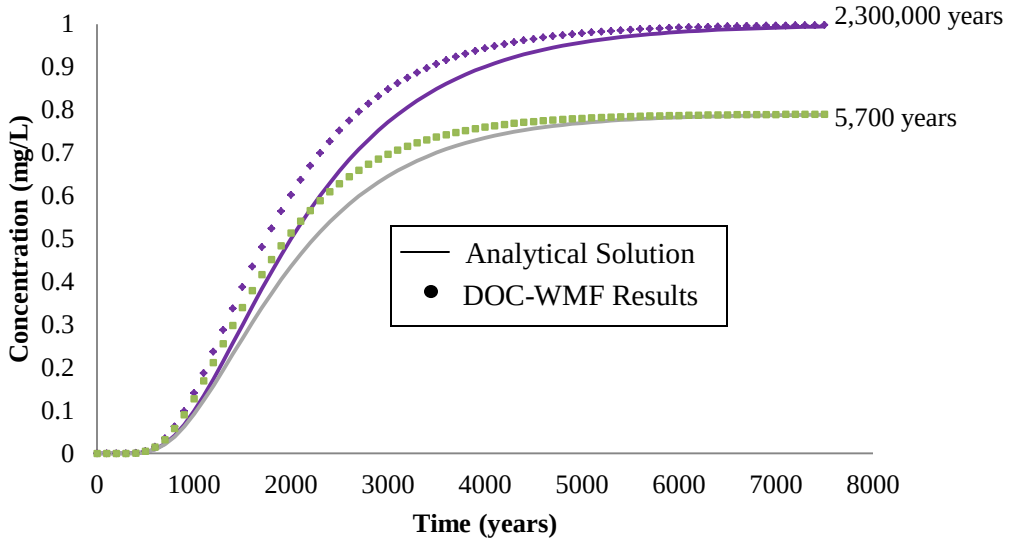


Table 3.6 – Regressed line parameters and T-test results for Scenario 5

Half life (years)	Slope	Intercept	R^2	Max Residual	T-test (slope)	T-test (intercept)
5,700	0.962	0.058	0.990	0.10	0.42	0.69
2,300,000	0.961	0.057	0.990	0.10	0.40	0.70

The Far Field was verified through examination of five scenarios. In all cases, the model and analytical solution results usually compare well. Regressed lines between model and analytical results had slopes of approximately 1 and small intercept values, with high correlation. The t-tests indicated that the null hypotheses that the slope is equal to 1.0 and intercept equal to 0.0 could not be rejected.

3.2 Buffer zone

Within DOC-WMF, the Near Field component consists of three zones. The first zone is the release from the interior of the waste package to the waste package surface and is represented by a Source element to a specialized Cell Pathway. The transport through the buffer is represented by a series of Cell Pathways in the second zone. The third zone represents a transition zone from the buffer material to the closest fracture in the Far Field.

The second zone, the transport through the buffer material, will be examined for verification purposes. This second zone is represented by a series of Cell Pathways which is a finite

difference approximation of the one-dimensional advection, dispersion and diffusion equation with solubility limits, sorption, decay and ingrowth.

Within the model, the buffer material can be represented as fully intact or degrading. For the fully intact case, it was assumed that there are no advective fluxes and the buffer is essentially treated as a diffusive barrier. The analytical solution for this scenario is the Ogata-Banks (1961) equation neglecting the advective components. The analytical solution assumes a constant concentration boundary at the beginning of the system and that the system has infinite length.

$$C(x,t) = \frac{C_0}{2}\left(erfc\left[\frac{x}{2\cdot(D\cdot t)^{0.5}}\right]\right) \qquad \textbf{3.6}$$

The intact buffer scenario (Scenario 6) was established in DOC-WMF. As the analytical solution assumes semi-infinite length, some adjustments had to be made to the model. More Cell Pathways were added in series until the model results at the verification point were no longer impacted by the number of cells in the pathway. The flow rate was set to zero, thereby neglecting advective fluxes and all other parameters were set to those in Table 3.7.

Table 3.7 – Parameter values used in buffer zone verification scenarios

Parameter	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
Buffer status	Intact	Intact	Degraded	Intact	Degraded
C_0	1 mg/L	1 mg/L	1 mg/L	1 mg/L	1mg/L
v	0	0	1×10^{-5} m/yr	0	1×10^{-5} m/yr
Flow rate	0 m^3/yr	0 m^3/yr	1×10^{-4} m^3/yr	0	1×10^{-4} m^3/yr
D	1.1×10^{-1} m^2/yr	1.1×10^{-1} m^2/yr	1.1×10^{-1} m^2/yr	1.1×10^{-1} m^2/yr	1.1×10^{-1} m^2/yr
Porosity	0.1	0.1	0.1	0.1	0.1
Cell width	1 m	2 m	1 m	1 m	1 m
K_d	0	0	0	5×10^{-5} kg/m^3	5×10^{-5} kg/m^3

The model results (yellow) and analytical solution results (blue) are presented on Figure 3.6 and visually the results compare well. A linear regression was conducted on the model results versus analytical solution values and obtained the statistics presented in Table 3.8. The slope was equal to 1.0, with a small intercept and a correlation factor equal to 1.0. T-tests were also conducted on the slope and intercept indicating good comparison (see Table 3.8). Overall, the comparison shows a good fit between model solution and analytical solution results.

Figure 3.6 – Model and analytical solution results for intact buffer, Cell width = 1 m (Scenario 6)

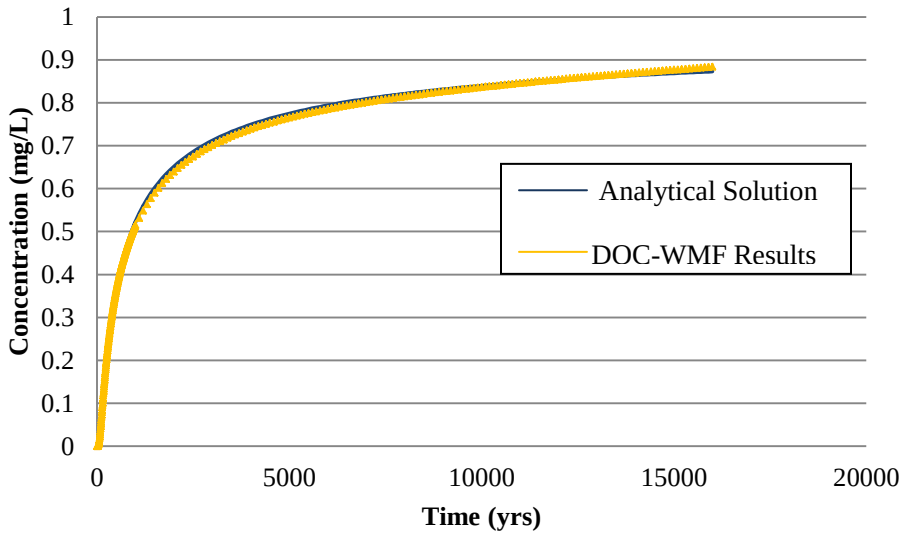


Table 3.8 – Regressed line parameters and T-test results for Buffer

Scenario	Slope	Intercept	R^2	Max Residual	T-test (slope)	T-test (intercept)
6	1.0	-0.001	1.0	0.012	0.19	0.13
7	0.98	0.011	1.0	0.011	1.8	1.5
8	1.0	-0.008	1.0	0.013	0.059	1.0
9	1.0	-0.005	1.0	0.01	0.95	0.92
10	1.0	-0.005	1.0	0.01	1.00	0.92

The next scenario (Scenario 7) had the same properties as that of Scenario 6, except that the length of the Cell Pathway was altered (see Table 3.7). The results of Scenario 7 are presented in Figure 3.7 with statistics in Table 3.8. Similar to Scenario 6, the results from Scenario 7 show a good relationship between model and analytical solution results.

The buffer material can also be modeled in a fashion that it degrades over time. A buffer degradation model calculates the percent of buffer that has degraded at a specific time step. The flow rate through the buffer for advective transport is calculated as the product of the percent degraded and the flow rate within the first leg of the Far Field. To examine the degraded buffer scenario, the Ogata Banks (1961) equation (3.1) was used with the properties presented in Table 3.7 (Scenario 8). The model and analytical solution results are presented in Figure 3.8 and

visually compare well. The statistics for the linear regression and t-tests are presented in Table 3.8. All of the calculated values indicate that the model and analytical solution compare well.

Figure 3.7 – Model and analytical solution results for fully intact buffer, Cell width = 2 m (Scenario 7)

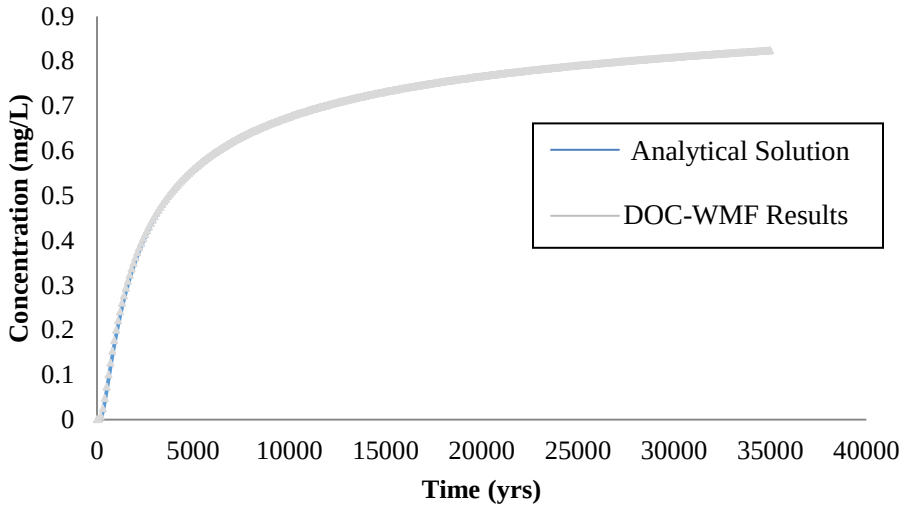
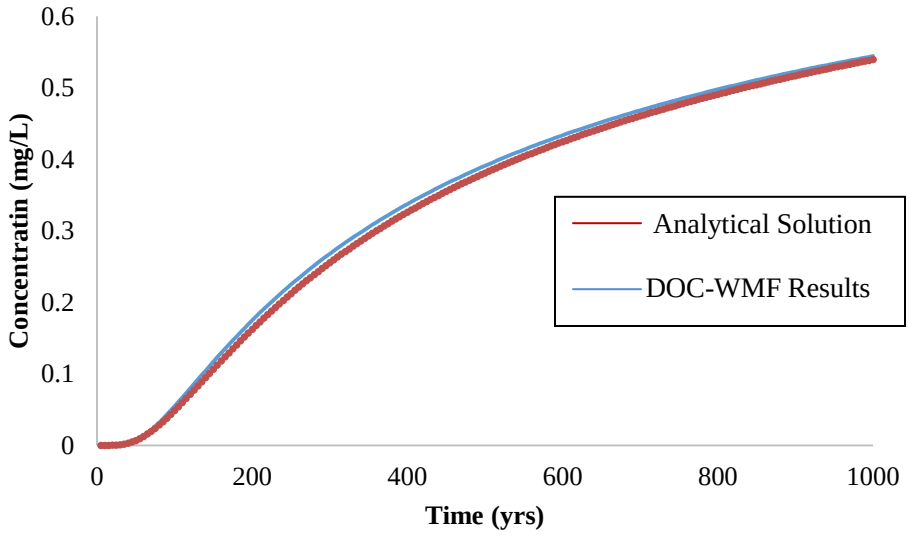


Figure 3.8 – Model and analytical solution results for degraded buffer (Scenario 8)



The final two scenarios that evaluate the buffer incorporate sorption. Scenario 9 investigates sorption in a fully intact buffer, while Scenario 10 incorporates sorption into a degrading buffer (Table 3.7).

The results with the intact buffer, Scenario 9, are presented in Figure 3.9 and those from the degradation buffer, Scenario 10 in Figure 3.10. Both scenarios compare well by visual examination. The statistics for both these scenarios are presented in Table 3.8. The regressed line parameters and the t-values indicate a good relationship between model and analytical solution results for both Scenarios.

Figure 3.9 – Intact buffer with sorption (Scenario 9)

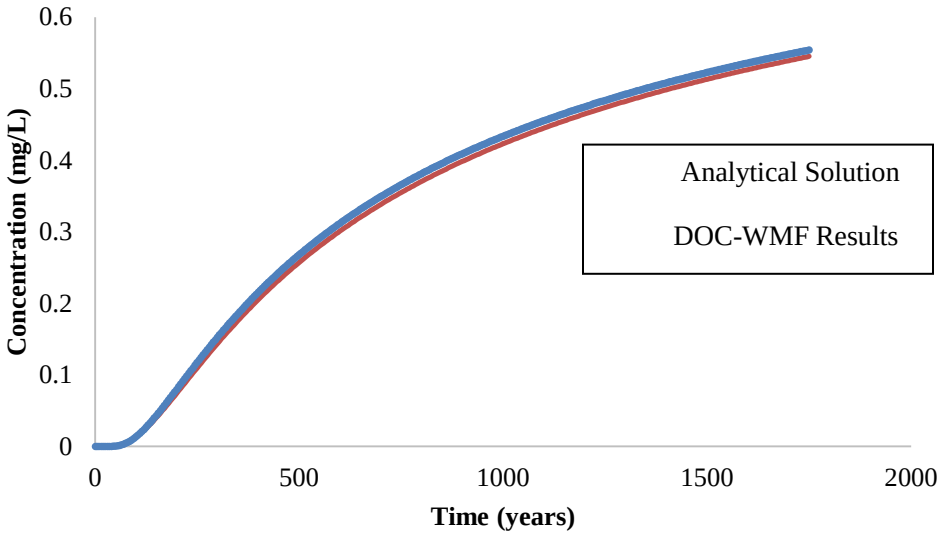
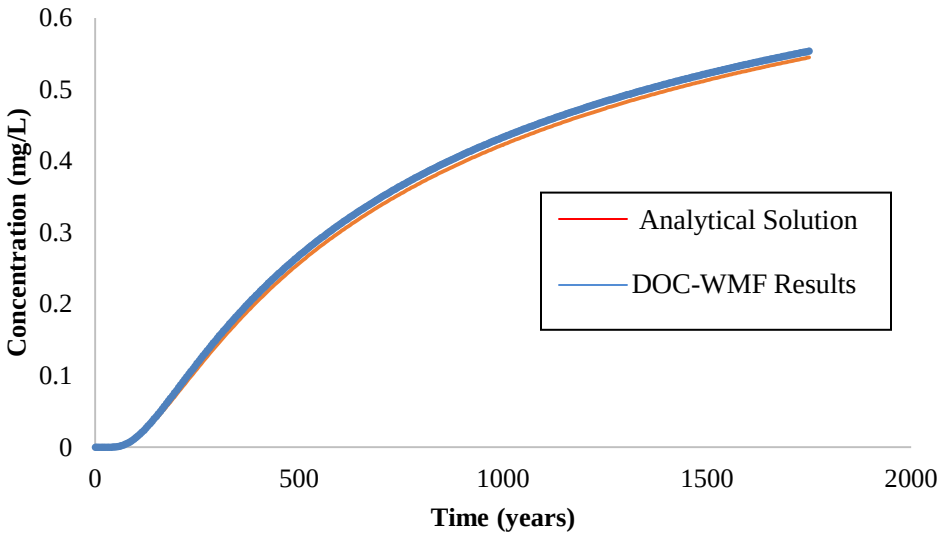


Figure 3.10 – Degraded buffer with sorption (Scenario 10)



The buffer was verified for various scenarios by visual examination, regression of model and analytical results and T-tests. In all cases, the model results were found to compare well with the analytical solution results.

3.3 Biosphere Component verification

The Biosphere Component within SOAR considers ingestion of drinking water as the only exposure pathway to calculate the dose rate. The Biosphere Component within DOC-WMF was adapted to incorporate many more exposure pathways in determining the total dose to a representative receptor according to methods and equations presented in CSA N288.1-14 (2014). The Biosphere Component received the release to well and surface water. Based on these releases, the numerous transfer equations presented in Section 2.5.1 were coded into DOC-WMF and used to calculate the transfer between the various compartments: soil, air, plant produce, animal produce, aquatic animals, aquatic plants, sediments and receptor.

The equations to calculate these transfer parameters are a function of numerous variables. Within the CSA N288.1-14 (2014), default values for each of these variables were provided. Also the CSA N288.1-14 (2014) contains tables with all of the transfer parameters calculated using these default values. To check that each transfer parameter equation was coded correctly within DOC-WMF, the default values provided by CSA N288.1-14 (2014) for each parameter were implemented in the model. Then the transfer parameters calculated by DOC-WMF with these default values were compared to those within the tables in CSA N288.1-14 (2014) and were found to be equal. Thereby, verifying that each transfer parameter equation was coded correctly in DOC-WMF.

As the transfer parameter calculations were verified, it was required to ensure that the dose calculations using these transfer parameters were also correct. Two sample dose calculations were presented within CSA N288.1-14 (2014) and were used to verify that the dose calculations using the already verified transfer parameters were coded correctly in DOC-WMF.

These sample scenarios consist of a release assumed to occur from a shoreline to a large lake. The receptor within this example is assumed to live at a distance of 3 km downstream from the release. The lake water is used for irrigation, bathing, swimming and drinking and the receptor consumes locally caught fish and locally grown fruits and vegetables. The parameters presented in Table 3.9 were used in the example for calculating the dilution factor and P_{02}, to a position 3,000 m downstream.

Table 3.9 – Example dispersion parameters

Parameter	Definition	Value
B	Annual average effluent recirculation factor	2
K	Proportionality coefficient used to derive the lateral dispersion coefficient	3.0×10^{-8}
D_0	Initial dilution at the point of discharge	1
D	Average water depth between the release point and the receptor	10 m

U_c	Annual average current speed in the direction towards the nearest representative person	0.09 m/s
Q_v	Annual average volumetric discharge rate of liquid effluent	10^5 L/s
A	Annual average fraction of time that the current direction is towards the nearest representative person	0.4

The first example assumes a release of C-14 and the pathways considered within this example are presented in Table 3.10. To calculate the dose per unit release, the sum of these transfer parameters presented in Table 3.10 were multiplied by P_{02}. $C_{0(w)}$ is the source release to the aquatic environment and P_{02} is the transfer from the source to the concentration within the lake considering dilution.

$$\frac{C_9}{C_{0(w)}} = P_{02} \cdot (sum\ of\ transfer\ paramters)$$

Table 3.10 – Pathways considered in C-14 example

Pathway Number	**Description**	**Transfer parameters [Sv/yr per Bq/L]**
1	Water immersion dose	$P(e)_{29}$
2	Water ingestion dose	$P(i)_{29}$
3	Groundshine dose following transfer from irrigation water to soil	$P_{23mass} \cdot P(e)_{3area9}$
4	Soil ingestion dose following transfer from irrigation water to soil	$P_{23mass} \cdot P(i)_{3mass9}$
5	Dose from ingesting fruit and vegetables following transfer from irrigation water to plants	P_{24} (fruits and vegetables)$\cdot P_{49}$ (fruits and vegetables)
6	Inhalation dose following transfer from irrigation water to soil to air	$P_{23mass} \cdot P_{3mass1} \cdot P(i)_{19}$
7	Immersion dose following transfer from irrigation water to soil to air	$P_{23mass} \cdot P_{3mass1} \cdot P(e)_{19}$
8	Dose from ingesting fish following transfer from water to fish	P_{26}(fish)$\cdot P_{69}$
9	External dose from exposure to contaminated sand following transfer from water to beach	$P_{28} \cdot P(e)_{89}$
10	Dose from ingesting sand following transfer from water to beach	$P_{28} \cdot P(i)_{89}$

The transfer parameter values required to calculate dose as presented by CSA N288.1-14 (2014) and those calculated within the DOC-WMF model are presented in Table 3.11.

The value of P_{02} was calculated from Equations 3.4 and 3.5 using parameters given in Table 3.9. It was found that the model, DOC-WMF, was different than that presented by the CSA N288.1-14 (2014) example. To determine the source of the problem, the calculation of P_{02} was done by hand using the same parameter values and was still found to differ with that from CSA N288.1-14 (2014) but did agree with that from the model. Examination of the parameter values and equations lead to the discovery that an error was made in the CSA N288.1-14 (2014) report by using a value of beta equal to 1 in the calculation of D_f and then using a value of beta equal to 2 in the determination of P_{02}. This adjustment was made within the model for this example only so that the remaining values could be compared. The other transfer parameters compare well between the model and those in CSA N288.1-14 (2014).

Table 3.11 – Transfer parameters used in example for C-14 release

Transfer parameter	Value within CSA Group	Value from DOC-WMF
P_{02}	4.65×10^{-6} s/L	4.49×10^{-6} s/L
$P(e)_{29}$	4.73×10^{-12} Sv/yr per Bq/L	4.73×10^{-12} Sv/yr per Bq/L
$P(i)_{29}$	6.26×10^{-7} Sv/yr per Bq/L	6.26×10^{-7} Sv/yr per Bq/L
P_{23area}	25.5 L/m^2	25.42 L/m^2
P_{23mass}	9.8×10^{-2} L/kg	9.776×10^{-2} L/kg
$P(e)_{3area9}$	5.61×10^{-14} Sv/yr per Bq/m^2	5.61×10^{-14} Sv/yr per Bq/m^2
$P(i)_{3mass9}$	1.57×10^{-12} Sv/yr per Bq/kg	1.566×10^{-12} Sv/yr per Bq/kg
P_{24} (fruit and vegetables)	69.4 L/kg	69.37 L/kg
P_{49} (fruit and vegetables)	$5.8 \times 10^{-8} \cdot 0.80$ Sv/yr per Bq/kg	$5.8 \times 10^{-8} \cdot 0.80$ Sv/yr per Bq/kg
P_{3mass1}	2.7×10^{-3} kg/m^3	2.667×10^{-3} kg/m^3
$P(i)_{19}$	1.01×10^{-7} Sv/yr per Bq/m^3	1.08×10^{-7} Sv/yr per Bq/m^3
$P(e)_{19}$	8.21×10^{-11} Sv/yr per Bq/m^3	8.21×10^{-11} Sv/yr per Bq/m^3
P_{26} (fish)	5.7×10^{3} L/kg	5.716×10^{3} L/kg
P_{69}	5.95×10^{-9} Sv/yr per Bq/kg	5.951×10^{-9} Sv/yr per Bq/kg
P_{28}	5.00×10^{1} L/kg	5.00×10^{1} L/kg
$P(e)_{89}$	5.56×10^{-14} Sv/yr per Bq/kg	5.56×10^{-14} Sv/yr per Bq/kg
$P(i)_{89}$	5.22×10^{-13} Sv/yr per Bq/kg	5.22×10^{-13} Sv/yr per Bq/kg

The dose per unit release for the various pathways were obtained from the model and compared against those presented by CSA N288.1-14 (2014) (Table 3.12). The results were found to compare well indicating that the Biosphere Component is calculating the doses correctly

A second example is presented in the CSA N288.1-14 (2014) for a release of I-131 and the same dispersion scenario as used for C-14 (Table 3.9). I-131 is a radionuclide that is not included in the list within DOC-WMF. As previously discussed in Section 2.1, new radionuclides can be incorporated through one of the inactive dummy radionuclides that have been coded into the model. The procedure for activating the dummy radionuclide by inputting the appropriate parameters is presented in Appendix A and in the User's manual. The parameter values for I-131, such as half life and dose coefficients and all others, were inputted for the first dummy radionuclide thereby including it in the model. Adding I-131 through this method had the added benefit of testing the method for adding other radionuclides as well as provided for further verification of the biosphere component.

Table 3.12 – Comparison of relative doses as presented by CSA N288.1-14 (2014) and predicted by DOC-WMF for C-14

Pathway Number	Dose [Sv/yr per Bq/s]	
	CSA N288.1-14 (2014)	DOC-WMF
1	2.20×10^{-17}	2.12×10^{-17}
2	2.91×10^{-12}	2.81×10^{-12}
3	6.65×10^{-18}	6.41×10^{-18}
4	7.15×10^{-19}	6.88×10^{-19}
5	1.50×10^{-11}	1.45×10^{-11}
6	1.24×10^{-16}	1.18×10^{-16}
7	1.01×10^{-19}	9.6×10^{-20}
8	1.58×10^{-10}	1.53×10^{-10}
9	1.29×10^{-17}	1.25×10^{-17}
10	1.21×10^{-16}	1.17×10^{-16}

The pathways considered in the example of I-131 release are presented in Table 3.13. One extra pathway is considered in this example as compared to that for the release of C-14. The values of each required transfer parameter presented by CSA N288.1-14 (2014) and those calculated by DOC-WMF are presented in Table 3.14. All values compare well except for $P(e)_{3area9}$ which was investigated further and it was discovered that the value presented by CSA N288.1-14 (2014) erroneously used the groundshine dose coefficient for I-129. Therefore, the model is calculating the correct value of $P(e)_{3area9}$ and was verified through hand calculation.

The resulting dose values presented by CSA N288.1-14 (2014) and DOC-WMF are presented in Table 3.15. Overall these values compare well except for pathway 3, which used the erroneous $P(e)_{3area9}$ value as previously discussed.

The Biosphere Component was verified successfully by ensuring that the transfer parameters and dose calculations were coded correctly. Also the method for adding in radionuclides not included within the model was found to function properly, also verifying this procedure.

Table 3.13 – Pathways considered in example for I-131

Pathway Number	Description	Transfer parameters [Sv/yr per Bq/L]
1	Water immersion dose	$P(e)_{29}$
2	Water ingestion dose	$P(i)_{29}$
3	Groundshine dose following transfer from irrigation water to soil	$P_{23mass} \cdot P(e)_{3area9}$
4	Soil ingestion dose following transfer from irrigation water to soil	$P_{23mass} \cdot P(i)_{3mass9}$
5	Dose from ingesting fruit and vegetables following transfer from irrigation water to plants	P_{24} (fruits and vegetables)$\cdot P_{49}$ (fruits and vegetables)
6	Dose from ingesting fruit and vegetables following transfer from irrigation water to soil to plants	$P_{23mass} \cdot P_{3mass4}$(fruit and vegetables)$\cdot P_{49}$(fruit and vegetables)
7	Inhalation dose following transfer from irrigation water to soil to air	$P_{23mass} \cdot P_{3mass1} \cdot P(i)_{19}$
8	Immersion dose following transfer from irrigation water to soil to air	$P_{23mass} \cdot P_{3mass1} \cdot P(e)_{19}$
9	Dose from ingesting fish following transfer from water to fish	P_{26}(fish)$\cdot P_{69}$
10	External dose from exposure to contaminated sand following transfer from water to beach	$P_{28} \cdot P(e)_{89}$
11	Dose from ingesting sand following transfer from water to beach	$P_{28} \cdot P(i)_{89}$

Table 3.14 – Transfer parameters used in example for I-131 release

Transfer parameter	Value within CSA Group	Value from DOC-WMF
P_{02}	4.65×10^{-6} s/L	4.49×10^{-6} s/L
$P(e)_{29}$	6.03×10^{-8} Sv/yr per Bq/L	6.01×10^{-8} Sv/yr per Bq/L
$P(i)_{29}$	2.38×10^{-5} Sv/yr per Bq/L	2.376×10^{-5} Sv/yr per Bq/L
P_{23area}	11.0 L/m^2	10.96 L/m^2
P_{23mass}	4.22×10^{-2} L/kg	4.216×10^{-2} L/kg
$P(e)_{3area9}$[1]	1.54×10^{-10} Sv/yr per Bq/m^2	2.898×10^{-9} Sv/yr per Bq/m^2
$P(i)_{3mass9}$	5.94×10^{-11} Sv/yr per Bq/kg	5.94×10^{-11} Sv/yr per Bq/kg
P_{24} (fruit and vegetables)	0.615 L/kg	0.614 L/kg
P_{3mass4} (fruit and vegetables)	5.00×10^{-3}	5.00×10^{-3}
P_{49} (fruit and vegetables)	$2.2 \times 10^{-6} \cdot 0.80$ Sv/yr per Bq/kg	$2.2 \times 10^{-6} \cdot 0.80$ Sv/yr per Bq/kg
P_{3mass1}	4.20×10^{-6} kg/m^3	4.118×10^{-6} kg/m^3
$P(i)_{19}$	1.68×10^{-4} Sv/yr per Bq/m^3	1.68×10^{-4} Sv/yr per Bq/m^3
$P(e)_{19}$	3.20×10^{-7} Sv/yr per Bq/m^3	3.198×10^{-7} Sv/yr per Bq/m^3
P_{26} (fish)	6.00 L/kg	6.00 L/kg
P_{69}	2.26×10^{-7} Sv/yr per Bq/kg	2.257×10^{-7} Sv/yr per Bq/kg
P_{28}	4.40×10^{3} L/kg	4.40×10^{3} L/kg
$P(e)_{89}$	1.99×10^{-9} Sv/yr per Bq/kg	1.986×10^{-9} Sv/yr per Bq/kg
$P(i)_{89}$	1.98×10^{-11} Sv/yr per Bq/kg	1.98×10^{-11} Sv/yr per Bq/kg

1. The value of $P(e)_{3mass9}$ reported by CSA N288.1-14 (2014) is erroneously for I-129

Table 3.15 – Comparison of relative doses as presented by CSA N288.1-14 (2014) and that predicted by DOC-WMF for I-131

Pathway Number	Dose [Sv/yr per Bq/s]	
	CSA N288.1-14 (2014)	DOC-WMF
1	2.80×10^{-13}	2.70×10^{-13}
2	1.11×10^{-10}	1.07×10^{-10}
3[1]	7.78×10^{-15}	1.43×10^{-13}
4	1.17×10^{-17}	1.13×10^{-17}
5	5.03×10^{-12}	5.03×10^{-12}
6	1.73×10^{-15}	1.67×10^{-15}
7	1.39×10^{-16}	1.31×10^{-16}
8	2.64×10^{-19}	2.49×10^{-19}
9	6.31×10^{-12}	6.08×10^{-12}
10	4.07×10^{-11}	3.93×10^{-11}
11	4.03×10^{-13}	3.91×10^{-13}

1. The dose for Pathway 3 reported by CSA N288.1-14 (2014) is due to error in calculation of transfer parameter

4.0 Test Cases

The finalized DOC-WMF was applied to two Test Cases, using the reported scenarios and parameters, and then comparing the model results. The Nuclear Waste Management Organization (NWMO)'s 5th Case Study was modeled using SOAR as part of a previous contract. The purpose for this contract was to re-model the 5th Case Study using DOC-WMF with the additional radionuclides and exposure pathways. This test case was conducted at a high-level as this was not the focus of this contract.

The Canadian Nuclear Laboratories (CNL) submitted an Environmental Impact Statement (EIS) for a Near Surface Disposal Facility Project (NSDF) for disposal of low- to mid-level radioactive waste at the Chalk River Laboratory (CRL) Site (CNL, 2017a and b). The parameters for the normal evolution scenario presented within the reports and through e-mail communication were used to model with DOC-WMF. Results were compared against those from the CNL reports.

The subsequent sections present the scenarios and required parameters as well as comparison of model results between DOC-WMF and those presented within the report.

4.1 Nuclear Waste Management Organization (NWMO)'s 5th Case Study

In a previous contract, the SOAR model was used to evaluate the Nuclear Waste Management Organization (NWMO)'s 5th Case Study of a hypothetical deep geological repository (DGR) of high-level nuclear waste in sedimentary rock (Osborne, 2015; NWMO, 2013 a and b). The NWMO in their assessment of the DGR conducted one-dimensional transport modeling and dose calculation using SYVAC3-CC4. The objective of the previous contract was to use the SOAR model with the parameters and scenario presented by the NWMO to independently model the 5th Case Study. The results from both models, SOAR and SYVAC3-CC4, were then compared to ascertain the suitability of using these models in the safety assessment. Overall, it was found that the SOAR model results compared well to the SYVAC3-CC4 results for the NWMO's 5th Case Study.

Through this exercise, it was found that the SOAR model had several restrictions. The main limitations of SOAR were that it only accounted for a total of 16 radionuclides and one exposure pathway to calculate the dose. Whereas the NWMO's modeling exercise using SYVAC3-CC4 considered 37 radionuclides and many exposure pathways, such as food ingestion and air inhalation. As previously discussed, DOC-WMF was created to overcome these limitations by accounting for an increased list of radionuclides including all those considered in the NWMO's 5th Case Study. Also, the Biosphere Component was expanded to account for many more exposure pathways.

DOC-WMF was used to re-model the NWMO's 5th Case study for the Reference Case. The full scenario including parameters can be found in the final report of the previous contract (Osborne, 2015) as well as NWMO (2013a and b). A summary of this case study is as follows:

- Hypothetical case study
- Deep disposal of high-level nuclear waste in a repository
- 500 m depth in limestone assumed free of fractures
- 3 waste packages placed in repository with undetected defects of 1 mm
- It would take 10,000 years for enough water to be present for transport out of the repository
- Provided with solubility limits, instant release fractions, hydraulic conductivity, porosity, free-water diffusivity and other required parameters (NWMO, 2013b)
- Provided with ingestion/inhalation rates (NWMO, 2013b) (Table 4.1)
- The overburden soil type denoted by NWMO (2013b) was clay

Table 4.1 – Receptor intake rates used for NWMO's 5th case study

Domestics water demand per person	110 m^3/yr
Air inhalation rate	8400 m^3/yr
Water ingestion rate	840 L/yr
Meat ingestion rate	103 g/d
Milk ingestion rate	283 g/d
Plant ingestion rate	796 g/d
Poultry ingestion rate	53 g/d
Fish ingestion rate	7.9 g/d
Soil ingestion rate	0.12 kg/yr

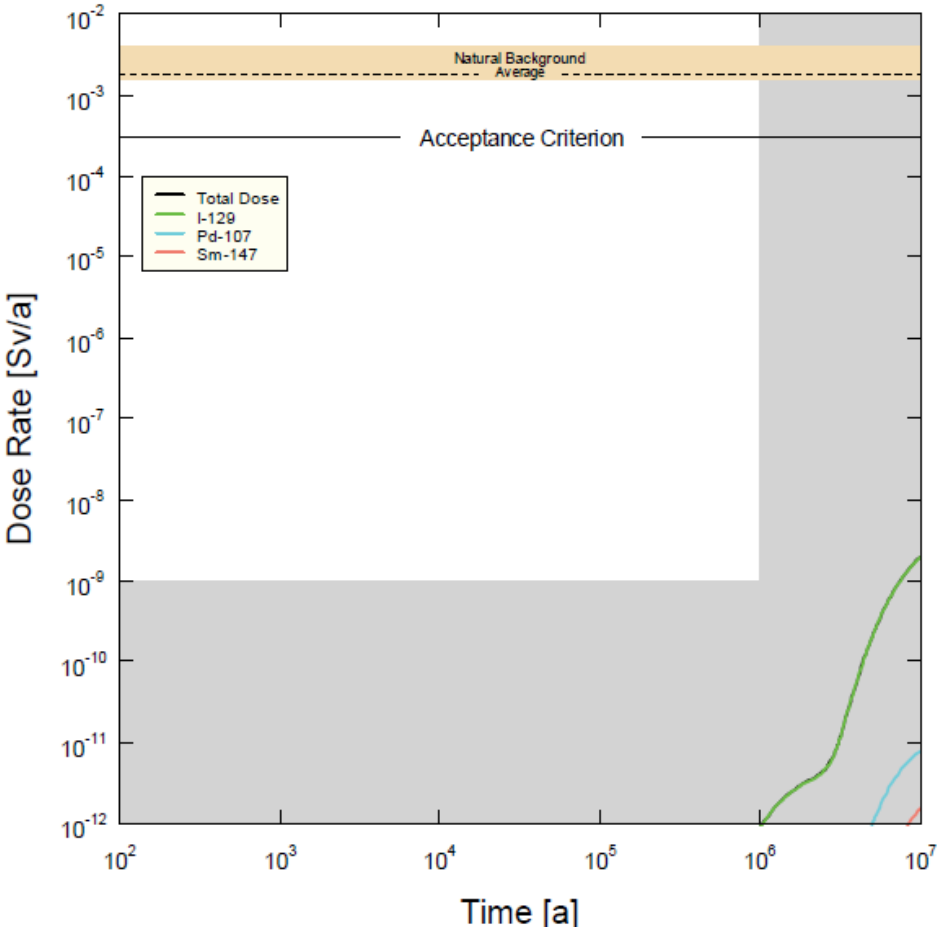
The modeling exercise using DOC-WMF was only conducted for the Reference Case presented by the NWMO, 2013a using deterministic values. There were a few differences between the DOC-WMF model run and that using SYVAC3-CC4 in NWMO (2013a). The first is that the NWMO used reference values for a large number of the parameters for the deterministic run. However for DOC-WMF these reference values were not used as the model and parameter database had been constructed using the underlying PDFs. Therefore, the mean of the associated PDF was used in the calculations. In a lot of cases the parameter values would have differed slightly but could still be used for general comparison. The reason for this difference was that the PDF of each the NWMO (2013b) parameters were used to create the parameter database for DOC-WMF not the reference values.

The other difference is that other than the ingestion/inhalation rates presented by the NWMO (2013b), the remaining parameters for the biosphere were maintained as the default values presented by CSA N288.1-14 (2014).

This comparison was only conducted at a high level, as it was not the main focus of this report, and the results were compared to ensure of the same order of magnitude. However, when comparing the results these differences should be recalled. Releases from other areas such as from the waste package, the Near Field and Far Field are presented in Osborne, 2015.

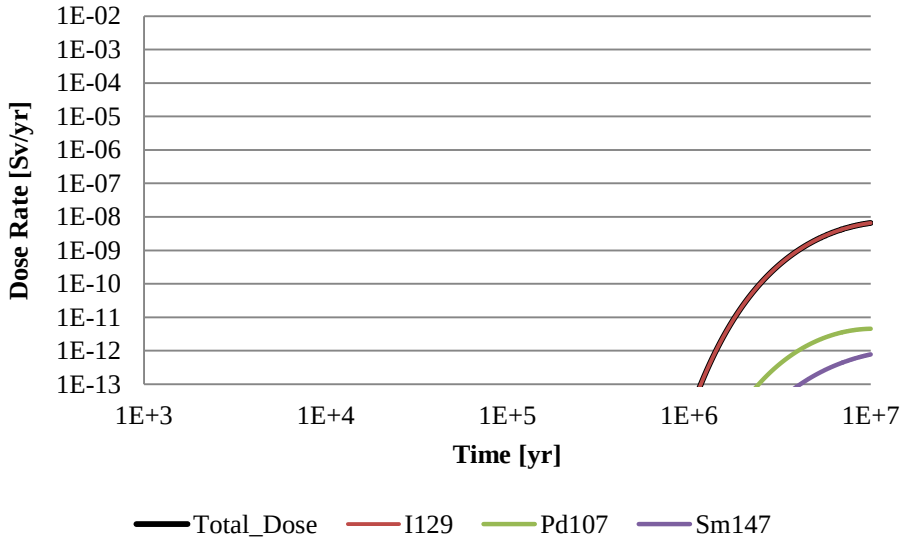
The Reference Case total dose rate over time predicted by the NWMO (2013a) model is shown in Figure 4.1. The total dose rate from NWMO (2013a) was 2 x 10^{-9} Sv/yr. The NWMO (2013a) model results showed I-129 contributing 99.5% of the total dose rate with 54% due to food ingestion and 46% due to water ingestion. The radionuclides with the second and third most contribution to total dose were Pd-107 and Sm-147 with dose rates of 7.9 x 10^{-12} Sv/yr and 1.6 x 10^{-12} Sv/yr.

Figure 4.1 – Reference Case results from SYVAC3-CC4 model (NWMO, 2013a)



The DOC-WMF model was run for this same Reference Case and the total dose rates over time are presented in Figure 4.2. Overall, the release began at approximately the same time and had a total dose rate in the same order of magnitude.

Figure 4.2 – DOC-WMF results for NWMO's 5th Case Study



For both models, the total dose rate reached 10^{-12} Sv/yr at times in the order of 10^{6} years. The total dose rate from DOC-WMF was 6 x 10^{-9} Sv/yr. Similar to the NWMO's results, those from DOC-WMF predicted that I-129 was the primary radionuclide, contributing with 99.9% of the total dose rate, with 45% from water ingestion and 55% from food ingestion. The second and third contributors to the total dose rate were Pd-107 and Sm-147, respectively. The total dose rates predicted by DOC-WMF are on the same order of magnitude as those from the NWMO modeling exercise, with both having I-129 providing the majority contribution to total dose rate. The radionuclides providing the second and third contribution in both models were Pd-107 and Sm-147, respectively for both models. The model results between the two codes overall compare well with the same radionuclides providing the majority of contribution to the total dose rate.

4.2 Chalk River Near Surface Disposal Facility

The purpose of the proposed near surface containment facility is for the disposal of legacy waste, current waste and for future decommissioning of facilities at the Chalk River site. The disposal facility will be designed as an engineered containment mound (ECM) and built at near surface level.

The EIS and supporting documentation was submitted to the Canadian Nuclear Safety Commission (CNSC) for licensing purposes. The ECM is designed to have a liner with leachate collection system and a second liner with leak detection system. A daily cover will be used to cover the waste and a final cover will be placed once all waste has been placed in the ECM.

Part of the EIS consisted of radionuclide transport modelling and predicting the dose to human receptors (CNL, 2017a). Two temporal situations were considered in the calculation of dose, as

well as airborne and waterborne emissions were evaluated. Both Operations phase and Post-Institutional phase scenarios were evaluated by the CNL.

The Operations phase assumes that no leachate will escape from the ECM but will be collected and treated in a Waste Water Treatment Plant (WWTP) prior to discharge. The concentrations within the treated leachate were assumed by the CNL to be at concentration equal the treatment targets. It was also assumed that no dilution occurred prior to reaching the East Swamp Stream.

The Post-Institutional phase is that period of time once the ECM will no longer be maintained, which is after the Year 2400. During this temporal phase, two failure scenarios were considered to represent the normal evolution by CNL (2017a) and are as follows:

1. Leachate Through the Base Liner: This failure scenario assumes that once the ECM is no longer maintained, the base liner may fail allowing leachate to be transported through the geosphere, then to the surface water and to various receptors.

2. Bathtub Effect Overflow Scenario: This failure scenario assumes that the liner remains intact but the cover fails allowing precipitation to enter and essentially fill and saturate the waste. Once the ECM is filled with water, the leachate will overflow the berm. Depending on the flow rate, the leachate either infiltrates into the groundwater system or can flow overland into Perch Creek.

The waterborne emission releases with transport through the geosphere are the scenarios of interest for this report as the test cases for DOC-WMF. CNL modelled these scenarios using RESRAD Version 3.1 to predict the source release and transport and IMPACT to predict the total dose rate. The parameters used by CNL in their modelling simulations were inputted into DOC-WMF to predict the transport through the geosphere, dispersion within the surface water and then the calculation of the dose rate.

4.2.1 Potential Critical Groups (PCGs)

Within the CNL analysis, four potential critical groups (PCGs) were identified for waterborne releases. Within this group of PCGs, some are full-time residential and some are seasonal that only reside part of the time. The list of PCGs considered for waterborne releases by the CNL are presented in Table 4.2.

Table 4.2 – Potential Critical Groups

Location	Distance from NSDF (km)
Cottager	3
Laurentian Valley	36
Pembroke	30
Petawawa	25

The CNL calculated the dose rate for each of the PCGs using IMPACT for 1-year old, 10-year old and adult receptors. CNL utilized the lifestyle survey (CNL, 2016) to obtain the habits of each group to determine the fraction of locally obtained food and the percent of water for different purposes utilized from the Ottawa River. These fractions will be discussed further in Section 9.3 for the development of the conceptual model for the Biosphere Component.

4.2.2 Source Releases

The predicted activity of the various contaminants for the Year 2400 by CNL was used to determine the source release for both of these Post-Institutional phase scenarios in their modelling activities to determine the dose. The predicted activities of the waste for the Year 2400 as reported by CNL (2017b) calculated using RESRAD Version 3.1 are presented in Table 4.3. Within CNL (2017b), the density of the waste (ρ_{waste}) was set equal to 1500 kg/m^3, the infiltration rate (q_{infil}) through the waste of 0.3 m/yr, the footprint of the ECM (A) is 107,865 m^2 and the emplacement waste depth (z_{depth}) to 16.85 m.

Table 4.3 – Radionuclide activity in the ECM in the Year 2400

Radionuclide	Concentration [Bq/g]	Radionuclide	Concentration [Bq/g]
Ac-227	6.70×10^{-4}	Pu-239	7.29×10^{-1}
Ag-108m	9.36×10^{-3}	Pu-240	1.11×10^{0}
Am-241	1.03×10^{1}	Pu-241	4.26×10^{-10}
Am-243	6.98×10^{-3}	Pu-242	3.44×10^{-3}
C-14	1.55×10^{1}	Ra-226	1.80×10^{-1}
Cl-36	7.07×10^{-2}	Ra-228	1.15×10^{-13}
Co-60	2.29×10^{-16}	Se-79	7.89×10^{-4}
Cs-135	2.43×10^{-3}	Sn-126	1.16×10^{-3}
Cs-137	3.00×10^{1}	Sr-90	7.18×10^{-2}
H-3	1.60×10^{-5}	Tc-99	2.52×10^{0}
I-129	5.43×10^{-1}	Th-228	1.13×10^{-13}
Mo-93	1.20×10^{-5}	Th-229	2.43×10^{-4}
Nb-93m	4.33×10^{0}	Th-230	4.86×10^{-3}
Nb-94	1.08×10^{1}	Th-232	1.20×10^{-13}
Ni-59	2.44×10^{-2}	U-233	6.89×10^{-3}
Ni-63	5.97×10^{-1}	U-234	1.42×10^{0}
Np-237	3.06×10^{-3}	U-235	9.12×10^{-2}
Pa-231	7.30×10^{-4}	U-236	1.27×10^{-5}
Pb-210	1.83×10^{-1}	U-238	4.55×10^{0}
Po-210	1.83×10^{-1}	Zr-93	4.33×10^{0}

4.2.2.1 Bathtub Scenario

The Bathtub Scenario assumes that over time the cover will fail while the base liner remains intact. In this case, the water would accumulate within the containment system and eventually contaminated water would overtop the sides. The contaminated water would release and CNL assumed that the contaminated water discharged directly to Perch Creek without any sorption or decay within the groundwater system (CNL, 2017b). It was also assumed that the failure occurred instantly, which is conservative as it would take time for the waste facility to fill up with water.

The source release, F [Bq/yr], was determined by CNL (2017b) using the following equation

$$F\left[\frac{Bq}{yr}\right] = \frac{Q \cdot q}{T \cdot \theta \cdot Rd}$$

Where

$$Rd = 1 + K_{da} \cdot \frac{\rho}{\eta}$$

$$Q[Bq] = Activity \cdot \rho_w \cdot T \cdot A$$

Q =	Inventory in ECM [Bq]
q =	Infiltration rate = 0.3 m/yr
T =	Waste thickness = 16.85 m
θ =	Moisture content = 0.266
Rd =	Retardation factor
A =	Area = 328.5 m x 282 m
η =	Effective porosity of the contaminated zone = 0.266
K_{da} =	The distribution coefficient in the contaminated zone – radionuclide specific
ρ =	The bulk density of the contaminated zone (1.5 g/cm^3)

The sorption parameters used were from Table A.26 in the CSA N288.1-14 and where values were missing for radionuclides the sorption was taken from other sources (communication via e-mail response from CNL).

The resulting radionuclide flux used as the source release for this scenario is presented in Table 4.4.

4.2.2.2 Failed Liner Scenario

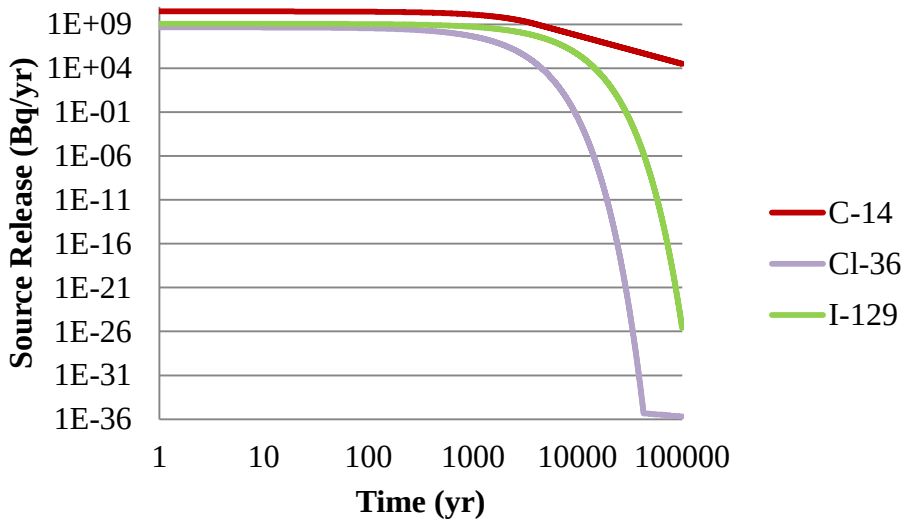
The failed liner scenario assumes that the liners fail allowing leachate to flow through to the surrounding subsurface. The contaminants are then transported through the groundwater system and release to Perch Creek and then to the Ottawa River. The source release for this scenario

was calculated by CNL using RESRAD OFFSITE (CNL, 2017a and b). The source release rates were provided by CNL in an e-mail and are located in a Microsoft Excel file called "Leachate_Flux_for_all_Radionuclides_21Jun17_xlsx.xlsx". This file contained yearly release rates in pCi/yr for each radionuclide as well as the ingrowth rates as predicted by IMPACT in their modelling. The data in this file was used to create the source release rates in Bq/yr to be incorporated as the source release rates in DOC_WMF_inputs.xlsx for DOC-WMF. Source release rates were provided for all radionuclides considered by CNL in their analyses. The source release rates for a subset of the radionuclides, C-14, Cl-36 and I-129 are presented in Figure 4.3 as an example.

Table 4.4 – Source release for Bathtub scenario (from CNL, 2017b)

Radionuclide	Concentration [Bq/yr]	Radionuclide	Concentration [Bq/yr]
Ac-227	1.07×10^{6}	Pu-239	2.14×10^{7}
Ag-108m	2.52×10^{6}	Pu-240	3.25×10^{7}
Am-241	7.77×10^{7}	Pu-241	1.25×10^{-2}
Am-243	5.25×10^{4}	Pu-242	1.01×10^{5}
C-14	2.48×10^{10}	Ra-226	3.07×10^{6}
Cl-36	3.71×10^{8}	Ra-228	1.95×10^{-6}
Co-60	1.16×10^{-8}	Se-79	1.16×10^{5}
Cs-135	2.12×10^{5}	Sn-126	8.32×10^{4}
Cs-137	2.62×10^{9}	Sr-90	3.36×10^{7}
H-3	2.92×10^{6}	Tc-99	3.29×10^{11}
I-129	9.67×10^{8}	Th-228	2.03×10^{-7}
Mo-93	3.09×10^{3}	Th-229	4.37×10^{2}
Nb-93m	5.60×10^{7}	Th-230	8.73×10^{3}
Nb-94	1.39×10^{8}	Th-232	2.15×10^{-7}
Ni-59	5.63×10^{6}	U-233	7.19×10^{5}
Ni-63	1.38×10^{8}	U-234	1.48×10^{8}
Np-237	3.93×10^{6}	U-235	9.51×10^{6}
Pa-231	1.31×10^{4}	U-236	1.32×10^{3}
Pb-210	5.90×10^{7}	U-238	4.75×10^{8}
Po-210	5.81×10^{8}	Zr-93	2.80×10^{7}

Figure 4.3 – Source release rates from CNL for Failed Liner Scenario



4.2.3 Conceptual Model

The DOC-WMF conceptual model is developed to describe CNL's normal evolution scenarios to obtain dose rate predictions in order to compare against those presented by CNL. The following sections discuss the parameters obtained from the CNL model scenarios in relation to the inputs required by DOC-WMF.

DOC-WMF provides the user with various options in terms of assigning the source release. For both the Bathtub and Failed Liner Scenarios as the source release is provided and therefore it was set as user-defined.

DOC-WMF has 55 radionuclides that are incorporated into the model. The model was also developed with the capability of adding up to eight additional radionuclides. The radionuclides considered by CNL in their analysis were presented in Table 9.2. Those radionuclides in this list that are not considered in DOC-WMF are: Ag-108m; Am-243; Mo-93; Nb-94; Ni-59; Ni-63; Pu-241; and Sn-126. These radionuclides were incorporated into DOC-WMF by adding parameters to these additional radionuclides. The extra radionuclides coded into DOC-WMF are labelled as Zz1 through Zz8.

4.2.3.1 Common Inputs

There are some common inputs that are required throughout the model. These common parameters include half-lives, free-water diffusivity and ensuring that the Species element is updated with the additional radionuclides. Within the Species element, the additional radionuclides not considered in DOC-WMF are assigned to one of the extra radionuclides labels as shown in Table 4.5.

Table 4.5 – Radionuclides considered in CNL not included in DOC-WMF

Radionuclide	Label in DOC-WMF	Molecular Weight (g/mol)	Half-lives (years)	Daughter products
Ag-108m	Zz1	107.906	418	
Am-243	Zz2	243.601	7370	
Mo-93	Zz3	92.9068	4000	Nb-93m
Nb-94	Zz4	93.9073	20,300	
Ni-59	Zz5	58.9343	1.01×10^5	Co-59
Ni-63	Zz6	62.9297	100.1	
Pu-241	Zz7	241.057	14.35	Am-241
Sn-126	Zz8	125.908	2.3×10^5	

The half-lives for each radionuclide considered in the model are inputted through the Excel input file called DOC_WMF_inputs.xlsx. Within this file, the half-lives were updated on the HalfLives tab as required.

The values of the free-water diffusivity were not considered by the CNL in their assessment as it was thought that advection and dispersion would dominate.

4.2.3.2 Waste Form Component

The Waste Form Component within DOC-WMF calculates the various inventories that are required if the source release is being determined through the GoldSim Source element, through the 1D decay equation or through consideration of decay and ingrowth. For the current case study, the source release is user-defined and therefore the Waste Form Component and associated parameters are not required.

As the inventories are not required for the source release method used for the NSDM, the parameters inputted through the Waste Form component have no effect on the model results and do not need to be changed or altered in any way. Therefore, the default parameters within DOC-WMF on the Waste Form dashboard, within the Excel input file, DOC_WMF_inputs.xlsx and the parameter database, DOC_WMF_inputs.mdb did not require any alterations.

4.2.3.3 Waste Package Component

The Waste Package Component computes the fraction of waste packages failed as well as the breach area fraction. These parameters are used within the GoldSim Source element to predict the radionuclide source release. The outputs from this component are only used when the GoldSim Source element is the release method of choice. For the NSDM test case, the source

release is user-defined and therefore the Waste Package Component settings do have any impact and do not require any alteration.

4.2.3.4 Near Field Component

The Near Field Component either calculates the source release from the information provided from the Waste Form and Waste Package components or downloads the values from the Excel File. The transport is then calculated from the waste disposal site through the buffer material (if present) and to the geosphere. The Near Field Component is divided into three zones: the transport from inside the waste package to the surface; through the buffer material; and through a transition zone to the nearest fracture. The first zone is essentially the calculation of the source release, which in this case is user-defined. For the NSDM case, there is no transport considered through a buffer material meaning that the second zone can be neglected. Finally the geosphere is assumed free of fractures meaning that the third zone is ignored.

On the Near Field Dashboard, the settings can be assigned as needed. The Source release method as previously discussed is the radionuclide concentrations are user-defined. This option is depicted on the Near Field Dashboard by selecting "From Excel in [Bq/yr]" under the Source release calculation method. The source release values for both the Bathtub and Failed Liner scenarios were presented in Section 4.2.3.6 were inputted to the DOC_WMF_inputs.xlsx on the Bqperyear tab.

As the buffer material is not considered for the NSDM test case, and is denoted by selecting the "Bypass the buffer (diffusive barrier)". This will result in the buffer material being ignored and therefore any parameters associated with the buffer, such as length, sorption of the buffer material are not required.

The third zone is neglected in this case as the geosphere is assumed free of fractures. By assigning the first leg in the Far Field Component to porous medium, this third zone is automatically neglected. Assigning the soil media in the Far Field will be discussed further in the next section.

The solubility limits were not utilized by CNL in their assessment as the radionuclide release is user-defined and inputted through the Excel file and were therefore ignored in the DOC-WMF assessment.

4.2.3.5 Far Field Component

4.2.3.5.1 Bathtub Scenario

As modelled by CNL (2017b), the release of radionuclides is assumed directly to Perch Creek as this was a conservative estimate in that no sorption would occur in the subsurface. In order to

model this within DOC-WMF, it was necessary to assign parameters to the Far Field that would essentially ignore the pathway. It is not possible to give a leg of the Far Field a length of zero and therefore each leg in the pathway was assigned a length of 0.0001 m and a hydraulic conductivity of 1 m/s. This combination of parameters resulted in the Far Field being essentially bypassed.

4.2.3.5.2 Failed Liner Scenario

The Far Field Component computes the transport of radionuclide transport through the various geological formations from the Near Field release to the Biosphere Component. The contaminants travel through the shortest pathway from the ECM to Perch Creek for 350 m (communication via e-mail with CNL). The subsurface parameters for the groundwater transport were obtained from CNL (2017) and are presented in Table 4.6. The site specific sorption parameters presented in CNL (2017) are presented in Table 4.7.

Table 4.6 – Hydrogeological properties as provided by CNL (2017b)

Parameter	Value
Length	350 m
Hydraulic conductivity	1.7×10^{-4} m/s
Gradient	0.007
Porosity	0.3
Density	1500 kg/m^3
Sorption	Refer to Table 4.3 for Site Specific values
Dispersivity	0.3 m

As the Far Field is split into a series of eight legs to the surface water, the total length was divided by eight to give each leg a length of 43.75 m. Each leg has the same flow and transport properties as the radionuclides are transported through the overburden alone and released to Perch Creek.

Table 4.7 – Site Specific sorption parameters used by CNL (2017b)

Radionuclide	K_d (m^3/kg)	Radionuclide	K_d (m^3/kg)
Ac	0.02	Pa	5.4
Ag	95	Pb	0.27
Am	1.9	Po	0.01
C	0.005	Pu	0.55
Cl	0	Ra	0.5
Co	0.06	Se	0.026
Cs	0.28	Sn	0.13
H	0.00006	Sr	0.013
I	0.001	Tc	0.0001
Mo	0.1	Th	3.2
Nb	0.75	U	0.035
Ni	0.4	Zr	1
Np	0.005		

4.2.3.6 Biosphere Component

The Biosphere Component requires ingestion and inhalation rates as inputs for DOC-WMF as well as various parameters to calculate the various transfer equations. The total inhalation rate and ingestion rates for water and food along with proportions of animal and plant produce types are inputted onto the Biosphere Component dashboard.

CNL (2017 a and b) considered the four PCGs (cottager, Pembroke, Petawawa, Laurentian Valley) for a 1-year old, 10-year old and an adult in their analysis. The percent of local food percentages and the percent of water used from the Ottawa River used by CNL were obtained in an e-mail response from CNL (Tables 4.8 and 4.9). CNL stated that these fractions were derived from lifestyle surveys (CNL, 2016).

The local fractions of food and water usage from the Ottawa River needed to be transferred into the various intake rates required for input to DOC-WMF. The default total ingestion/inhalation rates were obtained from CSA N288.1-14 for the 95th percentile and are presented in Tables 4.10 and 4.11 for each age range. The infant and child were assumed to represent the 1-year old and 10-year old, respectively. These default total intake rates were multiplied by the local fraction to obtain the various ingestion rates as inputs to DOC-WMF.

Table 4.8 – Local food fraction (From CNL via e-mail)

Food Type	Pembroke			Petawawa			Laurentian Valley			Cottager		
	1 year	10 year	Adult	1 year	10 year	Adult	1 year	10 year	Adult	1 year	10 year	Adult
Milk	92.7	80.3	49.6	92.7	80.3	49.6	92.7	80.3	49.6	92.7	80.3	49.6
Beef	0.2	0.5	1.6	0.1	0.3	1.2	0.4	1.1	3.9	0.1	0.3	0.1
Pork	0.1	0.3	0.7	0	0	0.1	0.2	0.5	1.0	0.1	0.1	0.3
Poultry	0.25	0.62	1.23	0.06	0.15	0.31	0.4	1.15	2.3	0.28	0.69	1.38
Eggs	0.1	0.3	0.8	0	0.1	0.2	0.1	0.5	1.4	0.1	0.5	1.2
Fruit & Berry	4.6	3.3	2.8	3.0	2.1	1.8	5.8	4.1	3.5	5.6	4.0	3.3
AG Veg	3.4	4.0	5.5	2.7	3.1	4.4	5.7	6.7	9.3	2.5	2.9	4.1
Root Veg	0.8	1.2	1.4	0.7	1.1	1.3	1.5	2.3	2.7	0.8	1.3	1.5
Fish	0.53	0.53	0.53	0.57	0.57	0.57	0.66	0.66	0.66	2.27	2.27	2.27

Table 4.9 – Percentage of water used from Ottawa River (from CNL via e-mail)

PCG	Drinking	Bathing	Pool	Beach	Irrigation
Cottager	1%	22%	94%	100%	38%
Pembroke	75%	94%	89%	100%	93%
Petawawa	86%	96%	84%	100%	90%
Laurentian Valley	3%	4%	68%	100%	7%

Table 4.10 – 95th Percentile intake rates from CSA N288.1-14

	Soil Ingestion (g/d)	Sediment Ingestion (kg/d)	Inhalation (m^3/yr)	Water ingestion (m^3/yr)
Infant	0.204	2.04×10^{-4}	2740	0.306
Child	0.185	1.85×10^{-4}	7850	0.482
Adult	0.02	2.0×10^{-5}	8400	1.08

Table 4.11 – Food ingestion rates based on 95th percentile energy intake from CSA N288.1-14

Food Type	1-year old		10-year old		Adult	
	g/d	kg/yr	g/d	kg/yr	g/d	kg/yr
Milk	930.5	339.6	875.1	319.4	516.1	188.4
Beef[1]	20.11	7.34	62.95	23	207.1	75.6
Pork	13.4	4.89	40.1	14.6	81.4	29.7
Poultry	31.6	11.5	83.8	30.6	159.8	58.3
Egg	8.2	2.99	30.9	11.3	79.0	28.8
Fruit & Berry	209.6	76.5	340.6	124.3	408.5	149.1
AG Veg/mushroom[2]	311.6	113.7	810.9	296.0	1203.1	439.1
Root vegetable[3]	33.1	12.1	118.4	43.2	196.7	71.8
Fish[4]	6.4	2.3	18.5	6.75	28.1	10.3

1. Includes: Beef, beef offal, veal, lamb, deer and rabbit
2. Includes: Grain, vegetables and mushrooms
3. Includes: potatoes
4. Includes: fresh-water fish

To obtain the ingestion rates required for each PCG and age, the following was assumed:

- The ingestion rate of each food type was the product of the default intake rate from CSA N288.1-14 of the food type multiplied by the appropriate local fraction. This was done for each food type to generate the inputs required for DOC-WMF.
- For plant produce the fraction of each type on the DOC-WMF dashboard (generic feed; grain; forage; potatoes; and general fruits and veggies) was required.
    - In the CNL analysis the plant produce was divided into: fruit and berry; AG Veg/mushroom; and root vegetable.
    - To obtain plant type fractions required as input by DOC-WMF
        - Fruit and Berry and AG Veg/mushroom from CNL were assumed to be general fruits and veggies in DOC-WMF
        - Root veg in CNL was assumed as potatoes in DOC-WMF
- Water ingestion rate assumed to be equal to the default total water intake multiplied by the percent drinking water obtained from the Ottawa River.

- The soil ingestion rate was assumed to be equal to the default intake rate multiplied by the percent irrigation water obtained from the Ottawa River. In other words the soil was contaminated through irrigation with contaminated water from the Ottawa River.

- The inhalation rate was determined by multiplying the total default air inhalation rate by the percent irrigation water obtained from the Ottawa River (as irrigation to soil is assumed to be the pathway by which contaminants reach the air compartment).

The resulting ingestion rates used in DOC-WMF for each PCG and age range are presented in Tables C.1 to C.4 in Appendix C.

The model also requires the dose coefficients for each age range. The dose coefficients as presented by CSA N288.1-14 were assigned to the model as was done by CNL. Where dose coefficients were missing, values were obtained from ICRP (2012) and via e-mail from CNL. All dose coefficients are presented in Appendix D.

Other assumptions that were made in regards to obtaining the required biosphere inputs are as follows:

- The only source of air contamination is from Ottawa River water used for irrigation purposes which then volatilizes to air.

- The CNL provided fractions of water used from the Ottawa River for swimming pools and bathing (Table 4.9). For the water immersion dose calculation considering bathing and swimming, the DOC-WMF model does not have a method to reduce the dose based on only a portion of the water coming from the Ottawa River and the remaining being uncontaminated water.

- Where any data was not provided by CNL for the Biosphere Component to calculate the various transfer parameters, the default values provided by CSA N288.1-14 were used.

- DOC-WMF does not consider ingestion of honey and therefore is ignored in the model. The ingestion of honey is not thought to be a large portion of the overall dose and neglecting this pathway is thought to be negligible in the final dose rate.

- The cottager is specified to reside at the cottage for 8% of the time. To obtain the dose rate reflecting this reduced residency time, the ingestion/inhalation rates were multiplied by 0.08.

Once the contaminants discharge to Perch Creek, dispersion occurs within Perch Creek and again within the Ottawa River to the PCG locations. CNL assumed that complete mixing occurs within Perch Creek and used the following equation to obtain the concentration within the Creek (communication via e-mail with CNL).

$$C_{PerchCreek} = \frac{Release\left[Bq/_s\right]}{Perch\ Creek\ Flow\ Rate} = \frac{Release\left[Bq/_s\right]}{56.1\ L/s}$$

For the Ottawa River, CNL estimated dilution factors from Section 6.2.2 of AECL (2011). For the cottager location, it was assumed that transverse mixing occurred across the width of the river as complete mixing had not yet occurred. The locations of Petawawa, Pembroke and Laurentian Valley are far enough downstream that it is possible. assume complete mixing had occurred. These assumptions were used in CNL for their modelling using IMPACT. CNL extracted the resulting dilution factors from the IMPACT model for each PCG and were provided in an e-mail and are presented in Table 4.12.

Table 4.12 – Dispersion factors used by CNL

PCG	Dispersion Factor (Bq/L)/(Bq/s)
Cottager	1.7×10^{-7}
Petawawa	2.6×10^{-6}
Pembroke	1.6×10^{-6}
Laurentian Valley	1.6×10^{-6}

Within the Biosphere Component, the dispersion type was set to user-defined and the appropriate value for each PCG was inputted on the dashboard.

4.2.4 Dose Calculation

The two post-institutional scenarios were assessed by CNL to calculate the dose to adult, 10-year old child and infant for PCGs of cottager, Pembroke, Petawawa and Laurentian Valley. The dose rates were calculated using IMPACT Version 5.5.1.

4.2.4.1 Bathtub Scenario Results

The Bathtub scenario was established in DOC-WMF according to conceptual model presented in Section 4.2. The dose to the various PCGs and age ranges as predicted by CNL (2017b) using

IMPACT and those predicted by DOC-WMF are presented in Table 4.13. As this scenario assumes constant and direct release to Perch Creek, the resulting concentration and therefore predicted dose does not change temporally.

Table 4.13 – Doses to PCGs due to Exposure to waterborne emission for Bathtub scenario (Event at year 2400) (CNL, 2017b)

Receptors	Dose to Adult [µSv/yr]		Dose to 10-year old Child [µSv/yr]		Dose to 1-year old infant [µSv/yr]	
	CNL	DOC-WMF	CNL	DOC-WMF	CNL	DOC-WMF
Cottager (3km)	2.6×10^{-3}	2.0×10^{-3}	2.5×10^{-3}	2.1×10^{-3}	1.8×10^{-3}	1.6×10^{-3}
Pembroke (30 km)	8.7×10^{-2}	5.9×10^{-2}	1.3×10^{-1}	0.65×10^{-1}	2.1×10^{-1}	1.3×10^{-1}
Petawawa (25 km)	8.8×10^{-2}	11.0×10^{-2}	1.3×10^{-1}	1.1×10^{-1}	2.1×10^{-1}	2.2×10^{-1}
Laurentian Valley (36 km)	7.0×10^{-2}	1.7×10^{-2}	1.1×10^{-1}	0.27×10^{-1}	2.0×10^{-1}	0.48×10^{-1}

Overall, DOC-WMF predicts total dose rates within an order of magnitude of those presented by CNL (2017b) for each PCG and age range. The slight differences are most likely due to the assumptions presented in the development of the conceptual model for the Biosphere Component, as discussed in Section 4.2.3.6. The IMPACT results from CNL and those from DOC-WMF compare well.

4.2.4.2 Failed Liner Scenario Results

The Failed liner scenario was established in DOC-WMF according to conceptual model presented in Section 4.2. The dose to the various PCGs and age ranges as predicted by CNL (2017b) using IMPACT and those predicted by DOC-WMF are presented in Table 4.14. For the cottager, it was assumed by CNL that the receptor would reside 8% of the time at the cottage. Therefore, Table 4.14 shows the total dose rate predicted by DOC-WMF, which is high compared to those obtained by CNL and that accounting for the shorter residency time. When the residency time is considered, the DOC-WMF results are closer to those presented by CNL. For the remainder of the discussion, the cottager dose rate will consider the 8% residency time.

By investigation the dose rates predicted by DOC-WMF for all PCG generally on same order of magnitude and show good comparison. However, DOC-WMF dose rates are slightly lower than those presented by CNL. This difference would be due to assumptions made in developing the conceptual model.

Table 4.14 – Maximum dose rates to PCGs due to Exposure to waterborne emission for Failed Liner scenario (Event at year 2400)

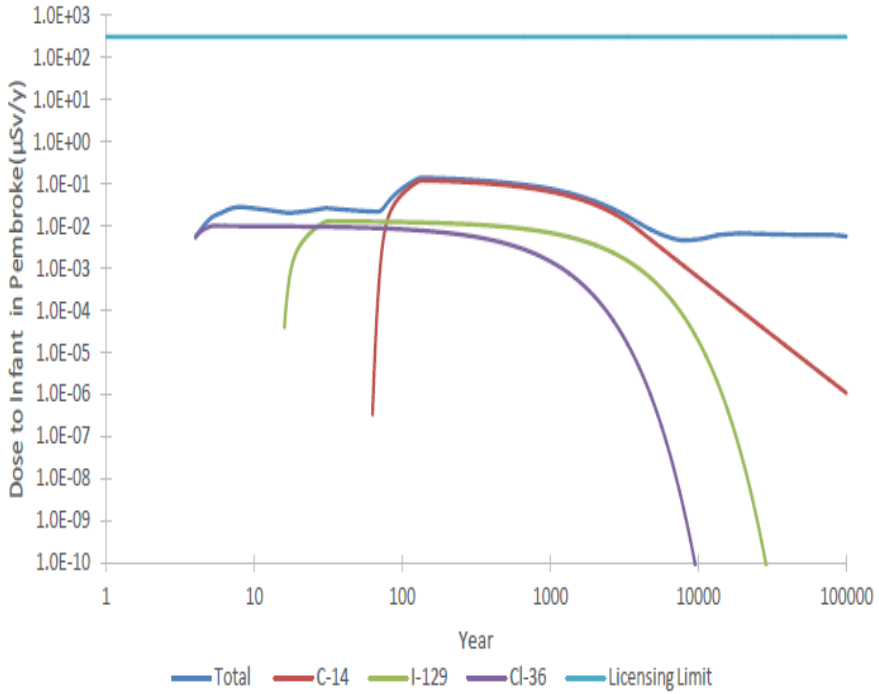
Receptors	Dose to Adult [µSv/yr]		Dose to 10-year old Child [µSv/yr]		Dose to 1-year old infant [µSv/yr]	
	CNL	DOC-WMF	CNL	DOC-WMF	CNL	DOC-WMF
Cottager (3km)	5.7×10^{-4}	11.0×10^{-4}	5.6×10^{-4}	27.0×10^{-4}	6.0×10^{-4}	54.0×10^{-4}
Considering 8% residency time		0.88×10^{-4}		2.16×10^{-4}		4.3×10^{-4}
Pembroke (30 km)	4.2×10^{-2}	1.4×10^{-2}	7.5×10^{-2}	2.8×10^{-2}	1.4×10^{-1}	0.53×10^{-1}
Petawawa (25 km)	3.9×10^{-2}	2.4×10^{-2}	7.3×10^{-2}	4.6×10^{-2}	1.4×10^{-1}	0.86×10^{-1}
Laurentian Valley (36 km)	3.8×10^{-2}	1.1×10^{-2}	7.1×10^{-2}	2.5×10^{-2}	1.4×10^{-1}	0.51×10^{-1}

The plot of dose rates versus time for the Pembroke infant as predicted by DOC-WMF is presented in Figure 4.4. Comparing the results with those presented by CNL (2017b) shows a good comparison between DOC-WMF and the CNL results in terms of the overall shapes of the graphs. In both cases, the contribution to dose due to Cl-36 was constant and then declined over time. At just after 10 years, I-129 began to increase and then leveled off and then began to decline. The dose due to C-14 began to increase just before 100 years and then slowly began to decline over time.

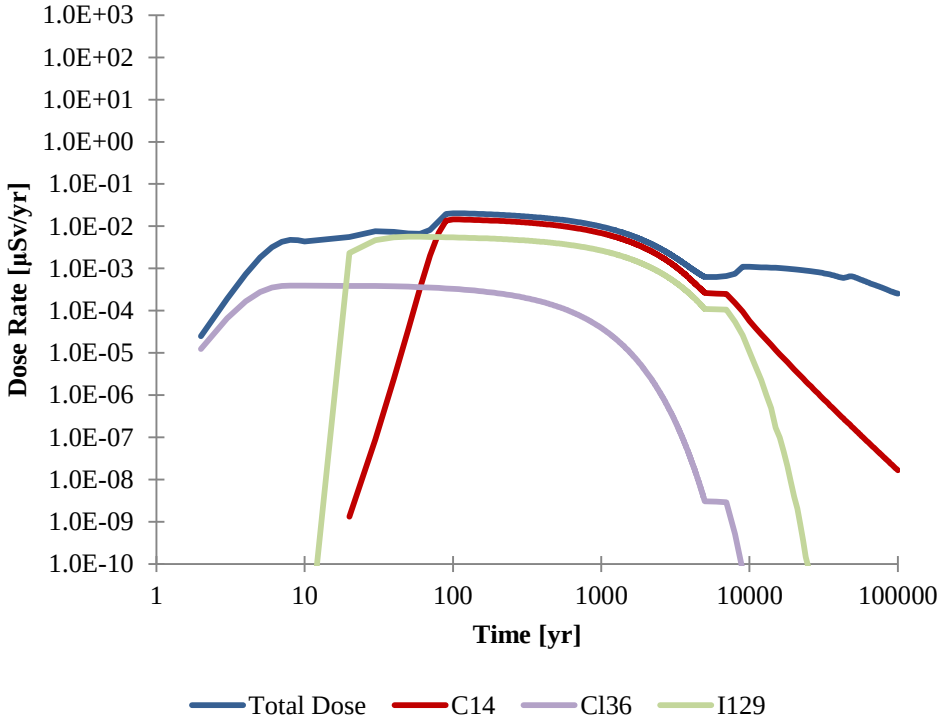
For the Failed Liner Scenario, the dose rates for each PCG and age range compare well as they are on the same order of magnitude. The plots of the dose rate versus time for the Pembroke 1-year old had similar shapes for each model. However, the dose rates predicted by DOC-WMF were consistently slightly lower than CNL results.

CNL only presents final maximum dose rates for each PCG and age as well as a plot of dose rates over time for a Pembroke 1-year old. CNL does not present interim results such as release from the Far Field. Also, the CNL results do not indicate percentage contribution to the dose rate due to various exposure pathways. In other words, which exposure pathways contributed the most to the dose rate from the analysis was not known. This information would be useful for comparison purposes as it would allow for understanding where the slight differences are occurring. By comparing the release to from the groundwater to the surface water, it could be determined if the release were the same. As well as being able to determine if both models are most impacted by the same exposure pathways would be beneficial.

Figure 4.4 – Predicted dose rates to an infant in Pembroke



(a) CNL



(b) DOC-WMF

Without this more detailed information it is only possible to compare the total dose rate and therefore determining exactly why DOC-WMF results were slightly lower can only be assumed. The exact cause of the difference is not known but may be due to assumptions used in conceptualizing the Biosphere Component. Many assumptions were made in regards to obtaining the ingestion rates and inhalation rates required for DOC-WMF. The percentage of local food intake from CNL was multiplied by default intakes rates from CSA N288.1-14 to get the food ingestion rate inputted to DOC-WMF.

For air contamination, within DOC-WMF, the only pathway to air was from the Ottawa River, then to soil through irrigation and volatilization to air. It is not known if the model used by CNL considered other pathways of air contamination. This assumption may underestimate the dose rate due to air inhalation and immersion.

The water ingestion rate in DOC-WMF was assumed to be equal to the percent reported for drinking from the Ottawa River by the default ingestion rate. The soil ingestion rate in DOC-WMF was assumed to be equal to the product of the fraction of irrigation water from the Ottawa River with the default soil ingestion rate. The food source for the animal produce in DOC-WMF was assumed to be equal to wet generic feed.

Another assumption is that where data was missing for the biosphere component, the default values from CSA N288.1-14 were used which may have slight impact on the predicted dose rates.

Even though DOC-WMF underestimated the dose rates for the Failed Liner Scenario, the results were of the same order of magnitude and the plot of dose rate versus time showed similar changes over time with the various assumptions used to conceptualize the scenario it is thought that DOC-WMF results compare well to those of CNL.

4.2.5 Chalk River Laboratory Test Case Summary

DOC-WMF successfully modeled both the Bathtub and Failed Liner Scenarios. The results from DOC-WMF were within an order of magnitude of those presented by CNL. The Failed Liner Scenario for a 1-year old Pembroke infant showed similar patterns for final dose rates.

CNL only provided final dose rates and did not present interim releases such as from the Far Field as an example. Also, CNL did not indicate which exposure pathway was contributing most to the overall dose. Having this information, would have aided in determining the reason for the slight differences between the model results.

5.0 Model Confidence

To gain confidence in the DOC-WMF model, the following points are presented:

- The model is coded within a known commercial simulation software called GoldSim. The advantages to using this software are many. The GoldSim elements contained within the code have been extensively tested and verified. This provides confidence in that using these elements will result in the desired outcome. Also, GoldSim checks units in any equations to ensure that formulas have been implemented correctly. If the implemented formula does not generate the defined units, then GoldSim will provide and error and not allow the model to be run until the error is fixed.

- DOC-WMF is adapted from the SOAR model which was developed by the US NRC. The SOAR developers conducted extensive testing of the SOAR model to provide model confidence. In some components, very little changes were made in the development of DOC-WMF and therefore the testing of SOAR in these areas would carry forward.

- Throughout the DOC-WMF model, notes have been placed within the Notes pane at the bottom of the model, as well as within the code itself. These notes provide explanation of that area of the code, any equations used and any assumptions implemented. These notes help users determine the functioning of the code throughout DOC-WMF.

- Verification of the DOC-WMF code was conducted as illustrated in Section 3.0 on the Near Field Component, Far Field Component and the Biosphere Components. The results were successfully compared against analytical solutions or reported values.

- Model runs were conducted using the GoldSim source element as the source release varying the total waste mass and the degradation rate. Decreases in total mass had the expected outcome of a decrease in dose rates. Decreases in degradation rates also resulted in a decrease in dose rate as expected. Increases in both of these parameters also results in increases in total dose rates, which is the expected outcome

- Model runs were conducted in varying the leg lengths within the Far Field. The leg lengths were decreased to very small values, and had the expected outcome of minimal change prior to release to the Biosphere Component. Large leg lengths had the effect of lower release to the Biosphere Component as expected.

- Additional model runs were conducted changing the inhalation and ingestion rates within the Biosphere Component inputs. Decreases in these values had the result of a decrease in total dose rate as expected. The reverse was observed due to increase in inhalation/ingestion rates.

Overall, the points listed above help improve the confidence of DOC-WMF. It was adapted from a well verified code, coded within established simulation software, and model runs are providing expected results.

6.0 Summary

The DOC-WMF model was developed to provide a tool for assessing various waste disposal options for radioactive waste. The model allows for the consideration of 55 radionuclides in the Waste Form to create a bound and unbound inventory that is sent to the Near Field. A method for adding in other radionuclides was developed by having the required coding done throughout the model for eight extra radionuclides that are currently inactive and do not affect model results. The user can activate these extra radionuclides as required by adding inventory and values to the required variables.

The Waste Package component remained the most similar to that from SOAR and considered various failure modes. The failure modes considered were localized corrosion, general corrosion and/or disruptive events. The Waste Package component sent the breach area and failure rate to the Near Field component to calculate the source release. The waste package inputs are only required if the DOC-WMF is set using the GoldSim Source Element as the source release.

The Near Field Component calculates the release from the inside of the waste package (Zone 1), through the buffer (Zone 2) and through a transition zone to the nearest fracture (Zone 3) to the Far Field. The user has several options for calculating the source release in Zone 1. The options are: through a Source element as conducted in the SOAR model; a one-dimensional decay equation; considering decay and ingrowth; and user-defined. The chosen source release method affects the parameters needed in the Waste Form and Waste Component. The GoldSim Source element requires information regarding both inventory and failure. The one-dimensional decay equation and the source release considering decay and ingrowth require the total initial inventory. The user-defined release methods do not require inventory or failure values.

The transport through the buffer material (zone 2) was verified successfully against analytical solutions. The buffer material may be considered intact where it is considered as a diffusive barrier, or allowed to degrade over time incorporating advective components. The buffer material may also be set to bypass in which this zone is ignored. The third zone represents a transition from the end of the buffer to the nearest fracture and is ignored if the first leg of the Far Field is set to porous media.

The Far Field Component was adapted to allow for further variations in the geology. The Far Field was also changed to allow for a release to surface water in addition to a well. The option of considering a second pathway was also incorporated. A feature was added that allowed for the option of ignoring sorption in the geosphere, which would be useful in conducting a sensitivity analysis. The Far Field Component was verified by comparing against analytical solutions under various scenarios.

The Biosphere Component was expanded to consider more exposure pathways in calculating the final dose according to CSA N288.1-14. The Biosphere Component was verified by first checking that the various transfer parameters equations were coded correctly by comparing the DOC-WMF results against those presented by CSA N288.1-14 (2014) using default parameters. A second verification of the Biosphere Component was by comparing dose calculations checked against examples of a source release for C-14 and I-131. The comparison between the doses

calculated in the examples and those from the model were good indicating that the model was calculating the dose correctly. Also, in order to assess the example for the I-131 (a radionuclide not considered within DOC-WMF) the method for adding in a new radionuclide was also successfully verified.

The Biosphere Component required large amounts of data which were brought in through the parameter database and the Excel input file. The values used in the database for these biosphere parameters were set as the default values presented by CSA N288.1-14 (2014).

The NWMO's 5th Case Study was modeled using SOAR in a previous contract (Osborne, 2015; NWMO, 2013a and b). The parameters presented for this case study were used in the creation of the DOC-WMF parameter database for solubility limits, relative inventory, sorption parameters, instant release fractions and others.

DOC-WMF was used to re-model the NWMO's 5th case study now considering the complete set of radionuclides and the expanded Biosphere Component of DOC-WMF. The Reference Case was examined using deterministic values. The parameter database contains the PDFs for the various required parameters and was set to the mean of each PDF. This differed from the NWMO modeling which used a reference value. The ingestion/inhalation rates reported by NWMO (2013b) were used however the remaining biosphere parameters remained as the CSA N288.1-14 (2014) default values. The results from DOC-WMF compared well against SYVAC3-CC4 both with a maximum total dose rate in the 10^{-9} Sv/yr range. The relative contribution from ingestion of food and ingestion of water were the same for both models.

The proposed NSDF for Chalk River Laboratories was assessed in the EIS (CNL, 2017a) and the supporting documentation (CNL, 2017b) and was used as the main test case for DOC-WMF. Two scenarios were assumed to represent the normal evolution of the waste facility for post-institutional control after the Year 2400. The first was the Bathtub Scenario which assumed that the cover fails while the liner remains intact. Over time the waste facility would fill with water and then overtop releasing radionuclides to Perch Creek. The second scenario was the Failed Liner Scenario which assumes that both the cover and liner fail, resulting in contaminated leachate discharging to the groundwater system, transporting radionuclides to Perch Creek. Both scenarios assume that the contaminants are transported within Perch Creek and then discharged to the Ottawa River.

The CNL provided the source release for the Bathtub scenario and assumes that the release begins immediately at the Year 2400; ignoring the time it would take for the NSDF to fill with water and overtop (CNL, 2017b). The source release rates for the Failed Liner Scenario were obtained in a Microsoft Excel file from e-mail communication with CNL for the purposes of this report. For both scenarios, the fraction of locally obtained food was used to determine the ingestion/inhalation rates for the various PCGs. The dispersion factors obtained from CNL via e-mail were used as the dispersion model and inputted through the Biosphere Component dashboard. The dose coefficients were obtained from CSA N288.1-14, from CNL and from ICRP (2012). Otherwise, many of the required parameters for the Biosphere Component were set as default values from CSA N288.1-14. The DOC-WMF model was run for each PCG and age-range and the results were compared.

DOC-WMF was used to model the Bathtub scenario for the same combination of PCGs and age ranges to calculate a range of dose rates using the provided source release and distance to receptor. The Far Field was set to values such that it would essentially be ignored similar to the CNL assessment.

The dose rates as predicted in the CNL analysis of the Bathtub Scenario using IMPACT were in the 10^{-3} to 10^{-2} μSv/yr range. The dose rates as predicted by DOC-WMF also ranged between 10^{-3} to 10^{-2} μSv/yr for the various PCGs and age ranges. The results from DOC-WMF and those presented by CNL (2017b) compare well for the Bathtub Scenario.

The Failed Liner scenario was modelled using the information provided from CNL for the source release over time using the information provided from CNL and default values from CSA N288.1-14.

The maximum dose rates presented by CNL (2017b) and those predicted by DOC-WMF for the Failed Liner Scenario compared favourably and were generally within an order of magnitude. Plots of dose rates versus time for a Pembroke 1-year old from CNL and DOC-WMF showed similar trends over time. However, the DOC-WMF results were consistently lower. CNL presented the final maximum dose rate for each PCG and age and dose rate over time for the Pembroke 1-year old. CNL did not present any interim results such as release from Far Field or provide any information regarding which exposure pathways have the most impact on the final dose rate. This information would aid in determining the reason why DOC-WMF results are slightly below those from CNL. With the available information, it was thought that the differences would be due to assumptions made in conceptualizing the Biosphere Component. However, the differences between the CNL and DOC-WMF were slight and it is thought that the Failed Liner Scenario results from CNL (2017b) and those from DOC-WMF compare well as the values are within an order of magnitude and the plots for a 1-year old in Pembroke are similar.

Overall, it was found that DOC-WMF was successful in modelling both the Failed Liner and Bathtub Scenarios as presented by CNL (2017b). The results for both scenarios are within an order of magnitude. This overall result continues to confirm the verification of the DOC-WMF model.

6.1 Model Limitations

The DOC-WMF model was developed in order to overcome some limitations inherent within the SOAR model as discussed in Section 1.1. DOC-WMF achieved this objective however there were still some limitations as will be discussed in the following paragraphs.

DOC-WMF added several source release options to the source release method already present within the SOAR model. The existing source release method from SOAR uses the GoldSim source element and was not altered from the original code. Therefore, the limitations inherent in this source release method remain unchanged from those in SOAR. These limitations include that only a generic waste package be considered and that all waste packages are contained within

one single repository in a simplistic manner. Therefore, changes in waste package configuration or separating into various vaults cannot be done with this model. DOC-WMF did not overcome this limitation for this particular source release method, however it allows for other choices of assigning the source release such as through decay, ingrowth and user-defined.

The Waste Form Component of DOC-WMF was adapted to allow for a total of 55 radionuclides from the 16 considered in SOAR. DOC-WMF was also provided with the ability of the user adding up to 8 more radionuclides. The limitation within DOC-WMF occurs if the user requires more than 8 additional radionuclides not included within DOC-WMF.

The Waste Form Component calculates a bound (that contained within solid waste matrix and releases slowly over time) and unbound inventory (that released instantaneously) of the initial waste mass for use if the GoldSim source release method is chosen. For this source release method, the degradation of the waste bound is incorporated through a degradation rate in 1/year which is then used to calculate the lifetime of the waste in years. The GoldSim source element uses this lifetime to determine how the bound waste form is released over time. However, other methods may exist to account for degradation of the bound waste form. An example of this was within the NWMO's 5th Case Study, which used a dissolution model to account for the bound form to release the waste. Incorporating this degradation method would not be possible within DOC-WMF.

The Waste Package Component was not altered significantly from that of SOAR. It provides various failure modes such as general corrosion, localized corrosion or through disruptive events. The user is limited to these failure modes to assign the failure if using the GoldSim source element as the release method.

The Far Field is restricted to two pathways from the repository to the biosphere. It is thought that this should be sufficient for most applications.

The Biosphere Component has been expanded to account for numerous exposure pathways in DOC-WMF from only ingestion of water being considered in SOAR. This adaptation is a great improvement, however further expansion could be conducted within this component. As an example doses to non-human biota could be considered in the future.

DOC-WMF does not consider indoor versus outdoor releases or releases due to fires. These may be areas where the model could be expanded in the future.

6.2 In review

DOC-WMF as previously discussed was developed in GoldSim. A user's manual was prepared for DOC-WMF and covers how to input data, data requirements, considerations and how to run the model. Some information on GoldSim is contained within the DOC-WMF user's manual but more information can be found through GoldSim manuals found at www.goldsim.com.

The main model file, "DOC_WMF_v1.gsm", requires the full version of GoldSim to operate. A version of the model requiring the free GoldSim player, "DOC_WMF_v1.gsp" is also included. The free GoldSim player is available from http://goldsim.com/Web/Downloads/. This player version allows for change in simulation settings including simulation time and probabilistic versus deterministic. Along with the model files, three parameter files are submitted. Two files are parameter databases: DOC_WMF_inputs.mdb; and DOC_WMF_dummy.mdb and the other is a Microsoft Excel file: DOC_WMF_inputs.xlsx.

The Microsoft excel input file "DOC_WMF_inputs.xlsx" is required for use by both the full and player versions as values are brought in from this file at the beginning of a new simulation. This input file must be contained within the same folder as the model file on the computer. Changes in parameter values can be changed within this file however it is imperative that each parameter remains in the same cell.

The two parameter databases contain information for all the GoldSim stochastic inputs for parameters with PDFs. The main input file "DOC_WMF_inputs.mdb" contains all the model inputs. The second input file "DOC_WMF_dummy.mdb" has all the information for the dummy variables required to add in future radionuclides. It is not necessary to carry out a global download prior to simulation, unless changes have been made to these files. Prior to being able to conduct a global download to the model, each of these two parameter databases needs to be added as data sources to the computer. This is done through the Control Panel, adding a 32-bit Data Source under the Administrative Tool's option. Further information on the database format and how to set up as a source on the computer will be provided in the DOC-WMF User's manual and through GoldSim manuals on www.goldsim.com.

The player version of DOC-WMF can be started by opening the file "DOC_WMF_v1.gsp". The parameters on the dashboards can be easily changed and will be incorporated into the model. The parameter values within the Microsoft Excel input file can be altered and saved, however it is imperative that each remain within the respective cell. Changing the parameters within the database is covered in the User's Manual.

DOC-WMF was developed, verified and applied to two Test Cases successfully. It has been developed in such a manner as to be generic allowing for a variety of applications.

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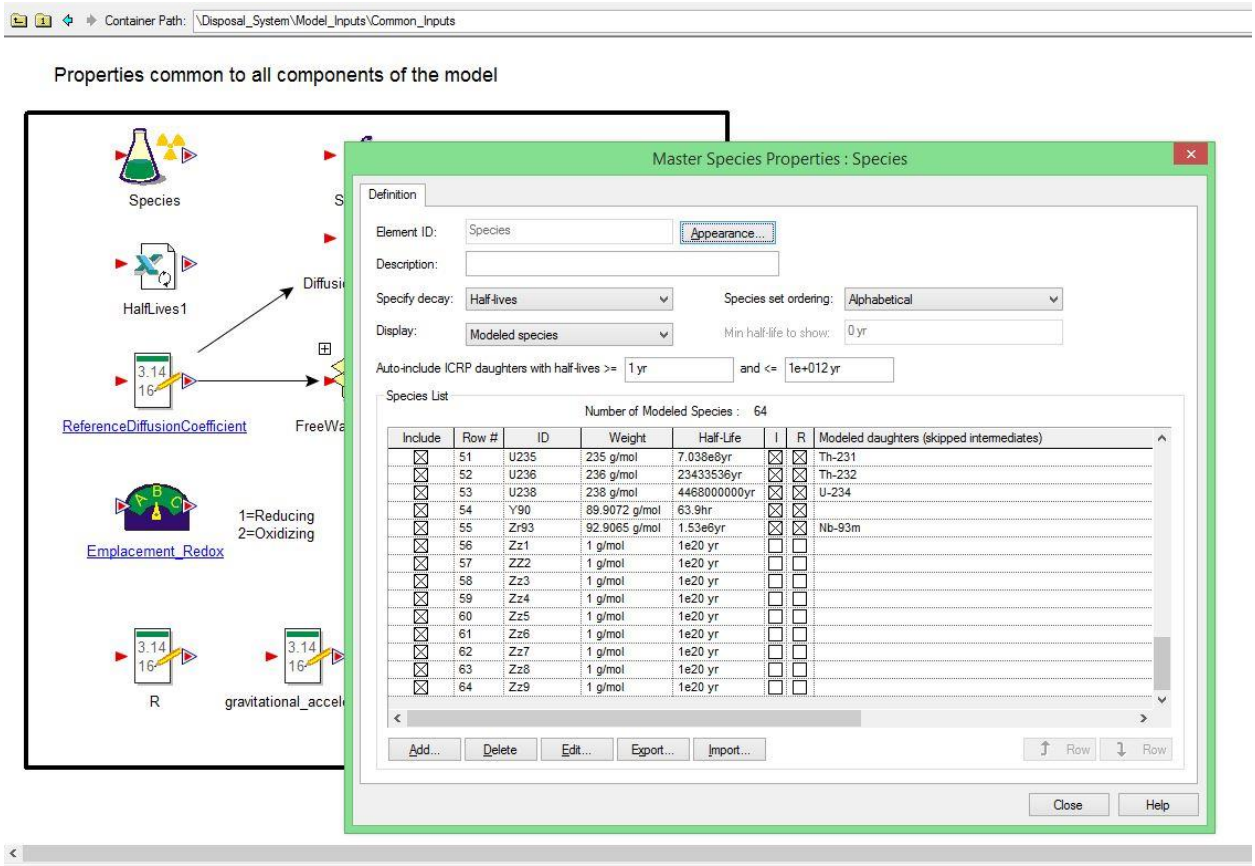
room emplacement of used CANDU fuel in copper containers in permeable plutonic rock, Volume 4: Biosphere model. Atomic Energy of Canada Limited Report AECL-11494-4. Pinawa, Canada.

Appendix A – Methodology for adding/removing radionuclide

Within DOC-WMF a total of 55 radionuclides have been included as specified in Section 2.1. In the event of a case study requiring additional radionuclides, eight extra "dummy" radionuclides were coded into DOC-WMF. These dummy radionuclides are inactive in that they have been assigned zero initial inventories and no ingrowth. As such, these extra radionuclides have no impact on the model results as long as they remain inactive. For those cases where extra radionuclides are required, these new radionuclides would need to be parameterized in order to essentially activate the dummy radionuclide. These dummy radionuclides have been named Zz1 through Zz8, and are located in rows 56 through 63 in the associated vectors indexed on the species list (see Figure A.1).

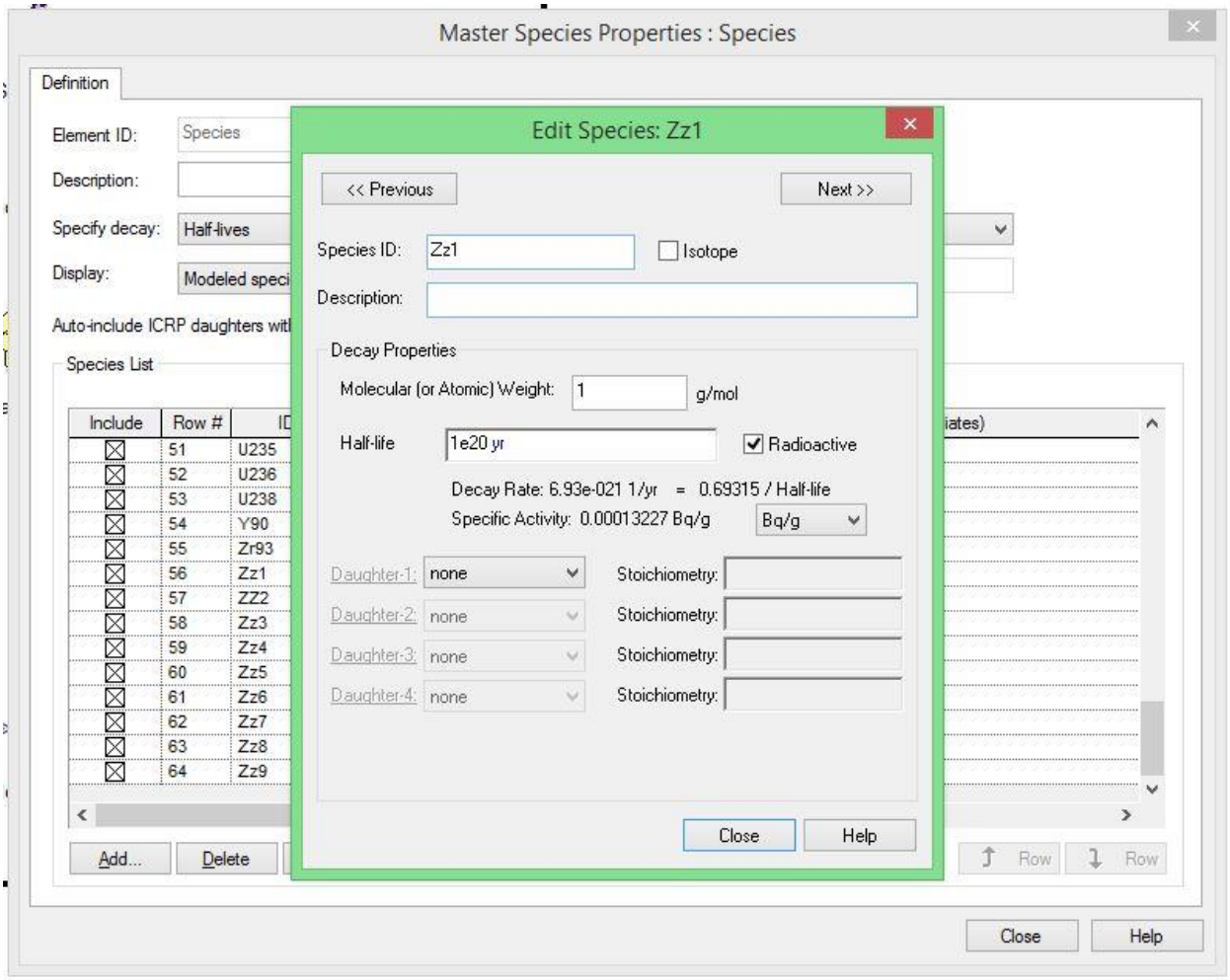
The first step is to set the molecular weight, half-life and stoichiometry in the GoldSim "Species" Element. For DOC-WMF, this Species element is located at Disposal_System\ Model_Inputs\ Common_Inputs. Within this species element, the radionuclides that are considered in the model (rows 1 through 55) as well as these dummy radionuclides (rows 56 through 64) are listed (see Figure A.1). It is imperative that each radionuclide remain with the same row number so that references throughout the model remain. Otherwise expressions that have been coded throughout the model may be linked incorrectly between radionuclides.

Figure A.1 – GoldSim Species element



To edit one of the species, the radionuclide is highlighted in the GoldSim "Species" element and then click on "Edit". The appropriate values required within this Species element are inputted into the window (see Figure A.2).

Figure A.2 – Edit window for radionuclide on Species element

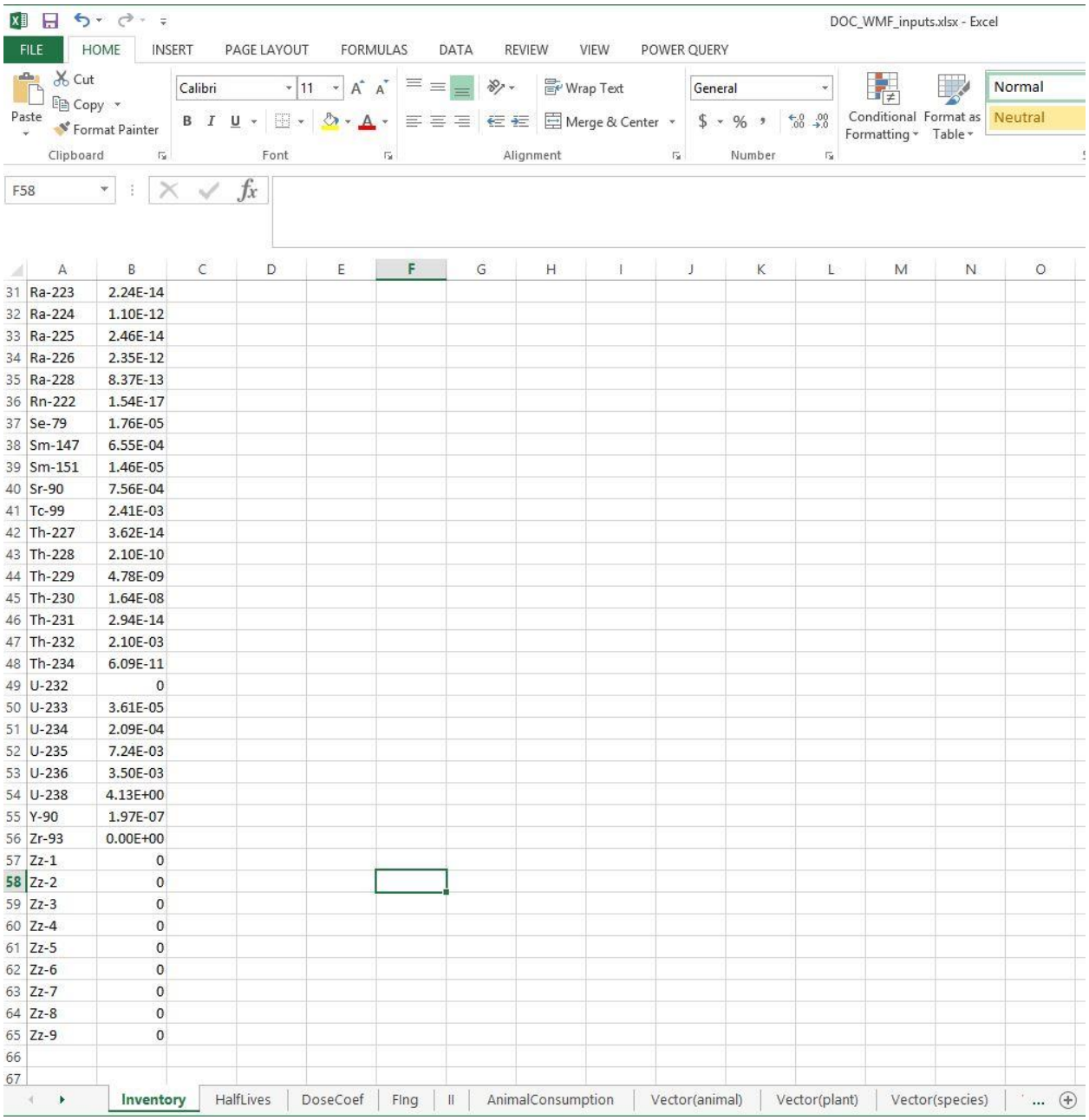


Various parameters associated with the model are brought in through the Excel input file "DOC_WMF_inputs.xlsx" (See Table A.1). Within this excel file, the cells associated to each dummy radionuclide have already been assigned (See Figure A.3 for example). The required values would have to be inputted into the appropriate cells and the file saved. The next time the model is run, these new values will be brought in for the simulation. It is important that each parameter remain in their respective Excel cell as they are referenced in the model. Changing locations may result in the wrong values being imported or a model error if no data is present in the cell.

Table A.1 – Parameters inputted through Excel

Inventory	Half-life	Dose coefficients	F_{ing}
II	BAF_{fish}	BAF_{plants}	λ_{vol}
Transfer_sediments	W_lake/W_river	S_g	S_b
CR	tf_potatoes		

Figure A.3 – DOC_WMF_inputs.xlsx



	A	B
31	Ra-223	2.24E-14
32	Ra-224	1.10E-12
33	Ra-225	2.46E-14
34	Ra-226	2.35E-12
35	Ra-228	8.37E-13
36	Rn-222	1.54E-17
37	Se-79	1.76E-05
38	Sm-147	6.55E-04
39	Sm-151	1.46E-05
40	Sr-90	7.56E-04
41	Tc-99	2.41E-03
42	Th-227	3.62E-14
43	Th-228	2.10E-10
44	Th-229	4.78E-09
45	Th-230	1.64E-08
46	Th-231	2.94E-14
47	Th-232	2.10E-03
48	Th-234	6.09E-11
49	U-232	0
50	U-233	3.61E-05
51	U-234	2.09E-04
52	U-235	7.24E-03
53	U-236	3.50E-03
54	U-238	4.13E+00
55	Y-90	1.97E-07
56	Zr-93	0.00E+00
57	Zz-1	0
58	Zz-2	0
59	Zz-3	0
60	Zz-4	0
61	Zz-5	0
62	Zz-6	0
63	Zz-7	0
64	Zz-8	0
65	Zz-9	0
66		
67		

Several other parameters are defined by PDFs and are assigned to GoldSim stochastic elements that are brought in through the parameter database "DOC_WMF_dummy.mdb" (see Table A.2). The stochastic elements associated with these dummy radionuclides are already linked to the database. When adding a new radionuclide the database is updated with the appropriate values and then downloaded to the model. The exact procedure for updating the database with assigned PDF and values as well as downloading are covered within the DOC-WMF User's Manual.

Table A.2 – Parameters associated with PDF and brought in through database

Free water diffusivity	Instant release fraction	Buffer diffusivity
Buffer sorption	Solubility limits	Sorption rock/soil type 1
Sorption rock/soil type 2	Sorption rock/soil type 3	Sorption rock/soil type 4
Sorption rock/soil type 5	Sorption rock/soil type 6	Sorption rock/soil type 7
Sorption rock/soil type 8		

To remove a radionuclide it should be done in a manner such that the row numbers on the species list are not changed and therefore should be left on the species list. To ignore a radionuclide the inventory should be set to zero in the Excel input file. On the GoldSim "Species" element it should be ensured that no other radionuclides in the list parent products of the radionuclide to be ignored. If one radionuclide does act as a parent, then remove the unwanted radionuclide from the list of daughter products. By carrying out these steps, the radionuclide will not be considered within the predictions and the associated dose will be zero.

Appendix B – DOC-WMF model parameters

Table B.1 – Default parameter values for Biosphere parameters

Parameter	Description	Default value	Source
L'	Annual average irrigation rate	1.1×10^{-5} L/m^2·s	CSA N288.1-14 (2014)
λ_e	Radioactive decay rate	See Table 2.3	
t	Duration of facility operation from commissioning to end of facility life	1.39×10^9 s (= 40 years)	CSA N288.1-14 (2014)
ER	Soil erosion rate	Sand = 1.5×10^{-8} kg/m^2/s Loam = 5×10^{-8} kg/m^2/s Clay = 5×10^{-8} kg/m^2/s Organic = 0 kg/m^2/s	CSA N288.1-14 (2014)
Θ	Volumetric water content	Sand = 0.1 Loam = 0.2 Clay = 0.3 Organic = 0.8	Beals (1985)
ρ_b	Soil bulk dry density	Sand = 1500 kg/m^3 Loam = 1300 kg/m^3 Clay = 1400 kg/m^3 Organic = 400 kg/m^3	CSA N288.1-14 (2014)
K_d	Soil partition coefficient of the radionuclide	See Table A.5	
Z_{soil}	Well-mixed soil layer thickness	0.20 m	CSA N288.1-14 (2014)
λ_{vol}	Volatilization rate constant (Gas evasion rate from soil) Lognormal PDF	I = 6.7×10^{-10} 1/s (GSD = 10) C-14 = 4.3×10^{-7} 1/s (GSD=3.3) Cl – 3.00×10^{-11} 1/s (GSD=10) Se – 1.00×10^{-9} 1/s (GSD=10)	Sheppard et al. (2002) Zach et al. (1996) Sheppard et al. (2004) Davis et al. (1993)

Table B.1 – Default parameter values for Biosphere parameters (continued)

Parameter	Description	Default value	Source
	Radon emission rate from soil	Log normal GM = 2.7 x 10^{-9} $(mol_{Rn222}/m^2 \cdot s)/(mol_{Ra226}/kg)$ GSD = 2.16	Sheppard et al. (2005)
q_{infil}	Net infiltration rate of water through the soil	Southern ON = 0.24 m/yr Western ON = 0.38 m/yr Eastern ON = 0.32 m/yr Québec = 0.35 m/yr Maritimes = 0.56 m/yr	CSA N288.1-14 (2014)
CR	Plant/soil concentration ratio	See Table A.6	
h_i	Harvest index	Generic feed crops = 1 Grain = 0.5 Forage = 1 Potatoes = 0.8 Generic fruits and vegetables = 0.8	CSA N288.1-14 (2014)
TS	Ratio of the total plant yield to the total above-ground yield (total below-ground yield for root crops)	2	CSA N288.1-14 (2014)
P	Long-term average precipitation rate	Southern ON = 2.49x10^{-8} m/s Western ON = 3.41x10^{-8} m/s Eastern ON = 3.03x10^{-8} m/s Québec = 3.19x10^{-8} m/s Maritimes = 4.51x10^{-8} m/s	CSA N288.1-14 (2014)
cf	Cropping frequency	One per year = 3.17 x 10^{-8} 1/s	CSA N288.1-14 (2014)
D_{res}	Dilution factor	23.8 s/m (assumes $A_f = 10^6$ m^2)	CSA N288.1-14 (2014)
C_{res}	Correction factor	1	
LAI	Leaf area index	3	CSA N288.1-14 (2014)

Table B.1 – Default parameter values for Biosphere parameters (continued)

Parameter	Description	Default value	Source
l_{wt}	Volume of water retained per unit leaf are	0.1 L/m^2	CSA N288.1-14 (2014)
η_i	Frequency of irrigation events using contaminated water	3.34×10^{-6} 1/s (assumes 20 irrigation events over hottest 10 weeks of growing season)	CSA N288.1-14 (2014)
tf	Translocation factor from foliage to consumable product	Potatoes = see Table A.6 Generic Fruits and Vegetables = 1	
t_e	Effective duration of the deposition	Generic feed crops = 5.18×10^6s Grain = 5.18×10^6s Forage = 2.59×10^6s Potatoes = 5.18×10^6s Generic Fruits and Vegetables = 5.18×10^6s	CSA N288.1-14 (2014)
λ_p	Physical removal processes such as wind, rain and plant growth	2.87×10^{-7} 1/s	CSA N288.1-14 (2014)
Y_c	Consumable plant yield	Generic feed crops = 0.6 kg/m^2 Grain = 0.4 kg/m^2 Forage = 0.5 kg/m^2 Potatoes = 2.1 kg/m^2 Generic Fruits and Vegetables = 1 kg/m^2	
WE_p	Water equivalent of the plant dry matter	0.56	CSA N288.1-14 (2014)
WE_a	Water equivalent of the animal product dry matter	See Table A.2	
WE_{aa}	Water equivalent of the aquatic animal dry matter	0.7 L/kg	CSA N288.1-14 (2014)
WE_{ap}	Water equivalent of the aquatic plant dry matter	0.56 L/kg	CSA N288.1-14 (2014)

Table B.1 – Default parameter values for Biosphere parameters (continued)

Parameter	Description	Default value	Source
DW_p	Dry/fresh weight ratio for plant products	Generic feed crops = 0.87 Grain = 0.87 Forage = 0.2 Potatoes = 0.21 Generic Fruits and Vegetables = 0.1	CSA N288.1-14 (2014)
DW_a	Dry/fresh weight ratio for animal products	See Table A.2	
$1\text{-}DW_{aa}$	Fractional water content of aquatic animals	0.75	CSA N288.1-14 (2014)
$1\text{-}DW_{ap}$	Fractional water content of aquatic plants	0.75	CSA N288.1-14 (2014)
DW_{aa}	Fractional dry weight content of freshwater fish	0.25	CSA N288.1-14 (2014)
DW_{ap}	Dry weight of aquatic plant per total fresh weight	0.25	CSA N288.1-14 (2014)
ID_p	Isotopic discrimination factor for plant metabolism	0.7	CSA N288.1-14 (2014)
ID_{ap}	Isotopic discrimination factor for aquatic plant metabolism	0.8	CSA N288.1-14 (2014)
ID_{aa}	Isotopic discrimination factor for aquatic animal metabolism	0.8	CSA N288.1-14 (2014)
f_{c_air}	Fraction of plant stable carbon derived from air	0.7	CSA N288.1-14 (2014)

Table B.1 – Default parameter values for Biosphere parameters (continued)

Parameter	Description	Default value	Source
f_{int}	Foliar interception velocity	Generic feed crops = 1 Grain = 1 Forage = 1 Potatoes = 0.5 Generic fruits and vegetables = 0.5	
f_{w_w}	Fraction of the animal water intake derived from direct ingestion of water	See Tables A.3 and A.4	Hart and Burt (2013)
f_{w_sw}	Fraction of the animal water intake derived from inhalation and skin absorption	See Tables A.3 and A.4	Hart and Burt (2013)
f_{w_pw}	Fraction of the animal water intake derived from water in the plant feed	See Tables A.3 and A.4	Hart and Burt (2013)
f_{w_dw}	Fraction of the animal water intake that results from the metabolic decomposition of the organic matter in the feed	See Tables A.3 and A.4	Hart and Burt (2013)
f_{sl}	Soil load on feed as consumed	See Table A.2	
k_{aw}	Fraction of water contaminated sources	1	CSA N288.1-14 (2014)
k_{af}	Fraction of feed from contaminated sources	1	
k''_w	Fraction of drinking water that is contaminated	1	
Q_w	Water consumption of the animal	See Tables A.3 and A.4	
Q_a	Air inhalation rate of the animal	See Table A.2	

Table B.1 – Default parameter values for Biosphere parameters (continued)

Parameter	Description	Default value	Source
Q_f	Feed consumption by the animal [kg/d]	See Tables A.3 and A.4	
Q_s	Soil consumption rate by animal from sources other than feed	See Table A.2	
F_{ing}	Fraction of animal's daily intake by ingestion that appears in each kg of produce	See Table A.9	
f'_{OBT}	OBT/HTO ratio in the animal	See Table A.2	IAEA, 2010
f_{OBT}	Fraction of total tritium in the animal product in the form of OBT as a result of HTO ingestion	See Table A.2	IAEA, 2010
t_h	Hold-up time between exposure to contamination and feeding	8.64×10^4s	
X_{1_C}	Concentration of stable carbon in air	0.21 gC/m^3	
X_{4_C}	Stable carbon concentration in feed	500 gC/kg	CSA N288.1-14 (2014)
X_{5_C}	Stable carbon concentration in animal	See Table A.2	
X_{6_C}	Stable carbon concentration in fish [gC/kg]	$M_{aa}=X_{6\_C}\cdot DW_{aa}$ = 111 gC/kg	CSA N288.1-14 (2014)
X_{7_C}	Stable carbon concentration in aquatic plants	$M_{aa}=X_{7\_C}\cdot DW_{aa}$ = 125 gC/kg	CSA N288.1-14 (2014)
RF_p	Reduction factor that accounts for the effect of soil water HTO concentrations that are lower than air moisture HTO concentrations	0.68	
H_a	Atmospheric absolute humidity	0.011 L/m^3	

Table B.1 – Default parameter values for Biosphere parameters (continued)

Parameter	Description	Default value	Source
BAF	Bioaccumulation factor	See Table A.8	
f_v	Fraction of the annual input of C-14 leaving the soil surface per annum	1	CSA N288.1-14 (2014)
M_{aa}	Mass of stable carbon in aquatic animals	121.8 gC/kg	CSA N288.1-14 (2014)
M_w	Mass of stable carbon in the dissolved inorganic phase in water	0.0213 gC/L	CSA N288.1-14 (2014)
f_0	Fraction of total time spent by the individual at the particular location (accounts for working and living at different locations)	1	
f_u	Time spent outdoors at a particular location as a fraction of total time spent at that location	0.2	
f_r	Dose reduction factor to account for non-uniformity of the ground surface	0.7	CSA N288.1-14 (2014)
I_w	Drinking water intake rate	2.96 L/d	U.S. EPA 95th percentile intake rate as specified in CSA N288.1-14 (2014)
I	Air inhalation rate	8400 m^3/yr	95th Percentile CSA N288.1-14 (2014)
I_f	Intake rate of plant, animal or fish produce [kg/yr]	Plant: 100 kg/yr Animal: 84.8 kg/yr Fish: 10.26 g/d	CSA N288.1-14 (2014)
I_s	Incidental intake of soil	0.02 g/d	95th Percentile CSA N288.1-14 (2014)

Table B.1 – Default parameter values for Biosphere parameters (continued)

Parameter	Description	Default value	Source
I_s	Incidental intake of sediment	0.00002 kg/d	CSA N288.1-14 (2014)
S_b	Building shielding factor, or fraction of the outdoor cloudshine dose that is received indoors	Pure beta emitters = 1 The pure beta emitters are C-14, Cl-36, Sr-90, Y-90, Cs-135, Cs-137, Bi-210, Kr-85, Sm-151, Se-79 and Tc-99 Others = 0.5	CSA N288.1-14 (2014)
S_g	Shielding factor for groundshine	Pure beta emitters = 0 Others = 0.2	CSA N288.1-14 (2014)
S_a	Skin surface area	2.19 m^2	95^{th} percentile CSA N288.1-14 (2014)
$(OF)_i$	Occupancy factor	1	CSA N288.1-14 (2014)
OF_w	Fraction of year spend swimming in surface water body	0.014 (assumes 1 hour swim per day, with 1/3 time at beaches and 2/3 in pool)	CSA N288.1-14 (2014)
OF'_w	Fraction of year spent taking baths	0.014 (≡ 20 minute bath every day)	CSA N288.1-14 (2014)
OF''_w	Fraction of year spent in a swimming pool	Groundwater = 0.014 (≡ 1 hour swim per day during summer months) Surface water = 0.028 (assumes 1 hour swim per day, with 1/3 time at beaches and 2/3 in pool)	CSA N288.1-14 (2014)
$(OF)_s$	Shoreline occupancy factor	0.02 (≡ 175 hours on contaminated shoreline per year)	
ρ_f	Modifying factor for food processing	1	CSA N288.1-14 (2014)
ρ_w	Removal factor to account for any water treatment	1	CSA N288.1-14 (2014)
ρ	Removal factor to account for processes such as sedimentation	1	CSA N288.1-14 (2014)

Table B.1 – Default parameter values for Biosphere parameters (continued)

Parameter	Description	Default value	Source
EF_s	Number of days per year in which incidental soil ingestion can occur	135 d/yr	CSA N288.1-14 (2014)
EF_{sed}	Number of days in year in which sediment ingestion can occur	45 d/yr	CSA N288.1-14 (2014)
g_f	Fraction of plant, animal or fish from contaminated sources	See table	Fn meat – need to check model
II	Inhalation/ingestion absorption ratio	See Table A.7	
W	Shore-width factor that describes the shoreline exposure geometry	Lake = 0.3 Riverbanks = 0.2	CSA N288.1-14 (2014)
v_g	Deposition velocity	Cl-36 = 2.53 x 10^{-2} m/s I-129 = 9.20 10^{-3} m/s Other = 6.47 10^{-3} m/s	
$(DF)_s$	Dilution factor for shoreline deposits	1	CSA N288.1-14 (2014)
D_c	Correction factor to account for finite size of bathtub	0.7	CSA N288.1-14 (2014)
D_s	Diffusion rate for wetted skin	0.2 ml/min·m^2	CSA N288.1-14 (2014)
$(DCF)_f$	Dose coefficient for intake by ingestion	See Table A.10	
$(DCF)_i$	Dose coefficient for inhalation	See Table A.10	
$(DCF)_a$	Effective dose coefficient for a semi-infinite cloud	See Table A.10	
$(DCF)_g$	Effective does coefficient for an infinite plane ground deposit	See Table A.10	

Table B.1 – Default parameter values for Biosphere parameters (continued)

Parameter	Description	Default value	Source
$(DCF)_w$	Dose coefficient for immersion in an infinite, uniformly contaminated water medium	See Table A.10	
$(DCF)_s$	Dose coefficient for a uniformly contaminated sediment	See Table A.10	
A_f	Area of irrigated field	Use site-specific data if known. Otherwise, assume = 10^6 m^2	CSA N288.1-14 (2014)
R_a	Ratio of concentration of tritium in air moisture at 1.5 m above ground to concentration of tritium in air moisture at ground level	0.7 if $A_f = 10^6$ m^2	CSA N288.1-14 (2014)
z_L	Depth of lake	4.6 m	NWMO (2013)
A_L	Area of lake	1000 m^2	NWMO (2013)
z_A	Height of air compartment	2 m	NWMO (2013)
$K_{water,Rn}$	Radon transfer coefficient from fresh water to air	6.7×10^{-6} $(mol/m^2 \cdot s)/(mol/m^3)$	Sheppard et al. (2002)
F_i	Correction factor to account for ice and lower temperature	0.8	NWMO (2013)
v_{ref}	Annual wind speed	2.36 m/s	NWMO (2013)
v_s	Wind speed at site	Assumed same as v_{ref} = 2.36 m/s	NWMO (2013)

Table B.2 – Default parameters for Biosphere Component that are a function of animal produce type

Produce type	Q_s [L/d]	Q_a [kg/d]	f_{OBT}	f'_{OBT}	f_{sl} [unitless]	WE_a	DW_a	X_{5_C}
Cow milk	0.2	91	0.04	0.042	0.1	0.67	0.1	65
Goat milk	0.02	13	0.07	0.075	0.1	0.67	0.1	65
Beef meat	0.1	91	0.11	0.12	0.1	0.8	0.3	201
Beef liver	0.1	91	0.11	0.12	0.1	0.8	0.3	201
Pork	0.03	23	0.13	0.15	0.001	0.9	0.5	304
Lamb	0.02	13	0.08	0.087	0.1	0.8	0.3	275
Poultry meat	0.005	0.7	0.1	0.11	0.001	0.8	0.3	244
Eggs	0.005	0.7	0.08	0.087	0.001	0.8	0.3	157
Deer	0.01	18	0.11	0.12	0.01	0.8	0.3	201
Rabbit	0.006	0.9	0.11	0.12	0.1	0.8	0.3	201
Canada goose	-	1.1	0.1	0.11	0.082	0.8	0.3	244
Mallard	-	0.45		0.11	0.02		0.3	

Table B.3 – Default parameter values for animal produce transfer parameters based on dry feed

Produce type	Q_w [L/d]	Q_f [kg/d]	f_{w_dw}	f_{w_pw}	f_{w_w}	f_{w_sw}
Cow milk	115	19.8	0.086	0.023	0.887	0.004
Goat milk	8	2.6	0.147	0.039	0.806	0.008
Beef meat	52	13.2	0.119	0.032	0.844	0.008
Beef liver	52	13.2	0.119	0.032	0.844	0.008
Pork	9	3.3	0.16	0.043	0.785	0.012
Lamb	5	1.7	0.152	0.041	0.795	0.012
Poultry meat	0.25	0.1	0.171	0.046	0.765	0.018
Eggs	0.25	0.1	0.171	0.046	0.765	0.018
Deer	8	2.5	0.143	0.038	0.808	0.011
Rabbit	0.54	0.11	0.1	0.027	0.864	0.01

Table B.4 – Default parameter values for animal produce transfer parameters based on wet feed

Produce type	Q_w [L/d]	Q_f [kg/d]	f_{w_dw}	f_{w_pw}	f_{w_w}	f_{w_sw}
Cow milk	89	19.8	0.062	0.44	0.495	0.003
Goat milk	5.9	2.6	0.082	0.582	0.332	0.004
Beef meat	43	13.2	0.071	0.51	0.413	0.005
Beef liver	43	13.2	0.071	0.51	0.413	0.005
Lamb	3.9	1.7	0.082	0.583	0.329	0.007
Deer	5.7	2.5	0.081	0.582	0.33	0.006
Rabbit	0.36	0.11	0.071	0.509	0.413	0.007
Canada goose	0.14	0.105	0.121	0.65	0.22	0.009
Mallard	0.06	-	-	-	0.22	0.009

Table B.5 – Soil-water sorption coefficients for overburden materials

Element	K_d [m^3/kg]				Source
	Sand	Loam	Clay	Organic	
Ac	0.45	1.5	2.4	5.4	NWMO (2013)
Am	2	9.6	8.1	0.11	NWMO (2013)
Bi	0.1	0.45	0.6	1.5	NWMO (2013)
C	0.005	0.02	0.001	0.07	CSA N288.1-14 (2014)
Cl	0.0001	0.0001	0.0001	2.2	NWMO (2013)
Co	0.06	1.3	0.54	0.99	NWMO (2013)
Cs	0.27	4.4	1.8	0.27	NWMO (2013)
H	0	0	0	0	CSA N288.1-14 (2014)
I	0.008	0.018	0.012	0.076	NWMO (2013)
Ir	0.003	0.003	0.003	0.003	IAEA (2010)
Kr	-	-	-	-	
Nb	0.17	2.5	2.5	2	CSA N288.1-14 (2014)
Np	0.0025	0.013	0.021	0.53	NWMO (2013)
Pa	0.54	1.8	2.7	6.6	NWMO (2013)
Pb	0.27	0.016	0	0.55	NWMO (2013)
Pd	0.055	0.18	0.27	0.67	NWMO (2013)
Po	0.15	0.4	3	7.3	NWMO (2013)
Pu	0.54	1.2	4.9	1.8	NWMO (2013)
Ra	0.047	0.047	0.047	0.047	NWMO (2013)
Rn	0	0	0	0	NWMO (2013)
Se	0.15	0.49	0.74	1.8	NWMO (2013)
Sm	0.245	0.8	1.3	3	NWMO (2013)
Sr	0.013	0.02	0.11	0.15	NWMO (2013)
Tc	0.00014	0.0001	0.0012	0.0015	NWMO (2013)
Th	3	3.3	5.4	0.089	NWMO (2013)
U	0.042	0.22	0.18	2.2	NWMO (2013)
Y	0.17	0.72	1	2.6	NWMO (2013)
Zr	0.6	2.2	3.3	7.3	NWMO (2013)

Table B.6 – Default concentration ratio values and translocation factors for potatoes

Element	CR		tf (potatoes)[1]	
	Value	**Reference**	Value	**Reference**
Ac	$3.43x10^{-3}$	NWMO (2013)	1	Assumed
Am	$1.70x10^{-3}$	CSA N288.1-14 (2014)	0.01	CSA N288.1-14 (2014)
Bi	$1.31x10^{-2}$	NWMO (2013)	1	Assumed
C	$2.20x10^{1}$	NWMO (2013)	1	CSA N288.1-14 (2014)
Cl	$8.90x10^{1}$	CSA N288.1-14 (2014)	1	CSA N288.1-14 (2014)
Co	$4.70x10^{-2}$	CSA N288.1-14 (2014)	0.1	CSA N288.1-14 (2014)
Cs	$5.30x10^{-2}$	CSA N288.1-14 (2014)	1	CSA N288.1-14 (2014)
H	-	CSA N288.1-14 (2014)	1	CSA N288.1-14 (2014)
I	$5.00x10^{-2}$	CSA N288.1-14 (2014)	0.1	CSA N288.1-14 (2014)
Ir	-		1	Assumed
Kr	-		1	Assumed
Nb	$2.90x10^{-2}$	CSA N288.1-14 (2014)	0.1	CSA N288.1-14 (2014)
Np	$8.40x10^{-3}$	CSA N288.1-14 (2014)	0.1	CSA N288.1-14 (2014)
Pa	$3.80x10^{-2}$	NWMO (2013)	0.1	CSA N288.1-14 (2014)
Pb	$2.40x10^{-3}$	NWMO (2013)	1	Assumed
Pd	$1.90x10^{-1}$	NWMO (2013)	1	Assumed
Po	$2.51x10^{-3}$	NWMO (2013)	1	Assumed
Pu	$1.40x10^{-4}$	NWMO (2013)	0.01	CSA N288.1-14 (2014)
Ra	$1.10x10^{-1}$	CSA N288.1-14 (2014)	1	CSA N288.1-14 (2014)
Rn	0.00	NWMO (2013)	0	Assumed
Se	$4.51x10^{-1}$	CSA N288.1-14 (2014)	1	CSA N288.1-14

				(2014)
Sm	$7.14x10^{-3}$	NWMO (2013)	1	Assumed
Sr	$8.70x10^{-1}$	CSA N288.1-14 (2014)	1	CSA N288.1-14 (2014)
Tc	$3.70x10^{0}$	CSA N288.1-14 (2014)	1	CSA N288.1-14 (2014)
Th	$3.30x10^{-3}$	CSA N288.1-14 (2014)	0.01	CSA N288.1-14 (2014)
U	$1.00x10^{-2}$	CSA N288.1-14 (2014)	0.1	CSA N288.1-14 (2014)
Y	$2.20x10^{-2}$	CSA N288.1-14 (2014)	0.1	CSA N288.1-14 (2014)
Zr	$3.20x10^{-3}$	CSA N288.1-14 (2014)	0.1	CSA N288.1-14 (2014)

1. Assumed a conservative value of 1 where data was not available

Table B.7 – Default values of P_{28} and II

Element	P_{28} [L/kg]	Reference	II	Reference
Ac	4500	NWMO (2013)	520	NWMO (2013)
Am	210000	IAEA (2010)	241	CSA N288.1-14 (2014)
Bi	1000	NWMO (2013)	11	NWMO (2013)
C	50	CSA N288.1-14 (2014)	0.02	CSA N288.1-14 (2014)
Cl	20	CSA N288.1-14 (2014)	0.63	CSA N288.1-14 (2014)
Co	43000	IAEA (2010)	1.71	CSA N288.1-14 (2014)
Cs	9500	IAEA (2010)	0.63	CSA N288.1-14 (2014)
H	0	CSA N288.1-14 (2014)	-	CSA N288.1-14 (2014)
I	4400	IAEA (2010)	0.63	CSA N288.1-14 (2014)
Ir	-		-	
Kr	-		-	

Nb	1700	CSA N288.1-14 (2014)	12.5	CSA N288.1-14 (2014)
Np	10	IAEA (2010)	241	CSA N288.1-14 (2014)
Pa	5400	CSA N288.1-14 (2014)	241	CSA N288.1-14 (2014)
Pb	2700	NWMO (2013)	3	NWMO (2013)
Pd	550	NWMO (2013)	100	NWMO (2013)
Po	1500	NWMO (2013)	5.6	NWMO (2013)
Pu	240000	IAEA (2010)	241	CSA N288.1-14 (2014)
Ra	7400	IAEA (2010)	1.1	CSA N288.1-14 (2014)
Rn	0	NWMO (2013)	0	NWMO (2013)
Se	560	CSA N288.1-14 (2014)	0.75	CSA N288.1-14 (2014)
Sm	2450	NWMO (2013)	480	NWMO (2013)
Sr	190	IAEA (2010)	0.91	CSA N288.1-14 (2014)
Tc	5	IAEA (2010)	0.75	CSA N288.1-14 (2014)
Th	190000	IAEA (2010)	101	CSA N288.1-14 (2014)
U	50	IAEA (2010)	6.5	CSA N288.1-14 (2014)
Y	1700	CSA N288.1-14 (2014)	1201	CSA N288.1-14 (2014)
Zr	1000	IAEA (2010)	12.5	CSA N288.1-14 (2014)

Table B.8 – Default BAF values for freshwater fish and plants

Element	**BAF [L/kg] (freshwater fish)**		**BAF [L/kg] (freshwater plant)**	
	Value	**Reference**	**Value**	**Reference**
Ac	25	NWMO (2013)		

Am	240	CSA N288.1-14 (2014) IAEA (2010)	3100	CSA N288.1-14 (2014)
Bi	15	NWMO (2013)		
C	5700	NWMO (2013)	5900	CSA N288.1-14 (2014)
Cl	50	NWMO (2013)	50	CSA N288.1-14 (2014)
Co	76	IAEA (2010)		
Cs	3500	NWMO (2013)		
HTO	0.75	CSA N288.1-14 (2014)	0.75	CSA N288.1-14 (2014)
OBT	0.14	CSA N288.1-14 (2014)	0.11	CSA N288.1-14 (2014)
I	6	CSA N288.1-14 (2014)	71	CSA N288.1-14 (2014)
Ir	-		-	
Kr	-		-	
Nb	300	CSA N288.1-14 (2014)	1200	CSA N288.1-14 (2014)
Np	150	NWMO (2013)	1900	CSA N288.1-14 (2014)
Pa	10	CSA N288.1-14 (2014) NWMO (2013)	300	CSA N288.1-14 (2014)
Pb	300	NWMO (2013)	1900	IAEA (2010)
Pd	10	NWMO (2013)		
Po	500	NWMO (2013)		
Pu	21000	CSA N288.1-14 (2014) IAEA (2010)	4000	CSA N288.1-14 (2014)
Ra	50	NWMO (2013)	1200	CSA N288.1-14 (2014)
Rn	0	NWMO (2013)		
Se	6000	CSA N288.1-14 (2014) IAEA (2010)	110	CSA N288.1-14 (2014)
Sm	30	NWMO (2013)		
Sr	2	CSA N288.1-14 (2014)	370	CSA N288.1-14 (2014)
Tc	20	CSA N288.1-14 (2014) NWMO (2013)	7.6	CSA N288.1-14 (2014)
Th	100	NWMO (2013)	2200	CSA N288.1-14 (2014)
U	50	NWMO (2013)	1100	CSA N288.1-14 (2014)
Y	20	CSA N288.1-14 (2014)	7100	CSA N288.1-14 (2014)
Zr	7	CSA N288.1-14 (2014)	3200	CSA N288.1-14 (2014)

Table B.9 – Default values of F_{ing} [d/kg][1]

Element	Cow milk	Goat milk	Beef meat	Beef liver	Pork	Lamb	Poultry	Eggs	Deer	Rabbit
Ac	$2x10^{-5}$		$2.5x10^{-5}$				$2.5x10^{-3}$			
Am	$4.2x10^{-7}$	$6.9x10^{-6}$	$5.0x10^{-4}$	$2.0x10^{-2}$	$7.4x10^{-5}$	$1.1x10^{-4}$	$1.2x10^{-3}$	$3.0x10^{-3}$	$2.3x10^{-4}$	$3.3x10^{-3}$
Bi	$5.0x10^{-4}$		$4.0x10^{-4}$				$4.0x10^{-2}$			
C	$2.8x10^{-2}$		$8.8x10^{-2}$				$8.5x10^{0}$			
Cl	$1.84x10^{-2}$	$1.84x10^{-2}$	$1.7x10^{-2}$	$2.8x10^{-2}$	$6.5x10^{-5}$	$2.6x10^{-1}$	$1.8x10^{0}$	$2.1x10^{0}$	$1.4x10^{-1}$	$2.0x10^{0}$
Co	$1.1x10^{-4}$	$5.0x10^{-3}$	$4.3x10^{-4}$	$1.0x10^{-1}$	$4.1x10^{-2}$	$1.2x10^{-2}$	$9.7x10^{-1}$	$3.3x10^{-2}$	$1.2x10^{-2}$	$1.8x10^{-1}$
Cs	$4.6x10^{-3}$	$1.1x10^{-1}$	$2.2x10^{-2}$	$3.0x10^{-2}$	$2.0x10^{-1}$	$1.9x10^{-1}$	$2.7x10^{0}$	$4.0x10^{-1}$	$1.5x10^{-1}$	$1.1x10^{2}$
H	-	-	-	-	-	-	-	-	-	-
I	$5.4x10^{-3}$	$2.2x10^{-1}$	$6.7x10^{-3}$	$2.0x10^{-3}$	$4.1x10^{-2}$	$3.0x10^{-2}$	$8.7x10^{-3}$	$2.4x10^{0}$	$3.2x10^{-2}$	$4.6x10^{-1}$
Ir	-	-	-	-	-	-	-	-	-	-
Kr	-	-	-	-	-	-	-	-	-	-
Nb	$4.1x10^{-7}$	$6.4x10^{-6}$	$2.6x10^{-7}$	$1.0x10^{-5}$	$2.0x10^{-4}$	$1.7x10^{-4}$	$3.0x10^{-4}$	$1.0x10^{-3}$	$3.0x10^{-4}$	$4.2x10^{-3}$
Np	$4.0x10^{-6}$	$5.3x10^{-5}$	$3.8x10^{-4}$	$2.0x10^{-2}$	$4.5x10^{-5}$	$4.0x10^{-4}$	$3.1x10^{-3}$	$9.7x10^{-3}$	$6.2x10^{-4}$	$8.9x10^{-3}$
Pa	$5.0x10^{-6}$	$1.7x10^{-5}$	$1.1x10^{-5}$	$1.1x10^{-3}$	$1.1x10^{-4}$	$3.4x10^{-4}$	$2.0x10^{-3}$	$2.0x10^{-3}$	$9.8x10^{-5}$	$1.4x10^{-3}$
Pb	$2.6x10^{-4}$	$6.0x10^{-3}$	$4.0x10^{-4}$			$7.1x10^{-3}$	$4.0x10^{-2}$			
Pd	$1.0x10^{-2}$		$4.0x10^{-3}$				$4.0x10^{-1}$			
Po	$3.4x10^{-4}$	$2.3x10^{-3}$	$4.5x10^{-3}$				$2.4x10^{0}$	$3.1x10^{0}$		
Pu	$1.0x10^{-5}$	$9.4x10^{-6}$	$1.1x10^{-6}$	$2.0x10^{-2}$	$2.8x10^{-5}$	$5.3x10^{-5}$	$9.2x10^{-4}$	$1.2x10^{-3}$	$2.5x10^{-4}$	$3.5x10^{-3}$
Ra	$3.8x10^{-4}$	$1.1x10^{-3}$	$1.7x10^{-3}$	$9.5x10^{-4}$	$2.2x10^{-3}$	$8.6x10^{-3}$	$3.0x10^{-2}$	$3.1x10^{-1}$	$4.6x10^{-3}$	$6.6x10^{-2}$
Rn	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Se	$4.0x10^{-3}$	$6.9x10^{-2}$	$1.0x10^{-1}$	$1.0x10^{-1}$	$3.2x10^{-1}$	$9.1x10^{-1}$	$9.7x10^{0}$	$1.6x10^{1}$	$4.9x10^{-1}$	$6.9x10^{0}$

Table B.9 – Default values of F_{ing} [d/kg] (continued)

Element	Cow milk	Goat milk	Beef meat	Beef liver	Pork	Lamb	Poultry	Eggs	Deer	Rabbit
Sm	$2.0x10^{-5}$		$5.0x10^{-3}$				$5.0x10^{-1}$			
Sr	$1.3x10^{-3}$	$3.0x10^{-2}$	$1.3x10^{-3}$	$3.0x10^{-4}$	$2.5x10^{-3}$	$1.5x10^{-3}$	$2.0x10^{-2}$	$3.5x10^{-1}$	$4.0x10^{-2}$	$1.9x10^{-1}$
Tc	$6.9x10^{-4}$	$1.1x10^{-3}$	$9.6x10^{-4}$	$4.0x10^{-2}$	$2.1x10^{-3}$	$4.7x10^{-3}$	$4.1x10^{-1}$	$1.9x10^{0}$	$3.4x10^{-3}$	$4.9x10^{-2}$
Th	$2.3x10^{-5}$	$7.7x10^{-5}$	$2.3x10^{-4}$	$6.3x10^{-2}$	$4.6x10^{-3}$	$1.3x10^{-2}$	$1.0x10^{-2}$	$1.0x10^{-2}$	$2.0x10^{-3}$	$2.8x10^{-2}$
U	$1.8x10^{-3}$	$1.4x10^{-3}$	$3.9x10^{-4}$	$6.9x10^{-4}$	$4.4x10^{-2}$	$7.4x10^{-3}$	$7.5x10^{-1}$	$1.1x10^{0}$	$7.3x10^{-1}$	$4.1x10^{-2}$
Y	$2.9x10^{-5}$	$2.0x10^{-5}$	$1.2x10^{-3}$	$1.0x10^{-2}$	$2.0x10^{-4}$	$1.0x10^{-2}$	$1.3x10^{-2}$	$3.9x10^{-3}$	$5.6x10^{-3}$	$7.9x10^{-2}$
Zr	$3.6x10^{-6}$	$5.5x10^{-6}$	$1.2x10^{-6}$	$1.0x10^{-5}$	$3.5x10^{-3}$	$4.5x10^{-5}$	$6.0x10^{-5}$	$2.0x10^{-4}$	$5.0x10^{-5}$	$7.1x10^{-4}$

1. Data obtained primarily from CSA N288.1-14 (2014) and missing data obtained from NWMO (2013) and IAEA (2010)

Appendix C – Biosphere Information for CNL Near Surface Waste Facility Test Case

Table C.1 – Percent of food ingested from local sources and intake rates for Pembroke

Intake	1-year old			10-year old			Adult		
	% Local	Local intake	Fraction	% Local	Local intake	Fraction	% Local	Local intake	Fraction
Milk	92.7	314.8 kg/yr	NA	80.3	256.5 kg/yr	NA	49.6	93.4 kg/yr	NA
Animal Produce									
Beef*	0.2	0.015 kg/yr	0.29	0.5	0.115 kg/yr	0.30	1.6	1.21 kg/yr	0.51
Pork	0.1	0.0049 kg/yr	0.095	0.3	0.044 kg/yr	0.11	0.7	0.21 kg/yr	0.088
Poultry	0.25	0.029 kg/yr	0.56	0.62	0.190 kg/yr	0.50	1.23	0.72 kg/yr	0.303
Egg	0.1	0.0030 kg/yr	0.058	0.3	0.034 kg/yr	0.09	0.8	0.23 kg/yr	0.097
Total		0.051 kg/yr			0.382 kg/yr			2.36 kg/yr	
Plant Produce									
Fruit and Berry	4.6	3.5 kg/yr	0.47	3.3	4.1 kg/yr	0.25	2.8	4.17 kg/yr	0.14
AG Veg/Mushroom	3.4	3.9 kg/yr	0.52	4.0	11.8 kg/yr	0.72	5.5	24.2 kg/yr	0.82
Root vegetable	0.8	0.096 kg/yr	0.013	1.2	0.036 kg/yr	0.031	1.4	1.01 kg/yr	0.034
Total		7.48 kg/yr			16.5 kg/yr			29.33 kg/yr	
Fish	0.53	0.012 kg/yr	NA	0.53	0.0358 kg/yr	NA	0.53	0.0546 kg/yr	NA
Soil	93	0.19 g/d	NA	93	0.17 g/d	NA	93	0.0186 g/d	NA
Sediment	100	2.04×10^{-4} kg/d	NA	100	1.85×10^{-4} kg/d	NA	100	2×10^{-5} kg/d	NA
Inhalation	93	2548 m^3/yr	NA	93	7301 m^3/yr	NA	93	7812 m^3/yr	NA
Water ingestion	75	0.2295 m^3/yr	NA	75	0.362 m^3/yr	NA	75	0.81 m^3/yr	NA

* Beef includes Beef + beef offal + veal + lamb + deer + rabbit

Table C.2 – Percent of food ingested from local sources and intake rates for Laurentian Valley

Intake	1-year old			10-year old			Adult		
	% Local	Local intake	Fraction	% Local	Local intake	Fraction	% Local	Local intake	Fraction
Milk	92.7	314.8 kg/yr	NA	80.3	256.5 kg/yr	NA	49.6	93.4 kg/yr	NA
Animal Produce									
Beef*	0.4	0.029 kg/yr	0.31	1.1	0.253 kg/yr	0.34	3.9	2.95 kg/yr	0.59
Pork	0.2	0.0098 kg/yr	0.10	0.5	0.073 kg/yr	0.10	1.0	0.30 kg/yr	0.060
Poultry	0.47	0.054 kg/yr	0.56	1.15	0.352 kg/yr	0.48	2.3	1.34 kg/yr	0.27
Egg	0.1	0.0030 kg/yr	0.031	0.5	0.0565 kg/yr	0.077	1.4	0.40 kg/yr	0.081
Total		0.096 kg/yr			0.734 kg/yr			4.99 kg/yr	
Plant Produce									
Fruit and Berry	5.8	4.44 kg/yr	0.40	4.1	5.1 kg/yr	0.197	3.5	5.22 kg/yr	0.11
AG Veg/Mushroom	5.7	6.48 kg/yr	0.58	6.7	19.8 kg/yr	0.765	9.3	40.8 kg/yr	0.85
Root vegetable	1.5	0.182 kg/yr	0.016	2.3	1.00 kg/yr	0.0383	2.7	1.94 kg/yr	0.04
Total		11.1 kg/yr			25.9 kg/yr			48.0 kg/yr	
Fish	0.66	0.015 kg/yr	NA	0.66	0.045 kg/yr	NA	0.66	0.068 kg/yr	NA
Soil	7	0.014 g/d	NA	7	0.013 g/d	NA	7	0.0014 g/d	NA
Sediment	100	2.04×10^{-4} kg/d	NA	100	1.85×10^{-4} kg/d	NA	100	2×10^{-5} kg/d	NA
Inhalation	7	191.8 m^3/yr	NA	7	549.5 m^3/yr	NA	7	588 m^3/yr	NA
Water ingestion	3	0.0092 m^3/yr	NA	3	0.014 m^3/yr	NA	3	0.032 m^3/yr	NA

* Beef includes Beef + beef offal + veal + lamb + deer + rabbit

Table C.3 – Percent of food ingested from local sources and intake rates for Petawawa

Intake	1-year old			10-year old			Adult		
	% Local	Local intake	Fraction	% Local	Local intake	Fraction	% Local	Local intake	Fraction
Milk	92.7	314.8 kg/yr	NA	80.3	256.5 kg/yr	NA	49.6	93.4 kg/yr	NA
Animal Produce									
Beef*	0.1	0.0073 kg/yr	0.515	0.3	0.069 kg/yr	0.55	1.2	0.91 kg/yr	0.77
Pork	0	0 kg/yr	0	0	0 kg/yr	0	0.1	0.030 kg/yr	0.025
Poultry	0.06	0.0069 kg/yr	0.485	0.15	0.046 kg/yr	0.36	0.31	0.18 kg/yr	0.15
Egg	0	0 kg/yr	0	0.1	0.011 kg/yr	0.09	0.2	0.058 kg/yr	0.049
Total		0.014 kg/yr			0.126 kg/yr			1.18 kg/yr	
Plant Produce									
Fruit and Berry	3.0	2.30 kg/yr	0.42	2.1	2.61 kg/yr	0.21	1.8	2.68 kg/yr	0.12
AG Veg/Mushroom	2.7	3.1 kg/yr	0.56	3.1	9.18 kg/yr	0.77	4.4	19.3 kg/yr	0.84
Root vegetable	0.7	0.085 kg/yr	0.016	1.1	0.048 kg/yr	0.039	1.3	0.93 kg/yr	0.041
Total		5.45 kg/yr			12.3 kg/yr			22.9 kg/yr	
Fish	0.57	0.013 kg/yr	NA	0.57	0.038 kg/yr	NA	0.57	0.059 kg/yr	NA
Soil	90	0.184 g/d	NA	90	0.167 g/d	NA	90	0.019 g/d	NA
Sediment	100	2.04×10^{-4} kg/d	NA	100	1.85×10^{-4} kg/d	NA	100	2×10^{-5} kg/d	NA
Inhalation	90	2466 m^3/yr	NA	90	7065 m^3/yr	NA	90	7560 m^3/yr	NA
Water ingestion	86	0.263 m^3/yr	NA	86	0.415 m^3/yr	NA	86	0.93 m^3/yr	NA

* Beef includes Beef + beef offal + veal + lamb + deer + rabbit

Table C.4 – Percent of food ingested from local sources and intake rates for Cottager

Intake	1-year old			10-year old			Adult		
	% Local	Local intake	Fraction	% Local	Local intake	Fraction	% Local	Local intake	Fraction
Milk	92.7	314.8 kg/yr	NA	80.3	256.5 kg/yr	NA	49.6	93.4 kg/yr	NA
Animal Produce									
Beef*	0.1	0.0073 kg/yr	0.15	0.3	0.069 kg/yr	0.20	1.0	0.756 kg/yr	0.38
Pork	0.1	0.0049 kg/yr	0.10	0.1	0.015 kg/yr	0.042	0.3	0.089 kg/yr	0.045
Poultry	0.28	0.032 kg/yr	0.68	0.69	0.21 kg/yr	0.60	1.38	0.80 kg/yr	0.40
Egg	0.1	0.0030 kg/yr	0.063	0.5	0.057 kg/yr	0.16	1.2	0.35 kg/yr	0.17
Total		0.047 kg/yr			0.35 kg/yr			2.00 kg/yr	
Plant Produce									
Fruit and Berry	5.6	4.3 kg/yr	0.59	4.0	5.0 kg/yr	0.35	3.3	4.9 kg/yr	0.21
AG Veg/Mushroom	2.5	2.8 kg/yr	0.39	2.9	8.6 kg/yr	0.61	4.1	18.0 kg/yr	0.75
Root vegetable	0.8	0.097 kg/yr	0.013	1.3	0.056 kg/yr	0.040	1.5	1.08 kg/yr	0.045
Total		7.22 kg/yr			14.1 kg/yr			24.0 kg/yr	
Fish	2.27	0.052 kg/yr	NA	2.27	0.15 kg/yr	NA	2.27	0.23 kg/yr	NA
Soil	38	0.078 g/d	NA	38	0.070 g/d	NA	38	0.0076 g/d	NA
Sediment	100	2.04×10^{-4} kg/d	NA	100	1.85×10^{-4} kg/d	NA	100	2×10^{-5} kg/d	NA
Inhalation	38	1041 m^3/yr	NA	38	2983 m^3/yr	NA	38	3192 m^3/yr	NA
Water ingestion	1	0.0031 m^3/yr	NA	1	0.0048 m^3/yr	NA	1	0.011 m^3/yr	NA

* Beef includes Beef + beef offal + veal + lamb + deer + rabbit

Table C.5 – Parameters required to model near-surface waste facility

Radionuclide	BAF fish (L/kg)	Volatilization Losses (1/yr)	P_{28} (Transfer from water to sediments) (L/kg)	Concentration Ratios	Translocation Factors
Ac-227	25	0	4500	3.43E-03	0
Ag-108m	110	0	9.5E04	1.7E-03	1
Am-241	240	0	2.1E05	6.3E-04	0.01
Am-243	240	0	2.1E05	6.3E-04	0.01
C-14	5700	13.6	50	22	1
Cl-36	50	9.47E-04	20	89	1
Co-60	76	0	4.3E04	4.7E-02	0.1
Cs-135	3500	0	9.5E03	5.3E-02	1
Cs-137	3500	0	9.5E03	5.3E-02	1
H-3	0	0	0	0	1
I-129	6	0.021	4.4E03	5.0E-02	0.1
Mo-93	460	0	1.0E02	3.6E-01	1
Nb-93m	300	0	1.70E3	2.9E-02	0.1
Nb-94	300	0	1.7E03	2.9E-02	0.1
Ni-59	21	0	1.4E03	4.7E-01	1
Ni-63	21	0	1.4E03	4.7E-01	1
Np-237	150	0	1.0E01	8.4E-03	0.1
Pa-231	10	0	5.4E03	3.8E-02	0.1
Pb-210	300	0	2.7E03	2.4E-03	0
Po-210	500	0	1.5E03	2.51E-03	0
Pu-239	21,000	0	2.4E05	1.4E-04	0.01
Pu-240	21,000	0	2.4E05	1.4E-04	0.01
Pu-241	21,000	0	2.4E05	1.4E-04	0.01
Pu-242	21,000	0	2.4E05	1.4E-04	0.01
Ra-226	50	0	7.4E03	1.1E-01	1
Ra-228	50	0	7.4E03	1.1E-01	1
Se-79	6,000	3.16E-02	5.6E02	4.5E-01	1
Sn-126	3,000	0	1.3E03	4.1E-01	1
Sr-90	2	0	1.9E02	8.7E-01	1

Table C.5 (continued) – Parameters required to model near-surface waste facility

Radionuclide	BAF fish (L/kg)	Volatilization Losses (1/yr)	P_{28} (Transfer from water to sediments) (L/kg)	Concentration Ratios	Translocation Factors
Tc-99	20	0	5	3.7	1
Th-228	100	0	1.9E05	3.3E-03	0.01
Th-229	100	0	1.9E05	3.3E-03	0.01
Th-230	100	0	1.9E05	3.3E-03	0.01
Th-232	100	0	1.9E05	3.3E-03	0.01
U-233	50	0	50	1.0E-02	0.1
U-234	50	0	50	1.0E-02	0.1
U-235	50	0	50	1.0E-02	0.1
U-236	50	0	50	1.0E-02	0.1
U-238	50	0	50	1.0E-02	0.1
Zr-93	7	0	1.0E03	3.2E-03	0.1

Appendix D – Dose Coefficients

Table D.1 – Ingestion dose coefficients (Sv/Bq)

Radionuclide	1-year old	10-year old	Adult	Radionuclide	1-year old	10-year old	Adult
Ac-227	3.10E-06	1.50E-06	1.10E-06	Pu-239	4.20E-07	2.40E-07	2.50E-07
Ag-108m	1.10E-08	4.30E-09	2.30E-09	Pu-240	4.20E-07	2.70E-07	2.50E-07
Am-241	3.70E-07	2.20E-07	2.00E-07	Pu-241	5.70E-09	5.10E-09	4.80E-09
Am-243	3.70E-07	2.20E-07	2.00E-07	Pu-242	4.00E-07	2.60E-07	2.40E-07
C-14	1.60E-09	8.00E-10	5.80E-10	Ra-226	9.60E-07	8.00E-07	2.80E-07
Cl-36	6.30E-09	1.90E-09	9.30E-10	Ra-228	5.70E-06	3.90E-06	6.90E-07
Co-60	2.70E-08	1.10E-08	3.40E-09	Se-79	2.80E-08	1.40E-08	2.90E-09
Cs-135	2.30E-09	1.70E-09	2.00E-09	Sn-126	3.00E-08	9.80E-09	4.70E-09
Cs-137	1.20E-08	1.00E-08	1.30E-08	Sr-90	7.30E-08	6.00E-08	2.80E-08
H-3 (HTO)	5.30E-11	2.50E-11	2.00E-11	Tc-99	4.80E-09	1.30E-09	6.40E-10
H-3 (OBT)	1.30E-10	6.30E-11	4.60E-11	Th-228	3.70E-07	1.50E-07	7.20E-08
I-129	2.20E-07	1.90E-07	1.10E-07	Th-229	1.00E-06	6.20E-07	4.90E-07
Mo-93	6.90E-09	4.00E-09	3.10E-09	Th-230	4.10E-07	2.40E-07	2.10E-07
Nb-93m	9.10E-10	2.70E-10	1.20E-10	Th-232	4.50E-07	2.90E-07	2.30E-07
Nb-94	9.70E-9	3.40E-9	1.70E-09	U-233	1.40E-07	7.80E-08	5.10E-08
Ni-59	3.40E-10	1.10E-10	6.30E-11	U-234	1.30E-07	7.40E-08	4.90E-08
Ni-63	8.40E-10	2.80E-10	1.50E-10	U-235	1.30E-07	7.10E-08	4.70E-08
Np-237	2.10E-07	1.10E-07	1.10E-07	U-236	1.30E-07	7.00E-08	4.70E-08
Pa-231	1.30E-06	9.20E-07	7.10E-07	U-238	1.20E-07	6.80E-08	4.50E-08
Pb-210	3.60E-06	1.90E-06	6.90E-07	Zr-93	7.60E-10	5.80E-10	1.10E-09
Po-210	8.80E-06	2.60E-06	1.20E-06				

Table D.2 – Air inhalation dose coefficients (Sv/Bq)

Radionuclide	1-year old	10-year old	Adult	Radionuclide	1-year old	10-year old	Adult
Ac-227	1.60E-03	7.72E-04	5.50E-04	Pu-239	7.70E-05	4.80E-05	5.00E-05
Ag-108m	8.70E-08	4.40E-08	3.70E-08	Pu-240	7.70E-05	4.80E-05	5.00E-05
Am-241	6.90E-05	4.00E-05	4.20E-05	Pu-241	9.70E-07	8.30E-07	9.00E-07
Am-243	6.80E-05	4.00E-05	4.10E-05	Pu-242	7.30E-05	4.50E-05	4.80E-05
C-14	1.70E-08	7.40E-09	2.00E-09	Ra-226	1.10E-05	4.90E-06	3.50E-06
Cl-36	2.60E-08	1.00E-08	7.30E-09	Ra-228	4.80E-05	2.00E-05	2.60E-06
Co-60	3.40E-08	1.50E-08	1.00E-08	Se-79	2.00E-08	8.70E-09	6.80E-09
Cs-135	9.90E-10	6.10E-10	6.90E-10	Sn-126	1.00E-07	4.10E-08	2.80E-08
Cs-137	5.40E-09	3.70E-09	4.60E-09	Sr-90	1.10E-07	5.10E-08	3.60E-08
H-3 (HTO)	8.00E-11	3.80E-11	3.00E-11	Tc-99	1.30E-08	5.70E-09	4.00E-09
H-3 (HT)	5.30E-15	2.50E-15	2.00E-15	Th-228	1.30E-04	5.50E-05	4.00E-05
I-129	2.00E-07	1.70E-07	1.70E-07	Th-229	1.90E-04	8.70E-05	7.10E-05
Mo-93	5.80E-09	2.80E-09	2.30E-09	Th-230	3.50E-05	1.60E-05	1.40E-05
Nb-93m	6.50E-09	2.50E-09	1.80E-09	Th-232	5.00E-05	2.60E-05	2.50E-05
Nb-94	3.70E-08	1.60E-08	1.10E-08	U-233	1.10E-05	4.90E-06	3.60E-06
Ni-59	1.50E-09	5.90E-10	4.40E-10	U-234	1.10E-05	4.80E-06	3.50E-06
Ni-63	1.90E-09	7.00E-10	4.80E-10	U-235	1.00E-05	4.30E-06	3.10E-06
Np-237	4.00E-05	2.20E-05	2.30E-05	U-236	1.00E-05	4.50E-06	3.20E-06
Pa-231	6.90E-05	3.90E-05	1.40E-04	U-238	9.40E-06	4.00E-06	2.90E-06
Pb-210	1.80E-05	7.20E-06	1.10E-06	Zr-93	6.40E-09	9.70E-09	2.50E-09
Po-210	1.40E-05	5.90E-06	4.30E-06				

Table D.3 – Air immersion dose coefficients ((Sv/yr)/(Bq/m^3))

Radionuclide	1-year old	10-year old	Adult	Radionuclide	1-year old	10-year old	Adult
Ac-227	2.39E-10	1.84E-10	1.84E-10	Pu-239	1.43E-10	1.08E-10	1.08E-10
Ag-108m	3.20E-06	2.46E-06	2.46E-06	Pu-240	1.40E-10	1.08E-10	1.08E-10
Am-241	2.77E-08	2.13E-08	2.13E-08	Pu-241	2.60E-12	3.69E-12	3.69E-12
Am-243	7.59E-08	8.68E-08	8.68E-08	Pu-242	1.19E-10	9.15E-11	9.15E-11
C-14	8.21E-11	8.21E-11	8.21E-11	Ra-226	1.16E-08	8.96E-09	8.96E-09
Cl-36	5.23E-09	5.23E-09	5.23E-09	Ra-228	1.85E-06	1.42E-06	1.42E-06
Co-60	4.89E-06	3.76E-06	3.76E-06	Se-79	1.24E-11	9.56E-12	9.56E-12
Cs-135	3.00E-10	3.00E-10	3.00E-10	Sn-126	8.65E-08	6.65E-08	6.65E-08
Cs-137	2.93E-09	2.93E-09	2.93E-09	Sr-90	3.10E-09	3.10E-09	3.10E-09
H-3	0	0	0	Tc-99	9.06E-10	9.06E-10	9.06E-10
I-129	1.15E-08	8.87E-09	8.87E-09	Th-228	3.32E-09	2.56E-09	2.56E-09
Mo-93	1.03E-09	7.95E-10	7.95E-10	Th-229	1.38E-07	1.06E-07	1.06E-07
Nb-93m	1.82E-10	1.40E-10	1.40E-10	Th-230	6.07E-10	4.67E-10	4.67E-10
Nb-94	2.95E-06	2.27E-06	2.27E-06	Th-232	2.97E-10	2.28E-10	2.28E-10
Ni-59	0	0	0	U-233	5.82E-10	4.48E-10	4.48E-10
Ni-63	0	0	0	U-234	2.51E-10	1.93E-10	1.93E-10
Np-237	3.64E-08	2.58E-08	2.58E-08	U-235	2.65E-07	2.04E-07	2.04E-07
Pa-231	6.44E-08	4.95E-08	4.95E-08	U-236	1.59E-10	1.22E-10	1.22E-10
Pb-210	2.31E-09	1.78E-09	1.78E-09	U-238	1.03E-10	7.89E-11	7.89E-11
Po-210	1.71E-11	1.31E-11	1.31E-11	Zr-93	0.0	0.00	0.00

Table D.4 – Water immersion dose coefficients ((Sv/yr)/(Bq/L))

Radionuclide	1-year old	10-year old	Adult	Radionuclide	1-year old	10-year old	Adult
Ac-227	5.33E-10	4.10E-10	4.10E-10	Pu-239	3.21E-10	2.47E-10	2.47E-10
Ag-108m	6.93E-06	5.33E-06	5.33E-06	Pu-240	3.28E-10	2.52E-10	2.52E-10
Am-241	6.32E-08	4.86E-08	4.86E-08	Pu-241	5.79E-12	4.45E-12	4.45E-12
Am-243	1.72E-07	1.32E-07	1.32E-07	Pu-242	2.77E-10	2.13E-10	2.13E-10
C-14	9.09E-11	9.09E-11	9.09E-11	Ra-226	2.85E-08	2.19E-08	2.19E-08
Cl-36	6.15E-09	6.15E-09	6.15E-09	Ra-228	0	0	0
Co-60	1.05E-05	8.11E-06	8.11E-06	Se-79	2.43E-11	1.37E-10	1.37E-10
Cs-135	3.28E-10	3.28E-10	3.28E-10	Sn-126	1.95E-07	1.50E-07	1.50E-07
Cs-137	3.27E-09	3.27E-08	3.27E-08	Sr-90	3.44E-09	3.44E-09	3.44E-09
H-3	0	0	0	Tc-99	9.88E-10	9.88E-10	9.88E-10
I-129	2.69E-08	2.07E-08	2.07E-08	Th-228	8.40E-09	6.46E-09	6.46E-09
Mo-93	2.43E-09	1.87E-09	1.87E-09	Th-229	3.07E-07	2.36E-07	2.36E-07
Nb-93m	4.26E-10	3.28E-10	3.28E-10	Th-230	1.62E-09	1.24E-09	1.24E-09
Nb-94	6.40E-06	4.92E-06	4.92E-06	Th-232	6.72E-10	5.17E-10	5.17E-10
Ni-59	0	0	0	U-233	1.29E-09	9.93E-10	9.93E-10
Ni-63	0	0	0	U-234	5.71E-10	4.39E-10	4.39E-10
Np-237	8.16E-08	6.28E-08	6.28E-08	U-235	5.86E-07	4.51E-07	4.51E-07
Pa-231	1.55E-07	1.19E-07	1.19E-07	U-236	3.65E-10	2.81E-10	2.81E-10
Pb-210	5.37E-09	4.13E-09	4.13E-09	U-238	3.26E-10	2.51E-10	2.51E-10
Po-210	3.70E-11	2.85E-11	2.85E-11	Zr-93	0	0	0

Table D.5 – Groundshine dose coefficients ((Sv/yr)/(Bq/m^2))

Radionuclide	1-year old	10-year old	Adult	Radionuclide	1-year old	10-year old	Adult
Ac-227	6.44E-12	4.95E-12	4.95E-12	Pu-239	1.16E-11	8.96E-12	8.96E-12
Ag-108m	6.56E-08	5.05E-08	5.05E-08	Pu-240	2.47E-11	1.90E-11	1.90E-11
Am-241	9.56E-10	7.35E-10	7.35E-10	Pu-241	7.06E-14	5.43E-14	5.43E-14
Am-243	1.51E-09	1.51E-09	1.51E-09	Pu-242	2.04E-11	1.57E-11	1.57E-11
C-14	5.21E-13	4.01E-13	4.01E-13	Ra-226	2.64E-10	2.03E-10	2.03E-10
Cl-36	4.59E-10	3.53E-10	3.53E-10	Ra-228	0	0	0
Co-60	9.44E-08	7.26E-08	7.26E-08	Se-79	8.49E-13	6.53E-13	6.53E-13
Cs-135	1.10E-12	8.49E-13	8.49E-13	Sn-126	2.24E-09	1.73E-09	1.73E-09
Cs-137	1.23E-10	9.44E-11	9.44E-11	Sr-90	6.73E-11	5.18E-11	5.18E-11
H-3	0	0	0	Tc-99	2.65E-12	2.04E-12	2.04E-12
I-129	8.00E-10	6.15E-10	6.15E-10	Th-228	9.63E-11	7.41E-11	7.41E-11
Mo-93	2.19E-10	1.68E-10	1.68E-10	Th-229	3.50E-09	2.69E-09	2.69E-09
Nb-93m	3.85E-11	2.96E-11	2.96E-11	Th-230	3.07E-11	2.37E-11	2.37E-11
Nb-94	6.27E-08	4.83E-08	4.83E-08	Th-232	2.26E-11	1.74E-11	1.74E-11
Ni-59	0	0	0	U-233	2.94E-11	2.26E-11	2.26E-11
Ni-63	0	0	0	U-234	3.07E-11	2.36E-11	2.36E-11
Np-237	1.03E-09	7.95E-10	7.95E-10	U-235	6.07E-09	4.67E-09	4.67E-09
Pa-231	5.29E-17	4.07E-17	4.07E-17	U-236	2.66E-11	2.05E-11	2.05E-11
Pb-210	1.02E-10	7.82E-11	7.82E-11	U-238	2.26E-11	1.74E-11	1.74E-11
Po-210	3.40E-13	2.61E-13	2.61E-13	Zr-93	0	0	0

Table D.6 – Beachshine dose coefficients ((Sv/yr)/(Bq/kg(dw sediment)))

Radionuclide	1-year old	10-year old	Adult	Radionuclide	1-year old	10-year old	Adult
Ac-227	1.30E-10	9.99E-11	9.99E-11	Pu-239	6.63E-11	5.10E-11	5.10E-11
Ag-108m	1.94E-06	1.49E-06	1.49E-06	Pu-240	3.72E-11	2.86E-11	2.86E-11
Am-241	1.21E-08	9.34E-09	9.34E-09	Pu-241	1.44E-12	1.11E-12	1.11E-12
Am-243	3.80E-08	9.34E-09	9.34E-09	Pu-242	3.24E-11	2.49E-11	2.49E-11
C-14	2.78E-12	2.78E-12	2.78E-12	Ra-226	7.61E-09	5.85E-09	5.85E-09
Cl-36	4.90E-10	4.90E-10	4.90E-10	Ra-228	1.84E-07	1.41E-07	1.41E-07
Co-60	2.81E-06	2.16E-06	2.16E-06	Se-79	6.09E-12	4.69E-12	4.69E-12
Cs-135	7.83E-12	7.83E-12	7.83E-12	Sn-126	4.32E-08	3.32E-08	3.32E-08
Cs-137	1.81E-10	1.81E-10	1.81E-10	Sr-90	1.37E-10	1.37E-10	1.37E-10
H-3	0	0	0	Tc-99	2.49E-11	2.49E-11	2.49E-11
I-129	3.35E-09	2.58E-09	2.58E-09	Th-228	2.06E-09	1.58E-09	1.58E-09
Mo-93	2.07E-10	1.59E-10	1.59E-10	Th-229	8.53E-08	6.56E-08	8.53E-08
Nb-93m	3.65E-11	2.81E-11	2.81E-11	Th-230	3.42E-10	2.63E-10	2.63E-10
Nb-94	1.78E-06	1.37E-06	1.37E-06	Th-232	1.55E-10	1.19E-10	1.19E-10
Ni-59	0	0	0	U-233	3.48E-10	2.67E-10	2.67E-10
Ni-63	0	0	0	U-234	1.02E-10	7.83E-11	7.83E-11
Np-237	1.94E-08	1.49E-08	1.49E-08	U-235	1.61E-07	1.24E-07	1.24E-07
Pa-231	4.24E-08	3.62E-08	3.62E-08	U-236	5.49E-11	4.22E-11	4.22E-11
Pb-210	8.46E-10	6.51E-10	6.51E-10	U-238	2.76E-11	2.12E-11	2.12E-11
Po-210	1.01E-11	7.77E-12	7.77E-12	Zr-93	0	0	0