GDSA Biosphere Model Software Requirements Document

Spent Fuel and Waste Disposition

Prepared for
U.S. Department of Energy
Spent Fuel and Waste Science Technology

Caitlin A Condon, Bruce A Napier, Saikat Ghosh, William C Weaver, Ciara B Varnum-Lowry

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APPENDIX E

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EXECUTIVE SUMMARY

The Spent Fuel and Waste Science and Technology (SFWST) Campaign of the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE), Office of Spent Fuel and Waste Disposition (SFWD) is conducting research and development (R&D) on geologic disposal of spent nuclear fuel (SNF) and high-level nuclear waste (HLW). This work includes the development of a biosphere model capable of assessing doses to potential receptors living in the biosphere exposed to radionuclides released from geologic disposal sites. The report presents the software requirements for the proposed biosphere model that would be compatible with the PFLOTRAN massively parallel subsurface flow and reactive transport code and the Geologic Disposal Safety Assessment (GDSA) program which is charged with development of generic deep geologic repository concepts and system performance assessment (PA) models.

The proposed biosphere model was designed to be flexible and generic in order to accommodate a variety of different sites and climate states. The source of radionuclides in the biosphere are the radionuclides in the groundwater as determined through PFLOTRAN simulation. The GDSA Biosphere model then assesses the potential movement of radionuclides through the surface biosphere and the subsequent exposure to a human receptor living in the biosphere. The pathways of exposure included in the biosphere model from either groundwater or surface water contaminated through groundwater include

- Ingestion of drinking water
- Ingestion of flora, fauna, and produced products (both terrestrial and aquatic)
- Ingestion (inadvertent) of shower water
- Ingestion (inadvertent) of recreational swimming water
- Ingestion (inadvertent) of soil
- Inhalation of volatilized water
- Inhalation of resuspended soils
- External exposure to contaminated ground
- External exposure to contaminated shoreline
- External exposure to contaminated water through surface water recreational activities

This report describes the mathematical basis for the transport and exposure of radionuclides in the biosphere model, the specific software requirements to develop the model, quality assurance guidance for development, and an implementation plan for the development of the first iteration of the biosphere model as well as long term goals for the model.

This report fulfills the GDSA Modeling and Integration - PNNL Work Package Level 3 Milestone – *GDSA Biosphere Model Implementation Plan*, M3SF-20PN010304091.

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NOMENCLATURE

BIOPRATA	An international collaboration forum that seeks to address key uncertainties in the assessment of environmental and human health impacts in the long term arising from release of radionuclides and other contaminants as a result of radioactive water management practices
CM	configuration management
DGR	deep geologic repository
DOE	U.S. Department of Energy
DSNF	DOE-managed SNF
ERMYN	Environmental Radiation Model for Yucca Mountain Nevada
FRAMES	Framework for Risk Analysis in Multimedia Environmental Systems
GDSA	Geologic Disposal Safety Assessment
GENII	Environmental Radiation Dosimetry Software
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IWM	Integrated Waste Management
LHS	Latin hypercube sampling
MODARIA	Modelling and DAta for Radiological Impact Assessments
NE	Nuclear Energy
NQA-1	Nuclear Quality Assurance -1
PA	Performance Assessment
PFLOTRAN	An open-source, state-of-the-art massively parallel subsurface flow and reactive transport code
PNNL	Pacific Northwest National Laboratory
QA	quality assurance
RESRAD	RESidual RADioactiv materials assessment code
RSA	repository safety analysis work
RQM	requirement
SDLC	software development life cycle process
SFWD	Spent Fuel and Waste Disposition
SFWST	Spent Fuel and Waste Science and Technology
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SQAP	Software Quality Assurance Plan
TECDOC	technical document
WIPP	Waste Isolation Pilot Plant
χ/Q	atmospheric dispersion factor(s); annual average normalized air concentration value(s)

1.0 INTRODUCTION

The Spent Fuel and Waste Science and Technology (SFWST) Campaign of the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE), Office of Spent Fuel and Waste Disposition (SFWD) is conducting research and development (R&D) on geologic disposal of spent nuclear fuel (SNF) and high-level nuclear waste (HLW) (Mariner, Connolly et al. 2019). This work includes the development of a biosphere model capable of assessing doses to potential receptors living in the biosphere exposed to radionuclides released from geologic disposal sites. The work presented in this report are the software requirements for the proposed biosphere model that would be compatible with the PFLOTRAN massively parallel subsurface flow and reactive transport code and the Geologic Disposal Safety Assessment (GDSA) program which is charged with development of generic deep geologic repository concepts and system performance assessment (PA) models.

1.1 Purpose and Scope

The SFWST GDSA work package is charged with developing a disposal system modeling and analysis capability for evaluating disposal system performance for nuclear waste in geologic media. Pacific Northwest National Laboratory (PNNL) is charged with designing and developing an open source biosphere model to assess annual dose and risk to a human receptor.

This software requirements document was developed to outline the purpose, scope, and requirements of the proposed GDSA Biosphere model. This document is meant to introduce the planned capabilities, limitations, and user interactions with the GDSA Biosphere model. This software requirements document will serve as a framework and requirements document throughout development of the GDSA Biosphere model.

This document is intended to be used by the software development team, GDSA Program, and stakeholders of the GDSA Biosphere model. This document will be used when establishing the scope of the model under development as well as associated testable performance requirements for the software. This document will clearly establish the framework of the biosphere model to aid the software developers and guide development of testable requirements. After document approval, this document will present the requirements that are tested during validation and verification of the model.

The purpose of the GDSA Biosphere model is to be a flexible, open-source code that will be a component of the PFLOTRAN subsurface model to determine the dose to a hypothetical maximally exposed individual living in the biosphere given a PFLOTRAN groundwater radionuclide concentration input. The first iteration of the GDSA Biosphere model will be a post-processing component of PFLOTRAN that will use PFLOTRAN output as the biosphere model input. Future iterations of this proposed GDSA Biosphere model could integrate the biosphere model capabilities more fully within the PFLOTRAN simulation. The proposed biosphere model is the first step in developing an integrated biosphere component within PFLOTRAN.

The proposed model is designed to be a generic biosphere assessment tool that can be used for assessment of the dose and risk associated with releases of radionuclides from a deep geological repository for a wide variety of sites and climates. The proposed GDSA Biosphere model is designed to be consistent with international recommendations and guidance for environmental assessment of deep geological repositories.

1.2 Background

Background information about the GDSA Program, international guidance for development of biosphere models, and related U.S. repository and other biosphere models is provided in the following sections.

1.2.1 GDSA Background

The proposed biosphere model will be a part of the GDSA Repository Safety Analysis Work (RSA) under the SFWST Campaign. “The overall objective of the GDSA RSA work package is to develop generic deep geologic repository concepts and system performance assessment (PA) models in several host-rock environments, and to simulate and analyze these generic repository concepts and models using the GDSA framework toolkit, and other tools as needed,” (Sevougian, Stein et al. 2019). The GDSA computational framework includes a variety of codes but the primary codes are PFLOTRAN, a reactive transport code, and Dakota, an uncertainty quantification and sensitivity code (Mariner, Connolly et al. 2019). “The full set of codes and tools in the GDSA Framework is used to probabilistically simulate the various possible mechanisms and pathways for release and migration of radionuclides from waste packages in a deep geologic repository to the biosphere” (Mariner, Connolly et al. 2019). The first iteration of the proposed GDSA Biosphere model will be compatible with PFLOTRAN output to allow users to model the dose to human receptors in the biosphere exposed to a ground water release of radionuclides. The proposed GDSA Biosphere model will be capable of modeling a variety of climate scenarios and user exposure pathways so that this biosphere model can eventually be used to support safety case analysis for repositories.

1.2.2 International Guidance

The International Atomic Energy Agency (IAEA) has published Safety Standards and technical documents (TECDOCs) about the development of geological disposal facilities for radioactive waste, which offer guidance on how to develop models to assess effects in the biosphere. The effects of a geological repository on human receptors in the biosphere can be evaluated through a safety assessment and development of safety cases. The safety assessment and safety cases systematically evaluate the risk of the geologic repository to determine if it meets safety requirements (IAEA 2011). The models used for the safety assessment and safety cases need to quantify the level of performance of a repository as well as the associated uncertainty (IAEA 2011). Confidence in the results of a safety analysis is directly related to the confidence in the underlying models; models used for safety analysis must accurately capture the pathways that result in radionuclides entering and moving through the biosphere from a geological repository (IAEA 2011). It is assumed that if humans are protected in the biosphere that the environment is also protected; there are no international standards for environmental protection against ionizing radiation (IAEA 2011).

The IAEA also has the Biosphere Modelling and Assessment Programme called BIOMASS, which focuses on understanding the transfer and movement of radionuclides within the environment (IAEA 2003). IAEA BIOMASS offers guidance on how to develop a logical and defensible biosphere model as well as example biosphere models that can be used to assess system performance.

BIOMASS presents as series of steps involved in developing a biosphere model, including (1) establish assessment context, (2) identify and justify scenario, (3) prepare biosphere description, (4) define receptors, (5) develop model, (6) perform calculations, (7) iterate (IAEA 2003). The identification and justification step involves identifying the main components of the biosphere system, determining whether the biosphere system needs to depict biosphere change, and then, if relevant, determining how biosphere change will be handled by the model (IAEA 2003). BIOMASS 6 (IAEA 2003) makes an important distinction about developing biosphere models, specifically:

> The biosphere(s) adopted for performance assessment should not be regarded as somehow simulating the actual biosphere that will necessarily be present when a future release to the biosphere occurs. Rather, it is appropriate to consider them as adequately representative of possible outcomes for assessment purposes, i.e., as "assessment biospheres."

BIOMASS guidance highlights the need to incorporate relevant International Features, Events, and Processes (FEPs) into the biosphere model and have a clear auditable trail of where they are incorporated. Creating an interaction matrix, which shows the features of the biosphere as leading diagonal elements and how the events and processes affect the features, can be a helpful way of presenting a biosphere conceptual model (IAEA 2003).

Models that are designed to assess the radiological exposure of future generations will have increased uncertainty; it is necessary to make assumptions about the behavior of the receptors to assess potential radiological exposures, but this comes with added model uncertainty. When developing a biosphere model, the focus should not be on creating a model that can serve as an exact, detailed representation of the biosphere but one that contains all the elements necessary to support radiological assessment (IAEA 2003). While simple models may garner criticism for their coarse representation of relevant ecological processes, overly complicated models can present other difficulties (IAEA 2003). The balance between simplicity and complexity in the model is found by demonstrating its fitness for the intended purpose, i.e., demonstrating that a model can defensibly be used to assess radiological releases to the biosphere (IAEA 2003). The BIOMASS model development guidance was developed to support a systematic approach to model design in order to create a consistent and complete biosphere model (IAEA 2003).

BIOPROTA is an international collaboration that addresses modeling assumptions and sources of uncertainty in the long-term assessment of releases from radioactive waste management (BIOPROTA 2014). BIOPROTA is a forum that serves to make the best sources of information and modeling assumptions available for assessment of biosphere effects related to radioactive waste disposal (Thorne 2012).

In order to assess the effects of releases from radioactive wastes on the biosphere, the geosphere-biosphere interface must be defined. The geosphere-biosphere interface is the point at which the releases from radioactive waste from a geological repository are released to the biosphere. The two most common classes of geosphere-biosphere interface are wells and groundwater discharge (BIOPROTA 2014). Generally, for a generic well geosphere-biosphere interface, the abstraction rates will be low and the well will be supplying water to a small group of people, but this water will serve to support all their water needs including those of animals and crops (BIOPROTA 2014). If the geosphere-biosphere interface is upwelling of groundwater, this will be dependent on the topographic lows of the site, which will correspond to the physical characteristics of the geosphere such as deformation zones or rock type (BIOPROTA 2014). BIOPROTA provides guidance on how to develop a biosphere model from a geosphere-biosphere interface, which includes defining the FEPs that will be incorporated in the model, as well as defining all the interactions between model components (BIOPROTA 2014). Other considerations for a biosphere model highlighted by BIOPROTA include the model timescale of interest, landscape development, potential human intrusions, and climate changes all of which could affect how radionuclides move through the biosphere (BIOPROTA 2014).

BIOPROTA issued a report in 2018 that includes a review and update of the BIOMASS model methodology and represents the collaborative views of BIOPROTA and IAEA MODARIA II Working Group 6 (WG6) (BIOPROTA 2018). Overall, the report reiterated that generally the original BIOMASS methodology is appropriate for developing biosphere models. One important distinction made in the 2018 report is that biosphere models are not only assessment tools; they also need to serve the needs of a variety of stakeholder to be successful. The 2018 report highlighted that standardized biosphere models may be difficult to apply to sites, so the focus should be on developing reference biosphere models that

were developed based on the international FEPs list. Climate change can be treated as an input in biosphere models; detailed climate change modeling can be conducted outside the biosphere model and those modeling efforts can inform the time-independent biosphere model (BIOPROTA 2018). For any biosphere model, the uncertainty and complexity of the model need to be managed in a way that is transparent to stakeholders. It is necessary to incorporate uncertainty into any biosphere model and to avoid risk dilution (BIOPROTA 2018). The complexity of the model should be driven by its fitness for purpose; the model should be simple enough to model a biosphere for its time scale, given the associated uncertainties with long time scale models, but not so simple that it is difficult to defend scientifically (BIOPROTA 2018). A biosphere model for long time scales will need to be simpler than a biosphere model focused on shorter time scales (BIOPROTA 2018). Compartment modeling can be a good solution to modeling a biosphere system mathematically (BIOPROTA 2018).

The following recommendations from the IAEA are relevant to the development of a GDSA Biosphere model (IAEA 2011):

- The international list of FEPs should be considered when designing a repository model.
- A modular systems approach for modeling releases from a geologic repository through environmental pathways should provide scenario flexibility.
- Models should be simple enough to be compatible with available data guided by expert judgment. Simple models will be more easily justified and easily understood, thereby supporting their use in compliance assessments.
- When appropriate, reasonable conservativism should be built into the model and documented.
- All assumptions and limitations of the models should be documented in a clear and traceable manner.
- Sensitivity, uncertainty, and how well a model represents an actual site need to be addressed in any model. This is necessary to assess compliance with safety requirements.

Any generic model developed will need to eventually be used to assess compliance with safety standards and regulations. It will be critical for any model developed to be flexible enough to reflect candidate site characteristics (IAEA 2014).

1.2.3 U.S Repository Models

The Waste Isolation Pilot Plant (WIPP) and Yucca Mountain, Nevada, both have associated biosphere models that are described in this section to provide relevant background for the proposed GDSA Biosphere model.

1.2.3.1 Waste Isolation Pilot Plant (WIPP)

WIPP is a DOE project that provides a facility that is demonstrating the safe disposal of radioactive wastes produced from national defense activities. The WIPP is located in the state of New Mexico, about 26 miles east of Carlsbad and 18 miles northeast of Loving (DOE 1980).

A multiple barrier approach that hinders the release of radioactivity is the limiting factor for the long-term integrity of the WIPP. The multiple barriers at the WIPP are the rock salt, the waste and its containers, and the hydrologic and geologic system in which the repository is embedded. The result of the long-term safety analysis for the WIPP determined that the voluminous rock salt bed is the important barrier, hindering the release of radioactivity. Furthermore, about 1,200 feet of rock salt and anhydrite are located beneath the waste horizon and an additional 1,200 feet of rock salt are located above the waste horizon. This 2,400-foot barrier is not expected to be exposed to a natural process that will disturb the rock salt barrier during the required modicum of time required for the waste to decay to innocuous

amounts. In the unlikely event of a breach of the rock salt barrier, the hydrologic and geologic system would become an essential barrier for hindering the release of radioactivity to the biosphere. The safety analysis focused on the effectiveness of the hydrologic and geologic system barrier, after a breaching event has disturbed the other two barriers (DOE 1980).

This safety analysis estimated the possible transport and release of radioactivity to the biosphere through different mechanisms, and involved the performance of simulations, including using LADTAP and AIRDOS II computer codes, to estimate the quantity of radionuclides that humans may be exposed to through different pathways. The main tool implemented in this safety assessment was the analysis of "scenarios." The term "scenario" means a "hypothetical sequence of events that could release radioactive material from a repository."

Five scenarios were selected for the safety analysis. Scenarios 1 through 4 simulated the introduction of radionuclides into the Magneta and Culebra aquifers; these radionuclides were transported in the aquifers to the outlet along the Pecos River near Malaga Bend, located approximately 15 miles southwest of the WIPP and this was the point where the radionuclides were released into the biosphere. Furthermore, Scenarios 1 through 4 are representative of scenarios for liquid breach and transport because they simulated the "existence of a water-filled communication that connects the repository with one or more aquifers," (DOE 1980). Scenario 5 simulated the introduction of radionuclides directly into the biosphere through a drill shaft that penetrated the repository (DOE 1980).

Figure 1.1 (DOE 1980) displays the analysis paths for the modeling scenarios, beginning with the source term and a description of each scenario. The source term was composed of the specifications of model repository, radionuclide inventories, and physical and chemical conditions of the waste. Next, the transport of radionuclides through the geosphere and the biosphere were simulated, ending with the simulation of human dose estimates (DOE 1980).

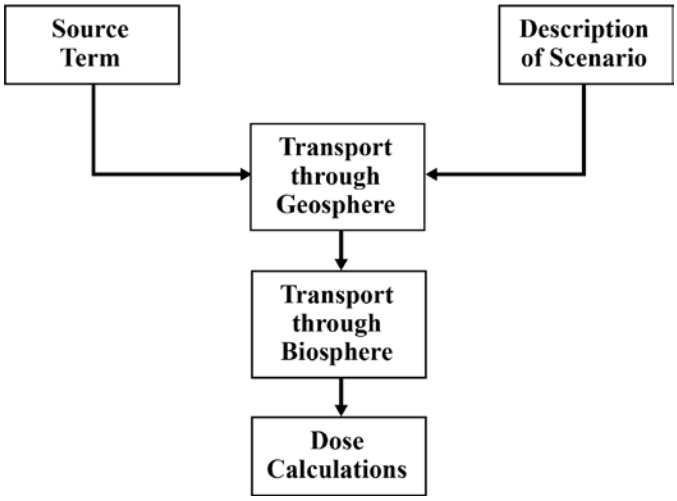

Figure 1.1. Modeling Release Scenarios for the WIPP Site from WIPP EIS (DOE 1980)

Radionuclides that are released to the biosphere can be reach human receptors through a variety of pathways. Humans can be exposed to radiation through external and/or internal pathways. The external pathways include both air immersion and direct exposure to media contaminated with radionuclides. Internal pathways include ingestion of contaminated plant, meats, and animal products or inhalation of radionuclides in the surrounding biosphere. Importantly, one pathway may dominate other pathways, this is called the critical pathway. Estimation of the associated radiation dose was completed using the computer code AIRDOS I.

1.2.3.2 Environmental Radiation Model for Yucca Mountain Nevada

The Environmental Radiation Model for Yucca Mountain Nevada (ERMYN) describes radionuclide transport processes in the biosphere and the associated human exposure that could occur as a result of a radionuclide release to the environment from the proposed geologic repository at Yucca Mountain. ERMYN is one of the process models that supports the Total System Performance Assessment (TSPA). In supporting the TSPA, the biosphere process model provides the tools for estimating the annual radiation dose to a receptor defined in the licensing rule (Title 10 of the *Code of Federal Regulations* Part 63 [10 CFR 63]) from the radionuclide concentrations in the groundwater and from volcanic ash deposited in the surface soil (DOE 2007).

ERMYN was developed to simulate the annual dose to the reasonably maximally exposed individual (RMEI), who is a member of a hypothetical community situated at a specified compliance location provided by a regulator. The RMEI would be representative of the most highly exposed individuals, located down gradient from Yucca Mountain, simulating the population of the region (DOE 2007). In addition, the hypothetical community is required to have the characteristics of the town of Amargosa Valley. The RMEI and a hypothetical community were defined by the U.S. Environmental Protection Agency (EPA) “to limit speculation about possible futures so that the performance assessments (PA) can provide meaningful input into the decision process and the decision process itself is not confounded with speculative alternatives” (DOE 2007).

Furthermore, the biosphere model allows the results of the geosphere transport to be converted to annual dose, consistent with the PA requirements specified in the licensing rule (10 CFR 63) (DOE 2007). The geosphere-biosphere interface is a combination of agricultural and domestic wells for the radionuclide releases in the groundwater or an erupting volcano for the releases resulting from an extrusive igneous event. For each of these two release modes, a separate biosphere model was constructed that includes conceptual and mathematical representations of an appropriate set of environmental transport and human exposure pathways. The purpose of the performance assessment is to document that, after permanent closure, the repository proposed at Yucca Mountain meets the performance objectives specified in the licensing rule (10 CFR 63) (DOE 2007). The assessment, including the geosphere and the biosphere representations, is only conducted for a specified site, a geologic repository at Yucca Mountain; this means that ERMYN can only be applied to the Yucca Mountain geologic repository (DOE 2007).

ERMYN is mathematically similar to the GENII model and is a strong tool for biosphere modeling at the Yucca Mountain site. The ERMYN model dose assessment is based on the specific pathway contributions for the human receptors being combined into to biosphere dose conversion factors which are based on the point of origin for the radionuclides with respect to the receptor (Rasmuson, Rautenstrauch et al. 2007). The use of these biosphere dose conversion factors (BCDFs) make it difficult to generalize the ERMYN model to more generalized environments.

1.2.4 GENII

The proposed GDSA Biosphere model has capabilities that overlap with existing biosphere models such as GENII. GENII was originally developed at PNNL as an environmental transport and dosimetry model for the Hanford Site (Napier 2012). Its inherent flexibility allowed it to be adapted to be a generic model for the EPA (Napier 2012). GENII Version 2 is a robust code that allows for the evaluation of radionuclide transport related to acute or chronic releases of radionuclides through air, water, or known environmental concentration culminating in dose calculations to the chosen receptor (Napier 2012). GENII Version 2 was developed as a Nuclear Quality Assurance-1 (NQA-1) software and, after evaluation by DOE in 2013, was listed as a DOE toolbox code (DOE 2020). The GENII code is included in the U.S. Nuclear Regulatory Commission (NRC) Radiation Protection Computer Code Analysis and Maintenance Program (RAMP) as an environmental analysis code (NRC 2020).

The GENII model was designed to incorporate the recommendations from the IAEA as well as guidance published in Federal Guidance Report 13 for environmental pathways of exposure (Napier, Strenge et al. 2012). The GENII code can be used to address the following user needs:

- Compliance: Determine if facility operation activities are regulatory compliant in terms of radiation dose limits.
- Design Requirements: How much material may be release and still meet the design criteria?
- Safety Analyses: How much redundancy is necessary to prevent this event?
- Accident Planning: How bad can an event be?

GENII is designed to address all of these user needs through model scenarios. The user is able to use GENII to define a use scenario that considers (1) radionuclide inventories, (2) radionuclide releases, (3) environmental transport, (4) environmental accumulation and dilution, and (5) subsequent human exposure.

A scenario in GENII is a conceptual model that describes patterns of human activity, events, and processes that result in radiation exposure to people. GENII is designed to allow flexible application of most scenarios of interest in a regulatory setting at an appropriate level of detail. GENII can be used for far-field scenarios such as atmospheric or surface water transport for either chronic or acute releases. GENII can also be used for near-field scenarios such as spills, buried waste, and groundwater use. GENII allows the user to define the source term from a library of 825 radionuclides (Napier, Strenge et al. 2012). GENII tracks not only the radionuclides the user designated in the source term throughout all movement through the scenario, but also automatically models the ingrowth of radionuclide decay products in parallel to the parent radionuclide.

GENII contains atmospheric transport modules that can support releases/assessment needs, including (1) chronic plume, (2) acute plume, (3) acute 95% percentile plume, (4) chronic puff, (5) acute puff, (6) chronic χ/Q, and (7) acute χ/Q. The GENII surface water models can be used for rivers, lakes, or nearshore ocean environments and can handle a variety of impoundments such as once-through ponds, fully mixed ponds, or partially mixed ponds. Following the dispersion of the radionuclides through either atmospheric or surface water the user can activate environmental accumulation and exposure modules to determine how the radionuclides move through the environment for either an acute or chronic release. The GENII user can also start the environmental accumulation model without modeling atmospheric or surface water dispersion by proving the environmental media concentration of radionuclides. The concentration of radionuclides in the environment can then be used for an environmental dose assessment using the GENII code or they can be used as transport media to the human receptors in the model for human dose assessment using the GENII code.

Dose to humans from GENII scenarios can include external and internal exposures to radionuclides released into the environment and can be evaluated for humans of various ages or groups of individuals. External exposure can include human exposure to radionuclides in transported air, in the soil (inadvertent ingestion), in the water (swimming), or on a shoreline (recreational activities). Internal exposure to radionuclides includes both inhalation and ingestion pathways. The human receptors can be exposed to inhaled radionuclides by breathing transported air, breathing resuspended soils, or breathing radionuclides volatilized from use of contaminated water indoors. The human receptor can be exposed to ingested radionuclides from leafy vegetables, other vegetables, fruit, grain, meat, milk, poultry, eggs, fish, crustaceans, mollusks, water plants, drinking water, shower water, swimming water, and soil. For all of these exposure pathways for human receptors, the concentrations of radionuclides are determined using the environmental transport and accumulation modules. GENII provides default values for consumption rates and exposure rates, but the user is able to customize these exposure rates for all the human receptors to customize the model scenario. GENII applies uncertainty and sensitivity analysis through the SUM3 processor within the Framework for Risk Analysis in Multimedia Environmental Systems (FRAMES).

GENII is a modular code that allows flexibility in developing modeling scenarios, which is consistent with the recommendations of the IAEA. The GDSA Biosphere model capabilities overlap with those of the GENII model and as such will leverage relevant proven methods and parameters (including mathematical implementation) used in the GENII model.

1.2.5 RESidual RADioactive Materials Assessment Codes

The RESidual RADioactive Materials Assessment Codes (RESRAD) are a family of codes developed by Argonne National Laboratory for DOE for analysis of potential human and biota exposure to residual radiation from environmental contamination. The RESRAD family includes the code RESRAD-ONSITE, RESRAD-OFFSITE, RESRAD-BUILD, RESRAD-RDD, and RESRAD-BIOTA (Yu, Gnanapragasam et al. 2019). The first RESRAD code developed was RESRAD-ONSITE. Developed in the 1980s and released in 1989, RESRAD-ONSITE evaluates radiological dose and excess cancer risk to individuals that work in or above contaminated soil (NUREG/CR-7268) (Yu, Gnanapragasam et al. 2019). In the 1990s, RESRAD-OFFSITE was developed to expand upon the objectives and enhance the functions of RESRAD-ONSITE.

Originally RESRAD-OFFSITE added an offsite soil accumulation submodel to the RESRAD-ONSITE modules. Later added features include the advective-dispersive groundwater transport submodel, ability to accept temporal information defining the releases from the contaminated soil, atmospheric transport submodel, and surface water body accumulation submodel—all added before the release of the code. The ability to model releases from the primary contamination that were delayed and/or distributed over time, the ability to model an equilibrium desorption release, and the ability to model transport by groundwater within the primary contamination were added in Version 3.1 (Yu, Gnanapragasam et al. 2019). In Version 3.2 the capability to model a submerged primary contamination and the choice between the International Commission on Radiological Protection Publication 38 (ICRP 38)- and ICRP 107-based transformation data were added. Version 4.0 added the option to model solubility-controlled release, diffusive release from contaminated material, and deposition of particulates over the catchment of the surface water body (Yu, Gnanapragasam et al. 2019).

RESRAD-OFFSITE is approved by the NRC for risk assessment in decommissioning and license termination. RESRAD-OFFSITE can be used for evaluating the human health and environmental impacts associated with waste disposal. The code accepts inputs for radionuclide release rates to deeper soils groundwater aquifer, air, or a water surface.

The RESRAD-OFFISTE code has a special model for carbon-14 radionuclide transport from soil to plants that will serve as the mathematical basis for the carbon-14 soil submodel for the GDSA Biosphere model.

1.3 Report Contents and Organization

The ensuing sections of this report describe features of the GDSA Biosphere model (Section 2.0) and associated functional requirements (Section 3.0). Sections 4.0 and 5.0, respectively, describe the software quality assurance plan and the implementation plan for the first iteration of the GDSA Biosphere model. Appendices A, B, and C contain supplementary information, including, respectively, a list of requirements for the GDSA Biosphere model, math for the Radioactive Chain Decay GENII Module, and equivalent and effective dose equations for specific exposure pathways.

2.0 GDSA BIOSPHERE MODEL DESIGN

The GDSA Biosphere model's capabilities, development relative to guiding international FEPS, and underlying assumptions and dependencies are described in the following sections.

2.1 Model Capabilities

The proposed first iteration of the GDSA Biosphere model will be an open-source model that will be compatible with outputs from PFLOTRAN. The biosphere model needs to be generic and flexible so that it can be used to model a variety of potential repository environments over long time scales of observation. The biosphere model will be capable of supporting repository biosphere assessment needs for regulatory compliance criteria as well stakeholder interests. The biosphere model will be transparent and documented such that any user will be able to determine how the model is calculating the values reported by the model.

In the first iteration of the GDSA Biosphere model the geosphere-biosphere interface will be limited to the extraction well for the contaminated aquifer. Both groundwater and surface water will be considered to be sources of radionuclides in the biosphere model, but surface water will be represented by a dilution of the groundwater taken from the extraction well. It is possible that in future iterations, the surface water will be defined directly based on release rates from the PFLOTRAN model rather a set dilution rate of the ground water.

The biosphere model will focus on calculating the annual dose to a hypothetical RMEI living at a place that relies on repository-contaminated water as the only source of water. The biosphere model will include all the pathways of exposure for the RMEI shown in Figure 2.1.

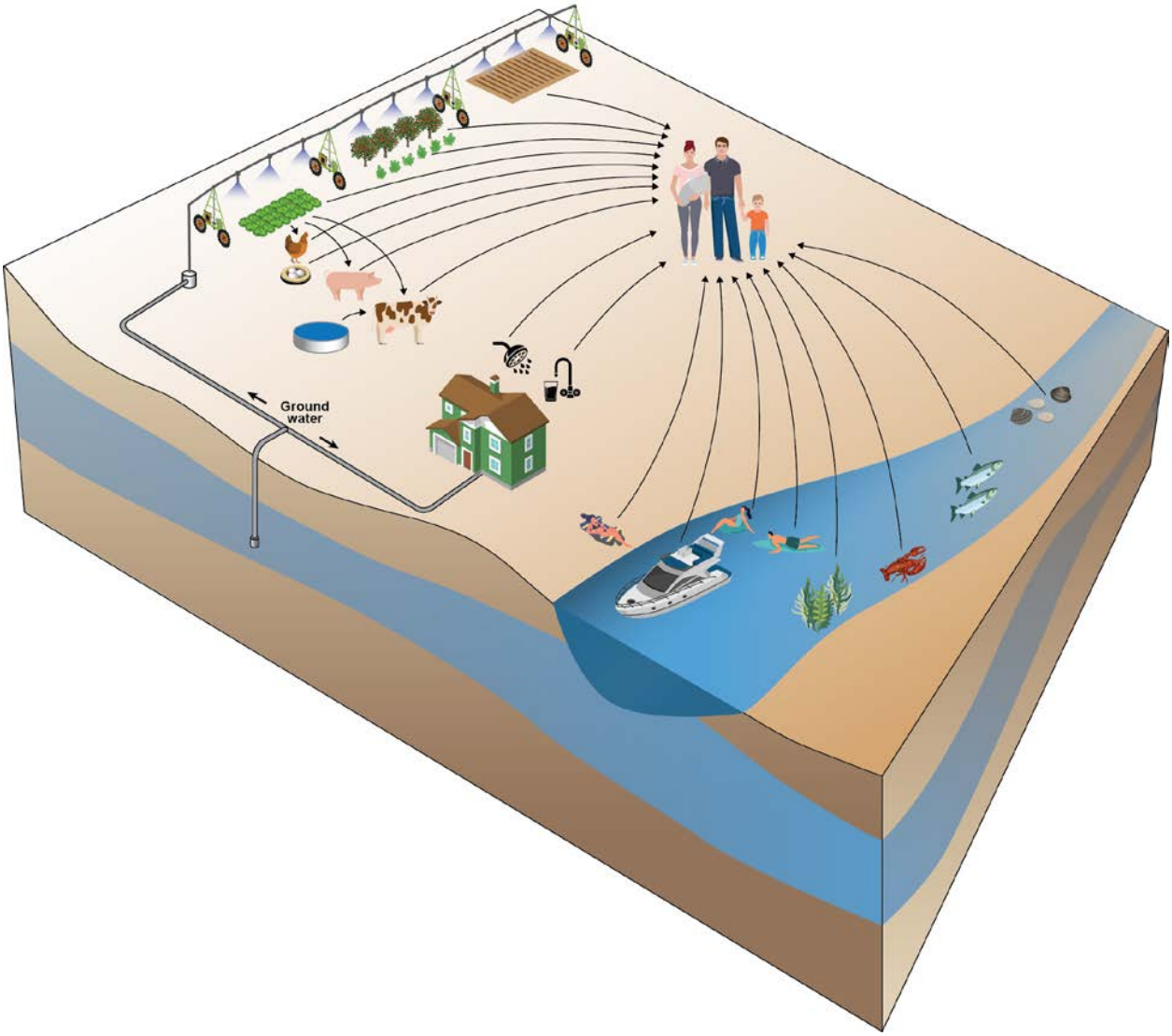

Figure 2.1. Biosphere Model Exposure Pathways

In it's full configuration, the GDSA Biosphere model will be a tool for assessing doses to potential receptors from radionuclides in the groundwater, as shown in Figure 2.1. The groundwater concentration of radionuclides is used to define the output from the well, which in turn is used to define the concentration in the surface water (if included) assuming contamination of surface water through aquifer upwelling. The groundwater (and the surface water) then serve as the primary source terms for radionuclides in the biosphere. All movement of repository radionuclides in the biosphere are sourced from liquid water. The biosphere model will capture all of the following pathways for radionuclides from either groundwater or surface water to the receptor:

- Either the groundwater or surface water can be used as the receptor's source of drinking water. The concentration of radionuclides in the drinking water will be affected by the water treatment processes as well as the holdup delay between the source of the water and the point of water consumption by the receptor. Both the water treatment effects and the holdup delay for the drinking water will be defined by the user. Once the water has reached the point of consumption for the receptor it is called domestic water. The receptor will be exposed to radionuclides by

drinking a standard amount of water per day (unless specifically changed by the user for the assessment scenario).

- Either the groundwater or surface water can be used as the source of water for the dwelling of the receptor. This can expose the receptor to inhaled volatilized radionuclides through showering or greenhouse uses of domestic water. The volatility of the radionuclides will be derived from the radionuclide data sets (or user defined), which will define what portion of the radionuclides that are in the water will be volatilized and then available for the user to inhale. User-defined receptor characteristics will determine the exposure for the receptor. For example, this pathway might be adjusted to represent the increased exposure to volatile radionuclides if the receptor is growing crops in a greenhouse for a scenario where the climate does not allow the receptor to grow crops outdoors.
- Either the groundwater or the surface water can be used as a source of irrigation for flora (crops or native plants). The flora that will be included in the model include leafy vegetables, grains, root vegetables, fruits, and a user-defined flora option. The plants take up radionuclides into their biomass based on known transfer ratios for radionuclides or specific activities for carbon-14. The plants are also contaminated by radionuclides in the soil being resuspended and landing on the plant surfaces. The plants will then be harvested by the receptor and there will be a specified holdup delay between when the plants are harvested and when the receptor consumes them. Then the receptor will consume the plants being exposed to radionuclides based on the user-defined flora specific ingestion rates. All crop radioactivity is assumed to be removed at harvest.
- Either the groundwater or surface water will be used as a source of drinking water for the biosphere fauna (farm animals and native animals). The animals or animal products that will be included in the model include milk animals, meat animals, poultry for eggs and meat, and a user-defined fauna option. The animals will drink the water, thereby contaminating themselves with radionuclides according to known transfer ratios for radionuclides. The animals will also consume flora (crops and native plants) that have been irrigated. If the plants are harvested for animal feed, rather than consumed fresh, they will have an associated holdup delay between plant harvest and animal consumption. The consumption of both contaminated plants and contaminated water will transfer radionuclides to the animals. The animal tissues (meat, native animal meat, or poultry) and animal products (milk or eggs) will be harvested and there will be an associated holdup delay between harvest and receptor consumption. The receptor's consumption of the animal products based on the user-defined ingestion rates.
- In areas that have received irrigation using either the groundwater or the surface water the soil profile is contaminated with radionuclides. The receptor can inhale radionuclides from resuspended contaminated soil. The inhalation of radionuclides through this pathway will be determined by the user-defined characteristics, i.e., how much time is spent near the contaminated soil source term. The receptor can receive dose from incidental soil ingestion. The receptor can also receive an external dose from time spent near the contaminated soils. Soil radioactivity is removed by radiological decay, crop harvest, and soil leaching. Human or biotic redistribution of soils are not considered.
- Surface water is the source of radionuclides for aquatic flora and fauna. The model will include aquatic flora and fauna including fish, crustacea, mollusks, aquatic plants, and the option for a user-defined aquatic flora or fauna to represent native species. The model transfers radionuclides to the aquatic flora and fauna through radionuclide-specific transfer ratios. The human receptors then harvest the aquatic flora and fauna for consumption and there is a holdup time between the harvest of the aquatic flora and fauna and the time of consumption by the receptor. The receptor's consumption of the aquatic flora and fauna will be based on the user-defined ingestion rates.

- The receptor can be exposed to an external dose from radionuclides through proximity to contaminated surface water through activities like boating or spending time on contaminated shoreline sediments. The dose to the receptor is dependent on the user-defined receptor characteristics for how much time the receptor spends boating or in close proximity to shoreline sediments.
- The receptor can be exposed to radionuclides by doing activities such as swimming in the surface water. The receptor will receive an external dose from radionuclides while the receptor is swimming. The receptor will also receive an internal exposure to radionuclides from accidental ingestion of surface water while swimming. The receptor's external exposure to radionuclides from swimming as well as accidental ingestion will be defined by the user-defined receptor characteristics.

The design of the biosphere model will be modular and time-independent. The modular design will make the model flexible for modeling a variety of potential repository sites. Furthermore, a modular design is recommended by the IAEA as a flexible and defensible way to develop a biosphere model (IAEA 2011). The model will be time-independent, meaning that it will not incorporate climate changes in the biosphere into the individual model runs. Rather, the user will use climate change models independently of the GDSA Biosphere model to define the climate of the modular biosphere model at user time periods of interest, and then the user will calculate the annual dose to the RMEI during those periods.

The biosphere model will be capable of handling a variety of climate scenarios based on the inputs of the user. The biosphere model will be flexible enough to represent a variety of ecosystem scenarios and, through this flexibility, will also be able to handle a variety of climate scenarios. The constant of any biosphere scenario is that there is a human receptor present. The climate at the site will affect how the receptor interacts with the biosphere but will not change some fundamental characteristics of the receptor, i.e., requires water to drink and food to eat. Many of the pathways of exposure for the receptor are those that allow the receptor to acquire drinking water and food from their immediate environment. The changing climate might affect the proportion of food from each potential pathway from which the receptor consumes products, or it might affect the way in which radionuclides moves through each receptor pathway and thereby affect the receptor's exposure to radionuclides. Climate changes in the biosphere can be captured using this biosphere model by adjusting the following user inputs:

- **Temperature, humidity, and precipitation rate**: The user will be able to define the biosphere and climate type by adjusting the temperature, humidity, and precipitation rate to reflect the biosphere of interest. These changes will affect how radionuclides migrate through the soil profile and affect the concentration of radionuclides in the crops.
- **Receptor activities**: The user will be able to define the user activities to reflect what would be appropriate for the given biosphere and climate. For example, you would be unlikely to have a receptor swimming or receiving recreational shoreline exposure in a polar climate, so the user would deactivate these pathways to reflect the changes in receptor activity.
- **Receptor consumption rates:** The specific biosphere and climate for the scenario will affect what types of food and what sources of drinking water are available to the user. The user will be able to modify the receptor consumption pathways in order to reflect the likely consumption habits of the receptor in a variety of biosphere and climate scenarios. One example of this would be to remove the receptor's consumption of aquatic plants and animals if the chosen biosphere will not likely have a surface water feature. To reflect changes in climate the user can change the proportion of each crop type that the receptor consumes based on the climate and resulting plant hardiness zone to reflect what the receptor is capable of successfully growing, feeding to livestock, and consuming. In the most extreme climate scenarios it is still assumed that the receptor is living in the biosphere and requires a source of food so you must assume that the receptor is using a greenhouse or other climate-controlled structure to grow the required crops and

livestock for survival. In this scenario the user will be able to adjust a few model inputs in order to assume that crops are grown in a greenhouse, including temperature and inhalation volatilization rate for the radionuclides to reflect the increased inhalation route of exposure for the receptor while tending crops in a controlled-climate environment.

The model will incorporate tools for evaluating both uncertainty analysis and sensitivity analysis for the inputs and calculations of dose.

2.2 International Features, Events, and Processes

The Organisation for Economic Co-Operation and Development Nuclear Energy Agency (NEA) has developed and published a list of FEPs that can help evaluate the "long-term safety or performance" of a geologic repository (NEA 2019). This list of FEPs was developed to "support national programmes in the production of their safety cases through the provision of a comprehensive and internationally accepted list of factors that may need to be considered when assessing the post-closure safety of DGRs" (NEA 2019). This list of FEPs was used as a guidance document when determining what pathways of exposure and variables needed to be incorporated in the GDSA Biosphere model. The FEPs under consideration for inclusion in the GDSA Biosphere model are those in FEP group 5—the biosphere FEPs (NEA 2019). Not all the biosphere FEPs are currently recommended for inclusion in the first iteration of the GDSA Biosphere model. The FEPS that will be included in the first iteration of the GDSA Biosphere model are listed in Table 2.1. FEPs that will not be included in the first iteration of the GDSA Biosphere model, but are relevant biosphere FEPs that could be incorporated into future iterations of the model, are listed in Table 2.2. The FEPs listed in Table 2.2 are not being incorporated into the first iteration of the GDSA Biosphere model because they were not identified as dominant or relevant pathways/variables to calculate annual dose to a human exposed to radionuclides from ground water. The FEPs listed in Table 2.2. could be incorporated into future iterations of the GDSA Biosphere model if the capabilities of the model are expanded.

Table 2.1. International FEPs Included in First Iteration of GDSA Biosphere Model (NEA 2019)

FEP #	FEP Title	FEP #	FEP Title
5	Biosphere factors	5.2.4	Habits (excluding diet)
5.1	Surface Environment	5.2.5	Food preparation and water processing
5.1.2	Biomes	5.3	Contaminant migration (biosphere)
5.1.3	Soils and sediments	5.3.1	Water-mediated migration (biosphere)
5.1.3.1	Surface soils	5.3.1.2	Migration associated with surface soil and overburden
5.1.4	Near-surface aquifers and water bearing features	5.3.1.3	Migration associated with surface water bodies
5.1.5	Terrestrial surface water bodies	5.3.1.5	Speciation and solubility (biosphere)
5.1.5.2	Lakes and rivers	5.3.1.6	Sorption and desorption (biosphere)
5.1.9	Vegetation	5.3.2	Gas-mediated migration (biosphere)
5.1.10	Animals	5.3.5	Uptake of contaminants by animals and plants
5.1.11	Climate and weather	5.3.6	Radioactive decay and ingrowth (biosphere)
5.1.14	Ecological/biological/microbial systems	5.4	Exposure factors
5.2	Human characteristics and behavior	5.4.1	Contaminated drinking water and food
5.2.1	Physical characteristics	5.4.3	Other contaminated environmental media
5.2.2.1	Community type	5.4.4	Exposure modes

FEP #	FEP Title	FEP #	FEP Title
5.2.2.3	Water source	5.4.4.1	Exposure of humans
5.2.2.4	Dwellings	5.4.5	Dosimetry and biokinetics
5.2.3	Diet and fluid intake	5.4.5.1	Dosimetry and biokinetics for humans
5.2.3.1	Farming diet	5.4.6	Radiological toxicity/effects
5.2.3.2	Hunter/gather diet	5.4.6.1	Radiological toxicity/effects for humans
5.2.3.3	Other diets		

Table 2.2. International FEPs Not Included in First Iteration of GDSA Biosphere Model (NEA 2019)

FEP #	FEP Title	FEP #	FEP Title
5.1.1	Topography and morphology	5.3.4	Human-action-mediated migration (biosphere)
5.1.3.2	Overburden	5.3.1.1	Groundwater discharge to biosphere
5.1.3.3	Aquatic sediments	5.3.1.4	Dissolution and precipitation (biosphere)
5.1.5.1	Wetlands	5.3.1.7	Colloid transport (biosphere)
5.1.5.3	Spring and discharge zones	5.3.3	Solid-mediated migration (biosphere)
5.1.6	Coastal features	5.4.2	Contaminated non-food products
5.1.7	Marine features	5.4.4.2	Exposure of non-human biota
5.1.8	Atmosphere	5.4.5.2	Dosimetry and biokinetics for non-human biota
5.1.12	Hydrological regime and water balance (near-surface)	5.4.6.2	Radiological toxicity/effects for non-human biota
5.1.13	Erosion and deposition	5.4.7	Chemical toxicity/effects
5.2.2	Community characteristics	5.4.7.1	Chemical toxicity/effects for humans
5.2.2.2	Community location	5.4.7.2	Chemical toxicity/effects for non-human biota

2.3 User Needs

The GDSA Biosphere model user will need to be able to interact with a user-friendly input format to develop biosphere modeling scenarios appropriate for repository assessment modeling. The user will need to develop a scenario based on model inputs that can reasonably represent the biosphere of interest at the selected time point of interest. The user will be able to make selections appropriate to the behavior of the RMEI based on the climate and conditions hypothesized for the time point of interest that can be reflected in the scenario. For example, if a modeler wants to look at a potential biosphere site that will likely be a tundra at the time point of interest, the modeler will apply the modules to adjust human behavior such as changing the food inputs to reflect a hunter gatherer with lower intakes of green leafy vegetables and fruits. The model needs to flexible so that the modeler can construct any reasonable scenario with groundwater or surface water as the source of radionuclides in the biosphere.

2.4 Assumptions and Dependencies

The following assumptions will be used to develop the first iteration of the GDSA Biosphere model:

- The only interface between the biosphere and the geosphere is well water from its extraction point in the aquifer. It is assumed to be a single well originating from a designated point in the aquifer. Surface water as a source in the biosphere model will be represented by a dilution of the

groundwater from the extraction point in the aquifer. Marine environments will not be modeled at this time.

- There are no other source of radionuclides in the biosphere other than the radionuclides released from the groundwater geosphere-biosphere interface.
- The annual dose calculated for the RMEI is a reasonably conservative assumption of the annual dose that a person living in the biosphere receives.
- Doses to non-human biota are not calculated. It is assumed that if the RMEI is protected from radiation risk that the non-human biota in the environment are also protected.
- The climate type as an input to the module is constant throughout the year that is modeled. The user is responsible for indicating the climate type for each modeling scenario.
- There are no other pathways of exposure for the RMEI than those captured in the interaction matrix (see Figure 3.1in Section 3.1).
- The doses calculated using the biosphere model do not include naturally occurring background doses.

3.0 GDSA BIOSPHERE MODEL REQUIREMENTS

This section presents the functional, external interface, and non-functional requirements for the proposed GDSA Biosphere model. The numbered requirements (RQMTs) cited in the narrative below are listed in Appendix A.

3.1 Functional Requirements

The GDSA Biosphere model will track radionuclide chain decay and ingrowth through pathways of exposure to the human receptor in the biosphere, as shown in Figure 3.1 and listed in Table 3.1. The user shall be able to define the source term of the model by specifying the radionuclides in the groundwater with associated well water withdrawal preferably through a PFLOTRAN output file (RQMT 3.1.1). The PFLOTRAN output file will provide radionuclide concentrations in the well water. The user should be able to select more than one groundwater source term by giving a groundwater source term an associated release period as long as the release periods do not overlap.

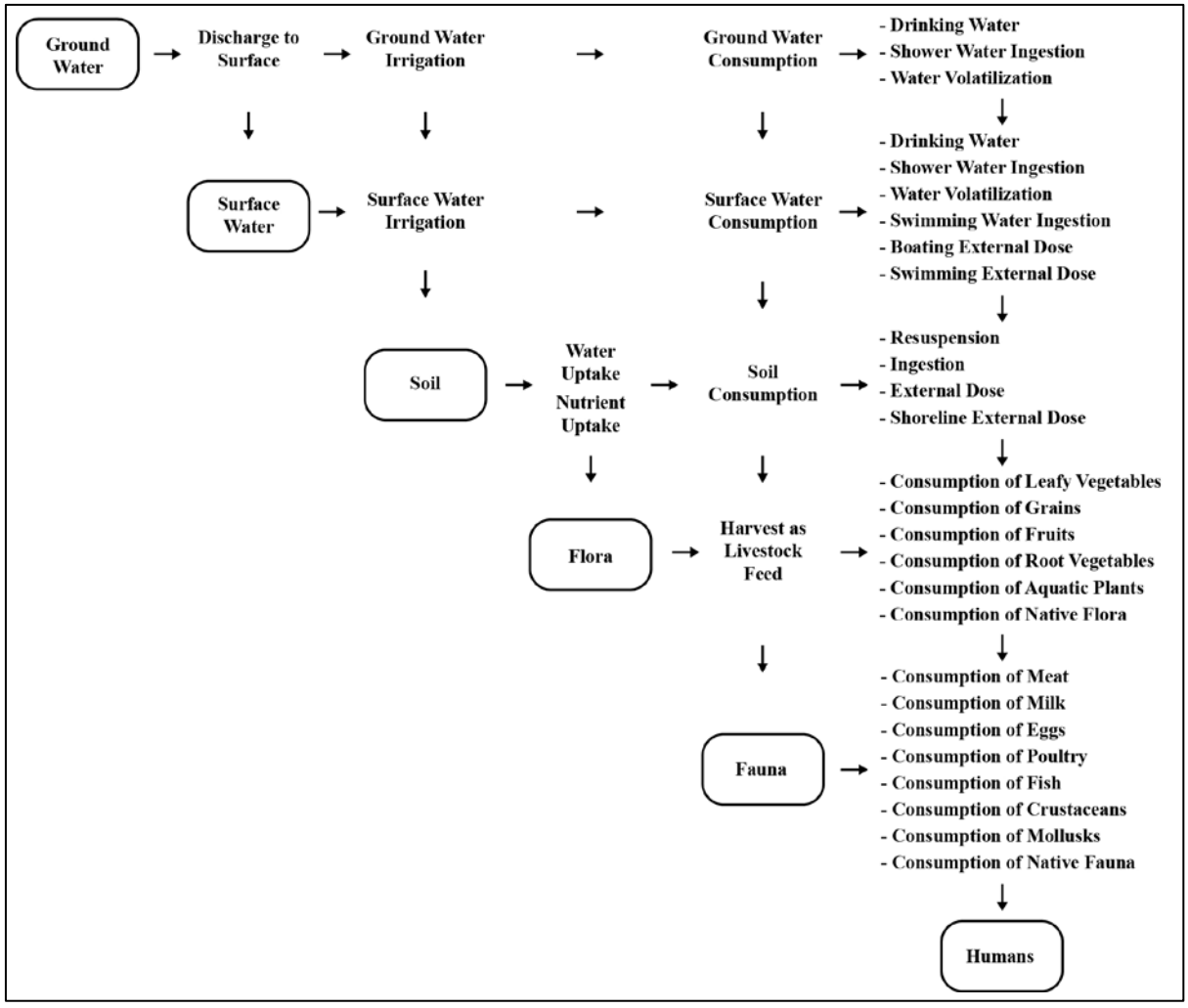

Figure 3.1. GDSA Biosphere Model Interaction Matrix

Figure 3.1 shows the major interaction matrix elements but does not depict the effect of water treatment that may occur between groundwater or surface water and human consumption of drinking water.

The user shall have the option to define the source term for the exposure pathways as either groundwater or surface water (as a dilution of groundwater) (RQMT 3.1.2). The user will have to define a groundwater source term but can designate that groundwater will only be used as a source for the surface water. While the initial source term is always groundwater output of PFLOTRAN, the biosphere model manages three source term categories over time for ideal functionality: groundwater, surface water, and soil.

Table 3.1. Human Pathways of Exposure for GDSA Biosphere Model

Source Term	Exposure Pathway	Exposure Route
Groundwater	Drinking Water	Ingestion
	Water Volatilization	Inhalation
	Shower Water Ingestion	Ingestion
	Irrigated Food Crops	Ingestion
	Irrigation/Animal Products	Ingestion
	Irrigated Ground Exposure	External
Surface Water	Drinking Water	Ingestion
	Water Volatilization	Inhalation
	Shower Water Ingestion	Ingestion
	Irrigated Food Crops	Ingestion
	Irrigation/Animal Products	Ingestion
	Irrigated Ground Exposure	External
	Swimming	External
	Swimming Water Ingestion	Ingestion
	Boating	External
	Shoreline Sediment	External
	Aquatic Foods	Ingestion
Soil	Soil Resuspension	Inhalation
	Soil Ingestion	Ingestion
	Ground Exposure	External

The user shall have the ability to define which pathways will be relevant to the scenario by being able to designate which of the potential pathways (Table 3.1) are active for the user-defined scenario (RQMT 3.1.3). The user should be able to activate any pathway as long as its source term is activated (Table 3.1). At a minimum, the user will be required to activate the groundwater source term as all other modules, including the surface water and soil source modules, depending on input from the groundwater source module. The user should have the ability to define the exposure year of interest for the receptor over the "lifetime" of the well. The user should have the ability to allow the ecosystem of interest to have a build-up of contamination from the groundwater to the soil source term from a defined period of irrigation of crops (RQMT 3.1.4). A general conceptual framework of the proposed biosphere model can be seen in Figure 3.2.

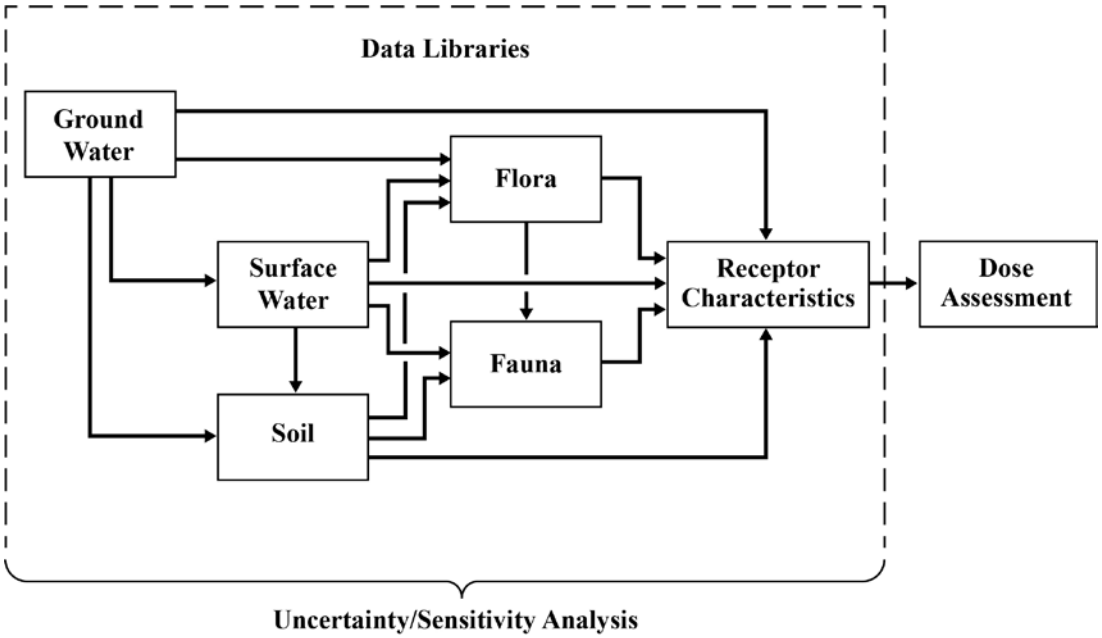

Figure 3.2. GDSA Biosphere Model Conceptual Framework

3.1.1 Data Libraries

A primary function of the GDSA Biosphere model will be to track radionuclide decay and ingrowth. The code shall track each radionuclide individually through the defined exposure pathways while tracking the ingrowth of each decay product individually through the defined exposure pathways (RQMT 3.1.1.1). The code shall be able to capture decay of radionuclides "in transit," i.e., moving through the biosphere (RQMT 3.1.1.2). Decay products that have short half-lives relative to the modeling period will be combined and tracked together ("implicit progeny") through the exposure model, consistent with the modeling practices of GENII and RESRAD (Napier, Strenge et al. 2012, Yu, Gnanapragasam et al. 2019).

The GDSA Biosphere model shall have an accompanying radionuclide database that will have radionuclide decay chain data for all radionuclides including in the biosphere model (RQMT 3.1.1.3). The user should be able to select any radionuclide from the radionuclide database to be included in the biosphere model exposure pathway analysis. If the user selects a radionuclide to be a part of the groundwater source term that has associated decay progeny, the code shall automatically include the relevant progeny in the exposure pathway analysis (RQMT 3.1.1.4). The user shall be able to select more than one radionuclide when defining the groundwater source term (RQMT 3.1.1.5).

In addition to the library of radionuclide data, the GDSA Biosphere model will have a library of dose coefficients appropriate for the proposed dose calculations and a library of default values for user input data options. The dose coefficients should be composed of the age-dependent dose coefficients presented in Federal Guidance Report 13, which are based on the ICRP 56, 67, 69, and 72 (Eckerman, Leggett et al. 1999; Eckerman, Leggett et al. 2006; Napier, Strenge et al. 2012). The library (or libraries) of default values will include values that the user will have the ability to input or adjust to best represent their proposed scenario. Examples of values that will be included in the library of defaults will be known

radionuclide-specific transfer ratios for radionuclides specific to the crops included in the GDSA Biosphere model. Other examples of data that should be included in the library or libraries of default values are reasonable consumption rates of the flora and fauna included in the GDSA Biosphere model per each potential age group of receptors, traditional water treatment reduction values, swimming water ingestion rates, etc. The library of default values should have default values for most user input values that can be reasonably found through the literature and data libraries of other biosphere models.

3.1.2 Radioactive Decay

The biosphere model shall be able to track radionuclide decay through radionuclide decay chains as well as radionuclide transfer between media compartments within the biosphere scenario (RQMT 3.1.2.1). There are many ways to approach representing radioactive decay in a model, ranging from analytical solutions, such as the Bateman equation, to solutions found through advanced numerical methods (Bateman 1910; Napier, Strenge et al. 2012). A potential methodology for representing radioactive decay and movement through the biosphere is to follow the methodology of the GENII model, which relies on compartment model math based on the work of Kennedy and Strenge (1992; Napier, Strenge et al. 2012). The GENII model relies on the principle that there are only two ways for radionuclides to be removed from a given media compartment; they must either physically move to another compartment through environmental transfer or they must decay and be transformed into another radionuclide (Napier, Strenge et al. 2012). The generalized differential equation for the rate of change of a radionuclide in a given compartment is shown in Equation (3.1) (Napier, Strenge et al. 2012).

$$\begin{aligned} &Rate\ of\ Change\ of\ Radionuclide\ C = \\ &-(Rate\ of\ physical\ Transfer\ of\ Raionuclide\ C\ out\ of\ Compartment) - \\ &(Rate\ of\ Radioactive\ Transition\ Loss\ of\ Radionuclide\ C) + \\ &(Rate\ of\ Radioactive\ Ingrowth\ of\ Radionuclide\ C) \end{aligned} \quad (3.1)$$

which can also be represented by Equation (3.2) (Napier, Strenge et al. 2012).

$$\frac{dA_c}{dt} = -L_c A_c(\mathrm{t}) - \lambda_{rc} A_c(t) + \sum_{n=1}^{c-1} d_{nc} \lambda_{rn} A_n(t) \quad (3.2)$$

where:

L_c = total rate constant for all physical transfers of chain member from the medium (days^{-1}),
$A_c(t)$ = quantity of chain member c at time t (atoms),
λ_{rc} = radioactive-transition rate constant for chain member c (days^{-1}),
$A_n(t)$ = quantity of chain member n at time t (atoms),
d_{nc} = fraction of precursor radionuclide transitions (chain member n) that result in production of the chain member c (dimensionless), and
λ_{rn} = radioactive-transition rate constant for chain member n (days^{-1}).

Evaluating decay and transitions of radionuclides requires a radionuclide data library that contains all associated radioactive decay data including half-lives, decay chains, and branching ratios. The presented differential equation can be integrated to provide the quantity of radionuclide c over the course of a time period rather than at a specific point in time. Furthermore, the presented equation can also be extended to represent radionuclide accumulation in a media compartment given an input rate of radionuclide c.

Accurately modeling radioactive decay and tracking not only the parent radionuclides but any subsequent decay product ingrowth through the biosphere modeling scenario is a critical function of the model, because all other model functions will rely on this feature. Appendix B presents detailed information about the GENII chain decay processor and foundational math, which is the mathematical model that will be adapted for the GDSA Biosphere model.

3.1.3 Source Terms and Environmental Media

The source terms for the GDSA Biosphere model will be groundwater, surface water, and soil. At a minimum the user must activate the groundwater source term in order to run the GDSA Biosphere model. The surface water source term in the first iteration of the biosphere model will be a surface water body composed of a set dilution of the groundwater source term. The soil source term for the GDSA Biosphere model will depend on what is introduced to the soil compartment from irrigation either from the groundwater or surface water compartments. The initial source of radionuclides in the biosphere originate from the groundwater source. All other environmental media (terrestrial and aquatic flora and fauna, as well as drinking water) are contaminated from the three biosphere model source terms. Special models are used to determine carbon-14 concentrations in environmental media, as described at the end of this section.

3.1.3.1 Groundwater

The user shall have the ability to assign one groundwater source for the biosphere model (RQMT 3.1.3.1). The groundwater source term will be compatible with the output from PFLOTRAN modeling. The groundwater source term should be able to accept inputs of groundwater radionuclide concentrations for designated time periods, which can exceed the time period of interest for the receptor dose calculation. The biosphere model will be compatible with the PFLOTRAN output so that the user can take the PFLOTRAN output for the designated well averaged over the period of interest and input that information directly into the groundwater source module of the biosphere model. The input options for the biosphere model shall be compatible with the units of the PFLOTRAN output to make it easy for users to use the biosphere model (RQMT 3.1.3.2).

3.1.3.2 Surface Water

The surface water term in the GDSA Biosphere model can be defined by the user as either a lake or river feature. The user shall have the ability to define what portion of the water in the surface water is from groundwater sources (to represent water upwelling from groundwater sources) (RQMT 3.1.3.3). In the first iteration of the GDSA Biosphere model, there will not be a marine environment component, but this feature could be added in later iterations of this model. The surface water features can only be activated for periods of time that have defined groundwater concentrations. It is assumed that no radionuclides are present in the water that do not originate from the groundwater source.

The concentration of radionuclides in the surface water feature will be defined by Equation (3.3). The concentration of radionuclides in the surface water shall be defined by the user (RQMT 3.1.3.4).

$$Surface\ Water\ Concentration_i = (GW_i)(F_{SW}) \tag{3.3}$$

where:

$\text{Surface Water Concentration}_i$ = concentration of radionuclide i at time x,
GW_i = concentration of radionuclide i at time x as defined in the groundwater source module, and
F_{SW} = user-provided dilution fraction (volumetric fraction of the surface water that is groundwater

3.1.3.3 Soil

The soil source term will be dependent on either the groundwater source term, the surface water source term, or both. The radionuclides in the soil source term in the GDSA Biosphere model originate from either the groundwater source term or the surface water source term. The only input of radionuclides into the soil compartment shall be from irrigation from either groundwater or surface water (RQMT

3.1.3.5) (Figure 3.3). The only loss terms for radionuclides from the soil compartment shall be through transfer to the plants and loss to harvest as well as loss from leaching out of the soil compartment into deeper soil zones that are not reachable by plants and humans in the biosphere (RQMT 3.1.3.6). These forms of loss are permanent for the soil compartment; there is no cycling through the soil compartment.

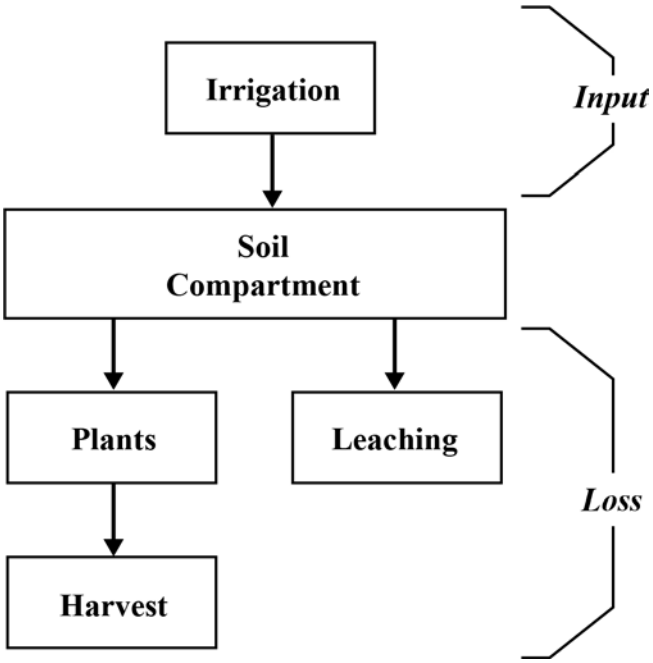

Figure 3.3. Soil Source Term Conceptual Model

The most extreme environmental situations for the soil compartment are that the soil is frozen or the ground is covered by ice or snow. It is assumed that the soil compartment for growing flora is not in a permafrost state, which would impede the movement of radionuclides through the source term. It is assumed that in the scenario where the ground would be frozen that the receptors would not be irrigating or would be irrigating crops in a greenhouse scenario. It is assumed that the loss rate from leaching in a greenhouse scenario is appropriate if the depth of the surface soil is set to the depth of the potting soil for the green house crops. Water lost from this greenhouse soil is assumed to leave the greenhouse as wastewater rather than entering the soil profile or the greenhouse floor. It is assumed that this greenhouse wastewater no longer represents a potential pathway to the receptors. For this scenario the user would also increase the shower volatilization term in order to represent the time spent in the greenhouse when they may be exposed to more volatized radionuclides from the warm environment in the greenhouse.

The concentration of individual radionuclides in the soil compartment shall be assessed in the model (RQMT 3.1.3.7). The concentration of individual radionuclides in the soil compartment can be described by differential Equation (3.4), which describes the changes in the number of atoms of a radionuclide in the soil compartment as it is affected by irrigation with contaminated water and loss from the compartment by leaching (Napier, Strenge et al. 2012).

$$\frac{dA_i(t)}{dt} = (R_{wi}) - (\lambda_{Li} + \lambda_i)A_i \tag{3.4}$$

where:

$A_i(t)$ = amount of radionuclide i in the surface soil zone at time, t (atoms),
R_{wi} = input rate from irrigation water (atoms/yr),

λ_i = rate constant for radioactive decay of radionuclide i (1/yr), and
λ_{Li} = rate constant for leaching of radionuclide from the surface soil zone (1/yr).

The rate constant for loss of radionuclides from the soil through leaching can be defined by Equation (3.5) (Baes and Sharp 1981; Napier, Strenge et al. 2012).

$$\lambda_{Li} = \frac{10^{-2}(P+I-E)}{d_s\theta_s[1+\frac{10^3 10^{-6}\rho_s}{\theta_s}Kd_{si}]} \quad (3.5)$$

where:

λ_{Li} = removal rate constant for activity of radionuclide i in the surface soil layer (1/yr),
P = total annual precipitation (cm/yr),
I = total irrigation rate (cm/yr),
E = total evapotranspiration rate (cm/yr),
ρ_s = surface soil bulk density (kg/m^3),
θ_s = surface soil volumetric water content (mL/cm^3),
Kd_{si} = surface soil distribution coefficient for radionuclide i (mL/g),
10^{-2} = unit conversion factor (m/cm),
10^3 = unit conversion factor (g/kg),
10^{-6} = units conversion factor (m^3/ml), and
d_s = depth of surface layer (cm).

The activity of radionuclide i in the surface soil will be converted to a soil concentration of radionuclide i. The loss of radionuclides through plants at harvest shall be applied as a loss to the soil concentration and is applied as a step function at the end of each year (Napier, Strenge et al. 2012) (RQMT 3.1.3.8). The loss is based on the concentration of radionuclides in the plant biomass at the time of harvest as well as well as the crop yield. The surface soil concentration can be calculated using Equation (3.6) (Napier, Strenge et al. 2012).

$$C_{si}(t_+) = C_{si}(t_-)[C_{si} - C_{hci}(Th_c)Y_c/C_{si}] \quad (3.6)$$

where:

$C_{si}(t_+)$ = surface soil concentration at soil location s for radionuclide i after correction for harvest removal at time t (Bq/m^2),
$C_{si}(t_-)$ = surface soil concentration at soil location s for radionuclide i before correction for harvest removal at time t (Bq/m^2), and
$C_{hci}(Th_c)$ = crop c concentration for radionuclide i at time of harvest (Bq/kg), and
Y_c = annual yield of crop c (kg/m^2).

3.1.3.4 Flora

Flora refers to all plant life in the biosphere. The user will be able to select some common crops but can also create custom flora in the biosphere model that can represent native flora or custom crops (RQMT 3.1.3.9). It is assumed that the flora in the model grow in the soil compartment with the water in the form of irrigation water from either the surface water or groundwater as defined by the user. For the case of native flora and fauna the user will have the ability to define the source of water as surface water, groundwater, or a combination of the two. Flora included in the model include leafy vegetables, other vegetables, cereal grains, fruits, and the user-defined native flora (Napier, Strenge et al. 2012).

The soil concentration that is used to estimate soil suspension and redeposition onto plants can be found by using a time integral of deposition from irrigation over the one-year assessment period (Napier, Strenge et al. 2012).

$$C_{ci}(T_{yr}) = C_{si}(T_{yr}) + \frac{R_{wit}}{(\lambda_i+\lambda_{Li})T_{yr}}\left[T_{yr} - \frac{1-e^{(\lambda_i\lambda_{Li})T_{yr}}}{\lambda_i}\right] \quad (3.7)$$

where:

$C_{ci}(T_{yr})$ = average concentration of radionuclide i in the farmland soil for crop type c during the current year (Bq/m^2),
$C_{si}(T_{yr})$ = average concentration during the current year of radionuclide i in the surface soil, at location s (where crop c is grown) for deposition from prior years (Bq/m^2),
R_{wit} = input rate from irrigation water (atoms/yr),
T_{yr} = one year exposure period (year),
λ_i = rate constant for radioactive decay of radionuclide i (1/yr), and
λ_{Li} = rate constant for leaching of radionuclide from the surface soil zone (1/yr).

The concentration of radionuclides in the plants shall be defined as the sum of contributions from uptake through the roots, deposition onto the plant surfaces (from irrigation and from resuspended soil), and from weathering losses (RQMT 3.1.3.10). The concentration in plants from the deposition from irrigation and resuspension can be calculated using Equation 3.8 (Soldat, Robinson et al. 1974; Napier, Strenge et al. 2012).

$$C_{dci}(T_{yr}) = \left[(3.15E7)C_{ci}(T_{yr})RF_cVd_ir_{dc} + R_{wit}\frac{12r_{ic}}{M_c}\right]\left[\frac{Tv_c}{B_c}\left(\frac{1-e^{-\lambda_{ei}Tg_c2.74E-3}}{\lambda_{ei}}\right)\right] \quad (3.8)$$

where:

$C_{dci}(T_{yr})$ = concentration of radionuclide i on plant type c at harvest from deposition processes for a one-year period (Bq/kg wet weight),
T_{yr} = one year exposure period (year),
r_{dc} = interception fraction for airborne dry deposition for plant type c (dimensionless);
R_{wit} = constant deposition rate of radionuclide i from water for year t (Bq/m^2yr),
$C_{ci}(T_{yr})$ = average concentration of radionuclide in in farmland soil from crop type c for the current one year period (Bq/m^2),
RF_c = resuspension factor for crop soil (m^{-1}),
Vd_i = deposition velocity of radionuclide i (m/sec),
12 = months per year (mo/yr),
r_{ic} = interception fraction for irrigation deposition to plant type c (dimensionless), generally equal to r_{wc},
M_c = irrigation period for plant type c (months),
Tv_c = translocation factor for plant type c (dimensionless),
B_c = total standing biomass for plant type c (kg wet weight/m^2),
λ_{ei} = effective loss rate constant from plant surfaces representing weathering (λ_{wi} in yr^{-1}), and radioactive decay for radionuclides I (λ_i in yr^{-1}),
λ_{ei} = $\lambda_{wi} + \lambda_i$,
Tg_c = crop growing period for plant type c(dy),
3.15E7 = units conversion factor (sec/yr), and
2.74E-3 = units conversion factor (yr/dy).

Atmospheric deposition will not be a feature of the first iteration of the biosphere code, so the interception fraction from airborne dry deposition for plant type c (r_{dc}) will only apply to the deposition of radionuclides onto plant surfaces that were released from the soil through resuspension and deposited by irrigation. The empirically derived Equation (3.9) can be used to represent the interception fraction for atmospheric deposition (r_{dc}) for grasses, leafy vegetables, grains, and user defined flora (Pinder, Ciravolo et al. 1988; Napier, Strenge et al. 2012).

$$r_{dc} = 1 - e^{-2.9B_cF_c} \quad (3.9)$$

where:

r_{dc} = interception fraction for atmospheric dry deposition to crop type c (dimensionless),

B_c = standing biomass of the growing vegetation for crop type c (kg wet weight/m^2), and
F_c = dry-to-wet weight biomass ratio for crop type c.

The empirical derived Equation (3.10) can be used to represent the interception fraction for atmospheric deposition (r_{dc}) for fruits and other vegetables (Napier, Strenge et al. 2012).

$$r_{dc} = 1 - e^{-3.6 B_c F_c} \tag{3.10}$$

where:

r_{dc} = interception fraction for atmospheric dry deposition to crop type c (dimensionless),
B_c = standing biomass of the growing vegetation for crop type c (kg wet weight/m^2), and
F_c = dry-to-wet weight biomass ratio for crop type c.

There are limited studies of the interception fraction for radionuclides from irrigation (r_{ic}), so the default value of 0.25 will be used if no better information is available as a deposition value for radionuclides on any plants from irrigation, as seen in the GENII code (Napier, Strenge et al. 2012).

The concentration of radionuclides in plant tissues shall include radionuclides that are absorbed through the roots (RQMT 3.1.3.11). The concentration in the plants from root uptake from the surface soil layer can be calculated using Equation (3.11) (Napier, Strenge et al. 2012).

$$C_{rci}(T_{yr}) = \frac{C_{ci}(T_{yr}) RP_{sc} Bv_{ci} f_c}{P_3} \tag{3.11}$$

where:

$C_{rci}(T_{yr})$ = concentration of radionuclide i in crop type c from root uptake pathways for a one-year period (Bq/kg wet weight),
Bv_{ci} = concentration ratio for root uptake of radionuclide i in crop type c (Bq/kg dry plant per Bq/kg wet weight),
f_c = dry-to-wet ratio for plant type c (kg dry plant/kg wet plant),
P_3 = areal soil density of farmland soil (kg/m^2), and
RP_{sc} = fraction of plant type c roots in surface soil zone (dimensionless).

The total concentration of radionuclide i in the crop type c from both the deposition from irrigation and resuspension as well as uptake from crops can be calculated using the Equation (3.12) (Napier, Strenge et al. 2012).

$$C_{hci}(T_{yr}) = C_{dci}(T_{yr}) + C_{rci}(T_{yr}) \tag{3.12}$$

where:

$C_{hci}(T_{yr})$ = concentration in plant type c at harvest for a one-year period (Bq/kg wet weight) and other terms are as previously defined,
$C_{dci}(T_{yr})$ = concentration of radionuclide i on plant type c at harvest from deposition processes for a one-year period (Bq/kg wet weight), and
$C_{rci}(T_{yr})$ = concentration of radionuclide i in crop type c from root uptake pathways for a one-year period (Bq/kg wet weight).

The biosphere code shall account for the difference in radionuclide concentration at the time of harvest and the time of consumption of the plant products (RQMT 3.1.3.12). In the GENII code, this is referred to as a "holdup delay" and it is used to account for the decay of radionuclides in the plant products between harvest and consumption (Napier, Strenge et al. 2012). This change in concentration in the plant products can be calculated using Equation (3.13).

$$C_{csi}(T_{yr}) = C_{hci}(T_{yr}) e^{-\lambda_i Th_c 2.74E-3} \tag{3.13}$$

where:

$C_{csi}(T_{yr})$ = concentration of radionuclide i in crop type c at location s at the time of consumption over a one year period (Bq/kg wet weight),
$C_{hci}(T_{yr})$ = concentration in plant type c at harvest for a one year period (Bq/kg wet weight) and other terms are as previously defined,
Th_c = holdup delay time between harvest and consumption for crop type c (dy),
λ_i = radiological decay constant for radionuclide i (yr^{-1}), and
2.74E-3 = conversion factor years per day (yr/dy).

3.1.3.5 Fauna

Fauna refers to the living animal life in the biosphere. The user will be able to use the pre-built fauna pathways or create a user-defined fauna to represent native fauna or a custom animal pathway (RQMT 3.1.3.13). Fauna concentration of radionuclides will be defined by what the fauna consumes through ingestion of flora, water, or soil (RQMT 3.1.3.14). The concentrations of the radionuclides in the fauna will define the concentrations in the animal products that the receptor will consume. Animal products included in the model include beef/meat, poultry, milk, and eggs (Napier, Strenge et al. 2012).

The concentration of radionuclide i in the animal product at the time of harvest, based on a one-year average, can be calculated using Equation (3.14) (Napier, Strenge et al. 2012).

$$C_{hai}(T_{yr}) = Fa_i[C_{wi}(T_{yr})d_{aw}U_{aw} + C_{ai}(T_{yr})d_{as}U_{as} + \sum_{f=1}^{N_{af}} C_{cfi}(T_{yr})d_{af}U_{af}] \quad (3.14)$$

where:

$C_{hai}(T_{yr})$ = concentration of radionuclide i in animal product a at harvest of the animal product for a one year period (Bq/kg),
T_{yr} = one year exposure period (year),
Fa_i = transfer coefficient that relates daily intake rate by an animal to the concentration in an edible animal product a (Bq/L milk per Bq/d for milk and Bq/kg meat per Bq/d for meat),
$C_{wi}(T_{yr})$ = average concentration of radionuclide i in water (Bq/L),
$C_{ai}(T_{yr})$ = average concentration of radionuclide i in soil consumed by animals for a year (Bq/kg dry soil),
$C_{cfi}(T_{yr})$ = concentration of radionuclide i in animal feed type f at time of consumption for a one-year period (Bq/kg wet weight),
d_{aw} = fraction of animal type a water intake that is contaminated (dimensionless),
U_{aw} = daily water intake rate for animal a (L/dy),
d_{as} = fraction of animal type a soil intake that is contaminated (dimensionless) (default set to 1.0),
U_{as} = daily soil intake rate for animal type a (kg/dy),
N_{af} = number of feed types, f, fed to animal type a,
d_{af} = fraction of animal type a feed type f intake that is contaminated (dimensionless), and
U_{af} = daily feed intake rate for animal type a of feed type f (kg/dy).

There will be a reduction in the activity of the radionuclides in the animal products between the time of harvest and consumption due to radioactive decay; the code shall account for this change in radionuclide concentration (RQMT 3.1.3.15). This time difference between harvest and consumption of animal products is referred to as the "holdup delay" and can be accounted for using Equation (3.15) (Napier, Strenge et al. 2012).

$$C_{asi}(T_{yr}) = C_{hai}(T_{yr})e^{-\lambda_i Th_a 2.74E-3} \quad (3.15)$$

where:

$C_{asi}(T_{yr})$ = concentration of radionuclide i in animal product a at usage location s at the time of consumption for a one-year period (Bq/kg wet weight),
Th_a = holdup delay time between harvest and consumption for animal product a (days),
λ_i = radiological decay constant for radionuclide i (years^{-1}), and
2.74E-3 = conversion factor years per day (yr/dy^{-1}).

3.1.3.6 Aquatic Flora and Fauna

Aquatic flora and fauna included in the model shall include fish, mollusks, invertebrates, and water plants (RQMT 3.1.3.16). The user shall have the ability to create a unique user-defined aquatic flora and fauna that can be used to represent unique native flora and fauna for a specific biosphere scenario (RQMT 3.1.3.17). The aquatic flora and fauna are exposed to radionuclides through the surface water. The concentrations of radionuclides in the flora and fauna shall be based on the average radionuclide concentration in the surface water over the course of the assessment year (RQMT 3.1.3.18).

The concentration of radionuclide i in the aquatic flora or fauna can be calculated using Equation (3.16), which will be based on the average concentration of radionuclides i in the surface water over the course of the assessment year (Napier, Strenge et al. 2012).

$$C_{hqi}(T_{yr}) = C_{wi}(T_{yr})B_{qi} \tag{3.16}$$

where:

$C_{hqi}(T_{yr})$ = concentration of radionuclide i in aquatic food type q at time of harvest (Bq/kg),
$C_{wi}(T_{yr})$ = concentration of radionuclide i in the water consumed by animals for a year (Bq/L), and
B_{qi} = bioaccumulation factor for radionuclide i in the edible portions of aquatic food type q (bq/kg wet flora/fauna per Bq/L water).

The code shall account for the differences in radionuclide concentration in the aquatic flora and fauna between the time of harvest and the time of consumption (RQMT 3.1.3.19). The concentration difference can be calculated using Equation (3.17) (Napier, Strenge et al. 2012).

$$C_{qwi}(T_{yr}) = C_{hqi}(T_{yr})e^{-\lambda_i Th_q 2.74E-3} \tag{3.17}$$

where:

$C_{qwi}(T_{yr})$ = concentration of radionuclide i in aquatic food flora or fauna q at water location w at time of harvest (Bq/kg wet weight),
$C_{hqi}(T_{yr})$ = concentration of radionuclide i in aquatic food type q at time of harvest (Bq/kg),
Th_q = holdup delay time between harvest and consumption for aquatic flora or fauna q (days), and
λ_i = radiological decay constant for radionuclide i (years^{-1}).

3.1.3.7 Carbon-14 Special Model

Carbon-14 (C-14) shall be treated as a special radionuclide in the GDSA Biosphere model because of its unique environmental movement qualities (RQMT 3.1.3.20). Humans and animals get the majority of their carbon from ingestion of plants and other animals; and plants get the majority of their carbon from the air. The GENII code follows an extremely conservative methodology of assuming that all carbon in the plant comes from the soil and determines the concentration of C-14 in the plants based on the specific activity of C-14 in the soil (Napier, Strenge et al. 2012). A more appropriate approach for C-14 modeling is based on the C-14 model in the RESRAD-Offsite code, which considers the movement of C-14 to the plant through the soil, foliar deposition of dust contaminated with C-14, and volatilized C-14 in the air around the plant being incorporated into the plant through photosynthesis (Yu, Gnanapragasam et al. 2019). In the RESRAD model, C-14 is modeled to follow stable carbon in the environment.

The RESRAD C-14 model considers the evasion rate ($C\text{-}14_{release}$) from carbon in the soil to carbon dioxide, which can then be taken up into the plant as a gas (Yu, Gnanapragasam et al. 2019). The RESRAD model user evasion rates of carbon from the soil to estimate the concentration of C-14 in the air above the soil where plants would absorb it using Equations (3.18) and (3.19) (Yu, Gnanapragasam et al. 2019).

$$C-14_{air,vol} = \frac{(3.17x10^{-8})(C-14_{release})(\sqrt{A})}{(2)(H_{mix})(V_{wind})} \quad (3.18)$$

where:

$C\text{-}14_{air,vol}$	=	C-14 concentration in air over the contaminated area due to volatilization (Bq/m^3),
$C\text{-}14_{release}$	=	C-14 flux (evasion rate) from the contaminated area, $Bq/(m^2/yr)$,
H_{mix}	=	height at which CO_2 gas is uniformly mixed (1 m for the plant, meat, and milk ingestion pathways),
A	=	area of release site, and
V_{wind}	=	wind velocity (assume typical average wind velocity for GDSA biosphere model, (m/sec), and
3.17E-8	=	conversion factor (yr/sec)

$$C-14_{release} = (C-14_{soil})(3.156x10^{7})(E_{c,C-14})(\rho_b)(d_s)(CF_{evasion,C-14}) \quad (3.18)$$

where:

10^6	=	unit conversion factor(cm^3/m^3)
$C\text{-}14_{soil}$	=	concentration of C-14 in contaminated soil (Bq/g),
3.156 $x10^7$	=	unit conversion factor (sec/yr),
$E_{c,C-14}$	=	evasion loss rate constant of C-14 in soil (1/sec),
ρ_s	=	surface bulk density (g/cm^3),
d_s	=	depth of surface layer, reference evasion depth (m), and
$CF_{evasion,C-14}$	=	cover and depth correction factor for evasion of C-14.

Equation (3.23) includes an evasion loss rate constant for C-14 in the soil, which can be found for different soil types in the published literature (Yu, Gnanapragasam et al. 2019). The effective rate C-14 loss rate from radioactive decay and leaching of C-14 from the soil compartment can be calculated using Equation (3.20) (Yu, Gnanapragasam et al. 2019).

$$SF_{E,C-14}(t) = e^{-((E_{c,C-14})(CF_{evasion,C-14})(t))} \quad (3.190)$$

where:

$S_{FE,C-14(t)}$	=	loss rate of C-14 from the soil compartment,
$E_{c,C-14}$	=	evasion loss rate constant of C-14 in soil (1/sec), and
$CF_{evasion,C-14}$	=	cover and depth correction factor for evasion of C-14.

While the C-14 in the air can then spread to other locations, for the first iteration of the GDSA Biosphere model it will be assumed that once C-14 leaves the vicinity of the growing plants it is no longer considered in this model. The concentration of C-14 that is incorporated into the plants from a gaseous pathway can be calculated according to Equation (3.21), assuming that C-14 follows stable C-12 in gaseous absorption through photosynthesis (Yu, Gnanapragasam et al. 2019). The model will still need to account for the transfer of C-14 to the plant mass from the soil compartment through contaminated water.

$$C-14_{plant,ps} = (C-14_{air})\left(\frac{F_a C-12_{plant}}{C-12_{air}}\right) \quad (3.201)$$

$$AP_{C-14} = \frac{F_a C-12_{plant}}{C-12_{air}}$$

where:

$C\text{-}14_{plant,ps}$ = concentration of C-14 in plants derived from photosynthesis(Bq/kg),
$C\text{-}14_{air}$ = concentration of C-14 (as CO_2) in air (pCi/m^3),
$AP_{C\text{-}14}$ = evasion loss rate constant of stable carbon in soil (0.0032 yr-1),
$C\text{-}12_{plant,ps}$ = $C\text{-}14_{plant,ps}$/C-14. Air to plant transfer factor for photosynthesis for C-14 (m^3/kg),
$C\text{-}12_{air}$ = concentration of stable carbon in air (kg/kg or dimensionless),
F_a = fraction of stable carbon in plants derived from carbon in air, and
$C\text{-}12_{plant}$ = stable carbon concentration in plant (i.e., fraction of plant mass that is carbon) (kg/kg or dimensionless).

The RESRAD-Offsite model assumes that the C-14 follows stable C-12 when considering the amount of C-14 that is absorbed into the plant through root uptake as seen in Equation (3.22) (Yu, Gnanapragasam et al. 2019).

$$C-14_{plant,ru} = C-14_{soil}(1000)\left(\frac{(F_s)(C-12_{plant})}{C-12_{soil}}\right) \quad (3.212)$$

where:

$C\text{-}14_{plant,ru}$ = concentration of C-14 in plants derived from root uptake (Bq/kg),
1000 = unit conversion factor (g/kg),
$C\text{-}12_{plant,up}$ = stable concentration in plant (kg/kg or dimensionless), and
F_s = fraction of stable carbon in plants derived from carbon in soil.

Similar to the movement of C-14 from air to plants and soil to plants, the movement of C-14 to livestock in the RESRAD model is assumed to follow stable carbon as seen in Equation 3.23 (Yu, Gnanapragasam et al. 2019).

$$IMTF = \frac{\frac{C-14_{animal\ product}}{Intake_{water}^{livestock} C-14_{water} + \sum_{feed} Intake_{feed}^{livestock} C-14_{feed} + \sum_{agri} Intake_{soil}^{livestock} C-14_{soil})(\frac{1000g}{kg})} = \frac{\frac{C-12_{animal\ product}}{Intake_{water}^{livestock} C-12_{water} + \sum_{feed} Intake_{feed}^{livestock} C-12_{feed} + \sum_{agri} Intake_{soil}^{livestock} C-12_{soil})(\frac{1000g}{kg})} \quad (3.223)$$

where:

IMTF = intake to meat or milk transfer factor for C-14 (d/kg);
$C\text{-}14_{animal\ product}$ = C-14 concentration in livestock water (pCi/L);
feed = (1) grazing plants, and (2) grain;
$Intake_{feed}^{livestock}$ = daily intake rate of grazing plants or grain by livestock (kg/dy);
$C\text{-}14_{feed}$ = C-14plant. C-14 concentration in grazing plants or grain (pCi/kg);
$Intake_{soil}^{livestock}$ = daily intake rate of soil by livestock at the agricultural field (kg/dy);
$C\text{-}14_{soil}$ = C-14 concentration in soil at the agricultural field (pCi/g);
$C\text{-}12_{animal\ product}$ = concentration of stable carbon, equivalent to fraction of stable carbon (assuming density of milk is 1 kg/L), in animal product (meat or milk) (0.24 kg/kg for meat, or 0.70 kg/L for milk);
$C\text{-}12_{water}$ = concentration of stable carbon, equivalent to fraction of stable carbon (assuming density of water is 1 kg/L), in livestock water (2.0×10^{-5} kg/L);
$C\text{-}12_{feed}$ = $C\text{-}12_{plant}$. Stable carbon concentration (i.e., mass fraction of stable carbon) in grazing plants or in grain (kg/kg; 0.4 for grain and 0.09 for pasture and silage); (available from published literature); and
$C\text{-}12_{soil}$ = concentration of stable carbon in soil, i.e., fraction of soil that is stable carbon (0.03 kg/kg or dimensionless).

The movement of Carbon-14 into aquatic flora and fauna shall use transfer ratios rather than C-14 specific special models (RQMT 3.1.3.21).

3.1.4 Dose Calculation Through Receptor Pathways

The user shall have the ability to define the receptor characteristics for the exposure pathways (RQMT 3.1.4.1). The GDSA Biosphere model is meant to be generic and adaptable so that many different biosphere scenarios could be modeled. This will largely be accomplished through the flexibility of the user characteristics. It is assumed that regardless of societal and environmental changes the human receptors will require drinking water and consume of a diet based on flora and fauna. All other characteristics of the receptor will be defined by the user in order to represent the scenario of interest.

For example, a user will be able to adjust the receptor characteristics such that the user could model a receptor as a member of a hunter gather society by adjusting their food and behavior parameters. This could be accomplished by changing the food input to primarily a representative native plant or animal species rather than the agricultural crops that are typically used as food inputs to maximally exposed individuals today.

All pathways of exposure in the biosphere model can be categorized as either external or internal. Internal exposures to radionuclides can be either ingestion or inhalation exposures. The first step in the dose assessment process is to estimate the receptor's external or internal exposure to radionuclides. These exposure pathways will depend on the user-defined scenario and the receptor characteristics. The calculation of radionuclide exposure is based on the concentration of that radionuclide in the medium, the intake/contact rate, the exposure duration, the receptor's daily activity patterns, and the receptor's annual activity patterns (Napier, Strenge et al. 2012).

Based on the intake and exposure estimates for each pathway, the committed equivalent and committed effective doses are calculated. The individual receptor doses should be presented as an effective dose for a receptor rather than equivalent doses to the receptor organs. The recommended ICRP dose coefficients and weighting factors should be used. For the public, ICRP-recommended values can be found in Federal Guidance Report 13 or in ICRP Publications 56, 67, 69, 71, and 72 (Napier, Strenge et al. 2012). The time period of integration for both the committed effective dose and the committed equivalent dose depends on the age of the receptor; age groups range from 3 months to adult and time periods of integration range from 50 years to 70 years (Napier, Strenge et al. 2012). The committed equivalent dose is the sum of the average absorbed dose for each radiation type, as shown in Equation (3.28) (Napier, Strenge et al. 2012).

$$H_t(\tau) = \sum_R w_R D_{T,R}(\tau) \tag{3.23}$$

where:

$H_t(\tau)$ = committed equivalent dose to target organ T over integrating period τ (Sv),
w_R = radiation weighting factor to derive the equivalent dose from the absorbed dose averaged over a tissue or organ and is based on the quality of radiation (dimensionless), and
$D_{T,R}(\tau)$ = average absorbed dose to target organ T over integrating period τ from radiation of type R (Gy).

To calculate the committed effective dose, which represents the total effect to the whole body, Equation (3.29) can be used, which is the sum of the organ equivalent doses with the tissue weight factors applied (Napier, Strenge et al. 2012).

$$E(\tau) = \sum_T w_T H_T(\tau) \tag{3.24}$$

where:

$E(\tau)$ = committed effective dose over integrating period τ (Sv);
w_T = tissue weighting factor, by which the equivalent dose in a tissue or organ is weighted to represent the relative contribution of that tissue or organ to the total detriment resulting from uniform irradiation of the body (dimensionless); and

$H_T(\tau)$ = committed equivalent dose to target organ T over integrating period τ (Sv).

The exposure and intake rate and subsequent equivalent dose and effective dose calculation methodologies are presented for each potential exposure pathway for the GDSA Biosphere model. The exposure and intake rates for all potential pathways are presented here and the pathway specific equations for effective and equivalent dose are presented in Appendix C and are consistent with the general equations presented in Equation 3.28 and 3.29.

3.1.4.1 Ingestion of Flora, Fauna, Aquatic Flora, and Aquatic Fauna

The ingestion exposure pathways for flora, fauna, or aquatic flora and fauna can be defined by the concentration of radionuclide i in the ingested food product and the consumption rate of the receptor. For the ingestion exposure for any these four pathways, the activity of ingested radionuclide i will be defined by the concentration of the radionuclide in the ingested medium (flora, fauna, aquatic flora, aquatic fauna) multiplied by the ingestion rate for the receptor (either chosen from the library of default values or by the user).

3.1.4.2 Ingestion of Water

The model shall have an exposure pathway representing the radionuclide exposure the receptor receives by ingesting water (RQMT 3.1.4.2). The average annual concentration of radionuclides in either surface water or groundwater can be used to calculate the receptor's exposure to radionuclides through drinking water. To determine the radionuclide concentration in the drinking water the code will account for the difference in radionuclide concentrations between the water source and the receptor, which can include water treatment and a holdup delay. The concentration of the domestic water at the point of ingestion for the receptor can be calculated using Equation (3.30) (Napier, Strenge et al. 2012).

$$C_{dwi}(T_{yr}) = C_{wi}(T_{yr}) TF_i e^{-\lambda_i Th_w 2.74E-3} \quad (3.25)$$

where:

$C_{dwi}(T_{yr})$ = concentration of radionuclide i in water at water usage location w at the time of consumption (Bq/L),
$C_{wi}(T_{yr})$ = concentration of radionuclide i in the water (Bq/L),
TF_i = water treatment purification factor giving the fraction of radionuclide i remaining in the water after treatment (dimensionless),
λ_i = radiological decay constant for radionuclide i ($years^{-1}$),
Th_w = holdup time between the water intake plant and the point of water use (days), and
2.74E-3 = units conversation factor (yrs/dy).

For the ingestion exposure of water, the activity of ingested radionuclide i will be defined by the concentration of the radionuclide in the water multiplied by the ingestion rate for the receptor.

3.1.4.3 Ingestion of Shower Water

The model shall have an exposure pathway representing the radionuclide exposure the receptor receives by inadvertently ingesting shower water (RQMT 3.1.4.3). The internal exposure received from the ingestion of shower water can be calculated using Equation (3.31) and is based on the daily and annual activity behaviors of the receptor's age group (Napier, Strenge et al. 2012).

$$I_{hwig}(T) = C_{dwi}(T) FE_{hrg} TE_{hrg} Tc_s U_{hwg} \quad (3.26)$$

where:

$I_{hwig}(T)$ = average exposure factor over time period T for radionuclide i from ingesting shower water at location r for individuals in age group g (Bq),

$C_{dwi}(T)$ = average concentration of radionuclide i in drinking water at water usage location w (Bq/L),
FE_{hrg} = frequency of showering events at water use location r for individual in age group g (events/dy),
TE_{hrg} = duration of an average shower event at water use location r for individuals in age group g (hr/event),
Tc_s = time correction set equal to T_{hrg} for chronic releases and to the lesser of (T_{ew}*8760 (hour/year))/(FE_{hrg}*TE_{hrg})) or (1 day) for acute releases,
T_{hrg} = annual exposure factor for showering at water use location r for individuals in age group g (days), and
U_{hwg} = uptake rate of water while showering for age group g (L/hr).

3.1.4.4 Ingestion of Swimming Water

The model shall have an exposure pathway that represents the radionuclide exposure the receptor receives by inadvertently ingesting surface water while swimming (RQMT 3.1.4.4). The internal exposure the receptor receives from the ingestion of swimming water can be calculated using Equation (3.32), and it is based on the daily and annual activity behaviors of the receptor's age group (Napier, Strenge et al. 2012).

$$I_{wwig}(T) = C_{wri}(T) FE_{wrg} TE_{wrg} Tc_s U_{swg} \tag{3.27}$$

where:

$I_{wwig}(T)$ = average exposure factor over time period T for radionuclide i from ingestion at swimming location r for individuals in age group g (Bq),
$C_{wri}(t)$ = average water concentration over time period T for radionuclide i in surface water at the recreational swimming location r (Bq/L),
FE_{wrg} = frequency of swimming events at water use location r for individuals in age group g (events/dy),
TE_{wrg} = duration of an average swimming event at water use location r for individuals in age group g (hrs/event),
Tc_s = time correction set equal to T_{wrg} for chronic releases and to the lesser of (T_{ew}*8760 (hour/year)/(FE_{wrg}*TE_{wrg})) or (1 day) for acute releases,
T_{wrg} = annual exposure factor for swimming at water use location r for individuals in age group g (day), and
U_{swg} = uptake rate of water while swimming for age group g (L/hr).

3.1.4.5 Ingestion of Soils

The model shall have an exposure pathway that represents the radionuclide exposure the receptor receives by inadvertently ingesting soil (RQMT 3.1.4.5). The concentration for the ingested soil is determined at a given location given the introduction of radionuclides from irrigation water. To be conservative, it is assumed that the ingested soil comes from the location where crops are irrigated; this location in the biosphere model will have the highest rate of irrigation and therefore will have the highest potential activity of radionuclides. The activity of the radionuclides is the average activity over the course of the assessment year. The average soil location at the point of soil ingested can be calculated using Equation (3.33) (Napier, Strenge et al. 2012).

$$C_{dsi}(T_{yr}) = \frac{10^3}{10^4 \rho_s d_s}\left[C_{si}(T_{yr}) + \frac{R_{wit}}{\lambda_i T_{yr}}\left(T_{yr} - \frac{1-e^{-\lambda_i T_{yr}}}{\lambda_i}\right)\right] \tag{3.28}$$

where:

$C_{dsi}(T_{yr})$ = Average concentration at soil location s for radionuclide i in soil consumed during the current year (Bq/kg),
$C_{si}(T_{yr})$ = Average surface soil concentration at soil location s for radionuclide i during the current year (Bq/m^2) ,
ρ_s = density of surface soil (g/cm^3),
d_s = thickness of surface soil layer (cm),
10^4 = units conversion factor (cm^2/m^2),
10^3 = units conversion factor (g/kg),
λ_i = radiological decay constant for radionuclide i (yr^{-1}),
R_{wit} = input rate from irrigation water (atoms/yr), and
T_{yr} = one year exposure period (year).

For the ingestion exposure received through ingested soils, the activity of ingested radionuclide i will be defined by the concentration of the radionuclide in the soil multiplied by the ingestion rate for the receptor.

3.1.4.6 Inhalation of Shower Volatilized Water

The model shall have an exposure pathway that represents the radionuclide exposure the receptor receives by inadvertently inhaling volatilized shower or indoor water (RQMT 3.1.4.6). Exposure to volatilized water in a greenhouse environment could also be characterized. The receptor could have an internal inhalation exposure pathway of inhaling volatilized water with radionuclides through activities where water is exposed to the open air such as showering, cooking, washing, etc. (Andelman 1990; Napier, Strenge et al. 2012). Most radionuclides are nonvolatile and this pathway will be unwarranted, but for volatile or gaseous radionuclides such as radon and krypton this pathway is required (Napier, Strenge et al. 2012). The inhalation of volatilized radionuclides is only considered for indoor air for the first iteration of the biosphere model. The concentration of radionuclides in the indoor air from volatilization of radionuclides from water can be calculated using Equation (3.34) (Napier, Strenge et al. 2012).

$$C_{vwi}(T_{yr}) = C_{wi}(T_{yr}) TF_i K_r e^{-\lambda_i Th_w 2.74E-3} \quad (3.29)$$

where:

$C_{vwi}(T_{yr})$ = concentration of radionuclide i in indoor air from volatilization from domestic water for the current year t (Bq/m^3),
$C_{wi}(T_{yr})$ = concentration of radionuclide i in the water (Bq/L),
TF_i = water treatment purification factor giving the fraction of radionuclide i remaining in the water after treatment (dimensionless),
K_r = Andelman volatilization factor for radionuclide pollutants (L/m^3),
λ_i = radiological decay constant for radionuclide i (year^{-1}),
Th_w = holdup time between the water intake plant and the point of water use (days), and
2.74E-3 = unit conversion factor (yrs/dy).

The volatilization factor for radionuclides is based on empirical values. For noble gases, including radon, it is recommended that the volatilization factor be 0.1 L/m^3 (Napier, Strenge et al. 2012). The minimum volatilization factor for nonvolatile radionuclides should be 3.0 x 10^{-5} (L/m^3) (Finley, Kerger et al. 1996; Napier 2012; Napier, Strenge et al. 2012). It is possible for a radionuclide to have a higher volatilization factor if it is part of a volatile compound.

The total intake of radionuclides that the receptor inhales can be calculated using Equation (3.35) (Napier, Strenge et al. 2012).

$$I_{vwig}(T) = C_{vwi}(T) U_{vwg} F_{vwg} T_{vwg} ED_{vwg} \quad (3.30)$$

where:

I_{vwig} = total intake of radionuclide i from indoor air inhalation over the period T at water usage location w for individuals in age group g (Bq),
$C_{vwi}(T)$ = average indoor air concentration for volatile radionuclide i at water usage location w over time period T (Bq/m^3),
U_{vwg} = inhalation rate for indoor air at water usage location w for individuals in age group g (m^3/dy),
F_{vwg} = fraction of a day that indoor inhalation occurs at water usage location w for individuals in age group g (dimensionless),
T_{vwg} = annual intake factor giving days per year that indoor air inhalation occurs at water usage location w for individuals in age group g, and
ED_{vwg} = exposure duration for the indoor air inhalation pathway at water usage location w for individuals in age group g (years).

3.1.4.7 Inhalation of Resuspended Soils

The model shall have an exposure pathway that represents the radionuclide exposure the receptor receives by inadvertently inhaling resuspended soils (RQMT 3.1.4.7). The receptor's inhalation of resuspended soils will be based on the resuspension factors that are also used to determine the resuspension of soils that were then deposited on flora surfaces. The resuspension factor relies on the assumption that the soil resuspended in the air has the same activity as the soil in the soil compartment at that location (Napier, Strenge et al. 2012). The concentration of radionuclide i in the air at the location of soil resuspension can be calculated using Equation (3.36) (Anspaugh, Shinn et al. 1975; Napier, Strenge et al. 2012).

$$C_{sai}(T_{yr}) = RF_a[C_{si}(T_{yr}) + \frac{R_{wit}}{(\lambda_i+\lambda_{Li})T_{yr}}\left(T_{yr} - \frac{1-e^{-(\lambda_i+\lambda_{Li})T_{yr}}}{\lambda_i}\right)] \quad (3.31)$$

where:
$C_{sai}(T_{yr})$ = air concentration of radionuclide i at soil resuspension exposure location a for a year (Bq/m^3),
RF_a = resuspension factor based on soil mass loading for soil exposure locations (m^{-1}),
$C_{si}(T_{yr})$ = average surface soil concentration over the current year at the soil exposure location s from material deposited in prior years (Bq/m^2),
λ_i = radiological decay constant for radionuclide i (yr^{-1}),
λ_{Li} = rate constant for leaching of radionuclide from the surface soil zone (1/yr),
R_{wit} = input rate from irrigation water (atoms/yr), and
T_{yr} = one-year exposure period (year).

The resuspension factor (RF_a) can be estimated using mass loading of the soil into the atmosphere, which can be calculated using Equation (3.37) (Napier, Strenge et al. 2012).

$$RF_a = \frac{S}{\rho_s d_{rs} 10^6} \quad (3.32)$$

where:
S = mass loading of soil in air (g/m^3),
ρ_s = surface soil density (g/cm^3),
d_{rs} = thickness of surface soil layer at resuspension location (m) (assumed to be the full thickness of the soil layer), and
10^6 = units conversion factor (cm^3/m^3).

The inhalation of resuspended soils can be calculated using Equation (3.38) (Napier, Strenge et al. 2012).

$$I_{saig}(T) = C_{sai}(T)U_{sag}F_{sag}T_{sag}ED_{sag} \quad (3.33)$$

where:

$I_{saig}(T)$ = total intake of radionuclide i from suspension inhalation over the period T at soil usage location a for individuals in age group g (Bq),
$C_{sai}(T)$ = average concentration of radionuclide i in air from resuspension over time period T at soil usage location s (Bq/m^3),
U_{sag} = inhalation rate of air for the resuspension pathway at soil usage location s for individuals in age group g (m^3/dy),
F_{sag} = fraction of a day that resuspension inhalation exposure occurs at soil usage location s for individuals in age group g (dimensionless),
T_{sag} = annual intake factor giving days per year that resuspension inhalation occurs at soil usage location s for individuals in age group g (dy/yr), and
ED_{sag} = exposure duration for the resuspension inhalation at soil usage location s for individuals in age group g (years).

3.1.4.8 Ground External Exposure

The model shall have an exposure pathway that represents the radionuclide external exposure the receptor receives from contaminated ground surfaces (RQMT 3.1.4.8). The ground exposure equation based on the GENII code considers activity patterns for the receptor's age group on a daily and annual basis (Napier, Strenge et al. 2012). The external exposure to the ground can be calculated using Equation (3.39) (Napier, Strenge et al. 2012).

$$I_{esig}(T) = {C_{esi}U_{esg}[SH_hFT_{hg} + SH_0FT_{og}]T_{esg}}/{8760} \quad (3.34)$$

where:

$I_{esig}(T)$ = average exposure factor over time period T for external exposure to ground for radionuclide i for individuals in age group g (Bq/kg),
$C_{esi}(T)$ = average soil concentration at the location of individual exposure for radionuclide i for time period T (Bq/kg),
U_{esg} = daily exposure factor giving hours of exposure to contaminated ground per day for individuals in age group g (hr/dy),
SH_h = shield factor for exposure to soil while inside a home (dimensionless),
FT_{hg} = fraction of time spent inside a home for individuals in age group g (dimensionless),
SH_o = shield factor for exposure to soil while outside (dimensionless),
FT_{og} = fraction of time spent outside for individuals in age group g (dimensionless),
T_{esg} = annual exposure factor given for external ground exposure for individuals in age group g (dy/yr), and
8760 = unit correction (hr/yr).

Swimming External Exposure

The model shall have an exposure pathway that represents the radionuclide external exposure the receptor receives from surface water swimming (RQMT 3.1.4.9). The swimming external exposure can be calculated using Equation 4.1.4.13 and the daily and annual activity behaviors of the receptor's age group (Napier, Strenge et al. 2012).

$$I_{wrig}(T) = C_{wri}(T)FE_{wrg}TE_{wrg}Tc_s \quad (3.35)$$

where:

$I_{wrig}(T)$ = average exposure factor over time period T for radionuclide i from swimming at recreational swimming location r for individuals in age group g (Bq/L),

$C_{wri}(T)$ = average water concentration over time period T for radionuclide i in surface water at the recreational swimming location r (Bq/L),
FE_{wrg} = frequency of swimming events at recreational swimming location r,
Tc_s = time correction set equal to $T_{wrg}/8760$ (hours/year) for chronic releases and to the lesser of ($1.0/FE_{wrg}*TE_{wrg}$) or ($1/T_{ew}*8760$)) for acute releases,
TE_{wrg} = duration of an average swimming event at recreational swimming location r for individuals in age group g (hrs/event),
T_{ew} = acute release time (year), and
T_{wrg} = annual exposure factor for swimming at recreational swimming location r for individuals in age group g (days).

3.1.4.9 Boating External Exposure

The model shall have an exposure pathway that represents the radionuclide external exposure the receptor receives from boating on contaminated surface water (RQMT 3.1.4.10). The boating external exposure can be calculated using Equation (3.41) (Napier, Strenge et al. 2012).

$$I_{brig}(T) = C_{bri}(T)(SB)FE_{brg}TE_{brg}Tc_b \tag{3.36}$$

where:

$I_{brig}(T)$ = average exposure factor over the period T for radionuclide i from boating at recreational boating location r for individuals in age group g (Bq/L),
C_{bri} = average water concentration of radionuclide i at recreational boating location r (Bq/L),
SB = shielding factor for boating exposures (dimensionless),
FE_{brg} = average frequency of daily boating events at recreational boating location r for individuals in age group g (events/dy),
TE_{brg} = duration of an average boating event at recreational boating location r for individuals in age group g (hrs/event),
Tc_b = time correction set equal to $T_{brg}/8760$ h/y for chronic releases and the lesser of ($1.0/FE_{brg}*TE_{brg}$)) or ($1/(T_{eb}*8760)$) for acute releases,
T_{cb} = acute release time (year), and
T_{brg} = annual exposure factor for recreational boating location individuals in age group g (day).

3.1.4.10 Shoreline Sediment External Exposure

The model shall have an exposure pathway that represents the radionuclide external exposure the receptor receives from time spent on contaminated surface water shorelines (RQMT 3.1.4.11). The shoreline sediment external dose can be calculated using Equation (3.42) and based on the daily and annual activity behaviors of the receptors age group (Napier, Strenge et al. 2012).

$$I_{srig}(T) = {C_{sri}(T)SW_rFE_{srg}TE_{srg}T_{srg}}/{8760} \tag{3.37}$$

where:

$I_{srig}(T)$ = average exposure factor over the period T for radionuclide i from shoreline exposure at recreational shoreline location r for individuals in age group g (Bq/kg),
C_{sri} = average shoreline sediment concentration of radionuclide i at recreational shoreline location r (Bq/kg) (will be defined by the water concentration, k_d values, and empirical data),

SW_r = shoreline width factor for the recreational shoreline location r for individuals in age group g (events/dy),
FE_{srg} = shoreline use event frequency at recreational shoreline location r for individuals in age group g (events/dy),
TE_{srg} = duration of each shoreline exposure event at recreational shoreline location r for individuals in age group g (events/dy),
T_{srg} = annual exposure factor for shoreline exposure at recreational shoreline location r for individuals in age group g (hr/event), and
8760 = unit correction (hrs/yr).

3.1.5 Risk Assessment

The GDSA Biosphere model shall present the risk associated with the user defined receptor radionuclide exposure (RQMT 3.1.5.1). The risk calculations will be based on risk slope factors which relate the risk of lifetime cancer incidence with the exposure to radionuclides through all ingestion intakes, all inhalation intakes, or external exposure. The risk factors for cancer incidence risk per pCi intake are documented in Federal Guidance Report 13 (Eckerman, Leggett et al. 1999).

3.1.5.1 Ingestion

For radionuclides that are ingested, the risk to the receptor can be calculated using Equation (3.43) (Napier, Strenge et al. 2012).

$$IR_{l2iah}(T) = 27(I_{l2ia}(T))(RF_{io}) \quad (3.38)$$

where:
$IR_{l2iah}(T)$ = lifetime cancer incidence risk (effect h) from ingestion exposure via pathway 1, medium 2 radionuclide i for the general population (a) for exposure over the period T (risk),
$I_{l2ia}(T)$ = ingestion intake of radionuclide i via exposure pathway l, at usage location 2, for the adult age group (a) over exposure time period T (Bq),
RF_{io} = risk factor for ingestion (o) of radionuclide i (risk/pCi), and
27 = units conversion factor (pCi/Bq).

3.1.5.2 Inhalation

For radionuclides that are inhaled, the risk to the receptor can be calculated using Equation (3.44) (Napier, Strenge et al. 2012).

$$IR_{eliah}(T) = 27(I_{elia}(T))(RF_{iof}) \quad (3.39)$$

where:
$IR_{eliah}(T)$ = lifetime cancer incidence risk (effect h) from inhalation exposure via pathway e, medium l radionuclide i for the general population (a) for exposure over the period T (risk),
$I_{elia}(T)$ = inhalation intake of radionuclide i via exposure pathway e, for medium l, for the age group (a) over exposure time period T (Bq),
RF_{irf} = risk factor for inhalation (r) of radionuclide i, lung absorption rate f (slow, medium or fast) (risk/pCi), and
27 = units conversion factor (pCi/Bq).

3.1.5.3 External Exposure

For external exposure to a contaminated ground surface, the risk to the receptor can be calculated using Equation (3.45) or Equation (3.46) (Napier, Strenge et al. 2012).

$$IR_{esiah}(T) = 27(10^{-3})(I_{esia}(T))(RF_{ig})(TE) \quad (3.40)$$

where:

$IR_{esiah}(T)$ = lifetime cancer incidence risk (effect h) from external exposure to ground (pathway e) at soil usage location s for radionuclide i for the general population (a) for exposure over the period T (risk),
$I_{esia}(T)$ = external exposure ground concentration average for radionuclide i at soil usage location s for the adult age group (a) over exposure time period T (Bq/kg)
RF_{ig} = risk factor for external exposure to ground (g) of radionuclide i (risk/year per pCi/g soil),
27 = unit conversion factor (pCi/Bq),
10^{-3} = unit conversion factor (kg/g), and
TE = exposure time (year).

$$IR_{sriah}(T) = 27(10^{-3})(I_{sria}(T))(RF_{ig})(TE) \quad (3.41)$$

where:

$IR_{sriah}(T)$ = lifetime cancer incidence risk (effect h) from external exposure to shoreline sediment (pathway s) at recreational water usage location r for radionuclide i for the general population (a) for exposure over the period T (risk),
$I_{sria}(T)$ = external exposure to shoreline sediment concentration time integral for radionuclide i at recreational water usage location r for the adult age group (a) over the exposure time period T (Bq h/m^2),
RF_{ig} = risk factor for external exposure to ground (g) of radionuclide i (risk/year per pCi/g soil),
27 = unit conversion factor (pCi/Bq),
10^{-3} = unit conversion factor (kg/g), and
TE = exposure time (year).

3.1.6 Sensitivity and Uncertainty Assessment

The GDSA Biosphere model shall incorporate calculations of risk and uncertainty associated with receptor dose and risk (RQMT 3.1.6.1). The biosphere model is intended to calculate the annual dose to humans caused by contaminated groundwater through several pathways. Significant uncertainties will always remain in the long-term safety assessment of waste disposal systems. It is therefore important to account the variability in dose estimates when modeling the future dose to humans from a geologic repository for its use as a safety indicator (Ciecior, Rohlig et al. 2018). Sources of uncertainty within the biosphere model may arise from

- scenarios of potential evolution pathways
- transfer and exposure models due to approximations
- input data about ecological and human habit parameters.

The analysis of uncertainty and sensitivity within the biosphere model will incorporate the uncertainty and sensitivity associated with the PFLOTRAN output, which is the biosphere model input.

Variability of input data can cause significant model uncertainty. It is therefore appropriate to present the propagation of input uncertainty into model outputs for safety assessment. A stochastic uncertainty analysis is useful for complex nonlinear models where there are many interdependent relationships between input parameters and model output. Therefore, an uncertainty assessment tool will be incorporated in the model that will allow the users to calculate the probabilistic estimates of the calculated annual dosage due to variability in model parameters.

Uncertainty and sensitivity analyses of a biosphere model can be beneficial in many ways. Such probabilistic assessment can help in future improvement of the model by identifying the most significant and model-sensitive pathways and parameters. Thereafter, the model can be simplified by removing the unimportant pathways and processes. Such analysis also helps in assessing the behavior of the model under variable conditions. Sensitivity analyses can help in understanding the key characteristics affecting the endpoint and thus assist in optimizing the design of the disposal facility.

It is crucial to understand the difference between the uncertainty and sensitivity of a model. Model uncertainty is the range of possible model outcomes resulting from input variability and model assumptions. While sensitivity analysis measures the change in the model output relative to a small change in input values. It thus assesses the model response to changes in input variables. The same set of model simulations can be used for both uncertainty and sensitivity analyses.

The model tool will incorporate a first-order Monte Carlo method to perform stochastic calculations of the model uncertainty. In a Monte Carlo approach, a set of random values from each of the input distributions is chosen and passed through the biosphere model to obtain a stochastic distribution of many prediction outcomes after executing the model several times. A large number of model simulations (100 to 10,000) can capture the significant model variability. The following steps are involved in the application of Monte Carlo method:

- Identify the probability distribution that describes the stochastic nature of the input variables.
- Generate a set of pseudo-random numbers from these input distributions.
- Repeat the simulations of the deterministic model with these set of input values to generate distribution of output values.
- Analyze the probability distribution of model output to determine model uncertainty.

The endpoint of the uncertainty analyses will be the total radionuclide dose to the receptor that will be used as the response of the biosphere model. It is required to provide probability distributions (uniform, normal or log-normal functions) of the input parameters to perform Monte Carlo stochastic analyses. Advanced stratified sampling techniques such as Latin Hypercube sampling (LHS) should be explored to reduce the number of model simulations and improve the computational speed.

The model will allow the user to select probability distributions for parameters from a variety of distribution functions such as normal or log-normal, uniform or exponential. The processor will set up the Monte Carlo input file based on the standard deterministic input data file and the selected distribution. Then the biosphere model will be executed based on a user-provided number of simulations. The tool will provide the users with data to visualize the cumulative frequency histograms and summary statistics of the calculated dosage values that are stochastically generated. The distribution of the model outputs will be statistically analyzed to determine variances between iterations and correlations with the input parameters. The contribution of the input variable to the uncertainty in output values will be determined using the Spearman rank correlation coefficient. In addition, sensitivity analysis will be performed to understand the impact of these input variables on the output variance. Sensitivity indices can be calculated using the ratio of the variance of the output and input (Luo,Yang 2007).

3.2 External Interface Requirements

The user will be required to provide all necessary input variables to run their chosen biosphere scenario. The user will need to have a thorough understanding of their biosphere scenario and exposure pathways of interest in order to provide the required variable information as input to the GDSA Biosphere model. The GDSA Biosphere model will be flexible and adaptable to able to be applicable to different

biosphere scenarios, which places the burden of defining the biosphere variables on the user. The user will need to provide reasonable variable inputs that will adequately bound their chosen biosphere scenario.

3.3 Non-Functional Requirements

The software shall have an associated user's guide (RQMT 3.3.1). The user's guide should include sufficient detail to allow a user that has access to the GDSA Biosphere model to run their chosen scenario as long as it fits within the scope of the biosphere model.

The software shall have an associated technical manual (RQMT 3.3.2). The technical manual should

- describe the mathematics that underlie all the code functions in sufficient detail for users to understand,
- provide transparency to the proposed GDSA Biosphere model, and
- reference the mathematical requirements that are associated with this requirements document.

Version control guidance will be provided throughout the software development process. This might be accomplished by using a GIT or other repository to maintain different versions of the GDSA Biosphere model during its development. Each version of the GDSA Biosphere model should be given a unique identifier.

4.0 QUALITY ASSURANCE

The proposed GDSA Biosphere model will have an associated software quality assurance plan. The software quality assurance plan shall be appropriate for the use and grade of the proposed biosphere model (RQMT 4.1). The quality assurance plan shall be documented in a software quality assurance plan (SQAP) prior to the development of the software (RQMT 4.2).

The following topics should be considered during the development of the SQAP:

- Software Grading: The SQAP for the development of the biosphere model will depend on the software grade. Initially, the software might be graded as proof of concept or prototype development and then upgraded into a higher grade of software with changed intended use. The project team should engage a software quality practitioner to examine the grading level and software quality activities.
- Configuration Management (CM): The SQAP should include a CM that addresses how version control and changes will be maintained. Configuration management is important to unique identification of software versions, reproducibility, and prevention of unintended use or alteration during development. Furthermore, the CM plan can include how to control access to the code during its development by team members who require access to the code.
- Coding Standards: The project team should agree to a set of coding standards before code development begins. Coding standards should be outlined before the development process and will be followed by all the developers and programmers. For example, there should be a standardized way to develop headers, variable, and comments to maintain transparency during development. Developers should work with the PFLOTRAN development team to keep coding standards consistent.
- Verification and Validation: The project team should agree on the requirements for the verification and validation of the code before development begins. The verification and validation plan may rely on the future development of test cases that will be used to test every requirement from the software requirements document and could be conducted by an independent reviewer. It is possible that test cases will be implemented that could test more than one requirement, but all requirements should be tested by at least one test case.
- Open-Source Software: The SQAP should address any specific requirements associated with the development of open-source software.

5.0 GDSA BIOSPHERE MODEL IMPLEMENTATION PLAN

5.1 First Iteration GDSA Biosphere Model Implementation

This section presents a series of recommended steps to take when developing the first iteration of the GDSA Biosphere model. Although the first iteration of the GDSA Biosphere model will be a stand-alone component of the PFLOTRAN code, it is imperative that the code be designed in collaboration with the PFLOTRAN development team to facilitate greater interaction and its integration into PFLOTRAN with future iterations of the model. Thoughtful design of the first iteration of the GDSA Biosphere model will build a foundational code that is compatible with the PFLOTRAN code and will increase its potential use and integration during future iterations.

1. **Determine the software requirements and purpose.**

   The project commenced with the current process of defining the software requirements that meet the user needs and purpose of the project. The requirements document will guide the next steps in designing and developing the biosphere model. This document serves as the software requirements document for the GDSA Biosphere model and should be used throughout the development of the GDSA Biosphere model.

2. **Establish the development team.**

   The development team established for this project could include a model developer(s), software interface designer (if a user interface will be developed), an independent tester, a quality assurance auditor, and a project manager. Some of the team roles will only be required during specific stages of the implantation plan. For example, the independent tester will only be required during the verification and validation phase of software development. It will be important to identify all the roles on the development team before the project begins, even if all the roles of the team may not be immediately filled. Establishing the development team should also include identifying any required training needed for each role on the team.

3. **Define the software design.**

   The next phase includes designing the software for the various components of the model. An architecture is developed in the software design phase that includes selection of a programming language, modules design, and identification of a relational database comprising the different levels of input data. The model will likely be developed and coded by integrating various subroutines for the exposure pathways with the radionuclide database and user custom inputs. The model development will be subdivided into small functional units for various FEPs and receptors.

   There are many options for programming languages and the selected programming language must be able to meet the requirements of the proposed GDSA Biosphere model as well as the requirements of the overall GDSA program so that it can serve as an effective open-source component of the PFLOTRAN code. One option for the GDSA Biosphere model programming language is Fortran.

   PFLOTRAN has been traditionally developed in Fortran programming language. PFLOTRAN developers continue to use Fortran language because of its modular structure and fast scientific computing capabilities. Although modern system languages such as C++ or Java can be used for true object-oriented programming (OOP), it would be beneficial to use Fortran to preserve collaboration with experienced domain scientists for continual development and maintenance of PFLOTRAN. Some of the OOP features, such as pointers and classes, were incorporated in PFLOTRAN code using Fortran 2003 while preserving the modular structure of Fortran 90 (Hammond, Lichtner et. al., 2013).

   It would therefore prudent to develop the biosphere model in Fortran language so that it is compatible with PFLOTRAN. Thus, PFLOTRAN users, familiar with the Fortran coding, can easily use the

GDSA Biosphere model as a component of PFLOTRAN. While the first iteration of the GDSA Biosphere model will serve as a stand-alone component, with thoughtful design it could be more fully integrated with the with PFLOTRAN code if it is developed in the same language. Additionally, model development in Fortran is platform-independent and can be executed after compilation on Windows and Linux operating systems. Such an approach will be consistent with PFLOTRAN, which is used by users on Windows and Linux systems. Fortran also has the feature of interoperability with C that can be used to interact with third-party programs in the future for further development.

Other programming languages will be explored to determine if they could meet the requirements of the GDSA Biosphere model and the GDSA program and could be a viable option for development of the GDSA Biosphere model.

4. Write the software quality assurance plan.

Once the code architecture and programming language have been proposed by the development team but before software development begins the SQAP should be developed (see Section 5 on quality assurance). The SQAP should be in place before development so that the software development team will follow the quality assurance guidelines and coding standards to improve readability, adaptability, and reusability of the code. A SQAP helps the software developer(s) follow specified guidelines so that the code can be easily understood and so that consistency in coding is maintained.

5. Develop the software.

Software development will follow an agile approach with simultaneous development and testing of various software components. Figure 5.1 shows the software development life cycle process (SDLC) that will be used as a guide for this project. In a waterfall SDLC process, traditionally each phase is completed before moving to a new phase and there is not overlapping of phases. An agile SDLC model that allows for the overlap of model development and testing phases will allow for software developers to more quickly identify and respond to any problems during development. The agile process allows for more effective communication between developers, testers, project managers and clients during the development phase leading to a developed software which is more likely to meet the needs of all the interested parties.

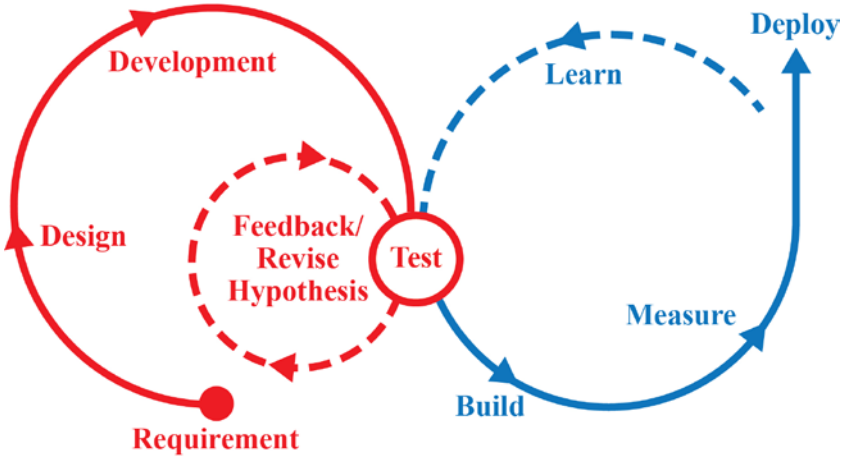

Figure 5.1. Conceptual Agile Software Development Process

Software development should likely start with the identification of the primary exposure pathways to begin the development process. The proposed biosphere model has many exposure pathways and focusing on initial development of the most critical pathways will allow the team to establish a proof of concept early in the development period. After proof of concept development of the most critical

exposure pathways the development team could develop the remaining exposure pathways from the groundwater to the human receptor in the biosphere model.

6. Verification and Validation

The developed software should undergo verification and validation at appropriate phases during the agile software development. Each functional unit or subroutine as well as the completed software should be tested for its functionality. The software should be verified with test cases to validate that that the software meets all the requirements in the finalized software requirements. A test case may be used to validate and verify more than one requirement, but all requirements should be validated and verified by at least one test case. After a comprehensive validation and verification of the software demonstrates that it meets the software requirements and adheres to the SQAP the software can be prepared for deployment.

The implementation plan is a high-level guide for the software development team, and it may need to be adjusted throughout the software development process to best allow the development team to produce software the adheres to the GDSA Biosphere model requirements, the SQAP, and the requirements surrounding the deployment of the developed software as open-source code that will be available as component of the PFLOTRAN code through the GDSA program.

5.2 Long-Term Implementation of GDSA Biosphere Model

The proposed model will be a first iteration of the GDSA Biosphere model, which will initially only interact with PFLOTRAN through use of the PFLOTRAN output as the biosphere input. While the biosphere model and PFLOTRAN will only minimally interact with the first iteration of the biosphere model, there is potential for future iterations of the biosphere model to more fully integrate with PFLOTRAN and become a part of the PFLOTRAN simulations rather than being a stand-alone component. One advantage of the GDSA Biosphere model being more fully integrated with PFLOTRAN would be the ease in handling modeling parameters that influence both the geosphere and the biosphere.

This potential integration of the biosphere model into PFLOTRAN could allow stakeholders more flexibility in their modeling scenarios and allow users to more easily capture how changes in any part of the PFLOTRAN simulation may affect the receptor dose in the biosphere. The implementation plan for the first iteration of the GDSA Biosphere model includes collaboration with the PFLOTRAN developers and thoughtful model design to more easily facilitate integration of the biosphere model into PFLOTRAN with future iterations of the model.

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Appendix A – Requirements List

Appendix A contains a reference list of all biosphere model requirements (RQMTs) established in the software requirements document ordered by point of appearance in the software requirements document.

3.1.1 The user shall be able to define the source term of the model by specifying the radionuclides in the groundwater with associated periods of release preferably through a PFLOTRAN output file (RQMT 3.1.1).

3.1.2 The user shall have the option to define the source term for the exposure pathways as either groundwater or surface water (as a dilution of groundwater) (RQMT 3.1.2).

3.1.3 The user shall have the ability to define which pathways will be relevant to the scenario by being able to designate which of the potential pathways (Table 4.1.1) are active for the user-defined scenario (RQMT 3.1.3).

3.1.4 The user should have the ability to allow the ecosystem of interest to have a buildup of contamination from the groundwater into the soil source term from a defined period of irrigation of crops (RQMT 3.1.4).

3.1.1.1 The code shall track each radionuclide individually through the defined exposure pathways while tracking the ingrowth of each decay product individually through the defined exposure pathways (RQMT 3.1.1.1).

3.1.1.2 The code shall be able to capture the decay of radionuclides “in transit” i.e., moving through the biosphere (RQMT 3.1.1.2).

3.1.1.3 The GDSA biosphere model shall have an accompanying radionuclide database that will have radionuclide decay chain data for all radionuclides including in the biosphere model (RQMT 3.1.1.3).

3.1.1.4 If the user selects a radionuclide to be a part of the groundwater source term that has associated decay progeny, the code shall automatically include the relevant progeny in the exposure pathway analysis (RQMT 3.1.1.4).

3.1.1.5 The user shall be able to select more than one radionuclide when defining the groundwater source term (RQMT 3.1.1.5).

3.1.2.1 The biosphere model shall be able to track radionuclide decay through radionuclide decay chains as well as radionuclide transfer between media compartments within the biosphere scenario (RQMT 3.1.2.1).

3.1.3.1 The user shall have the ability to assign one groundwater source for the biosphere model (RQMT 3.1.3.1).

3.1.3.2 The input options for the biosphere model shall be compatible with the units of the PFLOTRAN output to make it easy for users to use the biosphere model (RQMT 3.1.3.2).

3.1.3.3 The user shall have the ability to define what portion of the water in the surface water is from groundwater sources (to represent water upwelling from groundwater sources) (RQMT 3.1.3.3).

3.1.3.4 The concentration of radionuclides in the surface water shall be defined by the user (RQMT 3.1.3.4).

3.1.3.5 The only input of radionuclides into the soil compartment shall be from irrigation from either groundwater or surface water (RQMT 3.1.3.5).

3.1.3.6 The only loss terms for radionuclides from the soil compartment shall be through transfer to the plants and loss to harvest as well as loss from leaching out of the soil compartment into deeper soil zones that are not reachable by plants and humans in the biosphere (RQMT 3.1.3.6).

3.1.3.7 The concentration of individual radionuclides in the soil compartment shall be assessed in the model (RQMT 3.1.3.7).

3.1.3.8 The loss of radionuclides through plants and harvest shall be applied as a loss to the soil concentration and is applied as a step function at the end of each year (Napier, Strenge et al. 2012) (RQMT 3.1.3.8).

3.1.3.9 The user will be able to select some common crops but can also create custom flora in the biosphere model that can represent native flora or custom crops (RQMT 3.1.3.9).

3.1.3.10 The concentration of radionuclides in plants shall be defined as the sum of contributions from uptake through the roots, deposition onto the plant surfaces (from irrigation and from resuspended soil), and from weathering losses (RQMT 3.1.3.10).

3.1.3.11 The concentration of radionuclides in plant tissues shall include radionuclides that are absorbed through the roots (RQMT 3.1.3.11).

3.1.3.12 The biosphere code shall account for the difference in radionuclide concentration at the time of harvest and the time of consumption of the plant products (RQMT 3.1.3.12).

3.1.3.13 Fauna refers to the living animal life in the biosphere. The user will be able to use the pre-built fauna pathways or create a user-defined fauna to represent native fauna or a custom animal pathway (RQMT 3.1.3.13).

3.1.3.14 Fauna concentration of radionuclide will be defined by what the fauna consumes through ingestion of flora, water, or soil (RQMT 3.1.3.14).

3.1.3.15 There will be a reduction in activity of the radionuclides in the animal products between the time of harvest and consumption due to radioactive decay; the code shall account for this change in radionuclide concentration (RQMT 3.1.3.15).

3.1.3.16 Aquatic flora and fauna included in the model shall include fish, mollusks, invertebrates, and water plants (RQMT 3.1.3.16).

3.1.3.17 The user shall have the ability to create unique user-defined aquatic flora and fauna that can be used to represent unique native flora and fauna for a specific biosphere scenario (RQMT 3.1.3.17).

3.1.3.18 The concentrations of radionuclides in the flora and fauna shall be based on the average radionuclide concentration in the surface water over the course of the assessment year (RQMT 3.1.3.18).

3.1.3.19 The code shall account for the difference in radionuclide concentration in the aquatic flora and fauna between the time of harvest and the time of consumption (RQMT 3.1.3.19).

3.1.3.20 Carbon-14 shall be treated as a special radionuclide in the GDSA Biosphere because of its unique environmental movement qualities (RQMT 3.1.3.21).

3.1.3.21 The movement of Carbon-14 into aquatic flora and fauna shall use transfer ratios rather than C-14 specific special models (RQMT 3.1.3.22).

3.1.4.1 The user shall have the ability to define the receptor characteristics for the exposure pathways (RQMT 3.1.4.1).

3.1.4.2 The model shall have an exposure pathway representing the radionuclide exposure from the receptor ingesting water (RQMT 3.1.4.2).

3.1.4.3 The model shall have an exposure pathway representing the radionuclide exposure from the receptor inadvertently ingesting shower water (RQMT 3.1.4.3).

3.1.4.4 The model shall have an exposure pathway representing the radionuclide exposure from the receptor inadvertently ingesting surface water swimming (RQMT 3.1.4.4).

3.1.4.5 The model shall have an exposure pathway representing the radionuclide exposure from the receptor inadvertently ingesting soil (RQMT 3.1.4.5).

3.1.4.6 The model shall have an exposure pathway representing the radionuclide exposure from the receptor inadvertently inhaling volatilized shower or indoor water (RQMT 3.1.4.6).

3.1.4.7 The model shall have an exposure pathway representing the radionuclide exposure from the receptor inadvertently inhaling resuspended soils (RQMT 3.1.4.7).

3.1.4.8 The model shall have an exposure pathway representing the radionuclide external exposure to the receptor from contaminated ground surfaces (RQMT 3.1.4.8).

3.1.4.9 The model shall have an exposure pathway representing the radionuclide external exposure to the receptor from surface water swimming (RQMT 3.1.4.9).

3.1.4.10 The model shall have an exposure pathway representing the radionuclide external exposure to the receptor from boating on contaminated surface water (RQMT 3.1.4.10).

3.1.4.11 The model shall have an exposure pathway representing the radionuclide external exposure to the receptor from time spent on contaminated surface water shorelines (RQMT 3.1.4.11).

3.1.5.1 The GDSA Biosphere model shall present the risk associated with the user-defined receptor radionuclide exposure (RQMT 3.1.5.1).

3.1.6.1 The GDSA Biosphere model shall incorporate calculations of risk and uncertainty associated with the receptor dose and risk (RQMT 3.1.6.1).

3.3.1 The software shall have an associated user's guide (RQMT 3.3.1).

3.3.2 The software shall have an associated technical manual (RQMT 3.3.2).

4.1 The software quality assurance plan shall be appropriate for the use and grade of the proposed biosphere model (RQMT 4.1).

4.2 The quality assurance plan shall be documented in a software quality assurance plan prior to the development of the software (RQMT 4.2).

Appendix B – Radioactive Chain Decay GENII Module Math

This appendix presents the radioactive decay math and methodology as found in the GENII code. It is an excerpt from the GENII Version 2 Software Design Document, PNNL-14584, Rev. 4 (Napier, Strenge et al. 2012).

A general solution to first-order compartmental models is presented in this appendix for application to systems consisting of one physical medium that contains any number of radionuclide decay chain members. The solution can be applied to any such system involving physical transfers from the medium and radioactive chain decay with branching. The general analytical solution to the problem is described mathematically and extended to evaluation of the time integral of the radionuclide quantities and to cases involving deposition from outside sources. For deposition at a constant rate during a time period, the general solution can be applied to determine the quantity present during the time period and the time integral of the quantity during the time period.

Various methods have been described for evaluating systems involving radioactive decay (Bateman 1910; Friedlander and Kennedy 1955; Hamawi 1971; Scherpelz and Desrosiers 1980) and physical transfers between media (Gear 1971; Skrable et al. 1974; Hindmarsh 1983; Birchall and James 1989; Kirchner 1990). Some of these methods involve simple analytical solutions, such as the Bateman (1910) representation of the radioactive decay process without branching; others involve advanced numerical methods to solve multi-compartment systems such as the numerical differential equation solvers of Gear (1971) and Hindmarsh (1983) and the numerical matrix method described by Birchall and James (1989). The analytical solutions presented by Bateman (1910), Scherpelz and Desrosiers (1980), and Skrable et al. (1974) do not consider branching, but can account for branching by performing multiple applications of the equations to each possible decay path and summing the results appropriately, a method suggested by Friedlander and Kennedy (1955). The general solution presented in this paper includes chain decay with branching explicitly in the equations (Kennedy and Strenge 1992).

The general radioactive-decay-chain problem is illustrated in Figure B.1. In this figure each box represents a radionuclide decay chain member in a medium. Two types of transfers may be represented: radioactive decay between chain members and physical transfer from the medium. Radioactive transitions in this system are represented as flowing from upper boxes to lower boxes; any upper box may contribute material to any lower box. Because radioactive transitions within decay chains are irreversible, upward transfers, representing recycling of material, are not considered. Physical transfers out of the medium are indicated by the downward arrows from each box.

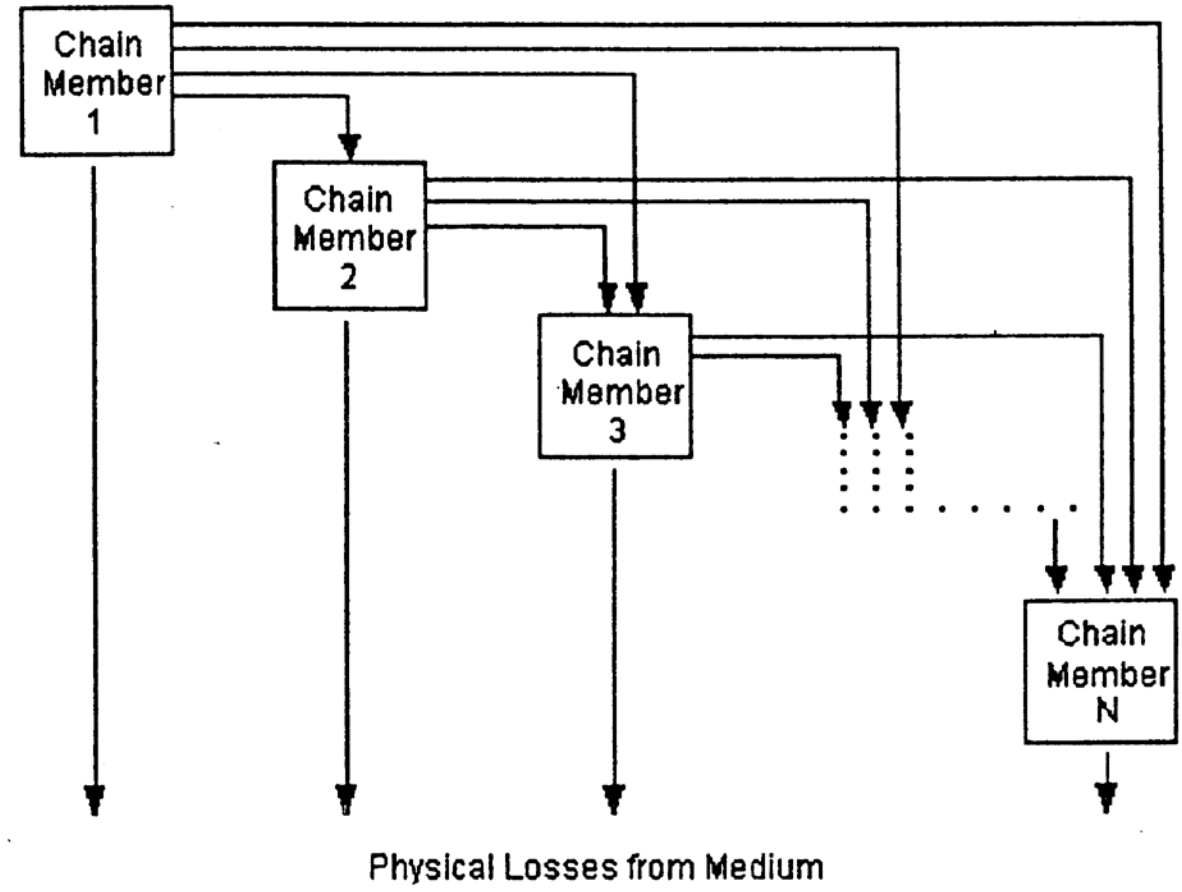

Figure B.1. A Representation of the General Radioactive-Decay-Chain Problem

Four applications are included of the general solution for the compartmental system of Figure B.1. First, the solution is presented for the evaluation of the quantity of radionuclides in each box as a function of time, based on a user-defined initial inventory. The general solution is presented for quantities expressed in units of atoms and activity. The solution then is extended for use to evaluate three additional situations. The first extension covers the evaluation of the time integral of the quantity in each box during a time period. The general solution also is shown to apply to cases involving deposition of radionuclides at a constant rate to a medium when the initial quantity in each box is zero. This application provides the quantity in each box after accumulation during a time period, and can be extended to provide the time integral of the quantity of each chain member from deposition accumulation during a time period.

General Solution

An algorithm for evaluations using the general solution equations is given to demonstrate translation of the method to computer applications. In the system of boxes as shown in Figure B.1, each box may involve (1) transfer to any other box lower in the system and (2) loss by radioactive decay within each box with generation of progeny in a lower box. Transfers between boxes are described by rate constants. The general differential equation for the change in the quantity of a radionuclide in the medium is described by the following word equation:

(Rate of change of chain member c) =

- (rate of physical transfer of chain member c out of the medium)

- (rate of radioactive-transition loss of chain member c)
+ (rate of radioactive-transition ingrowth of chain member c).

Radioactive transitions of precursor radionuclides are represented in the last term.

The equivalent mathematical form of this equation is

$$\frac{d\,A_c(t)}{d\,t} = -\,L_c\,A_c(t) - \lambda_{rc}\,A_c(t) + \sum_{n=1}^{c-1} d_{nc}\,\lambda_{rn}\,A_n(t) \qquad \text{(B.1)}$$

where L_c = total rate constant for all physical transfers of chain member c from the medium (d^{-1})

$A_c(t)$ = quantity of chain member c at time t (atoms)

λ_{rc} = radioactive-transition rate constant for chain member c (d^{-1})

$A_n(t)$ = quantity of chain member n at time t (atoms)

d_{nc} = fraction of precursor radionuclide transitions (chain member n) that result in production of the chain member c (dimensionless)

λ_{rn} = radioactive-transition rate constant for chain member n (d^{-1}).

To simplify the solution, the first two terms on the right side of Equation (B.1) can be combined as follows:

$$-\,L_c\,A_c(t) - \lambda_{rc}\,A_c(t) = -\,\lambda_{ec}\,A_c(t)$$

where λ_{ec} = effective loss rate constant for radionuclide c from the medium (d^{-1})

$$\lambda_{ec} = L_c + \lambda_{rc}$$

and other terms are as previously defined.

The first term on the right side of Equation (B.1) represents physical transfers of chain member c out of the medium. The rate constant, L_c, is the sum of all physical transfer rate constants from the media (for chain member c). The second term represents loss by radioactive transitions of the radionuclide of chain member c to progeny radionuclides in other boxes. The last term represents production of the chain member c from all precursor radionuclides.

The general solution can be summarized by the following four equations:

$$A_c(t) = \sum_{i=1}^{c} K_{ci}\,e^{-\lambda_{ei}\,t} \qquad \text{(B.2)}$$

$$K_{11} = A_1(0) \tag{B.3}$$

$$K_{cn}\,(n = 1 \rightarrow c - 1) = \frac{\sum_{i=n}^{c-1} d_{ic}\,\lambda_{ri}\,K_{in}}{\lambda_{ec} - \lambda_{en}} \tag{B.4}$$

and

$$K_{cc} = A_c(0) - \sum_{n=1}^{c-1} K_{cn} \tag{B.5}$$

The previous discussion and equations describe quantities of radionuclides expressed in units of atoms. Equations (B.2) through (B.5) can be easily converted to units of activity, such as Bq or Ci, using the general relationship between atom and activity units:

$$Q_c(t) = k\,A_c(t)\;\lambda_{rc} \tag{B.6}$$

where $Q_c(t)$ = activity of chain member c at time t (activity units)

k = constant of proportionality between activity units and atoms (activity·time/atom)

λ_{rc} = radioactive-transition rate constant (inverse time)

and $A_c(t)$ is as previously defined. When activity is expressed in Bq and time in seconds, the constant equals 1.

Substituting the expression in Equation (B.6) into Equations (B.2) through (B.5), with the terms slightly simplified, results in the following general solution with quantities expressed in activity units:

$$Q_c(t) = \lambda_{rc} \sum_{n=1}^{c} K_{cn}\,e^{-\lambda_{en} t} \tag{B.7}$$

$$K_{11} = \frac{Q_1(0)}{\lambda_{r1}} \tag{B.8}$$

$$K_{cn}\,(n = 1 \rightarrow c-1) = \frac{\sum_{i=n}^{c-1} d_{ic}\,\lambda_{ri}\,K_{in}}{\lambda_{ec} - \lambda_{en}} \qquad \text{(B.9)}$$

and

$$K_{cc} = \frac{Q_c(0)}{\lambda_{rc}} - \sum_{n=1}^{c-1} K_{cn} \qquad \text{(B.10)}$$

The forms of Equations (B.7) through (B.10) suggest some limitations on definition of numerical values for rate constants. First, all boxes must represent a radioactive material, because the radioactive-transition rate constant appears in the denominator of Equations (B.8) and (B.10). Stable elements at the end of a decay chain can be simulated as a material with a long but finite radioactive half-life. This limitation does not apply to the general solution expressed in atom units [Equations (B.2) through (B.5)] although a stable progeny will effectively terminate a radioactive decay chain, because the rate constant for a stable isotope is zero. Another limitation is that the effective rate constant for any two boxes, λ_{ec} and λ_{en}, must not be equal, because their difference appears in the denominator of Equations (B.4) and (B.9). This limitation applies only to pairs of chain members that have radioactive transfers from one to the other.

Use of the general solution given here requires definition of all rate constants and branching fractions. Data on radionuclide half-lives, decay chains, and fractional branching within chains have been published by Lederer and Shirley (1978) and the International Commission on Radiological Protection in ICRP Publication 38 (ICRP 1983).

Extension to Time-Integration

The discussions and equations to this point have centered on evaluation of the quantity of radionuclides present as a function of time. The general solution can be extended easily to provide the time integral of the quantity present during a time period. This extension is demonstrated by observing that the general solution includes the time variable, t, only in the exponential term of Equations (B.2) and (B.7). Obtaining the time-integral expression involves simply integrating the exponential expression and evaluating the integral from time zero to the desired time. The following sequence applied to Equation (B.7) illustrates these steps:

$$\int_0^t Q_i dt = \int_0^t \lambda_{ri}\left[\sum_{n=1}^{i} K_{in} e^{-\lambda_{en} t}\right] dt$$

$$= \lambda_{ri} \sum_{n=1}^{i} K_{in}\left[\int_0^t e^{-\lambda_{en} dt}\right]$$

$$= \lambda_{ri} \sum_{n=1}^{i} K_{in}\left[\frac{e^{-\lambda_{en} t}}{-\lambda_{en}}\right]_0^t, \qquad \text{(B.11)}$$

The general solution for the time now uses the following formula with Equations (B.8), (B.9), and (B.10):

$$\int_0^t Q_c \, d\,t = \lambda_{rc} \sum_{n=1}^{c} K_{cn}\left[\frac{1 - e^{-\lambda_{en} t}}{\lambda_{en}}\right] \qquad \text{(B.12)}$$

Extension to Deposition at a Constant Rate

Another extension of the general solution applies to deposition of radionuclides to a medium and accumulation during a time period. The extension assumes that there are initially no radionuclides in the medium. The differential equation for chain member c is based on Equation (B.1) with an added term representing the constant rate of deposition of chain member c to the medium, R_c:

$$\frac{d\,A_c(t)}{dt} = R_c - \lambda_{ec} A_c(t) + \sum_{n=1}^{c-1} d_{nc} \lambda_{rn} A_n(t) \qquad \text{(B.13)}$$

where R_c = constant deposition rate of chain member c to the medium (atoms/d) and other terms are as previously defined. The general solution to this problem is written as follows, with quantities expressed in activity units:

$$Q_c(t) = \lambda_{rc} \sum_{n=1}^{c} K_{cn}\left[\frac{1 - e^{-\lambda_{en} t}}{\lambda_{en}}\right] \qquad \text{(B.14)}$$

$$K_{11} = \frac{D_1}{\lambda_{r1}} \qquad \text{(B.15)}$$

$$K_{cn}\,(n = 1 \rightarrow c - 1) = \frac{\sum_{i=n}^{c-1} d_{ic}\,\lambda_{ri}\,K_{in}}{\lambda_{ec} - \lambda_{en}} \tag{B.16}$$

and

$$K_{cc} = \frac{D_c}{\lambda_{rc}} - \sum_{n=1}^{c-1} K_{cn} \tag{B.17}$$

where D_c is the constant deposition rate of chain member c expressed in terms of activity (pCi/d), and other terms are as previously defined.

This solution is identical to that for the time-integral problem except for substitution of D_c for $Q_c(0)$, and the integral of the exponential for the exponential as illustrated in Equations (B.11) and (B.12).

Extension to Deposition with the Time Integral

The equations for deposition at a constant rate with accumulation can be integrated to give the time integral of the quantities in each box during a time period. This integration, similar to that described in Equation (B.11), works as follows:

$$A_i(t) = \sum_{n=1}^{i} K_{in}\left[\frac{1 - e^{-\lambda_{en}t}}{\lambda_{en}}\right],$$

$$K_{11} = R_1,$$

$$K_{in}(n = 1 \rightarrow i - 1) = \frac{\sum_{j=n}^{i-1} d_{ji}\,\lambda_{rj}K_{jn}}{\lambda_{ei} - \lambda_{en}}, \qquad \text{(B.18)}$$

or

$$\int_0^t Q_c\,dt = \lambda_{rc}\sum_{n=1}^{c}\frac{K_{cn}}{\lambda_{en}}\left[t - \frac{1 - e^{-\lambda_{en}t}}{\lambda_{en}}\right] \qquad \text{(B.19)}$$

The general solution to the time integral of deposition at a constant rate with accumulation uses Equation (B.19) [in place of Equation (B.14)], and Equations (B.15), (B.16), and (B.17). These equations can be put in terms of atom units by using Equation (B.6), as illustrated earlier.

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Appendix C – Equivalent and Effective Dose Equations for Specific Exposure Pathways

This appendix contains the pathway-specific equivalent and effective dose equations that were described generally in Section 3.1.4.

C.1 Ingestion of Water

The equivalent dose from internal exposure to radionuclides through ingestion of drinking water can be calculated using Equation (C.1) (Napier, Strenge et al. 2012).

$$IH_{dwigT}(T) = I_{dwig}(T)HC_{igocT} \quad \text{(C.1)}$$

where:

$IH_{dwigT}(T)$ = equivalent dose to organ T from ingestion intake of radionuclide i in drinking water at usage location w for an individual in age group g for exposure over time period T (Bq/L),

$I_{dwig}(T)$ = ingestion intake of radionuclide i in drinking water at usage location w for individuals in age group g for exposure over time period T (Bq), and

HC_{iagT} = equivalent dose coefficient to organ T for ingestion intake of radionuclide I of class c for an individual in age group g (Sv/Bq).

The effective dose from internal exposure to radionuclides through ingestion of drinking water can be calculated using Equation (C.2) (Napier, Strenge et al. 2012).

$$IE_{dwig}(T) = I_{dwig}(T)EC_{igoc} \quad \text{(C.2)}$$

where:

$IE_{dwig}(T)$ = effective dose from ingestion intake of radionuclide i in drinking water at water usage location w for an individual in age group g for exposure time period T (Sv),

$I_{dwig}(T)$ = ingestion intake of radionuclide i in drinking water at water usage location w for individual in age group g for exposure over time period T (Bq), and

EC_{igoc} = effective dose coefficient for ingestion intake of radionuclide i of class c for an individual in age group g(Sv/Bq).

C.2 Inhalation Volatilized Water

The equivalent dose from internal exposure through inhalation of shower water can be calculated using Equation (C.3) (Napier, Strenge et al. 2012). This equation can also be adjusted to estimate inhalation of volatilized water in a greenhouse exposure scenario.

$$IH_{aaigT}(T) = I_{vwig}(T)HC_{igr\,c\,T} \quad \text{(C.3)}$$

where:

$IH_{aaigT}(T)$ = equivalent dose to organ T from inhalation intake of radionuclide I in air at air usage location a for an individual in age group g for exposure over time period T (Sv),

$I_{vwig}(T)$ = inhalation intake of radionuclide i in air usage location a for individuals in age group g for exposure over time period T (Bq), and

$HC_{igrc}T$ = equivalent dose coefficient to organ T for inhalation intake of radionuclide I of class c for an individual in age group g (Sv/Bq).

The effective dose from internal exposure through ingestion of shower water can be calculated using Equation C.4 (Napier, Strenge et al. 2012). This equation can also be adjusted to estimate inhalation of volatilized water in a greenhouse exposure scenario.

$$IE_{aaig}(T) = I_{aaig}(T)EC_{igr\,c} \quad \text{(C.4)}$$

where:

$IE_{aaig}(T)$ = effective dose from inhalation intake of radionuclide i in air at air usage location a for an individual in age group g for exposure over time period T (Sv),
$I_{aaig}(T)$ = inhalation intake of radionuclide i in air at air usage location a for individuals in age group g for exposure over time period T (Bq), and
EC_{igrc} = effective dose coefficient for inhalation intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

C.3 Ingestion of Shower Water

The equivalent dose from internal exposure through ingestion of shower water can be calculated using Equation C.5 (Napier, Strenge et al. 2012).

$$IH_{hwig}(T) = I_{hwig}(T)HC_{igocT} \quad \text{(C.5)}$$

where:

$IH_{hwigT}(T)$ = equivalent dose to organ T from ingestion intake of radionuclide i in shower water at water usage location w for an individual in age group g for exposure over time period T (Sv),
$I_{hwig}(T)$ = ingestion intake of radionuclide i in shower water at water usage location w for individuals in age group g for exposure over time period T (Bq), and
$HC_{igoc}T$ = equivalent dose coefficient to organ T for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The effective dose from internal exposure through ingestion of shower water can be calculated using Equation (C.6) (Napier, Strenge et al. 2012).

$$IE_{hwig}(T) = I_{hwig}(T)EC_{igoc} \quad \text{(C.6)}$$

where:

$IE_{hwig}(T)$ = effective dose from ingestion intake of radionuclide i in shower water at water usage location w for an individual in age group g for exposure over time period T (Sv),
$I_{hwig}(T)$ = ingestion intake of radionuclide i in shower water at water usage location w for individuals in age group g for exposure over time period T (Bq), and
EC_{igoc} = effective dose coefficient for ingestion intake of radionuclide i for an individual in age group g (Sv/Bq).

C.4 Ingestion of Food Crops

The equivalent dose from internal exposure through ingestion of flora (food crop) can be calculated using Equation (C.7) (Napier, Strenge et al. 2012).

$$IH_{csig}(T) = I_{csig}(T)HC_{igocT} \quad \text{(C.7)}$$

where:

$IH_{csigT}(T)$ = equivalent dose to organ T from ingestion intake of radionuclide i in flora c at soil usage location s for an individual in age group g for exposure over time period T (Sv),
$I_{csig}(T)$ = ingestion intake of radionuclide i in flora c at soil location s for individuals in age group g for exposure over time period T (Bq), and
$HC_{igoc}T$ = equivalent dose coefficient to organ T for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq)

The effective dose from internal exposure through ingestion of flora (food crop) can be calculated using Equation (C.8) (Napier, Strenge et al. 2012).

$$IE_{csig}(T) = I_{csig}(T)EC_{igoc} \tag{C.8}$$

where:

$IE_{csig}(T)$ = effective dose from ingestion intake of radionuclide i in flora c at soil usage location s for an individual in age group g for exposure over time period T (Sv),
$I_{csig}(T)$ = ingestion intake of radionuclide i in flora c at soil location s for individuals in age group g for exposure over time period T (Bq), and
EC_{igoc} = effective dose coefficient for ingestion intake of radionuclide i for an individual in age group g (Sv/Bq).

C.5 Ingestion of Animal Products

The equivalent dose from internal exposure through ingestion of fauna (animal products) can be calculated using Equation (C.9) (Napier, Strenge et al. 2012).

$$IH_{asig}(T) = I_{asig}(T)HC_{igocT} \tag{C.9}$$

where:

$IH_{asigT}(T)$ = equivalent dose to organ T from ingestion intake of radionuclide i in fauna c at soil usage location s for an individual in age group g for exposure over time period T (Sv),
$I_{asig}(T)$ = ingestion intake of radionuclide i in fauna c at soil location s for individuals in age group g for exposure over time period T (Bq), and
$HC_{igoc}T$ = equivalent dose coefficient to organ T for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The effective dose from internal exposure through ingestion of fauna (animal products) can be calculated using Equation (C.10) (Napier, Strenge et al. 2012).

$$IE_{asig}(T) = I_{asig}(T)EC_{igoc} \tag{C.10}$$

where:

$IE_{asig}(T)$ = effective dose from ingestion intake of radionuclide i in fauna c at soil usage location s for an individual in age group g for exposure over time period T (Sv),
$I_{asig}(T)$ = ingestion intake of radionuclide i in fauna c at soil location s for individuals in age group g for exposure over time period T (Bq), and
EC_{igoc} = effective dose coefficient for ingestion intake of radionuclide i for an individual in age group g (Sv/Bq).

C.6 Ground External Exposure

The equivalent dose from the external exposure to ground contamination can be calculated using Equation (C.11) (Napier, Strenge et al. 2012).

$$IH_{esig}(T) = I_{esig}(T) HC_{iagT} TE_g (3.15E7) \rho_s d_s \quad \text{(C.11)}$$

where:

$IH_{esigT}(T)$ = equivalent dose to organ T from external exposure to radionuclide i from contaminated soil at soil usage location s for an individual in age group g from exposure over time period T (Sv),
$I_{esig}(T)$ = external exposure average soil concentration for radionuclide i at soil usage location s for individuals in age group g for exposure over time period T (Bq/kg),
HC_{iagT} = equivalent dose coefficient to organ T for external exposure to ground for radionuclide i for adult (Sv/sec per Bq/m2),
TE_g = time of exposure (years),
ρ_s = surface soil bulk density (kg/m^3),
d_s = thickness of surface soil layer (m), and
3.15E7 = units correction (seconds/year).

The effective dose from the external exposure to ground contamination can be calculated using Equation (C.12) (Napier, Strenge et al. 2012).

$$IE_{erigT}(T) = I_{esig}(T) EC_{iag} TE_g (3.15E7) \rho_s d_s \quad \text{(C.12)}$$

where:

$IE_{esig}(T)$ = effective dose from external exposure to radionuclide i in contaminated soil at soil usage location s for an individual in age group g for exposure over time period T (Sv),
$I_{esig}(T)$ = external exposure average of soil concentration for radionuclide i for soil at soil usage location s for individuals in age group g for exposure over time period T (Bq/kg),
EC_{iag} = effective dose equivalent factor for external exposure from ground exposure (g) for radionuclide i for an adult (Sv/sec per Bq/m^2),
TE_g = time of exposure (years),
ρ_s = surface soil bulk density (kg/m^3),
d_s = thickness of surface soil layer (m), and
3.15E7 = units correction (sec/yr).

C.7 Swimming External Exposure

The equivalent dose from external exposure to radionuclides through swimming can be calculated using Equation (C.13) (Napier, Strenge et al. 2012).

$$IH_{wrigT}(T) = I_{wrig}(T) HC_{iawT} TE_w (3.15E7) \quad \text{(C.13)}$$

where:

$IH_{wrigT}(T)$ = equivalent dose to organ T from external exposure to radionuclide i while swimming at recreational water usage location r for an individual in age group g for exposure over time period T (Bq/L),
$I_{wrig}(T)$ = external exposure average water concentration for radionuclides i for swimming at recreational water usage location r for individuals in age group g for exposure over time period T (Bq/L),
HC_{iagT} = equivalent dose coefficient to organ T for external exposure from water immersion for radionuclide i for an adult (Sv/sec per Bq/L),
TE_w = time of exposure (years), and
3.15E7 = units corrections (sec/yr).

The effective dose from external exposure to radionuclides through swimming can be calculated using Equation (C.14) (Napier, Strenge et al. 2012).

$$IE_{wrig}(T) = I_{wrig}(T)EC_{iaw}TE_{w}(3.15E7) \quad \text{(C.14)}$$

where:

$IE_{wrig}(T)$ = effective dose from external exposure to radionuclide i in contaminated water at recreational water usage location r for an individual in age group g (Sv),
$I_{wrig}(T)$ = external exposure average water concentration for radionuclide i for swimming at recreational water usage location r for individuals in age group g (Bq/L),
EC_{iaw} = effective dose equivalent factor for external exposure from water immersion for radionuclide i for an adult (Sv/sec per Bq/L),
TE_{w} = time of exposure (years), and
3.15E7 = units corrections (sec/yr).

C.8 Ingestion of Swimming Water

The equivalent dose from internal exposure through ingestion of swimming water can be calculated using Equation (C.15) (Napier, Strenge et al. 2012).

$$IH_{wwig}(T) = I_{wwig}(T)HC_{igocT} \quad \text{(C.15)}$$

where:

$IH_{wwigT}(T)$ = equivalent dose to organ T from ingestion intake of radionuclide i in water at recreational water usage location w for an individual in age group g for exposure over time period T (Sv),
$I_{wwig}(T)$ = ingestion intake of radionuclide i in water at recreational water usage location w for individuals in age group g for exposure over time period T (Bq), and
$HC_{igoc}T$ = equivalent dose coefficient to organ T for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The equivalent dose from internal exposure through ingestion of swimming water can be calculated using Equation (C.16) (Napier, Strenge et al. 2012).

$$IE_{wwig}(T) = I_{wwig}(T)EC_{igoc} \quad \text{(C.16)}$$

where:

$IE_{wwig}(T)$ = effective dose from ingestion intake of radionuclide i in water at recreational water usage location w for an individual in age group g for exposure over time period T (Sv),
$I_{wwig}(T)$ = ingestion intake of radionuclide i in water at recreational water usage location w for individuals in age group g for exposure over time period T (Bq), and
EC_{igoc} = effective dose coefficient for ingestion intake of radionuclide i for an individual in age group g (Sv/Bq).

C.9 Boating External Exposure

The equivalent dose for external exposure from boating can be calculated using Equation (C.17) (Napier, Strenge et al. 2012).

$$IH_{brigT}(T) = \frac{I_{brig}(T)HC_{iawT}TE_{b}(3.15E7)}{2} \quad \text{(C.17)}$$

where:

$IH_{brigT}(T)$ = equivalent dose to organ T from external exposure to radionuclide i while boating at recreational water usage location r for an individual in age group g for exposure over time period T (Bq/L),
$I_{brig}(T)$ = external exposure average water concentration for radionuclides i for boating at recreational water usage location r for individuals in age group g for exposure over time period T (Bq/L),
HC_{iawT} = equivalent dose coefficient to organ T for external exposure from water immersion for radionuclide i for an adult (Sv/sec per Bq/L),
TE_b = time of exposure (years),
2 = factor to account for being at the water surface rather than immersed (dimensionless), and
3.15E7 = units corrections (sec/yr).

The effective dose from external exposure to radionuclides through boating can be calculated using Equation (C.18) (Napier, Strenge et al. 2012).

$$IE_{brig}(T) = \frac{I_{brig}(T) EC_{iaw} TE_b (3.15E7)}{2} \quad \text{(C.18)}$$

where:

$IE_{brig}(T)$ = effective dose from external exposure to radionuclide i boating in contaminated water at recreational water usage location r for an individual in age group g (Sv),
$I_{brig}(T)$ = external exposure average water concentration for radionuclide i for swimming at recreational water usage location r for individuals in age group g (Bq/L),
EC_{iaw} = effective dose equivalent factor for external exposure from water immersion (w) for radionuclide i for an adult (Sv/sec per Bq/L),
TE_b = time of exposure (years),
2 = factor to account for being at the water surface rather than immersed (dimensionless), and
3.15E7 = units corrections (sec/yr).

C.10 Shoreline Sediment External Exposure

The equivalent dose for external exposure to shoreline sediment can be calculated using Equation (C.19) (Napier, Strenge et al. 2012).

$$IH_{srigT}(T) = I_{srig}(T) HC_{iagT} TE_s (3.15E7) \rho_s d_s \quad \text{(C.19)}$$

where:

$IH_{srigT}(T)$ = equivalent dose to organ T from external exposure to radionuclide i from shoreline sediment at recreational water usage location r for an individual in age group g for exposure over time period T (Bq/L),
$I_{srig}(T)$ = external exposure average water concentration for radionuclide i for shoreline sediment at recreational water usage location r for individuals in age group g for exposure over time period T (Bq/L),
HC_{iagT} = equivalent dose coefficient to organ T for external exposure from exposure to ground for radionuclide i for an adult (Sv/sec per Bq/L),
TE_s = time of exposure (years),
3.15E7 = units corrections (sec/yr),
ρ_s = surface soil bulk density (kg/m^3), and
d_s = thickness of surface soil layer (m).

The effective dose from external exposure to radionuclides in shoreline sediment can be calculated using Equation (C.20) (Napier, Strenge et al. 2012).

$$IE_{srig}(T) = I_{srig}(T) EC_{iag} TE_s (3.15E7) \rho_s d_s \quad \text{(C.20)}$$

where:

$IE_{srig}(T)$ = effective dose from external exposure to radionuclide i in shoreline sediment at recreational water usage location r for an individual in age group g (Sv),
$I_{srig}(T)$ = external exposure average shoreline sediment concentration for radionuclide i for recreational water usage location r for individuals in age group g (Bq/L),
EC_{iag} = effective dose equivalent factor for external exposure from contaminated soil (g) for radionuclide i for an adult (Sv/sec per Bq/L),
TE_s = time of exposure (years),
2 = factor to account for being at the water surface rather than immersed (dimensionless), and
3.15E7 = units corrections (sec/yr).

C.11 Ingestion of Aquatic Foods

The equivalent dose from internal exposure through ingestion of aquatic flora and fauna can be calculated using Equation (C.21) (Napier, Strenge et al. 2012).

$$IH_{fwigT}(T) = I_{fwig}(T) HC_{igocT} \quad \text{(C.21)}$$

where:

$IH_{fwigT}(T)$ = equivalent dose to organ T from ingestion intake of radionuclide i in aquatic flora or fauna c at soil usage location s for an individual in age group g for exposure over time period T (Sv),
$I_{fwig}(T)$ = ingestion intake of radionuclide i in aquatic flora or fauna c at soil location s for individuals in age group g for exposure over time period T (Bq), and
$HC_{igoc}T$ = equivalent dose coefficient to organ T for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The equivalent dose from internal exposure through ingestion of aquatic flora and fauna can be calculated using Equation (C.22) (Napier, Strenge et al. 2012).

$$IE_{fwig}(T) = I_{fwig}(T) EC_{igoc} \quad \text{(C.22)}$$

where:

$IE_{fwig}(T)$ = effective dose from ingestion intake of radionuclide i in aquatic flora or fauna c at soil usage location s for an individual in age group g for exposure over time period T (Sv),
$I_{fwig}(T)$ = ingestion intake of radionuclide i in aquatic flora or fauna c at soil location s for individuals in age group g for exposure over time period T (Bq), and
EC_{igoc} = effective dose coefficient for ingestion intake of radionuclide i for an individual in age group g (Sv/Bq).

C.12 Inhalation of Resuspended Soils

The equivalent dose from the inhalation of resuspended soil can be calculated using Equation (C.23) (Napier, Strenge et al. 2012).

$$IH_{saigT}(T) = I_{saig}(T) HC_{igrcT} \quad \text{(C.23)}$$

where:

$IH_{saigT}(T)$ = equivalent dose to organ T from ingestion intake of radionuclide i in resuspended soil at air usage location a for an individual in age group g for exposure over time period T (Sv),
$I_{saig}(T)$ = ingestion intake of radionuclide i in resuspended soil at air usage location a for individuals in age group g for exposure over time period T (Bq), and
$HC_{igrc}T$ = equivalent dose coefficient to organ T for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The effective dose from internal exposure through inhalation can be calculated using Equation (C.24) (Napier, Strenge et al. 2012).

$$IE_{saig}(T) = I_{saig}(T)EC_{igrc} \quad \text{(C.24)}$$

where:

$IE_{saig}(T)$ = effective dose from ingestion intake of radionuclide i in resuspended soil at air usage location a for an individual in age group g for exposure over time period T (Sv),
$I_{saig}(T)$ = ingestion intake of radionuclide i in resuspended soil at air usage location a for individuals in age group g for exposure over time period T (Bq), and
EC_{igrc} = effective dose coefficient for ingestion intake of radionuclide i for an individual in age group g (Sv/Bq).

C.13 Ingestion of Soils

The equivalent dose from internal exposure through ingestion of soil can be calculated using Equation (C.25) (Napier, Strenge et al. 2012).

$$IH_{dsig}(T) = I_{dsig}(T)HC_{igocT} \quad \text{(C.25)}$$

where:

$IH_{dsigT}(T)$ = equivalent dose to organ T from ingestion intake of radionuclide i in soil at soil usage location s for an individual in age group g for exposure over time period T (Sv),
$I_{dsig}(T)$ = ingestion intake of radionuclide i in soil at soil location s for individuals in age group g for exposure over time period T (Bq), and
$HC_{igoc}T$ = equivalent dose coefficient to organ T for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The effective dose from internal exposure through ingestion of soil can be calculated using Equation (C.26) (Napier, Strenge et al. 2012).

$$IE_{dsig}(T) = I_{dsig}(T)EC_{igoc} \quad \text{(C.26)}$$

where:

$IE_{dsig}(T)$ = effective dose from ingestion intake of radionuclide i in soil at soil usage location s for an individual in age group g for exposure over time period T (Sv),
$I_{dsig}(T)$ = ingestion intake of radionuclide i in soil at soil location s for individuals in age group g for exposure over time period T (Bq), and
EC_{igoc} = effective dose coefficient for ingestion intake of radionuclide i for an individual in age group g (Sv/Bq).