DOCUMENT RELEASE AND CHANGE FORM

Prepared For the U.S. Department of Energy, Assistant Secretary for Environmental Management
By Washington River Protection Solutions, LLC., PO Box 850, Richland, WA 99352
Contractor For U.S. Department of Energy, Office of River Protection, under Contract DE-AC27-08RV14800

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Originator	Bergeron, Marcel P	*Bergeron, Marcel P*	02/01/2021
Responsible Manager	Rutland, Paul L	*Rutland, Paul L*	02/01/2021

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Responsible Manager	WRPS	11/24/2020	Rutland, Paul L Approved - IDMS data file att.
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Other: ORP SME	☒	☐	Lobos, Rodrigo A	Approved - IDMS data file att.

Comments Required for WRPS-Indicate Purpose of Document:

The purpose of this environmental model calculation file is to document the various calculations performed with a system-level model to support the Waste Management Area C Performance Assessment and Resource Conservation and Recovery Act of 1976 closure analysis. This revision contains updates made in response to internal review and NRC review of the WMA C WIR Evaluation and Performance Assessment.

APPROVED
By Sarah Harrison at 3:25 pm, Jan 28, 2021

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RPP-CALC-60451
Revision 1

WMA C System Model for Performance Assessment of Base Case, Uncertainty Analysis and Sensitivity Analysis

Prepared by:
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Prepared for:
Washington River Protection Solutions, LLC

Date:
January 2021

Prepared for the U.S. Department of Energy
Office of River Protection

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Version History

Version	Date	Author	Change Description
Draft A	01-Dec-2015	N. Hasan	Initial Draft for DOE-ORP Review
Draft B	05-Feb-2016	N. Hasan	Incorporates changes to Intruder Scenario description and associated figures. Minor edits to radon flux description.
Rev. 0	21-Jul-2016	N. Hasan	Update in response to Low-Level Waste Disposal Facility Federal Review Group comments. Include updated signature cover page for Low-Level Waste Disposal Facility Federal Review Group updates.
Rev. 0A	30-Sept-2020	N. Hasan	Draft created to facilitate checking of updates in response to internal review and NRC review of the WMA C WIR Evaluation and Performance Assessment. Updates include changes to: • Inadvertent intruder acute dose for the well driller scenario for the pipeline source in Table 7-1 and in Figures 7-12 and 7-13b. Figures 7-12 through 7-21 were all updated for a consistent presentation of inadvertent intruder results. • Section 7.8.2 (Summary of Tap water Non Cancer Hazards) that include text changes, minor modification of Table7-13, the addition of Table 7-14, and the addition of Figures 7-42 and 7-43. Checking of updates is limited to those identified above.
Rev. 1	28-Jan-2021	N. Hasan	Revision submitted to DOE-ORP review.

ENVIRONMENTAL MODEL CALCULATION COVER PAGE

SECTION 1: COMPLETED BY RESPONSIBLE MANAGER OR DESIGNEE

0A
RELEASE/ISSUE

Project: Waste Management Area C Performance Assessment

Date: 11/17/2020

Calculation Title and Description: WMA C System Model for Performance Assessment of Base Case, Uncertainty Analysis and Sensitivity Analysis

SECTION 2: COMPLETED BY PREPARER

Calculation No.: RPP-CALC-60451 Revision No.: 0A

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0A	Updates to pages 3-6, 3-7, 7-9, 7-10, Table 7-1, Table 7-2, and Figures 7-12 through 7-22 related to updates in results for the well driller scenario and treatment of end of institutional control in inadvertent intruder analysis Updates to Section 7.8.2 (Summary of Tap water Non Cancer Hazards) that include text changes, minor modification of Table 7-13, the addition of Table 7-14, and the addition of Figures 7-42 and 7-43. Checking of updates is limited to those identified above.	11/17/2020	See revision descrip-tion

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LIST OF TERMS

1-D	one-dimensional
244-CR vault	244-CR Process Tank Vault
3-D	three-dimensional
CFR	*Code of Federal Regulations*
CHPRC	CH2M HILL Plateau Remediation Company
DOE	U.S. Department of Energy
EMCF	Environmental Model Calculation File
EMMA	Environmental Model Management Archive
HI	hazard index
HQ	hazard quotient
PA	Performance Assessment
PoC	point of calculation
RCA	*Resource Conservation and Recovery Act of 1976* (RCRA) Closure Analysis
STOMP	Subsurface Transport over Multiple Phases
WMA	Waste Management Area

1.0 PURPOSE

The purpose of this environmental model calculation file (EMCF) is to document the various calculations performed with a system-level model to support the Waste Management Area (WMA) C Performance Assessment (PA) and *Resource Conservation and Recovery Act of 1976* (RCRA) closure analysis (RCA). Instead of performing calculations using specialized process-level models for each part of the subsystem, a single model is developed for a computationally efficient evaluation of the total system through coupling of processes at various scales that are relevant for evaluating the long-term performance and for comparison to the performance objectives. Some of the important submodels/processes that are included within the system model calculation architecture are: (a) waste form degradation and release from various residual inventory containing sources at closure (tanks and ancillary equipment); (b) flow and transport of contaminants through the vadose zone and saturated zone using an abstraction approach; (c) air-pathway transport of volatile contaminants; (d) calculation of effective dose and risk from exposure of radionuclides and chemicals at the assessment point for various exposure scenarios; (e) calculation of acute and chronic dose to the inadvertent intruder; and (f) radon flux calculation from residual waste.

The primary goal of the system model is to evaluate the uncertainty in estimating dose at the point of compliance due to uncertainty in input parameters and in recognition of environmental processes that are inherently uncertain. The system model is also used to evaluate sensitivity to certain input parameters. The system model is based on the abstraction of the three-dimensional (3-D) process-level flow and transport model described in RPP-RPT-58949, *Model Package Report Flow and Contaminant Transport Numerical Model used in WMA C Performance Assessment and RCRA Closure Analysis*. Details of the development of the system model are provided in RPP-RPT-58948, *Model Package Report System Model for the WMA C Performance Assessment and RCRA Closure Analysis Version 1.0*. The calculations performed with the system-level model are provided in this EMCF.

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2.0 BACKGROUND

Details of the development of the system model used in the calculations evaluated in this EMCF are provided in RPP-RPT-58948, *Model Package Report System Model for the WMA C Performance Assessment and RCRA Closure Analysis Version 1.0*.

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3.0 METHODOLOGY

The system-level model is implemented using GoldSim©[1] software (GoldSim Contaminant Transport Module User's Guide [GoldSim Technology Group 2014a]; GoldSim Distributed Processing Module User's Guide [GoldSim Technology Group 2014b]; GoldSim Probabilistic Simulation Environment User's Guide [GoldSim Technology Group 2014c]). The detailed methodology for various calculations performed with the system-level model is discussed in RPP-RPT-58948; for the convenience of the reader a brief description and reference to the different sections of RPP-RPT-58948 are provided here.

3.1 SELECTION OF TECHNICAL STAFF

The selection of staff for Revision 0A of this document is as follows.

3.1.1 Project Management

Marcel P. Bergeron, Washington River Protection Solutions, LLC (WRPS)

M.A., Geology, Indiana University
B.A., Geology, University of Vermont

Mr. Bergeron is a Principal Scientist in the Closure and Interim Measures Group within WRPS in Richland, Washington. He has 40 years of experience in a wide variety of hydrogeologic investigations and studies at radioactive and hazardous waste sites. Mr. Bergeron has significant experience in the application to subsurface flow and transport modeling with emphasis on risk and performance assessments supporting closure of hazardous chemical and radioactive waste facilities. At WRPS, he has been using his past experience and expertise in hydrogeologic characterization/interpretation, risk, and performance assessment for tank-related waste management, remediation, and closure issues and decisions.

3.1.2 Originator

Nazmul Hasan, INTERA, Inc.

M.S., Environmental Engineering, Washington State University
B.S., Civil Engineering, Bangladesh University of Engineering & Technology

Mr. Hasan is a hydrologist with 11 years of experience in numerical modeling of groundwater in the saturated and unsaturated zones, model calibration, groundwater management, geostatistics analysis, and programming in and application of multiple languages and codes.

[1] GoldSim© simulation software is copyrighted by GoldSim Technology Group LLC of Issaquah, Washington (see http://www.goldsim.com).

3.1.3 Checkers

David J. (DJ) Watson, Scientist, WRPS

M.S., Environmental Science, Washington State University
B.S., Geology, Washington State University

Mr. Watson has over 17 years of human health risk assessment and PA experience. He has over 14 years of environmental modeling experience, including: subsurface contaminant transport using STOMP©[2], pflotran[3], and TOUGH2[4]; air dispersion with AERMOD[5]; internal and external radiological dosimetry using IMBA®[6], DCAL[7], OLINDA[8], and RESRAD[9]; and system modeling using GoldSim©. He has worked in the areas of underground tank waste retrieval and tank closure, radiation dosimetry of both internally-deposited radionuclides and external exposure, nuclear fuel fabrication and transport, and geologic carbon dioxide (CO_2) sequestration. His work has supported U.S. Department of Energy (DOE), U.S. Nuclear Regulatory Commission, International Atomic Energy Agency, Joint Global Change Research Institute and other industrial and research organizations.

Mr. Watson was responsible for checking for the updates made to the inadvertent intruder acute dose results for the well driller scenario for the pipeline source in Table 7-1 and in Figures 7-12 and 7-13b. He also was responsible for checking that plots in Figures 7-12 through 7-21 were all updated for a consistent presentation of inadvertent intruder results.

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[2] Subsurface Transport Over Multiple Phases (STOMP©) is copyrighted by Battelle Memorial Institute, 1996.

[3] PFLOTRAN is open-source software and can be redistributed and/or modified under the terms of the GNU Lesser General Public License as published by the Free Software Foundation.

[4] TOUGH2 software was developed by Lawrence Berkeley National Laboratory, University of California, Berkeley, California with support from the Office of Science, Office of Basic Energy Sciences, Materials Sciences and Engineering Division of DOE.

[5] AERMOD atmospheric dispersion modeling system was developed by the AERMIC (American Meteorological Society [AMS]/EPA Regulatory Model Improvement Committee), a collaborative working group of scientists from the AMS and the EPA.

[6] Integrated Modules for Bioassay Assessment (IMBA)® is a registered trademark of Public Health England, London, United Kingdom; IMBA Expert™ DOE-Edition is a trademark of ACJ & Associates, Richland, Washington and U.K. Health Protection Agency, Oxfordshire, United Kingdom.

[7] DCAL (Dose and Risk Calculation) software was developed by the Dosimetry Research Group (now the Biosystems Modeling Team in the Advanced Biomedical Science and Technology Group) at Oak Ridge National Laboratory under the sponsorship of EPA.

[8] OLINDA code was written by Michael Stabin, PhD, CHP, Department of Radiology and Radiological Sciences, Vanderbilt University, Nashville, Tennessee.

[9] The RESRAD (RESidual RADioactive) family of codes is developed at Argonne National Laboratory, Lemont, Illinois, managed by UChicago Argonne, LLC, for the U.S. Department of Energy's Office of Science.

Kristin Singleton, Scientist, WRPS

B.S., Cellular and Molecular Biology, University of Nevada, Reno

Ms. Singleton has over 11 years of experience performing extensive human health risk assessments and performance assessments across the Hanford Site Tank Farms and River Corridor. Environmental modeling experience includes system modeling using GoldSim©. She has experience developing risk-based remediation goals in compliance with Federal and State regulations and interpreting modeling results for hazardous waste facilities and contaminated sites.

Ms. Singleton was responsible for checking updates to Section 7.8.2 (Summary of Tap Water Non-Cancer Hazards) that included text changes, minor modification of Table 7-13, the addition of Table 7-14, and the addition of Figures 7-42 and 7-43.

3.1.4 Senior Reviewer

Matthew Kozak, INTERA, Inc.

Ph.D., Chemical Engineering, University of Washington
B.S., Chemical Engineering, Cleveland State University

Dr. Kozak has more than 30 years of experience in the areas of performance assessment of near-surface and geological radioactive waste repositories, regulatory development, dose assessment for residual contamination of soils and buildings, toxic materials risk assessment, and mixed waste issues. He is the author of over 100 publications on these topics. He has supported national programs in the U.S. and countries in Europe, Asia, and Africa to site, develop, construct, and analyze facilities for disposal of radioactive waste.

He has participated in a number of international research programs, including the International Atomic Energy Agency's Coordinated Research Program on Improvement of Safety Assessment Methodologies, and its successor programs: Application of Safety Assessment Methodologies, Practical Illustration and Use of the Safety Case Concept in the Management of Near-Surface Disposal, and most recently Modelling and Data for Radiological Impact Assessments.

3.2 SOURCE RELEASE IMPLEMENTATION

The source term considers processes associated with release of contaminants from residual waste into the natural environment. Separate source terms are considered for each of the twelve 100-series tanks, four 200-series tanks, C-301 catch tank, 244-CR Process Tank Vault (244-CR vault), and pipelines, resulting in 19 separate source terms. The inventory used in the source term model includes the current estimate of the residual inventory and volume. Source terms for pits and diversion boxes are not explicitly considered but are incorporated as part of the pipeline source term.

Waste form degradation and release mechanisms were evaluated using experiments for ^{99}Tc, uranium, and chromium. Based on the observations, the following source release base models are implemented.

To make the source release model for ^{99}Tc consistent with the observations, an initial 6% fraction of the ^{99}Tc inventory is considered to be instantaneously available for release, while the remaining 94% fraction undergoes relatively slower release at the fractional rate of 6×10^{-4} day^{-1}.

The following solubility controls are imposed on the uranium concentrations.

- Apply a solubility limit of 1×10^{-4} M for 1,000 years (equivalent to reaction progress of 0.2) based on the assumption that amorphous uranium mineral phases such as $Na_2U_2O_7$(am) control the solubility.

- After 1,000 years, apply the solubility limit of 1×10^{-6} M, assuming $CaUO_4$ as the solubility-controlling mineral phase under $Ca(OH)_2$-saturated conditions (infill grout saturated and intact-tank conditions).

- If and when the tank is assumed to be degraded such that flow rates are fast enough not to equilibrate with the infill grout material and rather are $CaCO_3$ saturated (vadose zone water), then apply a solubility limit of 1×10^{-4} M for 1,000 years. Beyond this time, apply solubility limit of 2×10^{-5} M based on the long-term uranium concentrations, assuming minimal influence of $Ca(OH)_2$ water.

For chromium, a constant high dissolved concentration limit of 2,000 µg/L is imposed. This value is at the high end of observed values in tank C-202 leachate.

Observations of retrieved tanks show that the residual waste is primarily distributed on the tank bottoms (see Section 5.2 of RPP-RPT-42323, *Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates*). Consequently, the residual waste is conceptualized to be distributed in a uniform layer at the base of the tank. As long as tank wall integrity is maintained and the infill grout is not physically degraded, the primary contaminant transport process will be diffusive. The shortest diffusive pathway for release to the near-field environment is through the base of the tank. The diffusive thickness being considered is the 8-in. combined thickness of concrete and grout layer located at the base of the tank (ignoring the steel plate). The aqueous phase diffusive transport will occur along the water phase within the pore spaces of the grout and concrete layer. The effective diffusion coefficient of contaminant (which includes effects of tortuosity) along with sorption behavior within the grout and concrete layer are going to control the diffusive mass flux besides the concentration gradient.

The effective diffusion coefficient of mobile contaminants (such as ^{99}Tc) through the combined grout and concrete base mat is considered a key parameter that controls the diffusive flux. Over the past decade, several experiments have been conducted to determine the effective diffusion coefficient through concrete for relatively mobile contaminants under unsaturated conditions. The results of various experiments are presented in PNNL-23841, *Radionuclide Migration*

through Sediment and Concrete: 16 Years of Investigations. Of particular interest are the sediment-concrete half-cell experiments conducted in Year 2008 (for a period of 351 days) with ^{99}Tc and stable iodine.

The calculated effective diffusion coefficients of ^{99}Tc derived from the experimental results range from 6.6×10^{-9} cm^2/s to 1.6×10^{-7} cm^2/s, with a median value of about 3×10^{-8} cm^2/s. No particular measurable trend exists to indicate whether the effective diffusion coefficient varies with moisture content of the sediment. The highest ^{99}Tc diffusivities were predominantly observed in the non-carbonated concrete cores contacting spiked sediments. A clear effect from the addition of iron was not observed. In general, the increased carbonation reduced diffusion coefficients. For the purpose of the PA base case calculations, a best estimate value of 3×10^{-8} cm^2/s is chosen for the effective diffusion coefficient in concrete. This value is applied to all species diffusing through the concrete.

More detailed description and mathematical models used in source term modeling is provided in Section 4.2 of RPP-RPT-58948.

3.3 ABSTRACTION APPROACH FOR IMPLEMENTING GROUNDWATER TRANSPORT PATHWAY

The system model is implemented to reduce the computational time needed to carry out sensitivity and uncertainty analyses. The flow field for the vadose zone is derived from the 3-D Subsurface Transport over Multiple Phases (STOMP©)-based model calculations, abstracted to provide a close approximation to the full STOMP©-based solution. The objective of the system model is to evaluate the interaction of various submodels within the overall system. This is carried out by conducting transport analyses within the vadose zone and saturated zone for each source type (tank, ancillary equipment, and pipeline). The reasonableness of the abstraction approach was corroborated by comparisons of the results of the transport analysis conducted using the 1-D abstracted model to the full 3-D STOMP©-based model.

The flow field generated from the STOMP©-based model was evaluated prior to abstraction. The following aspects were considered during abstraction of flow field:

1. Variable hydrostratigraphic unit thickness within the model domain and its impact on flow velocity

2. Spatial and temporal variability in imposed recharge rates

3. Spatial and temporal variability in flow underneath the tank

4. Variable distances of tanks from the compliance location boundary.

The GoldSim©-based system model relies on the user to provide the moisture content, saturation, and Darcy flux as inputs; these flow-field related parameters were extracted from the STOMP©-based model. For the abstraction of the flow field, the primary regions of interest were

the ones underneath the various source locations within WMA C. Details of the flow field abstraction methodology are provided in Section 4.3 of RPP-RPT-58948.

3.4 IMPLEMENTATION OF ATMOSPHERIC TRANSPORT PATHWAY

Gases and vapors could travel upward from the residual inventory within tanks and ancillary equipment through the surface barrier to the ground surface. The principal mechanism by which nuclides migrate from the waste to the ground surface is gaseous diffusion. For tanks, in which the residual waste is predominantly on the bottom of the tank, this means that the gases are transported through the tank infill grout, the tank dome, the soil overburden, and the surface barrier. For pipelines, the diffusion would occur through the soil overburden and the surface barrier.

Releases to the atmospheric pathway are balanced with releases to the groundwater pathway. The partitioning of inventory into the aqueous and gaseous phase occurs within the source-term model (in the residual waste layer). The mass partitioned into the aqueous phase is then available for transport to the underlying vadose zone, while the partitioned fraction in the gas phase is available for upward transport to the atmosphere. Only the aqueous phase is considered in the vadose zone to maximize transport along the groundwater pathway. Similarly, to maximize the upward transport through the gas phase, the downward flow of water above the residual waste location is not modeled. In addition, any physical effect of the surface barrier on gaseous flux is ignored.

Of the radionuclides contained in residual inventory at closure, four could potentially originate as gas:

- Carbon-14 as CO_2 gas
- Hydrogen-3 (tritium) as H_2 gas
- Iodine-129 as I_2 gas
- Radon-222 as radon gas.

The atmospheric transport pathway calculations are conducted in three steps.

1. First, a calculation is performed to compute the upward diffusive flux from each source term to the surface. A zero-concentration boundary condition at the surface is imposed for the purpose of calculating the gaseous flux. This is conceptually equivalent to having a large enough wind speed above WMA C such that the air parcel is renewed constantly, thereby maximizing the diffusive gradient. For all sources except pipelines, while the infill grout is intact, upward gaseous diffusion of volatile contaminants is modeled from the residual waste layer towards the atmosphere. Upward diffusive gas phase transport through the tanks (or 244-CR vault) is modeled to occur along a 10-m-long pathway towards the land surface. This pathway is split into a lower 5 m thickness composed of infill grout material, followed by another 5 m thickness of soil overburden. For the pipeline source area, the diffusive length chosen is the pipeline diameter (0.076 m [3 in.]) and the 5 m thickness of the soil overburden. A surface barrier that will be emplaced at

closure over the tank farm will provide additional depth to the waste and therefore greater diffusive length. For the purpose of performing the air pathway calculations, this additional thickness is conservatively ignored. For all grouted facilities, the air content within the infill grout is assumed to be 6% based on characterization information (WSRC-TR-2005-00195, *Summary of Grout Development and Testing for Single Shell Tank Closure at Hanford*). The porosity and saturation of the infill grout for the purpose of diffusive release calculations are fixed over time. This is deemed to be conservative, as studies have indicated that chemical transformation of initial grout minerals will likely cause porosity reduction over time due to increased molar volume of the newly formed mineral phases.

2. Second, for each source area, the radionuclide transport in air along the downwind direction is performed using a Gaussian plume model, where advection and dispersion occur via wind movement to a receptor placed 100 m downwind at the point of calculation (PoC). As a continuous stream of gas (pollutants) is released into the steady wind in open atmosphere, the gas plume will travel with the mean wind speed. The plume will also spread out or disperse in the horizontal and vertical directions along the centerline.

3. In order to evaluate the effect of commingling of gas plumes from different sources that could lead to increased concentration at the receptor location located 100 m downwind, a separate calculation is performed, where the upward diffusive flux emanating from various sources (described in Step 1) are combined into a single point source, with the location near the approximate center point of the WMA C area. This is conceptually equivalent to a point source (i.e., stack source), but with the release rate (emission rate) equal to all the sources within the WMA C area. This point location is chosen to be the center of the pipeline area, which is 75 m from the WMA C fenceline. The total distance to the receptor is therefore 175 m.

4. The predominant wind direction in the 200 East Area is towards the southeast, and therefore in the general direction of groundwater flow. The average annual wind speed of 3.4 m/s (average from 1944 to 2004) is applied to the pathway for transport. The air mixing height is assumed to be 2 m, which is the approximate average height of an adult. The calculated air concentrations at the receptor location are used for evaluating air pathway dose.

For more details on calculations associated with the atmospheric pathway, the reader is referred to Section 4.4 of RPP-RPT-58948.

3.5 IMPLEMENTATION OF INADVERTENT INTRUDER SCENARIO

A hypothetical inadvertent intruder analysis is undertaken to meet the requirements of DOE O 435.1, *Radioactive Waste Management*. Guidance for the inadvertent intruder analysis

comes from DOE G 435.1-1, *Implementation Guide for Use with DOE M 435.1-1, Radioactive Waste Management Manual*, which states the following:

> "Although DOE *(U.S. Department of Energy)* is committed to retaining control of land containing residual radioactive material, such as disposed low-level waste, it is nonetheless appropriate to consider the impacts of potential inadvertent intrusion. Intrusion should be considered as an accident scenario which could occur during lapses of institutional controls. It is a hypothetical situation assumed simply to provide a basis for determining the acceptability of waste for near-surface disposal and may be used for establishing concentrations of radioactive material in a near-surface disposal facility."

Two types of exposure scenarios are considered to estimate dose to the hypothetical intruder: (1) an acute scenario and (2) a set of chronic scenarios. Acute scenarios evaluate the dose received from well drilling and subsequent exposure to residual waste in the drill cuttings; exposure is evaluated over a short time period. Chronic scenarios evaluate the dose received from spreading the drill cuttings over a specific area while living and/or working on that area. One acute exposure scenario and three chronic exposure scenarios are evaluated in the WMA C PA (RPP-ENV-58782), and brief descriptions of each scenario are provided in Table 3-1. The equations and input parameters are presented in the following sections, but additional details are provided in RPP-ENV-58813, *Exposure Scenarios for Risk and Performance Assessments in Tank Farms at the Hanford Site, Washington*.

Table 3-1. Descriptions of the Inadvertent Intruder Scenarios Evaluated in the Waste Management Area C Performance Assessment.

Scenario	Description
Acute Exposure: Well Driller	Dose is the result of drilling through Waste Management Area C. Exposure pathways include external exposure, inhalation of soil particulates, and incidental soil ingestion. Exposure occurs during the drilling operation while in contact with the drill cuttings. Exposure does not depend on the borehole diameter.
Chronic Exposure: Rural Pasture	Dose is the result of drilling a well that serves a rural pasture. Contaminated drill cuttings are mixed with the soil over the pasture area. Exposure pathways include external exposure, inhalation of soil particulates, incidental soil ingestion, and milk consumption.
Chronic Exposure: Suburban Garden	Dose is the result of drilling a well that serves a suburban garden. Contaminated drill cuttings are mixed with the soil over the area where a residence and a garden are constructed. Exposure pathways include external exposure, inhalation of soil particulates, incidental soil ingestion, and fruit and vegetable consumption.
Chronic Exposure: Commercial Farm	Dose is the result of drilling a well that serves a commercial farm. Contaminated drill cuttings are mixed with the soil over the commercial farm area. Exposure pathways are external exposure, inhalation of soil particulates, and incidental soil ingestion.

Reference: RPP-ENV-58813, *Exposure Scenarios for Risk and Performance Assessments in Tank Farms at the Hanford Site, Washington*.

The inadvertent intruder calculations are performed for all 19 sources (tanks and ancillary equipment). Although inadvertent intrusions into many of the tanks lead to potential doses, the

likelihood of intrusion is considered to be very small due to the significant mechanical barrier to drilling from the large thickness of grout that will fill tanks at closure. By comparison, drilling outside of the grouted tank area poses no such barrier to the intrusion. Therefore, the inadvertent intrusion through pipelines is more likely as pipelines would not provide any appreciable mechanical barrier to drilling compared to drilling through the Hanford unit sediments. For the pipeline source term, the activity in the drill cuttings is based on the contaminated pipeline area that is interrogated by the borehole. If the borehole diameter is greater than the pipeline diameter, then the width of the contaminated zone is restricted to the pipeline diameter. Note that the borehole diameter varies based on the chronic scenario being evaluated.

The waste transfer pipelines represent 98% of the total pipeline length within WMA C while remaining pipelines are gravity-fed cascade lines between the 100-series SSTs (RPP-PLAN-47559, *Single-Shell Tank Waste Management Area C Pipeline Feasibility Evaluation*). The waste transfer pipelines are likely to be intruded and therefore the calculations are based on the residual inventory within these pipelines, which are assumed to be 5% full of waste (RPP-PLAN-47559).

Inadvertent intruder dose is calculated at times consistent with regulatory guidance contained in NUREG-1854, *NRC Staff Guidance for Activities Related to U.S. Department of Energy Waste Determinations – Draft Final Report for Interim Use*. NUREG-1854 notes that it is inappropriate to strictly apply the waste classification system in Title 10, *Code of Federal Regulations* (CFR), Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste" (10 CFR 61), Subpart D—Technical Requirements for Land Disposal Facilities, § 61.55, Waste classification to tank farm residual wastes, because the underlying assumptions used in developing the generic waste classification system in 10 CFR 61.55 differ from the site-specific considerations at DOE tank farms. Nevertheless, NUREG-1854 further describes appropriate approaches for evaluating the conditions at DOE tank farms using the logic applied to the development of 10 CFR 61.55. They note that the depth to the waste and the use of robust intruder barriers are the determining conditions for the type and timing of intruder scenarios. A robust intruder barrier is defined as one that will prevent intrusion into the waste for 500 years.

NUREG-1854 concludes that for wastes at relatively shallow depths without robust intrusion barriers, it is appropriate to carry out the intrusion calculation at the end of institutional control: 100 years. For deeper wastes when robust intruder barriers exist, it is appropriate to assume that intrusion is prevented for at least 500 years, and therefore the intrusion calculation should be carried out at 500 years. For WMA C, these principles are applied by assuming that pipelines do not represent a significant intrusion barrier, and consequently the intrusion calculation is conducted beginning at 100 years after closure (end of institutional control period). By contrast, the tanks and infill grout represent very significant and robust barriers to intrusion, and therefore the intrusion calculation is conducted beginning at 500 years.

3.6 IMPLEMENTATION OF RADON FLUX CALCULATION

The modeling approach for calculating radon flux at the surface is slightly different than the approach for the other contaminants, because there is a different mechanism for emanation of

radon from the waste into air. Radon-222 is produced from the alpha decay of ^{226}Ra in the waste. During the decay, by alpha recoil the produced ^{222}Rn atom (initially in the solid phase) has the potential to end up in either solid, liquid, or gas phase, with the amount in gas available for further diffusion to the ground surface. The fraction of ^{222}Rn in the gas phase over the total ^{222}Rn produced at any time is called the emanation coefficient, which is typically determined empirically for a given material. The emanation coefficient is highly variable from one material to another, and depends on a variety of specific features of the contaminated material, including the distribution of radium within the material particles, grain size and pore size distributions, and moisture content of the contaminated material ("A comprehensive review of radon emanation measurements for mineral, rock, soil, mill tailing and fly ash" [Sakoda et al. 2011]). Emanation coefficients have not been measured for residual wastes. For the purposes of this assessment, the residual wastes are assumed to have emanation properties comparable to soils. NCRP Report No. 103, "Control of Radon in Houses" has recommended a nominal emanation coefficient of about 0.2 for soils, and this value is adopted for this PA. The target emanation coefficient is implemented in the GoldSim© model as the fractional mass of radon produced in the residual waste that enters the gas phase.

A 1-D transport model is used to calculate diffusive flux of radon assuming there is no downward migration of the parent radionuclide ^{226}Ra. This assumption was made to keep the ^{226}Ra fixed in the residual waste, with a constant diffusion path for the duration of the analysis. For more details on calculations associated with the atmospheric pathway, the reader is referred to Section 4.4 of RPP-RPT-58948.

3.7 SENSITIVITY ANALYSIS

Sensitivity analyses evaluate changes in calculated groundwater impacts that result from changes in input parameter estimates. Parameter value ranges used in these analyses were selected by one of several methods. As part of the scoping process leading up to the implementation of the PA, stakeholders expressed specific interest in seeing the results of specific sets of input parameters. In addition to these agreed sets of sensitivity analyses, additional sensitivity cases were identified during the implementation of the PA to evaluate the importance of specific safety functions on the behavior of the disposal system. The result is a set of sensitivity analyses intended to represent the effects of changing a broad set of input assumptions. It is also emphasized that these sensitivity analyses have been augmented by a probabilistic uncertainty analysis, which specifically evaluates parameter uncertainties. By contrast, the sensitivity analyses are generally intended to evaluate changes in the underlying assumptions upon which the model is based, to demonstrate the effect the alternative assumption has on the groundwater concentrations at the PoC 100 m downgradient of the facility fenceline.

The sensitivity analyses quantify the ranges of calculated groundwater concentration outcomes due to single-parameter or multiple-parameter changes that represent an underlying shift in the conceptual model. With respect to the defense-in-depth concept, the analyses quantify the impacts that alternative views of the natural and engineered barriers have on groundwater concentrations in the evaluation of total system performance. These analyses are an effective

tool for supporting closure action decisions for WMA C, because they demonstrate the complementary and redundant nature of the safety functions evaluated in the PA.

The set of sensitivity analyses are presented in Table 3-2. Each sensitivity analysis is assigned a shorthand designator so it can be easily referenced. A brief explanation of each sensitivity analysis is also provided in the table, to provide insight into the alternative assumptions it is intended to evaluate.

Table 3-2. Summary of Sensitivity Cases Simulated Using System Model.

Sensitivity Case Shorthand	Explanation
INV1	All parameters same as base case, except that the estimated inventory is based on the upper bound values. This is an exploration of the effect of alternative inventory assumptions.
GRT1	All parameters same as base case, except that after 5,000 years the grout degrades and the flow properties change to Hanford H2 sand values, with a step function change in the flow rate occurring at this time. This may represent an alternative in which the grout degradation is more rapid than the base case, either through weathering processes that are not included in the base case, or if failure occurs from unanticipated seismic activity.
GRT2	All parameters same as base case, except that after 1,000 years the grout degrades and the flow properties change to Hanford H2 sand values, with a step function change in the flow rate occurring at this time. This may represent an alternative in which the grout degradation is more rapid than the base case, either through weathering processes that are not included in the base case, or if failure occurs from unanticipated seismic activity.
GRT3	All parameters same as base case, except that after 500 years the grout degrades and the flow properties change to Hanford H2 sand values, with a step function change in the flow rate occurring at this time. This may represent an alternative in which the grout degradation is more rapid than the base case, either through weathering processes that are not included in the base case, or if failure occurs from unanticipated seismic activity.
GRT4	All parameters same as base case, except that after 0 years following closure, the grout degrades and the flow properties change to Hanford H2 sand values, with a step function change in the flow rate occurring at this time.
RLS1	All parameters same as base case, except that the release function is calculated assuming all waste is instantly available. This case evaluates a more conservative release function compared to the base case.
DIF1	All parameters same as base case, except that the release function is based on diffusion coefficient 1E-7 cm^2/s. This case represents the tank and base mat in worse condition than the base case, but still limited by diffusion.
DIF2	All parameters same as base case, except that the release function is based on linearly changing diffusion coefficient over 500 years from 1E-14 to 3E-8 cm^2/s. This case represents the tank and base mat degrading over 500 years after closure, but still limited by diffusion.
DIF3	All parameters same as base case, except that the tanks remain intact (no release) for 5,000 years, followed by advective release beginning immediately. This case represents the steel shell remaining intact for longer than the base case, potentially allowing ingrowth of uranium progeny, followed by advective release with associated potential for higher releases of the progeny.

In Table 3-2, the sensitivity analyses using the system model are subdivided into several categories corresponding to the categories of safety functions they are intended to evaluate. These are described below.

3.7.1 Inventory Sensitivity Analyses

An upper bound estimate of inventory is provided in RPP-RPT-42323. Since ^{99}Tc is the primary dose contributor for the groundwater pathway, a sensitivity case was performed by replacing the base case ^{99}Tc inventory with the upper bound value to evaluate the impact in terms of groundwater concentration at the PoC. Additionally, the residual volume based on the upper bound estimate was also updated to be consistent with the change in inventory. All other parameters were kept the same as in the system model base case.

Upper bound residual inventory of 89.7 Ci was estimated for ^{99}Tc for all the sources in WMA C, of which 81.40 Ci was estimated for tank 241-C-105 (C-105). In comparison, the estimated total ^{99}Tc inventory for the base case was 14.70 Ci of which 7.83 Ci was for tank C-105.

Another sensitivity case was run with the upper bound inventory of nitrate to support the RCA. The upper bound residual inventory for nitrate for all sources within WMA C was estimated at 66,000 kg. In comparison, the estimated total nitrate inventory for the base case was 36,100 kg, of which 783 kg was for tank C-105.

3.7.2 Grout Properties Sensitivity Analyses

In the base case, the grouted tanks were assumed to remain intact throughout the 10,000-year analysis time. To assess the impact of early failure of the tank due to unforeseen events, sensitivity cases are performed where the infill grout in the tank is assumed to provide no barrier to flow through the tank. For this purpose, the grout properties are replaced by H2 sand properties and flow through the tank is initiated at the following four degradation times:

1. Tank Degrades at 5,000 years after closure (GRT1)
2. Tank Degrades at 1,000 years after closure (GRT2)
3. Tank Degrades at 500 years after closure (GRT3)
4. Tank Degrades at 0 years after closure (GRT4).

3.7.3 Waste Form Sensitivity Analysis

In the base case, waste form degradation and dissolved concentration limits are applied in determining the source term release for some analytes, as discussed in Section 3.1. In this sensitivity analysis, such limits are removed to evaluate the impact on saturated zone concentration at the PoC.

As described in Section 3.1, the following source-term release models are applied for ^{99}Tc, uranium and chromium in the base case:

- For ^{99}Tc, 6% of the inventory is considered to be instantaneously available for release while the remaining 94% undergoes relatively slower release at the fractional rate of 6×10^{-4} day^{-1}

- For uranium, a solubility limit of 1×10^{-4} mol/L is applied for 1,000 years and 1×10^{-6} mol/L after 1,000 years of closure under intact tank conditions

- For chromium, a constant high dissolved concentration limit of 2,000 µg/L is imposed.

For the purpose of conducting the sensitivity analysis, all of the ^{99}Tc inventory was assumed to be instantaneously available for release and the solubility limit or dissolved concentration limits are not imposed for uranium and chromium.

3.7.4 Tank Flow Sensitivity Analyses

Diffusive release through the base of the tank (made up of grout and concrete layer) is the primary release mechanism from the tanks in the base case. The effective diffusion coefficient through the concrete and grout layer is a key parameter in determining the diffusive flux. For the base case, an effective diffusion coefficient of 3×10^{-8} cm^2/s was used; the following three sensitivity cases were performed to evaluate the impact of changing the effective diffusion coefficient.

1. Effective diffusion coefficient for the grout is changed to 1×10^{-7} cm^2/s (DIF1).

2. Effective diffusion coefficient for the grout varies linearly from 1×10^{-14} to 3×10^{-8} cm^2/s in the first 500 years after closure and remains constant afterwards at 3×10^{-8} cm^2/s (DIF2).

3. Tanks (including CR-Vault) remain fully intact with no diffusive release until 5,000 years. The tank becomes fully degraded at 5,000 years, resulting in both advective and diffusive releases. The effective diffusion coefficient remains the same as the base case (DIF3).

3.7.5 Evaluation of Long-Term Peak Dose

An additional evaluation case was run to evaluate the peak dose beyond the 10,000-year time frame. For this purpose, the base case flow field that was developed for the 10,000-year time period was extended such that assumptions of constant recharge rate were maintained and all the processes that were applicable over the 10,000-year time frame were assumed to be applicable for the extended duration. The only change made to the base case is the one where the grouted tanks (including the 244-CR vault) are considered to be degraded at 30,000 years post-closure. At this time, flow through the tank is applied based on the degraded tank flow field. The calculations were run for a period of 400,000 years.

3.8 UNCERTAINTY ANALYSIS

The vadose zone flow rates as a function of time were abstracted from the process-level models, and developed using the STOMP© code, which solves the Richards' equation for the unsaturated media. Outputs calculated by the 3-D STOMP©-based model were used to generate the flow field (spatially and temporally varying Darcy flux and moisture content), which were abstracted along with their uncertainty estimates for use in GoldSim©-based models. Because uncertainty in hydraulic properties and recharge rates affect the flow field in a complex manner, the abstraction was performed by first propagating the uncertainty in flow parameters using the STOMP©-based model and then evaluating the resulting flow field. Since running 3-D STOMP©-based models is numerically intensive, a selected combination of pre-determined hydraulic properties and recharge rates were used by setting the parameter values at various percentiles of their distribution. This approach led to development of possible range of flow fields (vertical Darcy flux and moisture contents) that were abstracted as inputs to the transport calculations using the GoldSim©-based system model for uncertainty analysis.

The reader is referred Section 5.2 of RPP-RPT-58948, for more details of the uncertainty analysis.

3.9 EXPOSURE SCENARIO FOR RCRA CLOSURE ANALYSIS (TAP WATER SCENARIO)

To meet RCRA requirements, risk-based calculations are performed using the tap water (resident) scenario. This scenario is used to estimate exposure to both radionuclides and chemicals to a resident receptor who uses the contaminated water from the well located at the PoC for domestic purposes. See Section 2.0 of RPP-RPT-58948 for more details.

4.0 ASSUMPTIONS AND INPUTS

All input parameters that were used in different components of the system model are provided in Section 4.6 of RPP-RPT-58948.

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5.0 SOFTWARE APPLICATIONS

The software used to perform this calculation are approved, managed, and used in compliance with the CH2M HILL Plateau Remediation Company (CHPRC) requirements of PRC-PRO-IRM-309, "Controlled Software Management."

5.1 APPROVED SOFTWARE

5.1.1 GoldSim©

5.1.1.1 Description. All calculations are performed using GoldSim© Pro simulator software, version 11.1.2. GoldSim© Pro simulator is approved for use by CHPRC at the Hanford Site in accordance with the requirements of PRC-PRO-IRM-309. The installed GoldSim© Pro simulator software was tested in accordance with the procedure per CHPRC-00175, *GoldSim Pro Software Management Plan*, Revision 1.

Software is registered on the Hanford Information System Inventory and is identified as approved for use. The identification for the software package used in the calculation are as follows:

- GoldSim© Pro
- Version 11.1.2
- Hanford Information System Inventory Identification Number: 2461
- Workstation type and property number: INTERA - 00606 (Used for Uncertainty Analysis); INTERA – 00708 (Used for other Analysis).

5.1.1.2 Software Installation and Checkout. The software installation and checkout form for GoldSim© is provided in Attachment 1 to this EMCF.

5.1.1.3 Statement of Valid Software Application. The following validates that GoldSim© is a valid software application and was applied in this EMCF within its range of intended uses for which it was tested and approved.

- GoldSim© Pro was utilized for DOE to assist in performing simulation of radioactive mass conservation including decay and ingrowth, contamination mass transport in subsurface environment and to perform human health dose and risk assessment for the Hanford Site.
- GoldSim© Pro as it is used in this EMCF has been implemented within the range of its limitations.

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6.0 CALCULATION

Most of the calculations are performed using GoldSim©. The WMA_C_PA_System_Model_Rev1.gsm file was used for the calculations. This model file is reviewed and checked and will be archived in Environmental Model Management Archive (EMMA) along with this EMCF and other supporting files. Supporting GoldSim© model files were used to provide information necessary for various input components to the WMA_C_PA_System_Model_Rev1.gsm model file and will be listed here. A screen capture of the main window of the WMA_C_PA_System_Model_Rev1.gsm file is provided in Figure 6-1.

GoldSim© uses container element for storing information for various components in the model. Each of the various components of the system model are stored in a specific container element in the model. Calculation procedure for various components of the system model is discussed below.

6.1 SOURCE RELEASE CALCULATION

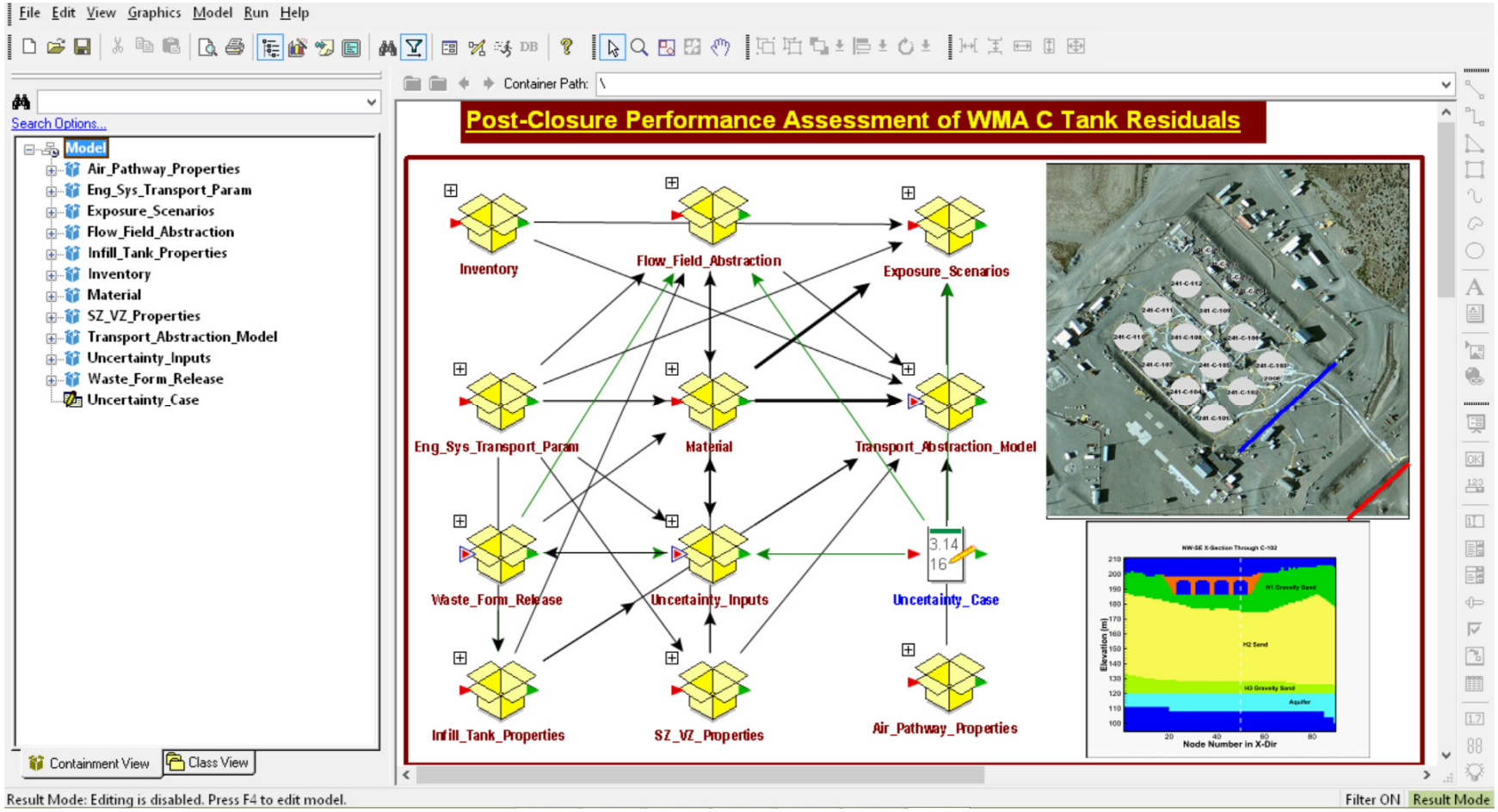
The GoldSim© cloning concept was used to calculate the waste release rates from each of the 19 sources (described in RPP-RPT-58948). One GoldSim© container was built for one source and then it was cloned for the other sources. Between the cloned containers only the source-specific parameters (inventory, volume, etc.) are varied. Figure 6-2 shows the cloned containers for 100-series tanks. 100-series tanks and 200-series tanks were cloned into two different groups because of their dimensions and its impact on diverting the flow fields around the tank structure (see Section 4.3 of RPP-RPT-58948).

Inside each of the cloned elements a GoldSim© source element and cell pathway element was used to calculate the release rates from the residual waste source to the vadose zone immediately below the source. Figure 6-3 shows the structure inside one of the cloned containers and in the subsequent containers.

6.2 ABSTRACTION OF FLOW FIELD

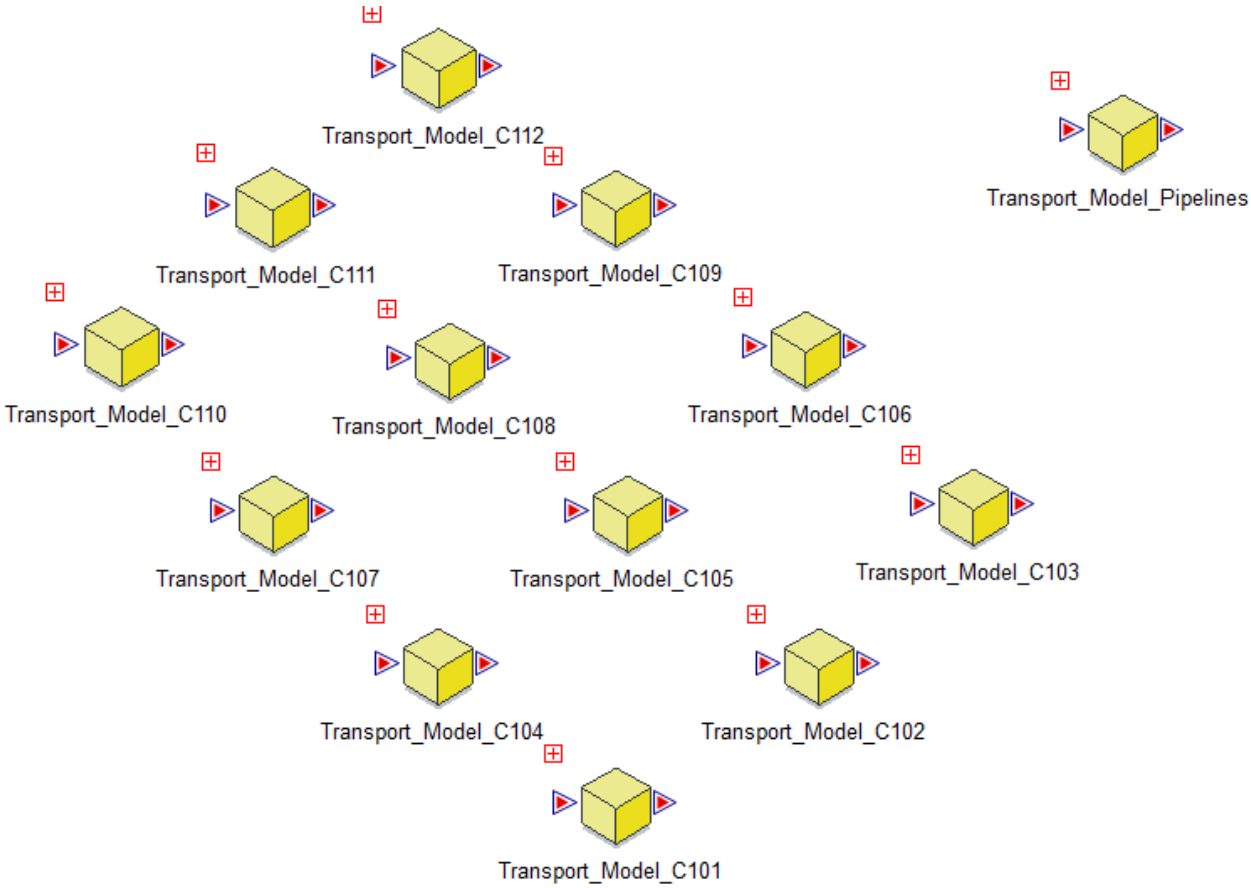
Flow fields (Darcy Flux and Moisture content) was extracted from WMA C STOMP© model output by following the methodology as described in Section 4.3 of RPP-RPT-58948. Different flow fields were extracted for different configurations of the STOMP© model such as the intact tank condition (base case: where tank was inactive in the model domain), degraded tank condition (where tanks were simulated as H2 sand), as well as flow fields for different percentiles of vadose zone hydraulic property to propagate uncertainty in the vadose zone hydraulic parameters. The flow field abstraction procedure was similar for each STOMP© model configuration. Several spreadsheets are used for the flow field implementation in the GoldSim© model. Spreadsheet names and purposes are mentioned in Table 6-1. These spreadsheets have been checked and will be archived in EMMA.

Figure 6-1. Top Level Configuration of the WMA_C_PA_System_Model_Rev1.gsm Model File.



GoldSim© simulation software is copyrighted by GoldSim Technology Group LLC of Issaquah, Washington (see http://www.goldsim.com).

Figure 6-2. Cloning of Sources in the GoldSim© Model.



GoldSim© simulation software is copyrighted by GoldSim Technology Group LLC of Issaquah, Washington (see http://www.goldsim.com).

6.3 GROUNDWATER PATHWAY AND ATMOSPHERIC PATHWAY DOSE CALCULATION

Groundwater pathway dose, atmospheric pathway dose and all-pathways dose calculation was performed with the WMA_C_PA_System_Model_Rev1.gsm file. Table 6-2 presents the spreadsheet needed for performing the calculation.

6.4 INADVERTENT INTRUDER DOSE CALCULATION

Inadvertent intruder dose calculation was performed with the WMA_C_PA_System_Model_Rev1.gsm file. Table 6-2 presents the spreadsheet needed for performing the calculation.

Figure 6-3. Structure of GoldSim© Model.

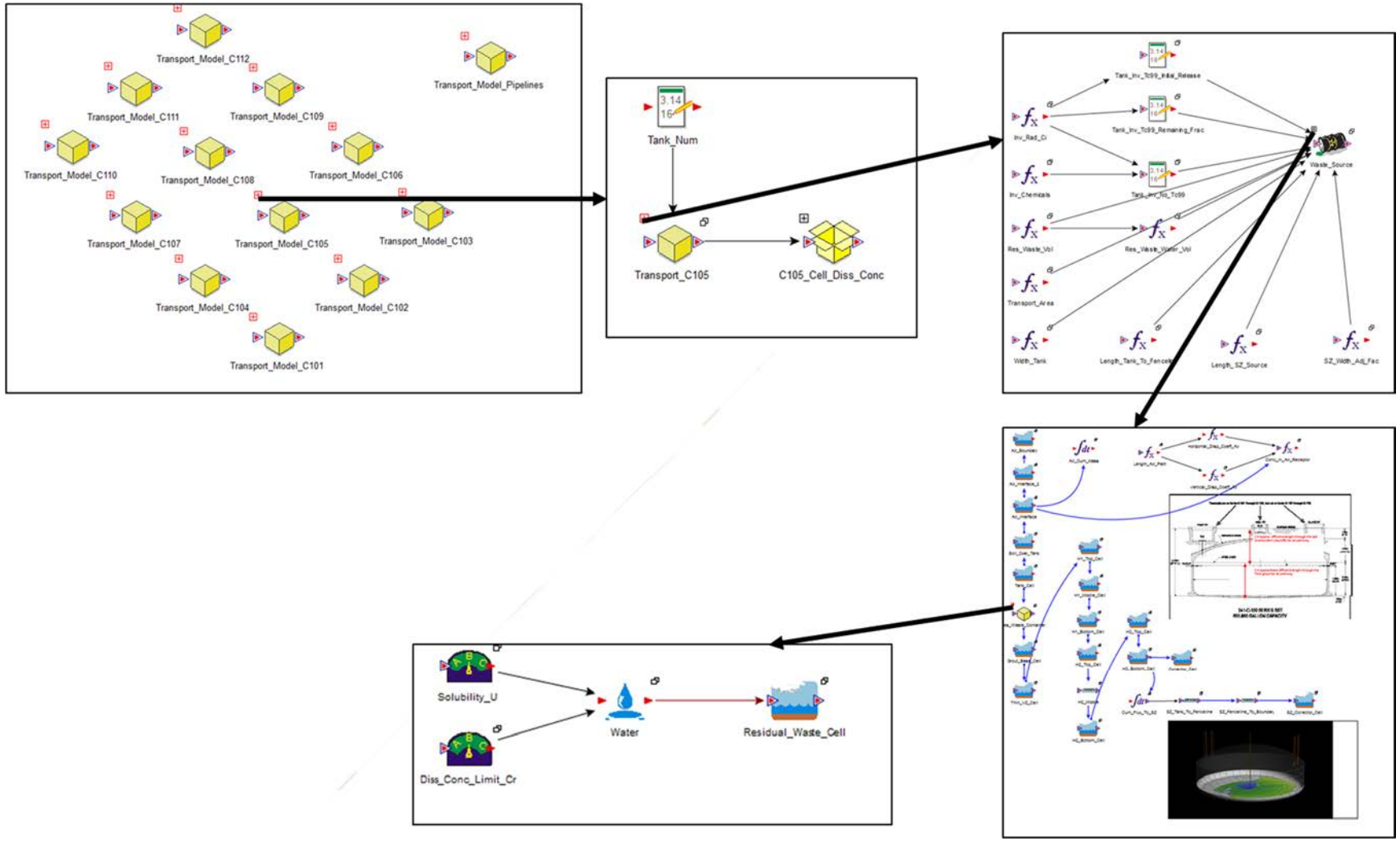


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Table 6-1. Spreadsheets Used for the Flow Field Abstraction.

Spreadsheet Name	Purpose
STOMP_Abstraction_Intact_Tank_Updated_2-25-2015.xlsx	Flow field for base case
STOMP_Abstraction_Degraded_Tank_Updated_2-20-2015.xlsx	Flow field for sensitivity case
Hyd_Prop_5thPercentile_Base_Recharge.xlsx	Flow field for 5th percentile vadose zone hydraulic properties
Hyd_Prop_25thPercentile_Base_Recharge.xlsx	Flow field for 25th percentile vadose zone hydraulic properties
Hyd_Prop_50thPercentile_Base_Recharge.xlsx	Flow field for 50th percentile vadose zone hydraulic properties
Hyd_Prop_75thPercentile_Base_Recharge.xlsx	Flow field for 75th percentile vadose zone hydraulic properties
Hyd_Prop_95thPercentile_Base_Recharge.xlsx	Flow field for 95th percentile vadose zone hydraulic properties

Table 6-2. Spreadsheet Used for the Atmospheric Pathway and Groundwater Pathway Dose Calculation.

Spreadsheet Name	Purpose
DCF_Air_Intruder_Parameter.xlsx	This file is read in GoldSim© model to get the dose conversion factors for atmospheric pathway, groundwater pathway and intruder dose calculation. This also contains input parameters needed for atmospheric pathway calculation and inadvertent intruder dose calculation.
All_Pathway_Parameter.xlsx	This file is read in GoldSim© to get the input parameters for all-pathways dose calculation.

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6.5 RADON FLUX CALCULATION

Radon flux calculation was performed using the WMA_C_PA_System_Model_Rev1-Radon_Flux file. The calculation approach is described in Section 3.5.

6.6 UNCERTAINTY ANALYSIS

Uncertainty analysis was performed using the WMA_C_PA_System_Model_Rev1.gsm model file and supporting Excel®[10] files for the flow field for different vadose zone hydraulic property

[10] Excel® is a registered trademark of Microsoft Corporation in the U.S. and other countries.

are listed in Table 6-1. Table 6-3 lists the other spreadsheets and GoldSim© models used to develop various uncertain parameters needed for uncertainty analysis using the WMA_C_PA_System_Model_Rev1.gsm model file. All the files listed in Table 6-3 have been checked independently and will be archived in EMMA.

Table 6-3. Spreadsheets and GoldSim© Model Used for the Uncertainty Analysis.

Spreadsheet/GoldSim© Model File Name	Purpose
Backfill_Uncertainty_7_7_2015.xlsx	Selection of different percentile vadose zone hydraulic property for Backfill unit.
H1_H3_Uncertainty_7_7_2015.xlsx	Selection of different percentile vadose zone hydraulic property for H1/H3 unit.
H2_Uncertainty_7_7_2015.xlsx	Selection of different percentile vadose zone hydraulic property for H2 unit.
WMAC_Backfill_Prop_Sampling.gsm	Developing 200 realizations of vadose zone hydraulic property for Backfill unit.
WMAC_H1_H3_Prop_Sampling.gsm	Developing 200 realizations of vadose zone hydraulic property for H1/H3 unit.
WMAC_H2_Prop_Sampling.gsm	Developing 200 realizations of vadose zone hydraulic property for H2 unit.
Uncertainty_VZ_Parameters_7_7_2015.xlsx	Summary table for different percentile vadose zone hydraulic property for different units.
Recharge_Scaling_5th_percentile_VZ_hyd_prop.xlsx	Regression equation development for 5th percentile vadose zone hydraulic properties.
Recharge_Scaling_25th_percentile_VZ_hyd_prop.xlsx	Regression equation development for 25th percentile vadose zone hydraulic properties.
Recharge_Scaling_50th_percentile_VZ_hyd_prop.xlsx	Regression equation development for 50th percentile vadose zone hydraulic properties.
Recharge_Scaling_75th_percentile_VZ_hyd_prop.xlsx	Regression equation development for 75th percentile vadose zone hydraulic properties.
Recharge_Scaling_95th_percentile_VZ_hyd_prop.xlsx	Regression equation development for 95th percentile vadose zone hydraulic properties.
Recharge_Scaling_Base_VZ_hyd_prop.xlsx	Regression equation development for base case vadose zone hydraulic properties.
Summary_regression_7_7_2015.xlsx	Summary of the regression equations used for recharge scaling.
Inventory_Uncertainty_All.gsm	Development of parameter distributions for residual inventory uncertainty and volume uncertainty.
Average_Over_Tanks.xlsx	Development of parameter distributions for residual inventory uncertainty and volume uncertainty.

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6.7 SENSITIVITY ANALYSIS

For each of the sensitivity analyses a separate GoldSim© model file was used. They are listed in Table 6-4.

Table 6-4. Spreadsheets and GoldSim© Model Used for the Sensitivity Analysis.

GoldSim© Model File Name	Purpose
Inventory Estimate	
WMA_C_PA_System_Model_Rev0_Sens_Case_inv1_NO3.gsm	INV1 (Tc-99) case
WMA_C_PA_System_Model_Rev0_Sens_Case_inv1_Tc99.gsm	INV1 (NO3) case
Tank Flow Safety Function	
WMA_C_PA_System_Model_Rev0_Sen_Case_dif1.gsm	DIF1 case
WMA_C_PA_System_Model_Rev0_SenCase_dif2.gsm	DIF2 case
WMA_C_PA_System_Model_Rev0_SenCase_dif3.gsm	DIF3 case
Grout Flow Safety Function	
WMA_C_PA_System_Model_Rev0_Sen_Case_grt1.gsm	GRT1 case
WMA_C_PA_System_Model_Rev0_Sen_Case_grt2.gsm	GRT2 case
WMA_C_PA_System_Model_Rev0_Sen_Case_grt3.gsm	GRT3 case
WMA_C_PA_System_Model_Rev0_Sen_Case_grt4.gsm	GRT4 case
Residual Chemistry Safety Function	
WMA_C_PA_System_Model_Rev0_Sens_Case_rls1.gsm	RLS1 case
Peak Dose Calculation	
WMA_C_PA_System_Model_Peak_Dose_Calc.gsm	Sensitivity case to calculate peak dose.

GoldSim© simulation software is copyrighted by GoldSim Technology Group LLC of Issaquah, Washington (see http://www.goldsim.com).

6.8 RISK/HAZARD ESTIMATION FOR TAP WATER SCENARIO

Risk calculation for tap water scenario was performed with the WMA_C_PA_System_Model_Rev1.gsm file. Table 6-5 presents the spreadsheet needed for performing the calculation.

Table 6-5. Spreadsheet Used for the Risk Calculation for RCRA Closure Analysis.

Spreadsheet Name	Purpose
Tapwater_Scenario_Parameters.xlsx	This file is read in GoldSim© model to get input parameters needed for risk calculation for the residential tap water scenario.

RCRA = *Resource Conservation and Recovery Act of 1976*

7.0 RESULTS/CONCLUSIONS

Results/conclusions are presented below for the three system model components: (a) source release function, (b) groundwater transport, and (c) air transport of radionuclides.

7.1 SOURCE RELEASE FUNCTION

A total of 19 different sources for releases to groundwater are evaluated in the PA, which contribute to the overall source term. These sources consist of the twelve 100-series tanks, four 200-series tanks, C-301 catch tank, 244-CR vaults, and pipelines. The residual inventory and waste volume associated with each source is treated separately, resulting in an analysis of transport through groundwater for each source.

The base case release rate for ^{99}Tc from each of the sources in the source term is presented in Figure 7-1. An initial large release rate occurs for the pipeline source, and is attributable to the assumption that releases from the pipelines are dominated by advection. The sharp decline in the release rate is a reflection of source inventory depletion, and to a lesser extent of declining flow rate as the system responds to the placement of the cover. At closure (during emplacement of surface cover), the recharge rate changes from Operations time period of 100 mm/yr to early Post-Closure recharge rate of 0.5 mm/yr (over the 500 years). As a result, the vertical flow rate through the vadose zone adjusts slowly to the imposed boundary conditions. Nearly all of the ^{99}Tc inventory associated with the pipeline source term is released by about 100 years after closure. In contrast, the release rate from grouted tanks increases gradually. This is partly attributable to an initial small release fraction (6%) of the ^{99}Tc inventory that is available for instantaneous release, while the rest of the inventory is made available gradually, reflecting the waste form degradation process. However, the gradual release occurs over a relatively short time, and the primary control for the tank release rates is the diffusive transport through the tank base mat with associated sorption.

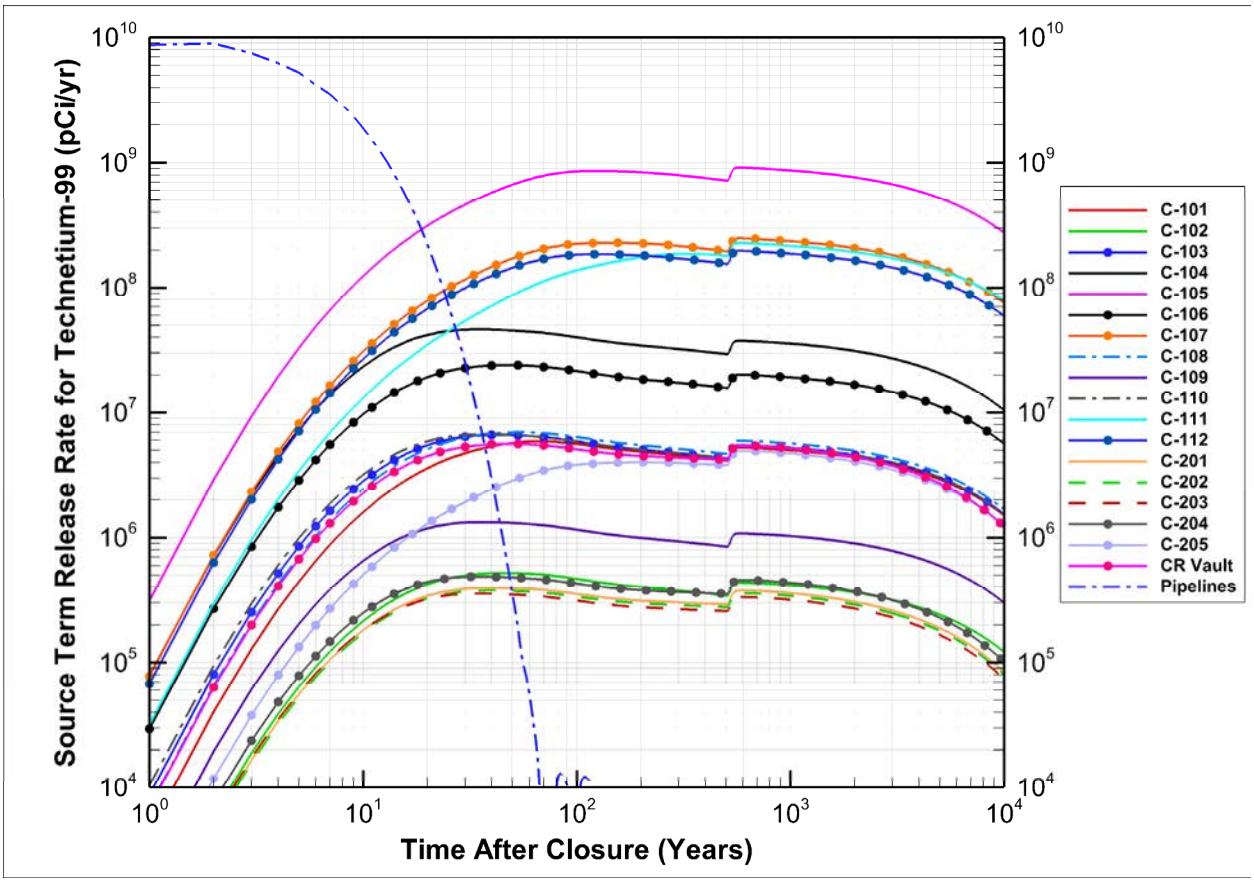
The magnitudes of release rates for ^{99}Tc from each source are proportional to the residual inventory of ^{99}Tc within each source. Therefore, the release rate from tank C-105 is the highest since it has the highest residual inventory (7.83 Ci at closure). Releases from tank 241-C-107, tank 241-C-111 (C-111), and tank 241-C-112 have similar releases rates, as they have similar residual inventories of ^{99}Tc (~2 Ci each). The release rates from other sources are much smaller, owing to their much smaller inventories.

The small rise in release rate noticeable at about 500 years is due to an increase in Darcy flux, when the surface barrier is assumed to transition to its degraded state and the recharge rate changes from 0.5 mm/yr to 3.5 mm/yr. The diffusive release rate shows a slow gradual decline over the simulated time period, indicating that not all of the inventory of ^{99}Tc has been released by the end of the simulation.

Figure 7-2 compares the concentration resulting from release of ^{99}Tc from the waste to that from the bottom of the tank base mat. There is a sharp initial spike in concentration due to the initial release fraction, followed by a gradual decrease in concentration. However, the concentrations

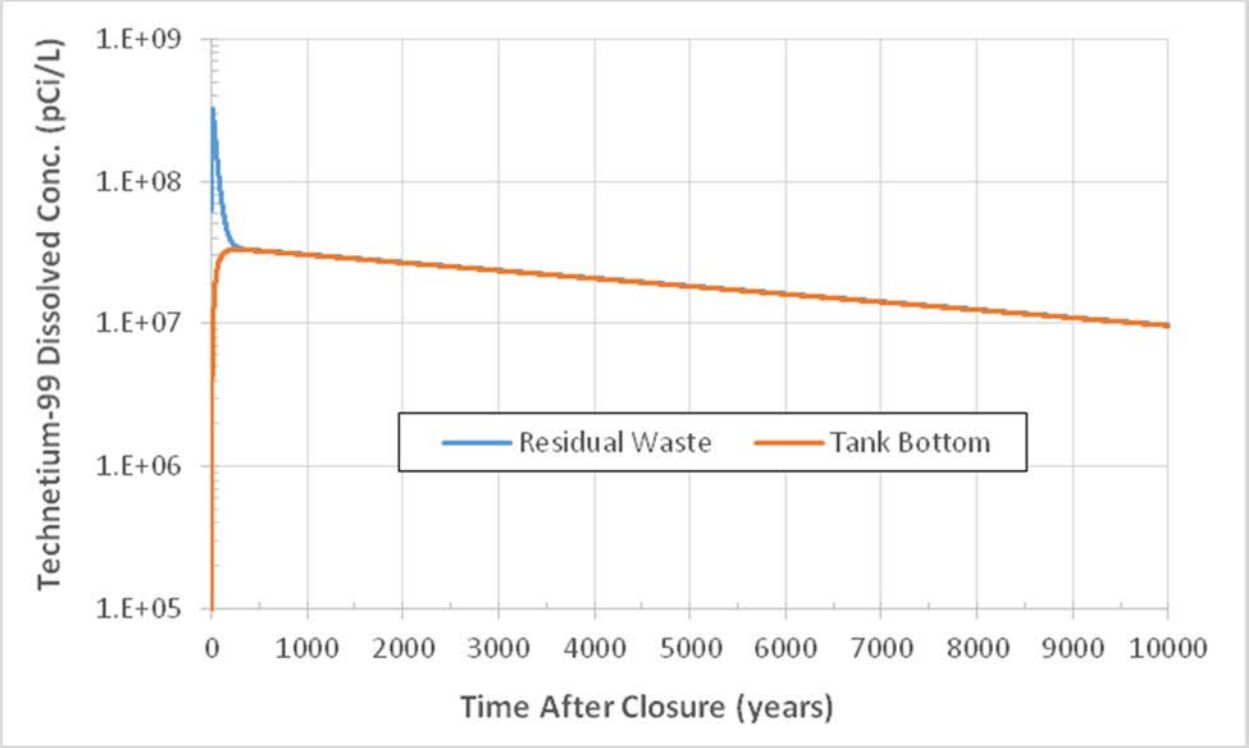
exiting the tank base mat bottom show an initial increase reflecting the establishment of a steady concentration gradient through the base mat. The concentration then slowly decreases as the inventory is slowly depleted by diffusion.

Figure 7-1. Release Rate of Technetium-99 (pCi/yr) from Each Source.



The release rate for ^{238}U from selected sources is presented in Figure 7-3; these sources illustrate representative behavior of the other sources in WMA C. The uranium solubility limits in the source cause the ^{238}U concentrations for several sources terms to be the same, and therefore only selected sources are presented in the figure. When the tank and infill grout are intact, the uranium solubility limit is set to 1×10^{-4} mol/L for the first 1,000 years and to 1×10^{-6} mol/L thereafter. Figure 7-4 presents two curves of the time-varying dissolved ^{238}U concentrations; one exiting the residual waste, and the other exiting out the bottom of the tank base mat for tank C-105. The general trends of these curves for tank C-105 provide good examples of the general shape of the similar curves for dissolved ^{238}U concentrations from other 100-series tanks. The concentrations released from the residual waste remain constant, consistent with the solubility limits, including the assumed step change at 1,000 years. This indicates that there is sufficient inventory of uranium retained in the tanks to maintain the solubility limit at the end of the simulation. The concentration leaving the tank remains at least an order of magnitude below the concentration leaving the residual waste, consistent with the sorption in the concrete and grout matrix.

Figure 7-2. Comparison of Dissolved Concentration of Technetium-99 (pCi/L) in the Residual Waste and Tank Bottom for Tank 241-C-105.



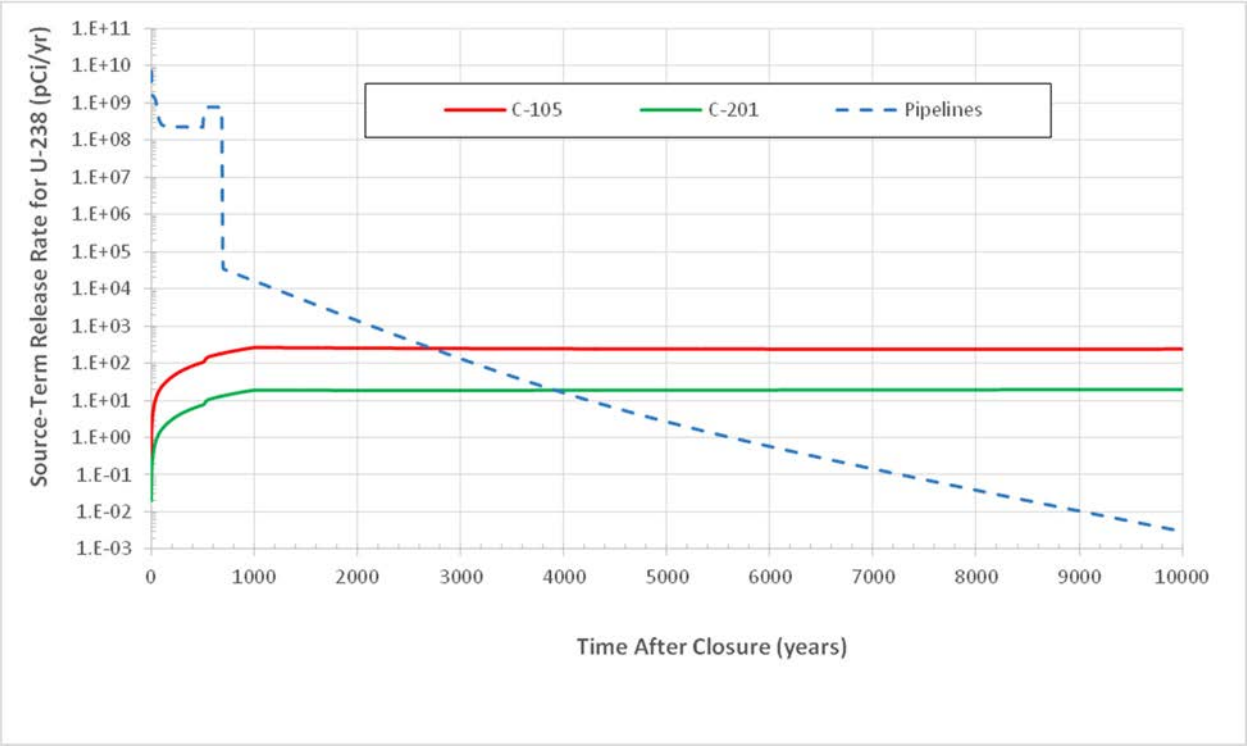
The difference in release rates between tank C-105 and tank 241-C-201 (Figure 7-3) are the result of different diffusive areas (tank bottom area). The release rate from the pipelines, as previously discussed, is primarily by advection, and therefore shows markedly different behavior. The pipeline release rate shows an initial decline, followed by increase at around 500 years and then steep decline at around 700 years. The first 700 years reflect the transient effect of changing recharge as the system responds—first, to the addition of the closure cover, and second, to the assumed degradation of the cover function. The steep decline after 700 years is attributable to depletion of the pipeline inventory, such that dissolved concentrations drop below the solubility limit. The long-term gradual decline following the steep decline reflects the effect of near-field concentrations on advective and diffusive releases through the pipeline. As the released uranium mass moves slowly through the vadose zone, some backward diffusion occurs to the source inventory cell due to reversal of concentration gradient (for the pipeline). This mass then advects out of the inventory cell resulting in a slowly declining release.

The release rates for uranium (total) from representative sources are presented in Figure 7-5. These exhibit similar behavior to the release rates for ^{238}U, as expected. The base case release rate for nitrate from each of the sources is presented in Figure 7-6.

An initial large release rate occurs for the pipeline source, and is attributable to the assumption that releases from the pipelines are dominated by advection. The sharp decline in the pipeline release rate is a reflection of source inventory depletion, and to a lesser extent a reflection of

declining flow rate as the system responds to the placement of the cover. Nearly all of the nitrate inventory associated with the pipeline source term is released by about 50 years after closure.

Figure 7-3. Release Rate of Uranium-238 (pCi/yr) from Representative Source Terms.



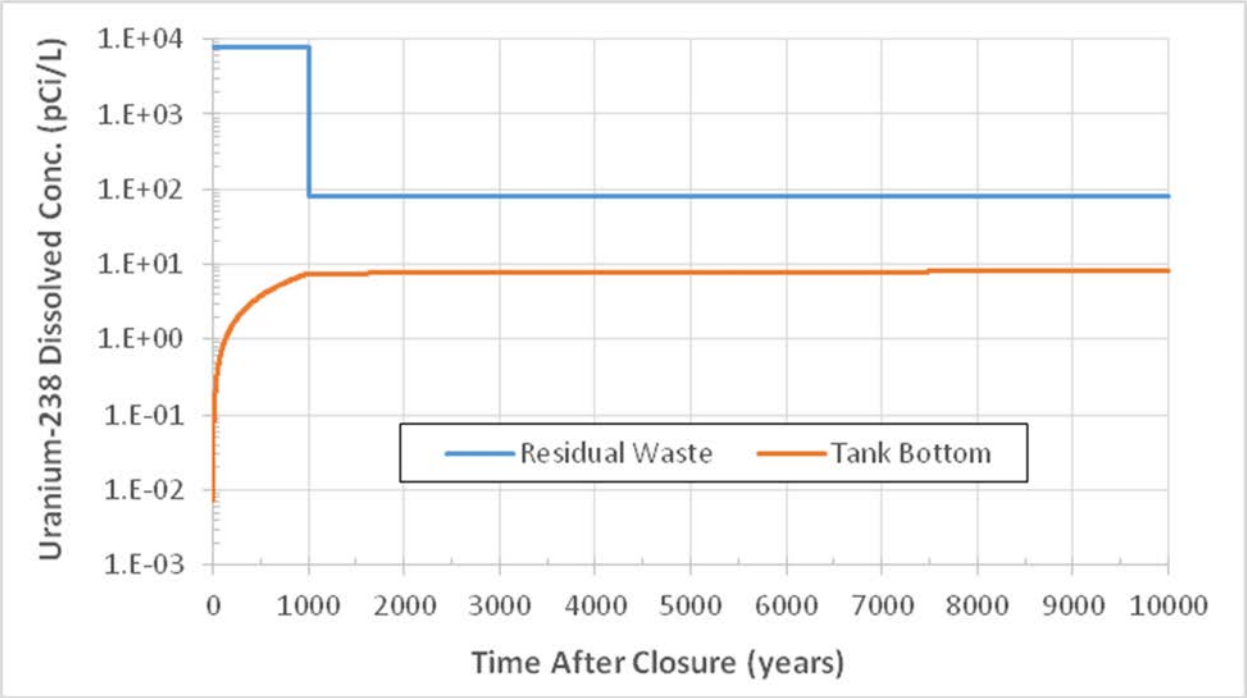
For all other analytes modeled, the releases are simpler, as no solubility limits or waste form degradation mechanisms are considered. For pipelines, the release is primarily by advection. For the remaining sources, where intact grouted tank conditions are assumed, the release mechanism is diffusion through the tank base mat. The effective diffusion coefficient for all of the analytes through the concrete and grout layer is 3×10^{-8} cm^2/s (based on the half-cell diffusion experiments (PNNL-23841) conducted on ^{99}Tc). Differences in diffusion behavior are the result of different partition coefficients (K_d), so that different apparent diffusion coefficients are applied to each analyte. The source release rates for all the modeled analytes are provided in Base_Case_Source_Term_Release_All_Analytes-05-19-2015.xlsx file. This file will be archived in EMMA along with this EMCF. These release rates were applied in the process model described in RPP-CALC-60448, *WMA C Performance Assessment Contaminant Fate and Transport Model to Evaluate Impacts to Groundwater* for groundwater pathway transport analysis.

7.2 GROUNDWATER TRANSPORT

For the base case analysis, groundwater transport pathway calculation was performed with the process model (RPP-RPT-58949) and groundwater transport results are presented in

RPP-CALC-60448. The maximum groundwater concentrations calculated with the process model were used in the system model to calculate the groundwater pathway dose.

Figure 7-4. Comparison of Dissolved Concentration of Uranium-238 (pCi/L) in the Residual Waste and Tank Bottom for Tank 241-C-105.



7.3 AIR TRANSPORT OF RADIONUCLIDES

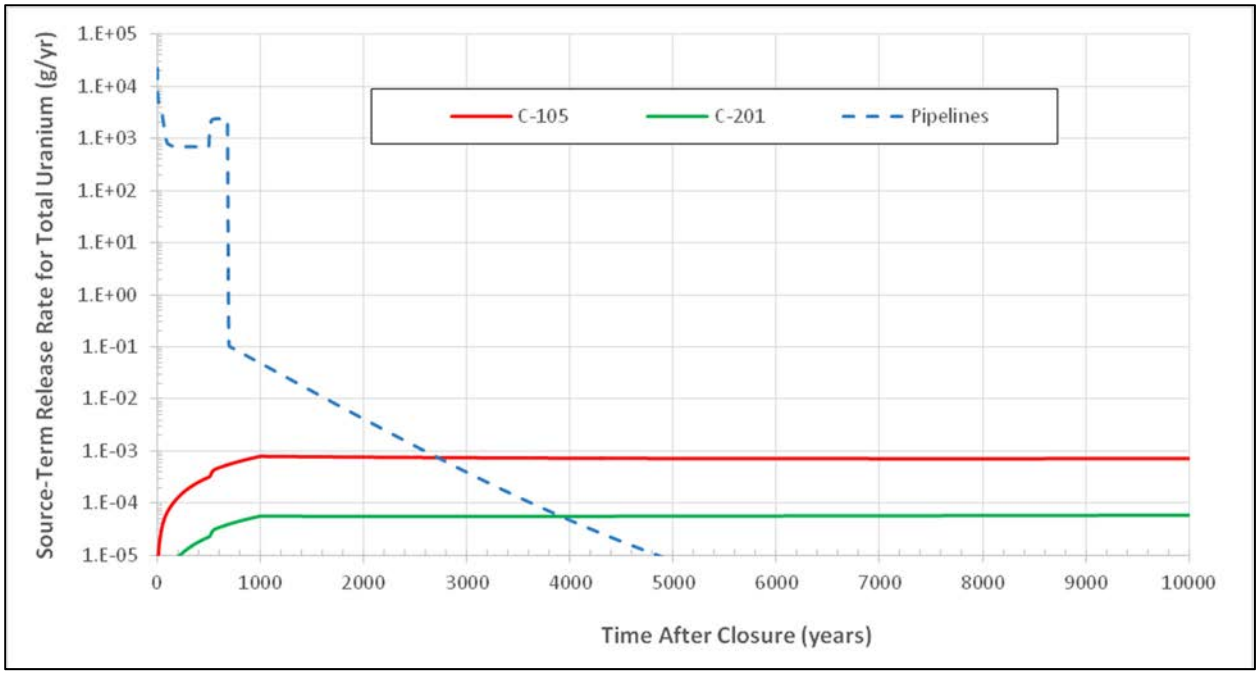
The atmospheric release is modeled for only those radionuclides that can partition into the gas phase from the dissolved phase (in water). These radionuclides are ^{14}C, ^{3}H (tritium), ^{129}I, and ^{222}Rn. The atmospheric release calculation methodology is described in Section 4.4 of RPP-RPT-58948, for WMA C sources, where the diffusive flux from the residual waste to the surface of the facility is calculated first. For the radionuclides that are included in the air pathway performance objective, an air transport calculation is performed to calculate the concentration at a receptor located 100 m downwind from the WMA C fenceline. The results of this calculation are presented in Figure 7-7 for ^{14}C, ^{3}H (tritium), and ^{129}I.[11]

The results in Figure 7-7 indicate that the atmospheric ^{3}H (tritium) release produces much higher concentrations than the other two at early times. The differences between the curves are attributable to differences in the K_d and Henry's Law behavior for the three contaminants. The release rate into the gas phase is dependent on both the K_d (which controls the partitioning between solid and liquid) and the Henry's Law constant (which controls the partitioning between liquid and vapor). The ^{3}H concentration declines sharply, both because of its short half-life and

[11] Radon-222 is not included in the air pathway performance objective. Instead, it has a separate criterion for flux from the facility surface.

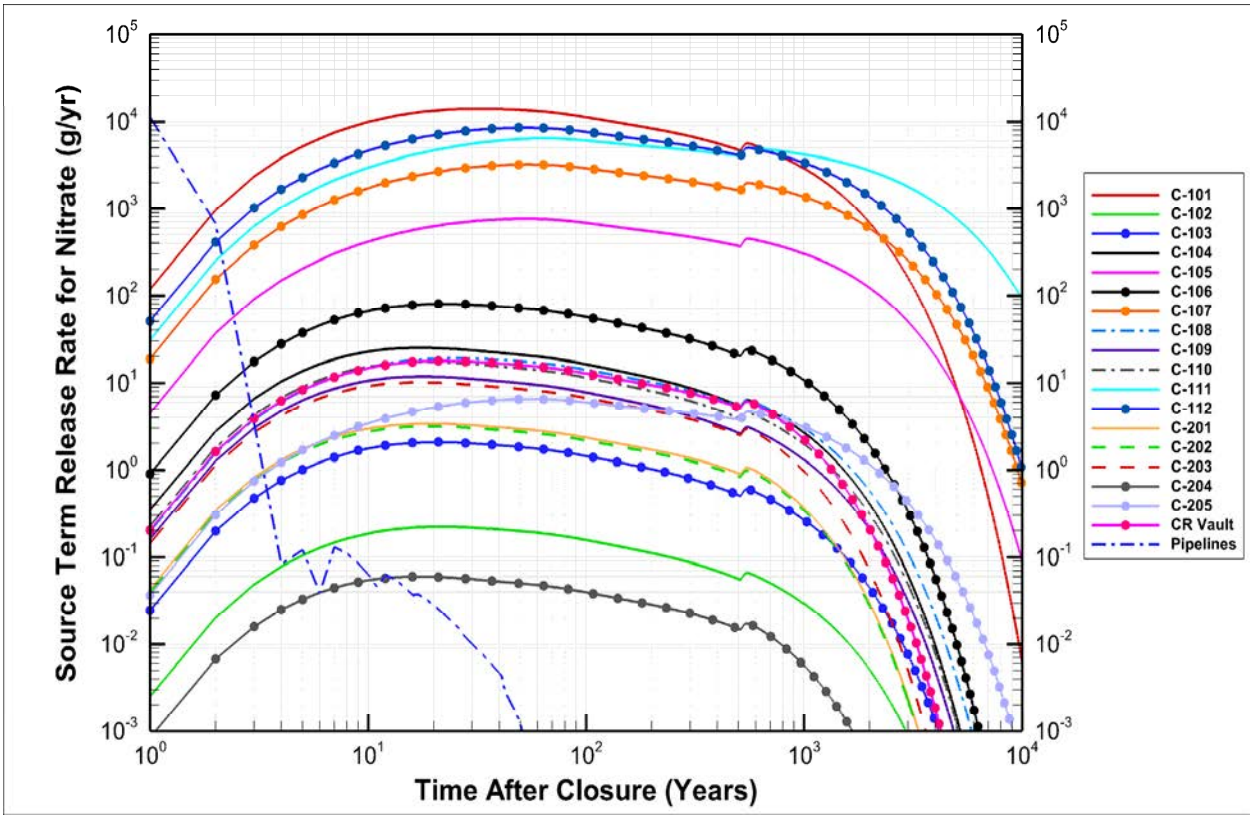
because the entire inventory is immediately available for release, having a low K_d and relatively high Henry's Law constant. By contrast, ^{129}I has a low K_d and a low Henry's Law constant (and a low inventory), so while its aqueous phase concentration is relatively high, it does not readily partition into the gas phase. The high K_d of ^{14}C keeps the aqueous concentration of ^{14}C low, limiting its availability to partition into the gas phase. The three contaminants therefore exhibit qualitatively different behavior because of the differences in their properties.

Figure 7-5. Release Rate of Total Uranium (g/yr) from Representative Sources.



The radon flux at the surface of the WMA C facility is calculated for each source separately. These sources are presented in Figure 7-8. The relative magnitude of the fluxes is the result of the initial residual inventory of ^{226}Ra and the amount of uranium inventory that decays to form ^{226}Ra and then to ^{222}Rn. The radon flux increases with time resulting from ingrowth due to decay of ^{234}U and ^{238}U inventory. The peak flux of 7×10^{-3} pCi/m^2/sec results from tank C-203 at the end of the simulation. This value is much lower than the 20 pCi/m^2/sec performance objective. The flux from other 200-series tanks and C-301 catch tank is also relatively high compared to the 100-series tanks. This is due to combination of high initial inventories of ^{234}U (and ^{238}U), smaller residual volume, and smaller cross-sectional area for the 200-series tanks and C-301 catch tank compared to the 100-series tanks and ancillary equipment resulting in higher concentration (and flux) of radon. For the analysis of radon flux, releases of contaminants from the residual waste are set to zero, so the inventory of ^{226}Ra is allowed to build up in the residual layer. This is a significant conservatism at long times, since uranium migrating downward through the groundwater pathway would decrease the later peaks. Despite this conservatism, even at 10,000 years the peak radon flux is several orders of magnitude below the performance objective. Tank C-106 contains little uranium, and as expected, ^{222}Rn flux decreases as the ^{226}Ra inventory is depleted through decay (Figure 7-8). The peak radon flux for the 1,000-year compliance period is about 2×10^{-4} pCi/m^2/s.

Figure 7-6. Release Rate of Nitrate (g/yr) from Each Source.



7.4 DOSE CALCULATION

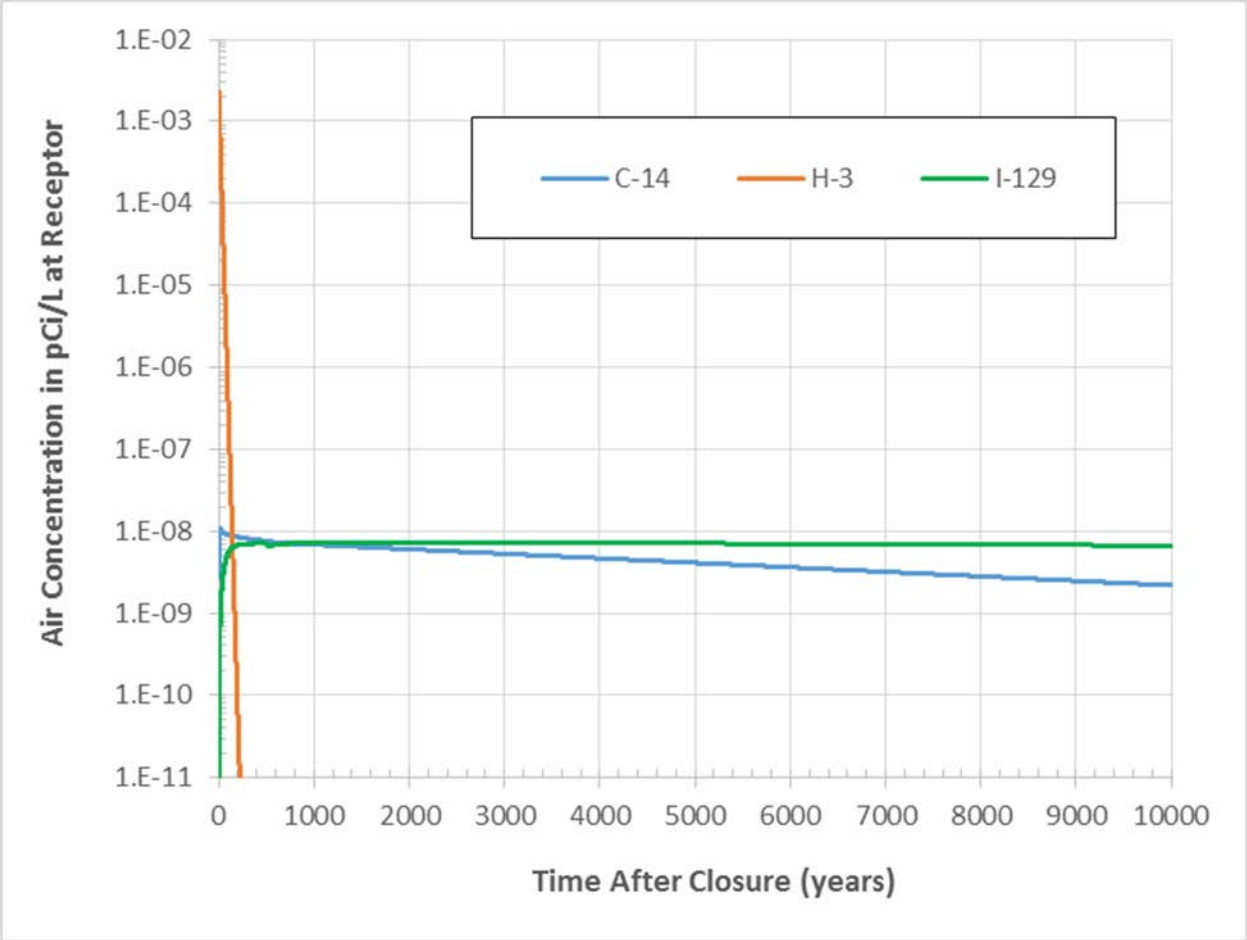
7.4.1 Groundwater Pathway Dose

Doses associated with the groundwater pathway are presented in Figure 7-9 for each PoC 100 m downgradient of the facility fenceline as defined in RPP-RPT-58949. Consistent with the groundwater protection concentration calculations, the peak dose in space is found at PoC 4. Consequently, PoC 4 is used as the compliance point for the PA all-pathways analysis.

7.4.2 Air Pathway Dose

Doses from radionuclides that may potentially be released in gaseous form are presented in Figure 7-10 along with the 10 mrem/yr air pathway dose performance objective from DOE O 435.1. Doses are very small, orders of magnitude below the dose performance objective, at all times. The peak dose of 2×10^{-3} mrem/yr occurs at very early time with ^{3}H being the primary dose contributor. Around 100 years, ^{129}I takes over as the primary dose contributor as ^{3}H dose declines due to its short half-life. Iodine-129 persists within the tank due to its long half-life and retention in the grout (from sorption), leading to a slow continuous diffusive flux. By about 500 years, the ^{129}I dose reaches a steady value, indicating that the concentration gradient in the air phase from the tank to the surface has reached a steady state.

Figure 7-7. Air Concentration for Volatiles at Receptor Location in pCi/L.

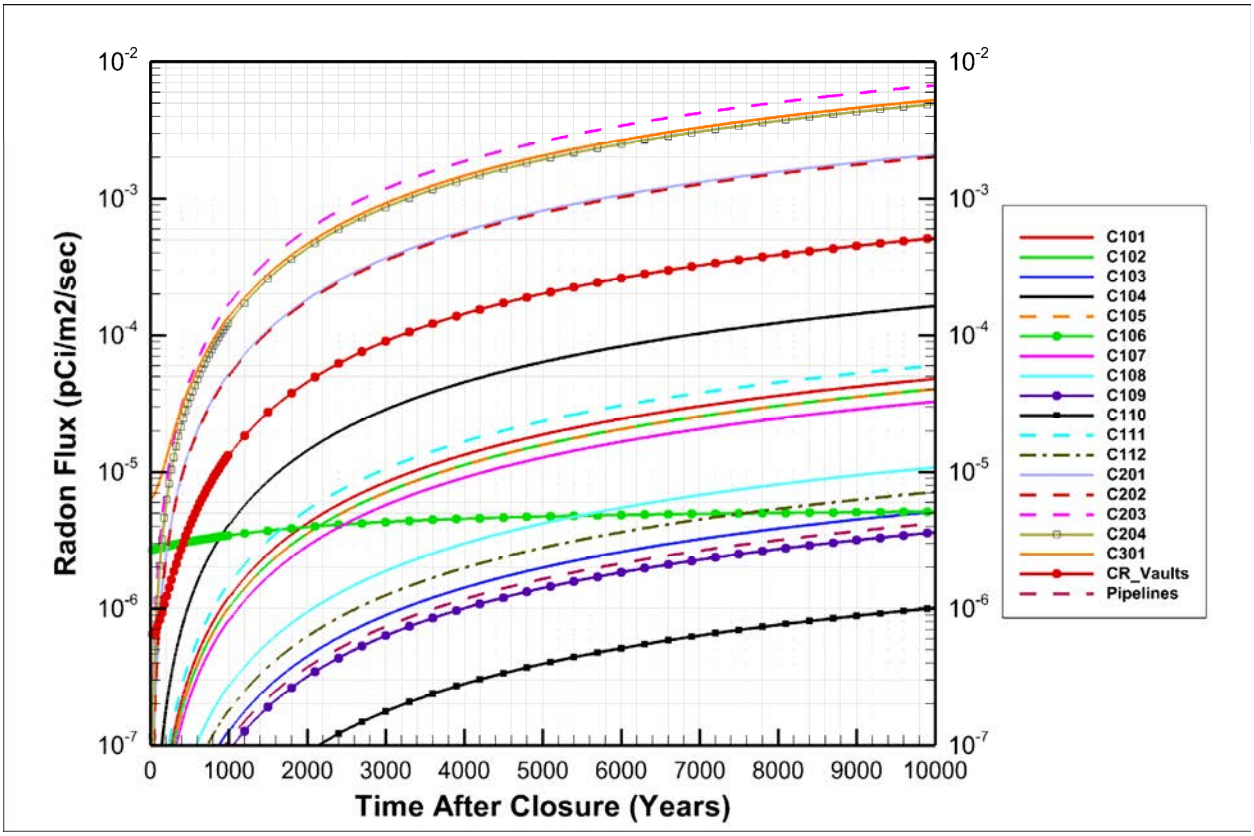


7.4.3 All-Pathway Dose

The all-pathways dose is a combination of dose from the groundwater pathway and air pathway. The receptor is considered to be a reasonably maximally-exposed individual and assumed to be located along the centerline of the air pathway plume and getting water from the well located at the highest concentration point in the aquifer at the 100 m boundary downgradient of the facility fenceline.

The all-pathway dose results for the groundwater (PoC 4) and the air pathway are presented in Figure 7-11 for all radionuclides that produced a nonzero dose result within 10,000 years. Also shown on the figure are the DOE O 435.1 compliance time and compliance dose, for comparison. The peak dose summed over all radionuclides within the compliance time period is 2×10^{-3} mrem/yr, primarily from ^{3}H release. Within the compliance time period, the early dose is due to contribution of ^{3}H and ^{129}I from the air pathway but after about 800 years the dose is dominated by ^{99}Tc contribution from the groundwater pathway. Within the sensitivity/uncertainty analysis time period (1,000 to 10,000 years), the peak dose summed over all radionuclides is 0.10 mrem/yr, which occurs about 1,500 years after closure.

Figure 7-8. Radon Flux at Surface of Waste Management Area C.



7.5 INTRUDER ANALYSIS RESULTS

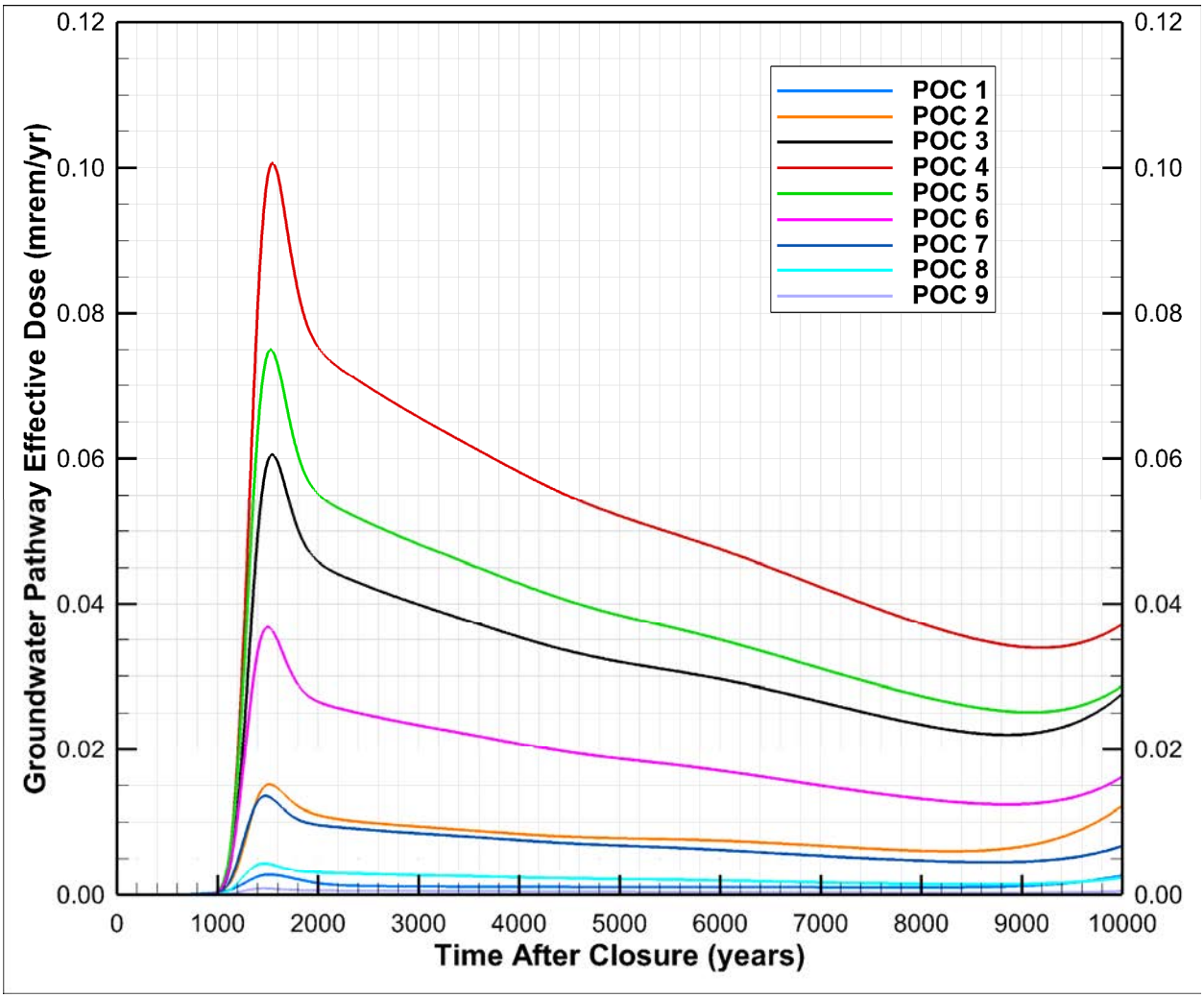
This section presents the calculated effective dose for each of the four inadvertent intruder scenarios. Graphic displays show the effective dose starting 100 years after closure for the sources that produce significant intruder dose. Over the compliance time period (1,000 years after closure), the relative contribution of radionuclides vary, but the total dose decreases, with highest dose being at 100 years. Table 7-1 summarizes the calculated effective doses for each intruder scenario, assuming intrusion at 100 years and 500 years for all of the 19 waste sources. Among the 19 sources, tank C-111 produced maximum intruder dose for all intruder scenarios.

7.5.1 Acute Exposure Dose

Figure 7-12 shows the calculated acute dose to the well driller, assuming the intrusion takes place 100 years or beyond for pipelines and 500 years or beyond for sources with substantial intrusion barriers. Among the 19 residual waste sources, the sources with the top six intruder doses are displayed in the figure. For all sources, the dose remains below the 500 mrem performance measure. Figure 7-13(a) shows the total well driller dose produced by tank C-301 residual waste source along with major dose-contributing radionuclides, while Figure 7-13(b) shows the results for the intruded pipeline source. The major contributor to dose to the well

driller is ^{239}Pu for both sources, although ^{137}Cs is an important contributor to intrusion into pipelines at early times. The major pathway for well driller dose is external exposure.

Figure 7-9. Groundwater Pathway Dose (mrem/yr) as a Function of Time for All Points of Calculation at the 100 Meters Compliance Distance.



POC = point of calculation

7.5.2 Chronic Exposure Dose

Figure 7-14 shows the calculated dose for the rural pasture scenario for the top six residual waste sources. All remain below the 100 mrem/yr performance measure throughout the simulated time period. Figure 7-15(a) shows the total rural pasture dose produced by intrusion into tank C-301 along with major dose-contributing radionuclides, while Figure 7-15(b) shows the results for intrusion into a pipeline. Strontium-90 is the major contributor to pipelines up until almost 500 years after closure, with major pathways being milk ingestion. Cesium-137 through the milk ingestion pathway is also a major contributor to dose at early time period. Plutonium-239 becomes the major contributor for both pipelines and tank residuals after 500 years following closure.

Figure 7-10. Results of the Air Pathway Dose Analysis. Note the logarithmic vertical and horizontal axis.

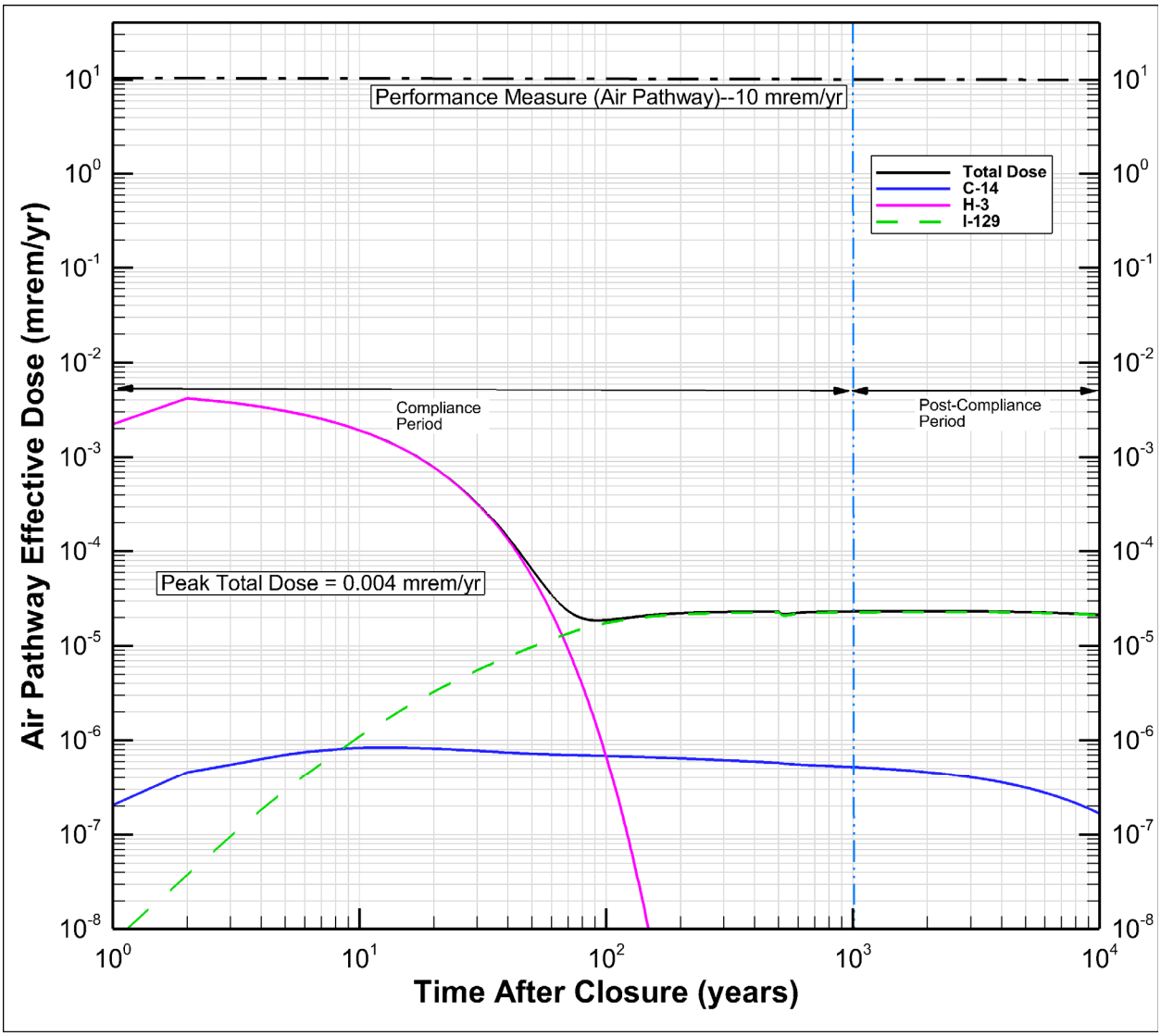
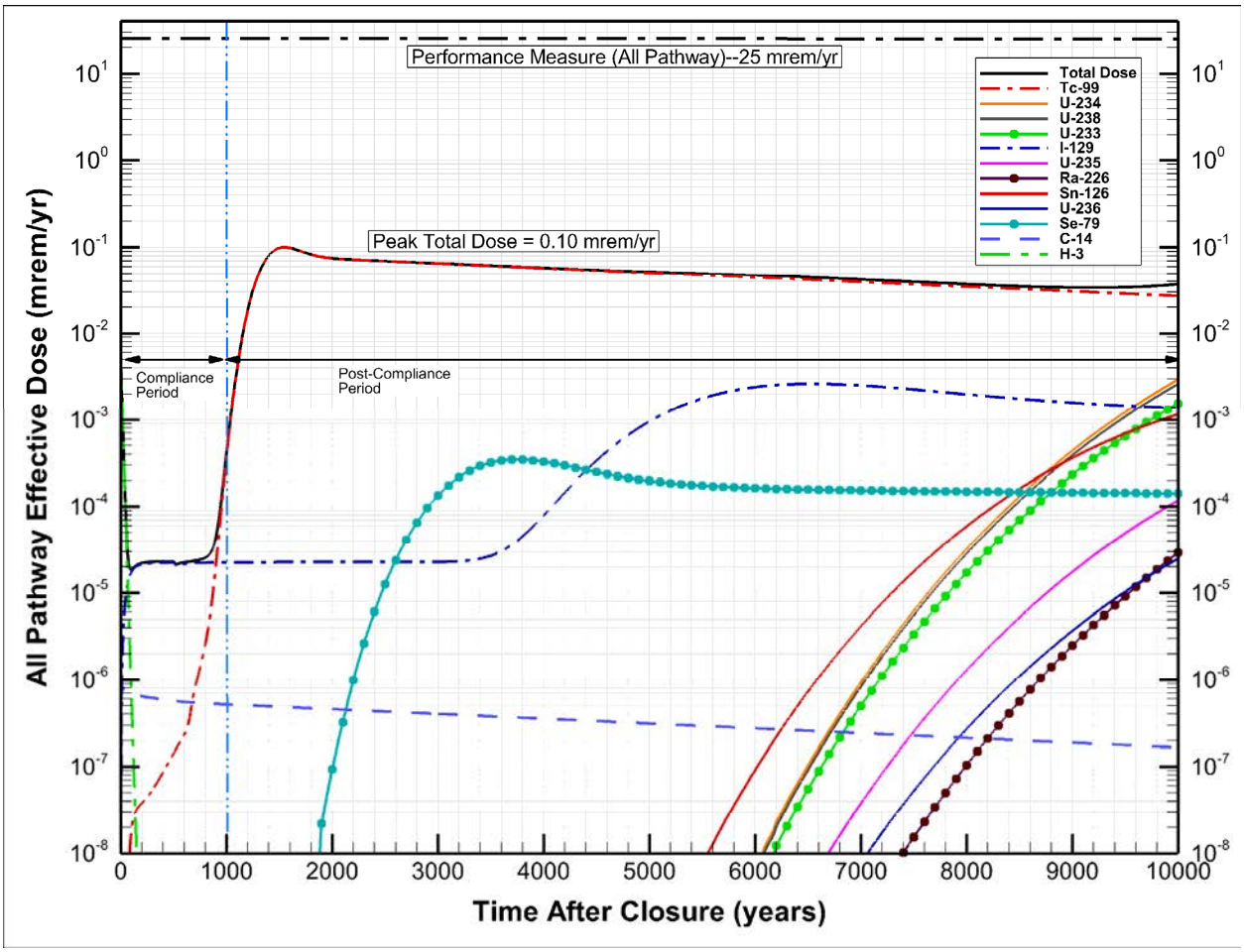


Figure 7-16 shows the calculated dose for the suburban garden scenario for the top six residual waste sources. All doses remain below the 100 mrem/yr performance measure throughout the compliance time period. Figure 7-17(a) shows the total suburban garden dose produced by intrusion into tank C-301 along with major dose-contributing radionuclides, while Figure 7-17(b) shows the results for intruded pipeline source. Strontium-90 is the major contributor up until about 300 years after closure (for intrusion into a pipeline source), with major pathways being vegetable ingestion. Cesium-137 through the vegetable ingestion pathway is also a major contributor to dose at early times. Plutonium-239 becomes the major contributor after 500 years for both pipelines and tank residuals.

Figure 7-18 shows the calculated dose for the commercial farm scenario for the top six residual waste sources. The dose from all residual waste sources remains below the 100 mrem/yr

performance measure throughout the simulated time period. Figure 7-19(a) shows the total commercial farm dose produced by intrusion into tank C-301 along with major dose-contributing radionuclides, while Figure 7-19(b) shows the results for intrusion into pipeline source. For intrusion into a pipeline source, ^{137}Cs and ^{90}Sr are the major contributor up until almost 300 years after, with major pathways being external exposure. Plutonium-239 and ^{241}Am become the major contributor to both pipelines and tank residuals after 500 years.

Figure 7-11. All-Pathways Dose Results that Includes Air and Groundwater Pathway Contributions at the Maximum Point of Concentration. The DOE O 435.1 compliance time (1,000 years) is shown as a vertical blue dashed line, and the compliance dose (25 mrem/yr) is shown as the black horizontal dashed line. Note the logarithmic vertical axis.



Reference: DOE O 435.1, Radioactive Waste Management.

Figure 7-20(a-b) shows the total dose produced by intrusion into tank C-301 and a pipeline residual waste source for all three chronic scenarios. For about the first 300 years after closure (for intrusion into a pipeline source), the rural pasture scenario produces higher dose than the other chronic scenarios; after that time the suburban garden dose is highest among all of the chronic scenarios. Within the first 300 years for intrusion into a pipeline after closure, the milk ingestion dose (dominant pathway in rural pasture scenario) from ^{90}Sr is higher than the

vegetable ingestion dose (dominant pathway in suburban garden scenario). After that, the total vegetable ingestion dose from ^{90}Sr, ^{241}Am and ^{239}Pu exceeds the total milk ingestion dose from ^{90}Sr, ^{241}Am and ^{239}Pu. So, if intrusion occurs at 100 years after closure, the rural pasture scenario will produce the highest chronic dose.

Table 7-1. Peak Effective Dose for the Inadvertent Intruder Scenarios for All Residual Waste Sources.

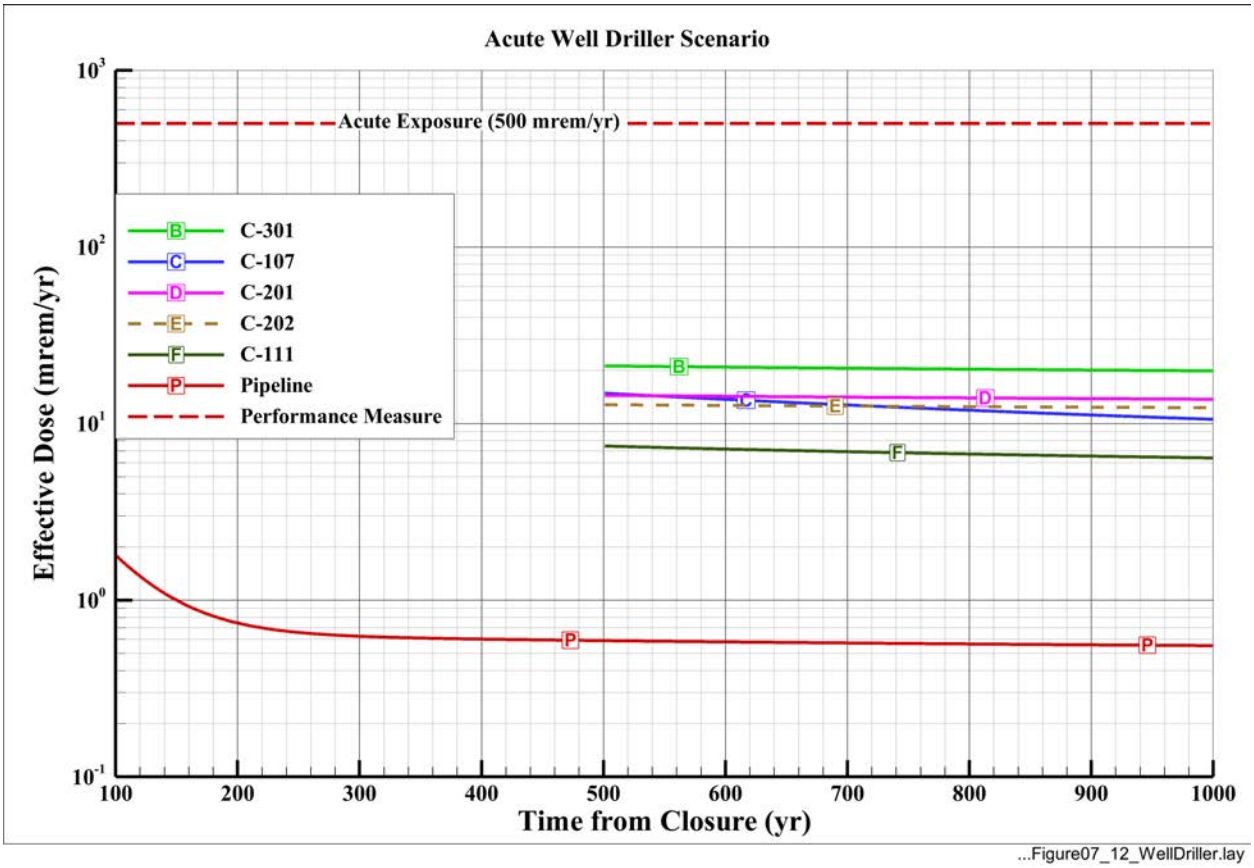
Source	Well Driller Acute Dose (mrem)	Commercial Farm Chronic Dose (mrem/yr)	Rural Pasture Chronic Dose (mrem/yr)	Suburban Garden Chronic Dose (mrem/yr)
241-C-101	1.24E+00	2.17E-03	1.44E-01	3.22E-01
241-C-102	4.59E+00	8.09E-03	5.37E-01	1.20E+00
241-C-103	4.09E-01	7.25E-04	6.14E-02	1.10E-01
241-C-104	5.77E-01	1.10E-03	1.21E-01	1.70E-01
241-C-105	3.80E+00	6.69E-03	7.18E-01	1.23E+00
241-C-106	3.47E+00	8.75E-03	8.93E-01	9.57E-01
241-C-107	1.49E+01	2.66E-02	1.82E+00	3.90E+00
241-C-108	5.80E-02	1.05E-04	1.09E-02	1.71E-02
241-C-109	3.10E-02	5.57E-05	7.63E-03	9.33E-03
241-C-110	8.24E-02	1.78E-04	1.99E-02	2.44E-02
241-C-111	7.47E+00	1.32E-02	1.40E+00	2.13E+00
241-C-112	3.48E-01	6.10E-04	9.17E-02	1.41E-01
241-C-201	1.45E+01	2.52E-02	1.58E+00	3.75E+00
241-C-202	1.28E+01	2.22E-02	1.39E+00	3.32E+00
241-C-203	4.61E-01	8.51E-04	7.25E-02	1.26E-01
241-C-204	5.60E-02	1.77E-04	2.97E-02	2.49E-02
241-C-301	2.12E+01	**3.86E-02**	2.69E+00	**5.57E+00**
CR-VAULT	3.91E+00	7.10E-03	4.96E-01	1.03E+00
Pipeline*	**1.8E-00**	1.13E-03	**8.21E+00**	3.92E+00

Note: Peak dose calculated at 500 years for all sources except for pipeline, which is reported at 100 years after closure.

*Maximum dose at 100 years after closure.

The peak dose for each scenario is shown in **bold**.

Figure 7-12. Effective Dose for the Well Driller Acute Exposure Scenario.



7.5.3 Inadvertent Intruder Analysis

The key parameter in the intruder analysis is concentration in the residual wastes. Calculated doses are linear with the activity of waste exhumed in the intrusion event. For example, the limiting inadvertent intruder scenario is the rural pasture scenario, as it leads to the highest dose at 100 years. The major dose contributors in this scenario are ^{90}Sr and ^{137}Cs. Decreasing the closure inventory (or concentration) of those two nuclides would result in a proportional decrease in the rural pasture dose.

Sensitivities of other key parameters depend on which exposure pathways are the most important dose contributors. The relative importance of various pathways is presented for each scenario in Table 7-2 for pipeline (most likely source for intrusion) at 100 years after closure. It provides insight into the group of parameters that will have the greatest impact on the dose, and therefore the uncertainty in dose would be most impacted by the uncertainty in those parameter values. The relative contribution to the overall dose by a given pathway is provided. Based on the results presented in Table 7-2, the parameters associated with external exposure pathway are deemed to be most important for well driller and commercial farm scenarios, parameters associated with milk ingestion pathway are most important for rural pasture scenario, and for suburban garden scenario the parameters associated with vegetable ingestion pathway are most important.

Figure 7-13. Effective Dose for the Well Driller Acute Exposure Scenario for (a) Tank 241-C-301 and (b) Pipeline Residual Waste.

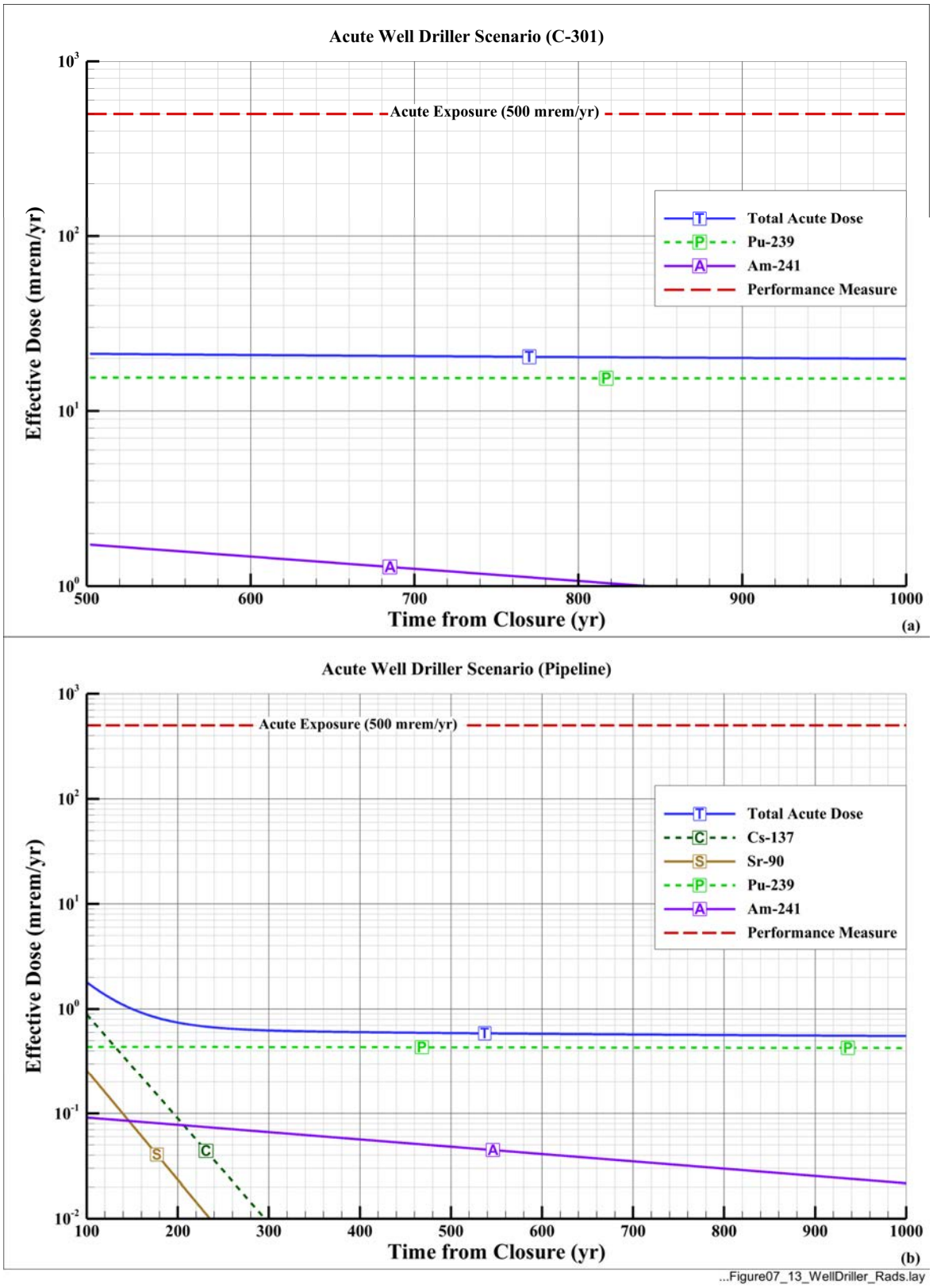
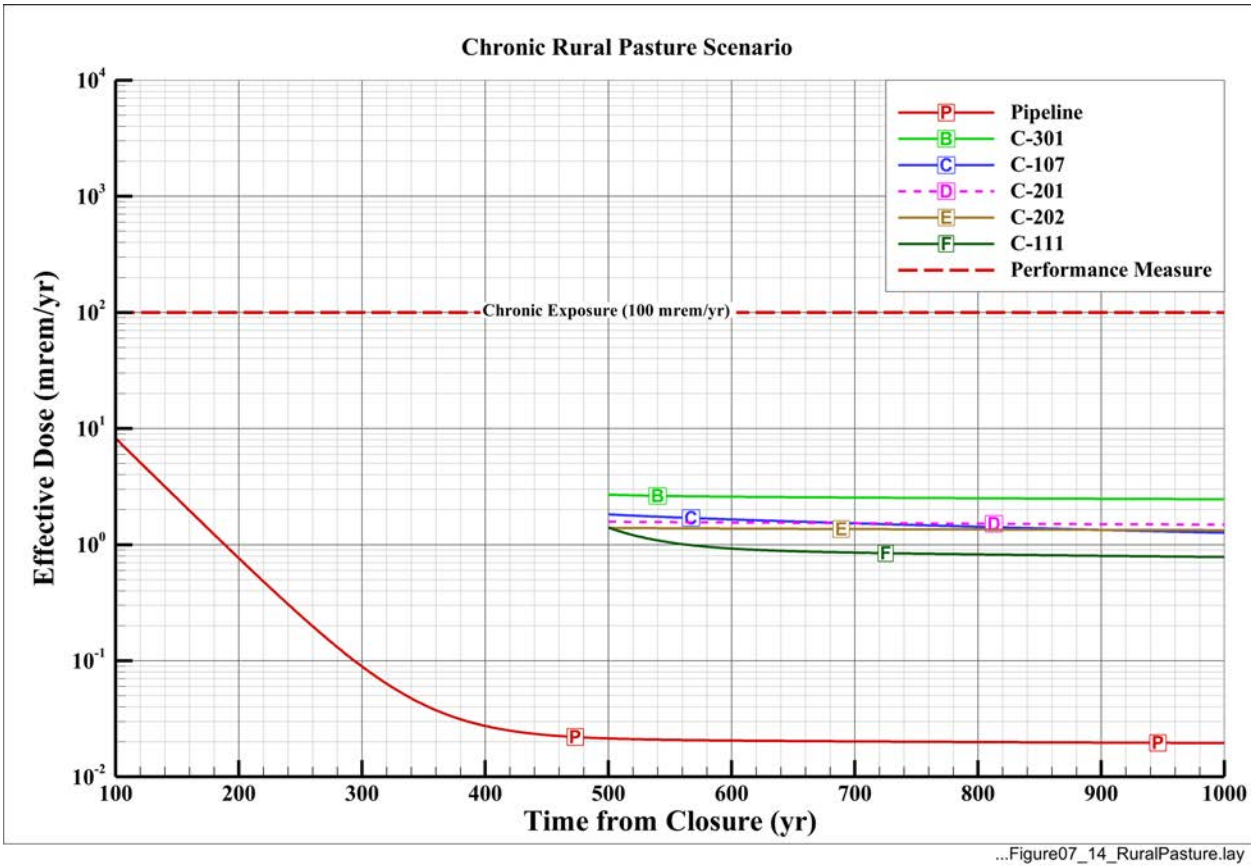


Figure 7-14. Effective Dose for the Rural Pasture Chronic Exposure Scenario.



A sensitivity analysis is performed to evaluate the impact of intrusion through an assumed fully plugged cascade pipeline. The cascade pipelines only occupy about 2% of the total pipeline length within WMA C. Performing intrusion calculation through the fully plugged cascade line will provide the bounding dose estimate for intrusion into a pipeline source. The calculations are performed in the same manner as discussed earlier for a pipeline source except that the cascade pipeline is assumed to be completely full (instead of 5% full for a waste transfer pipeline). The results of the three chronic scenarios are presented in Figure 7-21. Only the dose from the rural pasture scenario exceeds the performance measure at 100 years (about 160 mrem/yr) but quickly drops below within 20 years due to decay of ^{90}Sr. When compared to the dose estimates presented in Figure 7-20(b) for the transfer pipeline, the cascade pipeline dose values are a factor of 20 higher, indicating that the dose scales linearly with the waste volume assumption. The acute scenario dose for the cascade pipeline remains the same as that for the transfer pipeline (Figure 7-13b) as the calculation depends on the concentration of the residual waste, which is assumed to be the same.

Figure 7-15. Effective Dose for the Rural Pasture Chronic Exposure Scenario for (a) Tank 241-C-301 and (b) Pipeline Residual Waste.

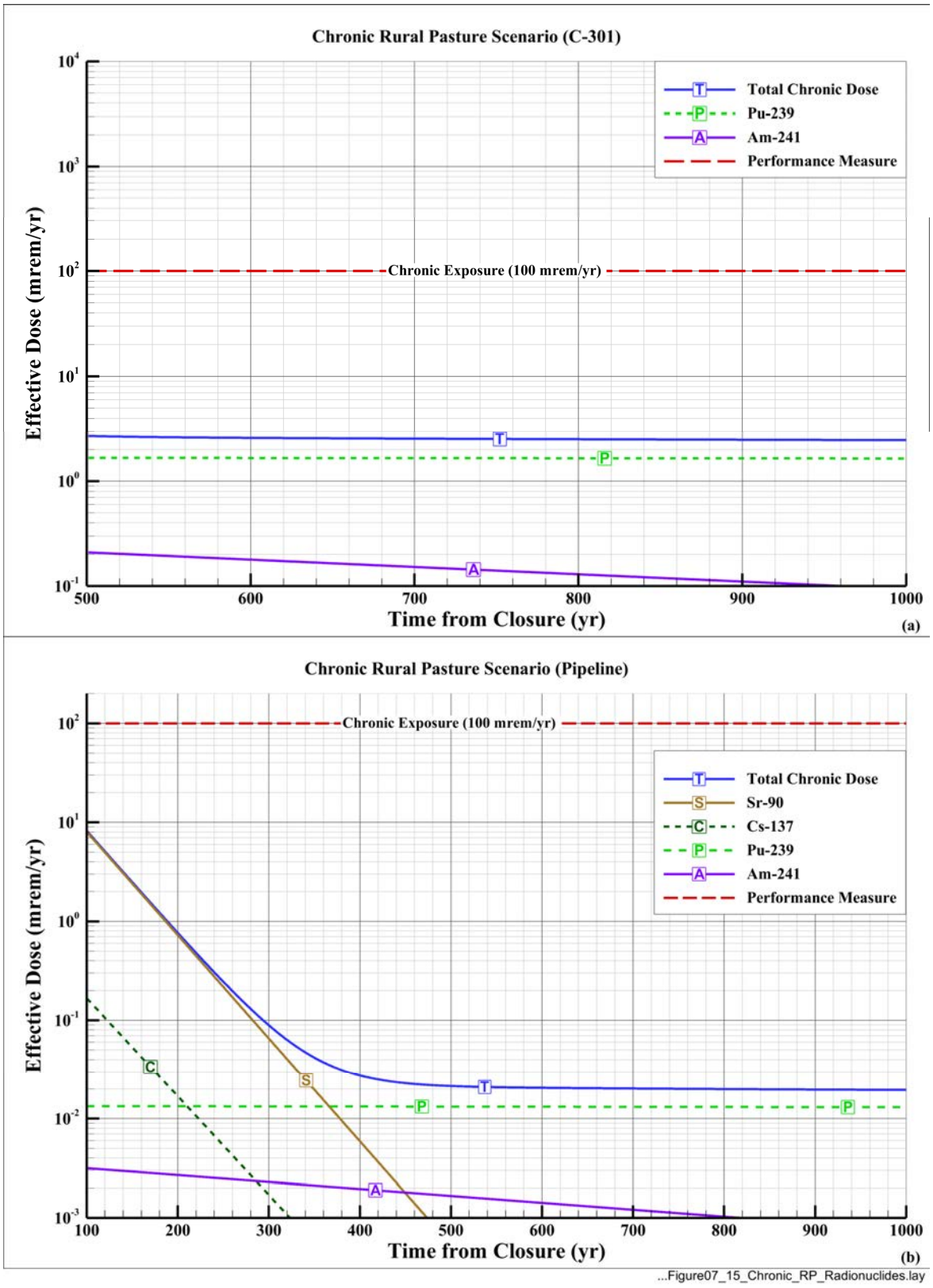
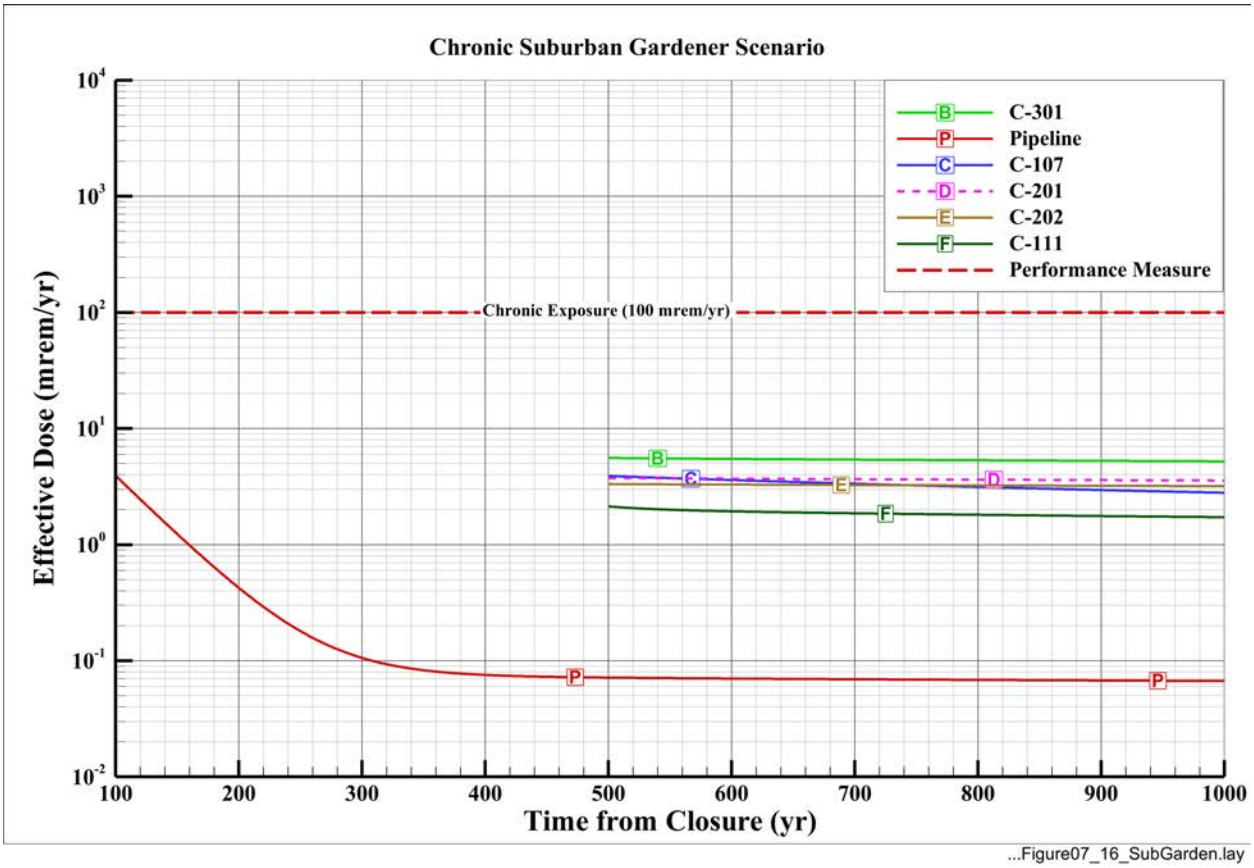


Figure 7-16. Effective Dose for the Suburban Garden Chronic Exposure Scenario.



7.6 UNCERTAINTY ANALYSIS RESULT

A full uncertainty analysis is undertaken by performing multi-realization simulations in the probabilistic mode using the GoldSim©-based system model. The GoldSim©-based system model is exercised by running 300 realizations. The results are presented in Figure 7-22 in terms of mean of total dose (from all radionuclides from the groundwater and atmospheric transport pathways) along with the mean dose contribution of individual radionuclides. The early dose (from 100 to 600 years) primarily results from the release of ^{3}H (tritium) and ^{129}I to the air pathway, and the late dose (past 1,000 years) results primarily from the ^{99}Tc release to the groundwater pathway. The mean dose reaches a peak value of about 0.17 mrem/yr around 3,400 years (post-closure time) and then declines gradually. Although the contribution of ^{99}Tc steadily declines, the mean total dose remains virtually unchanged beyond 7,000 years until the end of the analysis time. This is because of increasing dose contributions from uranium isotopes (primarily, ^{234}U, ^{238}U, and ^{233}U) that have relatively long half-lives and are relatively mobile (low K_d value).

Figure 7-17. Effective Dose for the Suburban Garden Chronic Exposure Scenario for (a) Tank 241-C-301 and (b) Pipeline Residual Waste.

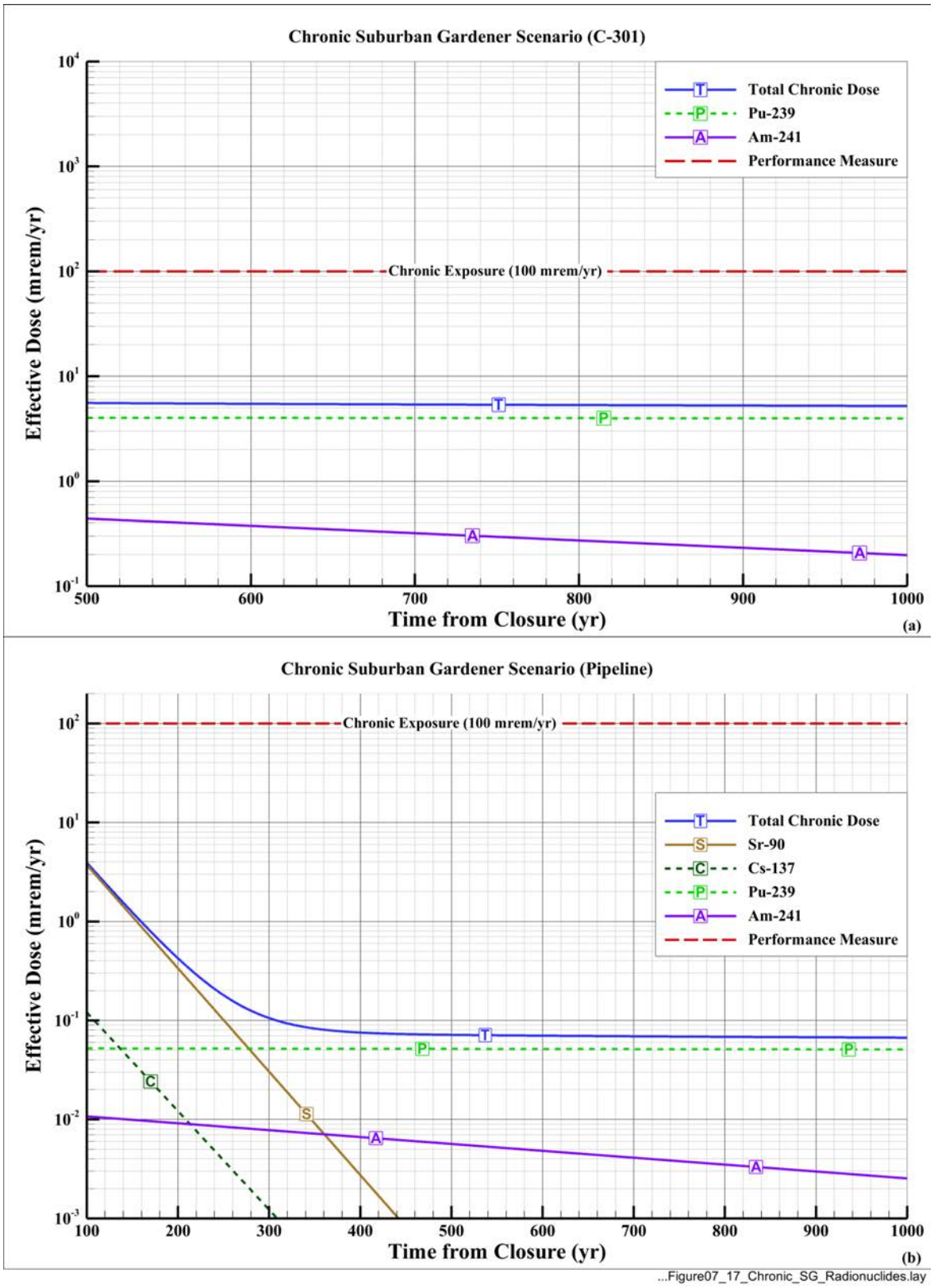
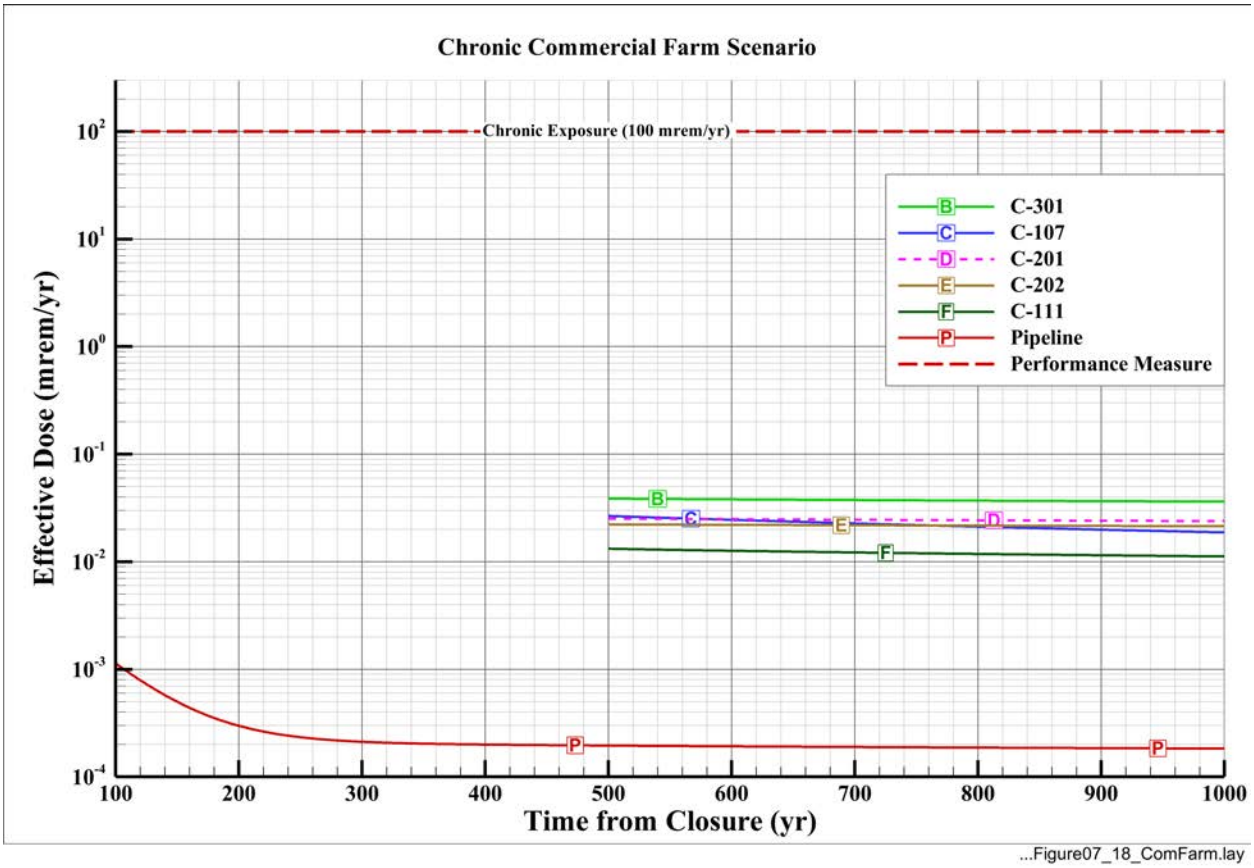


Figure 7-18. Effective Dose for the Commercial Farm Chronic Exposure Scenario.



Besides ^{99}Tc and uranium isotopes, other radionuclides of interest are ^{129}I, ^{226}Ra, ^{126}Sn, and ^{79}Se. The dose contribution of ^{129}I in the first 1,000 years is primarily from the atmospheric pathway, and beyond that primarily from the groundwater pathway. The ^{226}Ra dose results from an assumption that it is in secular equilibrium with the uranium decay series, and therefore—although it has a high K_d by itself—it appears at the 100m downgradient location (PoC). Tin-126 and ^{79}Se are relatively mobile (low K_d) and have relatively long half-lives (>200,000 years), and therefore show breakthrough at PoC within the simulated time period.

7.6.1 Evaluation of Uncertainty in Groundwater Pathway

Figure 7-23 shows the results of propagating parameter uncertainties in the groundwater pathway dose for 300 realizations, along with the mean, median, 5th, and 95th percentile values. The highest mean and median doses occur around 3,400 years. For all realizations, ^{99}Tc is the primary dose contributor, and thus the uncertainty in groundwater pathway dose is almost entirely due to uncertainty in ^{99}Tc dose. The mean of the total dose is higher than the median of the total dose and closer to the 75th percentile curve. This occurs because the values range over several orders of magnitude, so that an arithmetic mean will tend to be skewed to the higher values. The variance in dose, defined by the difference in 5th and 95th percentiles at a given time slice, is observed to decrease after 4,000 years. This is due to occurrence of larger number of realizations having relatively similar breakthrough curves. Prior to this time, some realizations

that have earlier ^{99}Tc breakthrough show a decline due to the variability in flow fields, leading to increased variance. At late time also (>7,000 years), the variance in dose increases marginally. This results from the increasing importance of uranium isotopes at late times.

To understand the relative influence of uncertain parameters on the peak dose resulting from the groundwater pathway, two realizations (Rlz#142 and Rlz# 295) were chosen that lead to the highest dose values (Figure 7-24).

In Rlz# 142, the peak dose value is about 2.5 mrem/yr, and it occurs around 2,400 years. This high dose value results from a combination of sampling the Darcy flux multiplier (0.33) near the low end of the uncertainty distribution and sampling the residual waste instantaneous ^{99}Tc release fraction (0.149) from the upper end of the distribution. In addition, the saturated zone dispersivity (2.3 m) is sampled at the lower end of the distribution. The high instantaneous release fraction leads to larger diffusive flux from the base of the tanks, and the lower Darcy flux multiplier leads to less dilution in the saturated zone leading to increased concentration in the aquifer. In addition, sampling lower dispersivity in the saturated zone leads to less dispersion and higher peak concentration that results in high dose.

In Rlz# 295, the peak dose value is about 1.8 mrem/yr and it occurs around 5,000 years. Unlike Rlz# 142, where the peak occurs quickly followed by steep decline, the dose curve in Rlz# 295 shows a gradual rise and a more gradual decline. This behavior results from a combination of sampling the Darcy flux multiplier (0.19) near the minimum value of the uncertainty distribution and sampling the ^{99}Tc inventory multiplier (1.36) from the upper end of the uncertainty distribution. This combination leads to increased residual inventory being available, along with lowest possible dilution in the saturated zone resulting in greater peak concentration. In this realization, the 25th percentile flow field is sampled that leads to lower pore water velocity in the vadose zone, and therefore the mass continues to arrive from the source term over a longer time period. This combination leads to gradual rise and gradual decline in the dose curve.

Some of the realizations presented in Figure 7-24 show a gradual rise late in time. This gradual increase is attributed to the increasing dose influence from uranium isotopes. Some of the realizations that show early peak dose result from sampling the 95th percentile flow field that leads to high pore-water velocity and earlier breakthrough.

Multivariate analyses were conducted to evaluate the importance of uncertain parameters on the groundwater pathway dose calculations. The analysis was conducted at the time of peak mean dose, which occurs about 3,400 years. The analysis was based on the ranks (rather than values) of the uncertain parameters. Two types of analyses were conducted: (a) the rank (Spearman) correlation coefficient and (b) the Importance Measure. Standardized rank regression coefficients and partial rank correlation coefficients were also computed, but they do not provide additional insight and are not discussed further. The total number of uncertain parameters that are implemented in the system model is 130.

Figure 7-19. Effective Dose for the Commercial Farm Chronic Exposure Scenario for (a) Tank 241-C-301 and (b) Pipeline Residual Waste.

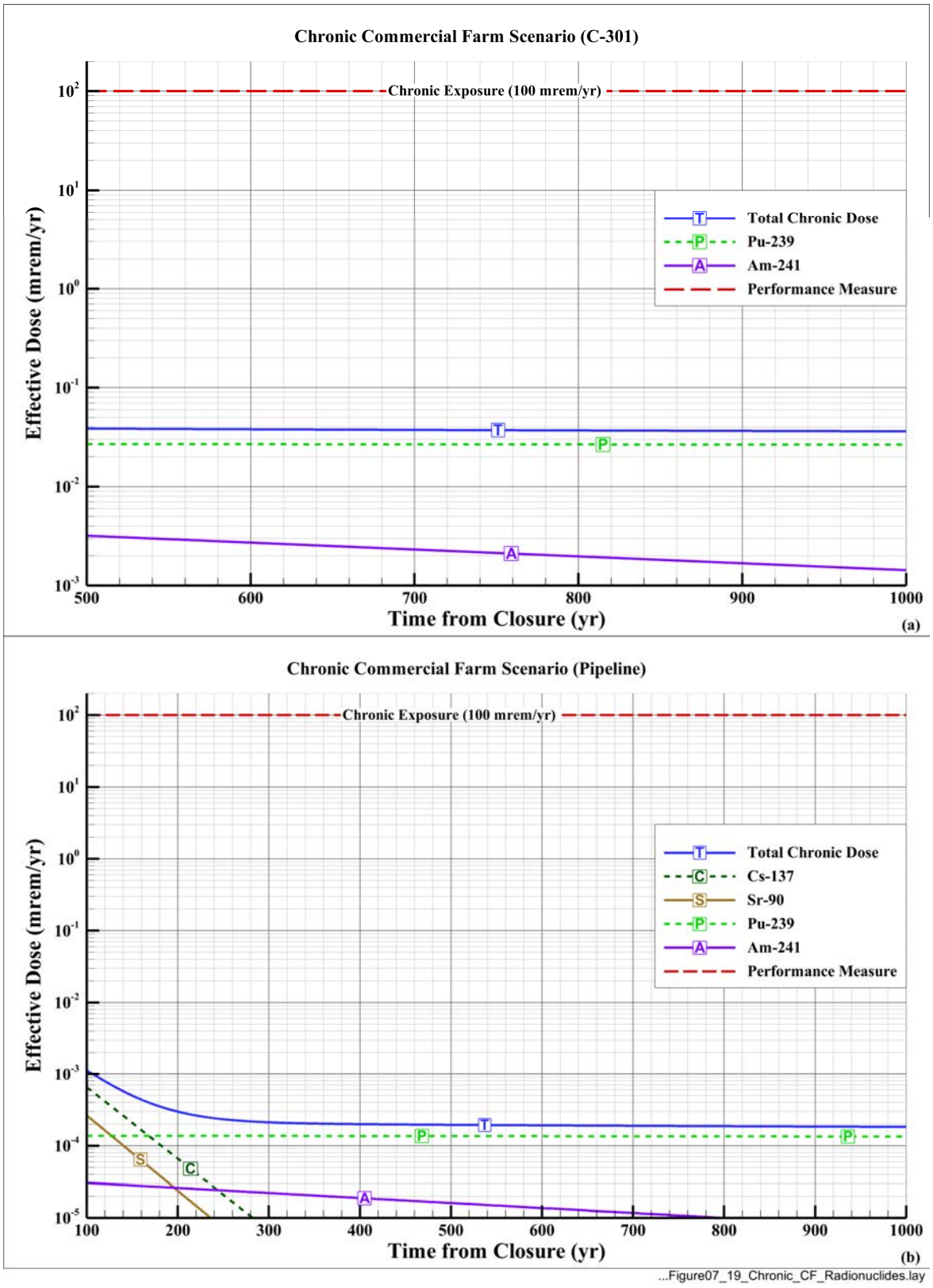


Figure 7-20. Effective Dose for All Three Chronic Exposure Scenarios for (a) Tank 241-C-301 and (b) Pipeline Residual Waste.

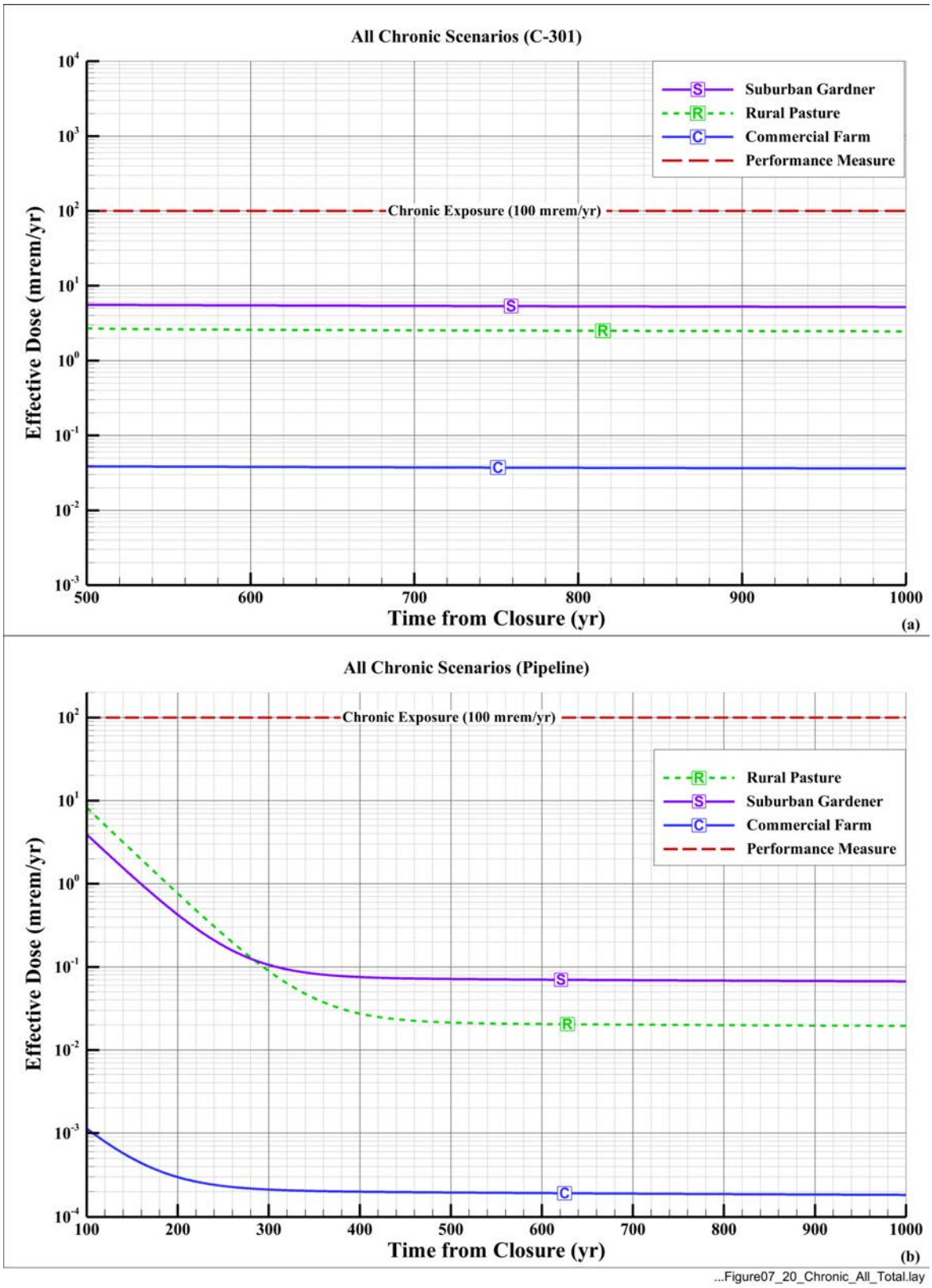


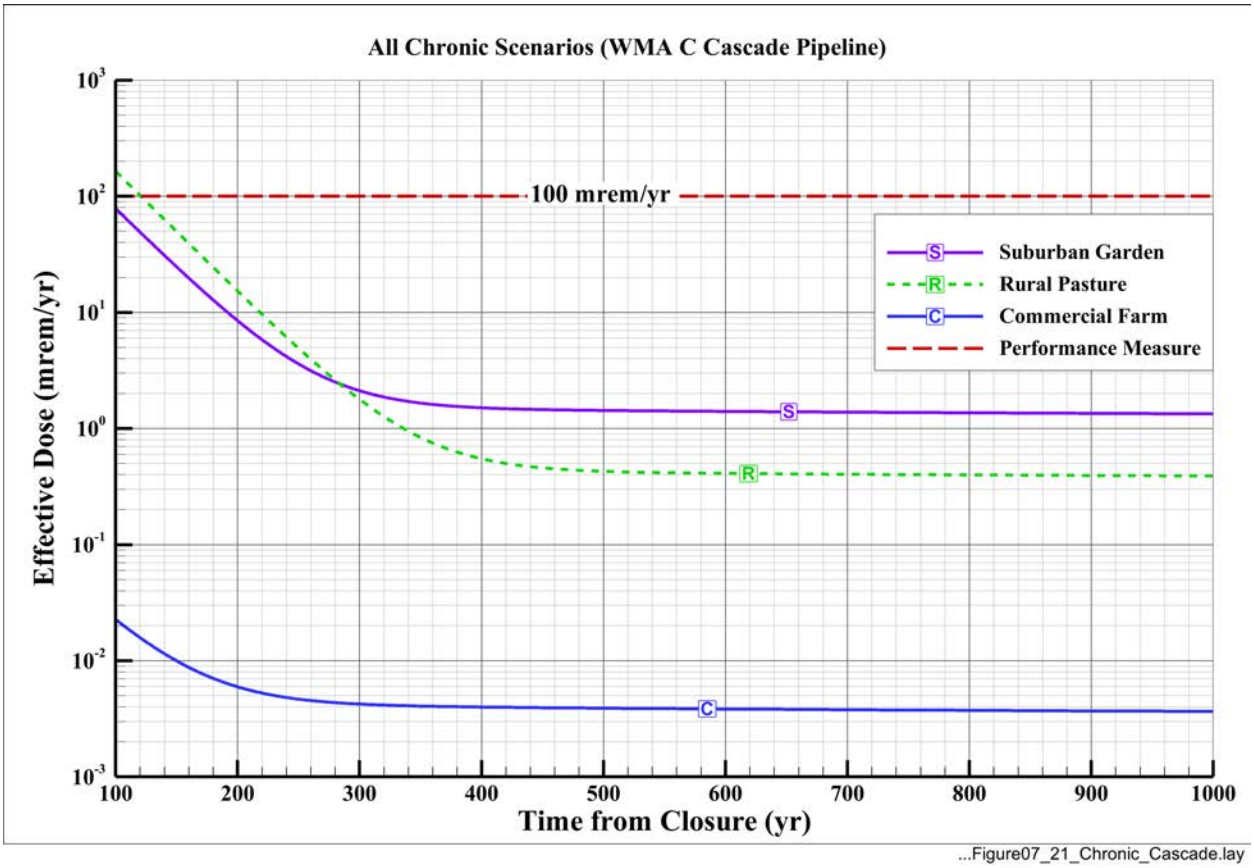
Table 7-2. Relative Fraction of Pathway Contributions to the Inadvertent Intruder Dose for Pipeline at 100 Years After Closure.

Scenario	Pathways				
	External Exposure	Soil Inhalation	Soil Ingestion	Milk Ingestion	Vegetable Ingestion
Well Driller	**0.59**	0.30	0.11	x	x
Rural Pasture	0.01	<0.01	<0.01	**0.98**	x
Suburban Garden	0.03	<0.01	<0.01	x	**0.96**
Commercial Farm	**0.69**	0.05	0.26	x	x

x = pathway not considered

Pathway contributing the most is highlighted for each scenario.

Figure 7-21. Effective Dose for All Three Chronic Exposure Scenarios for a Fully Plugged Cascade Pipeline.



The rank correlation coefficient expresses the extent to which there is a linear relationship between the selected result and an input variable. The coefficients range between -1 and 1 with

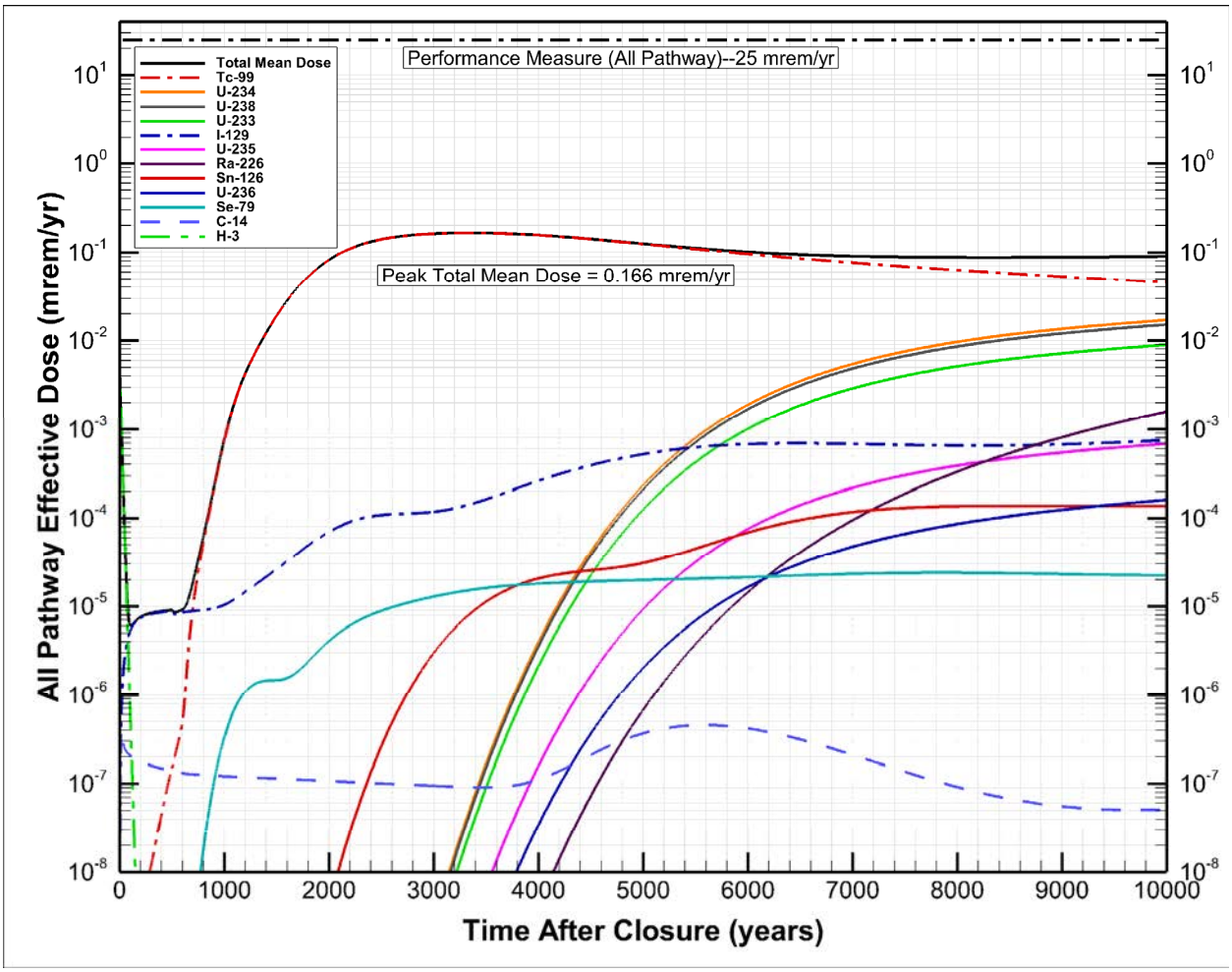
extreme values indicating strong negative or positive correlations. The calculation is performed using the following equation:

$$C_{rp,rank} = \frac{\sum_{i=1}^{n}(Rp_i - m_{Rp})(Rr_i - m_{Rr})}{\sqrt{\sum_{i=1}^{n}(Rp_i - m_{Rp})^2 \sum_{i=1}^{n}(Rr_i - m_{Rr})^2}} \quad (1)$$

Where:

$C_{rp,rank}$	=	the rank correlation coefficient
n	=	the number of selected data points (realizations)
Rp_i	=	the rank (from 1 to n) of output p for realization I
m_{Rp}	=	mean value of the rank of output p
m_{Rr}	=	mean value of the rank of output r.

Figure 7-22. All-Pathways Mean Dose Calculation Results Based on 300 Realizations.



The standardized rank regression coefficients and partial rank correlation coefficients also vary between -1 and 1. These calculations are based on the variable ranks rather than on the actual

values of the variables. The standardized rank regression coefficients provide a normalized measure of the linear relationship between variables and the result (dose). They are regression coefficients found when all of the variables and the results are transformed and expressed in terms of the number of standard deviations away from the mean. The partial correlation coefficients reflect the extent of the linear relationship between the selected result and an input variable, after removing the effects of any linear relationships between the other input variables and both the results and the input variable in question. Both formulations are based on NUREG/CR-4122, *A FORTRAN 77 Program and User's Guide for the Calculation of Partial Correlation and Standardized Regression Coefficients*.

Figure 7-23. Uncertainty in Groundwater Pathway Dose Based on 300 Realizations.

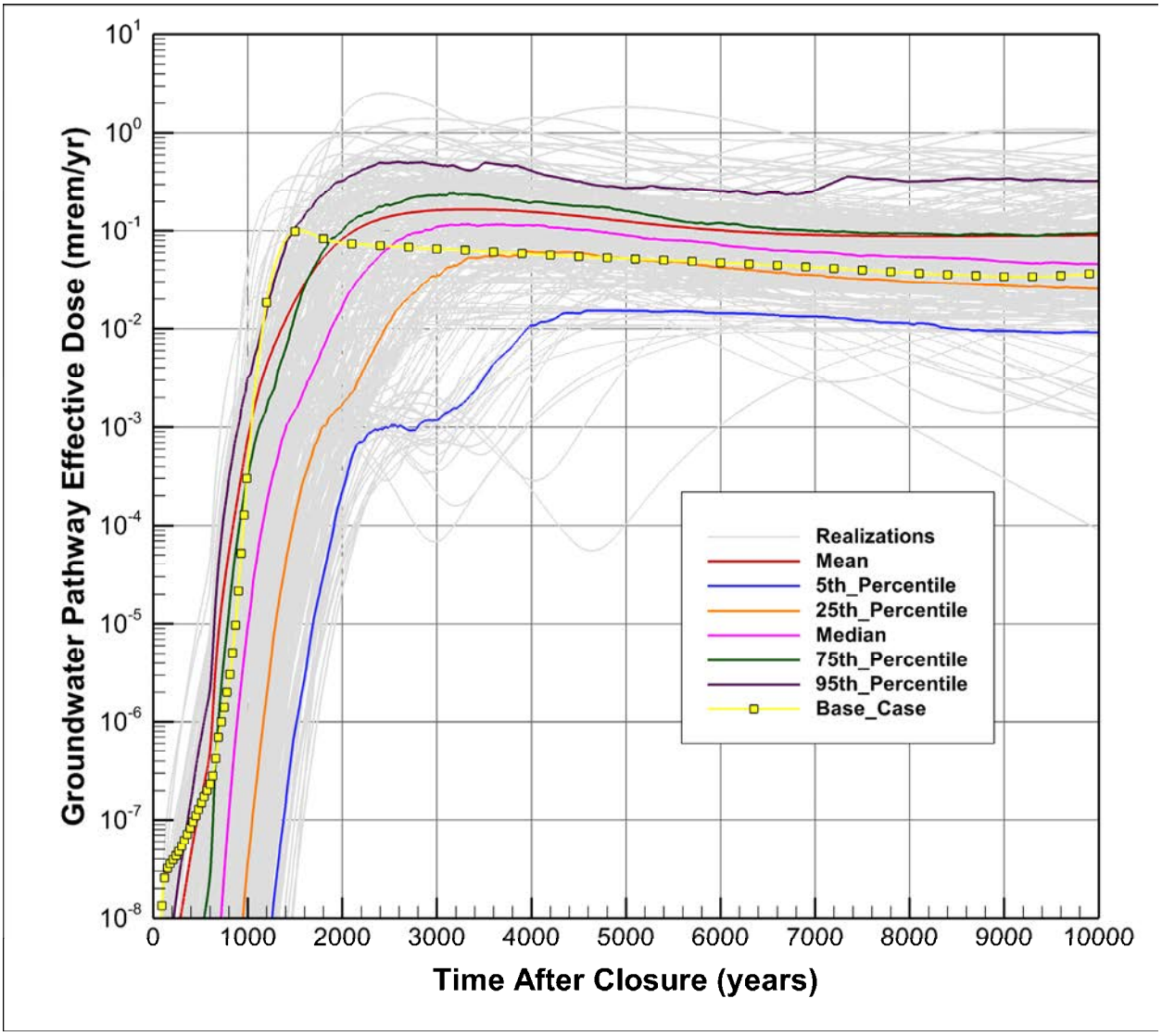
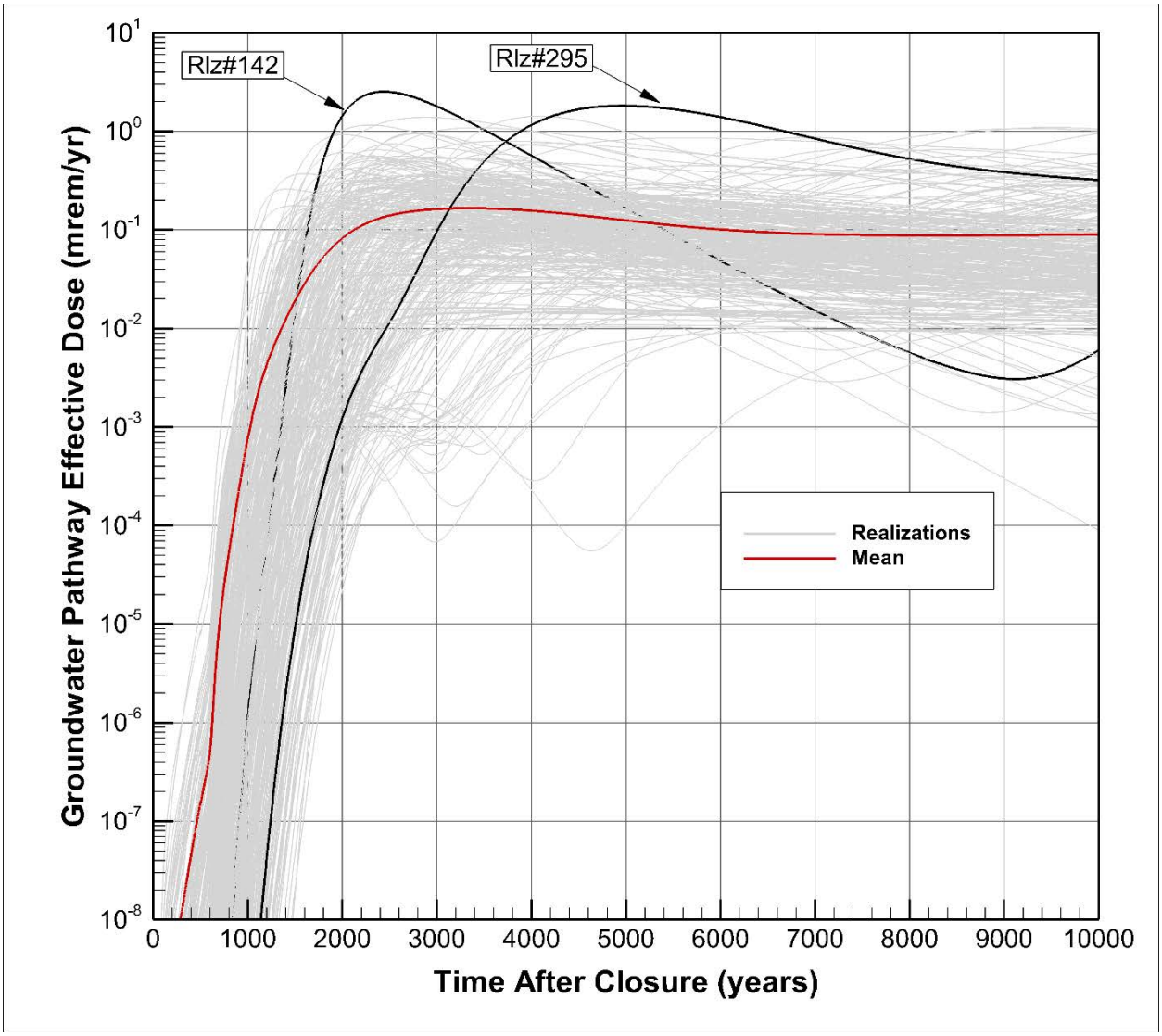


Figure 7-24. Selected Realizations for Groundwater Pathway Dose Analysis.



The Importance Measure (as calculated using GoldSim©) expresses the nonlinear, non-monotonic relationship between an input variable and the result, which the conventional correlation coefficient may not reveal. This measure varies between 0 and 1, and represents the fraction of the result's variance that is explained by the variable. The Importance Measure presented here is a normalized version of a measure discussed in "On the Relative Importance of Input Factors in Mathematical Models: Safety Assessment of Nuclear Waste Disposal" (Saltelli and Tarantola 2002), and is calculated as:

$$M_{y,i} = 1 - \frac{E[V_y(Y|X_i)]}{V_y} \tag{2}$$

Where:

$M_{y,i}$	=	the importance measure for the sensitivity of the result (Y) to input variable X_i
V_y	=	the current variance in the result Y
$E\left[V_y(Y\|X_i)\right]$	=	the expected value of V_y if the input variable X_i was perfectly known.

Thus, the Importance Measure $M_{y,i}$ represents the fraction of the result variance that is explained by X_i. For additional computational details, refer to Appendix B of the GoldSim User's Guide (GoldSim Technology Group 2014b).

The uncertainty analysis results of the 300 realization case for the groundwater pathway are presented in Table 7-3. Only those parameters are presented that contribute significantly to the uncertainty in total dose for the groundwater pathway. The results are sorted by the uncertain parameters from highest to lower numbers in terms of Importance Measure for those parameters that have correlation coefficients equal to or greater than about 0.2. Other uncertainty analysis measures (e.g., partial correlation coefficients) generally follow the same trend. The uncertainty analysis for the groundwater pathway is conducted by evaluating the dose from all realizations at time 3,400 years since the mean dose is the highest at this time. Therefore, the results of the multivariate analysis presented are only applicable to that time.

Based on the uncertainty analysis for the groundwater pathway conducted at the time of peak dose (around 3,400 years), the two most important uncertain parameters are found to be the vadose zone flow-field selector (hydraulic properties corresponding to the percentiles chosen from the vertical pore-water velocity cumulative distribution function) and the saturated zone Darcy flux multiplier (scales the base case Darcy flux in the aquifer). Both uncertain parameters are negatively correlated to the groundwater pathway dose. The linear relationships in these parameters can be inferred from the scatter plots shown in Figure 7-25. Choosing higher flow field leads to increased vertical pore water velocities, resulting in ^{99}Tc peak dose occurring earlier than 3,400 years. In such realizations, dose from ^{99}Tc (which is approximately the total dose) shows a declining trend at 3,400 years. On the other hand, realizations where lower flow field is selected tend to have delayed peak dose from ^{99}Tc, resulting in an upwardly increasing trend at 3,400 years. This combination results in a negative correlation between flow field and dose at 3,400 years. The negative correlation seen for the saturated zone Darcy flux multiplier is more intuitive, as the Darcy flux multiplier directly affects the volumetric flow rate in the aquifer, leading to dilution of the mass flux arriving from the vadose zone. Therefore, increasing the Darcy flux reduces the concentrations in the saturated zone for the simulated duration.

The coefficient of determination based on linear rank regression for uncertain parameters shown in Table 7-2 is approximately 0.75. This indicates that these six parameters represent about 0.75 fraction of the total variance in the peak dose result (around 3,400 years). The first two parameters alone account for more than half (0.59 fraction) of the total variance in the dose.

Table 7-3. Uncertain Parameters Important to Groundwater Pathway at (a) End of Compliance Time Period (1,000 Years after Closure) and (b) Time of Peak Dose (about 3,400 Years after Closure).

Stochastic Parameter ID	Description	Correlation Coefficient Based on Ranks	Standardized Regression Coefficient Based on Ranks	Partial Correlation Coefficient Based on Ranks	Importance Measures Based on Ranks
Kd_Sand_Uncert[Tc]	Uncertainty in K_d of Tc-99 for sand	-0.98	-0.97	-0.99	0.92
SZ_Dispersivity	Dispersivity in the saturated zone; used to scale the 1-D transport model values	-0.16	-0.02	-0.14	0.06
VZ_H2_Dispersivity_Uncert	Dispersivity in the vadose zone for the H2 Unit	0.18	0.11	0.64	0.06

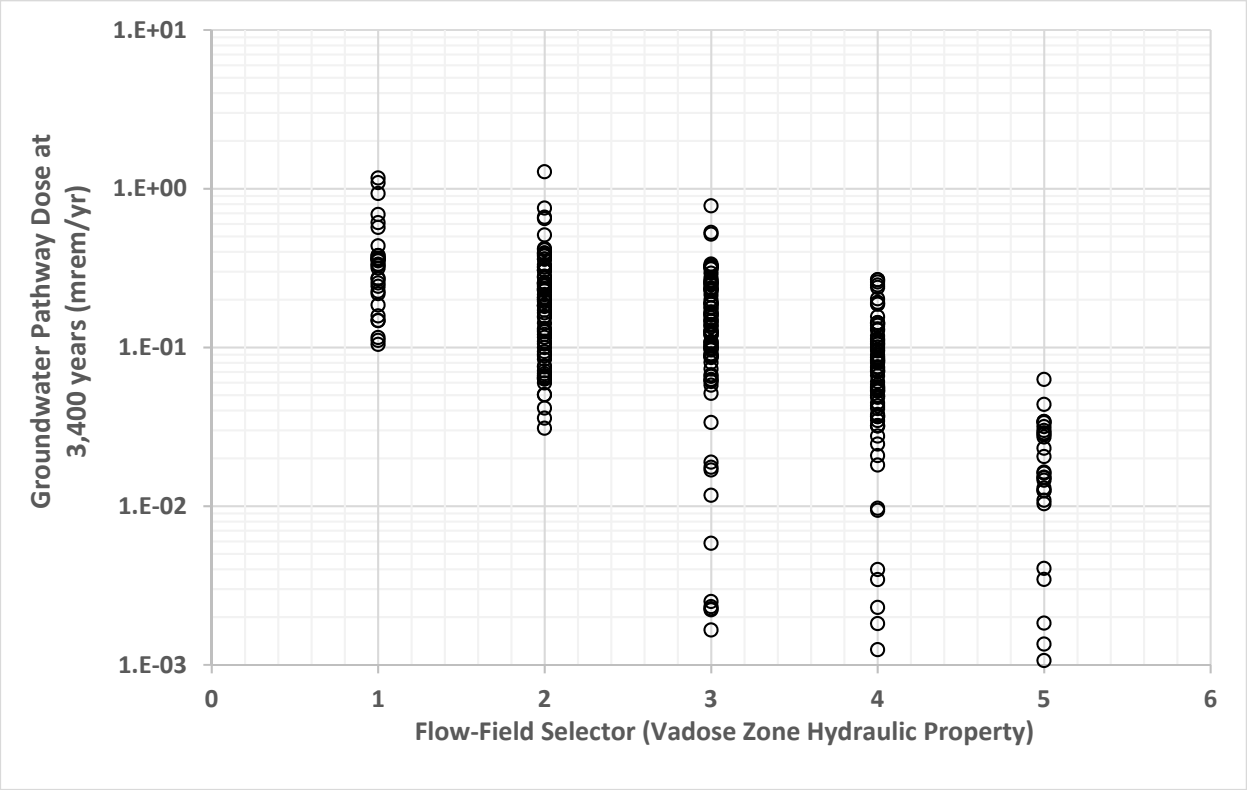
(a)

Stochastic Parameter ID	Description	Correlation Coefficient Based on Ranks	Standardized Regression Coefficient Based on Ranks	Partial Correlation Coefficient Based on Ranks	Importance Measures Based on Ranks
Hyd_Prop_Uncert	Vadose Zone Flow-Field selector based on pore-water velocity CDF	-0.63	-0.59	-0.78	0.40
Darcy_Flux_Mult_SZ	Darcy flux multiplier in the saturated zone	-0.44	-0.42	-0.67	0.22
Recharge_Late_PC_Uncert	Long-term recharge rate after degradation of surface cover; used in scaling the flow field	0.29	0.23	0.41	0.14
SZ_Dispersivity	Dispersivity in the saturated zone; used to scale the 1-D transport model values	-0.26	-0.23	-0.42	0.09
Kd_Sand_Uncert[Tc]	Uncertainty in K_d of Tc-99 for sand	-0.22	-0.18	-0.36	0.08
Tc99_Inv_Mult	Uncertainty in Tc-99 inventory; multiplies the base case value	0.22	0.19	0.36	0.06

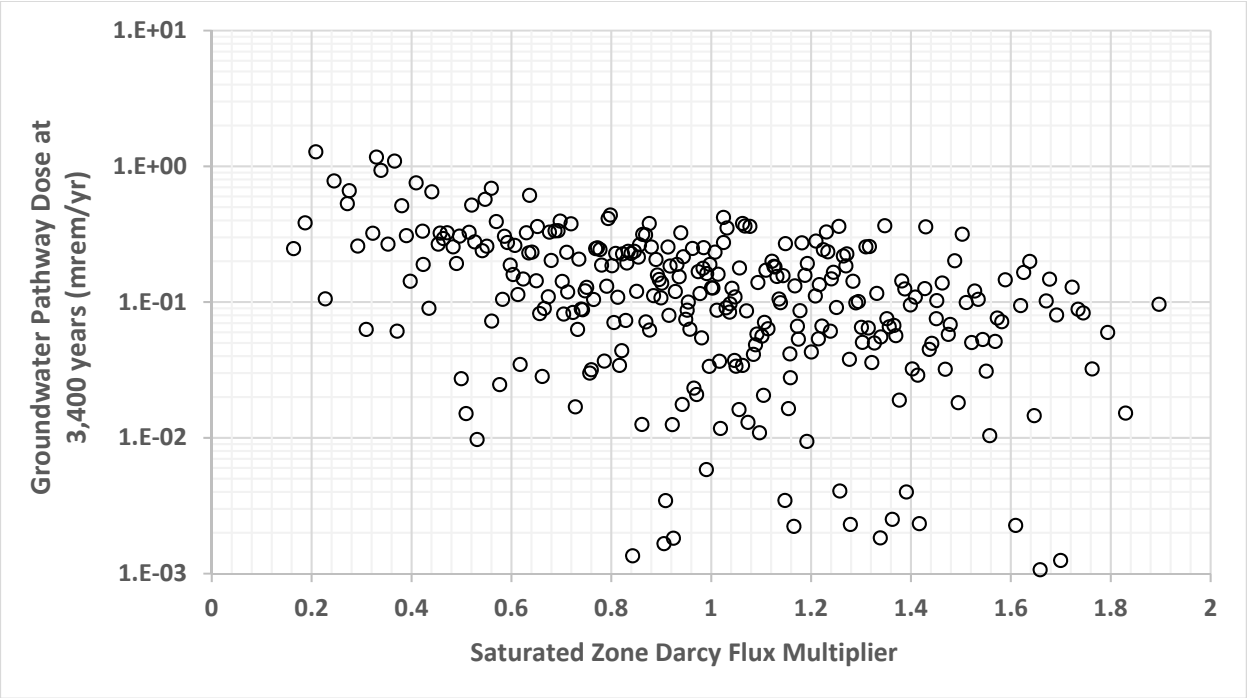
(b)

1-D = one-dimensional CDF = cumulative distribution function

Figure 7-25. Scatter Plots of Selected Uncertain Parameters Against Groundwater Pathway Dose at 3,400 Years.



(a)

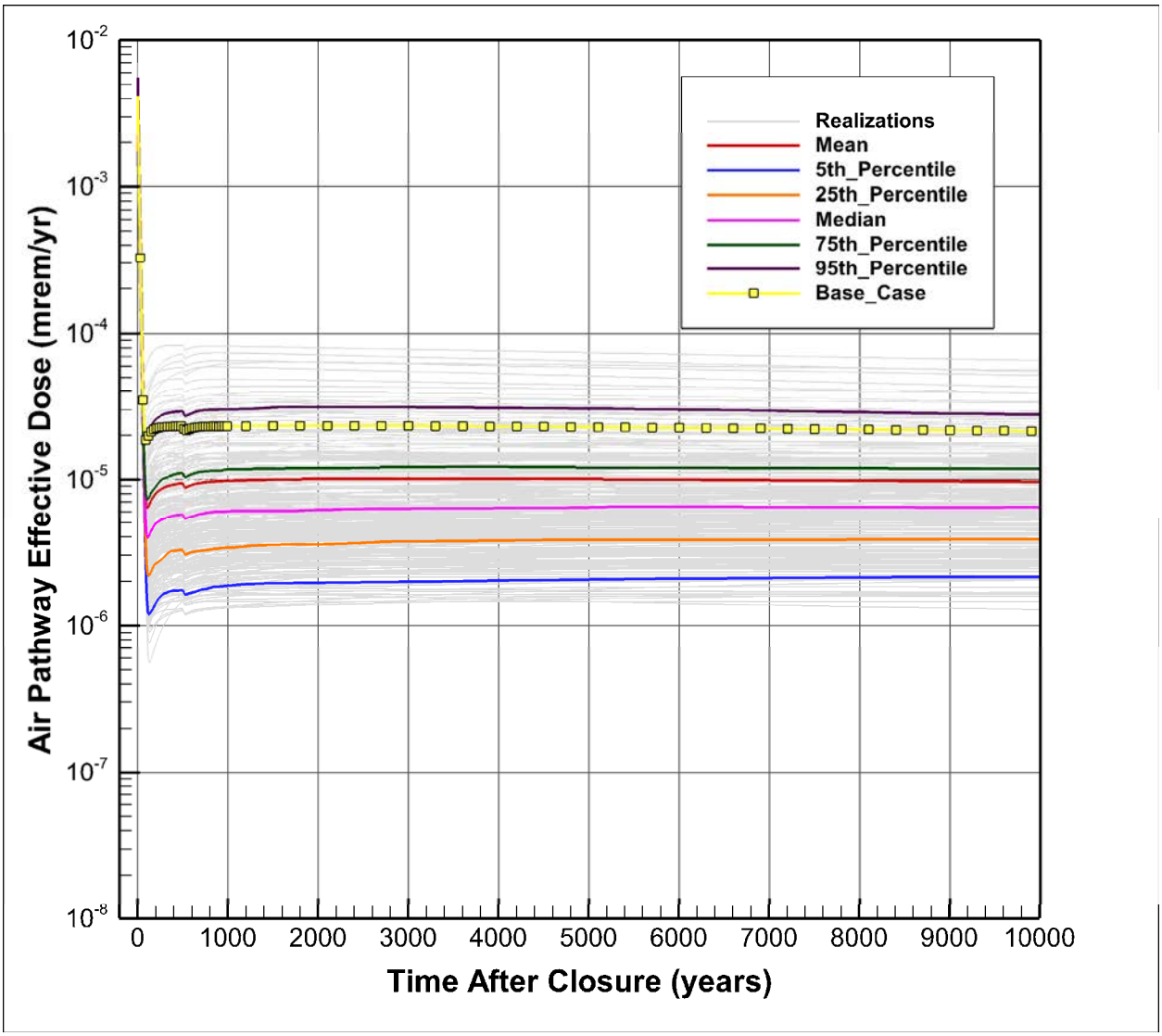


(b)

7.6.2 Evaluation of Uncertainty in the Atmospheric Pathway

Figure 7-26 presents the uncertainty in the atmospheric pathway dose for all 300 realizations, along with the mean, median, and other percentiles. In the first 100 years, ^{3}H (tritium) dose is the primary atmospheric pathway dose contributor, and after that it is ^{129}I. Hydrogen-3 dose declines sharply within the first 100 years due to its short half-life and limited inventory. The ^{129}I dose, however, increases gradually and reaches a steady value after 500 years. This is attributed to a relatively lower degree of partitioning into the air phase compared to ^{3}H (and ^{14}C), and a relatively larger degree of sorption to the tank infill grout material compared to ^{3}H. Due to these reasons, and in combination with long half-life, ^{129}I persists within the tank for a long time period. As shown in Figure 7-26, the dose resulting from atmospheric pathway remains negligibly small for all time periods.

Figure 7-26. Uncertainty in Atmospheric Pathway Dose Based on 300 Realizations.



The uncertainty analysis results of the 300 realization case for the atmospheric pathway are presented in Table 7-4 based on dose results at three different times: (a) early time period (at 2 years) to represent the early peak followed by steep decline; (b) intermediate time period (at 100 years) to represent the slowly increasing dose; and (c) long time period (at 1,000 years) to represent the steady dose. Only the parameters are presented that contribute significantly to the uncertainty in total dose for the atmospheric pathway. The results are sorted by the uncertain parameters from highest to lowest numbers in terms of Importance Measure (that have correlation coefficient of greater than 0.2).

At early time period represented by sharp rise and fall, since ^{3}H (tritium) dominates the dose, the most important uncertain parameter is found to be associated with the inventory. A strong positive correlation observed between dose and inventory uncertainty is not unexpected, indicating that increased inventory leads to larger concentration in the air pathway (see scatter plot presented in Figure 7-27). Uncertainty in wind speed shows a weak negative correlation, as it acts to dilute the concentration in air resulting from upward diffusive mass flux from the tanks.

In the intermediate time period (around 100 years), ^{129}I gradually becomes the dominant dose driver as ^{3}H dose continues to decline and ^{14}Co dose remains negligibly small. During this time, the total dose is seen to gradually increase with time. The most important uncertain parameter is associated with the K_d of ^{129}I for the grout tank infill material. A strong negative correlation is seen. This is expected as increased sorption of ^{129}I on the in-tank grout material will reduce the diffusive mass flux along the air pathway. Other important uncertain parameters in this time are related to tortuosity in the air pathway (used to calculate the effective diffusion coefficient) and residual inventory. See the scatter plots presented in Figure 7-28.

In the long time period (around 1,000 years), the ^{129}I dose reaches a steady value, indicating that the concentration gradient in the air phase from the tank to the surface has reached a steady-state. The most important uncertain parameter is associated with the K_d of ^{129}I for the grout tank infill material; a strong negative correlation is seen. The second most important uncertain parameter is associated with the residual inventory. See the scatter plots presented in Figure 7-29.

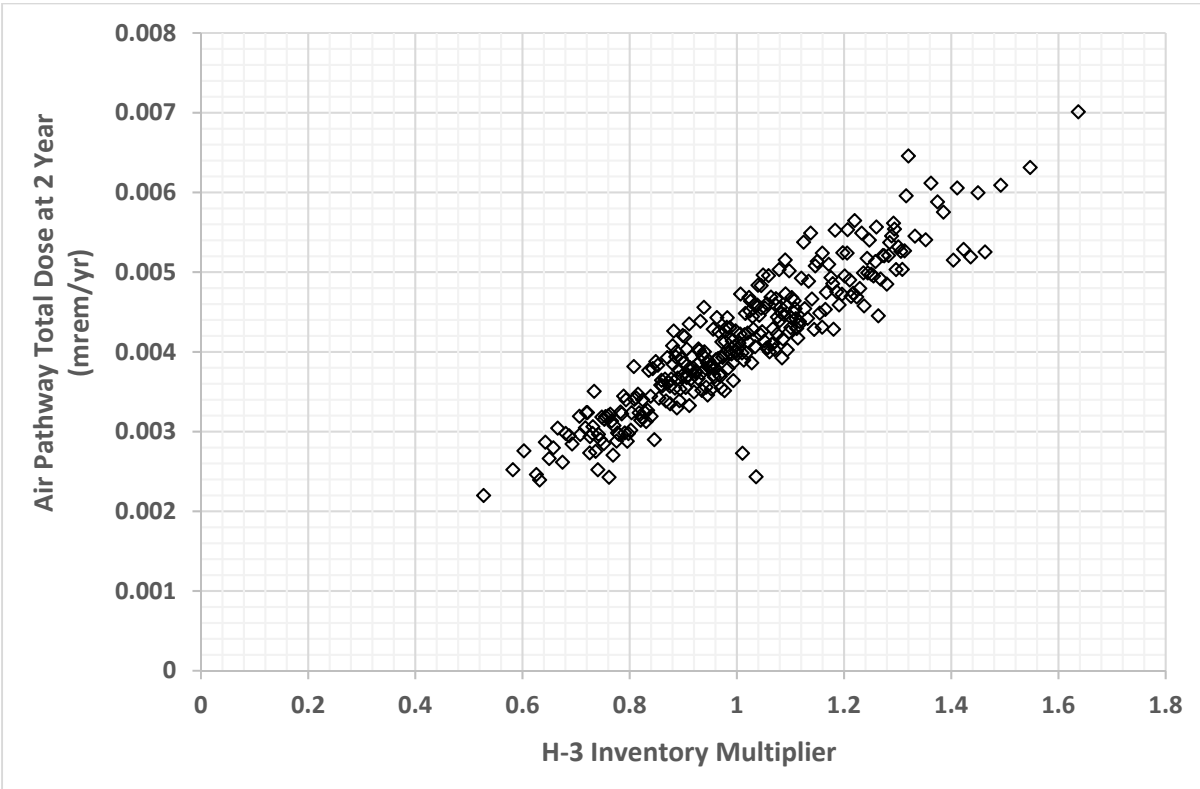
7.6.3 Statistical Stability

A stability analysis was conducted to determine whether a sufficient number of realizations were used to ensure that the results of the calculations are statistically stable. The 1-D abstraction model is statistically stable if the mean annual dose computed by the model is stable. Demonstrating stability of the mean annual dose requires evaluation of the sufficiency of sample size of uncertain parameters so that possible parameter combinations are adequately represented in the system analyzed. Performing uncertainty analysis with an inadequate number of realizations can result in erroneous interpretation of important uncertain parameters. Statistical stability is generally determined by demonstrating that the estimate of the mean annual dose does not depend on the sample size.

Table 7-4. Uncertain Parameters Important to Atmospheric Pathway Dose at Various Times.

Stochastic Parameter ID	Description	Correlation Coefficient Based on Ranks	Standardized Regression Coefficient Based on Ranks	Partial Correlation Coefficient Based on Ranks	Importance Measures Based on Ranks
At Early Time (2 years)					
H3_Inv_Mult	Uncertainty in H-3 inventory; multiplies the base case value	0.92	0.94	0.98	0.82
Wind_Speed_Stoch	Uncertainty in wind speed	-0.25	-0.3	-0.82	0.07
At Intermediate Time (100 years)					
Grout_Kd_Uncert[I]	Uncertainty in K_d of Iodine for Grout	-0.78	-0.70	-0.85	0.59
Soil_Air_Tort_Stoch	Uncertainty in tortuosity term for diffusive transport along the air pathway in the backfill soil	0.38	0.22	0.46	0.16
Grout_Air_Tort_Stoch	Uncertainty in tortuosity term for diffusive transport along the air pathway in the Grout material within the tank	0.28	0.31	0.58	0.13
I129_Inv_Mult	Uncertainty in I-129 inventory; multiplies the base case value	0.34	0.28	0.54	0.11
At Late Time (1,000 years)					
Grout_Kd_Uncert[I]	Uncertainty in K_d of Iodine for Grout	-0.88	-0.83	-0.94	0.74
I129_Inv_Mult	Uncertainty in I-129 inventory; multiplies the base case value	0.42	0.33	0.73	0.16
Soil_Air_Tort_Stoch	Uncertainty in tortuosity term for diffusive transport along the air pathway in the backfill soil	0.25	0.08	0.25	0.08

Figure 7-27. Scatter Plot of Selected Uncertain Parameters Against the Atmospheric Pathway Dose at Early Time Period (2 Years after Closure).

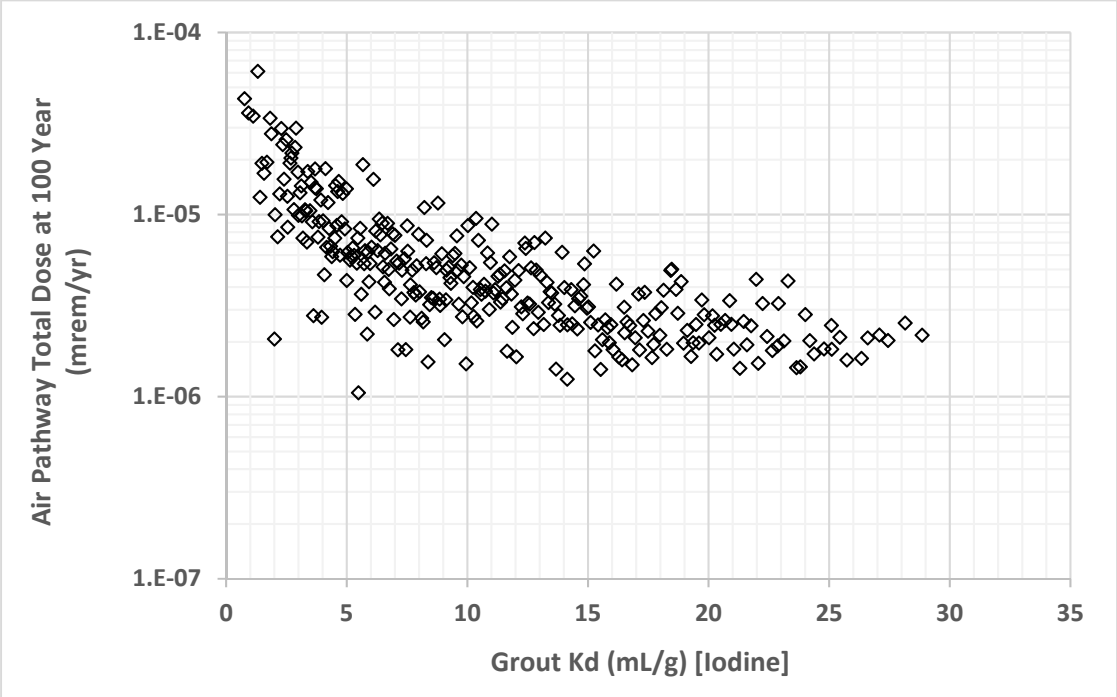


The total mean annual dose, $\overline{D}(\tau)$, for a multi-realization case is estimated at time τ by numerically evaluating

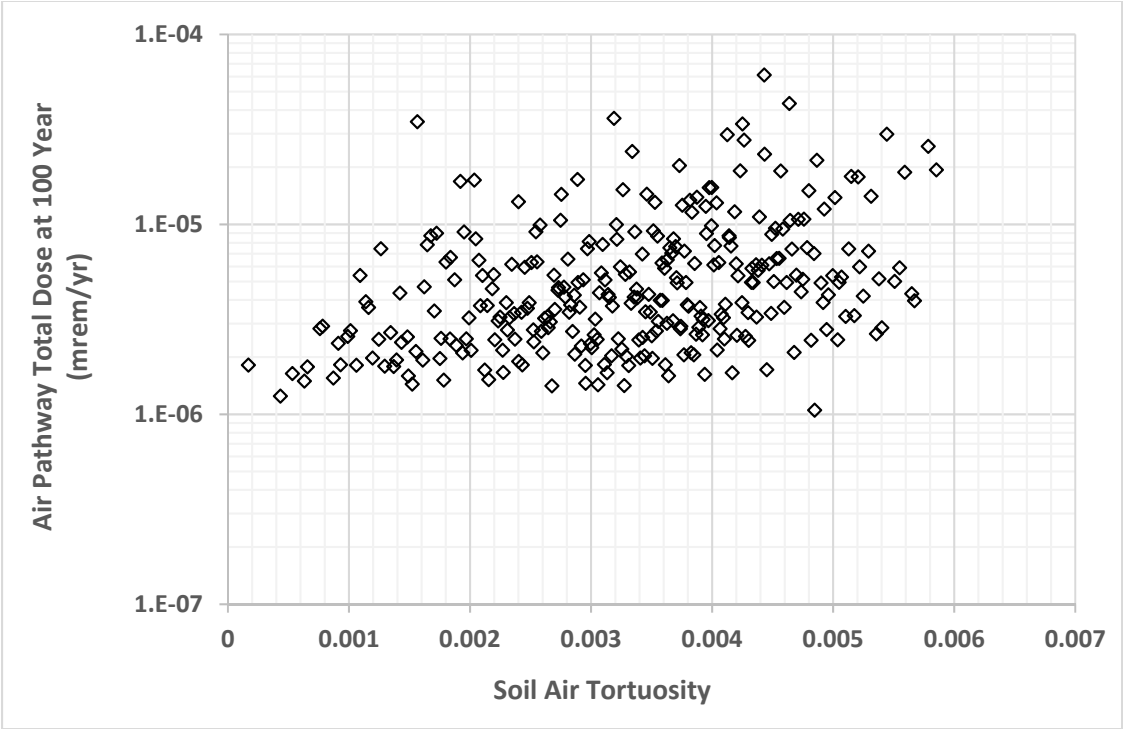
$$\overline{D}(\tau) = \int_E D(\tau|\mathbf{e})\, d_E(\mathbf{e}) dE \tag{3}$$

where E is a probability space comprising the epistemic uncertain parameters, and $D(\tau|\mathbf{e})$ computes the annual dose at time τ for a given element $\mathbf{e}$ (a vector of all uncertain parameters evaluated per realization) in E. The evaluation of the function $D(\tau|\mathbf{e})$ is performed by numerically solving a complex, coupled system of differential equations such as describing radionuclide decay, mass transport, flow, and other physical processes. The numerical integration is performed by the Monte Carlo technique and employing Latin Hypercube Sampling of epistemic uncertain parameters.

Figure 7-28. Scatter Plots of Selected Uncertain Parameters Against the Atmospheric Pathway Dose at Intermediate Time Period (100 Years after Closure).

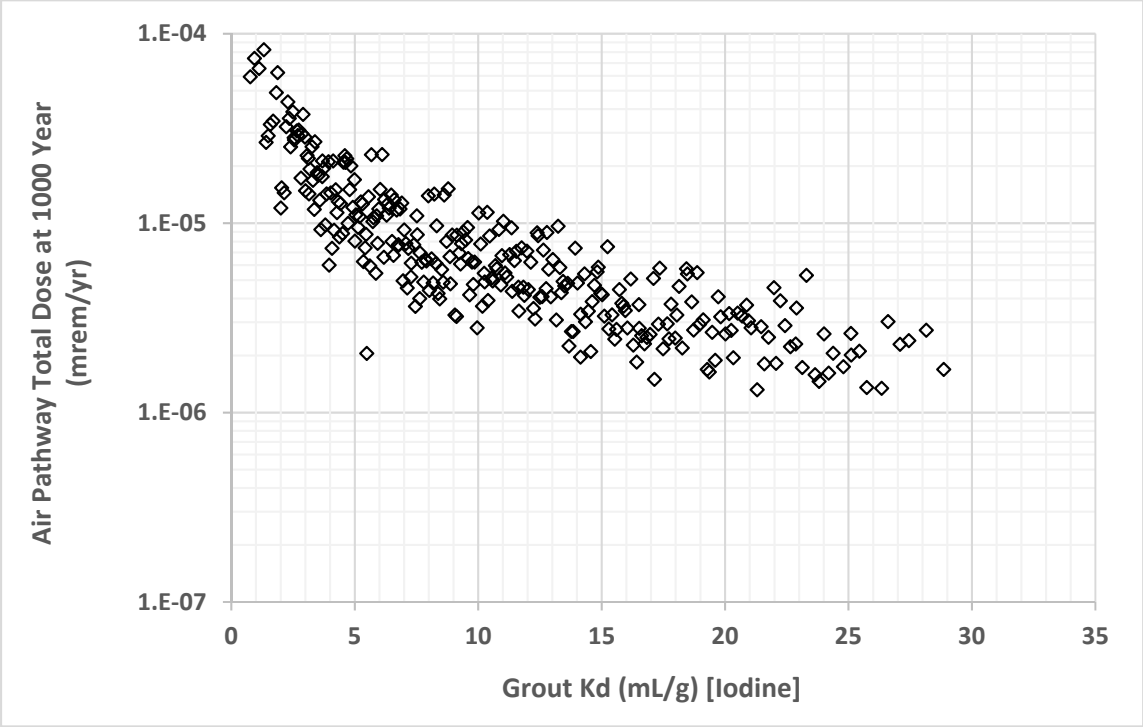


(a)

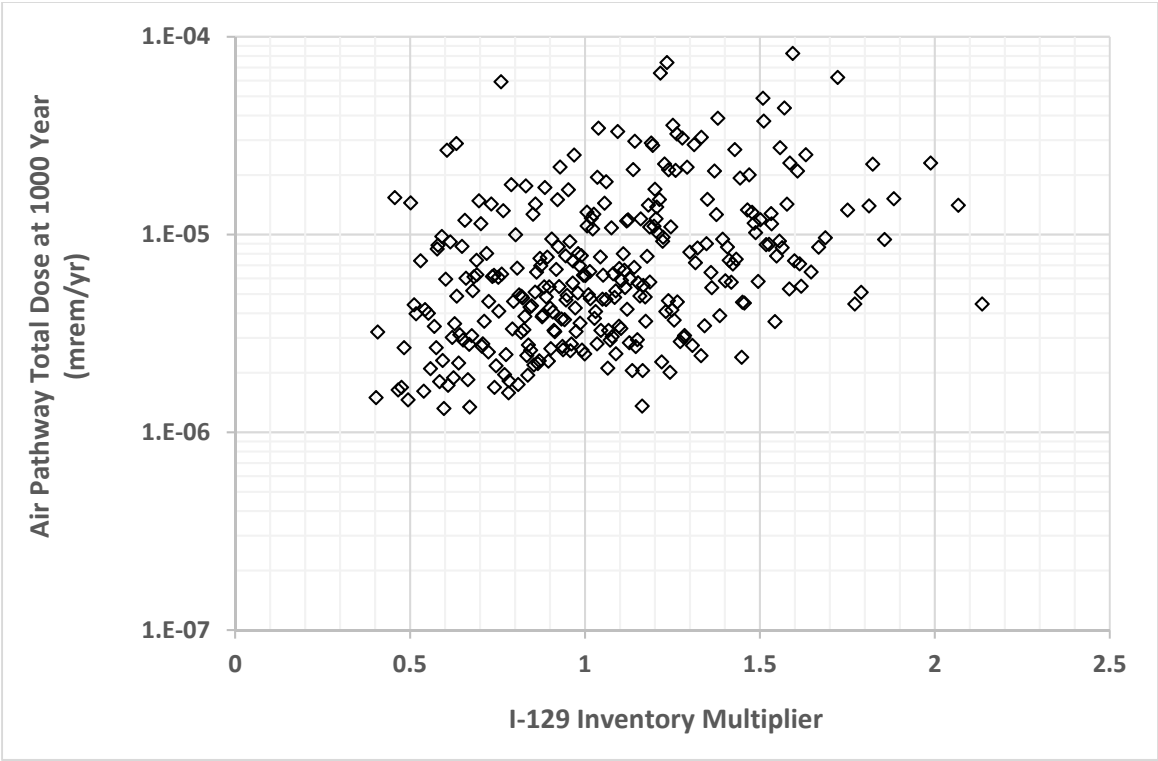


(b)

Figure 7-29. Scatter Plots of Selected Uncertain Parameters Against the Atmospheric Pathway Dose at Late Time Period (1,000 Years after Closure).



(a)



(b)

For stability analysis, the mean annual dose and uncertainty in underlying distribution is evaluated by performing calculations with different number of realizations (i.e., by varying the sample size). Since the atmospheric pathway dose remains negligibly small over all time compared to the groundwater dose, the stability analysis was performed with respect to the dose from groundwater pathway. Three cases were performed with an increasing number of realizations: (a) 100 realizations, (b) 300 realizations, and (c) 500 realizations. The dose statistics (mean, median, and 95th percentile) derived from these cases are compared in Figure 7-30. The results indicate that mean and median values among various cases are very similar. About 10% variance in the peak mean values between the three cases is seen, while the variance in the median values is even smaller. The variance in the 95th percentile values among different cases is slightly greater near the peak time, but still the peak mean dose is within a factor of two for all cases. The larger variation noticed in the 95th percentile for the 100 realization case indicates that only a few realizations have breakthrough at the 100-m downgradient location around 3,000 years, and as such the dose results are not stable due to small sample size. However, the 95th percentile curves for the 300 realization and 500 realization case are very similar, indicating adequate sample size has been reached. Based on these results, it can be concluded that 300 realizations are adequate for the purpose of performing uncertainty analysis.

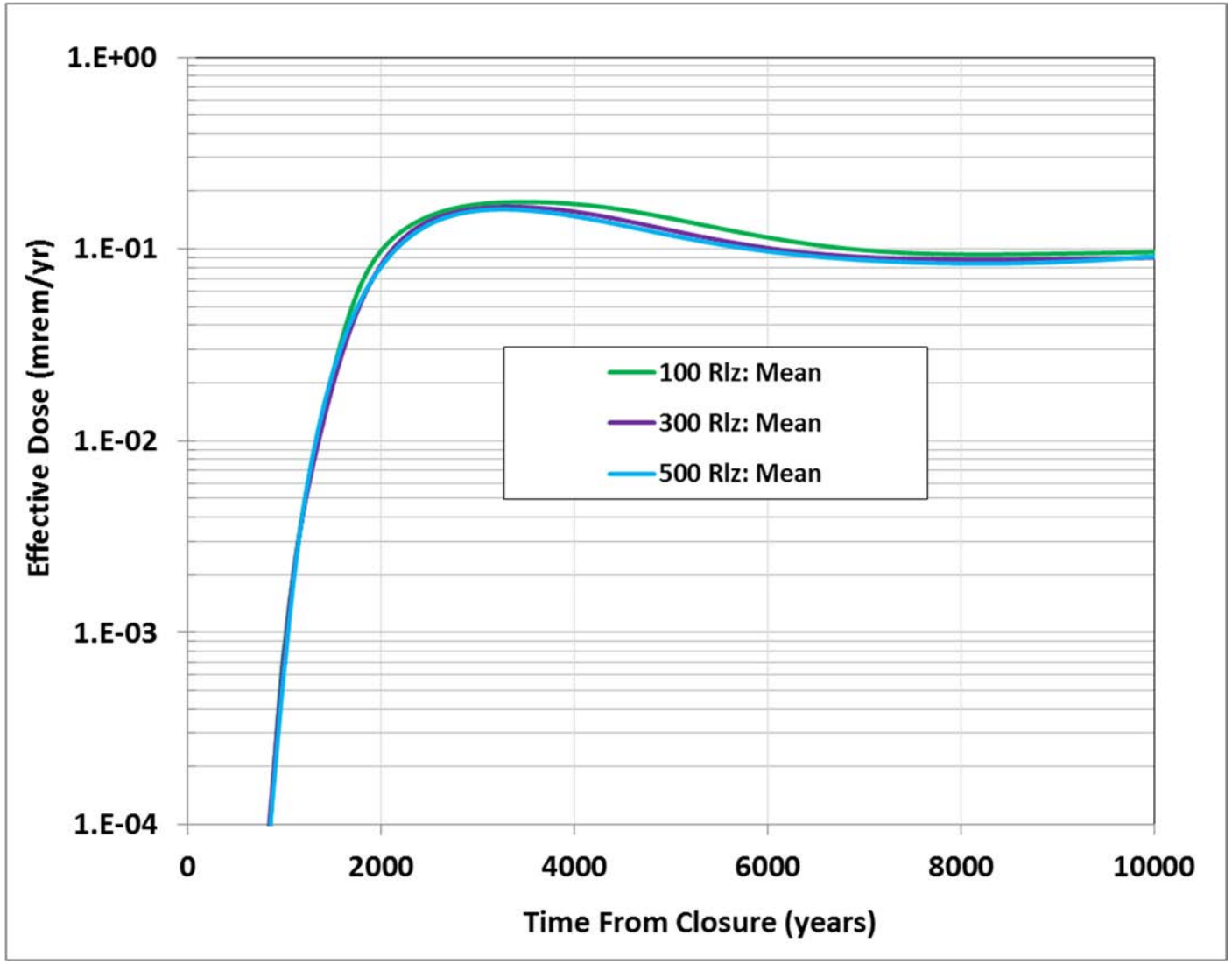
Figure 7-31 provides the upper and lower confidence limits on the grand mean (mean of the means) based on the three different cases at a 95% confidence level (significance level, $\alpha = 0.05$). The grand mean is shown in a thick black line and virtually overlaps the mean value from the 300 realization case. The range between the confidence bounds encompasses the mean from all three cases, indicating sufficiency of using 300 realizations for uncertainty analysis.

7.7 SENSITIVITY ANALYSIS

7.7.1 Inventory Sensitivity Analyses

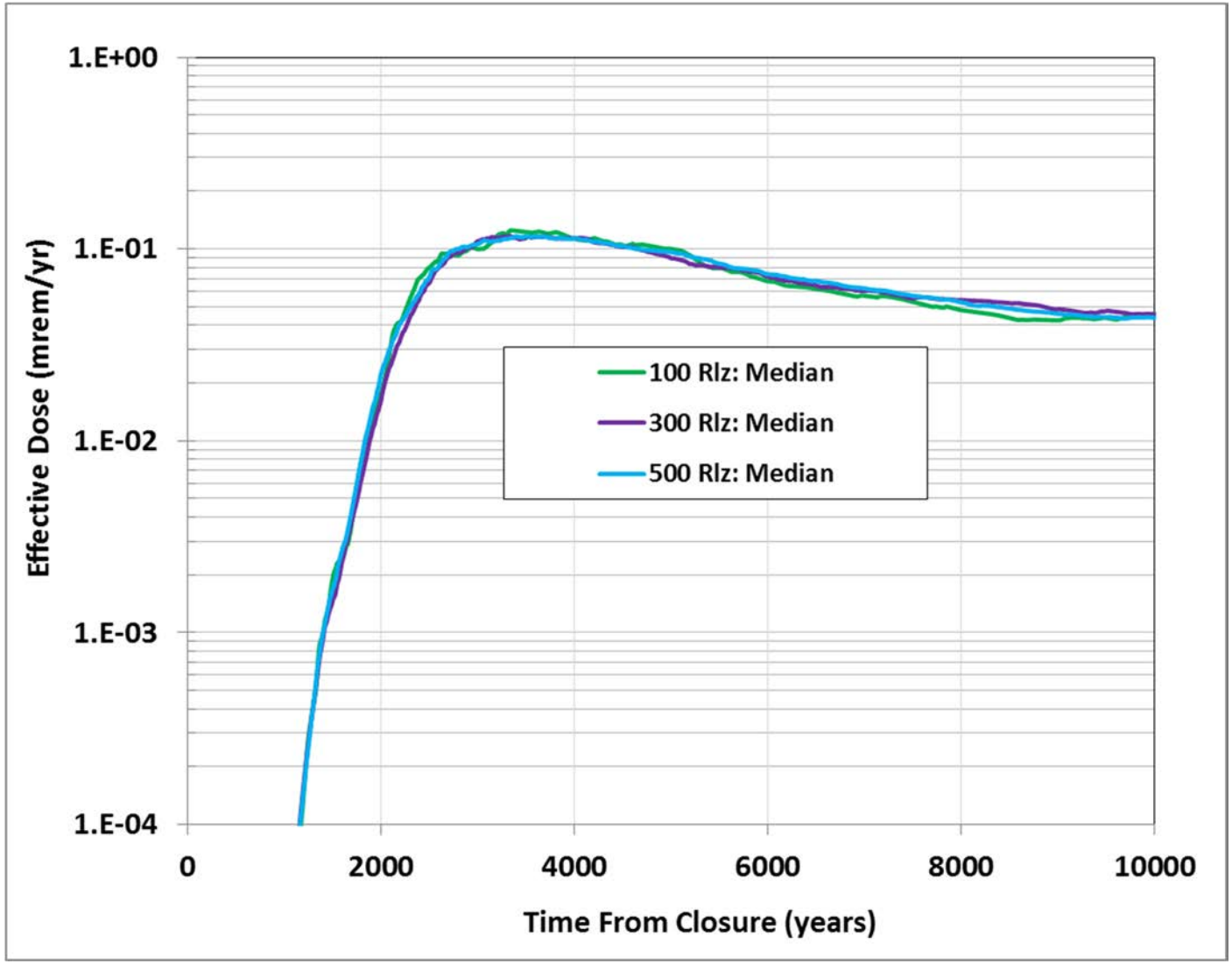
Figure 7-32(a) presents the results of the sensitivity case compared to the system-model base case. The peak groundwater concentration increased by a factor of five (compared to the base case), which is approximately the ratio of the inventories between the two cases (factor of six). Figure 7-32(b) presents the source term release rate of ^{99}Tc from tank C-105 to the vadose zone immediately below the tank. This release rate is proportional to the residual inventory change and indicates that source term release provides the predominant control on the observed differences in groundwater concentrations at the PoC. In the base case, the source term release rates show a decline after 500 years as most of the ^{99}Tc inventory is depleted by that time, while the upper bound case shows continued increase in the release rate until 1,000 years because of the higher inventory and longer time to deplete. For this reason the peak groundwater concentration for the upper bound case occurs after 600 years compared to the base case.

Figure 7-30. Statistical Stability Analysis with Different Number of Realizations, Comparing (a) Mean, (b) Median, and (c) 95th Percentile Values of the Groundwater Pathway Dose. (1 of 3 sheets)



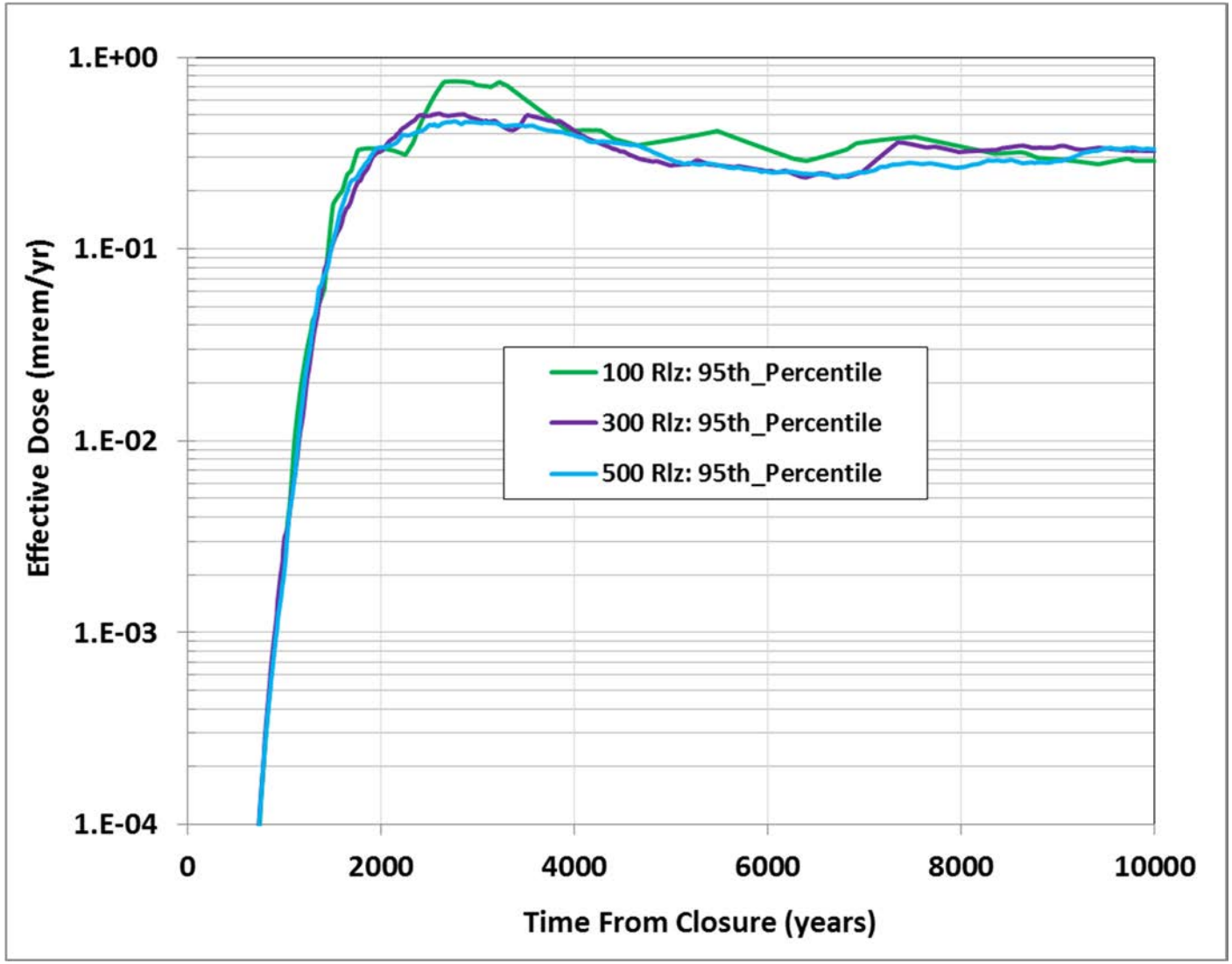
(a)

Figure 7-30. Statistical Stability Analysis with Different Number of Realizations, Comparing (a) Mean, (b) Median, and (c) 95th Percentile Values of the Groundwater Pathway Dose. (2 of 3 sheets)



(b)

Figure 7-30. Statistical Stability Analysis with Different Number of Realizations, Comparing (a) Mean, (b) Median, and (c) 95th Percentile Values of the Groundwater Pathway Dose. (3 of 3 sheets)



(c)

Figure 7-31. Confidence Limits on the Mean Effective Groundwater Pathway Dose.

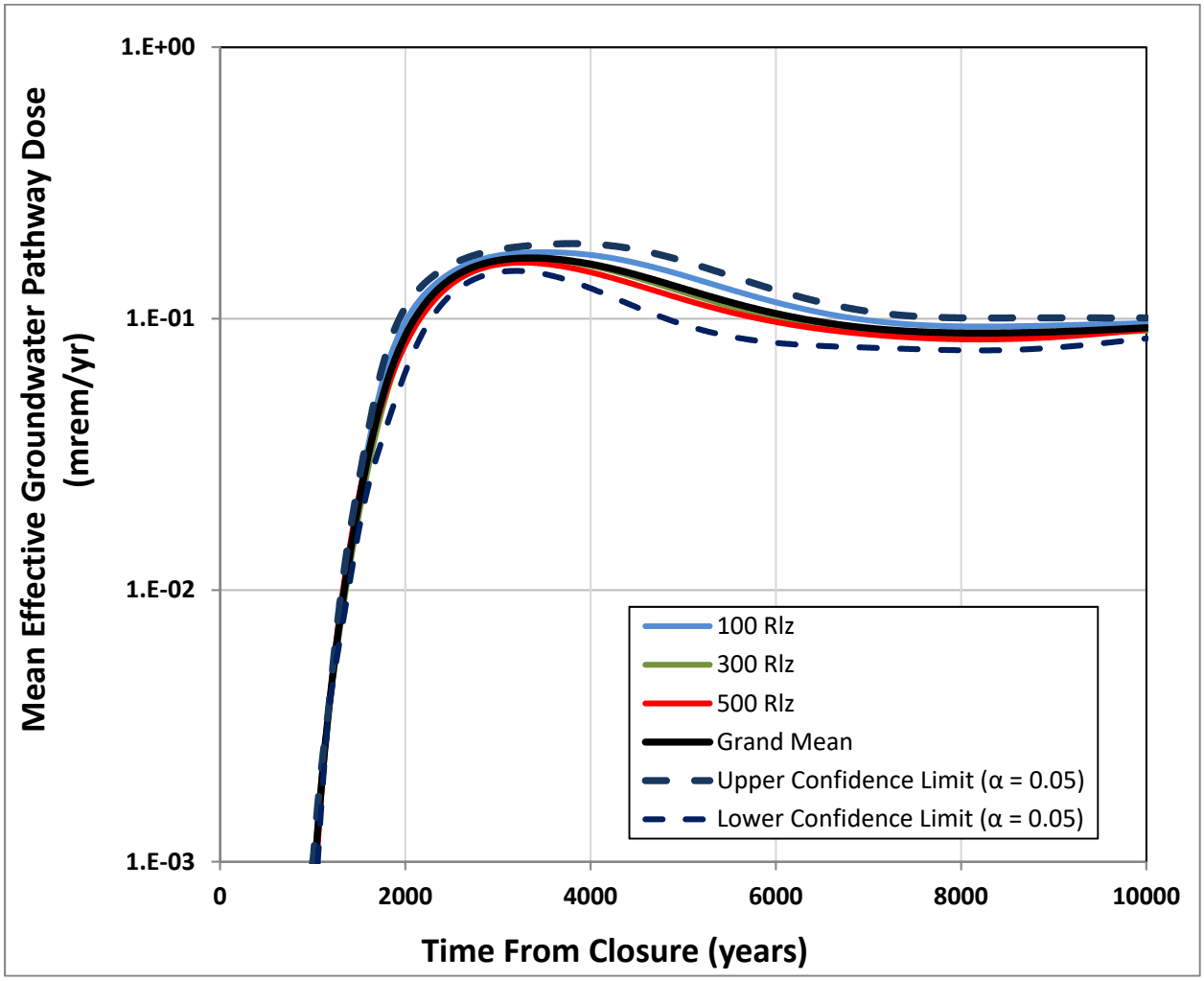
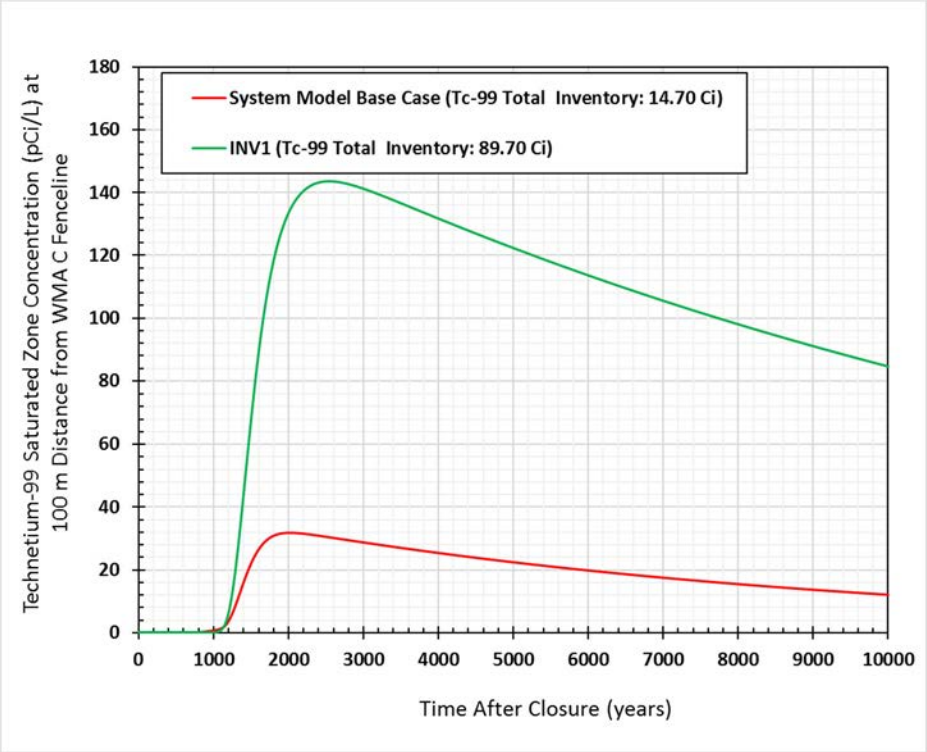
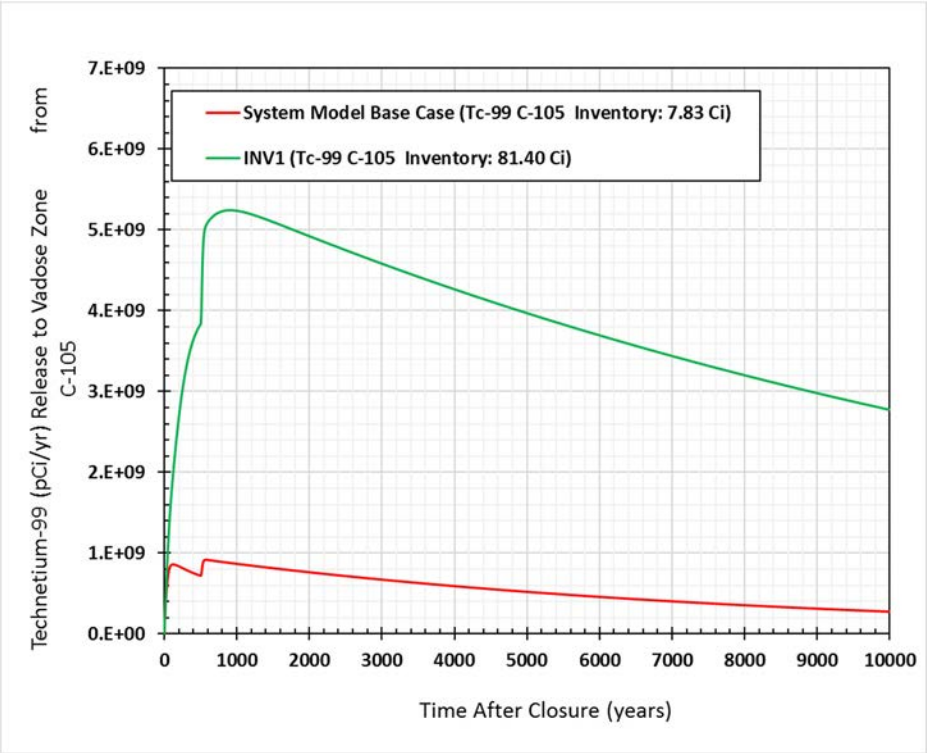


Figure 7-33(a) presents the results of the sensitivity case compared to the system-model base case. The peak groundwater concentration increased by approximately 19% (Table 7-5), while the approximate increase in total inventory was about 83%. This results primarily from the spatial distribution of tanks where the inventory increase occurred. Since the largest increase in inventory occurs in tanks C-102 (from 0.09 kg to 22,000 kg) and C-105 (from 783 kg to 8,140 kg), the PoCs of the highest concentrations change spatially compared to the base case, resulting in only 19% overall increase. Figure 7-33(b) presents the source term release rate of nitrate from tank C-105 (a representative tank) to the vadose zone immediately below the tank. This release rate is proportional to the residual inventory change, and indicates that source term release provides the predominant control on the observed differences in groundwater concentrations at the PoC. For the upper bounding inventory, the peak concentration is slightly delayed compared to the base case, due to the longer time it takes for the source to be depleted.

Figure 7-32. Comparison of Base Case and INV1 Case (a) Technetium-99 Concentration at 100 meter Boundary (b) Technetium-99 Release to Vadose Zone from Tank 241-C-105.

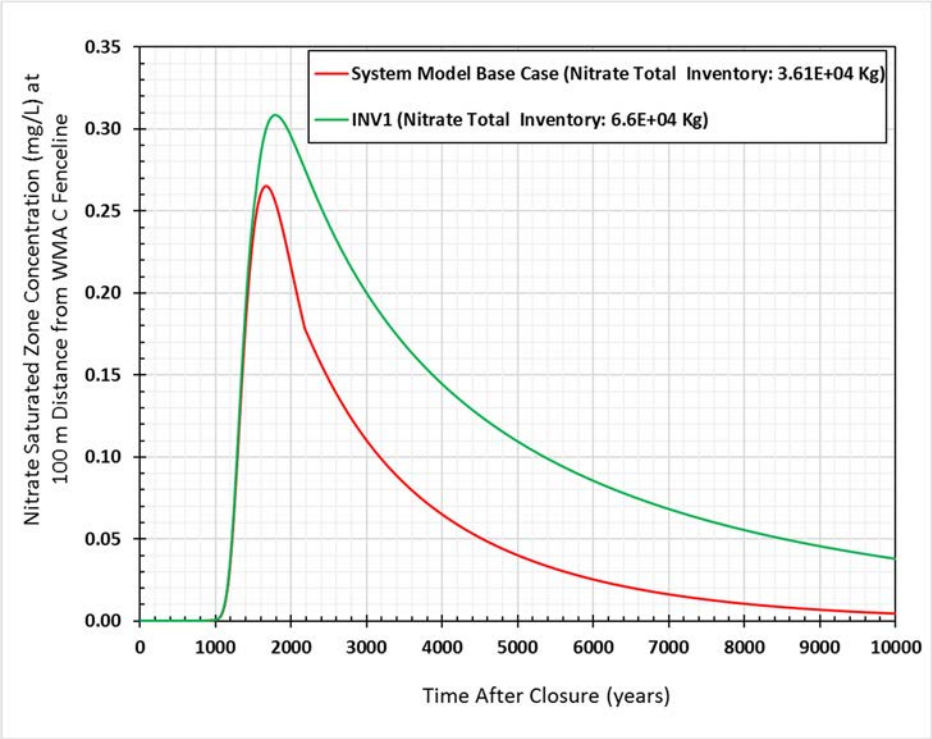


(a)

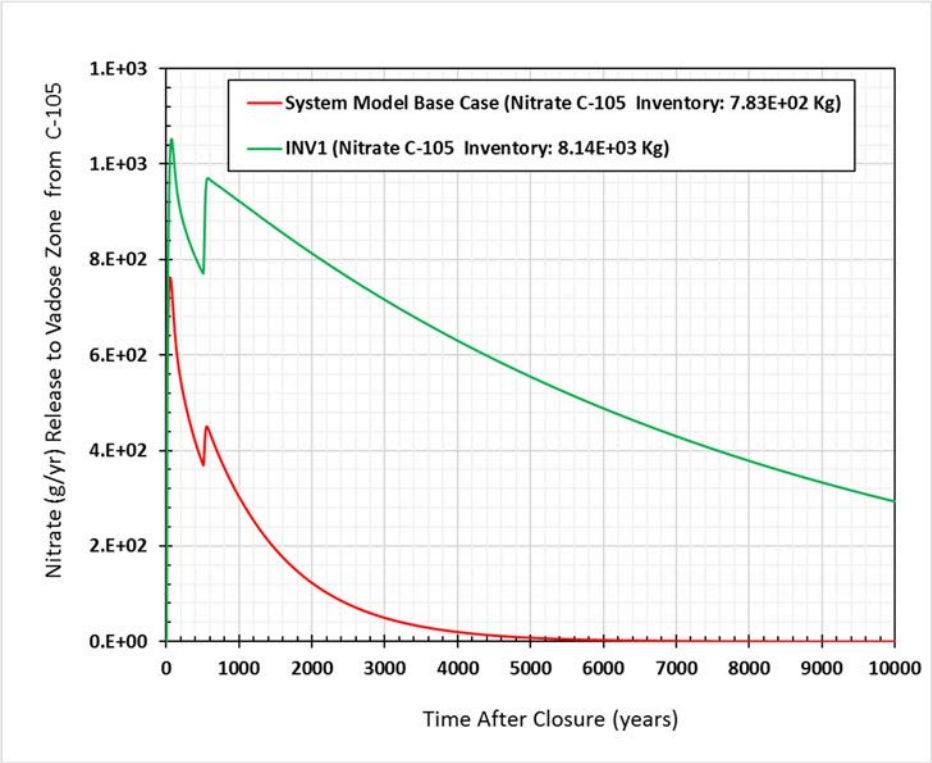


(b)

Figure 7-33. Comparison of Base Case and INV1 Case (a) Nitrate Concentration at 100 meter Boundary (b) Nitrate Release to Vadose Zone from Tank 241-C-105.



(a)



(b)

Table 7-5. Inventory Estimate Sensitivity Evaluation (Nitrate).

Inventory	Sensitivity Case Shorthand	Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure)	Maximum Concentration at Downgradient Point of Calculation (mg/L)
System model base case*	Base case	1,670	0.26
Upper bound Inventory for Nitrate	INV1	1,790	0.31

*The base case analysis was run using the system model for this comparison. The results differ slightly from the base case analysis results from Subsurface Transport Over Multiple Phases (STOMP)© (copyrighted by Battelle Memorial Institute, 1996).

7.7.2 Grout Flow Sensitivity Analyses

Figure 7-34(a) presents the ^{99}Tc concentration in the saturated zone at the PoC (cumulative for all the sources) and Figure 7-34(b) presents the ^{99}Tc release from tank C-105 to the vadose zone immediately below the tank for the three cases in comparison to the base case. Prior to the tank degradation time the ^{99}Tc release from the tank occurs by diffusion (same as the base case), and following tank degradation the release occurs by both advection and diffusion. The curves track the base case results until the degradation time. The magnitude in peak concentration (and peak release rate) reduces with the delayed tank degradation time due to inventory depletion from diffusive release prior to the start of advection.

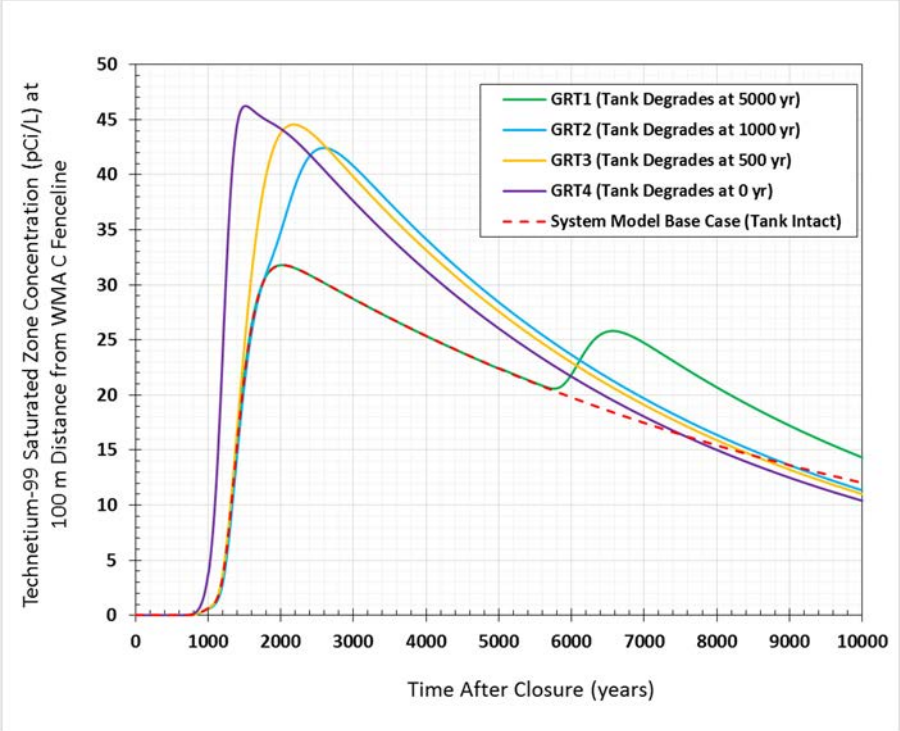
Figure 7-35(a) presents the nitrate concentration in the saturated zone at the PoC (cumulative for all the sources), and Figure 7-35(b) presents the nitrate release from tank C-105 to the vadose zone immediately below the tank for the three cases in comparison to the base case. Prior to the tank degradation time, the nitrate release from the tank occurs by diffusion (same as the base case) and, following tank degradation, the release occurs by both advection and diffusion. The curves track the base case results until the degradation time. The magnitude in peak concentration (and peak release rate) reduces with the delayed tank degradation time, due to inventory depletion from diffusive release prior to the start of advection.

7.7.3 Waste Form Sensitivity Analysis

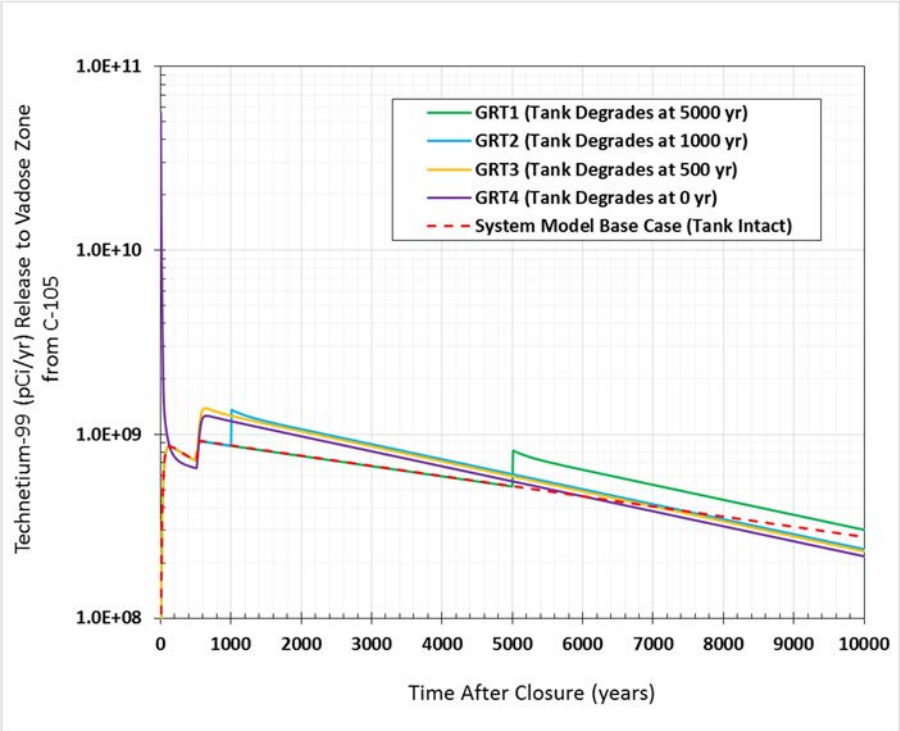
Figure 7-36(a) presents the ^{99}Tc concentration in the saturated zone at the PoC (cumulative for all the sources) and Figure 7-36(b) presents the ^{99}Tc release from tank C-105 to the vadose zone immediately below the tank. Figure 7-37 presents the ^{238}U concentration in the saturated zone.

For ^{99}Tc, very little difference is observed between the base case and sensitivity case. This is because the degradation rate used in the base case itself results in almost all of the ^{99}Tc inventory to be available for release within few years. The small difference in time in the waste form degradation results in negligible difference in the saturated zone concentrations due to larger dispersion caused by vadose zone and saturated zone processes.

Figure 7-34. Comparison of Base Case and GRT1, GRT2, GRT3, GRT4 Case (a) Technetium-99 Concentration at 100 meter Boundary (b) Technetium-99 Release to Vadose Zone from Tank 241-C-105.

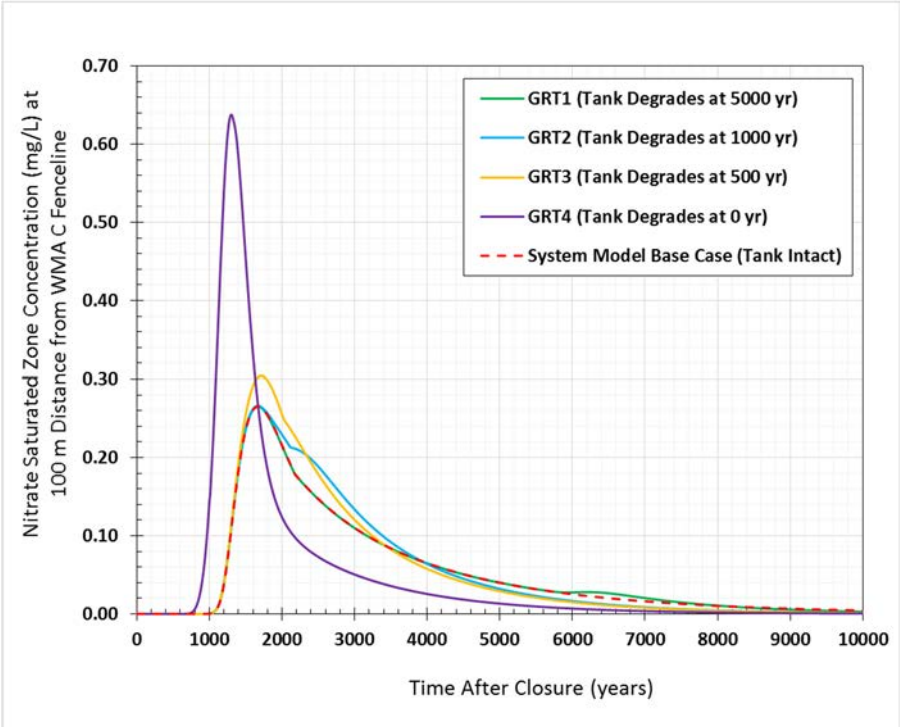


(a)

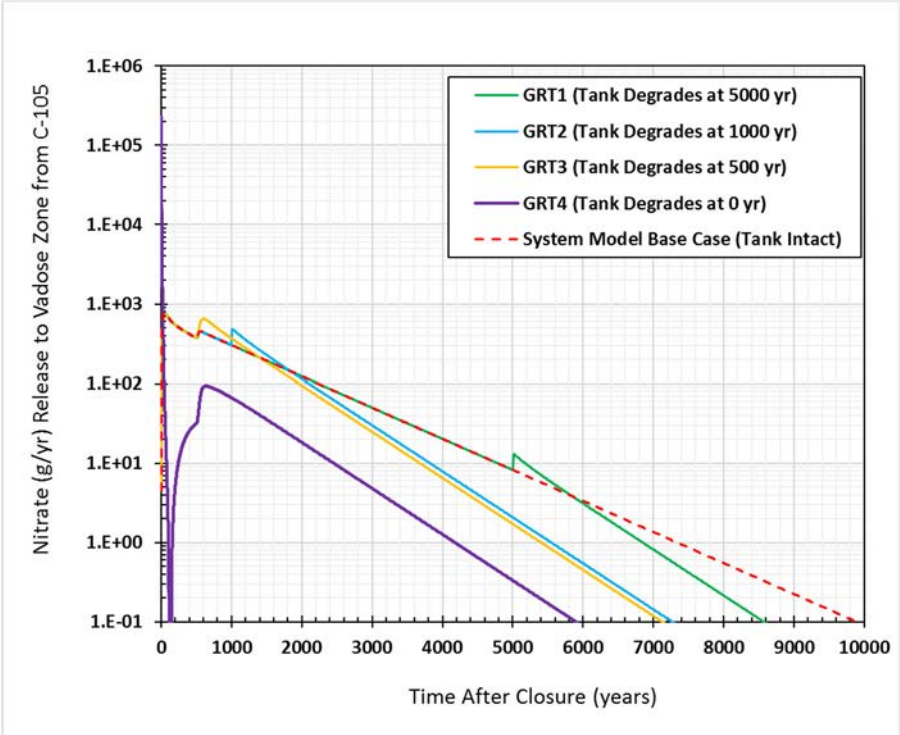


(b)

Figure 7-35. Comparison of Base Case and GRT1, GRT2, GRT3, GRT4 Case (a) Nitrate Concentration at 100 meter Boundary (b) Nitrate Release to Vadose Zone from Tank 241-C-105.

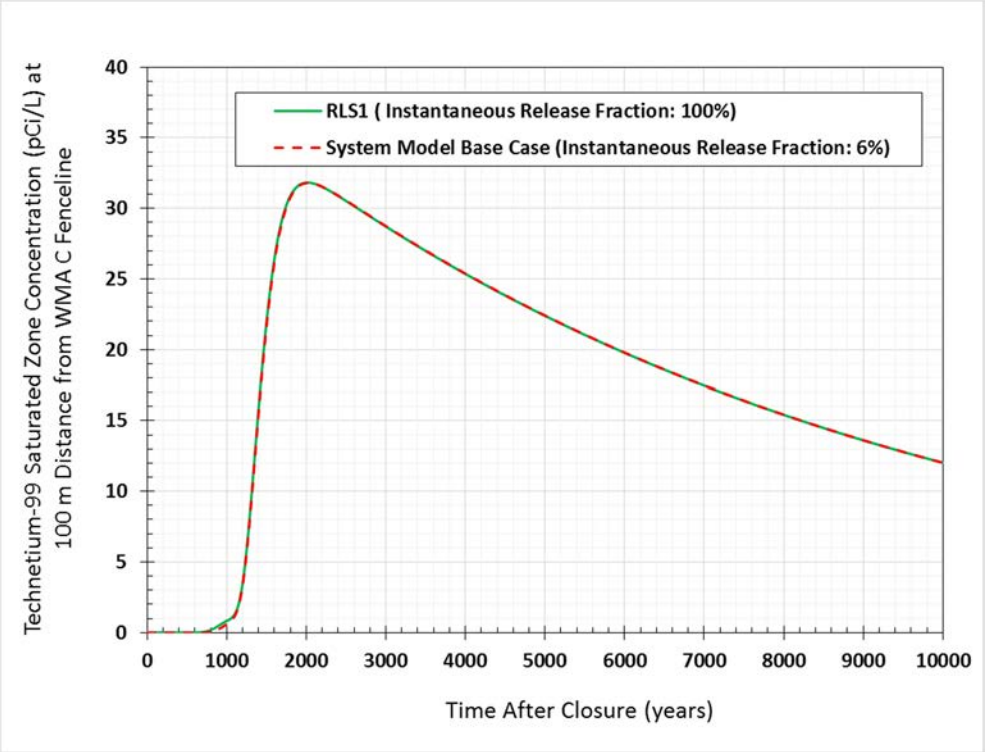


(a)

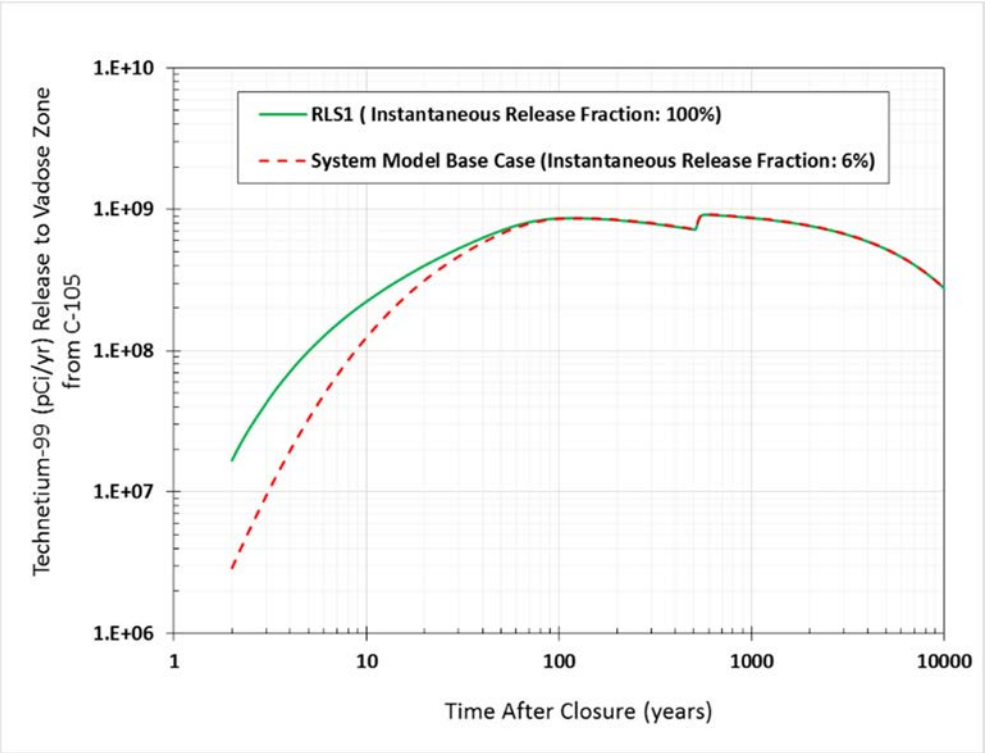


(b)

Figure 7-36. Comparison of Base Case and RLS1 Case (a) Technetium-99 Concentration at 100 meter Boundary (b) Technetium-99 Release to Vadose Zone from Tank 241-C-105.

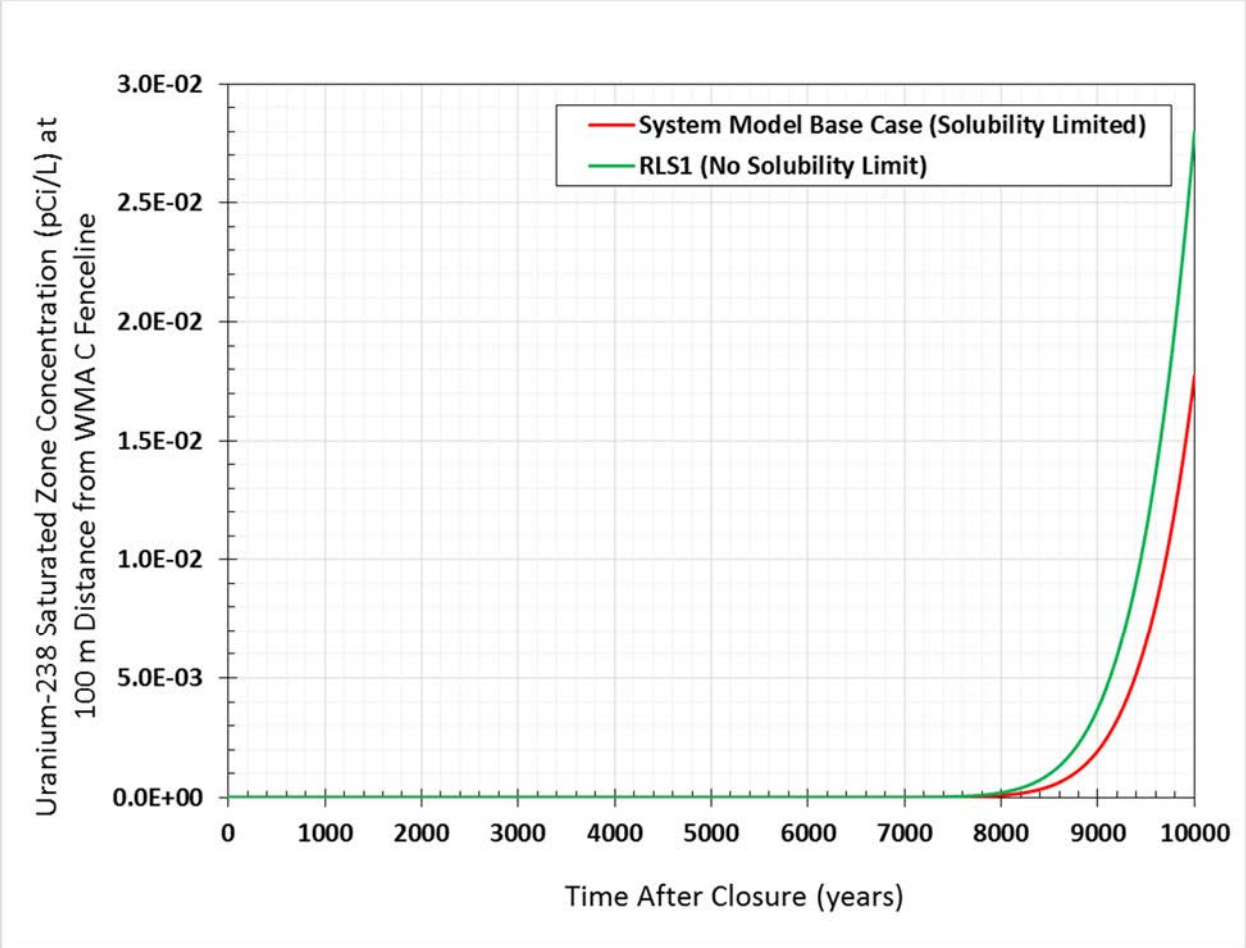


(a)



(b)

Figure 7-37. Comparison of Base Case and RLS1 Case for Uranium-238 Concentration at 100 meter Boundary.



For ^{238}U the increase in concentrations are appreciable, indicating the influence of the solubility/dissolved concentration limits. The effect on ^{238}U concentration is relatively small because the breakthrough curve for uranium is primarily from advective release from pipeline sources. Uranium is retarded within the tank due to sorption on the base mat (grout + concrete layer).

Figure 7-38 shows the comparison between the base case and removing the dissolved concentration limit for chromium. With no dissolved concentration limit as applied in the RLS1 case, the release rate and groundwater impacts from chromium are initially the same. However, the peak release and groundwater impacts under the RLS1 case is higher and arrives at a later time than the base case.

7.7.4 Tank Flow Sensitivity Analyses

Figure 7-39(a) presents the ^{99}Tc concentration in the saturated zone at the PoC and Figure 7-39(b) presents the ^{99}Tc release from tank C-105 to the vadose zone immediately below the tank for the three cases in comparison to the base case. For the DIF1 case, higher diffusion

coefficient results in higher diffusive release and higher peak concentration. Once the source inventory depletes (following the peak value) the curves follow the same trend as the base case. For the DIF2 case, due to the lower diffusion coefficient in the first 500 years, the diffusive flux and therefore the concentration is lower than the base case early on. For the DIF3 case, since no release is allowed from the grouted tank sources in the first 5,000 years, the only release prior to this time is from the pipeline source that results in a small increase in groundwater concentration around 1,000 years. After 5,000 years, both advective and diffusive release start resulting in higher peak concentration than the base case.

Figure 7-38. Comparison of Base Case and RLS1 Case for Chromium Concentration at 100 meter Boundary.

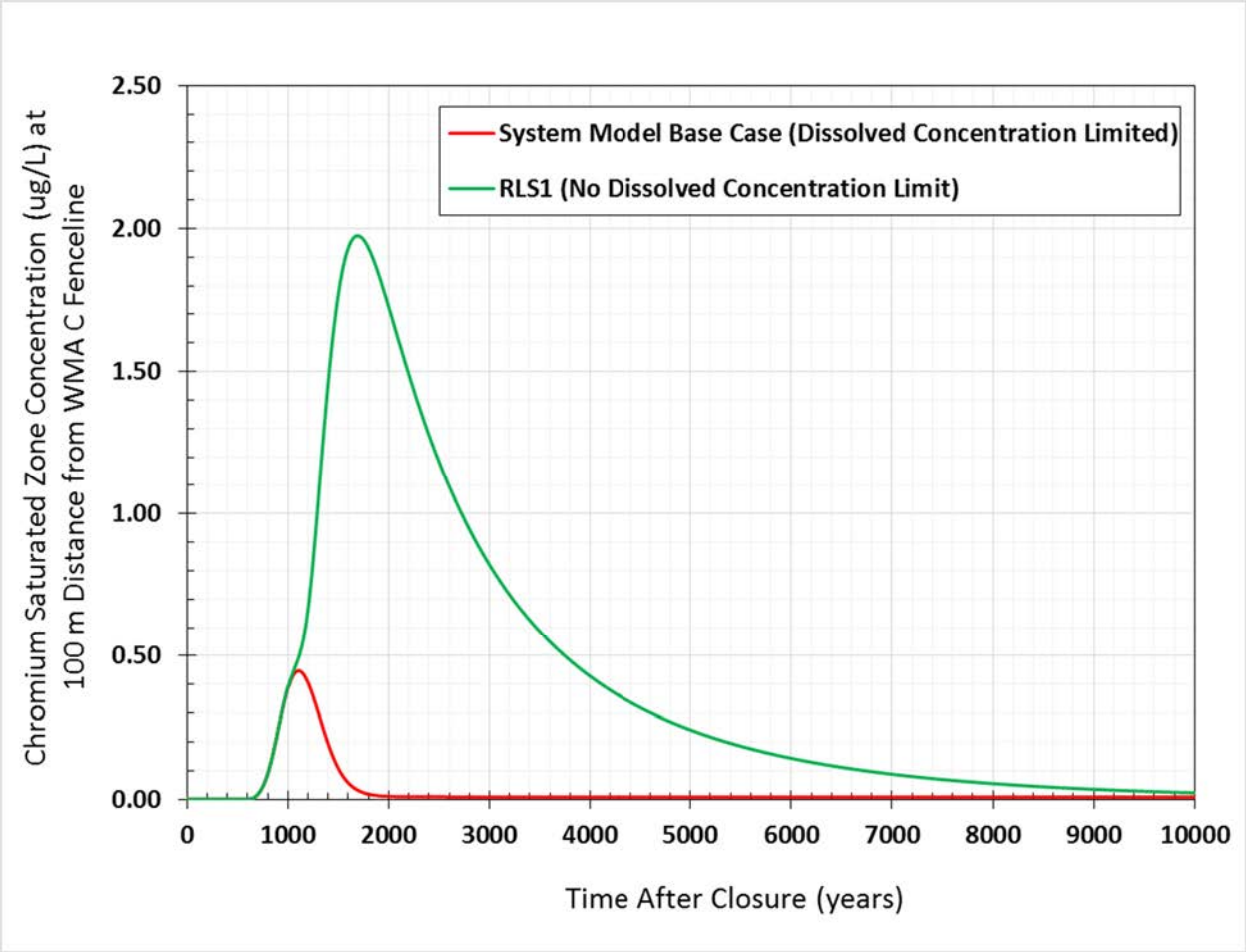


Figure 7-40(a) presents the nitrate concentration in the saturated zone at the PoC, and Figure 7-40(b) presents the nitrate release from tank C-105 to the vadose zone immediately below the tank for the three cases in comparison to the base case. For the DIF1 case, the higher diffusion coefficient results in a higher diffusive release and higher peak concentration. Once the source inventory depletes (following the peak value), the curves follow the same trend as the base case. For the DIF2 case, due to lower diffusion coefficient in the first 500 years, the diffusive flux, and therefore the concentration, is lower than the base case early on. For the DIF3 case, since no release is allowed from the grouted tank sources in first 5,000 years, the only

release prior to this time is from the pipeline source that results in a small increase in groundwater concentration around 1,000 years. After 5,000 years, both advective and diffusive releases start, resulting in a higher peak concentration than the base case.

7.7.5 Evaluation of Long-Term Peak Dose

The results for peak dose calculations are presented in Figure 7-41 in terms of effective dose for the groundwater pathway. The peak dose of 0.27 mrem/yr occurs around 15,000 year after closure. It is controlled by ^{99}Tc, uranium isotopes, and ^{226}Ra. The dose after 20,000 years from closure is dominated by ^{226}Ra (including progeny) resulting from ingrowth from uranium isotopes. After 30,000 years, a small rise in the ^{99}Tc dose is noticeable, which results from an increased release when advection through the tank is assumed. At the end of 400,000 years simulation, the dose contribution from ^{226}Ra and ^{210}Pb are increasing. Both result from ingrowth from uranium isotopes.

The results of various sensitivity cases are presented in Table 7-5 through Table 7-11.

7.8 RESULTS OF TAP WATER SCENARIO

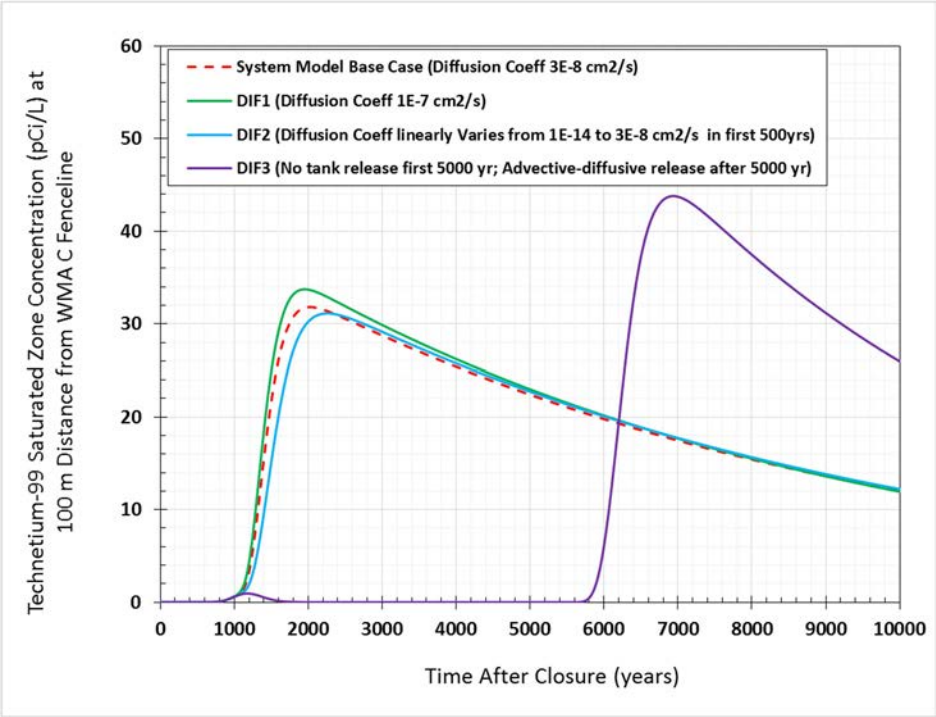
7.8.1 Summary of Tap Water Cancer Risks

A summary of the peak radiological cancer risk and time of peak occurrence is presented in Table 7-12.

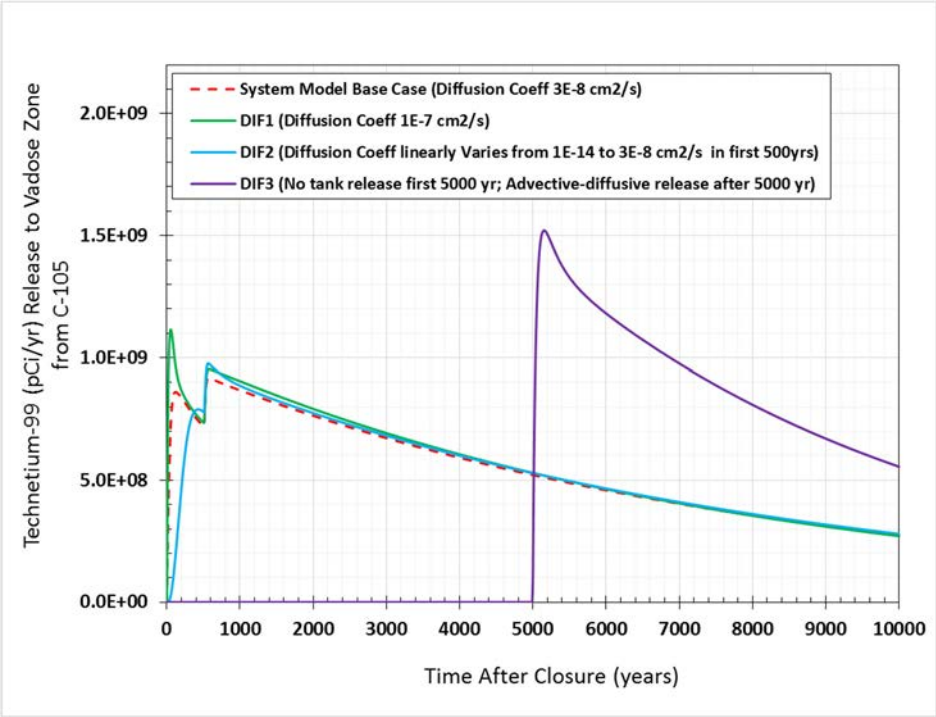
7.8.2 Summary of Tap Water Non-Cancer Hazards

Cumulative non-cancer hazards are presented in Figure 7-42 at the 100-m distance for each PoC. The peak cumulative non-cancer hazard index (HI) occurs at PoC 4. The cumulative non-cancer hazard results for PoC 4 are presented in Figure 7-43 for all chemicals that produced a nonzero hazard result within 10,000 years. The peak chemical non-cancer HI summed over all chemicals is about 0.07, which occurs at 1,440 years after closure. This HI is less than the target HI of 1. The key contributing chemicals at all times are fluoride (27% contribution), nitrite (54% contribution), nitrate (11% contribution), and cyanide (8% contribution). A summary of the peak chemical non-cancer hazard quotients and time of peak occurrence is presented in Table 7-13. Additionally, Table 7-14 presents a summary of chemical non-cancer hazard quotients and time of peak for all PoCs.

Figure 7-39. Comparison of Base Case and DIF1, DIF2, DIF3 Case (a) Technetium-99 Concentration at 100 meter Boundary (b) Technetium-99 Release to Vadose Zone from Tank 241-C-105.

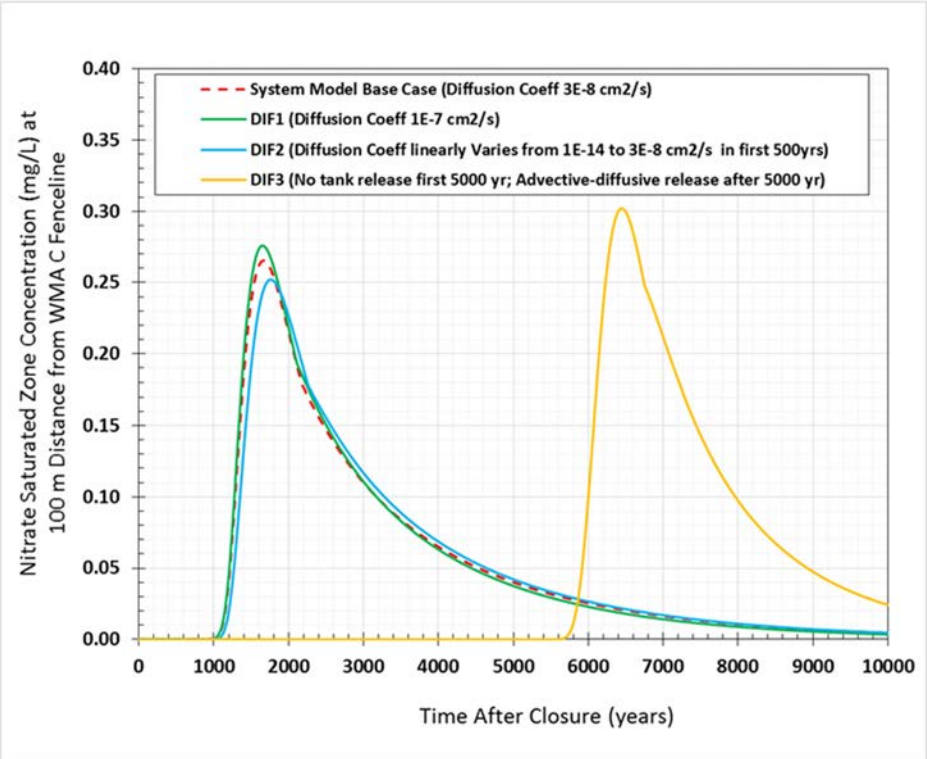


(a)

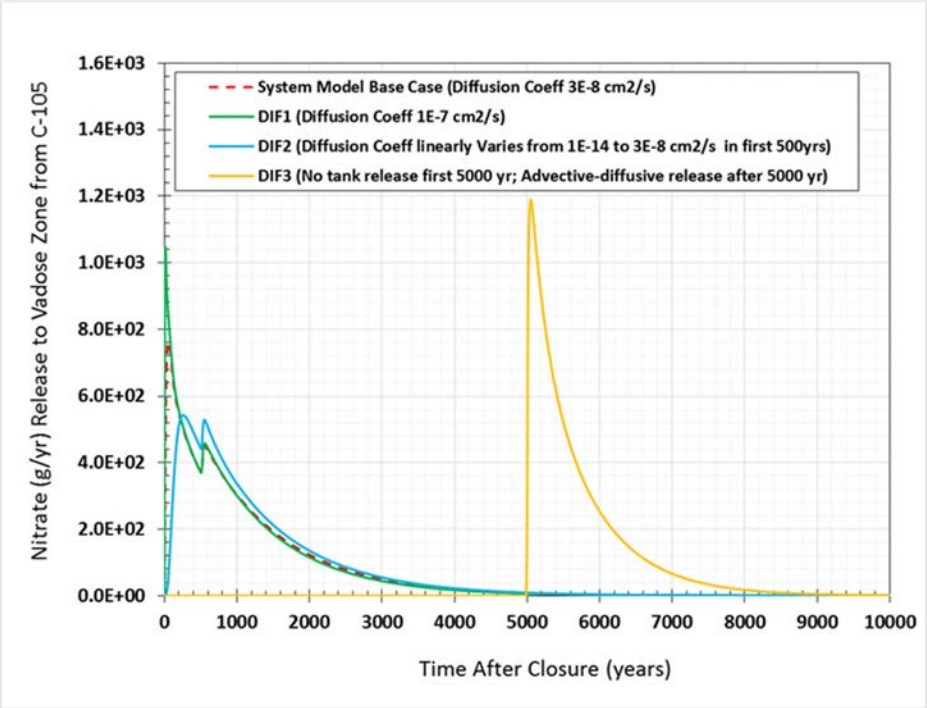


(b)

Figure 7-40. Comparison of Base Case and DIF1, DIF2, DIF3 Case (a) Nitrate Concentration at 100 meter Boundary (b) Nitrate Release to Vadose Zone from Tank 241-C-105.



(a)



(b)

Figure 7-41. Sensitivity Case Showing the Results of Peak Groundwater Pathway Dose Calculations.

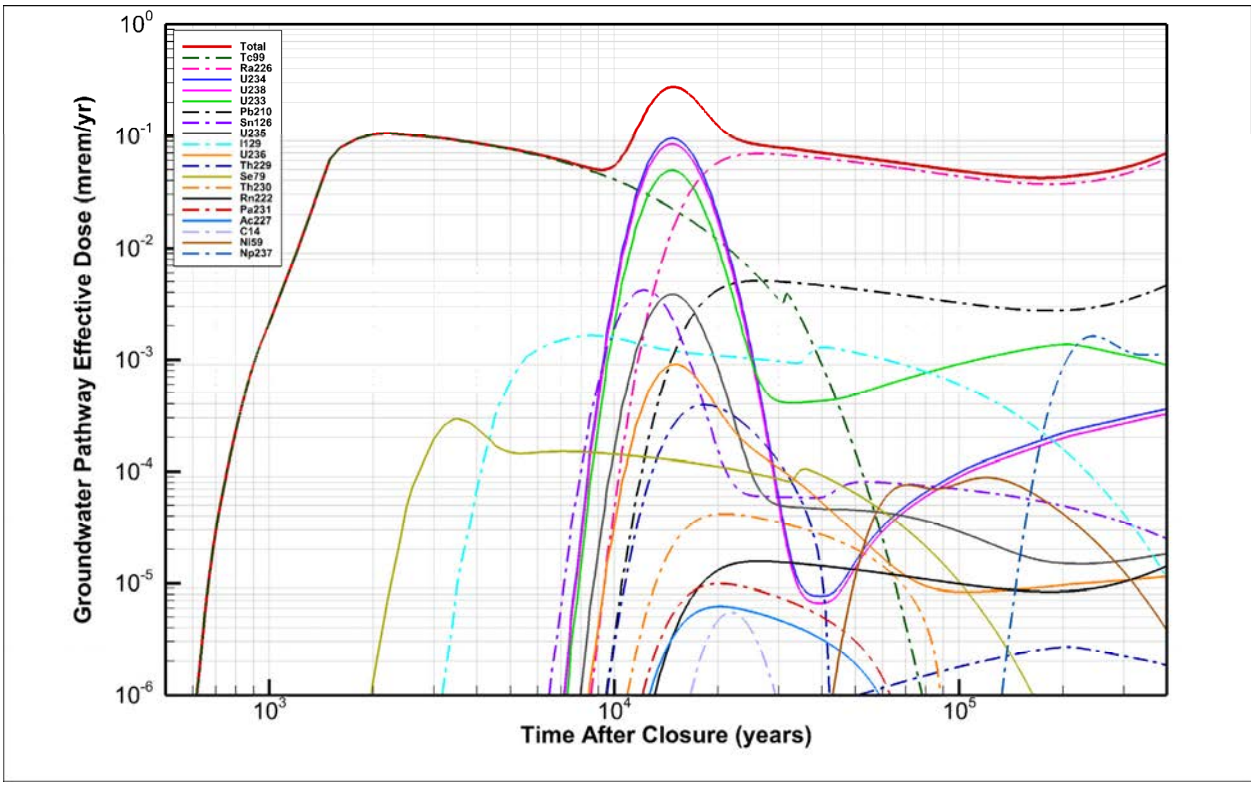


Table 7-6. Inventory Estimate Sensitivity Evaluation (Technetium-99).

Inventory	Sensitivity Case Shorthand	Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure)	Maximum Concentration at Downgradient Point of Calculation (pCi/L)
System model base case*	Base case	2,030	32
Upper bound Inventory for Technetium-99	INV1	2,480	144

*The base case analysis was run using the system model for this comparison. The results differ slightly from the base case analysis results from Subsurface Transport Over Multiple Phases (STOMP)© (copyrighted by Battelle Memorial Institute, 1996).

Table 7-7. Grout Flow Safety Function Sensitivity Evaluation (Technetium-99).

Tank Degradation Time	Sensitivity Case Shorthand	Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure)	Maximum Concentration at Downgradient Point of Calculation (pCi/L)
System model base case*	Base case	2,030	32
Tank Degrades at 5,000 yr	GRT1	2,030	32
Tank Degrades at 1,000 yr	GRT2	2,630	43
Tank Degrades at 500 yr	GRT3	2,190	45
Tank Degrades at 0 yr	GRT4	1,520	46

*The base case analysis was run using the system model for this comparison. The results differ slightly from the base case analysis results from Subsurface Transport Over Multiple Phases (STOMP)© (copyrighted by Battelle Memorial Institute, 1996).

Table 7-8. Grout Flow Safety Function Sensitivity Evaluation (Nitrate).

Tank Degradation Time	Sensitivity Case Shorthand	Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure)	Maximum Concentration at Downgradient Point of Calculation (mg/L)
System model base case	Base case	1,670	0.26
Tank Degrades at 5,000 yr	GRT1	1,670	0.26
Tank Degrades at 1,000 yr	GRT2	1,670	0.27
Tank Degrades at 500 yr	GRT3	1,710	0.30
Tank Degrades at 0 yr	GRT4	1,300	0.64

Table 7-9. Residual Chemistry Safety Function.

Residual Chemistry	Sensitivity Case Shorthand	Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure)	Maximum Concentration at Downgradient Point of Calculation (pCi/L)
System model base case for technetium-99*	Base case	2,030	32
100% Instantaneous release fraction for technetium-99	RLS1(technetium-99)	2,030	32
Solubility Limited release for Uranium	RLS1(Uranium-238)	Maximum concentration did not arrive within 10,000 years	Maximum concentration did not arrive within 10,000 years

*The base case analysis was run using the system model for this comparison. The results differ slightly from the base case analysis results from Subsurface Transport Over Multiple Phases (STOMP)© (copyrighted by Battelle Memorial Institute, 1996).

Table 7-10. Tank Flow Safety Function Sensitivity Evaluation (Technetium-99).

Tank Flow	Sensitivity Case Shorthand	Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure)	Maximum Concentration at Downgradient Point of Calculation (pCi/L)
System model base case *	Base case	2,030	32
Diffusion coefficient 1E-7 cm^2/s	DIF1	1,920	34
Linearly changing diffusion coefficient over 500 years from 1E-14 to 3E-8 cm^2/s	DIF2	2,230	31
Tanks remain intact (no release) for 5,000 years, followed by advective release beginning immediately.	DIF3	6,930	44

*The base case analysis was run using the system model for this comparison. The results differ slightly from the base case analysis results from Subsurface Transport Over Multiple Phases (STOMP)© (copyrighted by Battelle Memorial Institute, 1996).

Table 7-11. Tank Flow Safety Function Sensitivity Evaluation (Nitrate).

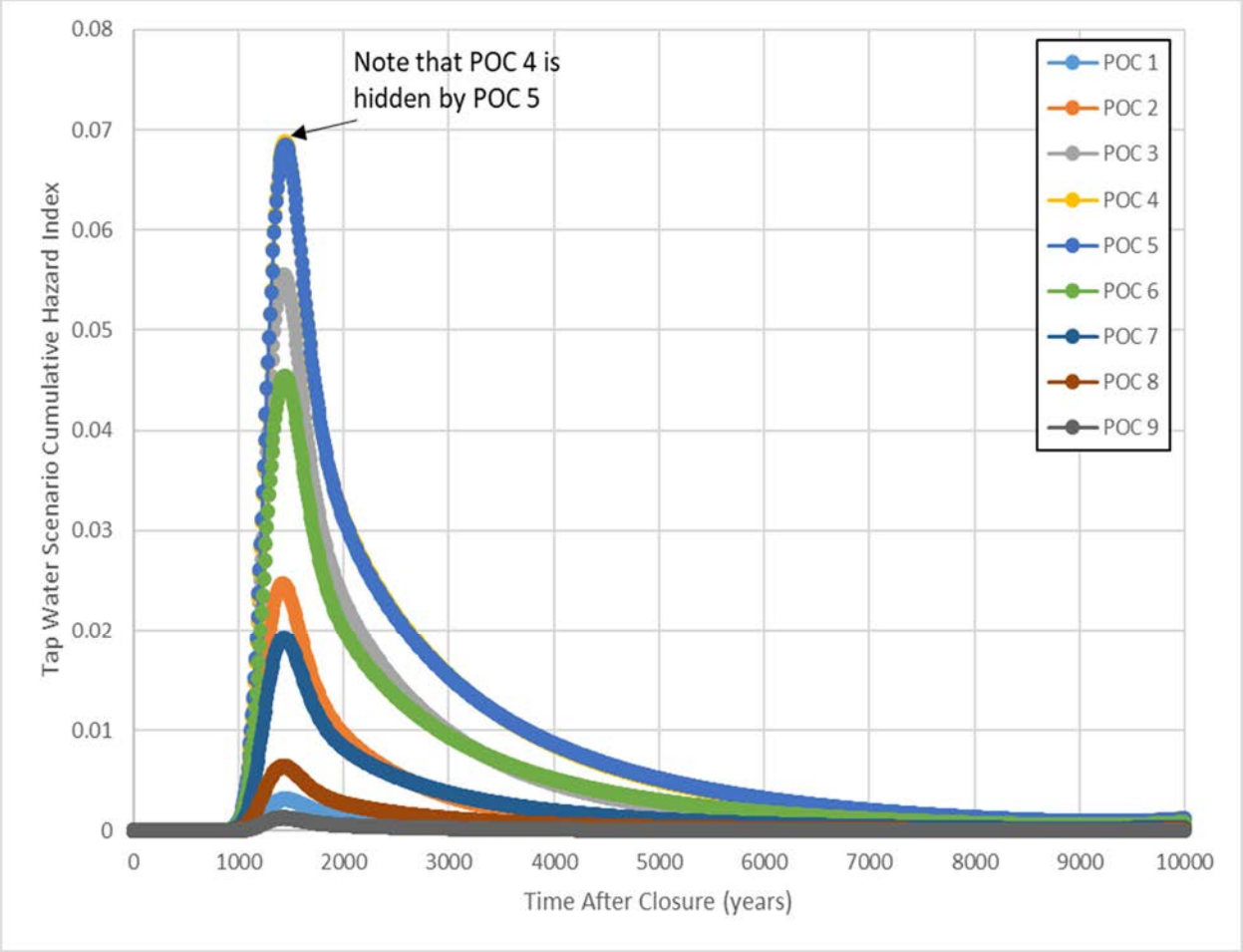
Tank Flow	Sensitivity Case Shorthand	Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure)	Maximum Concentration at Downgradient Point of Calculation (mg/L)
System model base case*	Base case	1,670	0.26
Diffusion coefficient 1E-7 cm^2/s	DIF1	1,650	0.27
Linearly changing diffusion coefficient over 500 years from 1E-14 to 3E-8 cm^2/s	DIF2	1,760	0.25
Tanks remain intact (no release) for 5,000 years, followed by advective release beginning immediately	DIF3	6,450	0.30

*The base case analysis was run using the system model for this comparison. The results differ slightly from the base case analysis results from Subsurface Transport Over Multiple Phases (STOMP)© (copyrighted by Battelle Memorial Institute, 1996).

Table 7-12. Summary of Peak Total Radiological Cancer Risk and the Time of Occurrence for All Radionuclides Giving Nonzero Risk in the Base Case Analysis.

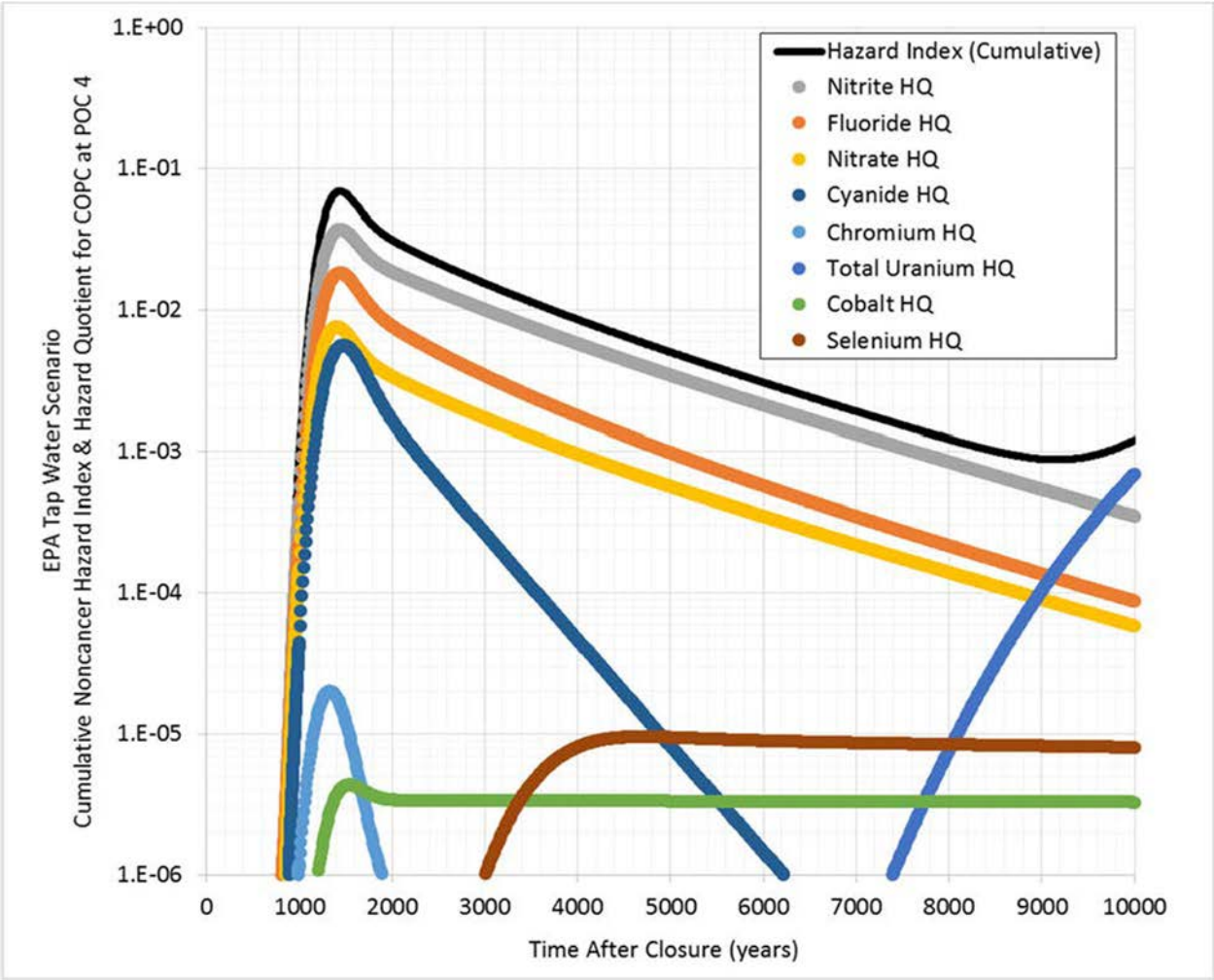
Radionuclide	Peak Total Risk	Time of Peak (years)	Peak Total Risk at 1,000 years
I-129	1.2E-8	6,430 to 6,650	0
Se-79	1.5E-9	3,690 to 3,820	0
Sn-126	2.3E-8	10,000	0
Tc-99	1.6E-6	1,530 to 1,570	6.2E-9
U-233	1.0E-8	10,000	0
U-234	2.0E-8	10,000	0
U-235	8.4E-10	10,000	0
U-236	1.7E-10	10,000	0
U-238	2.4E-8	10,000	0

Figure 7-42. EPA Tap Water (Residential) Scenario Cumulative Non-Cancer Hazard Index as a Function of Time for All Points of Calculation at the 100-meter Distance.



EPA = U.S. Environmental Protection Agency POC = Point of Calculation

Figure 7-43. EPA Tap Water (Residential) Scenario Cumulative Non-Cancer Hazard Index and Hazard Quotient for Each Constituent of Potential Concern for the Peak Groundwater Concentration at Point of Calculation 4.



EPA = U.S. Environmental Protection Agency HQ = Hazard Quotient POC = Point of Calculation

Table 7-13. Summary of Peak Chemical Hazard Quotients and Time of Occurrence for All Chemicals Giving Nonzero Hazard in the Base Case Analysis.

Chemical	Peak Hazard Quotient[1]	Time of Peak (years)	Peak Non-cancer Hazard Quotient at 1,000 years
Total Chromium[2, 3]	0.00002	1,330	0.0000012
Fluoride	0.018	1,440	0.00024
Nitrite	0.037	1,440	0.00044
Nitrate	0.0076	1,410	0.00015
Cobalt	0.0000044	1,540	0.000000025
Cyanide	0.0056	1,470 to 1,480	0.000044
Selenium	0.0000096	4,700	0
Tin	6.6E-11	10,000	0
Uranium	0.0007	10,000	0

[1]Peak hazard quotient is the peak throughout Waste Management C.

[2]The peak hazard quotient for chromium provided here is based on an estimated inventory for total chromium. If all of the total chromium inventory is assumed to be hexavalent chromium, the peak chemical hazard quotient would be 0.01, which occurs at about 1,330 years after closure.

[3] The hazard quotient for hexavalent chromium was calculated by using an RfDo of 0.003 mg/kg-day in the system model excel input file “Tapwater_Scenario_Parameters” sheet “nonrad Tox & Chemic-spec values.

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Table 7-14. Summary of Peak Chemical Hazard Quotients and Time of Occurrence for All Chemicals Giving Nonzero Hazard in the Base Case Analysis.

Constituent of Potential Concern	Point of Calculation 1		Point of Calculation 2		Point of Calculation 3		Point of Calculation 4		Point of Calculation 5		Point of Calculation 6		Point of Calculation 7		Point of Calculation 8		Point of Calculation 9	
	Hazard Quotient	Peak Year	Hazard Quotient	Peak Year	Hazard Quotient	Peak Year	Hazard Quotient	Peak Year	Hazard Quotient	Peak Year	Hazard Quotient	Peak Year	Hazard Quotient	Peak Year	Hazard Quotient	Peak Year	Hazard Quotient	Peak Year
Chromium	7.9E-06	1,420 – 1,430	1.2E-05	1,330	1.6E-05	1,310 – 1,320	2.0E-05	1,330	***2.2E-05***[a, b]	1,330	1.6E-05	1,320 – 1,330	7.3E-06	1,320	2.7E-06	1,310	5.8E-07	1,310
Cobalt	4.7E-08	1,580	4.3E-07	1,540 – 1,550	1.3E-06	1,530	4.4E-06	1,540	**7.9E-06**	1,530 – 1,540	7.0E-06	1,490	4.4E-06	1,450	2.0E-06	1,430 – 1,440	4.9E-07	1,430
Cyanide	2.8E-05	1,450 – 1,460	3.4E-04	1,440	0.0017	1440-1,450	0.0056	1,470 – 1,480	***0.0095***	1,500	0.0072	1,500	0.003	1,500	9.5E-04	1,490	1.8E-04	1,490
Fluoride	0.0012	1,490 – 1,500	0.0058	1,460	0.014	1,450	0.018	1,440	***0.020***	1,430	0.015	1,420 – 1,430	0.0067	1,420	0.0023	1,410 – 1,420	4.8E-04	1,410
Nitrate	5.5E-04	1,360 – 1,370	0.0058	1,360	0.094	1,370	0.0076	1,410	***0.0076***	1,420	0.0058	1,410	0.0028	1,410	9.3E-04	1,410	1.9E-04	1,400 – 1,410
Nitrite	0.0014	1,430	0.013	1,420	0.031	1,430	**0.037**	1,440	*0.032*	1,440	0.018	1,420	0.0070	1,420	0.0022	1410-1420	4.3E-04	1,410
Selenium	4.8E-08	4,650 – 4,710	4.7E-07	4,610 – 4,650	1.9E-06	4,610 – 4,680	9.6E-06	4,700	**1.8E-05**	4,680 – 4,740	1.3E-05	4,630 – 4,760	6.5E-06	4,590 – 4,650	2.7E-06	4,490 – 4,560	6.9E-07	4,360 – 4,440
Tin	1.7E-12	10,000	1.5E-11	10,000	3.6E-11	10,000	6.6E-11	10,000	1.1E-10	10,000	**1.1E-10**	10,000	8.5E-11	10,000	4.1E-11	10,000	1.1E-11	10,000
Uranium	1.7E-04	10,000	6.67E-04	10,000	**8.3E-04**	10,000	7.0E-04	10,000	1.7E-04	10,000	4.9E-04	10,000	2.5E-04	10,000	9.7E-05	10,000	2.2E-05	10,000
Total Hazard Index[c]	3.13E-03	1,440-1450	2.47E-02	1,440	5.55E-02	1,440	6.88E-02	1,440	6.85E-02	1,440	4.54E-02	1,440	1.92E-02	1,440	6.40E-03	1,440	1.28E-03	1,440

[a] The hazard quotients for chromium listed here are based on an estimated inventory for total chromium. In the base case, if all of the total chromium is assumed to be hexavalent chromium, the peak chemical hazard quotient at Point of Calculation 4 would be about 0.01, which occurs at about 1,330 years after closure.

[b] The hazard quotient for hexavalent chromium was calculated by using an RfDo of 0.003 mg/kg-day in the system model excel input file "Tapwater_Scenario_Parameters" sheet "nonrad Tox & Chemic-spec values.

[c] The total hazard index is given at the approximate time of the peak hazard index, it is not the sum of the peak hazard quotient, because the peaks do not always coincide.

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8.0 MODEL CONFIGURATION MANAGEMENT

All inputs and outputs for the development of WMA C PA models are committed to the Environmental Model Management Archive (EMMA) to maintain and preserve configuration managed models. Inputs include the input files used in the GoldSim© simulations. Basis information (that information collected to form the basis for model input parameterization) is also stored in the EMMA for traceability purposes.

During the checking process, an implementation error was identified in the scaling vector element whose values vary by the radionuclide and are either set to 0 or 1. This scaling vector is used in the calculation of inhalation dose coefficient for volatile radionuclides when inhaled with water vapor when water is taken from the pumping well located at the PoC (100 m downgradient from the WMA C fenceline). In this vector a value of 1 is applied to volatile radionuclides while a value of 0 is applied to the rest of the radionuclides. Due to the error, a value of 1.5 (instead of 1) was applied to ^{3}H in the vector element. There is no impact of this error on the dose as this calculation is only used in the groundwater pathway, and due to short half-life of ^{3}H, it is not a dose contributor to the groundwater pathway.

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ATTACHMENT 1

SOFTWARE INSTALLATION AND CHECKOUT FORMS

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CHPRC SOFTWARE INSTALLATION AND CHECKOUT FORM

Software Owner Instructions:

Complete Fields 1-13, then run test cases in Field 14. Compare test case results listed in Field 15 to corresponding Test Report outputs. If results are the same, sign and date Field 19. If not, resolve differences and repeat above steps.

Software Subject Matter Expert Instructions:

Assign test personnel. Approve the installation of the code by signing and dating Field 21, then maintain form as part of the software support documentation.

GENERAL INFORMATION:

1. Software Name: GoldSim Pro Software Version No.: 11.1.2

EXECUTABLE INFORMATION:

2. Executable Name (include path):

   Directory Path Redacted for Public Release

3. Executable Size (bytes): 1,718 KB

COMPILATION INFORMATION:

4. Hardware System (i.e., property number or ID):

   Compiled by vendor

5. Operating System (include version number):

   Windows 7 Professional

INSTALLATION AND CHECKOUT INFORMATION:

6. Hardware System (i.e., property number or ID):

   INTERA:00606

7. Operating System (include version number):

   Windows 7 Professional

8. Open Problem Report? ◉ No ○ Yes PR/CR No.

TEST CASE INFORMATION:

9. Directory/Path:

   Directory Path Redacted for Public Release

10. Procedure(s):

    per CHPRC-00224 Rev 1, GoldSim Pro Software Test Plan

11. Libraries:

    N/A

12. Input Files:

    FirstModel.gsm

13. Output Files:

    FirstModel.gsm

14. Test Cases:

    GS-ITC-1

15. Test Case Results:

    Match expected results as presented in CHPRC-00224 Rev 1, GoldSim Pro Software Test Plan

16. Test Performed By: N. Hasan

17. Test Results: ◉ Satisfactory, Accepted for Use ○ Unsatisfactory

18. Disposition (include HISI update):

    Accepted; installation added to HISI Entry

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CHPRC SOFTWARE INSTALLATION AND CHECKOUT FORM (continued)

1. Software Name: GoldSim Pro Software Version No.: 11.1.2

Prepared By:

19.	William E. Nichols (Digitally signed by William E. Nichols, Modeling Integration, Date: 2015.09.22 10:41:05 -07'00')	WE Nichols	
	Software Owner (Signature)	Print	Date

20. Test Personnel:

Rezwanul Hasan	N. Hasan	09-22-2015
Sign	Print	Date
Sign	Print	Date
Sign	Print	Date

Approved By:

21.		N/R per SMP	
	Software SME (Signature)	Print	Date

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ATTACHMENT 2

CHECKER LOGS

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1.0 Check of RPP-CALC-60451, Rev. 0a

1.1 Scope

Inadvertent intruder acute dose for the well driller scenario for the pipeline source in Table 7-1 and in Figures 7-12 and 7-13b. Figures 7-12 through 7-21 were all updated for a consistent presentation of inadvertent intruder results.

RPP-CALC-60451 and associated model were completely checked prior to the release of revision 0, therefore checking of revision 0a is limited to the items identified above.

1.2 Method

The WMA C PA system model (WMA_C_PA_System_Model_Rev1.gsm) was copied from the Environmental Model Management Archive (EMMA). Results from inadvertent intrusion into a fully-plugged pipeline were exported from the GoldSim model and multiplied in Microsoft Excel by 0.05 to represent the 20 times reduction in inventory that would be in a pipeline 5% full of waste. Those calculation results were then charted and compared to the new charts in Figures 7-12 through 7-21. The value for acute dose for the well driller scenario in table 7-1 was verified using the exported model results.

1.3 Results

The new dose over time charts for intruder scenarios in the EMCF RPP-CALC-60451 were compared with independently charted results exported from the same GoldSim model and found to match exactly. Additionally, pipeline results in table 7-1 of RPP-CALC-60451 were compared with the GoldSim results and found to match exactly.

Watson, David J

Digitally signed by Watson, David J
Date: 2020.11.17 11:53:20 -08'00'

Checker Log Supporting Revision 0A of RPP-CALC-60451
Changes to Tap Water Non-Cancer Hazard Results in Section 7.8.2

1.0 Scope

This checker's log focused on checking updates made to Section 7.8.2 (Summary of Tap water Non Cancer Hazards) that include text changes, minor modification of Table 7-13, the addition of Table 7-14, and the addition of Figures 7-42 and 7-43.

RPP-CALC-60451 and associated model were completely checked prior to the release of revision 0, therefore checking of Revision 0A is limited to the items identified above.

2.0 Method

The WMA C PA system model (WMA_C_PA_System_Model_Rev1.gsm) was copied from the Environmental Model Management Archive (EMMA) found in the RPP-CALC-60451, Rev. 0 within the Application folder. The tap water hazard index was calculated by calculating the hazard index at each point of calculation. The time history results were exported to excel to check Figure 7-42 in the EMCF.

The same WMA C PA system model was used to calculate the hazard quotients for individual contaminants from Tables 7-13 and 7-14 for each point of calculation. Time history results of hazard quotients were then exported to excel for each point of calculation. The hazard quotients and associated times of peak HQ results were compared to the equivalent model results summarized in Tables 7-13 and 7-14. Results of these calculations were also charted and compared to the equivalent results provided in Figure 7-43.

The hexavalent chromium hazard quotient was checked at POC 4 by following the methodology found in Table 7-13, footnote #3. Hexavalent chromium was checked by changing the RfDo from 1.5 mg/kg-day (chromium) to RfDo 0.003 mg/kg-day in the excel file "Tapwater_Scenario_Parameters" sheet "Nonrad Tox & Chem-spec values" and re-running the model. Hexavalent chromium hazard quotient was compared to the footnotes found in Tables 7-13 and 7-14.

3.0 Results

Tap water hazard quotients and hazard indices in Tables 7-13 and 7-14 and Figures 7-42 and 7-43 compared favorably with independently tabulated and charted results exported from the same GoldSim model and found to match. Differences identified were attributed to the significant figures reported and rounding.

Singleton, Kristin M

Digitally signed by Singleton, Kristin M
Date: 2020.11.19 16:29:26 -08'00'