



Addendum to In-Situ Decommissioning Contaminant Migration Modeling of C-Reactor (105-C) – Updated Moderator Tank Inventory (U)

**SRNS-TR-2024-00495
Revision 0**

September 2024

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LIST OF ACRONYMS AND ABBREVIATIONS

Ac-227	actinium-227
Al	aluminum
Am-241	americium-241
C-14	carbon-14
CM	contaminant migration
Co-60	cobalt-60
COC	contaminants of concern
CP	compliance period
Cr	chromium
Cs-137	cesium-137
DoD	Department of Defense
DOE	Department of Energy
EC&ACP	Environmental Compliance and Area Completion Projects
Fe	iron
ft	feet
gal	gallon
GWPS	groundwater protection standard
H-3	tritium
I-129	iodine-129
ISD	In-Situ Decommissioning
K _d	soil-water distribution coefficient
L	liter
m	meter
MCL	maximum contaminant level
mL	milliliter
mL/g	milliliter per gram
mol/L	mole per liter
Ni-59	nickel-59
Ni-63	nickel-63
Np-237	neptunium-237
NRC	Nuclear Regulatory Commission
Pa-233	protactinium-231
Pb-210	lead-210
PCB	polychlorinated biphenyls
pCi/L	picocuries per liter
PO	performance objectives
POA	point of assessment

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POTM	peak of the means
Pu-238	plutonium-238
Pu-239/240	plutonium-239/240
Pu-241	Plutonium-241
Pu-242	plutonium-242
QA	quality assurance
QC	quality control
Ra-226	radium-226
Ra-228	radium-228
ROD	Record of Decision
Sr-90	strontium-90
SRNL	Savannah River National Laboratory
SRNS	Savannah River Nuclear Solutions, LLC
SRS	Savannah River Site
SWRI	Southwest Research Institute
TCLP	toxicity characteristic leaching procedure
Th-229	thorium-229
Th-230	thorium-230
Th-232	thorium-232
U-233	uranium-233
U-234	uranium-234
U-235	uranium-235
U-236	uranium-236
U-238	uranium-238
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
WSRC	Westinghouse Savannah River Company, LLC

1.0 INTRODUCTION

A fate and transport model using GoldSim[®] was developed which evaluated In-situ Decommissioning (ISD) alternatives for four (4) lead and radionuclide sources within C-Reactor of Savannah River Site (SRS) in August of 2023 (Tetra Tech 2023). One of the four sources modeled in the 2023 effort was moderator water (also known as heavy water) that is contained in Tank 204 and Tank 205, located in the Storage Tank Room of C-Reactor. Heavy water is deuterium oxide (D₂O), and deuterium (D) is an isotope of hydrogen containing one proton and one neutron in the nucleus. At the time the modeling effort was completed, data from the heavy water was limited to tritium (H-3) and gamma-spectroscopy (detections included cobalt-60 [Co-60] and cesium-137 [Cs-137]) most recently analyzed in 1996, which were all included in the simulated source term. To verify that there are no additional contaminant migration (CM) contaminants of concern (COCs) within the heavy water, a sampling effort was completed in early 2024 to analyze for radionuclides, toxicity characteristic leaching procedure (TCLP) metals, total metals, and polychlorinated biphenyls (PCBs). The data from that effort was input into the existing GoldSim[®] model for the heavy water source inventory, and the simulations were rerun to verify original conclusions of the ISD alternatives. The purpose of the model update, results of sampling, updated model results, and conclusions are discussed further in this addendum.

1.1 Background and History

The C-Reactor building (105-C; Figure 1) is currently used to store tritiated-heavy water in two storage tanks: Tank 204 and Tank 205. These tanks are located within the Storage Tank Room, below and between the C-Reactor Personnel and Disassembly Areas. The volume of heavy water within Tank 204 and Tank 205 is approximately 60,567 liters (L) and 102,206 L (16,000 gallons [gal] and 27,000 gal), respectively.

Upon completion of on-going missions at the C-Reactor building, the details of the final ISD remedy will be selected in the final C-Area Operable Unit Record of Decision (ROD) (ROD

issuance scheduled for 2044). To evaluate ISD alternatives for the heavy water tanks, a GoldSim[®] contaminant fate and transport model was developed by a subcontractor and simulations were run following United States Department of Energy (USDOE), Nuclear Regulatory Commission (NRC), and United States Environmental Protection Agency (USEPA) guidance, and adhering to the approved SRS Environmental Compliance and Area Completion Projects (EC&ACP) protocols (Tetra Tech 2023 and Savannah River Nuclear Solutions, LLC [SRNS] 2023). GoldSim[®] is a general-purpose simulator that allows the evaluation of complex processes in a deterministic or stochastic environment. In the context of this modeling effort, the GoldSim[®] model was used to evaluate ISD alternatives to help decision makers evaluate the preferred path forward based on the estimated impact to groundwater and surface water for the heavy water storage tanks. The model takes into account site specific data, events (e.g., building collapse), processes (e.g., solubility-limited release of radionuclides), and flow paths.

For the heavy water storage tanks, two ISD alternatives were considered which included: 1) No Action, and 2) Solidifying the heavy water within the tanks and grouting the space around the tanks (Tetra Tech 2023). The modeling approach and common global assumptions for the model were taken from a previous modeling effort completed by the subcontractor for F-Area Hardened Facilities (Tetra Tech 2020 and Tetra Tech 2021).

The GoldSim[®] model produced predictions of groundwater concentrations at various points of assessment (POAs) downgradient from the source area: 1.0 meter (m) (3.28 feet [ft]) from the source area, at the C-Area fence-line, and at the location where groundwater discharges to surface water at Castor Creek (Figure 2). Model-generated predictions were then compared against performance objectives (POs) as applied during relevant compliance periods (CPs) that extended to 10,000 years. POs for ISD alternatives for the heavy water source were to meet groundwater protection standards (GWPS) for all constituents within the CP at each POA. The peak of the means (POTM) result for 1,000 realizations of each constituent was used to assess the results. Simulations were extended up to 100,000 years to estimate POTM concentrations of certain constituents, when appropriate. GoldSim[®] includes calculation of radioactive decay and ingrowth

of radionuclide species. For the heavy water source, the list of contaminants included in the 2023 fate and transport modeling effort included only H-3, Cs-137, and Co-60.

The previous modeling effort resulted in POs met for radionuclides present in the heavy water source inventory for every combination of ISD alternatives and POAs. This outcome is due to the time (150 ± 50 years) to failure of the heavy water containment tanks combined with short half-lives for H-3, Co-60, and Cs-137. The 2023 model provided a good framework for evaluating groundwater concentrations resulting from sources identified at the C-Reactor building, including the heavy water source. The 2023 model report provided one recommended improvement to the model, which was to analyze the heavy water for additional radionuclide inventory that may be present and include the results in the source inventory of the model (Tetra Tech 2023). This was recognized as a limitation of the previous model due to the potential of long-lived radionuclides to reach groundwater at levels above GWPS, if present.

Following the recommendations of the 2023 fate and transport model, the heavy water tanks were sampled in early 2024 for a comprehensive list of radionuclides, TCLP metals, total metals, and PCBs. The additional analytical data was input into the existing fate and transport model and the results are presented in this addendum. Additional details on the 2023 modeling effort are provided in the modeling report (Tetra Tech 2023).

2.0 FATE AND TRANSPORT MODEL UPDATE

The 2023 fate and transport modeling of the ISD scenarios was conducted in GoldSim[®] to evaluate radionuclide transport from the heavy water source within the C-Reactor building to identified POAs (Figure 2). Inputs to the 2023 model were based on the best estimates of the inventory (Tetra Tech 2023), inputs from the C-Area groundwater model (Westinghouse Savannah River Company, LLC [WSRC] 2000), SRS Geochemical Database (Kaplan 2021), the Hydraulic Property Data Package (Phifer et al. 2006), previous flow and transport models developed by and for SRS (Council 2008, 2009; and Hamm et al. 2019), and infiltration rates (Tetra Tech 2021) to

estimate recharge fluxes through concrete at various stages of degradation and applying to ISD alternatives.

Updates to the fate and transport model presented in this addendum are focused on the inventory of the heavy water source. No updates were made to the lead sources for this effort. The conceptual site model (CSM, Figure 3), model structure, contaminant migration parameters, and soil properties were retained in the updated model, except where noted. For the two ISD alternatives, all assumptions remained the same (i.e., time steps for building degradation and tank failure, thickness of grout, etc.). In the CSM, and for conservatism, the two tanks were modeled as one tank containing the total volume (162,773 L [43,000 gal]) and total contaminant inventory.

2.1 Tank Sampling and Analysis

The two heavy water storage tanks were sampled in early 2024 to support updating the fate and transport model in accordance with the *Sample and Analysis Plan for the C Area Moderator* (SRNS 2024). Sampling was performed using 118 milliliter (mL) bacon bomb samplers (grab sampler). Two sets of samples were collected from each heavy water tank, total of four samples, for analyses. For the first set of samples, 118 mL of heavy water was collected from eight depths within each tank using the bacon bomb sampler and combined for a 944 mL composite sample from each tank. The first set of samples were sent to Savannah River National Laboratory (SRNL) for radiological analyses. The second set of samples consisted of two 100 mL composite samples, collected from seven depths within each heavy water tank. The second set of samples were sent to Southwest Research Institute (SWRI) for TCLP metals, total metals, and PCB analyses.

SWRI performed analyses, quality assurance (QA)/quality control (QC), and data processing in accordance with the *Department of Defense (DoD)/Department of Energy (DOE) Consolidated Quality Systems Manual (QSM) for Environmental Laboratories* (Department of Defense [DoD]/Department of Energy [DOE] 2021). Based on SWRI QA/QC, all TCLP metals, total metals, and PCB results are valid and are of sufficient quality for use in the contaminant fate and transport model. All TCLP metals and PCB results were below detection limits in the analyzed

samples and therefore were not included in the model update. There were three metals detected in the total metals suit including aluminum (Al), chromium (Cr), and iron (Fe) (Table 1). The three detected metals were included in the model update.

Data received from SRNL were verified in accordance with their *Task Technical and Quality Assurance Plan for Routine Analytical Laboratory Support* (SRNL 2024b) for the two composite samples from each heavy water storage tank. The SRNL QA plan follows the requirements defined in SRS Manual 1Q, Procedure 2-7, *QA Program Requirements for Analytical Measurement Systems*, including the Special QA Program Requirements for ANSI/ASQ E4, NNSA NAP-24, and DOE/RW-0333P (SRNL 2024a). All radionuclide results from SRNL are valid and of sufficient quality for use in the contaminant fate and transport model. The SRNL results are presented in Table 1 along with respective GWPS. Radionuclides with results that were above the GWPS, or detected results for species with long-lived daughters, were input in the heavy water source inventory to be modeled. Radionuclide results that exceeded their respective GWPS included: americium-241 (Am-241), carbon-14 (C-14), Co-60, Cs-137, H-3, nickel-59 (Ni-59), nickel-63 (Ni-63), plutonium-238 (Pu-238), plutonium-239/2340 (Pu-239/240), and strontium-90 (Sr-90). Radionuclides that were detected below their GWPS, but have long-lived daughters with GWPS included: neptunium-237 (Np-237), plutonium-242 (Pu-242), uranium-235 (U-235), uranium-236 (U-236), and uranium-238 (U-238). Iodine-129 (I-129) was not detected in either sample with a minimum detectable activity of 5.14 picocuries per liter (pCi/L).

2.2 GoldSim® Model Update

New data from the 2024 sampling effort of the two heavy water storage tanks in C-Reactor were input into the GoldSim® model developed by a subcontractor for the C-Reactor building. As part of the subcontractor's scope in development of the initial GoldSim® model, placeholders were built in to allow a user to update the source inventory as new data became available. The existing GoldSim® model was used as a starting point, with updates to the model as follows in this section.

Within the *Materials* bin of the GoldSim[®] model, C-14, Ni-59, and Ni-63 were added to the list in *Species* (Figure 4). These radionuclides were not selected as placeholders in the previous model by the subcontractor. All radionuclides are included as part of the radioactive transport package in GoldSim[®] with the option to include or remove them from the model simulations. Half-life values were added for the three new radionuclides in *HalfLives* (Figure 5). The half-lives are used to correct, through radioactive decay and ingrowth of daughter radionuclides, source inventory through radioactive decay and ingrowth of daughter radionuclides based on date of sampling and assumed date of closure.

For new elements carbon and nickel, properties were updated in the GoldSim[®] model including soil-water distribution coefficients (K_d), oxidizing concrete solubilities, and cement leachate impact factors (Figure 6 and Table 2). Consistent with the previous modeling effort, all values in Table 2 were taken from the *Geochemical Data Package for Performance Assessment Calculations Related to the Savannah River Site* (Kaplan 2021).

In the *Transport* bin, a cell (*Sink*) and a function (*Mass_Flux*) were added to the model structure to remove all zero mass values that were created by the heavy water storage tanks during simulations (Figure 7). Negative mass is sometimes created at the *Source_Tanks* cell due to the low initial mass of some radionuclides. Negative mass results in fatal errors that abort simulations during a run of the model. The function that follows the *Source_Tanks* cell moves all constituents with negative mass to the *Sink* cell for each realization.

Table 1 provides a summary of inventory inputs for each of the newly considered radionuclides in the model. Source masses for detected radionuclides to be considered and for the three detected metals were input into *Inventory_Tanks* (Figure 8) based on concentration results of the 2024 sampling effort and assuming a total heavy water volume of 162,773 L (43,000 gal).

2.3 Simulation Results

The updated fate and transport model was run for 100,000 years to ensure peaks were seen for long-lived and mobile radionuclides simulated. 1,000 realizations were run in the simulation. Figure 9 presents a time-series plot for tritium over the first 1,000 years of the simulation at the 1.0 m (3.28 ft) POA for ISD alternative one, indicating a POTM activity concentration of 3.06E-06 pCi/L at 700 years. The results are consistent with the original model results from the subcontractor that indicated a POTM activity concentration of 4.64E-07 pCi/L at 700 years (Tetra Tech 2023 and Figure 10). Tritium in the updated model is predicted to remain below the MCL of 20,000 pCi/L for all ISD alternatives and all POAs.

Table 3 presents the POTM results for all modeled constituents in the 100,000 year simulation for ISD alternative one at the 1.0 m (3.28 ft) POA. There are no predicted exceedances of GWPS for any radionuclides or metals.

3.0 CONCLUSIONS

Based on the results of the updated GoldSim[®] model, the No Action ISD alternative will not exceed GWPS for any constituent detected in the heavy water tanks at all POAs and within all CPs considered. Tritium results from the updated GoldSim[®] model validate the model structure has not changed from the previous modeling effort completed by the subcontractor. Based on these results, the primary CM COC in the heavy water tank source is tritium. The model results are based on the long-time (150 ± 50 years) to failure of the steel storage tanks and the short half-life of H-3, Co-60, and Cs-137. This addendum supports the conclusions of the previous modeling effort and shows that all ISD alternatives for the heavy water source in C-Reactor will meet POs at all considered POAs.

Based on these conclusions, in consideration of CM COCs, it is recommended that the heavy water be left in containment within the steel storage tanks in the C-Reactor Storage Tank Room. Any

additional action taken (i.e., grouting the space surrounding the storage tanks, solidifying the heavy water, etc.) would be conservative and would further support meeting all CM COC POs.

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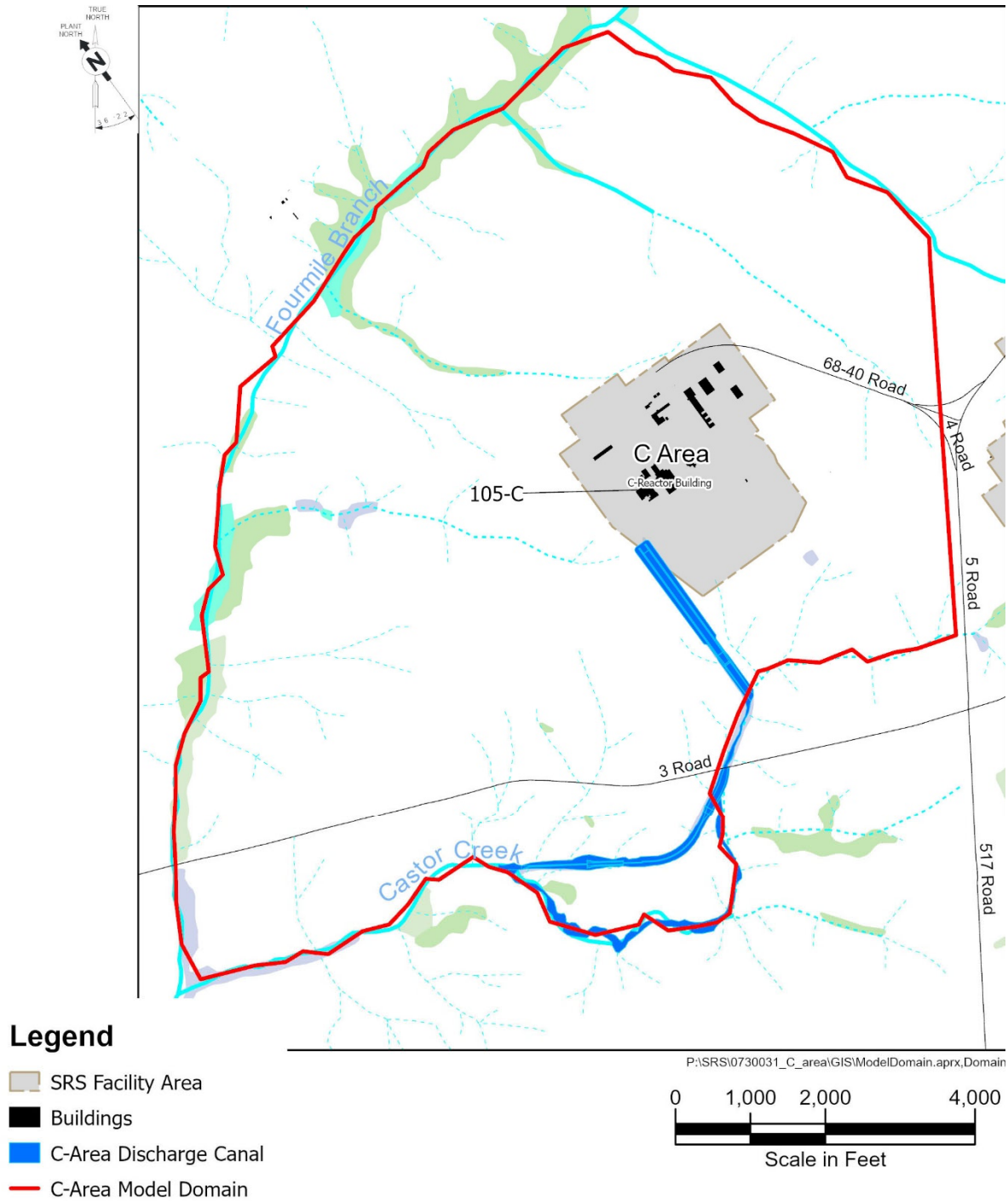


Figure 1. Location Map of C-Reactor Building (105-C)

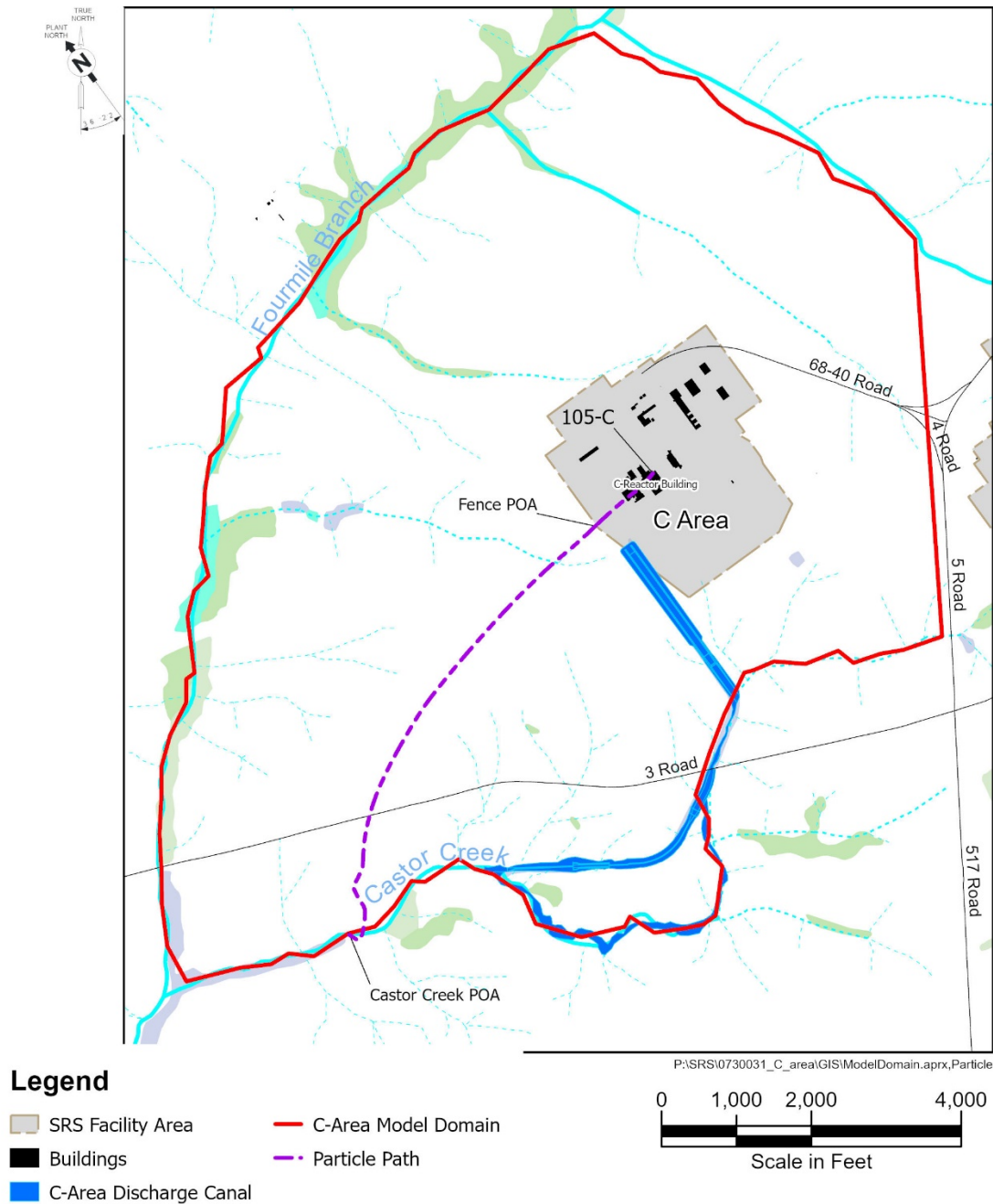


Figure 2. Particle Tracking and POA Locations for C-Reactor Heavy Water Source

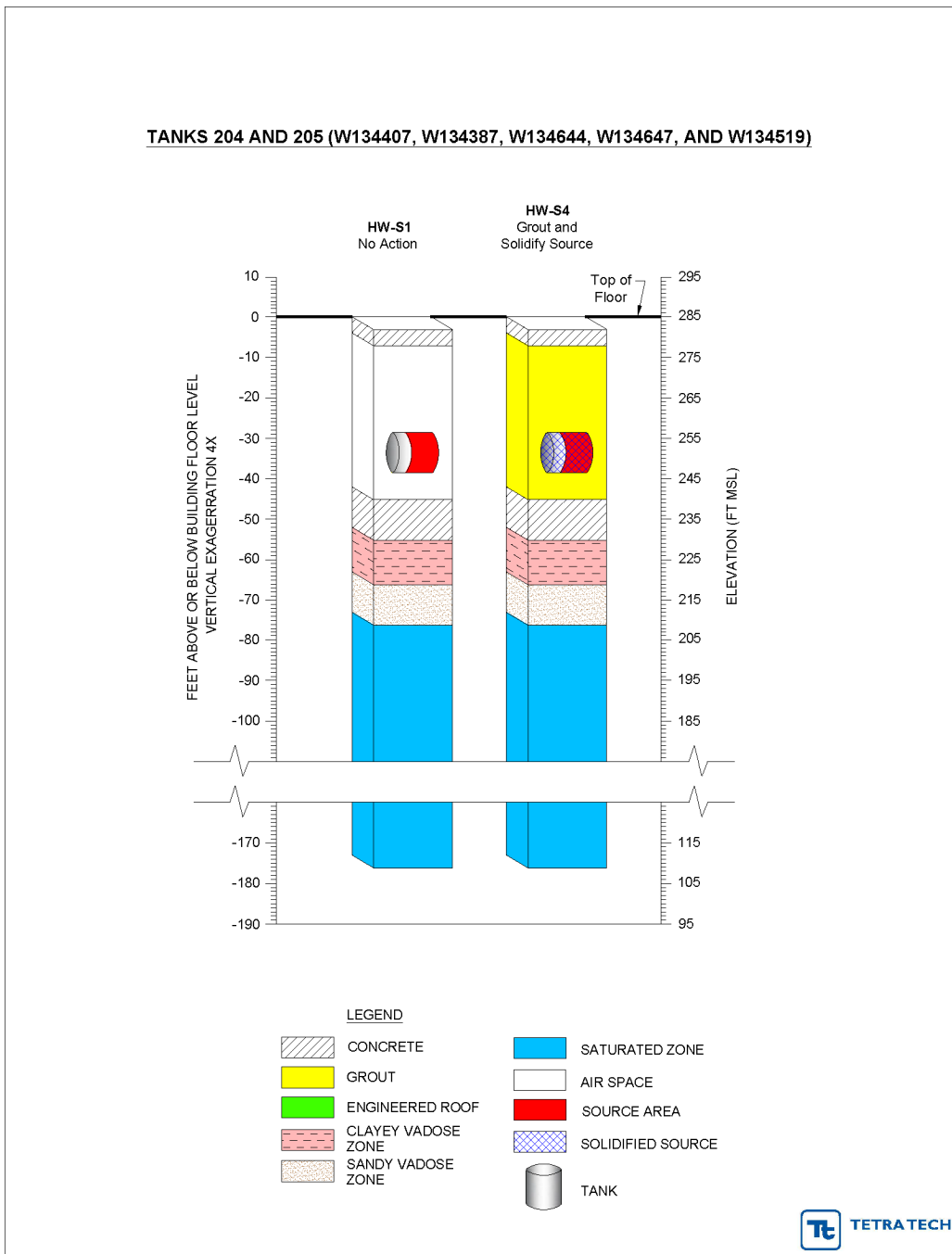


Figure 3. Conceptual Site Model for Tanks 204 and 205

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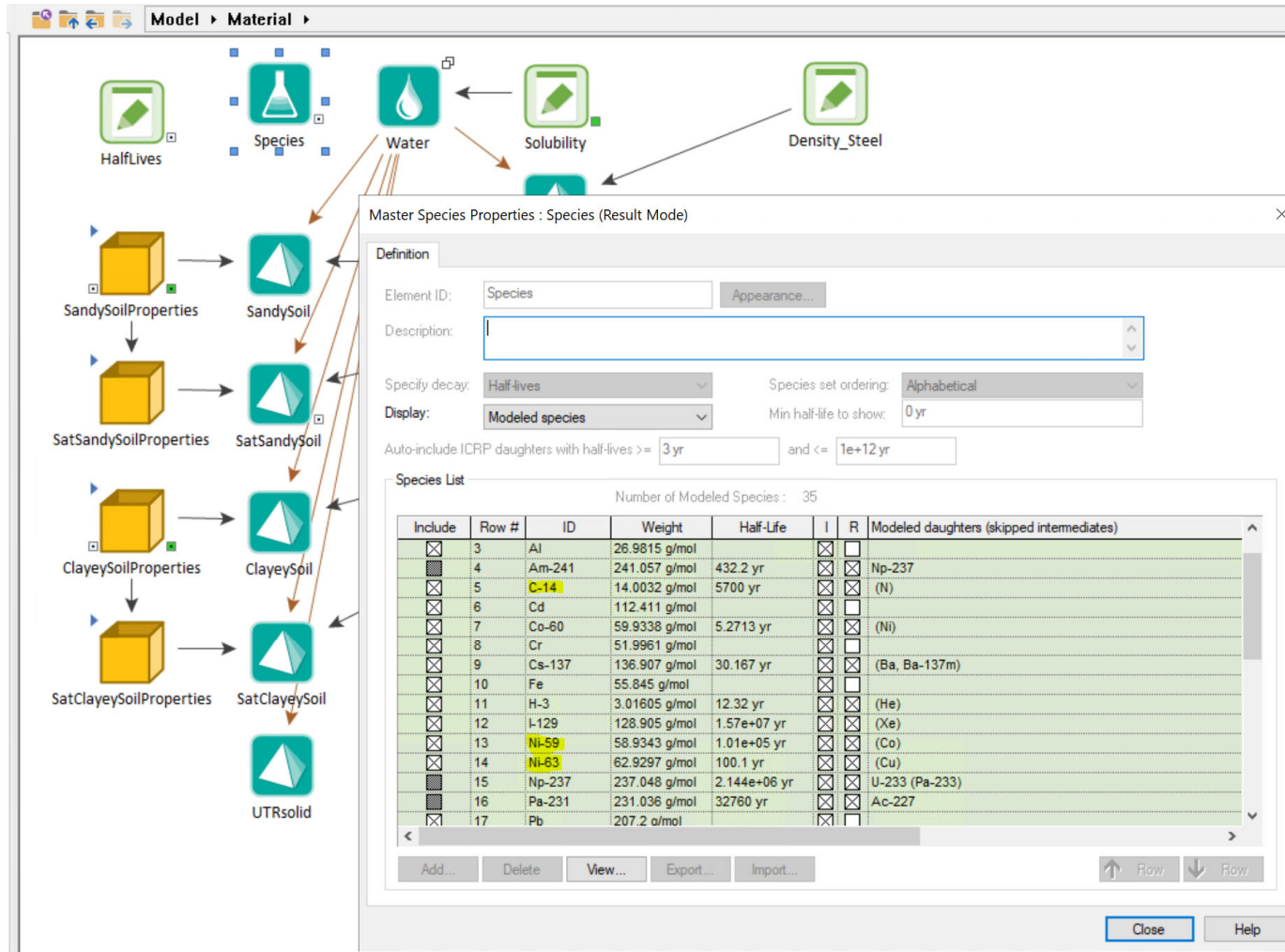


Figure 4. Added C-14, Ni-59, and Ni-63 to Species in GoldSim® Model

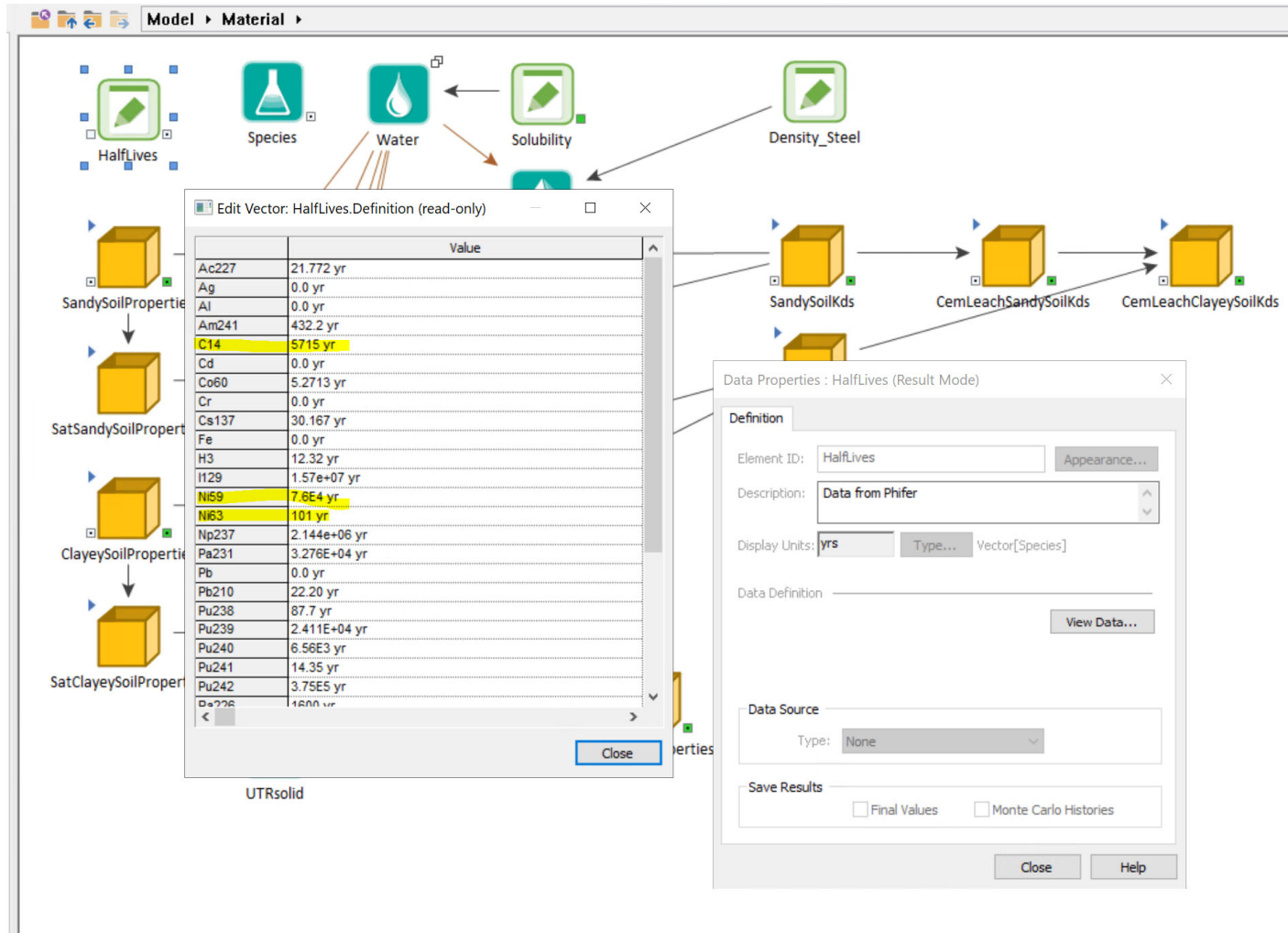


Figure 5. Updated Values in *HalfLives* in GoldSim® Model

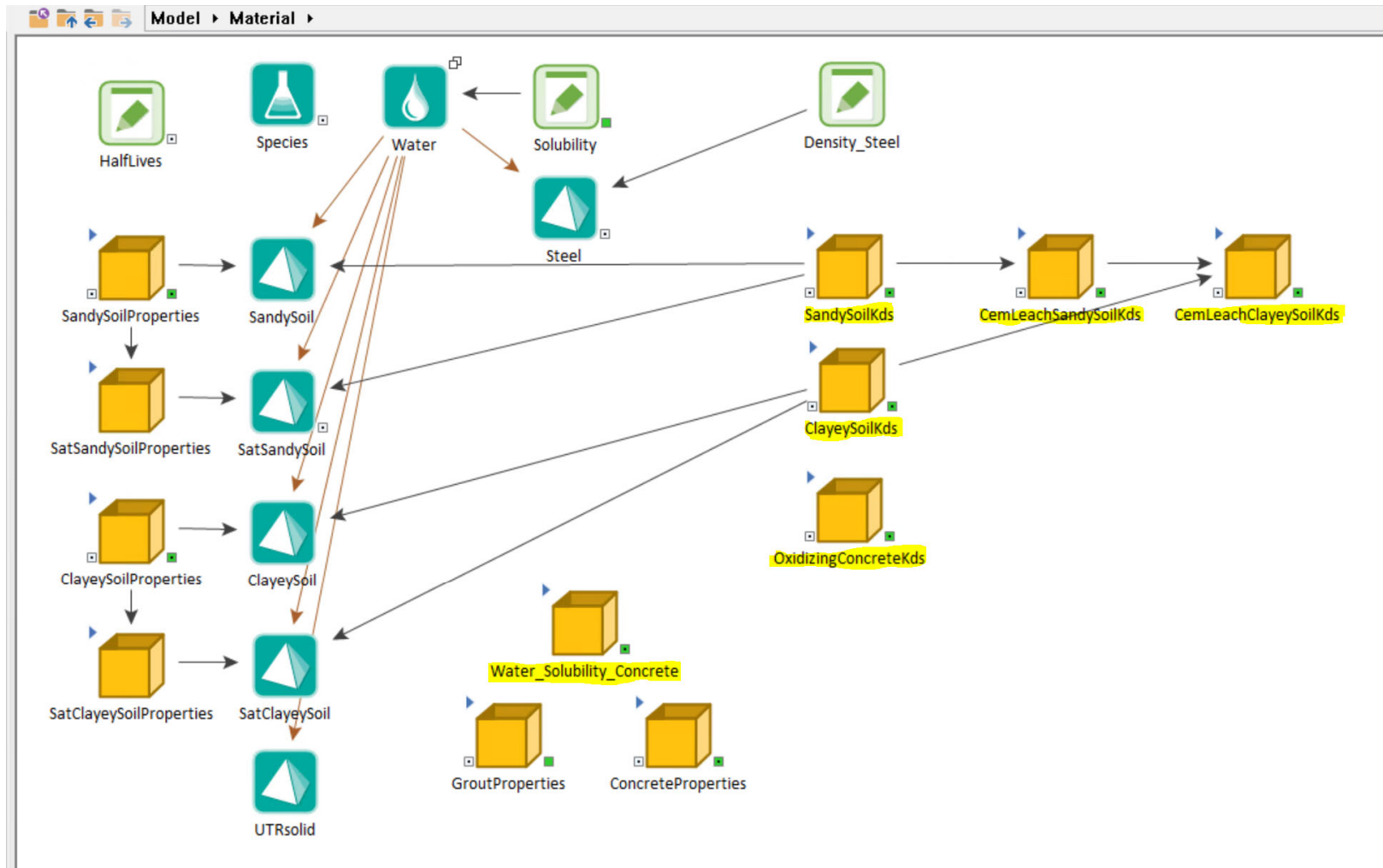


Figure 6. Updated Values in Soil and Concrete Property Containers of the *Materials* Bin

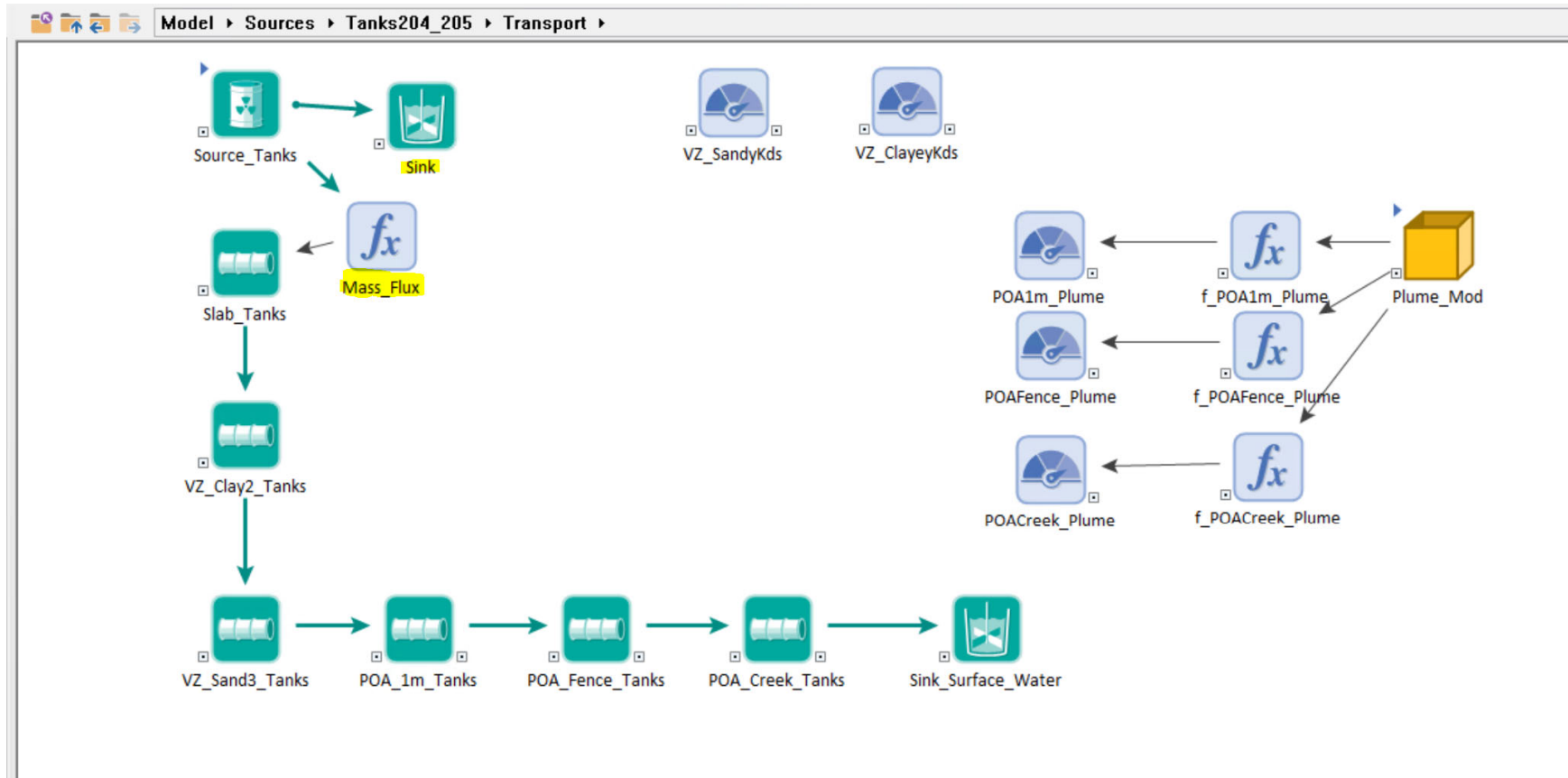


Figure 7. Added a Sink and Mass_Flux Function to Remove Negative Mass from the Simulation

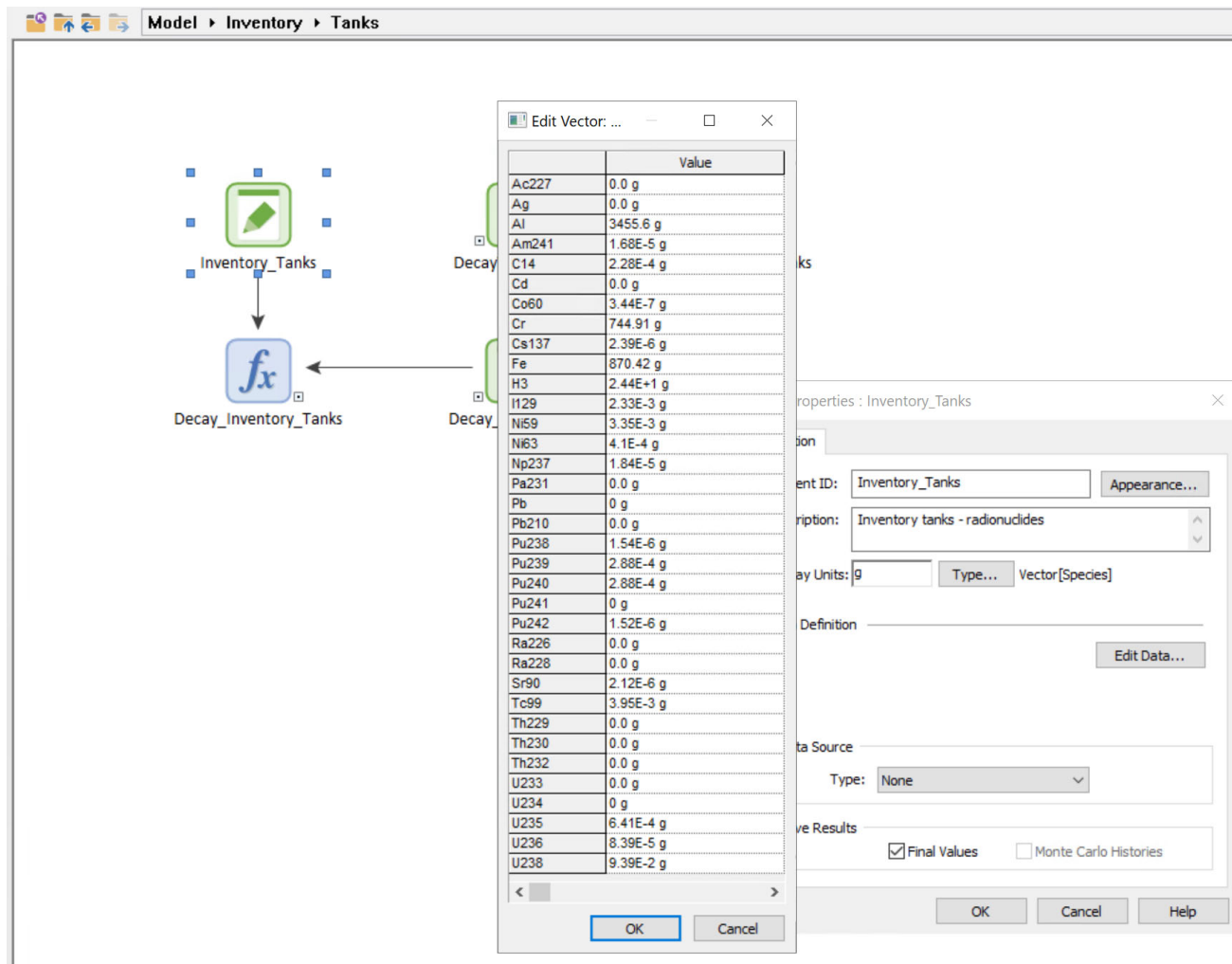


Figure 8. Inventory Inputs for All Constituents Detected in 2024 Sampling

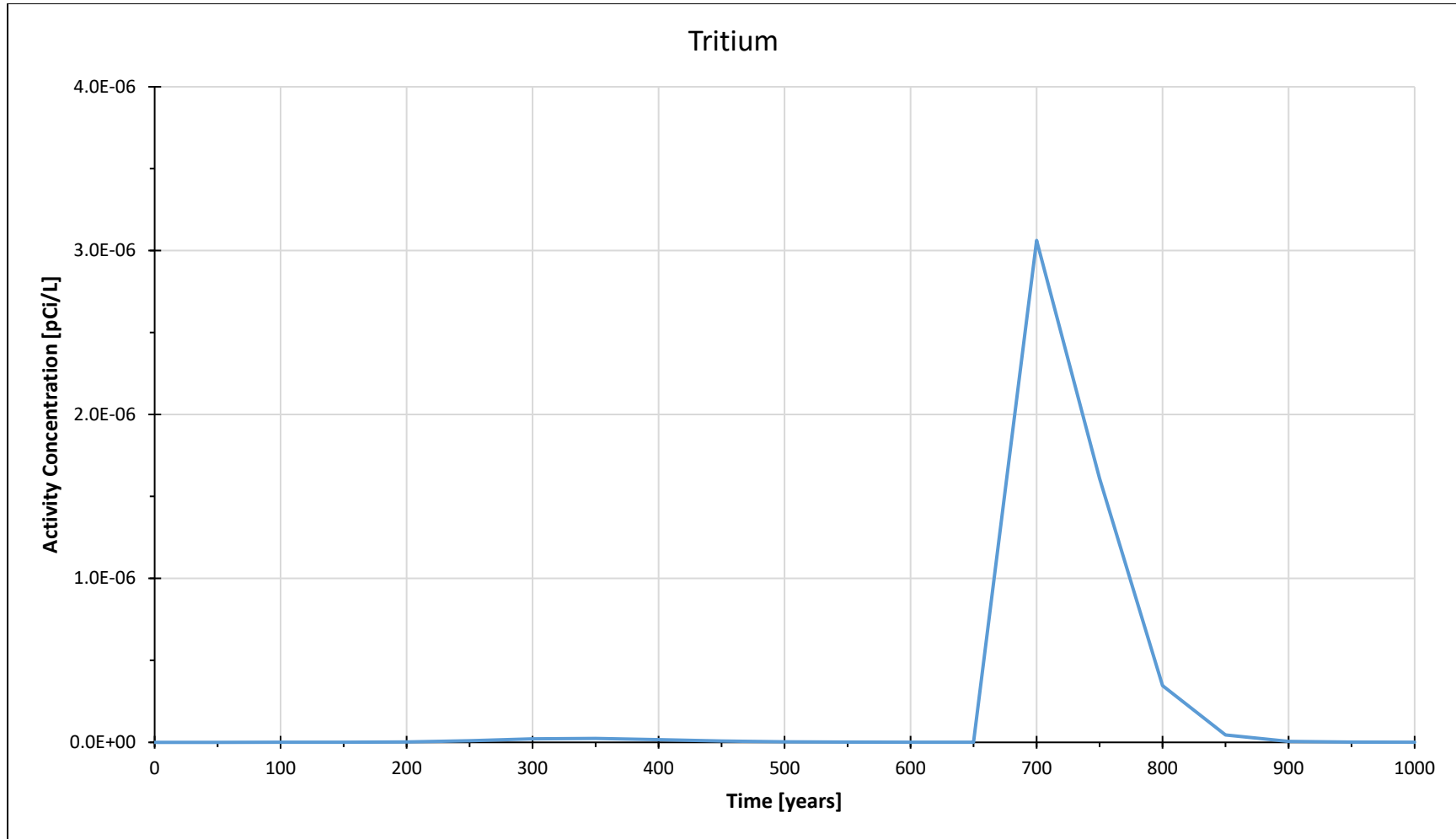


Figure 9. Updated Model Simulation Mean Results for 1,000 Realizations at the 1.0 m (3.28 ft) POA

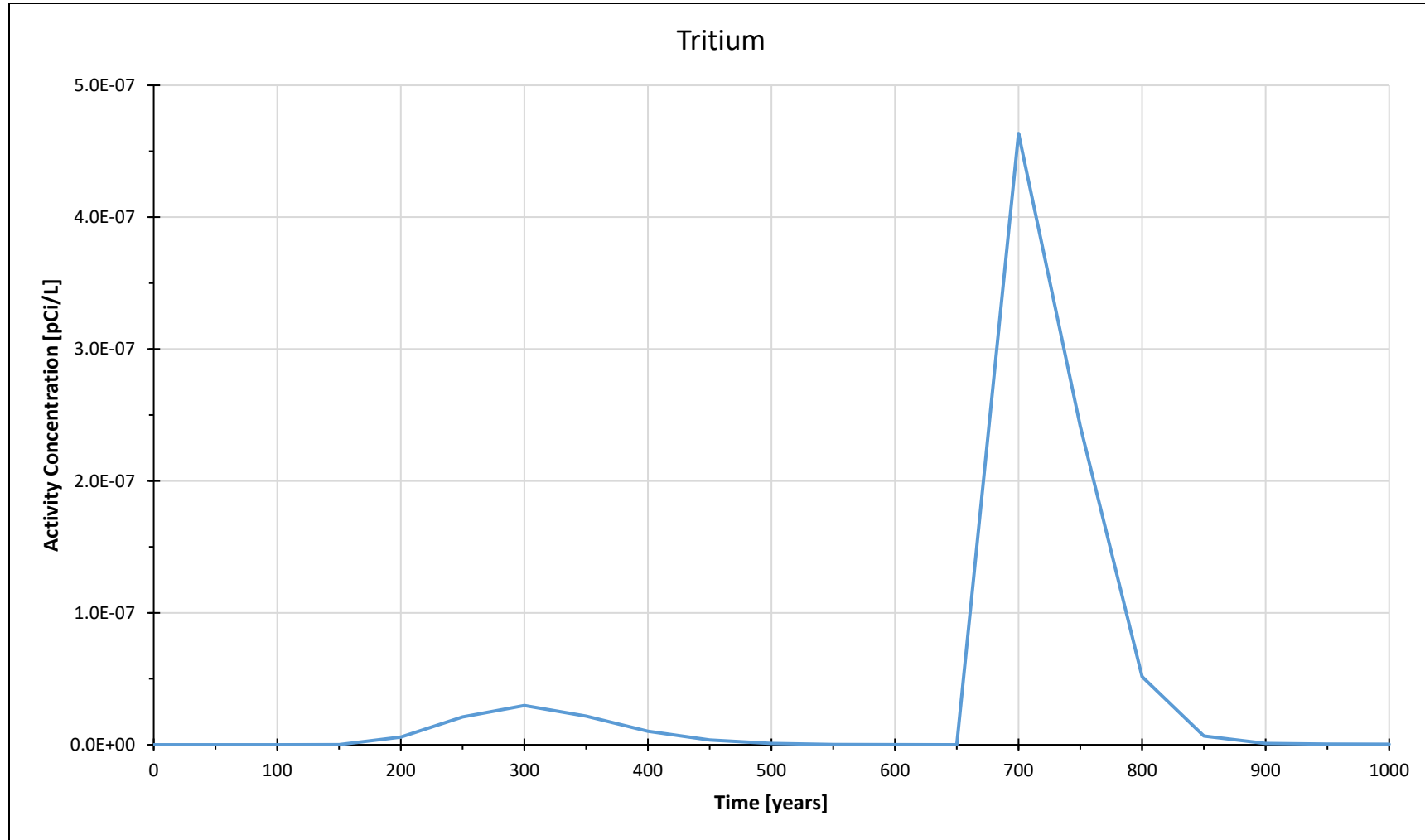


Figure 10. 2023 Model Simulation Mean Results for 1,000 Realizations at the 1.0 m (3.28 ft) POA

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Updated Moderator Tank Inventory (U)
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Table 1. Detected Results from 2024 Heavy Water Storage Tank Sampling

Analyte ^a	Laboratory	Result ^b	Units	GWPS ^c	Half-life [years]	Decay Type	Source Inventory [g]
Al	SWRI	2.12E+01	mg/L	2.00E+01	N/A	N/A	3.46E+03
Cr	SWRI	4.57E+00	mg/L	1.00E-01	N/A	N/A	7.45E+02
Fe	SWRI	5.34E+00	mg/L	1.40E+01	N/A	N/A	8.70E+02
Am-241	SRNL	3.50E+02	pCi/L	1.50E+01	4.33E+02	α, γ	1.68E-05
C-14	SRNL	6.31E+03	pCi/L	2.00E+03	5.72E+03	β	2.28E-04
Co-60	SRNL	2.32E+03	pCi/L	1.00E+02	5.27E+00	β, γ	3.44E-07
Cs-137	SRNL	1.27E+03	pCi/L	2.00E+02	3.01E+01	β, γ	2.39E-06
H-3	SRNL	1.45E+12	pCi/L	2.00E+04	1.23E+01	β	2.44E+01
I-129	SRNL	5.14E+00	pCi/L	1.00E+00	1.57E+07	β, γ	2.33E-03
Ni-59	SRNL	1.64E+03	pCi/L	3.00E+02	7.60E+04	β	3.35E-03
Ni-63	SRNL	1.43E+05	pCi/L	5.00E+01	1.01E+02	β	4.10E-04
Np-237	SRNL	8.02E-02	pCi/L	1.50E+01	2.14E+06	α, γ	1.84E-05
Pu-238	SRNL	1.61E+02	pCi/L	1.50E+01	8.77E+01	α, γ	1.54E-06
Pu-239 ^d	SRNL	2.21E+01	pCi/L	1.50E+01	2.41E+04	α, γ	5.80E-05
Pu-239/240 ^d	SRNL	4.06E+02	pCi/L	1.50E+01	-	-	2.88E-04
Pu-240 ^d	SRNL	1.85E+01	pCi/L	1.50E+01	6.56E+03	α, γ	1.31E-05
Pu-242	SRNL	3.63E-02	pCi/L	1.50E+01	3.75E+05	α, γ	1.52E-06
Sr-90	SRNL	1.82E+03	pCi/L	8.00E+00	2.88E+01	β	2.12E-06
U-235	SRNL	8.65E-03	pCi/L	1.50E+01	7.04E+08	α, γ	6.41E-04
U-236	SRNL	3.35E-02	pCi/L	1.50E+01	2.34E+07	α, γ	8.39E-05
U-238	SRNL	1.96E-01	pCi/L	1.50E+01	4.47E+09	α, γ	9.39E-02

^a Only analytes with detected results reported. Only exception is I-129, which had a detection limit greater than the GWPS.

^b Maximum detected result from both samples (Tank 204 or Tank 205) recorded.

^c GWPS are the USEPA maximum contaminant level (MCL), or the USEPA tapwater regional screening level in lieu of a MCL; POs for the contaminant fate and transport model are equal to the GWPS.

^d Pu-239 and Pu-240 are often indistinguishable in laboratory analysis; as a conservative approach, the highest mass from the three Pu-239/240 results was input into the Pu-239 and Pu-240 model source inventory.

g - grams

α - alpha decay

β - beta decay

γ - gamma decay

Table 2. Partitioning, Solubility, and Leachate Properties for New Elements

Analyte	Oxidizing Solubility [mole/L]			Soil-Water Distribution Coefficient (K_d) [mL/g]					Cement Leachate Impact Factor ^a
	Young Cement	Middle Cement	Old Cement	Sandy Soil	Clayey Soil	Young Cement	Middle Cement	Old Cement	
Carbon (C)	1.0E-05	1.0E-06	1.0E-05	1.0E+01	4.0E+02	2.0E+03	5.0E+03	5.0E+01	5.0
Nickel (Ni)	1.0E-07	1.0E-07	1.0E-06	7.0E+00	3.0E+01	7.0E+01	4.0E+02	4.0E+02	3.2

^a unitless

All values taken from *Geochemical Data Package for Performance Assessment Calculations Related to the Savannah River Site* (Kaplan 2021).

mole/L - mole per liter

K_d - soil-water partitioning coefficient

mL/g - milliliter per gram

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**Addendum to ISD CM Modeling of C-Reactor
 Updated Moderator Tank Inventory (U)
 Savannah River Site
 September 2024**

Table 3. POTM Results at the 1.0 m (3.28 ft) POA

Analyte	POTM	Units	GWPS	Exceed GWPS?
Ac-227	4.66E-10	pCi/L	15	NO
Al	5.26E-05	mg/L	20	NO
Am-241	0.00E+00	pCi/L	15	NO
C-14	1.08E-02	pCi/L	2000	NO
Co-60	0.00E+00	pCi/L	100	NO
Cr	1.88E-05	mg/L	0.1	NO
Cs-137	0.00E+00	pCi/L	200	NO
Fe	5.01E-05	mg/L	14	NO
H-3	4.46E-06	pCi/L	20000	NO
I-129	2.81E-04	pCi/L	1	NO
Ni-59	5.20E-02	pCi/L	300	NO
Ni-63	1.58E-13	pCi/L	50	NO
Np-237	1.32E-05	pCi/L	15	NO
Pa-231	1.10E-07	pCi/L	15	NO
Pb-210	7.69E-10	pCi/L	15	NO
Pu-238	0.00E+00	pCi/L	15	NO
Pu-239	2.42E-06	pCi/L	15	NO
Pu-240	0.00E+00	pCi/L	15	NO
Pu-241	0.00E+00	pCi/L	300	NO
Pu-242	0.00E+00	pCi/L	15	NO
Ra-226	4.90E-08	pCi/L	5	NO
Ra-228	0.00E+00	pCi/L	5	NO
Sr-90	0.00E+00	pCi/L	8	NO
Th-229	2.73E-09	pCi/L	15	NO
Th-230	5.36E-09	pCi/L	15	NO
Th-232	0.00E+00	pCi/L	15	NO
U-233	1.71E-08	pCi/L	15	NO
U-234	2.31E-07	pCi/L	15	NO
U-235	3.85E-08	pCi/L	15	NO
U-236	0.00E+00	pCi/L	15	NO
U-238	7.80E-07	pCi/L	15	NO

POTM - peak of the mean

GWPS - groundwater protection standard

pCi/L - picocurie per liter

mg/L - milligram per liter

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