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Special Analysis: An Assessment of Potential Dose Impacts from External Contamination on Naval Reactors Facility Waste Canisters

October 2022

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EXECUTIVE SUMMARY

This Special Analysis (SA) was performed to address a request by Naval Reactors Facility (NRF) Waste Programs for a permanent exception to limits of removable surface contamination on the exterior of waste canisters shipped to the Remote-Handled Low-Level Waste (RHLLW) Disposal Facility as specified in the waste acceptance criteria (WAC) (PLN-5446).

The purpose of this SA is to determine if the NRF-requested levels for removable surface contamination on the exterior of all NRF waste canisters is within the bounds of the current performance assessment (PA). This was done by calculating the groundwater all-pathways dose contribution from surface contamination on the exterior of NRF canisters for the following cases: (1) the exteriors of all NRF waste canisters are contaminated to the 10 CFR 835 Appendix D allowable limits in the current WAC, and (2) the exteriors of all NRF waste canisters are contaminated to the limits requested by NRF Waste Programs.

Dose impacts for each case were compared to each other and to the all-pathways dose for the PA base case. Dose impacts were also compared to the all-pathways dose limit specified in DOE O 435.1.

A simple assessment of the potential impacts of the increase in surface contamination using the NRF-requested limits on the biotic, air, and inadvertent intruder pathways was also performed.

Based on the results of this SA, the increase in canister exterior contamination limits requested by NRF are well within the bounds of the current PA and will not result in a violation of performance objectives. The results also show the increased limits do not reflect or necessitate a fundamental change to the PA conceptual model, nor a change to the way exterior contamination is not included in PA dose calculations.

Therefore, it is recommended the NRF request for an exception to the current limits for external surface contamination be accepted and the revised limits for NRF-generated waste canisters be added to the WAC. The monitoring plan will also be revised to identify external canister contamination as a potential mobile source term that may be detected by monitoring earlier than potential releases from waste.

The PA, composite analysis (CA), closure plan, and PA/CA maintenance plan do not require revision. Recommendations are also included for inclusion of NRF procedures used to limit water pool radionuclide variability (and thus canister surface contamination variability) to the waste generator certification process.

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ACRONYMS

CA	composite analysis
CFR	Code of Federal Regulations
DCF	dose conversion factor
DOE	U.S. Department of Energy
dpm	disintegrations per minute
ECF	Expended Core Facility
EDMS	Electronic Document Management System
FDS	facility disposition specialist
GIC	generator implementation crosswalk
IC	Institutional Control
INL	Idaho National Laboratory
LCC	large concept cask
MCM	Mixing-Cell Model
MCMF	Mixing-Cell Model for Flow
MCMT	Mixing-Cell Model for Transport
NRF	Naval Reactors Facility
NSFH	Naval Spent Fuel Handling
PA	performance assessment
RHINO	Remote-Handled Low-Level Waste Disposal Facility Inventory Online
RHLLW	Remote-Handled Low-Level Waste
RWDS	radioactive water demineralizer system
SA	special analysis
WAC	waste acceptance criteria

Special Analysis: An Assessment of Potential Dose Impacts from External Contamination on Naval Reactors Facility Waste Canisters

1. INTRODUCTION

This special analysis (SA) was performed to address a request by Naval Reactors Facility (NRF) Waste Programs for a permanent exception to limits of removable surface contamination on the exterior of waste canisters shipped to the Remote-Handled Low-Level Waste (RHLLW) Disposal Facility as specified in the waste acceptance criteria (WAC) [1].[1] Section 2.6 of the WAC states:

> *Waste canisters accessible for radiological contamination surveys shall be free of removable surface contamination on the outside of the disposal canister. Waste canisters not accessible for swiping shall utilize process controls to minimize loose contamination on canister surfaces as much as practical. All canisters and packaging received at the RHLLW Disposal Facility shall comply with contamination control limits of 10 CFR 835, Appendix D, "Surface Contamination Values."*

Table 1 shows the current WAC limits for removable surface contamination on waste canisters. These limits were adopted from 10 CFR 835, Appendix D, "Surface Contamination Values" [3]. The values in 10 CFR 835 Appendix D were developed to identify the need for posting of contamination areas and high contamination areas. They were adopted as limits in the RHLLW WAC because they represent de minimis levels in terms of dose impacts, and thus the surface contamination on canister exterior surfaces would not need to be reported and included in performance assessment (PA) dose calculations [10].

Table 1. RHLLW Disposal Facility removable surface contamination limits for canister external surfaces.

Group	Radionuclide	Surface Contamination Limits (dpm[a]/100cm^2)	(pCi[b]/100cm^2)
1	U-nat, U-235, U-238, and associated decay products	1,000	450
2	Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	20	9
3	Th-nat, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	200	90
4	Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above	1,000	450
5	Tritium and Special Tritium Compounds	10,000	4,504

a. dpm (disintegrations per minute) means the rate of emission by radioactive material as determined by correcting the counts per minute observed by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.

b. 10 CFR 835 Appendix D lists limits in units of dpm. Contamination limits were converted to units of pCi for this analysis using the conversion 1 pCi = 2.22 dpm.

Note: The surface contamination values in Table 1 apply to radioactivity deposited on, but not incorporated into the interior or matrix of, the contaminated item. Where surface contamination by both alpha- and beta-gamma-emitting nuclides exists, the limits established for alpha- and beta-gamma-emitting nuclides apply independently. The amount of removable radioactive material per 100 cm^2 of surface area should be determined by swiping the area with dry filter or soft absorbent paper, applying moderate pressure, and then assessing the amount of radioactive material on the swipe with an appropriate instrument of known efficiency.

1 During the initial waste generator certification assessment, it was discovered that NRF waste canisters could potentially not meet requirements outlined in Section 2.6 of the RHLLW WAC [1]. This issue was identified as condition CO 2022-1358 and will be tracked in accordance with LWP-13840, "Issues Management." [2]

Currently no waste from NRF has been placed at the RHLLW Disposal Facility that has been operating since 2019. NRF RHLLW analyzed in the PA [24] consists of irradiated metal hardware, surface contaminated trash, and depleted radioactive water demineralizer system (RWDS) modules loaded with contaminated resin beads. The waste canisters are loaded underwater in the Expended Core Facility (ECF) water pool due to high radiation levels. These high radiation levels prohibit raising the loaded waste canisters out of the water pool to measure removable surface contamination levels. The loaded waste canisters are raised from the ECF water pool directly into a shielded 55-ton cask through doors on the bottom of the cask while seated on a loading stand. Once the waste canister is loaded inside the 55-ton cask, NRF Waste Programs has provided documentation that there is no practical way to access the waste canister and perform contamination surveys using the method specified in 10 CFR 835 Appendix D [3].

Though NRF Waste Programs is not able to measure the surface contamination on waste canisters outside the water pool, process controls are used that are effective at reducing the amount of surface contamination on waste canisters. This three-step process includes: (1) operation of RWDS resin bed filtration modules that remove radionuclides from the water pool where the canisters are loaded and stored, (2) use of an underwater high-pressure wash of all accessible external surfaces of each canister prior to loading (hydroblitzing), and (3) use of a low-pressure rinse of the canister's exterior surfaces as the canister is pulled from the pool into the shipping cask through a circular ring that has 33 nozzles.

Because swipe surveys cannot be performed outside the water pool, NRF personnel performed underwater surveys of five 55-ton waste canisters by taking five swipes on each lid and 10 swipes on each shell before and after hydroblitzing. The swipes were removed from the water pool and gamma counted by NRF chemistry. The swipe data were used to estimate the average total activity by radionuclide on each waste canister. NRF determined the hydroblitz step reduces the amount of external contamination 52 to 96% (see Appendix A: Letter from Fluor Marine Propulsion to Robert Miklos, July 18, 2022, NRF-ENG-FE-00670). Despite this substantive reduction in canister contamination levels, the activity that remained, when compared to 10 CFR 835 Appendix D limits, remains problematic. The data indicate that, of the five swiped waste canisters, only one met all the removable surface contamination requirements of 10 CFR 835 Appendix D. Of the remainder, one waste canister exceeded the transuranic limit (Table 1, Group 2) and all four exceeded the beta-gamma emitter limit (Table 1, Group 4).

Even with the mitigating contamination reduction processes described above, NRF Waste Programs have determined it is likely the current surface contamination requirement in the WAC cannot be consistently met and have requested an exception to the requirement. Specifically, NRF Waste Programs is requesting a permanent exception to the current WAC Section 2.6 requirement for transuranic radionuclides (Table 1, Group 2) and beta-gamma emitting radionuclides (Table 1, Group 4) for all waste canisters shipped to the RHLLW Disposal Facility based on the inability to verify the surface contamination levels using the methods specified in 10 CFR 835 Appendix D and the contamination levels obtained using alternate methods that exceed the 10 CFR 835 Appendix D limits for transuranics and beta-gamma emitters (see Appendix A: Letter from Fluor Marine Propulsion to Robert Miklos, July 18, 2022, NRF-ENG-FE-00670).

Based on an analysis of data from the underwater swipes of the five 55-ton canisters in the ECF water pool, NRF Waste Programs have determined surface contamination levels that can be achieved with a 97.5% confidence level (applying a very high degree of conservatism [see Subsection 6.2] and implementing controls to significantly limit water pool radionuclide variability [see Subsection 6.3]) and is requesting an exception to increase the RHLLW WAC Section 2.6 surface contamination limits to these values. These requested levels are shown in Table 2 along with limits from the current RHLLW WAC. To ensure the requested limits will be met, the NRF-requested limits are based on swipe data from only the lids of the five canisters and not the shells as the lid results bound the shell results.

Table 2. RHLLW Disposal Facility surface contamination limits for canister external surfaces and limits requested by NRF Waste Programs.

Group	Radionuclide	Current WAC Limits for Removable Surface Contamination (pCi/100cm^2)	NRF Requested Limits for Removable Surface Contamination (pCi/100cm^2)
1	U-nat, U-235, U-238, and associated decay products	450	450
2	Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	9	**50**
3	Th-nat, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	90	90
4	Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above	450	**100,000**
5	Tritium and Special Tritium Compounds	4,504	4,504

* **BOLD** font indicates an increase over the current WAC limit. NRF has requested an increase for Group 2 (transuranics) and Group 4 (beta-gamma emitters).

1.1 Purpose and Scope

The primary role of an SA is to evaluate through modeling or other technical evaluation methods the impact of a proposed activity, discovery, or new information to the input and assumptions or results in the PA or composite analysis (CA); or to supplement or amend the analyses performed in the original PA and CA [23]. The purpose of this SA is to determine if the NRF-requested levels for removable surface contamination on the exterior of all NRF waste canisters is within the bounds of the current PA. This was done by calculating the groundwater all-pathways dose contribution from surface contamination on the exterior of NRF canisters for the following cases:

Case 1: The exteriors of all NRF waste canisters are contaminated to the 10 CFR 835 Appendix D allowable limits in the current WAC.

Case 2: The exteriors of all NRF waste canisters are contaminated to the limits requested by NRF Waste Programs.

For the RHLLW Disposal Facility, the groundwater all-pathways dose is the facility all-pathways dose. Dose impacts for each case were compared to each other and to the all-pathways dose for the PA base case. They were also compared to the all-pathways dose limit specified in DOE O 435.1 [7].

A simple assessment of the potential impacts of the increase in surface contamination using the NRF-requested limits on the biotic, air, and inadvertent intruder pathways was also performed.

2. SOURCE TERM

The source term for Case 1 assumes the exterior surface of all NRF waste canisters are contaminated to the 10 CFR 835 Appendix D limits specified in the current WAC for each radionuclide group. The source term for Case 2 assumes the exterior surface of all NRF waste canisters are contaminated to the levels requested by NRF Waste Programs in NRF-ENG-FE-00670 (see Appendix A) for each radionuclide group. The isotopic breakdown of the radionuclides in each group was determined from the underwater swipe data obtained by NRF on the five 55-ton waste canisters. These data were then used to determine the total activity of each radionuclide on all NRF canisters for both cases. Based on half-life and total activity, the list of radionuclides underwent a screening process to eliminate from further consideration those that would have an insignificant impact on the groundwater all-pathways dose calculated for this SA.

2.1 Analysis of Swipe Data on NRF Waste Canisters

The length of time the five 55-ton waste canisters had been in the water pool prior to being hydroblitzed and swiped ranged from approximately 10 months to nearly 3 years, which covers the period most canisters will be in the canal before removal and shipment. Table 3 contains the average total activity concentration by radionuclide for each waste canister. The radionuclides have also been placed into the appropriate 10 CFR 835 Appendix D groupings. The average activity concentrations from all five canisters (Table 3, last column) were used to determine the average total activity on a 55-ton canister and a Naval Spent Fuel Handling (NSFH[2]) canister (see Table 4) using the surface areas of the respective canister types. These values were then multiplied by the total capacity (number) of each canister type in the facility to estimate the total activity on each NRF canister type. The total activity on the 55-ton and NSFH canisters was then summed to obtain the total activity on all NRF canisters. The last column of Table 4 is the percentage of each radionuclide (by activity) in each group.

2 NSFH canister is the name for the larger waste canisters that will replace the 55-ton canisters when the new ECF is finished at NRF. The NSFH canister is referred to as the large concept cask (LCC) canister in the RHLLW Disposal Facility PA [24].

Table 3. Average measured isotopic activity concentration (Ci/cm^2)[a] on the exterior of five 55-ton canisters and the average activity concentration of all five canisters.

		Canister ID					
Group[b]	Isotope[c]	05-18-102	05-18-106	05-18-112	05-18-113	05-18-121	Average
1	U-234	6.14E-16	2.77E-17	1.08E-16	6.20E-18	5.58E-17	1.62E-16
	U-235	2.90E-16	1.31E-17	5.10E-17	2.93E-18	2.64E-17	7.67E-17
2	Am-241	2.61E-15	1.18E-16	4.58E-16	2.63E-17	2.37E-16	6.90E-16
	Cm-243	4.95E-16	2.23E-17	8.69E-17	4.99E-18	4.49E-17	1.31E-16
	Cm-244	7.58E-16	3.42E-17	1.33E-16	7.65E-18	6.89E-17	2.00E-16
	Cm-245	8.07E-17	3.64E-18	1.42E-17	8.15E-19	7.33E-18	2.13E-17
	Pu-238	5.11E-14	2.31E-15	8.97E-15	5.16E-16	4.64E-15	1.35E-14
	Pu-239	7.13E-16	3.22E-17	1.25E-16	7.19E-18	6.47E-17	1.88E-16
	Pu-240	8.03E-17	3.63E-18	1.41E-17	8.11E-19	7.29E-18	2.12E-17
	Pu-241	5.41E-14	2.44E-15	9.49E-15	5.46E-16	4.91E-15	1.43E-14
	U-233	6.14E-16	2.77E-17	1.08E-16	6.20E-18	5.58E-17	1.62E-16
	U-236	2.90E-16	1.31E-17	5.10E-17	2.93E-18	2.64E-17	7.67E-17
	I-129	1.27E-17	5.74E-19	2.23E-18	1.28E-19	1.15E-18	3.36E-18
3	None[d]	0	0	0	0	0	0
4	C-14	7.28E-12	3.29E-13	1.28E-12	7.35E-14	6.61E-13	1.92E-12
	Co-58	2.03E-13	9.14E-15	3.55E-14	2.04E-15	1.84E-14	5.36E-14
	Co-60	8.53E-11	3.85E-12	1.50E-11	8.61E-13	7.75E-12	2.26E-11
	Cr-51	4.54E-13	2.05E-14	7.97E-14	4.58E-15	4.12E-14	1.20E-13
	Cs-134	2.21E-15	1.00E-16	3.89E-16	2.24E-17	2.01E-16	5.84E-16
	Cs-137	1.09E-12	4.35E-13	5.36E-13	1.10E-14	2.23E-13	4.59E-13
	Eu-152	2.66E-11	1.20E-12	4.66E-12	2.68E-13	2.41E-12	7.03E-12
	Eu-154	3.22E-12	1.45E-13	5.64E-13	3.25E-14	2.92E-13	8.51E-13
	Eu-155	3.28E-13	1.48E-14	5.75E-14	3.31E-15	2.97E-14	8.67E-14
	Fe-55	4.52E-11	2.04E-12	7.94E-12	4.57E-13	4.11E-12	1.19E-11
	Fe-59	1.37E-13	6.20E-15	2.41E-14	1.39E-15	1.25E-14	3.62E-14
	Hf-175	8.28E-13	3.74E-14	1.45E-13	8.36E-15	7.52E-14	2.19E-13
	Hf-181	3.68E-12	1.66E-13	6.45E-13	3.71E-14	3.34E-13	9.72E-13
	Mn-54	1.04E-12	6.75E-14	1.83E-13	1.05E-14	9.47E-14	2.79E-13
	Nb-93m	3.10E-12	1.40E-13	5.44E-13	3.13E-14	2.81E-13	8.19E-13
	Nb-94	8.53E-14	3.85E-15	1.50E-14	8.61E-16	7.75E-15	2.26E-14
	Nb-95	4.28E-13	1.93E-14	7.52E-14	4.32E-15	3.89E-14	1.13E-13
	Ni-59	9.53E-13	4.30E-14	1.67E-13	9.62E-15	8.65E-14	2.52E-13
	Ni-63	3.71E-11	1.68E-12	6.51E-12	3.75E-13	3.37E-12	9.81E-12
	Ru-103	1.92E-13	8.68E-15	3.38E-14	1.94E-15	1.75E-14	5.08E-14
	Sb-125	1.78E-11	8.03E-13	3.12E-12	1.80E-13	1.62E-12	4.70E-12
	Sn-113	6.82E-13	3.08E-14	1.20E-13	6.89E-15	6.20E-14	1.80E-13
	Sr-90[d]	1.16E-12	5.22E-14	2.03E-13	1.17E-14	1.05E-13	3.06E-13
	Ta-182	4.66E-13	2.11E-14	8.18E-14	4.71E-15	4.23E-14	1.23E-13
	Tc-99	1.31E-13	5.92E-15	2.30E-14	1.32E-15	1.19E-14	3.46E-14
	Te-125m	4.11E-12	1.86E-13	7.21E-13	4.15E-14	3.73E-13	1.09E-12
	Zn-65	9.16E-13	4.14E-14	1.61E-13	9.25E-15	8.32E-14	2.42E-13
	Zr-95	2.00E-13	9.02E-15	3.51E-14	2.02E-15	1.81E-14	5.28E-14
5	H-3	7.93E-14	3.58E-15	1.39E-14	8.01E-16	7.20E-15	2.10E-14

a. Activity concentrations are the average of five lid swipes and 10 shell swipes performed on each canister.
b. See Table 1 for group description.
c. The only detectable radionuclides after hydroblitzing were Co-60, Cs-137, and Mn-54. The activity of other radionuclides was inferred based on established ratios to Co-60 in the ECF water pools. The activities were calculated from values in NRF-ENG-FE-00670, Attachment II (see Appendix A).
d. Sr-90 as a mixed fission product is included with Group 4 per 10 CFR 835 Appendix D, footnote 5 [23].

Table 4. Summary of average measured total activity (Ci) by canister type and for all canisters.

Group[a]	Isotope	Total for 1 55-ton Canister[b]	Total for 1 NSFH Canister[b]	Total for 168 55-ton Canisters[c]	Total for 195 NSFH Canisters[c]	Total for 55-ton and NSFH Canisters	Isotope Activity % in each Group
1	U-234	1.68E-11	3.50E-11	2.82E-09	6.83E-09	9.65E-09	67.9%
	U-235	7.94E-12	1.65E-11	1.33E-09	3.22E-09	4.56E-09	32.1%
					Total	1.42E-08	100%
2	Am-241	7.14E-11	1.49E-10	1.20E-08	2.90E-08	4.10E-08	2.4%
	Cm-243	1.35E-11	2.82E-11	2.28E-09	5.50E-09	7.78E-09	0.4%
	Cm-244	2.07E-11	4.32E-11	3.48E-09	8.43E-09	1.19E-08	0.7%
	Cm-245	2.21E-12	4.60E-12	3.71E-10	8.97E-10	1.27E-09	0.1%
	Pu-238	1.40E-09	2.91E-09	2.35E-07	5.68E-07	8.03E-07	46.1%
	Pu-239	1.95E-11	4.06E-11	3.28E-09	7.92E-09	1.12E-08	0.6%
	Pu-240	2.20E-12	4.58E-12	3.69E-10	8.93E-10	1.26E-09	0.1%
	Pu-241	1.48E-09	3.08E-09	2.49E-07	6.01E-07	8.50E-07	48.8%
	U-233	1.68E-11	3.50E-11	2.82E-09	6.83E-09	9.65E-09	0.6%
	U-236	7.94E-12	1.65E-11	1.33E-09	3.22E-09	4.56E-09	0.3%
	I-129	3.47E-13	7.24E-13	5.84E-11	1.41E-10	2.00E-10	0.0%
					Total	1.74E-06	100%
3	None[d]	0	0	0	0	0	0%
					Total	0	0%
4	C-14	1.99E-07	4.15E-07	3.35E-05	8.09E-05	1.14E-04	3.0%
	Co-58	5.55E-09	1.16E-08	9.32E-07	2.25E-06	3.19E-06	0.1%
	Co-60	2.33E-06	4.86E-06	3.92E-04	9.48E-04	1.34E-03	35.1%
	Cr-51	1.24E-08	2.59E-08	2.09E-06	5.05E-06	7.13E-06	0.2%
	Cs-134	6.05E-11	1.26E-10	1.02E-08	2.46E-08	3.47E-08	0.0%
	Cs-137	4.75E-08	9.90E-08	7.98E-06	1.93E-05	2.73E-05	0.7%
	Eu-152	7.28E-07	1.52E-06	1.22E-04	2.96E-04	4.18E-04	10.9%
	Eu-154	8.81E-08	1.83E-07	1.48E-05	3.58E-05	5.06E-05	1.3%
	Eu-155	8.97E-09	1.87E-08	1.51E-06	3.64E-06	5.15E-06	0.1%
	Fe-55	1.24E-06	2.58E-06	2.08E-04	5.03E-04	7.10E-04	18.6%
	Fe-59	3.75E-09	7.82E-09	6.30E-07	1.52E-06	2.15E-06	0.1%
	Hf-175	2.27E-08	4.72E-08	3.81E-06	9.20E-06	1.30E-05	0.3%
	Hf-181	1.01E-07	2.10E-07	1.69E-05	4.09E-05	5.78E-05	1.5%
	Mn-54	2.89E-08	6.02E-08	4.85E-06	1.17E-05	1.66E-05	0.4%
	Nb-93m	8.48E-08	1.77E-07	1.42E-05	3.45E-05	4.87E-05	1.3%
	Nb-94	2.33E-09	4.86E-09	3.92E-07	9.48E-07	1.34E-06	0.0%
	Nb-95	1.17E-08	2.44E-08	1.97E-06	4.76E-06	6.73E-06	0.2%
	Ni-59	2.61E-08	5.43E-08	4.38E-06	1.06E-05	1.50E-05	0.4%
	Ni-63	1.02E-06	2.11E-06	1.71E-04	4.12E-04	5.83E-04	15.2%
	Ru-103	5.26E-09	1.10E-08	8.83E-07	2.14E-06	3.02E-06	0.1%
	Sb-125	4.87E-07	1.01E-06	8.18E-05	1.98E-04	2.80E-04	7.3%
	Sn-113	1.87E-08	3.89E-08	3.14E-06	7.58E-06	1.07E-05	0.3%
	Sr-90[d]	3.17E-08	6.61E-08	5.33E-06	1.29E-05	1.82E-05	0.5%
	Ta-182	1.28E-08	2.66E-08	2.14E-06	5.18E-06	7.32E-06	0.2%
	Tc-99	3.58E-09	7.47E-09	6.02E-07	1.46E-06	2.06E-06	0.1%
	Te-125m	1.12E-07	2.34E-07	1.89E-05	4.57E-05	6.46E-05	1.7%
	Zn-65	2.51E-08	5.22E-08	4.21E-06	1.02E-05	1.44E-05	0.4%
	Zr-95	5.47E-09	1.14E-08	9.19E-07	2.22E-06	3.14E-06	0.1%
					Total	3.81E-03	100%
5	H-3	2.17E-09	4.52E-09	3.64E-07	8.81E-07	1.25E-06	100%
					Total	1.25E-06	100%

a. See Table 1 for group description.
b. Based on the average measured activities in Table 3 (last column) and surface areas of 103,525 cm^2 for a 55-ton canister and 215,658 cm^2 for an NSFH canister.
c. The capacity of the current RHLLW Disposal Facility is 168 55-ton canisters and 195 NSFH canisters.
d. Sr-90 as a mixed fission product is included with Group 4 per 10 CFR 835 Appendix D, footnote 5 [23].

2.2 Determination of Maximum Allowable Activities

To determine the maximum total activity of each radionuclide allowable by current WAC limits (Case 1) and NRF-requested limits (Case 2), the percentages of each isotope in each group (Table 4, last column) were multiplied by the total activity limits for each radionuclide group as shown in the last two columns in Table 5. The total activity limits in Table 5 were calculated according to the equation below.

(1)

where:

$Act_{tot\text{-}lim}$ = total activity limit if all canisters are contaminated to the activity limit concentration (Table 5, column 5 [Case 1] and column 6 [Case 2]) for each radionuclide group

$Act_{con\text{-}lim}$ = activity concentration limit (Table 5, column 3 [Case 1] and column 4 [Case 2]) for each radionuclide group

A_{tot} = total surface area of all 55-ton and NSFH canisters (168 cans × 103,525 cm^2/can + 195 cans × 215,658 cm^2/can = 59,445,431 cm^2)

Table 5. RHLLW Disposal Facility surface contamination limits for canister external surfaces and limits requested by NRF Waste Programs.

Group	Radionuclide	Current WAC Limits for Removable Surface Contamination (pCi/100cm^2)	NRF Requested Limits for Removable Surface Contamination (pCi/100cm^2)	Total Activity if all Canisters were contaminated to Current WAC Limits (Ci)	Total Activity if all Canisters were contaminated to NRF Requested Limits (Ci)
1	U-nat, U-235, U-238, and associated decay products	450	450	2.68E-04	2.68E-04
2	Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	9	**50**	5.35E-06	**2.97E-05**
3	Th-nat, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	90	90	0[a]	0[a]
4	Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above	450	**100,000**	2.68E-04	**5.94E-02**
5	Tritium and Special Tritium Compounds	4,504	4,504	2.68E-03	2.68E-03

a. Total activity is zero because there are no radionuclides in this group (see Tables 3 and 4). Sr-90 as a mixed fission product is included with Group 4 per 10 CFR 835 Appendix D, footnote 5 [23].

BOLD font indicates an increase over the current WAC limit. NRF has requested an increase for Group 2 (transuranics) and Group 4 (beta-gamma emitters).

Table 6 contains the maximum total activity of each radionuclide allowable by current WAC limits (Case 1) and NRF-requested limits (Case 2). The Case 1 and Case 2 totals for each group match the values from the last two columns in Table 5. The individual radionuclide activities for each case are based on the percentages from the last column in Table 4 and the total activities for each group in the last two columns of Table 5. The last column of Table 6 also lists the screening phase in the PA in which the radionuclide was screened from groundwater all-pathways dose consideration. Radionuclides not screened out were retained for full analysis in the PA. All radionuclides in Table 6 that were eliminated in screening Phases 1 and 2 of the PA were also eliminated from further consideration for this SA. Radionuclides screened out in Phase 1 have half-lives of less than 1 year and are insignificant contributors to the groundwater all-pathways dose. Only Cm-245 was screened out in Phase 2 of the PA. Because the maximum total amount as surface contamination on the exterior of NRF canisters if contaminated to NRF-requested levels is more than 10 times lower than the total surface contamination in the PA base-case inventory, Cm-245 was also eliminated from further consideration in this SA.

Other remaining radionuclides screened out during the Phase 3 screening of the PA were screened for this SA by calculating the Phase 3 screening dose using total activities based on the NRF-requested limits and Phase 3 dose-to-source ratios from the PA Phase 3 screening. Radionuclides with a Phase 3 screening dose greater than 1E-9 mrem/yr were retained for consideration in this SA. The only radionuclides that were screened during the Phase 3 PA screening that were retained for this SA are Am-241, U-233, and U-236. All radionuclides that were retained for full analysis in the PA were also retained for this SA. Table 7 contains the list of radionuclide source terms for determining Case 1 and Case 2 dose impacts in this SA. The only radionuclides in this list for which NRF is not requesting an increase in acceptable limits are H-3, U-234, and U-235. All others are in the transuranic group (Group 2) or beta-gamma emitter group (Group 4) for which NRF is requesting an increase in limits.

Table 6. Total activity (Ci) as external surface contamination if all NRF canisters were contaminated to maximum levels allowed by the WAC (Case 1) and allowed by NRF-requested levels (Case 2).

Group[a]	Isotope	Total Activity if all Canisters Contaminated to Current WAC Limits (Case 1) (Ci)[b]	Total Activity if all Canisters Contaminated to NRF Requested Limits (Case 2) (Ci)[c]	Screening Phase from PA that Radionuclide was Screened Out or Retained
1	U-234	1.82E-04	1.82E-04	Retained
	U-235	8.58E-05	8.58E-05	Retained
	Total	2.68E-04	2.68E-04	-----
2	Am-241	1.26E-07	7.00E-07	III
	Cm-243	2.39E-08	1.33E-07	III
	Cm-244	3.66E-08	2.03E-07	III
	Cm-245	3.90E-09	2.16E-08	II
	Pu-238	2.47E-06	1.37E-05	Retained
	Pu-239	3.44E-08	1.91E-07	Retained
	Pu-240	3.88E-09	2.15E-08	Retained
	Pu-241	2.61E-06	1.45E-05	Retained
	U-233	2.96E-08	1.65E-07	III
	U-236	1.40E-08	7.78E-08	III
	I-129	6.13E-10	3.40E-09	Retained
	Total	5.35E-06	2.97E-05	-----
3	None[d]	0	0	NA
	Total	0	0	-----
4	C-14	8.00E-06	1.78E-03	Retained
	Co-58	2.23E-07	4.95E-05	I
	Co-60	9.38E-05	2.08E-02	III
	Cr-51	4.99E-07	1.11E-04	I
	Cs-134	2.43E-09	5.40E-07	III
	Cs-137	1.91E-06	4.24E-04	III
	Eu-152	2.92E-05	6.49E-03	III
	Eu-154	3.54E-06	7.86E-04	III
	Eu-155	3.60E-07	8.01E-05	III
	Fe-55	4.97E-05	1.10E-02	III
	Fe-59	1.51E-07	3.35E-05	I
	Hf-175	9.10E-07	2.02E-04	I
	Hf-181	4.04E-06	8.99E-04	I
	Mn-54	1.16E-06	2.58E-04	I
	Nb-93m	3.41E-06	7.57E-04	III
	Nb-94	9.38E-08	2.08E-05	Retained
	Nb-95	4.71E-07	1.05E-04	I
	Ni-59	1.05E-06	2.33E-04	Retained
	Ni-63	4.08E-05	9.06E-03	III
	Ru-103	2.11E-07	4.69E-05	I
	Sb-125	1.96E-05	4.35E-03	III
	Sn-113	7.50E-07	1.67E-04	I
	Sr-90[d]	1.27E-06	2.83E-04	III
	Ta-182	5.12E-07	1.14E-04	I
	Tc-99	1.44E-07	3.20E-05	Retained
	Te-125m	4.52E-06	1.00E-03	I
	Zn-65	1.01E-06	2.24E-04	I
	Zr-95	2.20E-07	4.88E-05	I
	Total	2.68E-04	5.94E-02	-----
5	H-3	2.68E-03	2.68E-03	Retained
	Total	2.68E-03	2.68E-03	-----

a. See Table 1 for group description.
b. Radionuclide activities based on penultimate column in Table 5 and percentages from last column in Table 4.
c. Radionuclide activities based on last column in Table 5 and percentages from last column in Table 4.
d. Sr-90 as a mixed fission product is included with Group 4 per 10 CFR 835 Appendix D, footnote 5 [23].

Table 7. Radiological source term for Case 1 and Case 2.

Radionuclide	Group[a]	Total Maximum Activity if all Canisters were Contaminated to Current WAC Limits (Case 1) (Ci)	Total Maximum Activity if all Canisters were Contaminated to NRF Requested Limits (Case 2) (Ci)
U-234	1	1.82E-04	1.82E-04
U-235	1	8.58E-05	8.58E-05
I-129	2	6.13E-10	**3.40E-09**
Am-241	2	1.26E-07	**7.00E-07**
Pu-238	2	2.47E-06	**1.37E-05**
Pu-239	2	3.44E-08	**1.91E-07**
Pu-240	2	3.88E-09	**2.15E-08**
Pu-241	2	2.61E-06	**1.45E-05**
U-233	2	2.96E-08	**1.65E-07**
U-236	2	1.40E-08	**7.78E-08**
C-14	4	8.00E-06	**1.78E-03**
Nb-94	4	9.38E-08	**2.08E-05**
Ni-59	4	1.05E-06	**2.33E-04**
Tc-99	4	1.44E-07	**3.20E-05**
H-3	5	2.68E-03	2.68E-03

a. See Table 1 for group description.

BOLD font indicates an increase over the current WAC limit. NRF has requested an increase for Group 2 (transuranics) and Group 4 (beta-gamma emitting) radionuclides.

3. ANALYSIS OF PERFORMANCE

Dose impacts for this SA were calculated using the same computer codes used to calculate the PA groundwater all-pathways dose, with some slight modifications and some additional conservative assumptions. MCM was used to model the source zone, near-surface vadose zone, and vadose zone below the unsaturated alluvium [8]. MCM comprises two submodels: one for water flow (MCMF) and the other for transport (MCMT). GWSCREEN was used to model water flow and radionuclide transport in the aquifer [9]. Appendix B contains a summary of the modeling and calculations performed for this SA. A full description of the models, parameters, assumptions, and calculations is contained in the RHLLW Disposal Facility PA report [10] and further documented in ECAR-1892 (2018), "Groundwater Pathway Transport and Dose Calculations for the INL Remote-Handled Low-Level Waste Disposal Facility Performance Assessment" [13]. Below is a list of key assumptions used for the SA modeling. Any assumptions not listed below are not changed from the PA modeling.

1. The contamination from the underwater swipes is at least equal to or greater than the contamination that would be obtained using the dry-swipe method specified by 10 CFR 835 Appendix D. NRF has applied process knowledge to validate this assumption. It is NRF work practice to use wetted (damp) wipes as a decontamination method for removal of loose (removable) surface contamination. Using this premise, it is arguable that wetted or underwater swipes remove additional contamination that would not normally adhere to dry swipes. The dry swiping methods specified in Note 4 of 10 CFR 835 Appendix D are used primarily to represent the loose (removable) surface contamination that could adhere to the clothing or skin of personnel (and, if disturbed, result in an airborne risk of inhalation). Additionally, since it is understood at NRF that wetted swipes must be allowed to dry before alpha and beta emitters can be accurately measured, dry swipes are advantageous for efficiently characterizing and controlling contamination at work sites. These limitations in detection were understood for the underwater canister surveys; thus, all swipes were measured before and after drying to ensure accuracy of activity analysis. Based on this process knowledge for the effectiveness and application of dry versus wetted (underwater) swiping, the assumption was made that contamination collected by underwater swipes would be conservatively equivalent or exceed that of dry swipes.

2. Residual contamination present on the surface of the canisters is immediately available for wash-off when contacted by infiltrating water. No sorption or desorption is assumed. Container corrosion has no impact on the release of external surface contamination.
3. The SA source term from Table 7 also includes the following significant progeny of Am, Pu, and U isotopes (Ac-227, Np-237, Pa-231, Pb-210, Ra-226, Ra-228, Th-228, Th-229, Th-230, and Th-232).
4. Am-241 is the only radionuclide in the SA source term (see Table 7) not included in the PA base case. The K_d value for Am was taken from the value in the Phase 3 screening (340 mL/g). For cement altered sorption in the alluvium, the K_d was reduced based on the ratio of the K_d values for cement altered and clean alluvium for Pu.
   - Pu K_d for clean alluvium = 1480 mL/g
   - Pu K_d for cement altered alluvium = 21 mL/g
   - Am K_d for cement altered alluvium = 340 mL/g × (21/1480) = 4.82 mL/g.
5. All-pathways dose factors were the same as those used for the RH-LLW PA with dose coefficients from DOE [11]. The Am-241 all-pathways dose factor was calculated using the same methodology. The all-pathways dose factor for Am-241 is 6.69E5 rem-m^3/Ci-yr.
6. The SA inventories of U-233 and U-236 were not modeled explicitly but were included in their respective decay chains. U-233 was included in the Am-241 parent decay chain and U-236 was included in the Pu-240 parent decay chain.
7. Infiltration into the source zone is assumed to be the value for disturbed soil (18 cm/yr) for the 20-year operating period, followed by the cap infiltration rate of 0.1 cm/yr for the next 500 years, followed by a linear increase to 1 cm/yr over the next 500 years. The infiltration is assumed a constant 1 cm/yr after the 1,000-year compliance period. Infiltration for the vadose zone is assumed to be the same as the base case PA. This is the same as the assumption for the PA base-case model but is repeated here for clarity.
8. The surface contamination source term (activity) for all NRF waste canisters was assumed to be placed in the west-side source (see Figure 1) and only the west-side source was modeled. This is a conservative assumption because in the PA model the 55-ton array is part of the west-side source, and the larger NSFH array (a.k.a. HFEF-LCC array) is part of the east-side source. Concentrating the entire inventory into the smaller west-side source is conservative by more than a factor of 2.
9. The dose was calculated using groundwater concentrations from 100 m downgradient of the west-side source in the direction of maximum impact at the west-side receptor location shown in Figure 1. Although the receptor could not reside there during the 100-year institutional control period, it is an appropriate location for the balance of the 1,000-year compliance and post-compliance periods.
10. The groundwater all-pathways dose is the facility all-pathways dose. The groundwater all-pathways dose analysis assumes the receptor consumes (1) contaminated groundwater, (2) leafy vegetables and produce irrigated with contaminated groundwater, and (3) milk and meat from animals that consume contaminated water and pasture grass irrigated with contaminated groundwater. This is the same as the assumption for the PA base-case model but is repeated here for clarity.
11. The 20-year operating period for the current facility design is assumed to conclude in 2039.

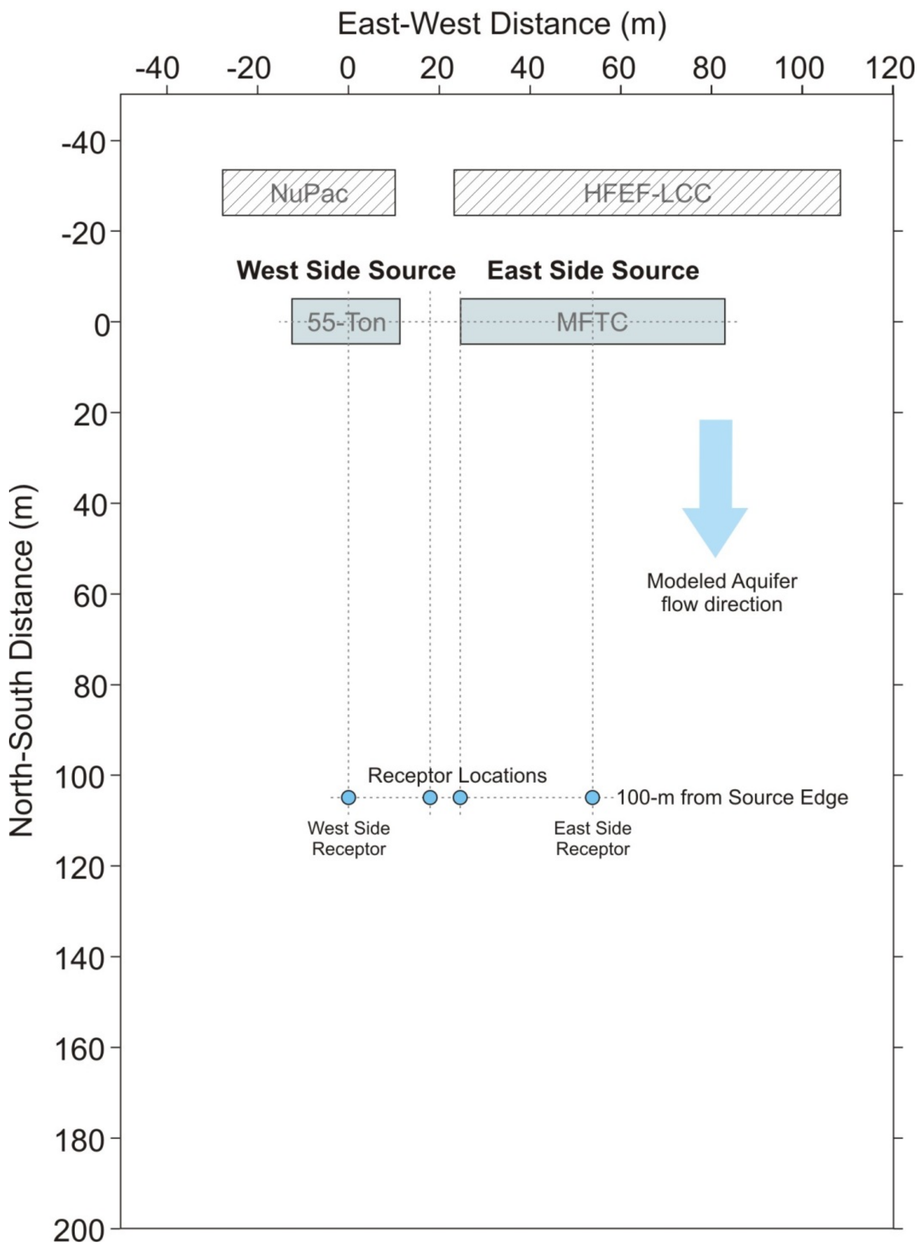

Figure 1. Layout of the west-side source zone, east-side source zone, and grid used to determine the maximum dose 100 m from the vault arrays. (Figure 3-2 from the PA [10]).

4. RESULTS

Table 8 and Table 9 contain the potential contribution to the groundwater all-pathways dose for Case 1 and Case 2, respectively. Maximum doses are shown for each radionuclide for the institutional control period, the balance of compliance period, and the post-compliance period. Figure 2 and Figure 3 show the dose time history for all parent radionuclides and the overall total dose for Case 1 and Case 2, respectively.

Table 8. Groundwater all-pathways dose contribution as a function of time from surface contamination on the NRF canisters for Case 1: all canisters contaminated to maximum limits allowed by the current WAC.

Parent	Progeny	Max Dose IC Period[a] (mrem/yr)	Max Dose Balance of Compliance Period[b] (mrem/yr)	Max Dose Post-Compliance Period[c] (mrem/yr)	Time of Max Dose IC Period[a] (year)	Time of Max Dose Compliance Period[b] (year)	Time of Max Dose Post-Compliance Period[c] (year)
C-14		1.13E-17	2.31E-08	1.37E-06	2134	3040	5389
H-3		1.97E-13	1.59E-12	1.85E-29	2134	2214	3041
I-129		2.30E-25	8.22E-15	6.01E-09	2134	3040	11889
Nb-94		1.05E-43	8.71E-33	4.77E-14	2134	3040	192039
Ni-59		6.81E-43	7.07E-32	1.06E-11	2134	3040	208039
Tc-99		3.43E-15	1.04E-07	1.09E-07	2134	3040	3155
Am-241		3.43E-47	8.57E-37	6.61E-32	2134	3040	9089
	Np-237	5.22E-39	2.05E-27	2.12E-11	2134	3040	63789
	U-233	1.12E-30	8.04E-20	1.95E-08	2134	3040	35789
	Th-229	2.23E-32	2.02E-21	4.74E-09	2134	3040	43789
Pu-241		5.98E-56	4.15E-54	8.39E-64	2134	2264	3041
	Am-241	6.94E-44	2.48E-33	2.68E-29	2134	3040	7889
	Np-237	7.12E-37	7.73E-25	1.51E-11	2134	3040	58789
	U-233	8.00E-39	9.59E-26	2.10E-12	2134	3040	48789
	Th-229	1.56E-40	2.36E-27	5.67E-13	2134	3040	57789
U-234		6.55E-27	4.73E-16	1.21E-04	2134	3040	35789
	Th-230	3.74E-30	3.40E-19	2.06E-06	2134	3040	58789
	Ra-226	2.36E-32	5.11E-21	3.72E-06	2134	3040	61789
	Pb-210	2.17E-32	2.12E-20	3.35E-05	2134	3040	61789
Pu-240		4.60E-55	4.55E-44	5.77E-27	2134	3040	96039
	U-236	4.76E-31	3.45E-20	9.68E-09	2134	3040	36789
	Th-232	1.70E-39	1.55E-28	1.33E-15	2134	3040	180039
	Ra-228	5.07E-39	5.24E-28	7.21E-15	2134	3040	136039
	Th-228	2.42E-40	2.70E-29	4.56E-16	2134	3040	92039
U-235		2.95E-27	2.13E-16	6.00E-05	2134	3040	36789
	Pa-231	8.36E-30	8.05E-19	4.06E-06	2134	3040	53789
	Ac-227	1.95E-30	2.85E-19	6.34E-06	2134	3040	53789
Pu-238		1.28E-52	1.08E-44	1.28E-44	2134	3040	3239
	U-234	7.22E-34	1.18E-22	5.89E-10	2134	3040	36789
	Th-230	4.12E-37	8.38E-26	1.00E-11	2134	3040	58789
	Ra-226	2.59E-39	1.17E-27	1.81E-11	2134	3040	61789
	Pb-210	2.38E-39	4.57E-27	1.64E-10	2134	3040	61789
Pu-239		4.11E-54	4.37E-43	6.32E-21	2134	3040	208039
	U-235	3.38E-39	7.16E-28	3.68E-13	2134	3040	51789
	Pa-231	9.55E-42	2.66E-30	3.59E-14	2134	3040	80789
	Ac-227	2.22E-42	9.06E-31	5.61E-14	2134	3040	80789
Maximum Totals		2.01E-13	1.27E-07	2.05E-04	2134	3040	37789

a. Institutional Control (IC) period, 100 years following facility closure (2039-2139).
b. Balance of compliance period is the 900 years following the 100-year IC period (2139-3039). The 100-year IC period and the 900-year balance of compliance period make up the 1000-year compliance period.
c. Post-compliance period is after the 1000-year compliance period (> 3039).

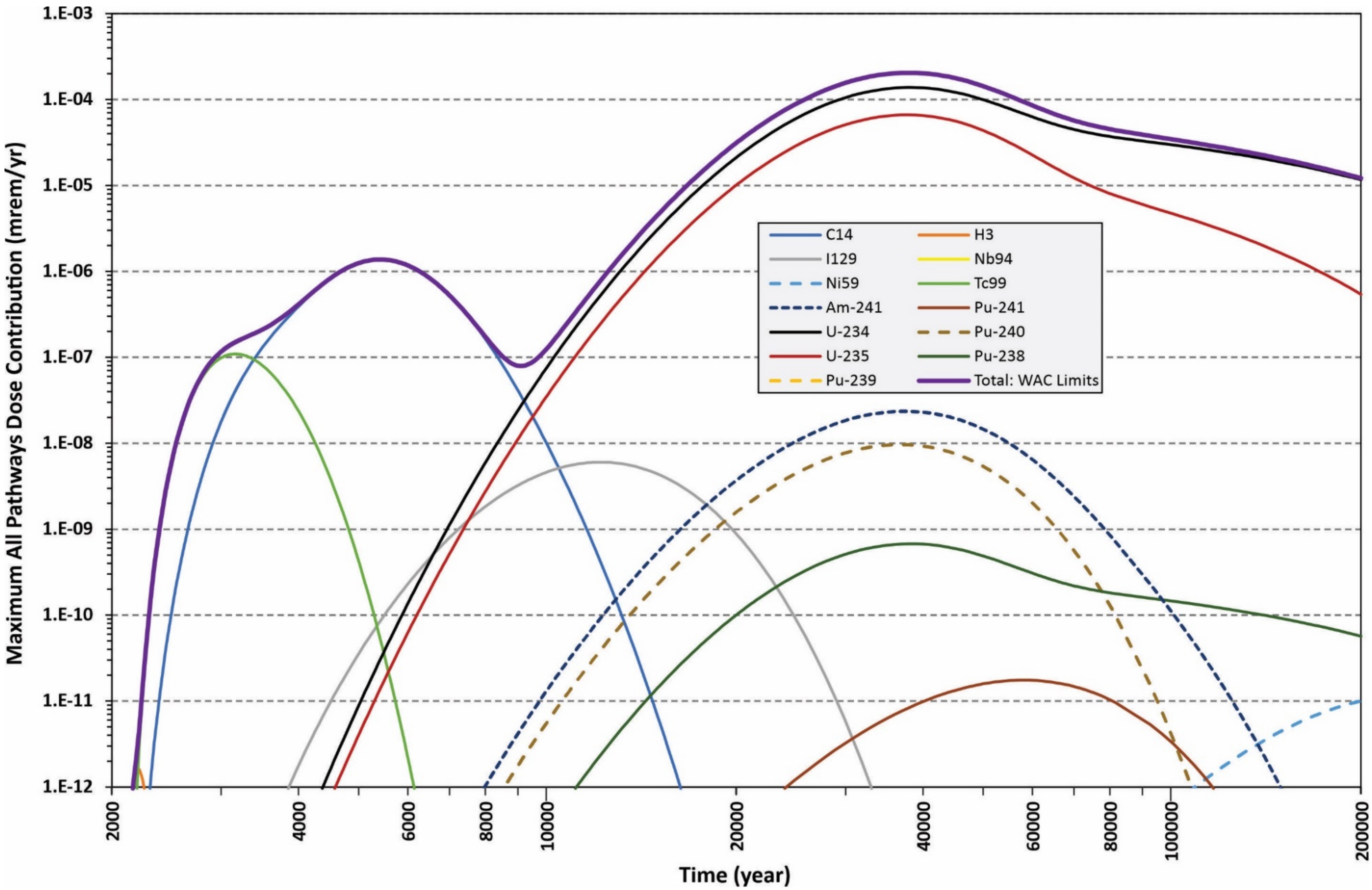

Figure 2. All-pathways dose as a function of time from surface contamination on the NRF canisters for Case 1: all canisters assumed contaminated to maximum limits allowed by the WAC (from 10 CFR 835 Appendix D). Dose contribution of progeny are included in the parent dose.

Table 9. Groundwater all-pathways dose contribution as a function of time from surface contamination on the NRF canisters for Case 2: all canisters contaminated to maximum limits requested by NRF.

Parent	Progeny	Max Dose IC Period[a] (mrem/yr)	Max Dose Balance of Compliance Period[b] (mrem/yr)	Max Dose Post-Compliance Period[c] (mrem/yr)	Time of Max Dose IC Period[a] (year)	Time of Max Dose Compliance Period[b] (year)	Time of Max Dose Post-Compliance Period[c] (year)
C-14		2.50E-15	5.13E-06	3.05E-04	2134	3040	5389
H-3		1.97E-13	1.59E-12	1.85E-29	2134	2214	3041
I-129		1.28E-24	4.57E-14	3.34E-08	2134	3040	11889
Nb-94		2.33E-41	1.94E-30	1.06E-11	2134	3040	192039
Ni-59		1.51E-40	1.57E-29	2.36E-09	2134	3040	208039
Tc-99		7.616E-13	2.30E-05	2.42E-05	2134	3040	3155
Am-241		1.90E-46	4.76E-36	3.67E-31	2134	3040	9089
	Np-237	2.90E-38	1.14E-26	1.18E-10	2134	3040	63789
	U-233	6.20E-30	4.47E-19	1.09E-07	2134	3040	35789
	Th-229	1.24E-31	1.12E-20	2.63E-08	2134	3040	43789
Pu-241		3.32E-55	2.31E-53	4.66E-63	2134	2264	3041
	Am-241	3.86E-43	1.38E-32	1.49E-28	2134	3040	7889
	Np-237	3.96E-36	4.29E-24	8.40E-11	2134	3040	58789
	U-233	4.45E-38	5.33E-25	1.17E-11	2134	3040	48789
	Th-229	8.69E-40	1.31E-26	3.15E-12	2134	3040	57789
U-234		6.56E-27	4.74E-16	1.21E-04	2134	3040	35789
	Th-230	3.75E-30	3.40E-19	2.06E-06	2134	3040	58789
	Ra-226	2.36E-32	5.12E-21	3.72E-06	2134	3040	61789
	Pb-210	2.17E-32	2.13E-20	3.36E-05	2134	3040	61789
Pu-240		2.56E-54	2.53E-43	3.21E-26	2134	3040	96039
	U-236	2.65E-30	1.91E-19	5.38E-08	2134	3040	36789
	Th-232	9.46E-39	8.62E-28	7.37E-15	2134	3040	180039
	Ra-228	2.82E-38	2.91E-27	4.00E-14	2134	3040	136039
	Th-228	1.35E-39	1.50E-28	2.53E-15	2134	3040	92039
U-235		2.95E-27	2.13E-16	6.00E-05	2134	3040	36789
	Pa-231	8.36E-30	8.05E-19	4.06E-06	2134	3040	53789
	Ac-227	1.95E-30	2.85E-19	6.34E-06	2134	3040	53789
Pu-238		7.10E-52	6.00E-44	7.10E-44	2134	3040	3239
	U-234	4.01E-33	6.54E-22	3.27E-09	2134	3040	36789
	Th-230	2.29E-36	4.66E-25	5.57E-11	2134	3040	58789
	Ra-226	1.44E-38	6.52E-27	1.01E-10	2134	3040	61789
	Pb-210	1.32E-38	2.54E-26	9.09E-10	2134	3040	61789
Pu-239		2.28E-53	2.43E-42	3.51E-20	2134	3040	208039
	U-235	1.88E-38	3.98E-27	2.05E-12	2134	3040	51789
	Pa-231	5.31E-41	1.48E-29	2.00E-13	2134	3040	80789
	Ac-227	1.23E-41	5.03E-30	3.12E-13	2134	3040	80789
Maximum Totals		9.61E-13	2.82E-05	3.05E-04	2134	3040	5389

a. Institutional Control (IC) period, 100 years following facility closure (2039-2139).
b. Balance of compliance period is the 900 years following the 100-year IC period (2139-3039). The 100-year IC period and the 900-year balance of compliance period make up the 1,000-year compliance period.
c. Post-compliance period is after the 1,000-year compliance period (> 3039).

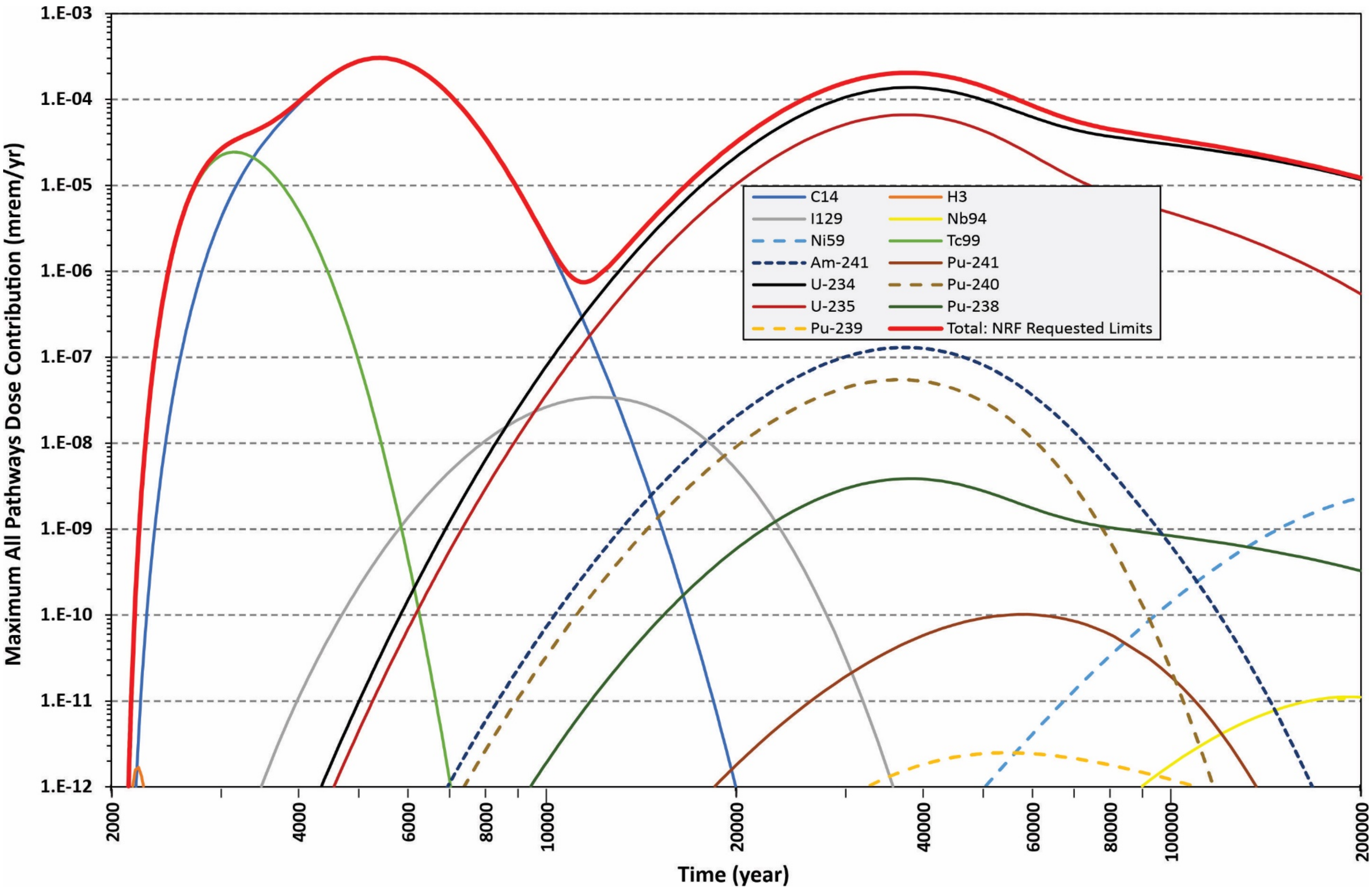

Figure 3. All-pathways dose as a function of time from surface contamination on the NRF canisters for Case 2: all canisters assumed contaminated to maximum limits requested by NRF. Dose contribution of progeny are included in the parent dose.

Figure 4 below compares the maximum theoretical groundwater all-pathways dose contribution as a function of time for the two cases examined. During the first 8,000 years following facility closure (up to approximately year 10,000), the maximum dose for Case 2 is approximately two orders of magnitude greater; because during this time, the dose is controlled by Tc-99 and C-14. These are in the beta-gamma emitter group (Group 4), a group for which NRF is requesting an increase in allowable surface contamination levels. However, after approximately year 10,000, the dose is controlled by U-234 and U-235, and the dose levels are the same for each case because these radionuclides are not in a group for which NRF has requested an increase.

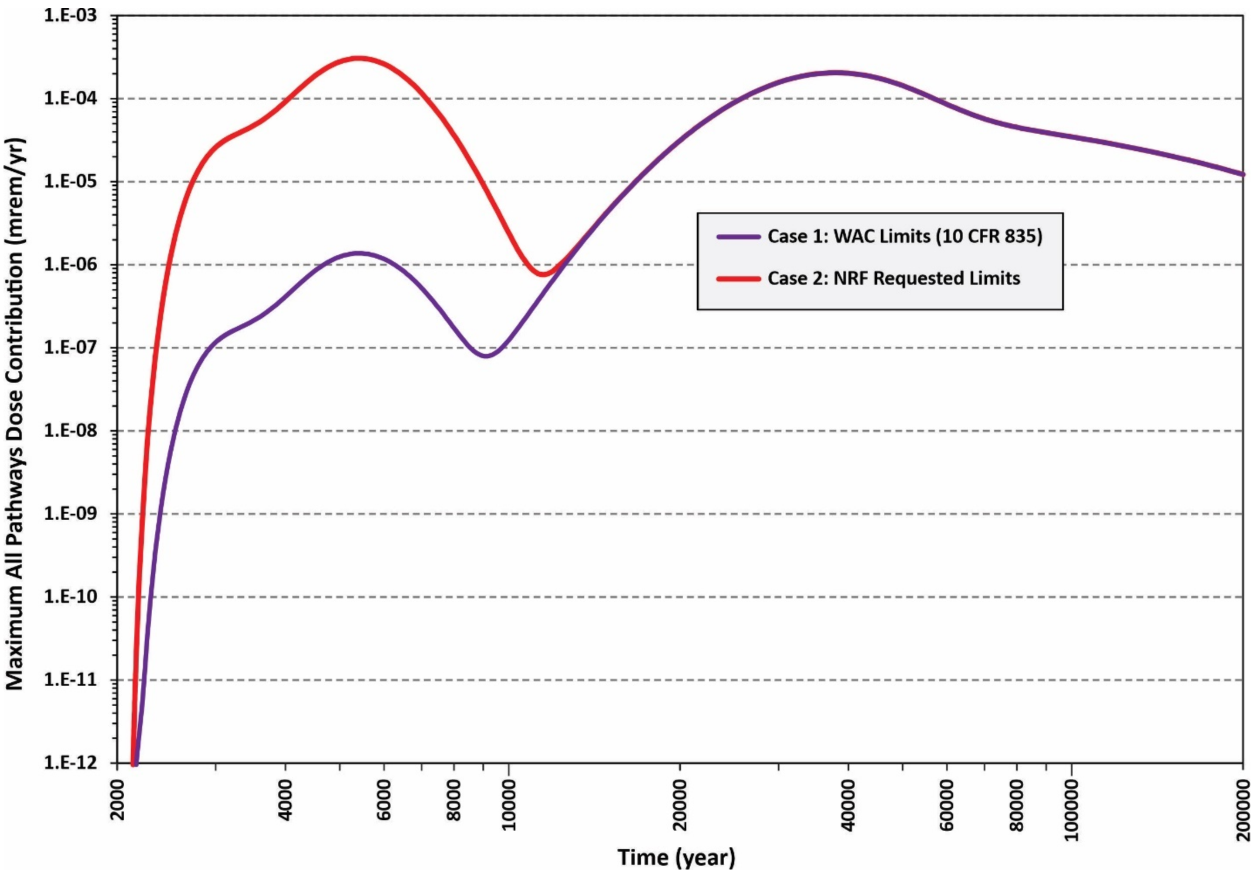

Figure 4. Comparison of all-pathways dose as a function of time from surface contamination on the NRF canisters. Canisters are assumed contaminated to current WAC limits (Case 1), and maximum levels requested by NRF (Case 2).

Table 10 shows the overall maximum dose contribution for Case 2 is about 50% greater than Case 1, but the maximum dose of both cases is very low. The maximum potential dose contribution using the NRF-requested limits (3.05E-04 mrem/yr) is more than 2,100 times less than the maximum PA base-case dose (0.642 mrem/yr), and more than 81,000 times less than the DOE O 435.1 all-pathways dose limit (25 mrem/yr) [7]. In addition, the maximum dose occurs after the 1,000-year compliance period. Perhaps even more important is the difference in maximum potential dose between Case 1 and Case 2. The difference in dose between Case 1 and Case 2 is 1.00E-04 mrem/yr (3.05E-04 - 2.05E-04), which is more than 6,400 times less than the max PA base-case dose (0.642 mrem/yr) and 250,000 times less than the DOE O 435.1 all-pathways dose limit (25 mrem/yr) [7].

Table 10. Comparison of maximum dose contribution for the two cases of surface contamination to the PA base-case dose and the DOE O 435.1 dose limit.

Level of Surface Contamination on	Max Dose (mrem/yr)	Max PA Base-Case	DOE O 435.1 Dose

NRF Waste Canisters		Dose (mrem/yr)	Limit (mrem/yr)
Case 1: WAC limits (10 CFR 835)	2.05E-04 (year 37789)[a]	0.642 (year 21739)[a]	25 (0-1000 years after closure)[b]
Case 2: NRF-requested limits	3.05E-04 (year 5389)[a]		

a. Maximum dose for both cases and the PA base case occurs after the 1000-year compliance period.
b. The 25 mrem/yr dose limit from DOE O 435.1 applies during the 1000-year compliance period.

5. ASSESSMENT OF POTENTIAL IMPACTS ON OTHER EXPOSURE PATHWAYS

In the PA, the biotic and air pathway doses were low, and these pathways were screened from inclusion in the all-pathways dose. The inadvertent intruder pathway doses (acute and chronic) presented in the PA were much less than DOE O 435.1 standards [7]. Although it is highly unlikely the increased surface contamination on NRF waste canisters would impact these conclusions, a simple assessment of the potential impacts on the biotic, inadvertent intruder, and air pathways was performed by comparing the increase in total maximum radionuclide activities on NRF waste canisters using the NRF-requested limits to the appropriate PA base-case inventories.

The biotic and intruder pathway exposure scenarios in the PA were assessed using the 61 radionuclides that passed the Phase 2 groundwater screening. In both cases, the entire PA base-case inventory was assumed to be accessible and available for transport, and neither the concrete vaults nor the stainless-steel waste containers were credited for protecting the waste. Table 11 compares the increase in total maximum activity as surface contamination on NRF waste canisters using the requested limits to the total PA base-case inventories. All the radionuclides in Table 7 were included in the biotic and intruder pathways analysis in the PA. The last column of Table 11 shows the total maximum increases in surface contamination using NRF-requested limits are an insignificant percentage of the PA base-case inventories used to calculate both the biotic and intruder pathway doses in the PA. Therefore, the increase in surface contamination on NRF canisters using the requested limits will have a negligible impact on the biotic and intruder pathway doses as presented in the PA.

In the PA a three-step inventory screening procedure was used for the air pathway similar to the groundwater pathway, but used different criteria. The air pathway screening began by considering all radionuclides that could volatilize at the conditions expected in the RHLLW Disposal Facility. None of the nine radionuclides eliminated in the first two steps of the PA air pathway screening (Ar-37, Ar-39, Ar-42, I-131, I-132, I-133, Kr-81, Kr-85, and Xe-131m) are included in the source term for this SA. The three radionuclides included in the third and final screening step of the PA air pathway analysis (C-14, H-3, and I-129) are included in this SA.

The third step of the PA air pathway screening took credit for corrosion of radionuclides in activated metals by releasing the radionuclides into the subsurface as the metal corroded. No such procedure was applied to the radionuclides in other waste forms (surface contamination and resins). Therefore, it is appropriate to compare the increase in surface contamination using NRF-requested limits to the surface contamination and resin inventories of the PA. Table 12 compares the increase in total maximum activity as surface contamination on NRF waste canisters using the requested limits to the PA base-case inventories of surface contamination and resins. The last column of Table 12 shows the total maximum increase in surface contamination using NRF-requested limits is an insignificant percentage of the PA base-case inventories of surface contamination and resins. Therefore, the increase in surface contamination on NRF canisters using the requested limits will have a negligible impact on the air pathway doses as presented in the PA.

Table 11. Comparison of the increase in total maximum activity to the PA base-case inventory to assess impacts to the biotic and intruder pathways.

Radionuclide	Total Maximum	Total Maximum	Increase in Total	Total PA	Increase in Total

	Activity if all Canisters were Contaminated to Current WAC Limits (Ci)[a]	Activity if all Canisters were Contaminated to NRF Requested Limits (Ci)[a]	Maximum Activity using NRF Requested Limits over Current WAC Limits (Ci)	Base-Case Inventory (Ci)[b]	Maximum Activity as a Percent of PA Base-Case Inventory
C-14	8.00E-06	**1.78E-03**	**1.77E-03**	2.14E+02	0.00083%
H-3	2.68E-03	2.68E-03	0	1.99E+03	0%
I-129	6.13E-10	**3.40E-09**	**2.79E-09**	5.38E-02	0.00001%
Nb-94	9.38E-08	**2.08E-05**	**2.07E-05**	5.71E+01	0.00004%
Ni-59	1.05E-06	**2.33E-04**	**2.32E-04**	1.82E+03	0.00001%
Tc-99	1.44E-07	**3.20E-05**	**3.19E-05**	5.24E+00	0.00061%
Am-241	1.26E-07	**7.00E-07**	**5.74E-07**	2.79E-01	0.00021%
Pu-238	2.47E-06	**1.37E-05**	**1.12E-05**	3.68E-01	0.0031%
Pu-239	3.44E-08	**1.91E-07**	**1.57E-07**	5.56E-01	0.00003%
Pu-240	3.88E-09	**2.15E-08**	**1.77E-08**	1.76E-01	0.00001%
Pu-241	2.61E-06	**1.45E-05**	**1.19E-05**	1.97E+01	0.00006%
U-233	2.96E-08	**1.65E-07**	**1.35E-07**	8.38E-05	0.16%
U-236	1.40E-08	**7.78E-08**	**6.38E-08**	5.88E-05	0.11%
U-234	1.82E-04	1.82E-04	0	6.09E-04	0%
U-235	8.58E-05	8.58E-05	0	3.71E-03	0%

a. From Table 7, Columns 2 and 3.

b. From Table 2-14, Column 5, RHLLW Performance Assessment [10].

BOLD font indicates an increase over the current WAC limit. NRF has requested an increase for Group 2 (transuranics) and Group 4 (beta-gamma emitting) radionuclides.

Table 12. Comparison of the increase in total maximum activity to the PA base-case inventory of surface contamination and resin waste forms to assess impacts to the air pathway.

Radionuclide	Increase in Total Maximum Activity using NRF Requested Limits over Current WAC Limits (Ci)[a]	Total PA Base-Case Inventory of Surface Contamination and Resin Waste Forms (Ci)[b]	Increase in Total Maximum Activity as a Percent of PA Base-Case Inventory of Surface Contamination and Resin Waste Forms
C-14	**1.77E-03**	9.13E+00	0.019%
H-3	0	3.86E+00	0%
I-129	**2.79E-09**	5.38E-02	0.000005%

a. From Table 11, Column 4.

b. From Table 2-14, Sum of Columns 3 and 4, RHLLW Performance Assessment [10].

BOLD font indicates an increase over the current WAC limit. NRF has requested an increase for Group 2 (transuranics) and Group 4 (beta-gamma emitting) radionuclides.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Performance Objective Impact

The results of this SA show the maximum potential dose contribution to the PA all-pathways dose using the NRF-requested limits for exterior canister contamination is only slightly greater than the dose contribution using the current WAC limits. The slight increase in dose is an insignificant fraction of the maximum PA base-case dose and DOE O 435.1 all-pathways dose limit (25 mrem/yr) [7]. In addition, the increase in requested limits will have a negligible impact on the biotic, air, and intruder pathway doses calculated in the PA. Based on the results of this SA, the increase in canister exterior contamination limits requested by NRF are well within the bounds of the current PA and will not result in a violation of performance objectives. The results also show the increased limits do not reflect or necessitate a fundamental change to the PA conceptual model nor a change to the way exterior contamination is not included in PA dose calculations by RHINO[3]. Specific recommendations resulting from the overall performance objective conclusions (WAC revision and monitoring plan revision) are summarized in Subsection 6.4. The PA [10], CA [4,5], closure plan [14], and PA/CA maintenance plan [15]do not require revision.

6.2 Source Term Conservativeness

It is important to ensure the input data informing the SA be sufficiently conservative to ensure there is a high degree of confidence that all canisters proposed for disposal meet the revised WAC surface contamination limits proposed by NRF. As waste canisters will not be individually surveyed to demonstrate compliance with the WAC (due to challenges with performing direct contamination surveys of highly radioactive loaded waste canisters), sufficient margin must be included in the SA input data to ensure uncertainty associated with individual canister contamination levels is accounted for and bounded by the analysis.

It is also important to ensure the SA input data is sufficiently conservative so as to preclude having to revisit the analysis. It is important to ensure the source terms are sufficiently bounding to ensure changing conditions or future actions will not require the revised surface contamination levels to need to be revisited.

The source term that served as input data for this SA was derived to be very conservative to account for canister-to-canister uncertainty and to ensure the limits provide sufficient margin so as not to require revisiting the limits during the projected operational lifecycle of the disposal facility.

Dose impacts in the SA were calculated based on the total inventory on all NRF canisters assuming all canisters were contaminated to the requested limits (i.e., every canister and every exterior surface is contaminated to the maximum extent allowed under the proposed revised WAC limits). It is recognized that there is a very small chance contamination on a single canister could exceed the limits; however, were this to occur, the cumulative contamination on all canisters will be considerably less than the total inventory evaluated in the SA. To ensure this is the case additional conservative measures were taken in determining the requested limits. These include:

- The 97.5% confidence limits were based on the lid swipe data only. Plots in NRF-ENG-FE-00670 (Appendix A) show lid surface contamination results are much higher than sidewall shell results; however, shell contamination levels were ignored for the source term used as input to the SA.
- NRF added additional margin (5 to 10%) to the 97.5% confidence levels to establish proposed surface contamination limits, which resulted in concurrent conservativeness in the SA input source term definition.

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[3] RHINO (Remote-Handled Low-Level Waste Disposal Facility Inventory Online) is an NQA-1 software application for accepting, managing, and tracking the receipt of waste and its disposal location. The technical and functional requirements for RHINO are found in TFR-981, “Remote Handled-LLW Inventory Online Database” [24].

- NSFH canisters are expected to have much lower surface contamination levels than 55-ton canisters because: 1) the NSFH facility is new and contamination associated with past operational practices will not exist, 2) the NSFH facility has been designed with higher demineralizer flow rates, which will result in a much lower overall contamination level associated with residual contamination buildup in the facility over time, and 3) residence time of new canisters in the water pool is anticipated to be much less (days) than current practices at ECF. The surface area of all NSFH canisters is 71% of the total surface area of all NRF canisters. Therefore, the dose impacts in the SA would be less if external contamination on NSFH canisters was significantly lower than modeled in this SA.

Even with these conservative assumptions, the maximum potential dose contribution using the NRF-requested limits is thousands of times less than the max PA base-case dose and tens of thousands of times less than the DOE O 435.1 all-pathways dose limit [7].

6.3 Variability Analysis

An understanding of the variability of water pool source term data, which directly affects the potential contamination that may accumulate on waste canisters while located in the water pool, is essential to ensure this SA is bounding, and the canister-to-canister variability is limited (thereby providing increased confidence in process knowledge being used to characterize canisters and demonstrating compliance with the WAC). Several recommendations for inclusion of variability management water pool operations procedures are derived herein and discussed in Subsection 6.4, below.

NRF utilizes process controls to maintain the total activity level of the water pool to ≤ 5.0E-05 µCi/mL. RWDS modules are required to be in operation whenever work evolutions are performed that could potentially change the activity level in the water pool. Additionally, NRF Chemistry performs gamma spectroscopy on water samples to ensure the above limit is adhered to. These water samples are taken weekly according to NRF 1663.12 [16], when process evolutions expected to raise the activity level of the water pool are performed, and when indications of increased activity levels are found (e.g., increased radiation level above the water line). In the event the NRF water pool exceeds the established limit, response procedures are employed that can include securing all work in the water pool until the activity level has returned to acceptable limits through the RWDS filtration system.

It is recognized that the longer waste canisters reside within in the water pool, the higher the potential for increased contamination levels. The analysis performed on the surface contamination on the exterior of the waste canisters was performed on waste canisters with residence time in the water pool of less than 3 years. NRF expects canisters will be in the water pool less than 3 years prior to loading and will perform underwater swipes on any waste canister that exceeds 3 years in the water pool prior to loading. The purpose of these swipes will be to confirm every canister remains compliant with the WAC even though it has been submerged longer than 3 years. The requirement to perform swipes in the event canisters are submerged for longer than 3 years will be added to NRF implementing procedure, WP7000 [17].

NRF work procedure, NRF 3018 [18], requires evaluation of nuclide distributions for standard areas of generation every 3 years. The periodicity is set based on the need to validate the standard model upon which water pool source terms are based. The processes that can affect contamination buildup do not change. The periodicity is further supported by weekly water pool samples. The water pool nuclide distribution was originally developed to characterize waste generated during water pool operations to support defueling of M130/140 containers and processing of spent cores for loading into overpacks. Four underwater swipes were taken at 25 different sample locations in the water pool.

The samples are collected using solid swipes underwater. The samples are dried and shipped to a DOE Consolidated Audit Program laboratory (GEL Laboratories) for radionuclide analysis. All samples undergo gamma spectroscopy. Samples are also homogenized by location and then undergo chemical speciation for individual analyses for:

Am-241, Cm-242, Cm-243/244, Cm-245/246, Pu-238, Pu-239/240, Pu-241), and U-233/234, U-235/236, U-238, I-129, Sr-90, Fe-55, Ni-63, Tc-99, H-3, and C-14.

All radionuclide analytical methods used by GEL Laboratories are developed using DOE and Environmental Protection Agency standards

Any change in source term determinations indicated by swipe campaigns will be communicated to the RHLLW Disposal Facility, facility disposition specialist (FDS).

6.4 Summary of Recommendations

Based on the overall impact to the performance analysis indicated by the results of the SA (and the conservativeness of the analysis based on the derivation of the source term analyzed), it is recommended the NRF request for an exception to the current limits for external surface contamination be accepted and the revised limits for NRF be added to the WAC. The monitoring plan will also be revised to identify external canister contamination as a potential mobile source term that may be detected by monitoring earlier-than-potential releases from waste. Specific recommendations and timing of implementation (in parentheses) include:

- Revision of the WAC to reflect the NRF proposed surface contamination levels for surface contamination on NRF-generated canisters (prior to canister acceptance).
- Revision of the monitoring plan to identify external canister contamination as a potential mobile source term that may be detected by monitoring earlier-than-potential releases from waste [prior to next (FY23) monitoring event].
- The implementing procedure for the water pool sampling, NRF 1663.12 [16], will be added to the NRF Generator Implementation Crosswalk (GIC) and assessed as part of generator certification (prior to initial certification and annually thereafter as part of generator re-certification).
- The requirement to perform swipes in the event canisters are submerged for longer than 3 years will be added to NRF implementing procedure, WP 7000 [17], and this procedure will be added to the GIC and assessed as part of generator certification (prior to initial certification and annually thereafter as part of generator recertification).
- The implementing procedure for the periodic swipe campaign, NRF 3018 [24], will be added to the GIC and assessed as part of generator certification (prior to initial certification and annually thereafter as part of generator recertification). Any change in source term determinations indicated by swipe campaigns will be communicated to the RHLLW Disposal Facility FDS (at the time of occurrence).

7. REFERENCES

1. Idaho National Laboratory. 2018. PLN-5446, Revision 1, “Waste Acceptance Criteria for the Remote-Handled Low-Level Waste Disposal Facility.”
2. Idaho National Laboratory. 2022. LWP-13840, Revision 14, “Issues Management.”
3. Code of Federal Regulations, Office of the Federal Register. 10 CFR 835, Appendix D, “Surface Contamination Values.”
4. U.S. Department of Energy. 2011. DOE/ID-11422, “Composite Analysis for the Idaho National Laboratory Remote-Handled Low-Level Waste Disposal Facility.”
5. U.S. Department of Energy. 2017. DOE/ID-11577, “Addendum to the Composite Analysis for the Idaho National Laboratory Remote-Handled Low-Level Waste Disposal Facility.”
6. U.S. Department of Energy. 2017. DOE-STD-5002-2017, “Disposal Authorization Statement and Tank Closure Documentation.”
7. U.S. Department of Energy. 2021. Order 435.1, Change 2, “Radioactive Waste Management.”

8. Rood, A. S., 2010, “Mixing Cell Model: A One-Dimensional Numerical Model for Assessment of Water Flow and Contaminant Transport in the Unsaturated Zone,” ICP/EXT-05-00748, Idaho Cleanup Project, Idaho National Laboratory.

9. Rood, A. S., 2003, “GWSCREEN: A Semi-Analytical Model for Assessment of the Groundwater Pathway from Surface or Buried Contamination, Theory and User's Manual, Version 2.5,” INEEL/EXT-98-00750, Idaho National Engineering and Environmental Laboratory.

10. U.S. Department of Energy. 2018. DOE/ID-11421, “Performance Assessment for the Idaho National Laboratory Remote-Handled Low-Level Waste Disposal Facility.”

11. U.S. Department of Energy. 2011. DOE-STD-1196-2011, “Derived Concentration Technical Standard.”

12. Idaho National Laboratory. 2018. TFR-981, “Remote Handled-LLW Inventory Online Database.”

13. Idaho National Laboratory. 2018. ECAR-1892, “Groundwater Pathway Transport and Dose Calculations for the INL Remote-Handled Low-Level Waste Disposal Facility Performance Assessment.”

14. Idaho National Laboratory. 2012. PLN-3370, “Preliminary Closure Plan for the Idaho National Laboratory Remote-Handled Low-Level Waste Disposal Facility.”

15. Idaho National Laboratory. 2017. PLN-3368, Revision 1, “Maintenance Plan for the Idaho National Laboratory Remote-Handled Low-Level Waste Disposal Facility Performance Assessment and Composite Analysis.”

16. Idaho National Laboratory. 2020. NRF 1663.12, Revision 15, “ECF Water Pool Systems and Water Quality Standards,” Naval Reactors Facility (NRF).

17. Idaho National Laboratory. 2019. Technical Work Document No. WP7000, “Type IV Waste Canister Operations,” Naval Reactors Facility (NRF).

18. Idaho National Laboratory. 2020. NRF 3018, Revision 3, “NRF Activity Estimating Procedure,” Naval Reactors Facility (NRF).

Appendix A

Letter from Fluor Marine Propulsion to Robert Miklos, July 18, 2022, NRF-ENG-FE-00670

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FLUOR®

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NRF-ENG-FE-00670

July 18, 2022

Robert P. Miklos, Production Facility Division Director
Materials and Fuels Complex

Subject: NRF; Remote-Handled Low Level Waste Disposal Facility; Request for Waste Acceptance Criteria Exception; For Action

Dear Robert P. Miklos:

PURPOSE

This letter requests an exception to the current Remote-Handled Low-Level Waste Disposal Facility (RHLLW) Waste Acceptance Criteria (WAC) Section 2.6 requirement regarding surface contamination limits for waste canisters shipped from the Naval Reactors Facility (NRF) and provides proposed surface contamination limits that NRF can meet with at least a 97.5 percent confidence level.

BACKGROUND

NRF is preparing to begin 55-Ton Scrap Cask (55-Ton) shipments to the RHLLW in summer 2022 and New Spent Fuel Handling (NSFH) Facility Cask (NFC) shipments in 2029. These shipments are required to meet the RHLLW WAC as contained in PLN-5446. Section 2.6 of the WAC states:

> Waste canisters accessible for radiological contamination surveys shall be free of removable surface contamination on the outside of the disposal canister. Waste canisters not accessible for swiping shall utilize process controls to minimize loose contamination on canister surfaces as much as practical. All canisters and packaging received at the RHLLW Disposal Facility shall comply with contamination control limits of 10 CFR 835, Appendix D, "Surface Contamination Values."

Correspondence between NRF and Battelle Energy Alliance (BEA) has indicated that the surface contamination limit for 55-Ton waste canisters will likely not be met as discussed in BEA letter CCN 251244 dated March 31, 2022. BEA requested that NRF provide a request for deviation to the RHLLW WAC requirement 2.6 for surface contamination on NRF waste canisters. As defined in section 6.5 of the WAC, a deviation is a temporary inability to meet a requirement that will be corrected. NRF has determined that the WAC surface contamination requirement cannot be consistently met. NRF is requesting a permanent exception to the current RHLLW WAC section 2.6 requirement for transuranic nuclides and beta-gamma emitters for all waste canisters shipped to the RHLLW based on the inability to verify the surface contamination levels using the methods specified in 10 Code of Regulations (CFR) 835

Appendix D and the contamination levels obtained using alternate methods that exceed the 10 CFR 835 Appendix D limits for beta-gamma emitters and transuranics.

DISCUSSION

10 CFR 835 Appendix D specifies the method to obtain removable (also known as "loose") surface contamination measurements as "…swiping the area with a dry filter or soft absorbent paper…". The specified method to obtain total (fixed + removable) contamination is "as observed by an appropriate detector." NRF is not able to use the 10 CFR 835 Appendix D methods to measure the removable or total surface contamination on above water dry waste canisters after they have been loaded with irradiated waste due to the high radiation levels of the contents and physical limitations of the equipment. NRF is confident that the removable and total surface contamination limits will be met for the 55-Ton Scrap cask and trailer, (i.e. part of the packaging) based on process knowledge and the long history of removable and total surface contamination surveys performed during each shipment cycle.

NRF waste canisters are loaded underwater in the Expended Core Facility (ECF) water pool with irradiated and surface contaminated waste or depleted Radioactive Water Demineralizer Systems (RWDS) modules. The irradiated waste is generated underwater due to the extremely high radiation and contamination levels of the waste. Loaded waste canisters typically have radiation levels of several thousand R/hr on contact. The high radiation levels prohibit safely raising loaded waste canisters out of the water pool where removable surface contamination levels could be verified with a swipe, and the high radiation levels would completely mask any total surface contamination scans. Waste canisters shipped to the RHLLW will not exceed the WAC on contact radiation limit of 60,000 R/hr.

Empty waste canisters could be lowered into the water pools then raised out of the water to be directly swiped or surveyed, but these surveys would not be representative of the actual process at NRF. As previously discussed in CCN 251244, even an empty contaminated canister with a submergence time of a few weeks that was raised from the water pools had contamination levels that would exceed the WAC.

Loaded waste canisters are raised from the water pools directly into the shielded 55-Ton through the doors on the bottom of the cask while the cask is seated on a loading stand. Once the waste canister is inside the 55-Ton there is no practical way to access the waste canister for contamination surveys.

Based on the high waste canister radiation levels and the limitations of the 55-Ton there is no way to measure the surface contamination of NRF waste canisters using the methods required in 10 CFR 835 Appendix D.

<u>Surface Contamination Mitigating Actions</u>
While NRF is not able to measure the surface contamination on the loaded waste canisters above water, NRF does take action to minimize the amount of surface contamination on the outside of waste canisters prior to loading a canister in the 55-Ton.

The first mitigating action that reduces surface contamination on waste canisters is placing RWDS underwater in each zone where waste canisters are loaded and prepared for shipment. RWDS are large underwater resin bed filters roughly the same size as a Type IV Waste

Canister that clean and recirculate the water pool water at about 100 gallons per minute each. RWDS are strategically placed in areas where high contamination is generated, including fuel processing zones where waste canisters are loaded with irradiated waste and zones where surface contaminated debris is typically stored and loaded into waste canisters. RWDS are replaced about every five years and are a proven method to reduce contamination levels in the ECF water pools.

The second mitigating action NRF takes to reduce waste canister surface contamination is procedurally requiring NRF technicians to hydroblitz all accessible external surfaces of the waste canister prior to loading it in the 55-Ton. This is performed by qualified, supervised technicians per an approved work document. Completion is recorded for each waste canister. A hydroblitzer is a modified pressure washer that works underwater with an operating pressure over 3000 psi. The hydroblitzers use high pressure water containing less than 5E-6 µCi/mL of radioactivity. NRF recently performed underwater swipes (also known as “smears”) on five waste canisters in the ECF water pools to obtain surface contamination data and to determine the effectiveness of hydroblitzing waste canisters. Hydroblitzing is shown to reduce surface contamination levels on waste canisters by about 52-96 percent as shown in Table 1. The five swiped waste canisters have been underwater for about one to three years which is typical of most waste canisters. Waste canisters will not be submerged at NRF longer than ten years.

Table 1. Hydroblitzing Effectiveness

Canister ID	Date Submerged	Average Contamination Before Hydroblitzing (pCi/100cm^2)	Average Contamination After Hydroblitzing (pCi/100cm^2)	Contamination Level Reduction
05-18-102	12/6/2019	51,678	24,245	53%
05-18-106	3/16/2021	20,768	1,139	95%
05-18-112	1/5/2021	8,983	4,298	52%
05-18-113	9/14/2021	6,028	245	96%
05-18-121	1/5/2021	19,995	2,221	89%

The third mitigating action NRF takes is rinsing each waste canister as it is loaded into the 55-Ton. Waste canisters are raised into the 55-Ton through a circular opening in the loading stand. The loading stand was installed in 2018 and has a circular opening surrounded by a ring of 33 nozzles that direct low pressure water (~35 psi) to all outer surfaces of the waste canister lid and shell (see Figure 1 and Figure 2). The nozzles provide complete spray coverage of the top and sides of the waste canister as it is raised into the 55-Ton. The spray system also uses water containing less than 5E-6 µCi/mL of radioactivity to rinse waste canisters. NRF does not have any data on the effectiveness of the loading stand spray system due to the previously discussed physical limitations of the 55-Ton that prevent access to the waste canister, but expects that it does reduce removable surface contamination levels on waste canisters.

NRF has exhausted all available decontamination strategies to reduce surface contamination levels on waste canisters. NRF was unable to identify any reasonable additional strategies that could potentially reduce contamination levels further than those already in place.

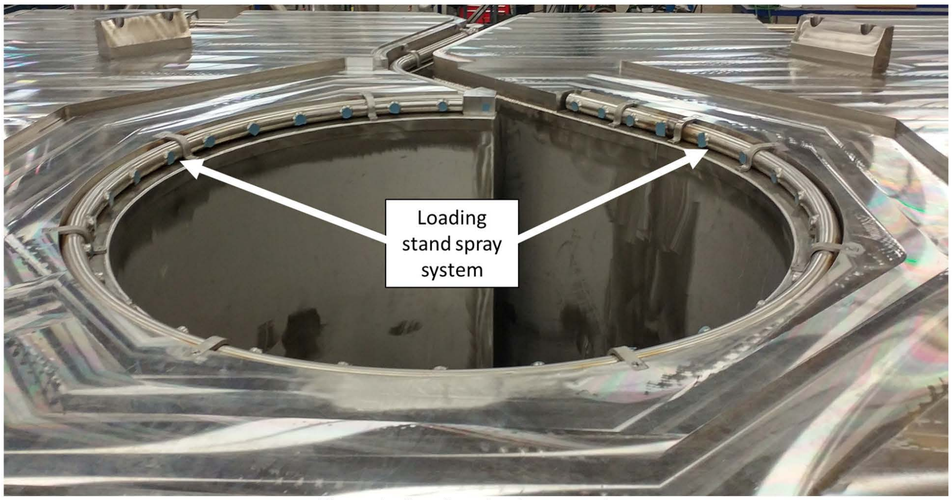


Figure 1. Loading stand spray system.

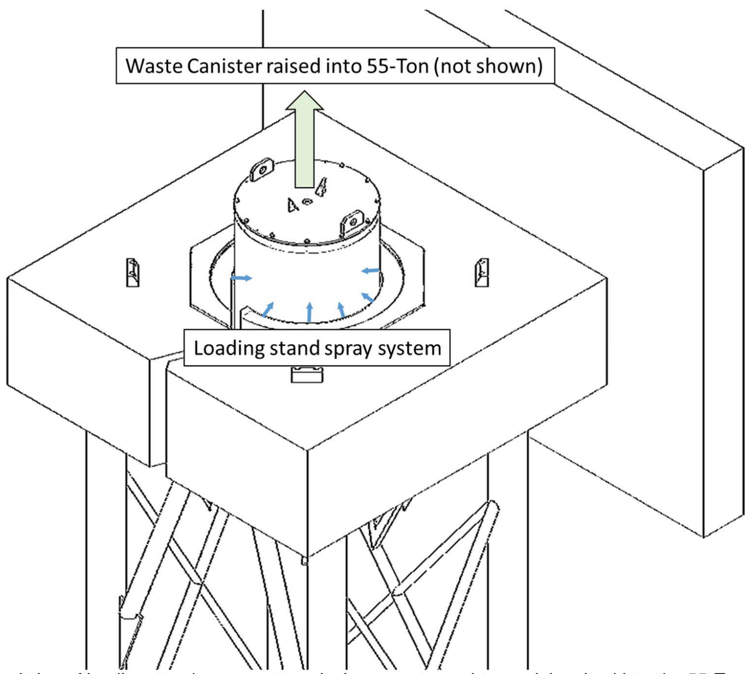


Figure 2. Depiction of loading stand spray system rinsing a waste canister as it is raised into the 55-Ton Scrap Cask (not shown).

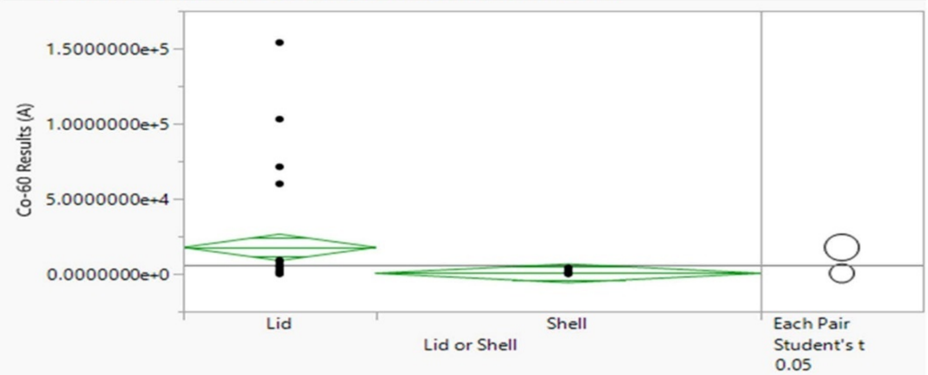
Recommended Contamination Limits
The underwater swipes do not meet the 10 CFR 835 Appendix D requirement to use dry filter or soft absorbent paper to measure the removable surface contamination but they are the only reasonable removable surface contamination measurements that can be obtained. As previously discussed total surface contamination scans are impossible due to the high radiation levels of the items within waste canisters, but the amount of fixed contamination is expected to be negligible since the waste canisters are made of stainless steel with at least a 125 Ra surface finish.

For each waste canister five swipes were performed on the lid and ten swipes on the shell before and after hydroblitzing. The swipes were removed from the water pools and gamma counted by NRF Chemistry. The swipe data was used to estimate the average total activity by radionuclide on each waste canister after hydroblitzing which is available in Attachment (I). The average total activity by radionuclide was converted to DPM/100cm^2 and pCi/100cm^2 over the entire waste canister outer surface and then compared against the 10 CFR 835 Appendix D limits in Attachment (II). The data indicates that waste canisters have a maximum total surface contamination of about 25 µCi. For information the Type IV Waste Canister external surface area is about 16,046 in^2.

The average surface contamination data in Attachment (II) indicates that only one of the five swiped waste canisters met all the removable surface contamination requirements of 10 CFR 835 Appendix D. One waste canister exceeded the transuranic limit and four exceeded the beta-gamma emitter limit. It is clear that surface contamination levels on waste canisters will not consistently be reduced to the limits of 10 CFR 835 Appendix D. Although the waste canisters were not swiped after being rinsed by the loading stand spray system, the spray system is not expected to reduce the contamination as significantly as hydroblitzing due to the much lower operating pressure.

To determine achievable surface contamination limits, NRF first sought to determine if there was a significant difference between the lid and shell swipe activity results. A student's t-test comparing the post hydroblitz lid and shell swipes mean Co-60 activities indicated that there is a significant different between the lid and shell swipe activity means as shown in Figure 3.

Oneway Analysis of Co-60 Results (A) By Lid or Shell



Means Comparisons

Comparisons for each pair using Student's t

Confidence Quantile

t	Alpha
1.99300	0.05

LSD Threshold Matrix

Abs(Dif)-LSD

	Lid	Shell
Lid	-12438	6451
Shell	6451	-8795

Positive values show pairs of means that are significantly different.

Figure 3. Students T-test results comparing mean waste canister lid Co-60 activities against mean waste canister shell Co-60 activities.

Based on the results of the student's t-test NRF decided to ignore the waste canister shell swipe data when determining the proposed radionuclide limits since the mean lid surface contamination levels bound the mean shell surface contamination levels. Using the sample size of n=25 lid swipes, NRF determined the 95 percent confidence level for each of the radionuclide groups as shown in Tables 3 and 4. Since there is no need to consider a lower surface contamination limit a 95 percent confidence level means that NRF is 97.5 percent confident that waste canister surface contamination will be below the upper limits shown in Tables 2 and 3.

NRF recognizes that there is likely some correlation between an increase in surface contamination levels and the length of time a waste canister is submerged in the water pool, however, the longest submerged waste canister (05-18-102) was in a water pool with unusually high contamination disturbance for most of its submergence time. NRF suspects that the location of the waste canister had a greater impact on the elevated surface contamination levels than the submergence time did. NRF is not able to provide a meaningful correlation between submergence time and waste canister surface contamination at this time because the longest submergence time is only about two and a half years. The Table 2 and Table 3 data ignores submergence time.

Table 2. Waste Canister Lid Mean Total Activity and 97.5% Confidence Level (DPM/100cm^2)

Radionuclides	Mean (DPM/100cm^2)	97.5% Confidence Level (DPM/100cm^2)
U-nat, U-235, U-238, and associated decay products	0.42	0.79
Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	50.97	96.75
Th-nat, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	0	0
Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above	111,632	211,873
Tritium and Special Tritium Compounds	36.49	69.25

Table 3. Waste Canister Lid Mean Total Activity and 97.5% Confidence Level (pCi/100cm2)

Radionuclides	Mean (pCi/100cm^2)	97.5% Confidence Level (pCi/100cm^2)
U-nat, U-235, U-238, and associated decay products	0.19	0.36
Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	22.94	43.54
Th-nat, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	0.00	0.00
Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above	50,234.44	95,343.92
Tritium and Special Tritium Compounds	16.42	31.16

The 97.5 percent confidence levels for the uranium, thorium, and tritium radionuclide groups are significantly below the 10 CFR 835 Appendix D limits, therefore NRF does not need a WAC exception for these groups.

Since no other reasonable decontamination methods are available to further reduce waste canister surface contamination, NRF requests an exception to the RHLLW WAC waste canister surface contamination limits for the transuranics and beta-gamma emitters groups. The requested limits that NRF can meet with 97.5 percent confidence are shown and bolded in Table 4 (DPM/100cm^2) and Table 5 (pCi/100cm^2, for reference). The requested limits are based on the 97.5 percent confidence levels but were rounded up for conservatism and simplicity. The method to develop these limits based on underwater swipe data and process knowledge meets the RHLLW WAC definition of "Process knowledge that has measured values as a basis," which is one of the approved methods for determining radionuclide activity content as specified in section 2.0 of the RHLLW WAC.

Table 4. Requested Changes to 10 CFR 835 Appendix D Surface Contamination Limits (DPM/100cm²)

	Removable (DPM/100cm²)		**Total (Fixed + Removable) (DPM/100cm²)**	
Radionuclide	10 CFR 835 Limit	Proposed Limit	10 CFR 835 Limit	Proposed Limit
U-nat, U-235, U-238, and associated decay products	1,000	1,000	5,000	5,000
Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	20	**110**	500	500
Th-nat, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	200	200	1,000	1,000
Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above	1,000	**222,222**	5,000	**222,222**
Tritium and Special Tritium Compounds	10,000	10,000	N/A	N/A

Table 5. Requested Changes to 10 CFR 835 Appendix D Surface Contamination Limits (pCi/100cm²)

	Removable (pCi/100cm²)		**Total (Fixed + Removable) (pCi/100cm²)**	
Radionuclide	10 CFR 835 Limit	Proposed Limit	10 CFR 835 Limit	Proposed Limit
U-nat, U-235, U-238, and associated decay products	450	450	2,250	2,250
Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	9	**50**	225	225
Th-nat, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	90	90	450	450
Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above	450	**100,000**	2,250	**100,000**
Tritium and Special Tritium Compounds	4,504	4,504	N/A	N/A

NSFH Facility Waste Cask

The NSFH Facility at NRF is being built to handle spent fuel from M-290 containers, and will also ship waste canisters to the RHLLW via the NFC. Like the ECF system, NSFH Facility canisters will be loaded with waste in a water pool and lifted into the NFC from below. NRF will be unable to measure the surface contamination levels on the NSFH Facility canisters once loaded with waste, and cannot prove that these waste canisters shipped to the RHLLW meet the surface contamination limits of 10 CFR 835 Appendix D. However, the proposed exception to the WAC for the ECF canisters will also enable shipments of the NSFH Facility canisters. It is expected that the NSFH Facility canisters will have lower levels of surface contamination due to their origination from a newer facility. Similar mitigation steps to reduce surface contamination will also be taken including hydroblitzing and using 200 gallon per minute demineralizer systems. For these reasons, the proposed exception to the WAC limits will also support NSFH Facility waste shipments.

For information the external surface area of the NFC canister is about 36,250 in^2. The NFC canister lids will be submerged in the water pools a few days before the waste canister is shipped and is not expected to have significant contamination buildup. The top face surface area of the lid is about 2,827 in^2, therefore the external surface area of the waste canister shell without the lid is about 33,423 in^2.

CONCLUSION

NRF has exhausted all available decontamination strategies to reduce surface contamination levels on waste canisters to the contamination levels required by the WAC. NRF requests an exception to increase the RHLLW WAC section 2.6 surface contamination limits based on the inability to obtain dry surface contamination measurements and the previously discussed underwater swipe measurements. NRF will continue to use process controls to minimize contamination on the waste canisters by using RWDS to filter the water pool water, hydroblitzing waste canisters prior to shipment, and using the loading stand spray system during each loading evolution.

KENNETH BOYLAN
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Date: 2022.07.18 12:56:41 -06'00'

Kenneth Boylan, Engineer
Water Pool Waste Engineering
Fuel Engineering

Attachments:
(I) Average Waste Canister Surface Contamination After Hydroblitzing
(II) Waste Canister Surface Contamination vs 10 CFR 835 Appendix D

CONCURRENCE

SIGNATURE / DATE	ROLE	COMMENTS / SCOPE
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DANIEL MERGENTHAL Digitally signed by mergenda@nnpp.gov (1000004565) Date: 2022.07.11 15:24:11 -06'00'	Derivative Classifier	
KEITH VELDKAMP Digitally signed by veldkakr@nnpp.gov (1000011048) Date: 2022.07.12 09:56:05 -06'00'	Author's Manager	
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Average Waste Canister Surface Contamination After Hydroblitzing

Prepared by:

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Water Pool Waste Engineering
Fuel Engineering

Attachment (I) to
NRF-ENG-FE-00670
Page 2

Canister	05-18-102	05-18-106	05-18-112	05-18-113	05-18-121
Am-241	2.70E-10	1.22E-11	4.74E-11	2.73E-12	2.45E-11
C-14	7.54E-07	3.40E-08	1.32E-07	7.61E-09	6.85E-08
Cm-243	5.12E-11	2.31E-12	8.99E-12	5.17E-13	4.65E-12
Cm-244	7.85E-11	3.54E-12	1.38E-11	7.92E-13	7.13E-12
Cm-245	8.36E-12	3.77E-13	1.47E-12	8.43E-14	7.59E-13
Co-58	2.10E-08	9.47E-10	3.68E-09	2.12E-10	1.90E-09
Co-60	8.83E-06	3.99E-07	1.55E-06	8.91E-08	8.02E-07
Cr-51	4.70E-08	2.12E-09	8.25E-09	4.75E-10	4.27E-09
Cs-134	2.29E-10	1.04E-11	4.02E-11	2.31E-12	2.08E-11
Cs-137	1.12E-07	4.51E-08	5.54E-08	1.13E-09	2.31E-08
Eu-152	2.75E-06	1.24E-07	4.83E-07	2.77E-08	2.50E-07
Eu-154	3.33E-07	1.50E-08	5.84E-08	3.36E-09	3.02E-08
Eu-155	3.39E-08	1.53E-09	5.95E-09	3.42E-10	3.08E-09
Fe-55	4.68E-06	2.11E-07	8.22E-07	4.73E-08	4.25E-07
Fe-59	1.42E-08	6.42E-10	2.50E-09	1.44E-10	1.29E-09
H-3	8.21E-09	3.71E-10	1.44E-09	8.29E-11	7.46E-10
Hf-175	8.57E-08	3.87E-09	1.50E-08	8.65E-10	7.78E-09
Hf-181	3.80E-07	1.72E-08	6.68E-08	3.84E-09	3.45E-08
I-129	1.32E-12	5.94E-14	2.31E-13	1.33E-14	1.19E-13
Mn-54	1.08E-07	6.98E-09	1.90E-08	1.09E-09	9.80E-09
Nb-93m	3.21E-07	1.45E-08	5.63E-08	3.24E-09	2.91E-08
Nb-94	8.83E-09	3.99E-10	1.55E-09	8.91E-11	8.02E-10
Nb-95	4.43E-08	2.00E-09	7.78E-09	4.47E-10	4.03E-09
Ni-59	9.87E-08	4.46E-09	1.73E-08	9.96E-10	8.96E-09
Ni-63	3.84E-06	1.73E-07	6.74E-07	3.88E-08	3.49E-07
Pu-238	5.29E-09	2.39E-10	9.28E-10	5.34E-11	4.80E-10
Pu-239	7.38E-11	3.33E-12	1.30E-11	7.45E-13	6.70E-12
Pu-240	8.32E-12	3.75E-13	1.46E-12	8.39E-14	7.55E-13
Pu-241	5.60E-09	2.53E-10	9.83E-10	5.65E-11	5.08E-10
Ru-103	1.99E-08	8.99E-10	3.49E-09	2.01E-10	1.81E-09
Sb-125	1.84E-06	8.31E-08	3.23E-07	1.86E-08	1.67E-07
Sn-113	7.06E-08	3.19E-09	1.24E-08	7.13E-10	6.41E-09
Sr-90	1.20E-07	5.41E-09	2.10E-08	1.21E-09	1.09E-08
Ta-182	4.83E-08	2.18E-09	8.47E-09	4.87E-10	4.38E-09
Tc-99	1.36E-08	6.12E-10	2.38E-09	1.37E-10	1.23E-09
Te-125m	4.25E-07	1.92E-08	7.47E-08	4.29E-09	3.86E-08
U-233	6.36E-11	2.87E-12	1.12E-11	6.42E-13	5.77E-12
U-234	6.36E-11	2.87E-12	1.12E-11	6.42E-13	5.77E-12
U-235	3.01E-11	1.36E-12	5.28E-12	3.03E-13	2.73E-12
U-236	3.01E-11	1.36E-12	5.28E-12	3.03E-13	2.73E-12
Zn-65	9.49E-08	4.28E-09	1.67E-08	9.58E-10	8.61E-09
Zr-95	2.07E-08	9.34E-10	3.63E-09	2.09E-10	1.88E-09
Total Activity (Ci)*	**2.51E-05**	**1.18E-06**	**4.45E-06**	**2.54E-07**	**2.30E-06**

*The only detectable radionuclides after hydroblitzing were Co-60, Cs-137, and Mn-54. Other radionuclides were inferred based on established ratios to Co-60 in the ECF water pools.

Waste Canister Surface Contamination vs. 10 CFR 835 Appendix D

Prepared by:

Kenneth Boylan, Engineer
Water Pool Waste Engineering
Fuel Engineering

Attachment (II) to
NRF-ENG-FE-00670
Page 2

Average Waste Canister Surface Contamination in DPM/100cm² *

Canister	05-18-102	05-18-106	05-18-112	05-18-113	05-18-121	Type
Am-241	5.80E-01	2.62E-02	1.02E-01	5.85E-03	5.26E-02	TRU
C-14	1.62E+03	7.31E+01	2.84E+02	1.63E+01	1.47E+02	βγ
Cm-243	1.10E-01	4.96E-03	1.93E-02	1.11E-03	9.98E-03	TRU
Cm-244	1.69E-01	7.61E-03	2.96E-02	1.70E-03	1.53E-02	TRU
Cm-245	1.79E-02	8.10E-04	3.15E-03	1.81E-04	1.63E-03	TRU
Co-58	4.50E+01	2.03E+00	7.90E+00	4.54E-01	4.09E+00	βγ
Co-60	1.90E+04	8.56E+02	3.33E+03	1.91E+02	1.72E+03	βγ
Cr-51	1.01E+02	4.56E+00	1.77E+01	1.02E+00	9.16E+00	βγ
Cs-134	4.92E-01	2.22E-02	8.64E-02	4.97E-03	4.47E-02	βγ
Cs-137	2.41E+02	9.67E+01	1.19E+02	2.44E+00	4.95E+01	βγ
Eu-152	5.90E+03	2.66E+02	1.04E+03	5.96E+01	5.36E+02	βγ
Eu-154	7.15E+02	3.23E+01	1.25E+02	7.21E+00	6.49E+01	βγ
Eu-155	7.28E+01	3.29E+00	1.28E+01	7.35E-01	6.61E+00	βγ
Fe-55	1.01E+04	4.54E+02	1.76E+03	1.01E+02	9.13E+02	βγ
Fe-59	3.05E+01	1.38E+00	5.36E+00	3.08E-01	2.77E+00	βγ
H-3	1.76E+01	7.96E-01	3.09E+00	1.78E-01	1.60E+00	Tritium
Hf-175	1.84E+02	8.31E+00	3.23E+01	1.86E+00	1.67E+01	βγ
Hf-181	8.17E+02	3.69E+01	1.43E+02	8.24E+00	7.42E+01	βγ
I-129	2.82E-03	1.28E-04	4.96E-04	2.85E-05	2.56E-04	TRU
Mn-54	2.32E+02	1.50E+01	4.07E+01	2.34E+00	2.10E+01	βγ
Nb-93m	6.89E+02	3.11E+01	1.21E+02	6.95E+00	6.25E+01	βγ
Nb-94	1.90E+01	8.56E-01	3.33E+00	1.91E-01	1.72E+00	βγ
Nb-95	9.52E+01	4.30E+00	1.67E+01	9.60E-01	8.64E+00	βγ
Ni-59	2.12E+02	9.56E+00	3.72E+01	2.14E+00	1.92E+01	βγ
Ni-63	8.25E+03	3.72E+02	1.45E+03	8.32E+01	7.49E+02	βγ
Pu-238	1.14E+01	5.13E-01	1.99E+00	1.15E-01	1.03E+00	TRU
Pu-239	1.58E-01	7.15E-03	2.78E-02	1.60E-03	1.44E-02	TRU
Pu-240	1.79E-02	8.06E-04	3.13E-03	1.80E-04	1.62E-03	TRU
Pu-241	1.20E+01	5.43E-01	2.11E+00	1.21E-01	1.09E+00	TRU
Ru-103	4.27E+01	1.93E+00	7.50E+00	4.31E-01	3.88E+00	βγ
Sb-125	3.95E+03	1.78E+02	6.94E+02	3.99E+01	3.59E+02	βγ
Sn-113	1.52E+02	6.85E+00	2.66E+01	1.53E+00	1.38E+01	βγ
Sr-90	2.57E+02	1.16E+01	4.51E+01	2.59E+00	2.33E+01	βγ
Ta-182	1.04E+02	4.68E+00	1.82E+01	1.05E+00	9.41E+00	βγ
Tc-99	2.91E+01	1.31E+00	5.11E+00	2.94E-01	2.64E+00	βγ
Te-125m	9.13E+02	4.12E+01	1.60E+02	9.22E+00	8.29E+01	βγ
U-233	1.37E-01	6.16E-03	2.40E-02	1.38E-03	1.24E-02	TRU
U-234	1.37E-01	6.16E-03	2.40E-02	1.38E-03	1.24E-02	U-nat
U-235	6.45E-02	2.91E-03	1.13E-02	6.51E-04	5.86E-03	U-nat
U-236	6.45E-02	2.91E-03	1.13E-02	6.51E-04	5.86E-03	TRU
Zn-65	2.04E+02	9.20E+00	3.57E+01	2.06E+00	1.85E+01	βγ
Zr-95	4.44E+01	2.00E+00	7.79E+00	4.48E-01	4.03E+00	βγ
Total Activity (DPM/100cm²)	**5.40E+04**	**2.53E+03**	**9.55E+03**	**5.45E+02**	**4.93E+03**	

*The only detectable radionuclides after hydroblitzing were Co-60, Cs-137, and Mn-54. Other radionuclides were inferred based on established ratios to Co-60 in the ECF water pools.

Average Waste Canister Surface Contamination Compared against the 10 CFR 835 Appendix D Limits in DPM/100cm^2

Radionuclide	10 CFR 85 Limit (Removable)	05-18-102	05-18-106	05-18-112	05-18-113	05-18-121
U-nat, U-235, U-238, and associated decay products	1,000	2.01E-01	9.08E-03	3.53E-02	2.03E-03	1.83E-02
Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	20	**2.46E+01**	1.11E+00	4.32E+00	2.49E-01	2.24E+00
Th-nat, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	200	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above	1,000	**5.39E+04**	**2.53E+03**	**9.54E+03**	5.44E+02	**4.92E+03**
Tritium and Special Tritium Compounds	10,000	1.76E+01	7.96E-01	3.09E+00	1.78E-01	1.60E+00

Red Bolded levels exceed the 10 CFR 835 Appendix D limits

Average Waste Canister Surface Contamination in pCi/100cm² *

Canister	05-18-102	05-18-106	05-18-112	05-18-113	05-18-121	Type
Am-241	2.61E-01	1.18E-02	4.58E-02	2.63E-03	2.37E-02	TRU
C-14	7.28E+02	3.29E+01	1.28E+02	7.35E+00	6.61E+01	βγ
Cm-243	4.95E-02	2.23E-03	8.69E-03	4.99E-04	4.49E-03	TRU
Cm-244	7.58E-02	3.42E-03	1.33E-02	7.65E-04	6.89E-03	TRU
Cm-245	8.07E-03	3.64E-04	1.42E-03	8.15E-05	7.33E-04	TRU
Co-58	2.03E+01	9.14E-01	3.55E+00	2.04E-01	1.84E+00	βγ
Co-60	8.53E+03	3.85E+02	1.50E+03	8.61E+01	7.75E+02	βγ
Cr-51	4.54E+01	2.05E+00	7.97E+00	4.58E-01	4.12E+00	βγ
Cs-134	2.21E-01	1.00E-02	3.89E-02	2.24E-03	2.01E-02	βγ
Cs-137	1.09E+02	4.35E+01	5.36E+01	1.10E+00	2.23E+01	βγ
Eu-152	2.66E+03	1.20E+02	4.66E+02	2.68E+01	2.41E+02	βγ
Eu-154	3.22E+02	1.45E+01	5.64E+01	3.25E+00	2.92E+01	βγ
Eu-155	3.28E+01	1.48E+00	5.75E+00	3.31E-01	2.97E+00	βγ
Fe-55	4.52E+03	2.04E+02	7.94E+02	4.57E+01	4.11E+02	βγ
Fe-59	1.37E+01	6.20E-01	2.41E+00	1.39E-01	1.25E+00	βγ
H-3	7.93E+00	3.58E-01	1.39E+00	8.01E-02	7.20E-01	Tritium
Hf-175	8.28E+01	3.74E+00	1.45E+01	8.36E-01	7.52E+00	βγ
Hf-181	3.68E+02	1.66E+01	6.45E+01	3.71E+00	3.34E+01	βγ
I-129	1.27E-03	5.74E-05	2.23E-04	1.28E-05	1.15E-04	TRU
Mn-54	1.04E+02	6.75E+00	1.83E+01	1.05E+00	9.47E+00	βγ
Nb-93m	3.10E+02	1.40E+01	5.44E+01	3.13E+00	2.81E+01	βγ
Nb-94	8.53E+00	3.85E-01	1.50E+00	8.61E-02	7.75E-01	βγ
Nb-95	4.28E+01	1.93E+00	7.52E+00	4.32E-01	3.89E+00	βγ
Ni-59	9.53E+01	4.30E+00	1.67E+01	9.62E-01	8.65E+00	βγ
Ni-63	3.71E+03	1.68E+02	6.51E+02	3.75E+01	3.37E+02	βγ
Pu-238	5.11E+00	2.31E-01	8.97E-01	5.16E-02	4.64E-01	TRU
Pu-239	7.13E-02	3.22E-03	1.25E-02	7.19E-04	6.47E-03	TRU
Pu-240	8.03E-03	3.63E-04	1.41E-03	8.11E-05	7.29E-04	TRU
Pu-241	5.41E+00	2.44E-01	9.49E-01	5.46E-02	4.91E-01	TRU
Ru-103	1.92E+01	8.68E-01	3.38E+00	1.94E-01	1.75E+00	βγ
Sb-125	1.78E+03	8.03E+01	3.12E+02	1.80E+01	1.62E+02	βγ
Sn-113	6.82E+01	3.08E+00	1.20E+01	6.89E-01	6.20E+00	βγ
Sr-90	1.16E+02	5.22E+00	2.03E+01	1.17E+00	1.05E+01	βγ
Ta-182	4.66E+01	2.11E+00	8.18E+00	4.71E-01	4.23E+00	βγ
Tc-99	1.31E+01	5.92E-01	2.30E+00	1.32E-01	1.19E+00	βγ
Te-125m	4.11E+02	1.86E+01	7.21E+01	4.15E+00	3.73E+01	βγ
U-233	6.14E-02	2.77E-03	1.08E-02	6.20E-04	5.58E-03	TRU
U-234	6.14E-02	2.77E-03	1.08E-02	6.20E-04	5.58E-03	Unat
U-235	2.90E-02	1.31E-03	5.10E-03	2.93E-04	2.64E-03	Unat
U-236	2.90E-02	1.31E-03	5.10E-03	2.93E-04	2.64E-03	TRU
Zn-65	9.16E+01	4.14E+00	1.61E+01	9.25E-01	8.32E+00	βγ
Zr-95	2.00E+01	9.02E-01	3.51E+00	2.02E-01	1.81E+00	βγ
Total Activity (pCi/100cm²)	**2.43E+04**	**1.14E+03**	**4.30E+03**	**2.45E+02**	**2.22E+03**	

*The only detectable radionuclides after hydroblitzing were Co-60, Cs-137, and Mn-54. Other radionuclides were inferred based on established ratios to Co-60 in the ECF water pools.

Average Waste Canister Surface Contamination Compared against the 10 CFR 835 Appendix D Limits in pCi/100cm^2

Radionuclide	10 CFR 85 Limit (Removable)	05-18-102	05-18-106	05-18-112	05-18-113	05-18-121
U-nat, U-235, U-238, and associated decay products	450	9.05E-02	4.09E-03	1.59E-02	9.13E-04	8.22E-03
Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	9	**1.11E+01**	5.00E-01	1.94E+00	1.12E-01	1.01E+00
Th-nat, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	90	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above	450	**2.43E+04**	**1.14E+03**	**4.29E+03**	2.45E+02	**2.22E+03**
Tritium and Special Tritium Compounds	4,504	7.93E+00	3.58E-01	1.39E+00	8.01E-02	7.20E-01

Red Bolded levels exceed the 10 CFR 85 Appendix D limits

METADATA		ADD TO ADSARS	Yes [X] No [ ]
Addressee Name(s)	Robert P. Miklos, Production Facility Division Director		
Document Number	NRF-ENG-FE-00670	Revision	
Subject	NRF; Remote-Handled Low Level Waste Disposal Facility; Request for Waste Acceptance Criteria Exception; For Action		
Classification	Unclassified	Author Name	Kenneth Boylan, Engineer
Issue Date	July 18, 2022	Need-to-Know	PRNR-REP
Retention Schedule	Control Requirements for Specialized Work Areas (121)	Project	Remote-Handled Low Level Waste Disposal Facility
Keywords	Remote-handled low-level waste disposal facility; contamination levels; Type IV Waste Canisters	References	N/A
Design Review #	N/A	NR Category	GC – NRF Servicing and Program Projects
Comments	-		

FOR INFORMATION [ ]	FOR ACTION [X]	CREATE A COMMITMENT	Yes [ ] No [X]		
Commitment Type	-	Short Description			
Full Description					
Cognizant Individual		Requesting Individual			
Cognizant NR Project Officer	☐Aircraft Carriers/Surface Ships ☐Shipyard	☐NRF ☐Submarines	☐Primes/Labs Only ☐US/UK	☐Prototypes/MTS	
Due Date	-	Est. Completion Date	-		
Impact Statement					
Impact Statement Type	-	Work Project	-	Priority	-

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Appendix B

Groundwater Pathway Transport and Dose Calculations for the Special Analysis of External Contamination on NRF Waste Canisters

Groundwater Pathway Transport and Dose Calculations for the Special Analysis of External Contamination on NRF Waste Canisters

B-1. SCOPE AND BRIEF DESCRIPTION

The purpose of this appendix is to document groundwater pathway modeling and dose calculations performed for this Special Analysis (SA). The computer models, input parameters and calculations performed for the SA are consistent with the models, parameters and calculations used for the RHLLW Disposal Facility (PA) (DOE-ID 2018) and further documented in ECAR-1892 (2018), "Groundwater Pathway Transport and Dose Calculations for the INL Remote-Handled Low-Level Waste Disposal Facility Performance Assessment." The computational structure, model input files, and pre- and post-processing scripts are presented. Model input files and scripts are included as an attachment to this appendix. The large model output files are only included as electronic attachments to this report. All files required to reproduce results are attached in a zip file included with the native file of this report that can be accessed by selecting "Additional Information" (select Native File) in the Idaho National Laboratory (INL) Electronic Document Management System (EDMS).

B-2. MODEL PARAMETER INPUTS AND ASSUMPTIONS

All model parameter inputs and assumptions are documented in the RHLLW Disposal Facility PA (DOE-ID 2018) and ECAR-1892 (2018). Any additional parameters or assumptions that vary from the PA modeling are included in the Discussion/Analysis Section of this Appendix (Section B-4), and Section 3 of the main report.

B-3. COMPUTER CODE VALIDATION

All computer code modeling and calculations for the SA were performed on an iMac Workstation (3.6 GHz 8 Core Intel® Core i9 CPU) running OS X 11.6.8 using the gfortran Fortran compilers. Computer input files and scripts are provided in the attachment at the end of this Appendix. Computer output files are not provided in the attachments due to their size, but are provided on electronic media. All electronic files, including code input, output, executable files, scripts, databases, and spreadsheet files are contained in a zip file that can be accessed by selecting "Additional Information" (select Native File) in the INL EDMS.

The MCM computer code (Rood 2021) was developed at INL and is used to model the release of radionuclides from the source zone and flow and contaminant transport through the alluvium and vadose zone. It also was used for the Radioactive Waste Management Complex PA (DOE-ID 2007) and the Idaho CERCLA Disposal Facility PA (DOE-ID 2011) at INL. The MCM software theory, verification and validation, test plan, and configuration management plan are documented in Rood (2021). Version 041320 MCMF was used for the flow modeling and Version 020321 MCMT was used for the transport modeling.

The GWSCREEN computer code (Rood 2003), Version 2.5a Version date 04/04/2008, was used to model radionuclide transport in the saturated zone [9]. It also was used to model radionuclide release and transport through the vadose zone and aquifer for the groundwater pathway Phase 3 screening. GWSCREEN also was used for the Radioactive Waste Management Complex PA (DOE-ID 2007) and the Idaho CERCLA Disposal Facility PA (DOE-ID 2011) at INL. Installation and validation of the software is documented in *Software Verification and Validation Plan for the GWSCREEN Code* (Rood 1993) and the *GWSCREEN Configuration Management, Validation Test Plan, and Validation Test Report* (EDF-7372).

Microsoft® Office Excel® Office 365 (16.64 22081401) running under iMac OS X 11.6.8 was used for several supporting calculations along with Microsoft® Windows® 10 Pro Build 19044.1826 was run under Parallels Desktop 18 for Mac. To validate the calculations performed with Excel, the formulas in all calculation cells were checked for accuracy and a sample of the calculations were checked by hand.

Other computer codes and scripts used in the analysis, including their validation, are documented in ECAR-1892 (2018). These codes include the FORTRAN code INFIL.FOR which was used to calculate infiltration through the alluvium and vadose zone, and the Perl script MKMCMT.PL which was used to construct MCMT input files for the source, alluvium, and aquifer.

B-4. DISCUSSION/ANALYSIS

B-4.1 Computer Codes and Program Flow

The groundwater transport calculations for the RHLLW Disposal Facility PA were performed by combining the two west vault arrays (55-ton and NuPac) into a single source zone, and the two east vault arrays (MFTC and HFEF/LCC) into a single source zone (see Figure B-1). For this SA, the NRF surface contaminated waste canisters were conservatively assumed to only be in the west array, and therefore only the west receptor was evaluated for doses. This is conservative because the west array is the smaller of the two and adding the LCC canisters (a.k.a. NSFH canisters) from the east array to the smaller west array where the NRF 55-ton canisters will be placed, concentrates the NRF source and increases the dose.

Groundwater transport calculations were performed using two computer codes. Source (waste) zone, alluvium, and vadose zone calculations were performed with the MCM computer code (Rood 2021), and aquifer calculations were performed with the GWSCREEN computer code Version 2.5a Version date 04/04/2008 (Rood 2003) [9]. MCM is composed of two codes: MCMF and MCMT. MCMF computes water flow and saturation calculations and produces a file of water fluxes that can vary as a function of time and space. Radionuclide transport is performed in the MCMT code, which reads the water flux file produced by MCMF. The version dates of the MCMF and MCMT codes is 041320 and 020321, respectively. The code INFIL.FOR was used to calculate the infiltration through the cap (engineered cover) simulating its failure over time and provided water flux input to MCMF.

The program flow to establish water fluxes through the source zone containing the surface contaminated canisters and radionuclide transport to the aquifer are illustrated in Figures B-2 through B-4. Water flux contacting the surface contaminated canisters is defined by the infiltration through disturbed soil for 20-years of facility operations followed by infiltration through the cap. Disturbed soil infiltration was 18 cm/yr and cap infiltration was 0.1 cm/yr for 500 years post-closure of the facility, followed by a linear increase in infiltration up to 1 cm/yr for the next 500 years, and 1 cm/yr for all times greater than 1000 years post-closure. For alluvium and vadose zone, the PA infiltration rates were used. Thus, the only difference in the infiltration for surface contamination was the infiltration assigned in the source. In the PA, the infiltration that contacted the waste was controlled by the container integrity whereas no container integrity was assumed for surface contamination.

For the MCMT simulations (Figure B-5), the surface contamination inventory is placed in the cells representing the waste as an initial condition. For conservatism, no sorption (i.e., K_d) is applied so radionuclides wash off the surface of the canister with the infiltrating water. The remainder of the modeling including transport through the alluvium and vadose zone, and transport in the aquifer is identical to that described in ECAR-1892 (2018).

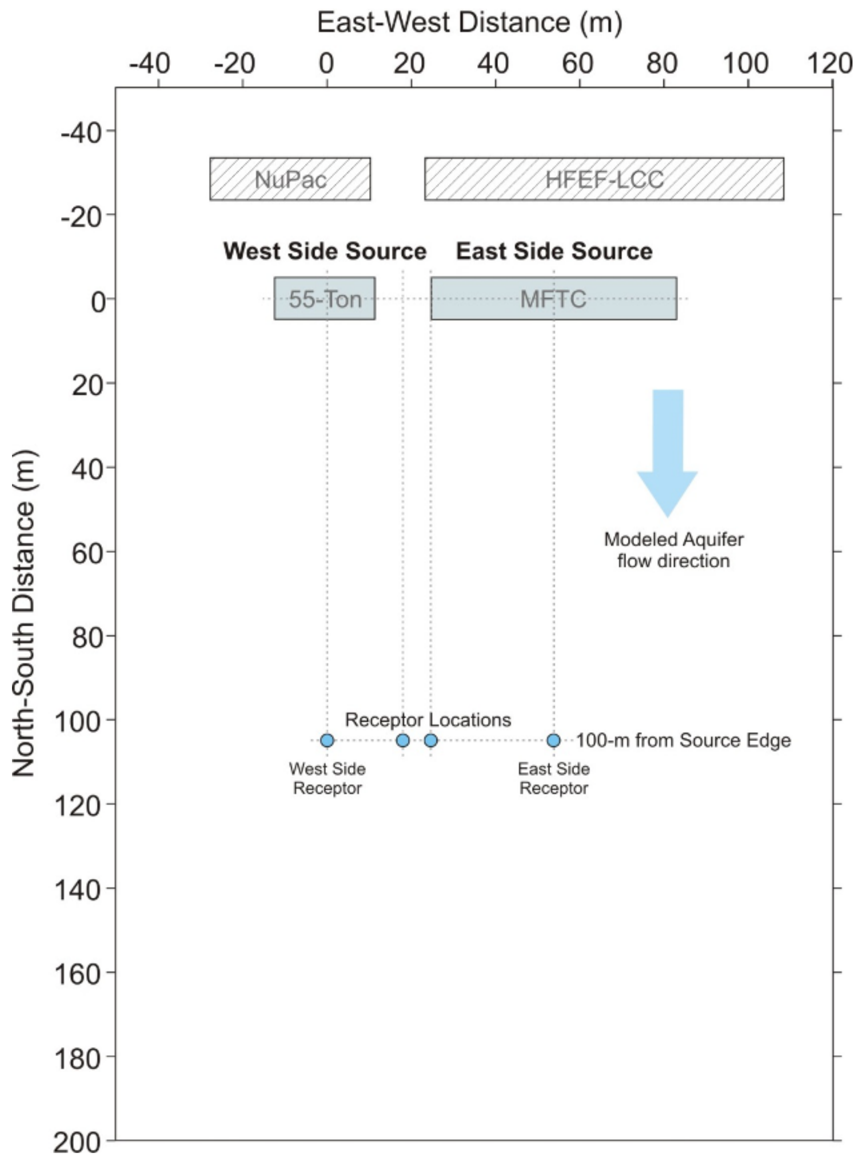

Figure B-1. Groundwater model layout of the west-side and east-side source zones. All surficial contamination was placed in the west array and therefore the west-side receptor would have the highest doses.

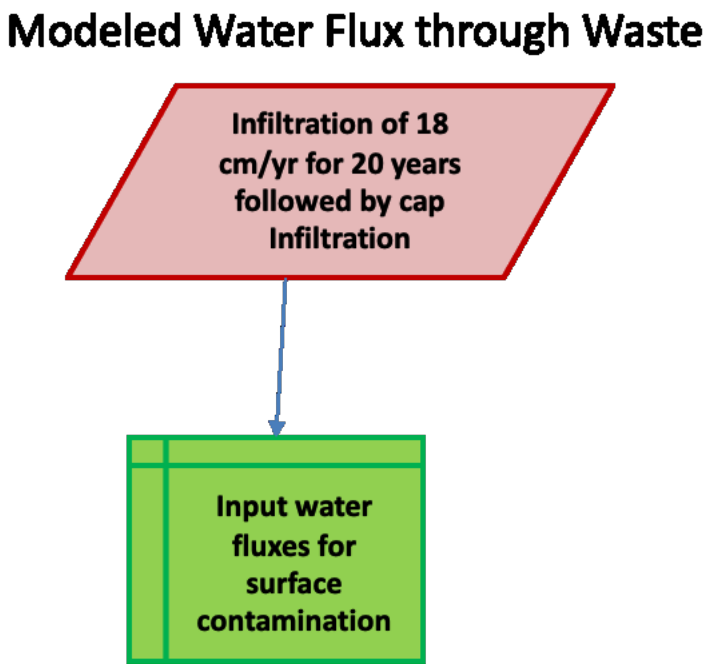

Figure B-2. Flow diagram showing infiltration applied to surface contamination on canisters in west array.

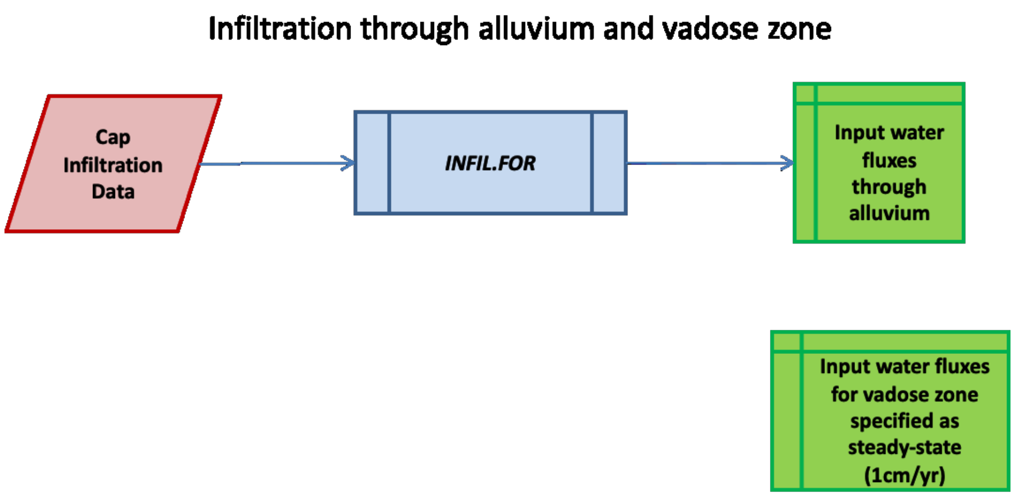

Figure B-3. Flow diagram showing infiltration through alluvium and vadose zone.

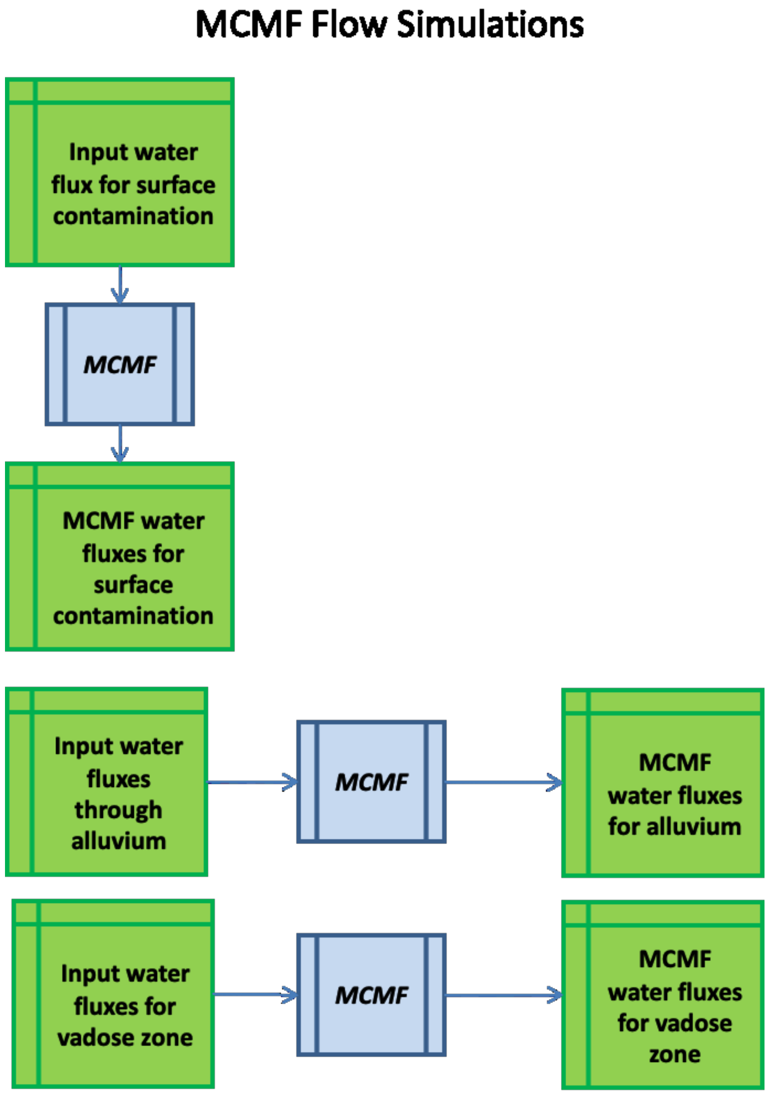

Figure B-4. Flow diagram showing MCMF calculations for the source, alluvium, and vadose zone for surface contamination on canisters in the west array. Input water fluxes for the alluvium are generated using INFIL.FOR.

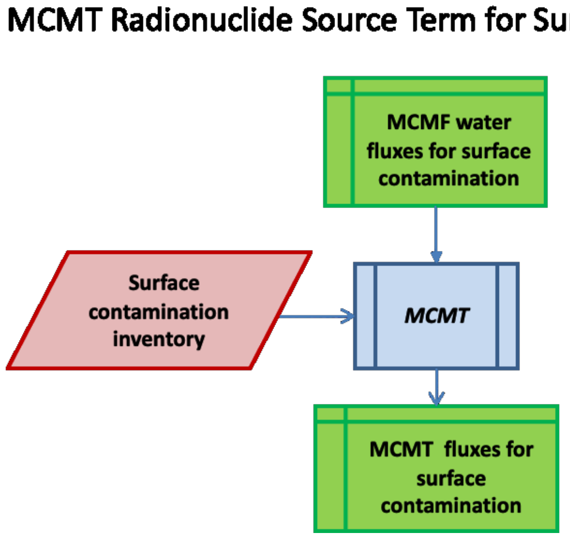

Figure B-5. Flow diagram showing MCMT simulations for surface contamination on canisters in the west array.

B-4.2 MCMT Radionuclide Group Designations

MCMT only allows 10 radionuclides per simulation. Therefore, multiple input files were necessary to address the suite of radionuclides considered in this SA. The four groups for this SA are shown below.

Group 1: C-14, H-3, I-129, Nb-94, Ni-59, Tc-99, aAm-241, (aNp-241), (aU-233), (aTh-229)

Group 2: bPu-241, (bNp-237), (bU-233), (bTh-229), cU-234, (cTh-230), (cRa-226), (cPb-210).

Group 3: dPu-240, (dU-236), (dTh-232), (dRa-228), (dTh-228), eU-235, (ePa-231), (eAc-227)

Group 4: fPu-238, (fU-238), (fU-234), (fTh-230), (fRa-226), (fPb-210), gPu-239, (gU-235), (gPa-231), (gAc-227).

MCMT writes GWSCREEN-compatible release (flux to the aquifer) files based on the name of the radionuclide; therefore, it was necessary to add a prefix to each actinide decay chain to distinguish between radionuclide parents and decay products from other decay chains. Actinide decay chains with significant decay products in terms of dose impact (decay products shown in parentheses) are designated a, b, c, d, e, f, and g. In general, each parent decay chain is treated separately. However, key radionuclides also include U-233 and U-236. These radionuclides (U-233 and U-236) did not contribute very much to the total dose, so they were not modeled as separate chains, but instead their inventories were included in the Am-241 decay chain and Pu-240 decay chain, respectively.

Doses were calculated by running the models using a unit inventory (1 Ci) for each radionuclide. Actual doses were then calculated by scaling to the actual surface contamination inventory. This was done so that changes to the inventory could be made and doses recalculated without having to rerun the models. This scaling was performed in the spreadsheet that compiled the results. Because some radionuclides listed as surface contamination also appear as decay chain members (U-233 and U-236), it was necessary to adjust their unit inventories. The inventory entered for U-233 in the Am-241 decay chain was the ratio of the U-233 inventory to the Am-241 inventory given in Table 7 of the SA (1.65E-7 Ci/7.00E-7 Ci × 1 Ci= 0.236 Ci). Likewise, the inventory entered for U-236 in the Pu-240 decay chain is the ratio of the U-236 inventory to the Pu-240 inventory (7.78E-8 Ci/2.15E-8 Ci × 1 Ci = 3.62 Ci). The ratios are the same for both the Case 1 and Case 2 inventories in Table 7 of the SA.

B-4.3 Perl Scripts

The number of MCMT input files required to run the base-case model was quite large (over 100 files); therefore, Perl scripts were written to facilitate the creation of these files. The script MKMCMT.PL writes these files. The top part of the script file defines all user input. The remaining part of the script writes the files. The scripts used to write the alluvium and vadose zone files is included in the attachments at the end of this Appendix in lieu of including all input files for the alluvium and vadose zone. For the source files, the MCMT files were constructed by hand.

B-4.4 GWSCREEN Aquifer Simulation

The PA base-case GWSCREEN simulation included all radionuclides and progeny that were simulated in MCMT. GWSCREEN calculates both radionuclide concentration in the aquifer and radiological ingestion dose. For these calculations, release (flux to the aquifer) files were read for each radionuclide (including ingrown progeny) simulated with MCMT (see MCMT Radionuclide Group Designations). Progeny ingrowth during transit in the aquifer from the source to the 100-m downgradient receptor was not considered due to the relatively short time for ingrowth to occur (0.4 year, see Eq. 1).

$$T_{aq} = \left(L_s/2+100\right)/\left(V_{aq}/\phi_{aq}\right) = \left(10\ \mathrm{m}/2+100\ \mathrm{m}\right)/\left(16\ \mathrm{m/y}/0.06\right) = 0.4\ \mathrm{y} \qquad (1)$$

where

T_{aq} = transit time to receptor in the aquifer (year)

L_s = length of the source parallel to groundwater flow (m)

V_{aq} = aquifer Darcy velocity (m/year)

f_{aq} = effective aquifer porosity.

The PA base-case GWSCREEN input files are named east.par for east array sources and west.par for west array sources. Because only the west array was simulated, only west.par is shown in the attachments at the end of this Appendix. For source superposition, the center of the model domain is defined as the center of the west source.

B-4.5 Superposition of Sources

GWSCREEN has the option to simulate multiple sources and superimpose the results on one another to compute concentrations and doses at fixed locations or as a function of space for a selected time. Because only the west array was simulated, and doses were not added to the PA results but were instead reported separately, no source superposition was necessary.

B-4.6 All-Pathways Dose Factors in GWSCREEN

GWSCREEN requires input of an exposure scenario and dose conversion factors to calculate dose from ingestion of groundwater. This subroutine can be used to calculate the all-pathways dose by substituting the all-pathways dose factor (in units of rem/year per Ci/m^3) for the dose conversion factor and adjusting the exposure scenario so that the total ingestion rate over the period of a year is 1.0. The all-pathways dose assumes the receptor consumes: (1) contaminated groundwater, (2) leafy vegetables and produce irrigated with contaminated groundwater, and (3) milk and meat from animals that consume contaminated water and pasture grass irrigated with contaminated groundwater. The annual dose calculation for radionuclides in GWSCREEN is given by:

$$D = C \times \frac{WI}{1000} \times EF \times DCF \qquad (2)$$

where

D = dose (rem/yr)

C = groundwater concentration (Ci/m^3)

WI = daily water ingestion rate (L/d)

EF = exposure frequency (d/year)

DCF = dose conversion factor (rem/Ci).

The water ingestion rate in GWSCREEN is converted from L/d to m^3/d by dividing it by 1,000 L/m^3. The all-pathways dose per unit concentration factor has units of rem/yr per Ci/m^3 and incorporates the ingestion rate and exposure time in the dose factor. Substituting the all-pathways dose per unit concentration for the dose conversion factor requires that $WI/1{,}000 = 1.0$ and $EF = 1.0$, and therefore negates these terms in the dose calculation since ingestion rates and exposure frequency and duration are already incorporated in the all-pathways dose per unit concentration factor. Therefore, *WI* is set to 1,000, *EF* is set to 1.0, and the *DCF* is replaced by the all-pathways dose per unit concentration. The dose calculation is then given by

$$D = C \times APDF \qquad (3)$$

where

$APDF$ = all-pathways dose per unit concentration factor (rem/yr per Ci/m^3)

The all-pathways dose calculation is performed in a spreadsheet using the database "*AllPathwayDoseFactors_DOE1196-rw.mdb*," which can be found in the supporting information for ECAR-1892 (2018). Dose coefficients are from DOE-STD-1196-2011 (DOE 2011). The all-pathway dose per unit concentration factors used in the calculations are presented in Table B-1.

Table B-1. Nuclide-specific dose coefficients and all-pathways dose per unit concentration factors.

Nuclide	Progeny	Reference Person Dose Coefficient (rem/Ci)[a]	All-Pathways Dose per Unit Concentration Factor (rem-m^3/Ci-year)	Comment
C-14	---------	2.34E+03	5.86E+03	
H-3	---------	7.77E+01	1.74E+02	
I-129	---------	4.48E+05	6.92E+05	
Nb-94	---------	8.25E+03	7.47E+04	
Ni-59	---------	2.95E+02	2.92E+02	
Am-241	---------	8.81E+05	6.69E+05	
	Np-237	4.63E+05	3.53E+05	
	U-233	2.23E+05	1.78E+05	
	Th-229D	3.33E+06	2.52E+06	(includes Ra-225, Ac-225, and Bi-213)
Pu-239	---------	1.07E+06	8.10E+05	
	U-235D	2.05E+05	1.63E+05	(includes Th-231)
	Pa-231	2.07E+06	1.57E+06	
	Ac-227D	2.32E+06	1.72E+06	(includes Fr-223, Ra-223, Pb-211, and Th-227)
Pu-240	---------	1.07E+06	8.10E+05	
	U-236	2.02E+05	1.61E+05	
	Th-232	1.03E+06	7.81E+05	
	Ra-228D	5.92E+06	4.51E+06	(includes Ac-228)

Nuclide	Progeny	Reference Person Dose Coefficient (rem/Ci)[a]	All-Pathways Dose per Unit Concentration Factor (rem-m^3/Ci-year)	Comment
	Th-228D	9.35E+05	7.01E+05	(includes Ra-224, Pb-212, and Bi-212)
Tc-99	---------	3.33E+03	6.26E+03	
U-235D	---------	2.05E+05	1.63E+05	(includes Th-231)
	Pa-231	2.07E+06	1.57E+06	
	Ac-227D	2.32E+06	1.72E+06	(includes Fr-223, Ra-223, Pb-211, and Th-227)
Pu-238	---------	9.73E+05	7.40E+05	
	U-234	2.15E+05	1.71E+05	
	Th-230	9.36E+05	7.11E+05	
	Ra-226D	1.68E+06	1.30E+06	(includes Pb-214 and Bi-214)
	Pb-210D	1.03E+07	7.91E+06	(includes Bi-210 and Po-210)

a. Reference person dose coefficients from DOE-STD-1196-2011 applied to direct ingestion of groundwater. Adult dose coefficient from DOE-STD-1196-2011 applied to all food ingestion intakes.

c. **Note**: The "D" suffix in some of the radionuclide names indicates the progeny listed in the comment column are assumed to be in secular equilibrium and the reported dose coefficients and all-pathways dose factor includes the contributions from those progeny.

B-4.7 GWSCREEN Post-Processing and Final Dose Calculations

The GWSCREEN results were post-processed to extract groundwater concentrations at the receptor location and all-pathways dose for a unit inventory. The Perl scripts GETCONC.PL and GETDOSE.PL (documented in supporting files for ECAR-1892) were used to extract these values as a function of time. These scripts pull the concentration and dose time history from the GWSCREEN output file (west.out) for each radionuclide by receptor and organize it in a manner that can be easily processed by a spreadsheet. The concentration data (in Ci/m^3) and dose data (in rem) are then pasted into the spreadsheet. The spreadsheet for the surface contamination results was named "*RHLLW-SurfaceContam.xlsm*." The west.out and spreadsheet files can be found in the supporting information for this SA.

The dose results were then scaled to the actual inventory in the spreadsheet "*RHLLW-SurfaceContam.xlsm*" using the equation:

$$D_i = Du_i \times \frac{Q_p}{Qu} \qquad (4)$$

where

D = dose for the actual inventory (rem/yr)

Du = dose for a unit inventory of the parent (rem/yr)

Q_p = actual inventory for the parent (Ci)

Qu = unit inventory for the parent (Ci).

B-4.8 Intermediate Results

Figures B-6 through B-10 show the intermediate results that include fluxes from the source to the alluvium (Figure B-6), fluxes from the alluvium to the vadose zone (Figure B-7), fluxes from the vadose to the aquifer (Figure B-8), concentrations in the aquifer (Figure B-9), and all-pathway doses (Figure

B-10). All flux results are presented for a unit inventory of each radionuclide. Differences in the flux reflect sorption and decay during transit. Note that for the source flux to the alluvium, all radionuclides were conservatively assumed to have zero sorption, and therefore the only difference between fluxes for unit inventories would be decay. Because the removal of surface contamination from the canisters is relatively rapid, only H-3 (12.3-year half-life) shows any difference from the remainder of the radionuclide fluxes. The concentration and all-pathways dose figures have been scaled to inventories in Table 7 for the NRF-requested limits (Case 2 in the SA).

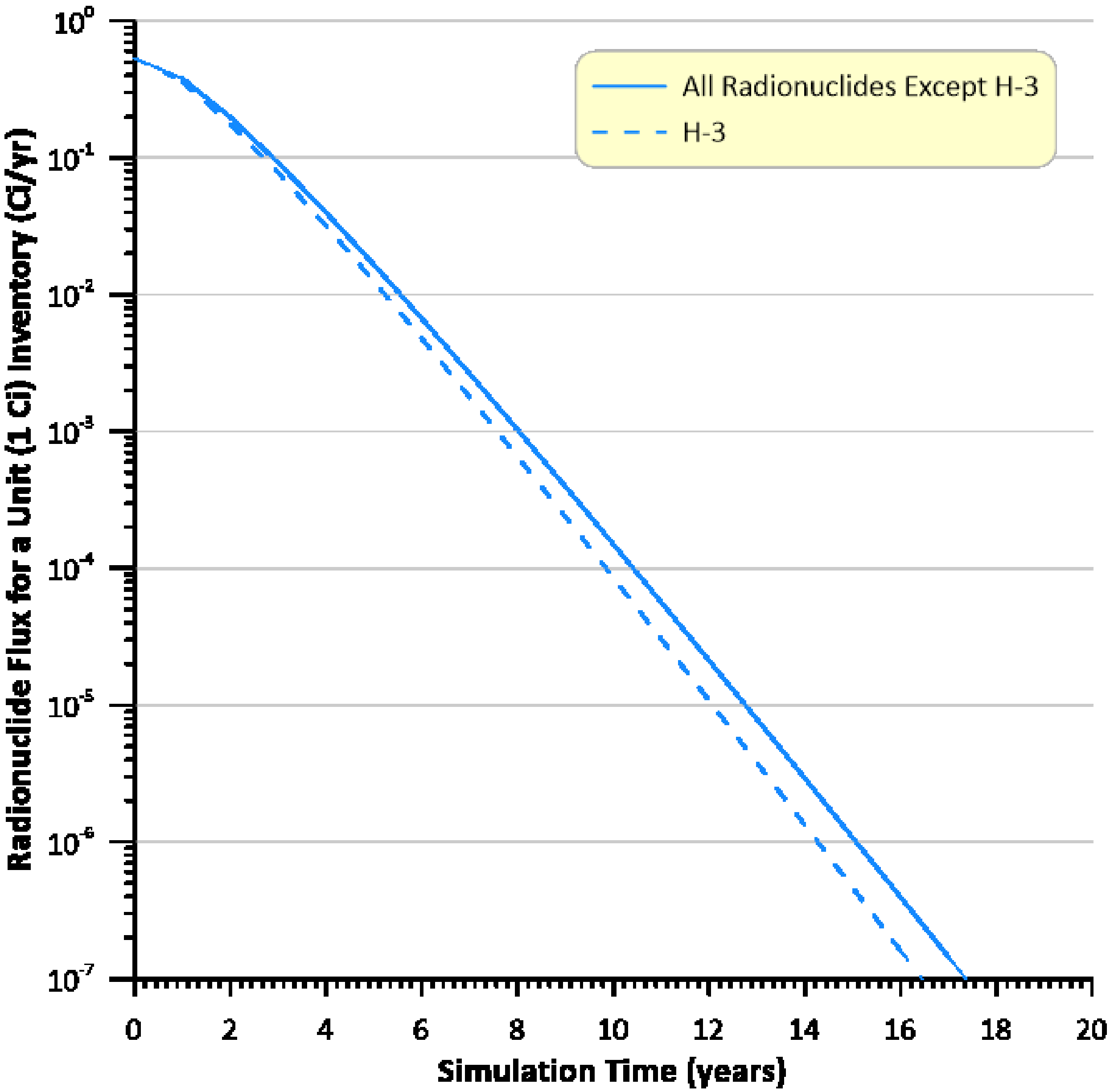

Figure B-6. Radionuclide fluxes from the source zone to the alluvium for surface contaminated containers and unit inventories for each radionuclide.

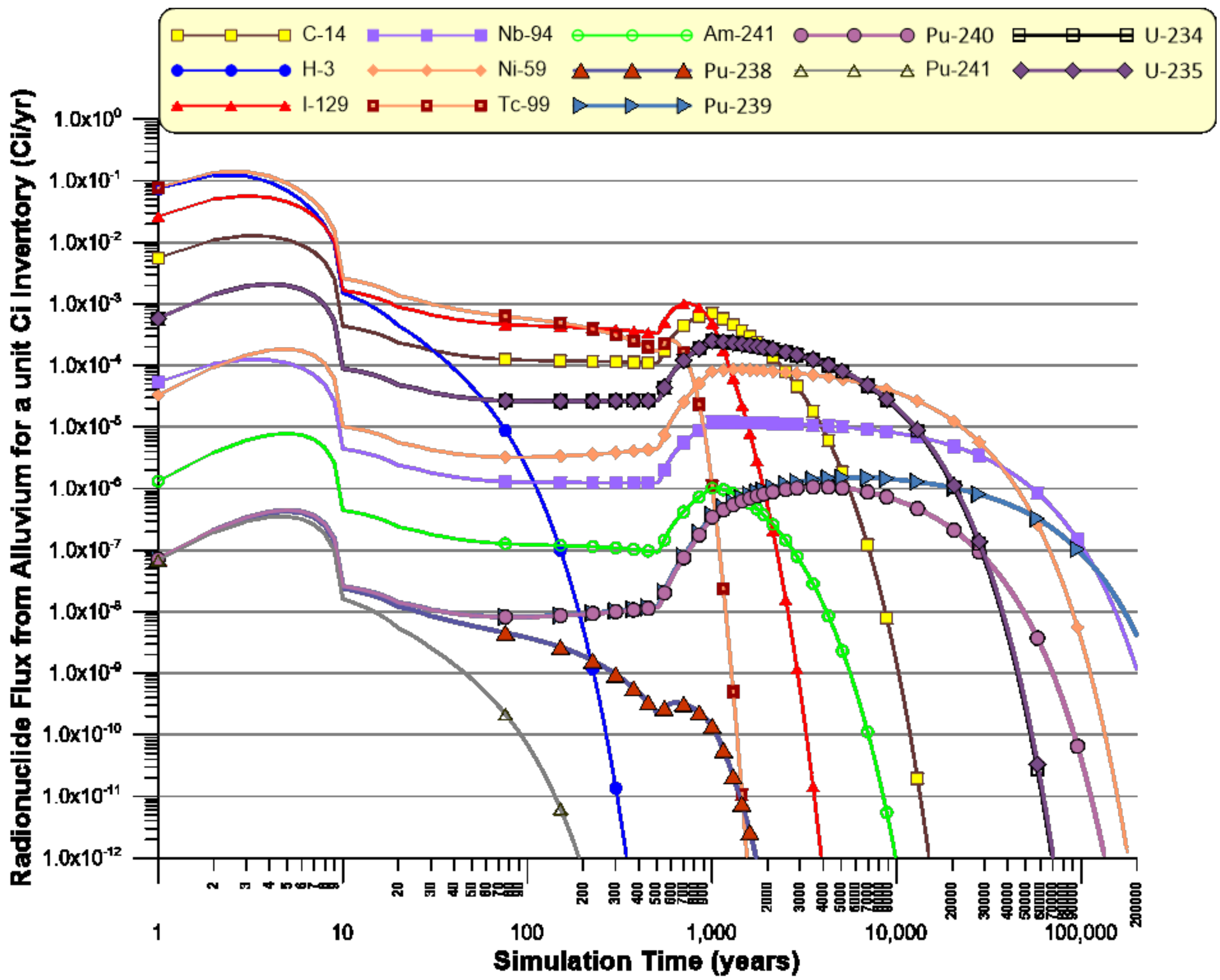

Figure B-7. Radionuclide fluxes from the alluvium zone to the vadose zone for surface contaminated containers and unit inventories for each radionuclide.

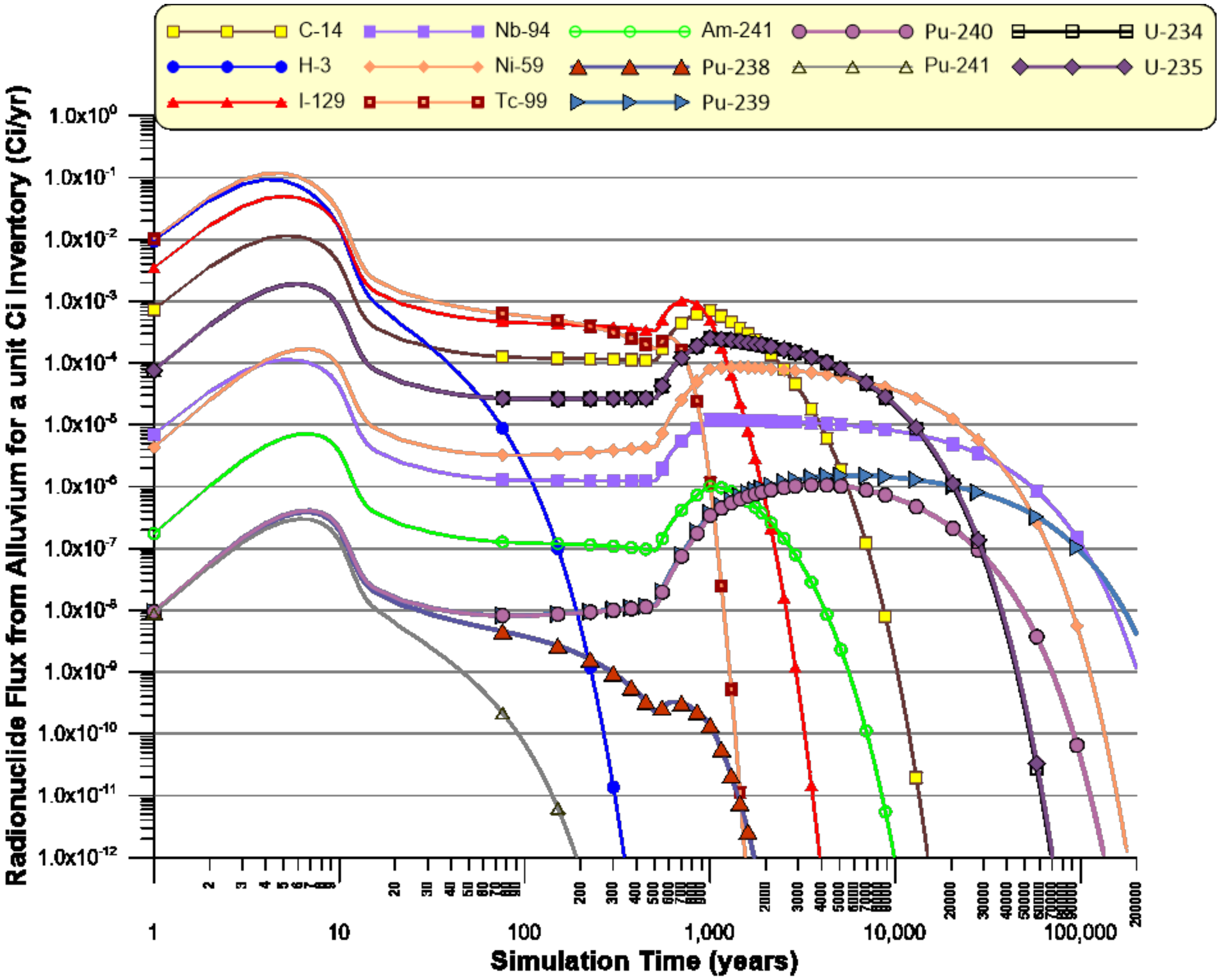

Figure B-8. Radionuclide fluxes from the vadose zone to the aquifer for surface contaminated containers and unit inventories for each radionuclide.

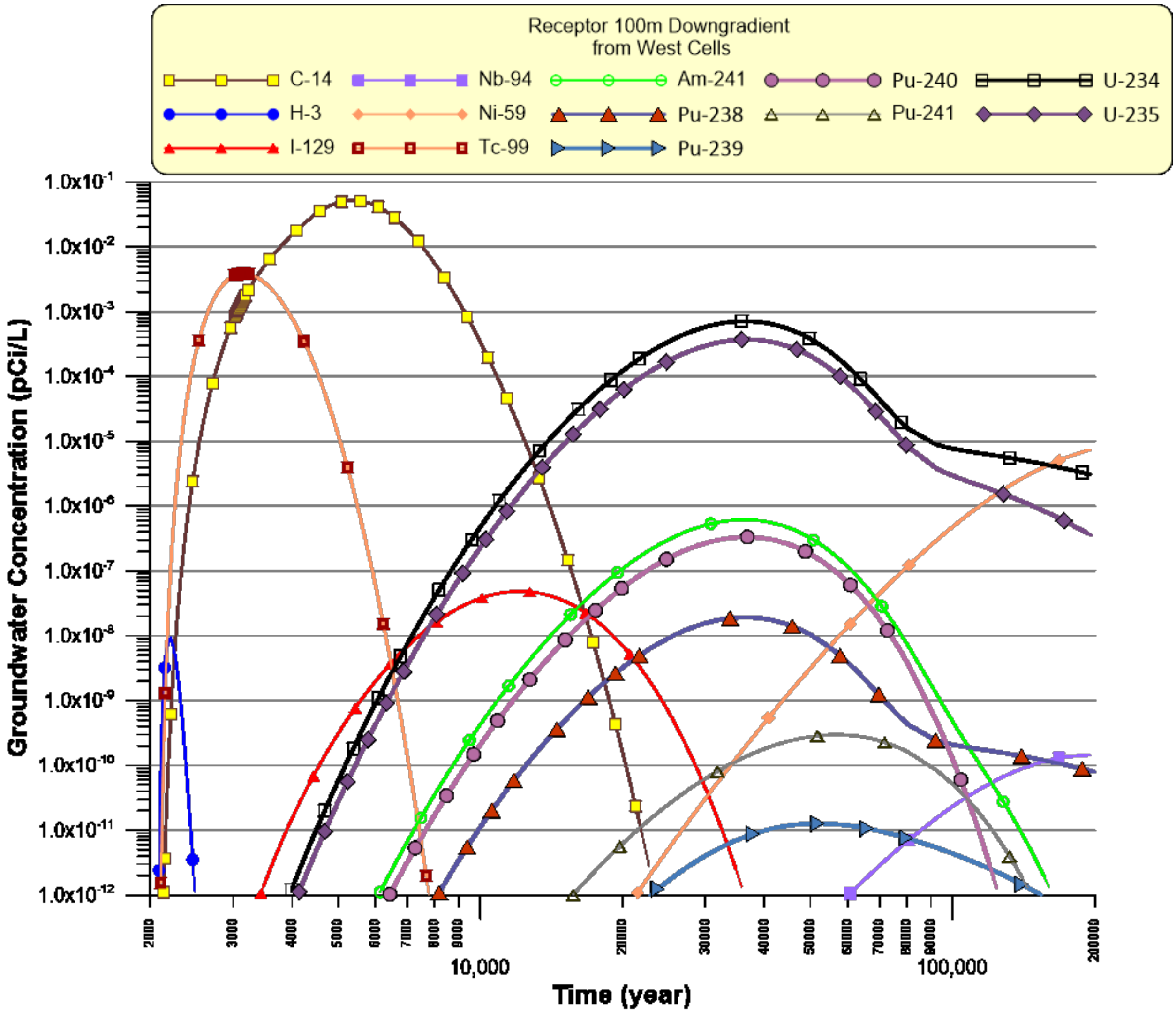

Figure B-9. Radionuclide concentrations in the groundwater 100-m downgradient from the west array from surface contaminated containers and inventories in Table 7 for the NRF-requested limits.

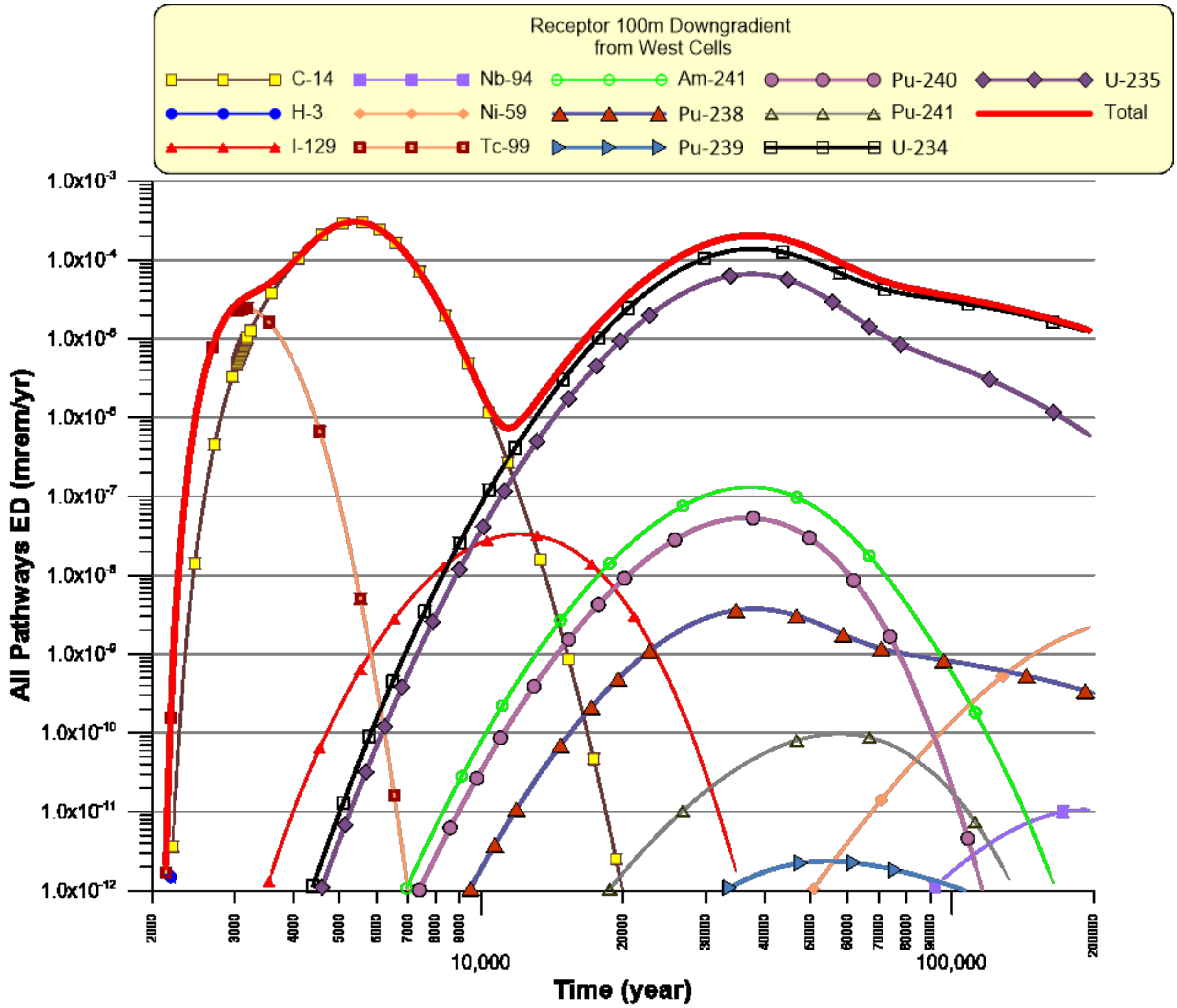

Figure B-10. Radionuclide all-pathway dose in the groundwater 100-m downgradient from the west array from surface contaminated containers and inventories in Table 7 for the NRF-requested limits.

Attachments to Appendix B

Infiltration File for Source (src.out)

```
Time (yr)    Water Flux (m/yr)
 0.00000E+00  1.80000E-01
 2.00000E+01  1.80000E-01
 2.10000E+01  1.00000E-03
 5.20000E+02  1.00000E-03
 1.02000E+03  1.00000E-02
 5.00000E+06  1.00000E-02
```

Infiltration File for Alluvium (alluv.out, created with infil.for)

```
Time (yr)    Water Flux (m/yr)  infil.for Ver 110923  ftype: 1 incap: 1.000000000000000E-03
infail: 1.000000000000000E-02 p1: 500.0000000000000 p2: 0.000000000000000E+00 ctype: 1 mclt:
-3.000000000000000 stdv: 1.000000000000000 minflx: 1.000000000000000E-06
 0.00000E+00  9.98650E-04
 1.00000E+00  9.99968E-04
 4.33000E+00  1.00000E-03
 7.66000E+00  1.00000E-03
 1.09900E+01  1.00000E-03
 4.63870E+02  1.00000E-03
 4.67200E+02  1.00000E-03
 4.70530E+02  1.00000E-03
 4.73860E+02  1.00000E-03
 4.77190E+02  1.00000E-03
 4.80520E+02  1.00000E-03
 4.83850E+02  1.00000E-03
 4.87180E+02  1.00000E-03
 4.90510E+02  1.00000E-03
 4.93840E+02  1.00000E-03
 4.97170E+02  1.00000E-03
 5.00500E+02  1.00900E-03
 5.03830E+02  1.06894E-03
 5.07160E+02  1.12888E-03
 5.10490E+02  1.18882E-03
 5.13820E+02  1.24876E-03
 5.17150E+02  1.30870E-03
 5.20480E+02  1.36864E-03
 5.23810E+02  1.42858E-03
 5.27140E+02  1.48852E-03
 5.30470E+02  1.54846E-03
 5.33800E+02  1.60840E-03
 5.37130E+02  1.66834E-03
 5.40460E+02  1.72828E-03
 5.43790E+02  1.78822E-03
 5.47120E+02  1.84816E-03
 5.50450E+02  1.90810E-03
 5.53780E+02  1.96804E-03
 5.57110E+02  2.02798E-03
 5.60440E+02  2.08792E-03
 5.63770E+02  2.14786E-03
 5.67100E+02  2.20780E-03
 5.70430E+02  2.26774E-03
 5.73760E+02  2.32768E-03
 5.77090E+02  2.38762E-03
 5.80420E+02  2.44756E-03
 5.83750E+02  2.50750E-03
 5.87080E+02  2.56744E-03
 5.90410E+02  2.62738E-03
 5.93740E+02  2.68732E-03
 5.97070E+02  2.74726E-03
 6.00400E+02  2.80720E-03
 6.03730E+02  2.86714E-03
 6.07060E+02  2.92708E-03
 6.10390E+02  2.98702E-03
 6.13720E+02  3.04696E-03
 6.17050E+02  3.10690E-03
```

6.20380E+02	3.16684E-03
6.23710E+02	3.22678E-03
6.27040E+02	3.28672E-03
6.30370E+02	3.34666E-03
6.33700E+02	3.40660E-03
6.37030E+02	3.46654E-03
6.40360E+02	3.52648E-03
6.43690E+02	3.58642E-03
6.47020E+02	3.64636E-03
6.50350E+02	3.70630E-03
6.53680E+02	3.76624E-03
6.57010E+02	3.82618E-03
6.60340E+02	3.88612E-03
6.63670E+02	3.94606E-03
6.67000E+02	4.00600E-03
6.70330E+02	4.06594E-03
6.73660E+02	4.12588E-03
6.76990E+02	4.18582E-03
6.80320E+02	4.24576E-03
6.83650E+02	4.30570E-03
6.86980E+02	4.36564E-03
6.90310E+02	4.42558E-03
6.93640E+02	4.48552E-03
6.96970E+02	4.54546E-03
7.00300E+02	4.60540E-03
7.03630E+02	4.66534E-03
7.06960E+02	4.72528E-03
7.10290E+02	4.78522E-03
7.13620E+02	4.84516E-03
7.16950E+02	4.90510E-03
7.20280E+02	4.96504E-03
7.23610E+02	5.02498E-03
7.26940E+02	5.08492E-03
7.30270E+02	5.14486E-03
7.33600E+02	5.20480E-03
7.36930E+02	5.26474E-03
7.40260E+02	5.32468E-03
7.43590E+02	5.38462E-03
7.46920E+02	5.44456E-03
7.50250E+02	5.50450E-03
7.53580E+02	5.56444E-03
7.56910E+02	5.62438E-03
7.60240E+02	5.68432E-03
7.63570E+02	5.74426E-03
7.66900E+02	5.80420E-03
7.70230E+02	5.86414E-03
7.73560E+02	5.92408E-03
7.76890E+02	5.98402E-03
7.80220E+02	6.04396E-03
7.83550E+02	6.10390E-03
7.86880E+02	6.16384E-03
7.90210E+02	6.22378E-03
7.93540E+02	6.28372E-03
7.96870E+02	6.34366E-03
8.00200E+02	6.40360E-03
8.03530E+02	6.46354E-03
8.06860E+02	6.52348E-03
8.10190E+02	6.58342E-03
8.13520E+02	6.64336E-03
8.16850E+02	6.70330E-03
8.20180E+02	6.76324E-03
8.23510E+02	6.82318E-03
8.26840E+02	6.88312E-03
8.30170E+02	6.94306E-03
8.33500E+02	7.00300E-03
8.36830E+02	7.06294E-03
8.40160E+02	7.12288E-03
8.43490E+02	7.18282E-03
8.46820E+02	7.24276E-03
8.50150E+02	7.30270E-03
8.53480E+02	7.36264E-03

```
 8.56810E+02  7.42258E-03
 8.60140E+02  7.48252E-03
 8.63470E+02  7.54246E-03
 8.66800E+02  7.60240E-03
 8.70130E+02  7.66234E-03
 8.73460E+02  7.72228E-03
 8.76790E+02  7.78222E-03
 8.80120E+02  7.84216E-03
 8.83450E+02  7.90210E-03
 8.86780E+02  7.96204E-03
 8.90110E+02  8.02198E-03
 8.93440E+02  8.08192E-03
 8.96770E+02  8.14186E-03
 9.00100E+02  8.20180E-03
 9.03430E+02  8.26174E-03
 9.06760E+02  8.32168E-03
 9.10090E+02  8.38162E-03
 9.13420E+02  8.44156E-03
 9.16750E+02  8.50150E-03
 9.20080E+02  8.56144E-03
 9.23410E+02  8.62138E-03
 9.26740E+02  8.68132E-03
 9.30070E+02  8.74126E-03
 9.33400E+02  8.80120E-03
 9.36730E+02  8.86114E-03
 9.40060E+02  8.92108E-03
 9.43390E+02  8.98102E-03
 9.46720E+02  9.04096E-03
 9.50050E+02  9.10090E-03
 9.53380E+02  9.16084E-03
 9.56710E+02  9.22078E-03
 9.60040E+02  9.28072E-03
 9.63370E+02  9.34066E-03
 9.66700E+02  9.40060E-03
 9.70030E+02  9.46054E-03
 9.73360E+02  9.52048E-03
 9.76690E+02  9.58042E-03
 9.80020E+02  9.64036E-03
 9.83350E+02  9.70030E-03
 9.86680E+02  9.76024E-03
 9.90010E+02  9.82018E-03
 9.93340E+02  9.88012E-03
 9.96670E+02  9.94006E-03
 1.00000E+03  1.00000E-02
 1.00333E+03  1.00000E-02
 5.00000E+05  1.00000E-02
```

Infiltration File for Vadose Zone (vz.out, created with infil.for

```
Time (yr)    Water Flux (m/yr)  infil.for Ver 110421  ftype: 1 incap: 1.000000000000000E-02
infail: 1.000000000000000E-02 p1: 500.0000000000000 p2: 0.000000000000000E+00 ctype: 1 mclt:
-2.000000000000000 stdv: 1.000000000000000 minflx: 1.000000000000000E-06
 0.00000E+00  9.77250E-03
 1.00000E+00  9.98650E-03
 1.09900E+01  1.00000E-02
 1.00000E+03  1.00000E-02
 1.00999E+03  1.00000E-02
 5.00000E+05  1.00000E-02
```

MCMF Input File for Source

```
MCMF run  - source water flux  title [title of project (a80)]
'src.flx'                           fileout [name of MCMT water flux file (a80)]
'../../infiltration/src.out'
1.0e-6 .0001  1.0e-60                eps,h1,hmin [accuracy, initial time step, minimum time step]
2  1  2000  0.19  5e-4  0  B     mlayer,nmat,nkt,qmax,qmin,iflag,abin
$[no# of layers, no# of materials, no# of pnts in vanG curves, max value of q, min value of q]
```

```
$[iflag: (0) initial moisture based on first record in infiltration file (1) provide initial
moisture]
$[abin: (A)scii or (B)inary]
$[read in initial moisture contents if iflag(1)=1, 20 values per line are read for each cell
beginning with the uppermost cell]

$ [Material properties are input by defining the range of cells where they apply]

$ Material 1:   High Permeability Alluvium (from Table A-7-1 DOE/NE-ID-11227)
1  2                                    h,j [beginning cell, ending cell]
1.60   1.82                          thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
8798.  0.32   0.0002   100  1.4  0.5  -1.   sk(h),ths(h),thr(h),alpha(h),rn(h) [Sat conductivity
(m/yr) sat moist content, resid moist content, vanG alpha, vanG n]

$ [Time output parameters]
4           ntimes [number of output time periods]
$ [Repeat t1,t2,tp for each ntime]
0.0    1000  10.0        t1(i),t2(i),tp(i) [beginning time of output ending time of output, print
step]
1200   1.0e4 200.0
1.1e4  8.0e4 500.0
8.1e4  5.0e5 1000.
2.0e6          tmax [maximum time of output]
1          ncout [number of flux traces]
2
```

MCMF Input File for Alluvium

```
MCMF run  - alluvium water flux  title [title of project (a80)]
alluv.flx                             fileout [name of MCMT water flux file (a80)]
'../../infiltration/alluv.out'                         fileppt [net infiltration rate file (a80)]
1.0e-6 .0001  1.0e-60                eps,h1,hmin [accuracy, initial time step, minimum time step]
5  2  2000  0.20  1e-6  1  B     mlayer,nmat,nkt,qmax,qmin,iflag,abin
$[no# of layers, no# of materials, no# of pnts in vanG curves, max value of q, min value of q]
$[iflag: (0) initial moisture based on first record in infiltration file (1) provide initial
moisture]
$[abin: (A)scii or (B)inary]
$[read in initial moisture contents if iflag(1)=1, 20 values per line are read for each cell
beginning with the uppermost cell]

2.459E-01 2.521E-01 2.521E-01 2.521E-01 2.521E-01

$ [Material properties are input by defining the range of cells where they apply]

$ Material 0  HPAlluvium
1  1    h,j [beginning cell, ending cell]
5.000e-001  1.65e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
2.68e4  3.733e-001  0.085  1.0532e+006  1.17514
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]
$ Material 1  SCLAlluv
2  5    h,j [beginning cell, ending cell]
1.950e+000  1.820e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
1.148e+002  3.900e-001  1.000e-001  5.900e+000  1.480e+000  3.243e-001  5.000e-001
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]

$ [Time output parameters]
4           ntimes [number of output time periods]
$ [Repeat t1,t2,tp for each ntime]
0.0    1000  10.0        t1(i),t2(i),tp(i) [beginning time of output ending time of output, print
step]
1200   1.0e4 200.0
1.1e4  8.0e4 500.0
8.1e4  5.0e5 1000.
2.0e6          tmax [maximum time of output]
1          ncout [number of flux traces]
4
```

MCMF Input File for Vadose Zone

```
RHLLWPA MCMF run  for the vadose zone     title [title of project (a80)]
vz.flx                             fileout [name of MCMT water flux file (a80)]
'../../infiltration/vz.out'                              fileppt [net infiltration rate file
(a80)]
1.0e-6 .0001  1.0e-60                 eps,h1,hmin [accuracy, initial time step, minimum time step]
50  11 500 0.11 0.0005  0  B     mlayer,nmat,nkt,qmax,qmin,iflag,abin
$[no# of layers, no# of materials, no# of pnts in vanG curves, max value of q, min value of q]
$[iflag: (0) initial moisture based on first record in infiltration file (1) provide initial
moisture]
$[abin: (A)scii or (B)inary]
$[read in initial moisture contents if iflag(1)=1, 20 values per line are read for each cell
beginning with the uppermost cell]


$ [Material properties are input by defining the range of cells where they apply]

$ Material 0  Basalt
1  5    h,j [beginning cell, ending cell]
2.940e+000  2.000e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
9.100e+001  5.000e-002  1.000e-003  2.500e+000  1.000e+001  9.000e-001  5.000e-001
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]
$ Material 1  Interbed
6  6    h,j [beginning cell, ending cell]
2.000e+000  1.500e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
1.053e+000  4.590e-001  1.630e-001  6.200e-002  1.480e+000  6.900e-001  9.330e+000
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]
$ Material 2  Basalt
7  11    h,j [beginning cell, ending cell]
2.820e+000  2.000e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
9.100e+001  5.000e-002  1.000e-003  2.500e+000  1.000e+001  9.000e-001  5.000e-001
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]
$ Material 3  Interbed
12  13    h,j [beginning cell, ending cell]
2.000e+000  1.500e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
1.053e+000  4.590e-001  1.630e-001  6.200e-002  1.480e+000  6.900e-001  9.330e+000
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]
$ Material 4  Basalt
14  16    h,j [beginning cell, ending cell]
2.430e+000  2.000e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
9.100e+001  5.000e-002  1.000e-003  2.500e+000  1.000e+001  9.000e-001  5.000e-001
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]
$ Material 5  Interbed
17  19    h,j [beginning cell, ending cell]
2.670e+000  1.500e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
1.053e+000  4.590e-001  1.630e-001  6.200e-002  1.480e+000  6.900e-001  9.330e+000
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]
$ Material 6  Basalt
20  24    h,j [beginning cell, ending cell]
2.480e+000  2.000e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
9.100e+001  5.000e-002  1.000e-003  2.500e+000  1.000e+001  9.000e-001  5.000e-001
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]
$ Material 7  Interbed
25  26    h,j [beginning cell, ending cell]
2.000e+000  1.500e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
1.053e+000  4.590e-001  1.630e-001  6.200e-002  1.480e+000  6.900e-001  9.330e+000
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]
$ Material 8  Basalt
27  28    h,j [beginning cell, ending cell]
2.500e+000  2.000e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
9.100e+001  5.000e-002  1.000e-003  2.500e+000  1.000e+001  9.000e-001  5.000e-001
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
```

```
moist content, vanG alpha, vanG n vanG m vanG l]
$ Material 9  Interbed
29  30    h,j [beginning cell, ending cell]
2.000e+000  1.500e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
1.053e+000  4.590e-001  1.630e-001  6.200e-002  1.480e+000  6.900e-001  9.330e+000
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]
$ Material 10  Basalt
31  50    h,j [beginning cell, ending cell]
2.960e+000  2.000e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
9.100e+001  5.000e-002  1.000e-003  2.500e+000  1.000e+001  9.000e-001  5.000e-001
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]


$ [Time output parameters]
4           ntimes [number of output time periods]
$ [Repeat t1,t2,tp for each ntime]
0.0    1000  10.0        t1(i),t2(i),tp(i) [beginning time of output ending time of output, print
step]
1200   1.0e4 200.0
1.1e4  8.0e4 500.0
8.1e4  5.0e5 1000.
2.0e6          tmax [maximum time of output]
1          ncout [number of flux traces]
$ [Read only if ncout>0]
50         ncoutput(i) [cell numbers for each flux trace
$ [End of Parameter Definition File]
```

MCMT Input File for Source, Group 1

```
Group1 Fission Activation Products and Am-241 RHLLW PA NRF contamination on can surface
'../../mcmf/src/src.flx'
NONE
1e-006 0.0001 1e-090                      eps h1 hmin [accuracy, initial time step, minimum time
step]
2 10 1 1 B           mlayer nprog nmat iunits abin [number of layers,number of contaminants,
number of materials, units, (A)scii or (B)inary]
$[abin: (A)scii or (B)inary]
$ [iunits: (1) Ci (2) Bq  (3) mg]
C-14       H-3        I-129      Nb-94      Ni-59      Tc-99       aAm-241    aNp-237    aU-233
aTh-229            cname [contaminant names (6 characters)]
14         3          129        94         59         99          241         237        233
229         molecular weight (g/mol)
1.000e+009 1.000e+009 1.000e+009 1.000e+009 1.000e+009 1.000e+009  1.000e+009 1.000e+009
1.000e+009 1.000e+009    solubility (mg/m3)
5.730e+003 1.230e+001 1.570e+007 2.030e+004 7.500e+004 2.110e+005  4.320e+002 2.140e+006
1.590e+005 7.340e+003    half life (years)
0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000  1.000e+000 1.000e+000
1.000e+000 0.000e+000     branching ratio
0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000  0.000e+000 0.000e+000
0.000e+000 0.000e+000     diffusion coefficient in water (m2/yr)
-1.0       -1.0       -1.0       -1.0       -1.0       -1.0        -1.0       -1.0       -1.0
-1.0        lbc
$ Initial Inventories (Ci)
$-----------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------
---------------------------
$   1         2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
19         20
$-----------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------
---------------------------
$ C-14
5.000e-001 5.000e-001

$ H-3
5.000e-001 5.000e-001
```

```
$ I-129
5.000e-001 5.000e-001

$ Nb-94
5.000e-001 5.000e-001

$ Ni-59
5.000e-001 5.000e-001

$ Tc-99
5.000e-001 5.000e-001

$ Am-241
5.000e-001 5.000e-001

$ Np-237
0.000e+000 0.000e+000

$ U-233
1.180e-001 1.180e-001

$ Th-229
0.000e+000 0.000e+000


$ Kd Values (ml/g)
$-----------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------
---------------------------
$   1          2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
19         20
$-----------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------
---------------------------
$  C-14
0.000e+000 0.000e+000

$  H-3
0.000e+000 0.000e+000

$  I-129
0.000e+000 0.000e+000

$  Nb-94
0.000e+000 0.000e+000

$  Ni-59
0.000e+000 0.000e+000

$  Tc-99
0.000e+000 0.000e+000

$ Am-241
0.000e-001 0.000e-001

$ Np-237
0.000e+000 0.000e+000

$ U-233
0.000e+000 0.000e+000

$ Th-229
0.000e+000 0.000e+000

$ kx rate constants (1/yr)
$-----------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------
---------------------------
$   1          2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
```

```
  19        20
$---------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------
---------------------------
$  C-14
0.000e+000 0.000e+000

$  H-3
0.000e+000 0.000e+000

$  I-129
0.000e+000 0.000e+000

$  Nb-94
0.000e+000 0.000e+000

$  Ni-59
0.000e+000 0.000e+000

$  Tc-99
0.000e+000 0.000e+000

$ Am-241
0.000e-001 0.000e-001

$ Np-237
0.000e+000 0.000e+000

$ U-233
0.000e+000 0.000e+000

$ Th-229
0.000e+000 0.000e+000

1.000e+001  5.800e+001  0.000e+000      [length (m)  width (m)  alphaL (m)

$ [Material properties are input by defining the range of cells where they apply]

$ Material 0  Waste
1  2    h,j [beginning cell, ending cell]
1.600e+000  1.820e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
8.798e+003  3.200e-001  2.000e-004  1.000e+002  1.400e+000  2.857e-001  5.000e-001
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]

$ Output Times

8                 ntimes [number of output time periods]
0.000e+000  5.000e+002  1.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
5.020e+002  2.000e+003  2.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
2.005e+003  3.000e+003  5.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
3.010e+003  5.000e+003  1.000e+001          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
5.025e+003  1.000e+004  2.500e+001          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
1.010e+004  3.000e+004  1.000e+002          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
3.050e+004  1.000e+005  5.000e+002          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
1.010e+005  2.100e+005  2.000e+003          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
$ [End of Parameter Definition File]
```

MCMT Input File for Source, Group 2

```
Group2 Actinides Basecase RHLLW PA NRF contamination on can surface
'../../mcmf/src/src.flx'
```

```
NONE
1e-006 0.0001 1e-090                      eps h1 hmin [accuracy, initial time step, minimum time
step]
2 9 1 1 B           mlayer nprog nmat iunits abin [number of layers,number of contaminants,
number of materials, units, (A)scii or (B)inary]
$[abin: (A)scii or (B)inary]
$ [iunits: (1) Ci (2) Bq  (3) mg]
 bPu-241    bAm-241    bNp-237    bU-233     bTh-229     cU-234     cTh-230   cRa-226    cPb-210
cname [contaminant names (6 characters)]
 241        241          237        233        226       234        230       226        210
molecular weight (g/mol)
 1.000e+009 1.000e+009 1.000e+009 1.000e+009 1.000e+009 1.000e+009 1.000e+009 1.000e+009
1.000e+009     solubility (mg/m3)
 1.440e+001 4.320e+002 2.140e+006 1.590e+005 7.340e+003 2.440e+005 7.540e+004 1.600e+003
2.230e+001     half life (years)
 1.000e+000 1.000e+000 1.000e+000 1.000e+000 0.000e+000 1.000e+000 1.000e+000 1.000e+000
0.000e+000      branching ratio
 0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000
0.000e+000      diffusion coefficient in water (m2/yr)
-1.0       -1.0       -1.0       -1.0       -1.0       -1.0        -1.0       -1.0       -1.0
lbc
$ Initial Inventories (Ci)
$-----------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------
---------------------------
$   1          2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
19         20
$-----------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------
---------------------------
$ Pu-241
5.000e-001 5.000e-001

$ Am-241
0.000e+000 0.000e+000

$ Np-237
0.000e+000 0.000e+000

$ U-233
0.000e+000 0.000e+000

$ Th-229
0.000e+000 0.000e+000

$ U-234
5.000e-001 5.000e-001

$ Th-230
0.000e+000 0.000e+000

$ Ra-226
0.000e+000 0.000e+000

$ Pb-210
0.000e+000 0.000e+000


$ Kd Values (ml/g)
$-----------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------
---------------------------
$   1          2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
19         20
$-----------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------
---------------------------
$ Pu-241
0.000e+000 0.000e+000
```

```
$ Am-241
0.000e+000 0.000e+000

$ Np-237
0.000e+000 0.000e+000

$ U-233
0.000e+000 0.000e+000

$ Th-229
0.000e+000 0.000e+000

$ U-234
0.000e+000 0.000e+000

$ Th-230
0.000e+000 0.000e+000

$ Ra-226
0.000e+000 0.000e+000

$ Pb-210
0.000e+000 0.000e+000

$ kx rate constants (1/yr)
$-------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------
---------------------------
$   1          2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
19         20
$-------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------
---------------------------
$ Pu-241
0.000e+000 0.000e+000

$ Am-241
0.000e+000 0.000e+000

$ Np-237
0.000e+000 0.000e+000

$ U-233
0.000e+000 0.000e+000

$ Th-229
0.000e+000 0.000e+000

$ U-234
0.000e+000 0.000e+000

$ Th-230
0.000e+000 0.000e+000

$ Ra-226
0.000e+000 0.000e+000

$ Pb-210
0.000e+000 0.000e+000

1.000e+001  5.800e+001  0.000e+000      [length (m)  width (m)  alphaL (m)

$ [Material properties are input by defining the range of cells where they apply]

$ Material 0  Waste
1  2    h,j [beginning cell, ending cell]
1.600e+000  1.820e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
8.798e+003  3.200e-001  2.000e-004  1.000e+002  1.400e+000  2.857e-001  5.000e-001
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
```

```
moist content, vanG alpha, vanG n vanG m vanG l]

$ Output Times

8                 ntimes [number of output time periods]
0.000e+000  5.000e+002  1.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
5.020e+002  2.000e+003  2.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
2.005e+003  3.000e+003  5.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
3.010e+003  5.000e+003  1.000e+001          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
5.025e+003  1.000e+004  2.500e+001          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
1.010e+004  3.000e+004  1.000e+002          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
3.050e+004  1.000e+005  5.000e+002          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
1.010e+005  2.100e+005  2.000e+003          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
$ [End of Parameter Definition File]
```

MCMT Input File for Source, Group 3

```
Group3 Actinides Basecase RHLLW PA NRF contamination on can surface
'../../mcmf/src/src.flx'
NONE
1e-006 0.0001 1e-090                      eps h1 hmin [accuracy, initial time step, minimum time
step]
2 8 1 1 B           mlayer nprog nmat iunits abin [number of layers,number of contaminants,
number of materials, units, (A)scii or (B)inary]
$[abin: (A)scii or (B)inary]
$ [iunits: (1) Ci (2) Bq  (3) mg]
dPu-240    dU-236     dTh-232    dRa-228    dTh-228    eU-235     ePa-231    eAc-227
cname [contaminant names (6 characters)]
240        236        232        228        228        235        231        227
molecular weight (g/mol)
1.000e+009 1.000e+009 1.000e+009 1.000e+009 1.000e+009 1.000e+009 1.000e+009 1.000e+009
solubility (mg/m3)
6.537e+003 2.342e+007 1.405e+010 5.750e+000 1.910e+000 7.040e+008 3.280e+004 2.177e+001    half
life (years)
1.000e+000 1.000e+000 1.000e+000 1.000e+000 0.000e+000 1.000e+000 1.000e+000 0.000e+000
branching ratio
0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000
diffusion coefficient in water (m2/yr)
-1.0       -1.0       -1.0       -1.0       -1.0       -1.0        -1.0       -1.0          lbc
$ Initial Inventories (Ci)
$-----------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------
---------------------------
$   1          2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
19         20
$-----------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------
---------------------------
$ Pu-240
5.000e-001 5.000e-001

$ U-236
1.810e-000 1.810e-000

$ Th-232
0.000e+000 0.000e+000

$ Ra-228
0.000e+000 0.000e+000

$ Th-228
```

```
0.000e+000 0.000e+000

$ U-235
5.000e-001 5.000e-001

$ Pa-231
0.000e+000 0.000e+000

$ Ac-227
0.000e+000 0.000e+000

$ Kd Values (ml/g)
$-----------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------
---------------------------
$   1          2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
19         20
$-----------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------
---------------------------
$ Pu-240
0.000e+000 0.000e+000

$ U-236
0.000e+000 0.000e+000

$ Th-232
0.000e+000 0.000e+000

$ Ra-228
0.000e+000 0.000e+000

$ Th-228
0.000e+000 0.000e+000

$ U-235
0.000e+000 0.000e+000

$ Pa-231
0.000e+000 0.000e+000

$ Ac-227
0.000e+000 0.000e+000

$ kx rate constants (1/yr)
$-----------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------
---------------------------
$   1          2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
19         20
$-----------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------
---------------------------
$ Pu-240
0.000e+000 0.000e+000

$ U-236
0.000e+000 0.000e+000

$ Th-232
0.000e+000 0.000e+000

$ Ra-228
0.000e+000 0.000e+000

$ Th-228
0.000e+000 0.000e+000

$ U-235
```

```
0.000e+000 0.000e+000

$ Pa-231
0.000e+000 0.000e+000

$ Ac-227
0.000e+000 0.000e+000

1.000e+001  5.800e+001  0.000e+000      [length (m)  width (m)  alphaL (m)

$ [Material properties are input by defining the range of cells where they apply]

$ Material 0  Waste
1  2    h,j [beginning cell, ending cell]
1.600e+000  1.820e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
8.798e+003  3.200e-001  2.000e-004  1.000e+002  1.400e+000  2.857e-001  5.000e-001
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]

$ Output Times

8                 ntimes [number of output time periods]
0.000e+000  5.000e+002  1.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
5.020e+002  2.000e+003  2.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
2.005e+003  3.000e+003  5.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
3.010e+003  5.000e+003  1.000e+001          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
5.025e+003  1.000e+004  2.500e+001          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
1.010e+004  3.000e+004  1.000e+002          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
3.050e+004  1.000e+005  5.000e+002          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
1.010e+005  2.100e+005  2.000e+003          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
$ [End of Parameter Definition File]
```

MCMT Input File for Source, Group 4

```
Group4 Actinides Basecase RHLLW PA NRF contamination on can surface
'../../mcmf/src/src.flx'
NONE
1e-006 0.0001 1e-090                      eps h1 hmin [accuracy, initial time step, minimum time
step]
2 9 1 1 B           mlayer nprog nmat iunits abin [number of layers,number of contaminants,
number of materials, units, (A)scii or (B)inary]
$[abin: (A)scii or (B)inary]
$ [iunits: (1) Ci (2) Bq  (3) mg]
 fPu238     fU-234     fTh-230    fRa-226    fPb-210     gPu-239    gU-235     gPa-231    gAc-227
cname [contaminant names (6 characters)]
  238        234        230        226        210          239        235        231        227
molecular weight (g/mol)
 1.000e+009 1.000e+009 1.000e+009 1.000e+009 1.000e+009  1.000e+009 1.000e+009 1.000e+009
1.000e+009  solubility (mg/m3)
 8.770e+001 2.440e+005 7.540e+004 1.600e+003 2.230e+001  2.410e+004 7.040e+008 3.280e+004
2.177e+001  half life (years)
 1.000e+000 1.000e+000 1.000e+000 1.000e+000 0.000e+000  1.000e+000 1.000e+000 1.000e+000
0.000e+000   branching ratio
 0.000e+000 0.000e+000 0.000e+000 0.000e+000 0.000e+000  0.000e+000 0.000e+000 0.000e+000
0.000e+000   diffusion coefficient in water (m2/yr)
-1.0       -1.0       -1.0       -1.0        -1.0        -1.0       -1.0       -1.0       -1.0
lbc
$ Initial Inventories (Ci)
$-----------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------
---------------------------
```

```
$   1          2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
19         20
$--------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------
---------------------------
$ Pu-238
5.000e-001 5.000e-001

$ U-234
0.000e+000 0.000e+000

$ Th-230
0.000e+000 0.000e+000

$ Ra-226
0.000e+000 0.000e+000

$ Pb-210
0.000e+000 0.000e+000

$ Pu-239
5.000e-001 5.000e-001

$ U-235
0.000e+000 0.000e+000

$ Pa-231
0.000e+000 0.000e+000

$ Ac-227
0.000e+000 0.000e+000

$ Kd Values (ml/g)
$--------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------
---------------------------
$   1          2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
19         20
$--------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------
---------------------------
$ Pu-238
0.000e-001 0.000e-001

$ U-234
0.000e+000 0.000e+000

$ Th-230
0.000e+000 0.000e+000

$ Ra-226
0.000e+000 0.000e+000

$ Pb-210
0.000e+000 0.000e+000

$ Pu-239
0.000e-001 0.000e-001

$ U-235
0.000e+000 0.000e+000

$ Pa-231
0.000e+000 0.000e+000

$ Ac-227
0.000e+000 0.000e+000

$ kx rate constants (1/yr)
```

```
$-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
$   1          2          3          4          5          6          7          8          9
10         11         12         13         14         15         16         17         18
19         20
$-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
$ Pu-238
0.000e-001 0.000e-001

$ U-234
0.000e+000 0.000e+000

$ Th-230
0.000e+000 0.000e+000

$ Ra-226
0.000e+000 0.000e+000

$ Pb-210
0.000e+000 0.000e+000

$ Pu-239
0.000e-001 0.000e-001

$ U-235
0.000e+000 0.000e+000

$ Pa-231
0.000e+000 0.000e+000

$ Ac-227
0.000e+000 0.000e+000

1.000e+001  5.800e+001  0.000e+000      [length (m)  width (m)  alphaL (m)

$ [Material properties are input by defining the range of cells where they apply]

$ Material 0  Waste
1  2    h,j [beginning cell, ending cell]
1.600e+000  1.820e+000     thick(h) rho(h) [thickness (m) bulk density (g/cm^3)]
8.798e+003  3.200e-001  2.000e-004  1.000e+002  1.400e+000  2.857e-001  5.000e-001
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]


$ Output Times

8                 ntimes [number of output time periods]
0.000e+000  5.000e+002  1.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
5.020e+002  2.000e+003  2.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
2.005e+003  3.000e+003  5.000e+000          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
3.010e+003  5.000e+003  1.000e+001          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
5.025e+003  1.000e+004  2.500e+001          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
1.010e+004  3.000e+004  1.000e+002          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
3.050e+004  1.000e+005  5.000e+002          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
1.010e+005  2.100e+005  2.000e+003          t1(i),t2(i),tp(i) [beginning time of output ending
time of output, print step]
$ [End of Parameter Definition File]
```

Perl Script for Creating MCMT Alluvium Files

```
# mkmcmt.pl
# This script is a general script for writing multiple mcmt files for the same
# lithology and a given set of radionuclides. All input is provided upfront

# Written for the BEA by: Arthur S. Rood
# August 2, 2011

# usage perl mkmcmt.pl

# ===================================================================================
#                       User Input
# ===================================================================================
# Number of radionuclide groups
      $ngroups=4;
# Radionuclide independent parameters and control parameters
      $fileppt="'../../mcmf/alluv/alluv.flx'";
      $eps=1.0e-6;
      $h1=0.0001;
      $hmin=1.0e-90;
      $mlayer=5;
      $nmat=2;
      $iunits=1;
      $abin="B";
      $len=10;
      $width=25;
      $alphaL=0;

#     Output Times
      $ntimes=8;
      @t1 = (0.0,502,2005,3010,5025,10100,30500,101000);
      @t2 = (500,2000,3000,5000,10000,30000,100000,210000);
      @tp = (1,2,5,10,25,100,500,2000);


# Lithology Definitions
      $Nlithology=2;
      @LNames=("HPAlluvium","SCLAlluv");               # SCLAlluv - sandy clay loam alluvium
#     Note: Default values for rl and rm; rl=0.5 rm=1-1/rl

#     Data for lithology HPAlluvium
      $i=0;
      $sk{$LNames[$i]}=2.68e4.0 ;
      $ths{$LNames[$i]}=0.3733 ;
      $thr{$LNames[$i]}=0.0085 ;
      $alpha{$LNames[$i]}=1.532e6;
      $rn{$LNames[$i]}=1.17514;
      $rl{$LNames[$i]}=0.5;
      $rm{$LNames[$i]}=1-1/$rn{$LNames[$i]} ;

#     Data for lithology SCLAlluv
      $i=1;
      $sk{$LNames[$i]}=114.756;
      $ths{$LNames[$i]}=0.39 ;
      $thr{$LNames[$i]}=0.100;
      $alpha{$LNames[$i]}=5.9;
      $rn{$LNames[$i]}=1.48;
      $rl{$LNames[$i]}=0.5;
      $rm{$LNames[$i]}=1-1/$rn{$LNames[$i]} ;

#     Assign lithology for each material
#     Lithology=name of lithology
#     h=beginning cell
#     j=ending cell
#     thick=thickness (m)
#     rho=bulk density (g/cm3)
      @Lithology = ($LNames[0],$LNames[1]);
      @ih = (1,2);
      @ij = (1,5);
      @thick = (0.5,1.95,1.95,1.95,1.95);
```

```
      @rho = (1.65,1.82,1.82,1.82,1.82);

# Radionuclide Data
# half lives (years)
   %halflives = (
                'C-14'  =>   5730,
                'Cl-36'  =>  3.01e5,
                'H-3'   =>  12.3,
                'I-129'  => 1.57e7,
                'Mo-93'  => 3500.0,
                'Nb-94'  => 2.03e4,
                'Ni-59'  => 7.5e4,
                'Tc-99'  => 2.11E5,
                'Pu-241'  => 1.445e1,
                'Am-241'  =>  4.32e2,
                'Np-237'  => 2.14e6,
                'U-233'  =>  1.59e5,
                'Th-229'  => 7.34e3,
                'Pu-239'  => 2.41e4,
                'U-235'  =>  7.04e8,
                'Pa-231'  => 3.28e4,
                'Ac-227'  => 21.77,
                'Pu-240'  => 6537.0,
                'U-236'  => 2.342E7,
                'Th-232'  => 1.405E10,
                'Ra-228'  => 5.75,
                'Th-228'  => 1.91,
                'Pu-238'  => 87.7,
                'U-238'  =>  4.47e9,
                'U-234'  =>  2.44e5,
                'Th-230'  => 7.54e4,
                'Ra-226'  => 1600.,
                'Pb-210'  => 22.3);

   %mw        = (

                'C-14'  =>   14,
                'Cl-36'  =>  36,
                'H-3'  =>  3,
                'I-129'  => 129,
                'Mo-93'  => 93,
                'Nb-94'  => 94,
                'Ni-59'  => 59,
                'Tc-99'  =>  99,
                'Pu-241'  => 241,
                'Am-241'  => 241,
                'Np-237'  => 237,
                'U-233'  =>  233,
                'Th-229'  => 226,
                'Pu-239'  => 239,
                'U-235'  =>  235,
                'Pa-231'  => 231,
                'Ac-227'  => 227,
                'Pu-240'  => 240.0,
                'U-236'  => 236,
                'Th-232'  => 232,
                'Ra-228'  => 228,
                'Th-228'  => 228,
                'Pu-238'  =>  238,
                'U-238'  =>  238,
                'U-234'  =>  234,
                'Th-230'  => 230,
                'Ra-226'  => 226,
                'Pb-210'  => 210);

# solubility (mg/m^3)
   %sol      = (
                'C-14'  =>   1e9,
                'Cl-36'  =>  1e9,
                'H-3'  =>    1e9,
                'I-129'  =>  1e9,
```

```
                'Mo-93'  =>  1e9,
                'Nb-94'  =>  1e9,
                'Ni-59'  =>  1e9,
                'Tc-99'  =>  1e9,
                'Pu-241'  => 1e9,
                'Am-241'  =>  1e9,
                'Np-237'  => 1e9,
                'U-233'  =>  1e9,
                'Th-229'  => 1e9,
                'Pu-239'  => 1e9,
                'U-235'  =>  1e9,
                'Pa-231'  => 1e9,
                'Ac-227'  => 1e9,
                'Pu-240'  => 1e9,
                'U-236'  =>  1e9,
                'Th-232'  => 1e9,
                'Ra-228'  => 1e9,
                'Th-228'  => 1e9,
                'Pu-238'  => 1e9 ,
                'U-238'  =>  1.19e4,
                'U-234'  =>  1e9,
                'Th-230'  => 1e9,
                'Ra-226'  => 1e9,
                'Pb-210'  => 1e9);

# diffusion in water (m^2/yr)
   %dwater      = (
                'C-14'  =>   0,
                'Cl-36'  =>  0,
                'H-3'  =>    0,
                'I-129'  =>  0,
                'Mo-93'  =>  0,
                'Nb-94'  =>  0,
                'Ni-59'  =>  0,
                'Tc-99'  =>  0,
                'Pu-241'  => 0,
                'Am-241'  =>  0,
                'Np-237'  => 0,
                'U-233'  =>  0,
                'Th-229'  => 0,
                'Pu-239'  => 0,
                'U-235'  =>  0,
                'Pa-231'  => 0,
                'Ac-227'  => 0,
                'Pu-240'  => 0,
                'U-236'  =>  0,
                'Th-232'  => 0,
                'Ra-228'  => 0,
                'Th-228'  => 0,
                'Pu-238'  => 0,
                'U-238'  =>  0,
                'U-234'  =>  0,
                'Th-230'  => 0,
                'Ra-226'  => 0,
                'Pb-210'  => 0);

   %br       = (
                'C-14'  =>  0,
                'Cl-36'  => 0,
                'H-3'    => 0,
                'I-129'  => 0,
                'Mo-93'  => 0,
                'Nb-94'  => 0,
                'Ni-59'  => 0,
                'Tc-99'  => 0,
                'Pu-241'  =>1,
                'Am-241'  => 1,
                'Np-237'  =>1,
                'U-233'  => 1,
                'Th-229'  => 0,
                'Pu-239'  => 1,
```

```
                'U-235'  =>  1,
                'Pa-231'  => 1,
                'Ac-227'  => 0,
                'Pu-240'  => 1,
                'U-236'  =>  1,
                'Th-232'  => 1,
                'Ra-228'  => 1,
                'Th-228'  => 0,
                'Pu-238'  => 1,
                'U-238'  =>  1,
                'U-234'  =>  1,
                'Th-230'  => 1,
                'Ra-226'  => 1,
                'Pb-210'  => 0);

%lbc        = (
                'C-14'  =>   -1.0,
                'Cl-36'  =>  -1.0,
                'H-3'    =>  -1.0,
                'I-129'  =>  -1.0,
                'Mo-93'  =>  -1.0,
                'Nb-94'  =>  -1.0,
                'Ni-59'  =>  -1.0,
                'Tc-99'  =>  -1.0,
                'Pu-241'  => -1.0,
                'Am-241'  => -1.0,
                'Np-237'  => -1.0,
                'U-233'  =>  -1.0,
                'Th-229'  => -1.0,
                'Pu-239'  => -1.0,
                'U-235'  =>  -1.0,
                'Pa-231'  => -1.0,
                'Ac-227'  => -1.0,
                'Pu-240'  => -1.0,
                'U-236'  =>  -1.0,
                'Th-232'  => -1.0,
                'Ra-228'  => -1.0,
                'Th-228'  => -1.0,
                'Pu-238'  =>  1.0,
                'U-238'  =>  -1.0,
                'U-234'  =>  -1.0,
                'Th-230'  => -1.0,
                'Ra-226'  => -1.0,
                'Pb-210'  => -1.0);

%progeny    = (
                'C-14'  =>  'NONE',
                'Cl-36'  => 'NONE',
                'H-3'    => 'NONE',
                'I-129'  => 'NONE',
                'Mo-93'  => 'NONE',
                'Nb-94'  => 'NONE',
                'Ni-59'  => 'NONE',
                'Tc-99'  => 'NONE',
                'Pu-241'  => 'Am-241',
                'Am-241'  => 'Np-237',
                'Np-237'  =>'U-233',
                'U-233'  => 'Th-229',
                'Th-229'  => 'NONE',
                'Pu-239'  => 'U-235',
                'U-235'  =>  'Pa-231',
                'Pa-231'  => 'Ac-227',
                'Ac-227'  => 'NONE',
                'Pu-240'  => 'U-236',
                'U-236'  =>  'Th-232',
                'Th-232'  => 'Ra-228',
                'Ra-228'  => 'Th-228',
                'Th-228'  => 'NONE',
                'Pu-238'  =>  'U-234',
                'U-238'  =>  'U-234',
                'U-234'  =>  'Th-230',
```

```
                'Th-230'  => 'Ra-226',
                'Ra-226'  => 'Pb-210',
                'Pb-210'  => 'NONE');

   %element   = (
                'C-14'  =>  'C',
                'Cl-36'  => 'Cl',
                'H-3'    => 'H',
                'I-129'  => 'I',
                'Mo-93'  => 'Mo',
                'Nb-94'  => 'Nb',
                'Ni-59'  => 'Ni',
                'Tc-99'  => 'Tc',
                'Pu-241'  => 'Pu',
                'Am-241'  => 'Am',
                'Np-237'  =>'Np',
                'U-233'  => 'U',
                'Th-229'  => 'Th',
                'Pu-239'  => 'Pu',
                'U-235'  =>  'U',
                'Pa-231'  => 'Pa',
                'Ac-227'  => 'Ac',
                'Pu-240'  => 'Pu',
                'U-236'  =>  'U',
                'Th-232'  => 'Th',
                'Ra-228'  => 'Ra',
                'Th-228'  => 'Th',
                'Pu-238'  =>  'Pu',
                'U-238'  =>  'U',
                'U-234'  =>  'U',
                'Th-230'  => 'Th',
                'Ra-226'  => 'Ra',
                'Pb-210'  => 'Pb');

#     Kd data
                # HPAlluvium - sand layer cement impacted
                $kd{$LNames[0]}{C} = 0;
                $kd{$LNames[0]}{Cl} = 0;
                $kd{$LNames[0]}{H} = 0;
                $kd{$LNames[0]}{I} = 0.0;
                $kd{$LNames[0]}{Mo} = 1.4;
                $kd{$LNames[0]}{Nb} = 0.0;
                $kd{$LNames[0]}{Ni} = 2.1;
                $kd{$LNames[0]}{Tc} = 0.0;
                $kd{$LNames[0]}{Np} = 2.0;
                $kd{$LNames[0]}{U} = 0.2;
                $kd{$LNames[0]}{Th} = 12.0;
                $kd{$LNames[0]}{Pu} = 21.0;
                $kd{$LNames[0]}{Pa} = 4.5;
                $kd{$LNames[0]}{Ac} = 72.0;
                $kd{$LNames[0]}{Ra} = 2.5;
                $kd{$LNames[0]}{Pb} = 2.0;
                $kd{$LNames[0]}{Am} = 4.82;  # reduced from Alluv value by the ratio of reduction
for Pu (i.e., 21/1480 x 340 mL/g)

                # SLCAlluv cement impacted
                $kd{$LNames[1]}{C} = 2;
                $kd{$LNames[1]}{Cl} = 0;
                $kd{$LNames[1]}{H} = 0;
                $kd{$LNames[1]}{I} = 0.3;
                $kd{$LNames[1]}{Mo} = 14.0;
                $kd{$LNames[1]}{Nb} = 224.0;
                $kd{$LNames[1]}{Ni} = 30.0;
                $kd{$LNames[1]}{Tc} = 0.0;
                $kd{$LNames[1]}{Np} = 18.0;
                $kd{$LNames[1]}{U} = 10.0;
                $kd{$LNames[1]}{Th} = 150.0;
                $kd{$LNames[1]}{Pu} = 1480.0;
                $kd{$LNames[1]}{Pa} = 825.0;
                $kd{$LNames[1]}{Ac} = 360.0;
                $kd{$LNames[1]}{Ra} = 250.0;
```

```
                $kd{$LNames[1]}{Pb} = 54.0;
                $kd{$LNames[1]}{Am} = 340.0;
                # Am Kd from DOE 2006 Operable Unit 3-14 Tank Farm Soil and Groundwater Remedial
Investigation/Baseline Risk Assessment, DOE/NE-ID-11227, U.S. Department of Energy Idaho
Operations Office, April 2006.

# Nuclide Groups
# group 1 C-14    H-3   I-129   Nb-94   Ni-59   Tc-99 Am-241 Np-237 U-233, Th-229
                $i=0;
                $title[$i]="Group1 Fission Activation Products and Am-241";
                $gname[$i]="Group1";
                $nprog[$i]=10;
                $nname[$i][0]="C-14";
                $nname[$i][1]="H-3";
                $nname[$i][2]="I-129";
                $nname[$i][3]="Nb-94";
                $nname[$i][4]="Ni-59";
                $nname[$i][5]="Tc-99";
                $nname[$i][6]="Am-241";
                $nname[$i][7]="Np-237";
                $nname[$i][8]= "U-233";
                $nname[$i][9]="Th-229";

                $nalias{$gname[$i]}{$nname[$i][0]}='C-14';
                $nalias{$gname[$i]}{$nname[$i][1]}='H-3';
                $nalias{$gname[$i]}{$nname[$i][2]}='I-129';
                $nalias{$gname[$i]}{$nname[$i][3]}='Nb-94';
                $nalias{$gname[$i]}{$nname[$i][4]}='Ni-59';
                $nalias{$gname[$i]}{$nname[$i][5]}='Tc-99';
                $nalias{$gname[$i]}{$nname[$i][6]}= "aAm-241";
                $nalias{$gname[$i]}{$nname[$i][7]}= "aNp-237";
                $nalias{$gname[$i]}{$nname[$i][8]}= "aU-233";
                $nalias{$gname[$i]}{$nname[$i][9]}= "aTh-229";

                $filerel[$i] ="'../src/surface/grp1FT01.dat'";
                $fname[$i] = "mcmt1.par";
#               initialze inventory array
                for $j (0..$nprog[$i]-1)
                {
                  for $k (0..$mlayer-1)
                  {
                    $inv[$i][$j][$k]=0.0;
                  }
                }
#               now assign to individual cells inv[group][nprog][mlayer]
#            - all initial inventory is zero
#               initialize kx values to zero
                for $j (0..$nprog[$i]-1)
                {
                  for $k (0..$mlayer-1)
                  {
                    $kx[$i][$j][$k]=0.0;
                  }
                }
#             - all kx values are zero

# group 2 bPu-241    bAm-241    bNp-237    bU-233     bTh-229    cU-234    cTh-230    cRa-226
cPb-210

                $i=1;
                $title[$i]="Group2 Actinides Container Surface RHLLW PA";
                $gname[$i]="Group2";
                $nprog[$i]=9;
                $nname[$i][0]="Pu-241";
                $nname[$i][1]="Am-241";
                $nname[$i][2]="Np-237";
                $nname[$i][3]= "U-233";
                $nname[$i][4]="Th-229";
                $nname[$i][5]="U-234";
                $nname[$i][6]="Th-230";
                $nname[$i][7]="Ra-226";
```

```
                $nname[$i][8]="Pb-210";

                $nalias{$gname[$i]}{$nname[$i][0]}= "bPu-241";
                $nalias{$gname[$i]}{$nname[$i][1]}= "bAm-241";
                $nalias{$gname[$i]}{$nname[$i][2]}= "bNp-237";
                $nalias{$gname[$i]}{$nname[$i][3]}= "bU-233";
                $nalias{$gname[$i]}{$nname[$i][4]}= "bTh-229";
                $nalias{$gname[$i]}{$nname[$i][5]}='cU-234';
                $nalias{$gname[$i]}{$nname[$i][6]}='cTh-230';
                $nalias{$gname[$i]}{$nname[$i][7]}='cRa-226';
                $nalias{$gname[$i]}{$nname[$i][8]}='cPb-210';

                $filerel[$i] ="'../src/surface/grp2FT01.dat'";
                $fname[$i] = "mcmt2.par";
#               initialze inventory array
                for $j (0..$nprog[$i]-1)
                {
                  for $k (0..$mlayer-1)
                  {
                    $inv[$i][$j][$k]=0.0;
                  }
                }
#               now assign to individual cells inv[group][nprog][mlayer]
#               initialize kx values to zero
                for $j (0..$nprog[$i]-1)
                {
                  for $k (0..$mlayer-1)
                  {
                    $kx[$i][$j][$k]=0.0;
                  }
                }
#             - all kx values are zero

# group 3 dPu-240    dU-236     dTh-232    dRa-228    dTh-228    eU-235     ePa-231    eAc-227

                $i=2;
                $title[$i]="Group3 Actinides Container Surface RHLLW PA";
                $gname[$i]="Group3";
                $nprog[$i]=8;
                $nname[$i][0]="Pu-240";
                $nname[$i][1]="U-236";
                $nname[$i][2]="Th-232";
                $nname[$i][3]="Ra-228";
                $nname[$i][4]="Th-228";
                $nname[$i][5]="U-235";
                $nname[$i][6]="Pa-231";
                $nname[$i][7]="Ac-227";
                $nalias{$gname[$i]}{$nname[$i][0]}='dPu-240';
                $nalias{$gname[$i]}{$nname[$i][1]}='dU-236';
                $nalias{$gname[$i]}{$nname[$i][2]}='dTh-232';
                $nalias{$gname[$i]}{$nname[$i][3]}='dRa-228';
                $nalias{$gname[$i]}{$nname[$i][4]}='dTh-228';
                $nalias{$gname[$i]}{$nname[$i][5]}='eU-235';
                $nalias{$gname[$i]}{$nname[$i][6]}='ePa-231';
                $nalias{$gname[$i]}{$nname[$i][7]}='eAc-227';
                $filerel[$i] ="'../src/grp3FT01.dat'";
                $fname[$i] = "mcmt3.par";
#               initialze inventory array
                for $j (0..$nprog[$i]-1)
                {
                  for $k (0..$mlayer-1)
                  {
                    $inv[$i][$j][$k]=0.0;
                  }
                }
#               now assign to individual cells inv[group][nprog][mlayer]
#               initialize kx values to zero
                for $j (0..$nprog[$i]-1)
                {
                  for $k (0..$mlayer-1)
                  {
```

```
                  $kx[$i][$j][$k]=0.0;
                }
              }
#             - all kx values are zero

# group 4 fPu238     fU-234     fTh-230    fRa-226    fPb-210     gPu-239    gU-235     gPa-231
gAc-227

              $i=3;
              $title[$i]="Group4 Actinides Surface Container RHLLW PA";
              $gname[$i]="Group4";
              $nprog[$i]=9;
              $nname[$i][0]="Pu-238";
              $nname[$i][1]="U-234";
              $nname[$i][2]="Th-230";
              $nname[$i][3]="Ra-226";
              $nname[$i][4]="Pb-210";
              $nname[$i][5]="Pu-239";
              $nname[$i][6]="U-235";
              $nname[$i][7]="Pa-231";
              $nname[$i][8]="Ac-227";

              $nalias{$gname[$i]}{$nname[$i][0]}='fPu-238';
              $nalias{$gname[$i]}{$nname[$i][1]}='fU-234';
              $nalias{$gname[$i]}{$nname[$i][2]}='fTh-230';
              $nalias{$gname[$i]}{$nname[$i][3]}='fRa-226';
              $nalias{$gname[$i]}{$nname[$i][4]}='fPb-210';
              $nalias{$gname[$i]}{$nname[$i][5]}='gPu-239';
              $nalias{$gname[$i]}{$nname[$i][6]}='gU-235';
              $nalias{$gname[$i]}{$nname[$i][7]}='gPa-231';
              $nalias{$gname[$i]}{$nname[$i][8]}='gAc-227';

              $filerel[$i] ="'../src/grp4FT01.dat'";
              $fname[$i] = "mcmt4.par";
#             initialze inventory array
              for $j (0..$nprog[$i]-1)
              {
                for $k (0..$mlayer-1)
                {
                  $inv[$i][$j][$k]=0.0;
                }
              }
#             now assign to individual cells inv[group][nprog][mlayer]
#             initialize kx values to zero
              for $j (0..$nprog[$i]-1)
              {
                for $k (0..$mlayer-1)
                {
                  $kx[$i][$j][$k]=0.0;
                }
              }
#             - all kx values are zero

# ====================================================================================
#                     End of User Input
# ====================================================================================



# Loop to write each MCMT file

      for $i (0..$ngroups-1)
      {
        open(PARFILE,">$fname[$i]");
        print PARFILE "$title[$i]\n";
        print PARFILE "$fileppt\n";
        print PARFILE "$filerel[$i]\n";
        print PARFILE "$eps $h1 $hmin                      eps h1 hmin [accuracy, initial time
step, minimum time step]\n";
        print PARFILE "$mlayer $nprog[$i] $nmat $iunits $abin           mlayer nprog nmat iunits
abin [number of layers,number of contaminants, number of materials, units, (A)scii or (B)inary]
```

```
\n";
        print PARFILE "\$[abin: (A)scii or (B)inary] \n";
        print PARFILE "\$ [iunits: (1) Ci (2) Bq  (3) mg]\n";
# nuclide names
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%-11s",$nalias{$gname[$i]}{$nname[$i][$j]};
        }
        print PARFILE "         cname [contaminant names (6 characters)]\n";
#  molecular weight
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%-11d",$mw{$nname[$i][$j]};
        }
        print PARFILE "    molecular weight (g/mol) \n";
#  solubility
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%10.3e ",$sol{$nname[$i][$j]};
        }
        print PARFILE "   solubility (mg/m3)\n";
#  half life
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%10.3e ",$halflives{$nname[$i][$j]};
        }
        print PARFILE "   half life (years) \n";
#  branching ratio
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%10.3e ",$br{$nname[$i][$j]};
        }
        print PARFILE "    branching ratio \n";
#  water diffusion coefficient
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%10.3e ",$dwater{$nname[$i][$j]};
        }
        print PARFILE "    diffusion coefficient in water (m2/yr) \n";
#  lbc
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%10.3e ",$lbc{$nname[$i][$j]};
        }
        print PARFILE "    lower boundary condition \n";
        print PARFILE "\n";


# initial inventories
        print PARFILE "\$ Initial Inventories (Ci) \n";
        $temp=wheader();
        for $j (0..$nprog[$i]-1)
        {
          print PARFILE "\$ $nname[$i][$j] \n";
          $count=1;
          for $k (0..$mlayer-1)
          {
            printf PARFILE "%10.3e ", $inv[$i][$j][$k];
            $count=$count+1;
            if($count>20)
            {
              $count=1;
              print PARFILE "\n";
            }

          }
          print PARFILE "\n";
          print PARFILE "\n";
        }
        print PARFILE "\n";
# Kd values
```

```
        print PARFILE "\$ Kd Values (ml/g)\n";
        $temp=wheader();
#       Fill in temporary array
        for $j (0..$nprog[$i]-1)
        {
          $count=0;
          for $ii (0..$nmat-1)
          {
            print "$ii  $Lithology[$ii] $nname[$i][$j] $element{$nname[$i][$j]}\n";
            for $jj ($ih[$ii]..$ij[$ii])
            {
              $kdtemp[$count]=$kd{$Lithology[$ii]}{$element{$nname[$i][$j]}};
              $count=$count+1;
            }
          }
          $count=1;
          print PARFILE "\$  $nname[$i][$j] \n";
          for $k (0..$mlayer-1)
          {
            printf PARFILE "%10.3e ", $kdtemp[$k];
            $count=$count+1;
            if($count>20)
            {
              $count=1;
              print PARFILE "\n";
            }

          }
          print PARFILE "\n";
          print PARFILE "\n";

        }

# kx rate constants
        print PARFILE "\$ kx rate constants (1/yr) \n";
        $temp=wheader();
        for $j (0..$nprog[$i]-1)
        {
          print PARFILE "\$ $nname[$i][$j] \n";
          $count=1;
          for $k (0..$mlayer-1)
          {
            printf PARFILE "%10.3e ", $kx[$i][$j][$k];
            $count=$count+1;
            if($count>20)
            {
              $count=1;
              print PARFILE "\n";
            }

          }
          print PARFILE "\n";
          print PARFILE "\n";
        }

# Length, width, and alphaL
        printf PARFILE "%10.3e  %10.3e  %10.3e      [length (m)  width (m)  alphaL (m)
\n",$len,$width,$alphaL;

# Material properties
        print PARFILE "\n";
        print PARFILE "\$ [Material properties are input by defining the range of cells where
they apply]\n";
        print PARFILE "\n";

        for $j (0..$nmat-1)
        {
          print PARFILE "\$ Material $j  $Lithology[$j] \n";
          print PARFILE "$ih[$j]  $ij[$j]    h,j [beginning cell, ending cell] \n";
```

```
          printf PARFILE "%10.3e  %10.3e     thick(h) rho(h) [thickness (m) bulk density
(g/cm^3)]\n",$thick[$j],$rho[$j];
          printf PARFILE "%10.3e  %10.3e  %10.3e  %10.3e  %10.3e  %10.3e  %10.3e
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]\n",

$sk{$Lithology[$j]},$ths{$Lithology[$j]},$thr{$Lithology[$j]},$alpha{$Lithology[$j]},$rn{$Litholo
gy[$j]},$rm{$Lithology[$j]},$rl{$Lithology[$j]};
        }
        print PARFILE "\n";
# Output times

        print PARFILE "\n";
        print PARFILE "\$ Output Times \n";
        print PARFILE "\n";
        print PARFILE "$ntimes                 ntimes [number of output time periods]\n";
        for $j (0..$ntimes-1)
        {
          printf PARFILE "%10.3e  %10.3e  %10.3e          t1(i),t2(i),tp(i) [beginning time of
output ending time of output, print step]\n",
          $t1[$j],$t2[$j],$tp[$j];

        }

        print PARFILE "\$ [End of Parameter Definition File]\n";
        close PARFILE;

      }

      sub wheader
      {
# Writes header
        print PARFILE "\$";
        for $j (1..20)
        {
          print PARFILE "-----------";
        }
        print PARFILE "\n";
        print PARFILE "\$";
        for $j (1..9)
        {
          print PARFILE "   $j       ";
        }
        for $j (10..20)
        {
          print PARFILE "   $j      ";
        }
        print PARFILE "\n";
        print PARFILE "\$";
        for $j (1..20)
        {
          print PARFILE "-----------";
        }
        print PARFILE "\n";



      }
```

Perl Script for Creating MCMT Vadose Zone Files

```
# mkmcmt.pl
# This script is a general script for writing multiple mcmt files for the same
# lithology and a given set of radionuclides. All input is provided upfront

# Written for the BEA by: Arthur S. Rood
# August 2, 2011

# usage perl mkmcmt.pl
```

```
# ================================================================================
#                       User Input
# ================================================================================
# Number of radionuclide groups
      $ngroups=4;
# Radionuclide independent parameters and control parameters
      $fileppt="'../../mcmf/vz/vz.flx'";
      $eps=1.0e-4;
      $h1=0.0001;
      $hmin=1.0e-90;
      $mlayer=50;
      $nmat=11;
      $iunits=1;
      $abin="B";
      $len=10;
      $width=25.;
      $alphaL=0;

#     Output Times
      $ntimes=8;
      @t1 = (0.0,502,2005,3010,5025,10100,30500,101000);
      @t2 = (500,2000,3000,5000,10000,30000,100000,210000);
      @tp = (1,2,5,10,25,100,500,2000);

# Lithology Definitions
      $Nlithology=2;
      @LNames=("Basalt","Interbed");
#     Note: Default values for rl and rm; rl=0.5 rm=1-1/rl

#     Data for lithology Basalt
      $i=0;
      $sk{$LNames[$i]}=91.0 ;
      $ths{$LNames[$i]}=0.05 ;
      $thr{$LNames[$i]}=0.001 ;
      $alpha{$LNames[$i]}=2.5 ;
      $rn{$LNames[$i]}=10.0;
      $rl{$LNames[$i]}=0.5;
      $rm{$LNames[$i]}=1-1/$rn{$LNames[$i]} ;

#     Data for lithology Interbed
      $i=1;
      $sk{$LNames[$i]}=1.053  ;
      $ths{$LNames[$i]}=0.459  ;
      $thr{$LNames[$i]}=0.163  ;
      $alpha{$LNames[$i]}=0.062  ;
      $rn{$LNames[$i]}=1.48  ;
      $rm{$LNames[$i]}=0.69  ;
      $rl{$LNames[$i]}=9.33  ;

#     Assign lithology for each material
#     Lithology=name of lithology
#     h=beginning cell
#     j=ending cell
#     thick=thickness (m)
#     rho=bulk density (g/cm3)
      @Lithology =
($LNames[0],$LNames[1],$LNames[0],$LNames[1],$LNames[0],$LNames[1],$LNames[0],$LNames[1],$LNames[
0],$LNames[1],$LNames[0]);
      @ih = (1,6, 7,12,14,17,20,25,27,29,31);
      @ij = (5,6,11,13,16,19,24,26,28,30,50);
      @thick = (2.94, 2.0, 2.82, 2.0, 2.43, 2.67, 2.48, 2.0, 2.5, 2.0, 2.96);
      @rho =   (2.0,  1.5, 2.0,  1.5, 2.0,  1.5,  2.0,  1.5, 2.0, 1.5, 2.0);

# Radionuclide Data
# half lives (years)
   %halflives = (               'C-14'  =>   5730,
                  'Cl-36'  =>  3.01e5,
                  'H-3'    =>  12.3,
                  'I-129'  => 1.57e7,
                  'Mo-93'  => 3500.0,
                  'Nb-94'  => 2.03e4,
```

```
                 'Ni-59'  => 7.5e4,
                 'Tc-99'  => 2.11E5,
                 'Pu-241'  => 1.445e1,
                 'Am-241'  =>  4.32e2,
                 'Np-237'  => 2.14e6,
                 'U-233'  =>  1.59e5,
                 'Th-229'  => 7.34e3,
                 'Pu-239'  => 2.41e4,
                 'U-235'  =>  7.04e8,
                 'Pa-231'  => 3.28e4,
                 'Ac-227'  => 21.77,
                 'Pu-240'  => 6537.0,
                 'U-236'  => 2.342E7,
                 'Th-232'  => 1.405E10,
                 'Ra-228'  => 5.75,
                 'Th-228'  => 1.91,
                 'Pu-238'  => 87.7,
                 'U-238'  =>  4.47e9,
                 'U-234'  =>  2.44e5,
                 'Th-230'  => 7.54e4,
                 'Ra-226'  => 1600.,
                 'Pb-210'  => 22.3);

   %mw         = (

                 'C-14'  =>   14,
                 'Cl-36'  =>  36,
                 'H-3'  =>  3,
                 'I-129'  => 129,
                 'Mo-93'  => 93,
                 'Nb-94'  => 94,
                 'Ni-59'  => 59,
                 'Tc-99'  =>  99,
                 'Pu-241'  => 241,
                 'Am-241'  => 241,
                 'Np-237'  => 237,
                 'U-233'  =>  233,
                 'Th-229'  => 226,
                 'Pu-239'  => 239,
                 'U-235'  =>  235,
                 'Pa-231'  => 231,
                 'Ac-227'  => 227,
                 'Pu-240'  => 240.0,
                 'U-236'  => 236,
                 'Th-232'  => 232,
                 'Ra-228'  => 228,
                 'Th-228'  => 228,
                 'Pu-238'  =>  238,
                 'U-238'  =>  238,
                 'U-234'  =>  234,
                 'Th-230'  => 230,
                 'Ra-226'  => 226,
                 'Pb-210'  => 210);

# solubility (mg/m^3)
   %sol      = (
                 'C-14'  =>   1e9,
                 'Cl-36'  =>  1e9,
                 'H-3'  =>    1e9,
                 'I-129'  =>  1e9,
                 'Mo-93'  =>  1e9,
                 'Nb-94'  =>  1e9,
                 'Ni-59'  =>  1e9,
                 'Tc-99'  =>  1e9,
                 'Pu-241'  => 1e9,
                 'Am-241'  =>  1e9,
                 'Np-237'  => 1e9,
                 'U-233'  =>  1e9,
                 'Th-229'  => 1e9,
                 'Pu-239'  => 1e9,
                 'U-235'  =>  1e9,
```

```
                 'Pa-231'  => 1e9,
                 'Ac-227'  => 1e9,
                 'Pu-240'  => 1e9,
                 'U-236'  =>  1e9,
                 'Th-232'  => 1e9,
                 'Ra-228'  => 1e9,
                 'Th-228'  => 1e9,
                 'Pu-238'  => 1e9 ,
                 'U-238'  =>  1.19e4,
                 'U-234'  =>  1e9,
                 'Th-230'  => 1e9,
                 'Ra-226'  => 1e9,
                 'Pb-210'  => 1e9);

# diffusion in water (m^2/yr)
   %dwater      = (
                 'C-14'  =>   0,
                 'Cl-36'  =>  0,
                 'H-3'  =>    0,
                 'I-129'  =>  0,
                 'Mo-93'  =>  0,
                 'Nb-94'  =>  0,
                 'Ni-59'  =>  0,
                 'Tc-99'  =>  0,
                 'Pu-241'  => 0,
                 'Am-241'  =>  0,
                 'Np-237'  => 0,
                 'U-233'  =>  0,
                 'Th-229'  => 0,
                 'Pu-239'  => 0,
                 'U-235'  =>  0,
                 'Pa-231'  => 0,
                 'Ac-227'  => 0,
                 'Pu-240'  => 0,
                 'U-236'  =>  0,
                 'Th-232'  => 0,
                 'Ra-228'  => 0,
                 'Th-228'  => 0,
                 'Pu-238'  => 0,
                 'U-238'  =>  0,
                 'U-234'  =>  0,
                 'Th-230'  => 0,
                 'Ra-226'  => 0,
                 'Pb-210'  => 0);

   %br        = (
                 'C-14'  =>  0,
                 'Cl-36'  => 0,
                 'H-3'    => 0,
                 'I-129'  => 0,
                 'Mo-93'  => 0,
                 'Nb-94'  => 0,
                 'Ni-59'  => 0,
                 'Tc-99'  => 0,
                 'Pu-241'  =>1,
                 'Am-241'  => 1,
                 'Np-237'  =>1,
                 'U-233'  => 1,
                 'Th-229'  => 0,
                 'Pu-239'  => 1,
                 'U-235'  =>  1,
                 'Pa-231'  => 1,
                 'Ac-227'  => 0,
                 'Pu-240'  => 1,
                 'U-236'  =>  1,
                 'Th-232'  => 1,
                 'Ra-228'  => 1,
                 'Th-228'  => 0,
                 'Pu-238'  => 1,
                 'U-238'  =>  1,
                 'U-234'  =>  1,
```

```
             'Th-230'  => 1,
             'Ra-226'  => 1,
             'Pb-210'  => 0);

%lbc       = (
             'C-14'  =>   -1.0,
             'Cl-36'  =>  -1.0,
             'H-3'    =>  -1.0,
             'I-129'  =>  -1.0,
             'Mo-93'  =>  -1.0,
             'Nb-94'  =>  -1.0,
             'Ni-59'  =>  -1.0,
             'Tc-99'  =>  -1.0,
             'Pu-241'  => -1.0,
             'Am-241'  => -1.0,
             'Np-237'  => -1.0,
             'U-233'  =>  -1.0,
             'Th-229'  => -1.0,
             'Pu-239'  => -1.0,
             'U-235'  =>  -1.0,
             'Pa-231'  => -1.0,
             'Ac-227'  => -1.0,
             'Pu-240'  => -1.0,
             'U-236'  =>  -1.0,
             'Th-232'  => -1.0,
             'Ra-228'  => -1.0,
             'Th-228'  => -1.0,
             'Pu-238'  =>  1.0,
             'U-238'  =>  -1.0,
             'U-234'  =>  -1.0,
             'Th-230'  => -1.0,
             'Ra-226'  => -1.0,
             'Pb-210'  => -1.0);

%progeny   = (
             'C-14'  =>  'NONE',
             'Cl-36'  => 'NONE',
             'H-3'    => 'NONE',
             'I-129'  => 'NONE',
             'Mo-93'  => 'NONE',
             'Nb-94'  => 'NONE',
             'Ni-59'  => 'NONE',
             'Tc-99'  => 'NONE',
             'Pu-241'  => 'Am-241',
             'Am-241'  => 'Np-237',
             'Np-237'  =>'U-233',
             'U-233'  => 'Th-229',
             'Th-229'  => 'NONE',
             'Pu-239'  => 'U-235',
             'U-235'  =>  'Pa-231',
             'Pa-231'  => 'Ac-227',
             'Ac-227'  => 'NONE',
             'Pu-240'  => 'U-236',
             'U-236'  =>  'Th-232',
             'Th-232'  => 'Ra-228',
             'Ra-228'  => 'Th-228',
             'Th-228'  => 'NONE',
             'Pu-238'  =>  'U-234',
             'U-238'  =>  'U-234',
             'U-234'  =>  'Th-230',
             'Th-230'  => 'Ra-226',
             'Ra-226'  => 'Pb-210',
             'Pb-210'  => 'NONE');

%element   = (
             'C-14'  =>  'C',
             'Cl-36'  => 'Cl',
             'H-3'    => 'H',
             'I-129'  => 'I',
             'Mo-93'  => 'Mo',
             'Nb-94'  => 'Nb',
```

```
                  'Ni-59'  => 'Ni',
                  'Tc-99'  => 'Tc',
                  'Pu-241'  => 'Pu',
                  'Am-241'  => 'Am',
                  'Np-237'  =>'Np',
                  'U-233'  => 'U',
                  'Th-229'  => 'Th',
                  'Pu-239'  => 'Pu',
                  'U-235'  =>  'U',
                  'Pa-231'  => 'Pa',
                  'Ac-227'  => 'Ac',
                  'Pu-240'  => 'Pu',
                  'U-236'  =>  'U',
                  'Th-232'  => 'Th',
                  'Ra-228'  => 'Ra',
                  'Th-228'  => 'Th',
                  'Pu-238'  =>  'Pu',
                  'U-238'  =>  'U',
                  'U-234'  =>  'U',
                  'Th-230'  => 'Th',
                  'Ra-226'  => 'Ra',
                  'Pb-210'  => 'Pb');

#     Kd data
                # Basalt
                $kd{$LNames[0]}{C} = 0;
                $kd{$LNames[0]}{Cl} = 0;
                $kd{$LNames[0]}{H} = 0;
                $kd{$LNames[0]}{I} = 0;
                $kd{$LNames[0]}{Mo} = 0;
                $kd{$LNames[0]}{Nb} = 0;
                $kd{$LNames[0]}{Ni} = 0;
                $kd{$LNames[0]}{Tc} = 0;
                $kd{$LNames[0]}{Np} = 0;
                $kd{$LNames[0]}{U} = 0;
                $kd{$LNames[0]}{Th} = 0;
                $kd{$LNames[0]}{Pu} = 0;
                $kd{$LNames[0]}{Pa} = 0;
                $kd{$LNames[0]}{Ac} = 0;
                $kd{$LNames[0]}{Ra} = 0;
                $kd{$LNames[0]}{Pb} = 0;
                $kd{$LNames[0]}{Am} = 0;

                # Interbed
                $kd{$LNames[1]}{C} = 0.5;
                $kd{$LNames[1]}{Cl} = 0;
                $kd{$LNames[1]}{H} = 0;
                $kd{$LNames[1]}{I} = 3.0;
                $kd{$LNames[1]}{Mo} = 10.0;
                $kd{$LNames[1]}{Nb} = 160.0;
                $kd{$LNames[1]}{Ni} = 100.0;
                $kd{$LNames[1]}{Tc} = 0.1;
                $kd{$LNames[1]}{Np} = 18.0;
                $kd{$LNames[1]}{U} = 10.0;
                $kd{$LNames[1]}{Th} = 500.0;
                $kd{$LNames[1]}{Pu} = 1140.0;
                $kd{$LNames[1]}{Pa} = 550.0;
                $kd{$LNames[1]}{Ac} = 300.0;
                $kd{$LNames[1]}{Ra} = 500.0;
                $kd{$LNames[1]}{Pb} = 270.0;
                $kd{$LNames[1]}{Am} = 340.0;
                # Am Kd from DOE 2006 Operable Unit 3-14 Tank Farm Soil and Groundwater Remedial
Investigation/Baseline Risk Assessment,
                # DOE/NE-ID-11227, U.S. Department of Energy Idaho Operations Office, April 2006.

# Nuclide Groups
# group 1 C-14    H-3   I-129   Nb-94   Ni-59   Tc-99 Am-241 Np-237 U-233, Th-229
                $i=0;
                $title[$i]="Group1 Fission Activation Products and Am-241";
                $gname[$i]="Group1";
                $nprog[$i]=10;
```

```
                $nname[$i][0]="C-14";
                $nname[$i][1]="H-3";
                $nname[$i][2]="I-129";
                $nname[$i][3]="Nb-94";
                $nname[$i][4]="Ni-59";
                $nname[$i][5]="Tc-99";
                $nname[$i][6]="Am-241";
                $nname[$i][7]="Np-237";
                $nname[$i][8]= "U-233";
                $nname[$i][9]="Th-229";

                $nalias{$gname[$i]}{$nname[$i][0]}='C-14';
                $nalias{$gname[$i]}{$nname[$i][1]}='H-3';
                $nalias{$gname[$i]}{$nname[$i][2]}='I-129';
                $nalias{$gname[$i]}{$nname[$i][3]}='Nb-94';
                $nalias{$gname[$i]}{$nname[$i][4]}='Ni-59';
                $nalias{$gname[$i]}{$nname[$i][5]}='Tc-99';
                $nalias{$gname[$i]}{$nname[$i][6]}= "aAm-241";
                $nalias{$gname[$i]}{$nname[$i][7]}= "aNp-237";
                $nalias{$gname[$i]}{$nname[$i][8]}= "aU-233";
                $nalias{$gname[$i]}{$nname[$i][9]}= "aTh-229";

                $filerel[$i] ="'../alluv/grp1FT01.dat'";
                $fname[$i] = "mcmt1.par";
#               initialze inventory array

                for $j (0..$nprog[$i]-1)
                {
        $inv[$i][$j][0]=1.0e-20;
                  for $k (1..$mlayer-1)
                  {
                    $inv[$i][$j][$k]=0.0;
                  }
                }

#               now assign to individual cells inv[group][nprog][mlayer]
#            - all initial inventory is zero
#               initialize kx values to zero
                for $j (0..$nprog[$i]-1)
                {
                  for $k (0..$mlayer-1)
                  {
                    $kx[$i][$j][$k]=0.0;
                  }
                }
#             - all kx values are zero

# group 2 bPu-241    bAm-241    bNp-237    bU-233     bTh-229    cU-234    cTh-230    cRa-226
cPb-210

                $i=1;
                $title[$i]="Group2 Actinides Container Surface RHLLW PA";
                $gname[$i]="Group2";
                $nprog[$i]=9;
                $nname[$i][0]="Pu-241";
                $nname[$i][1]="Am-241";
                $nname[$i][2]="Np-237";
                $nname[$i][3]= "U-233";
                $nname[$i][4]="Th-229";
                $nname[$i][5]="U-234";
                $nname[$i][6]="Th-230";
                $nname[$i][7]="Ra-226";
                $nname[$i][8]="Pb-210";

                $nalias{$gname[$i]}{$nname[$i][0]}= "bPu-241";
                $nalias{$gname[$i]}{$nname[$i][1]}= "bAm-241";
                $nalias{$gname[$i]}{$nname[$i][2]}= "bNp-237";
                $nalias{$gname[$i]}{$nname[$i][3]}= "bU-233";
                $nalias{$gname[$i]}{$nname[$i][4]}= "bTh-229";
                $nalias{$gname[$i]}{$nname[$i][5]}='cU-234';
                $nalias{$gname[$i]}{$nname[$i][6]}='cTh-230';
```

```
                $nalias{$gname[$i]}{$nname[$i][7]}='cRa-226';
                $nalias{$gname[$i]}{$nname[$i][8]}='cPb-210';

                $filerel[$i] ="'../alluv/grp2FT01.dat'";
                $fname[$i] = "mcmt2.par";

#               initialze inventory array
                for $j (0..$nprog[$i]-1)
                {
        $inv[$i][$j][0]=1.0e-20;
                  for $k (1..$mlayer-1)
                  {
                    $inv[$i][$j][$k]=0.0;
                  }
                }
#               now assign to individual cells inv[group][nprog][mlayer]
#               initialize kx values to zero
                for $j (0..$nprog[$i]-1)
                {
                  for $k (0..$mlayer-1)
                  {
                    $kx[$i][$j][$k]=0.0;
                  }
                }
#             - all kx values are zero

# group 3 dPu-240    dU-236     dTh-232    dRa-228    dTh-228    eU-235     ePa-231    eAc-227

                $i=2;
                $title[$i]="Group3 Actinides Container Surface RHLLW PA";
                $gname[$i]="Group3";
                $nprog[$i]=8;
                $nname[$i][0]="Pu-240";
                $nname[$i][1]="U-236";
                $nname[$i][2]="Th-232";
                $nname[$i][3]="Ra-228";
                $nname[$i][4]="Th-228";
                $nname[$i][5]="U-235";
                $nname[$i][6]="Pa-231";
                $nname[$i][7]="Ac-227";
                $nalias{$gname[$i]}{$nname[$i][0]}='dPu-240';
                $nalias{$gname[$i]}{$nname[$i][1]}='dU-236';
                $nalias{$gname[$i]}{$nname[$i][2]}='dTh-232';
                $nalias{$gname[$i]}{$nname[$i][3]}='dRa-228';
                $nalias{$gname[$i]}{$nname[$i][4]}='dTh-228';
                $nalias{$gname[$i]}{$nname[$i][5]}='eU-235';
                $nalias{$gname[$i]}{$nname[$i][6]}='ePa-231';
                $nalias{$gname[$i]}{$nname[$i][7]}='eAc-227';
                $filerel[$i] ="'../alluv/grp3FT01.dat'";
                $fname[$i] = "mcmt3.par";
#               initialze inventory array
                for $j (0..$nprog[$i]-1)
                {
        $inv[$i][$j][0]=1.0e-20;
                  for $k (1..$mlayer-1)
                  {
                    $inv[$i][$j][$k]=0.0;
                  }
                }

#               now assign to individual cells inv[group][nprog][mlayer]
#               initialize kx values to zero
                for $j (0..$nprog[$i]-1)
                {
                  for $k (0..$mlayer-1)
                  {
                    $kx[$i][$j][$k]=0.0;
                  }
                }
#             - all kx values are zero
```

```
# group 4 fPu238     fU-234     fTh-230    fRa-226    fPb-210     gPu-239    gU-235     gPa-231
gAc-227

                $i=3;
                $title[$i]="Group4 Actinides Surface Container RHLLW PA";
                $gname[$i]="Group4";
                $nprog[$i]=9;
                $nname[$i][0]="Pu-238";
                $nname[$i][1]="U-234";
                $nname[$i][2]="Th-230";
                $nname[$i][3]="Ra-226";
                $nname[$i][4]="Pb-210";
                $nname[$i][5]="Pu-239";
                $nname[$i][6]="U-235";
                $nname[$i][7]="Pa-231";
                $nname[$i][8]="Ac-227";

                $nalias{$gname[$i]}{$nname[$i][0]}='fPu-238';
                $nalias{$gname[$i]}{$nname[$i][1]}='fU-234';
                $nalias{$gname[$i]}{$nname[$i][2]}='fTh-230';
                $nalias{$gname[$i]}{$nname[$i][3]}='fRa-226';
                $nalias{$gname[$i]}{$nname[$i][4]}='fPb-210';
                $nalias{$gname[$i]}{$nname[$i][5]}='gPu-239';
                $nalias{$gname[$i]}{$nname[$i][6]}='gU-235';
                $nalias{$gname[$i]}{$nname[$i][7]}='gPa-231';
                $nalias{$gname[$i]}{$nname[$i][8]}='gAc-227';

                $filerel[$i] ="'../alluv/grp4FT01.dat'";
                $fname[$i] = "mcmt4.par";
#               initialze inventory array
                for $j (0..$nprog[$i]-1)
                {
        $inv[$i][$j][0]=1.0e-20;
                  for $k (1..$mlayer-1)
                  {
                    $inv[$i][$j][$k]=0.0;
                  }
                }
#               now assign to individual cells inv[group][nprog][mlayer]
#               initialize kx values to zero
                for $j (0..$nprog[$i]-1)
                {
                  for $k (0..$mlayer-1)
                  {
                    $kx[$i][$j][$k]=0.0;
                  }
                }
#             - all kx values are zero

# ==================================================================================
#                       End of User Input
# ==================================================================================

# Loop to write each MCMT file

      for $i (0..$ngroups-1)
      {
        open(PARFILE,">$fname[$i]");
        print PARFILE "$title[$i]\n";
        print PARFILE "$fileppt\n";
        print PARFILE "$filerel[$i]\n";
        print PARFILE "$eps $h1 $hmin                      eps h1 hmin [accuracy, initial time
step, minimum time step]\n";
        print PARFILE "$mlayer $nprog[$i] $nmat $iunits $abin           mlayer nprog nmat iunits
abin [number of layers,number of contaminants, number of materials, units, (A)scii or (B)inary]
\n";
        print PARFILE "\$[abin: (A)scii or (B)inary] \n";
        print PARFILE "\$ [iunits: (1) Ci (2) Bq  (3) mg]\n";
# nuclide names
        for $j (0..$nprog[$i]-1)
        {
```

```
          printf PARFILE "%-11s",$nalias{$gname[$i]}{$nname[$i][$j]};
        }
        print PARFILE "         cname [contaminant names (6 characters)]\n";
#  molecular weight
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%-11d",$mw{$nname[$i][$j]};
        }
        print PARFILE "    molecular weight (g/mol) \n";
#  solubility
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%10.3e ",$sol{$nname[$i][$j]};
        }
        print PARFILE "   solubility (mg/m3)\n";
#  half life
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%10.3e ",$halflives{$nname[$i][$j]};
        }
        print PARFILE "   half life (years) \n";
#  branching ratio
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%10.3e ",$br{$nname[$i][$j]};
        }
        print PARFILE "    branching ratio \n";
#  water diffusion coefficient
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%10.3e ",$dwater{$nname[$i][$j]};
        }
        print PARFILE "    diffusion coefficient in water (m2/yr) \n";
#  lbc
        for $j (0..$nprog[$i]-1)
        {
          printf PARFILE "%10.3e ",$lbc{$nname[$i][$j]};
        }
        print PARFILE "    lower boundary condition \n";
        print PARFILE "\n";

# initial inventories
        print PARFILE "\$ Initial Inventories (Ci) \n";
        $temp=wheader();
        for $j (0..$nprog[$i]-1)
        {
          print PARFILE "\$ $nname[$i][$j] \n";
          $count=1;
          for $k (0..$mlayer-1)
          {
            printf PARFILE "%10.3e ", $inv[$i][$j][$k];
            $count=$count+1;
            if($count>20)
            {
              $count=1;
              print PARFILE "\n";
            }

          }
          print PARFILE "\n";
          print PARFILE "\n";
        }
        print PARFILE "\n";
# Kd values


        print PARFILE "\$ Kd Values (ml/g)\n";
        $temp=wheader();
#       Fill in temporary array
        for $j (0..$nprog[$i]-1)
        {
```

```
          $count=0;
          for $ii (0..$nmat-1)
          {
            print "$ii  $Lithology[$ii] $nname[$i][$j] $element{$nname[$i][$j]}\n";
            for $jj ($ih[$ii]..$ij[$ii])
            {
              $kdtemp[$count]=$kd{$Lithology[$ii]}{$element{$nname[$i][$j]}};
              $count=$count+1;
            }
          }
          $count=1;
          print PARFILE "\$  $nname[$i][$j] \n";
          for $k (0..$mlayer-1)
          {
            printf PARFILE "%10.3e ", $kdtemp[$k];
            $count=$count+1;
            if($count>20)
            {
              $count=1;
              print PARFILE "\n";
            }

          }
          print PARFILE "\n";
          print PARFILE "\n";

        }

# kx rate constants
        print PARFILE "\$ kx rate constants (1/yr) \n";
        $temp=wheader();
        for $j (0..$nprog[$i]-1)
        {
          print PARFILE "\$ $nname[$i][$j] \n";
          $count=1;
          for $k (0..$mlayer-1)
          {
            printf PARFILE "%10.3e ", $kx[$i][$j][$k];
            $count=$count+1;
            if($count>20)
            {
              $count=1;
              print PARFILE "\n";
            }

          }
          print PARFILE "\n";
          print PARFILE "\n";
        }

# Length, width, and alphaL
        printf PARFILE "%10.3e  %10.3e  %10.3e      [length (m)  width (m)  alphaL (m)
\n",$len,$width,$alphaL;

# Material properties
        print PARFILE "\n";
        print PARFILE "\$ [Material properties are input by defining the range of cells where
they apply]\n";
        print PARFILE "\n";

        for $j (0..$nmat-1)
        {
          print PARFILE "\$ Material $j  $Lithology[$j] \n";
          print PARFILE "$ih[$j]  $ij[$j]    h,j [beginning cell, ending cell] \n";
          printf PARFILE "%10.3e  %10.3e     thick(h) rho(h) [thickness (m) bulk density
(g/cm^3)]\n",$thick[$j],$rho[$j];
          printf PARFILE "%10.3e  %10.3e  %10.3e  %10.3e  %10.3e  %10.3e  %10.3e
sk(h),ths(h),thr(h),alpha(h),rn(h) rm(h),rl(h) [Sat conductivity (m/yr) sat moist content, resid
moist content, vanG alpha, vanG n vanG m vanG l]\n",

$sk{$Lithology[$j]},$ths{$Lithology[$j]},$thr{$Lithology[$j]},$alpha{$Lithology[$j]},$rn{$Litholo
```

```
gy[$j]},$rm{$Lithology[$j]},$rl{$Lithology[$j]};
        }
        print PARFILE "\n";
# Output times

        print PARFILE "\n";
        print PARFILE "\$ Output Times \n";
        print PARFILE "\n";
        print PARFILE "$ntimes                 ntimes [number of output time periods]\n";
        for $j (0..$ntimes-1)
        {
          printf PARFILE "%10.3e  %10.3e  %10.3e          t1(i),t2(i),tp(i) [beginning time of
output ending time of output, print step]\n",
          $t1[$j],$t2[$j],$tp[$j];

        }

        print PARFILE "\$ [End of Parameter Definition File]\n";
        close PARFILE;

      }

      sub wheader
      {
# Writes header
        print PARFILE "\$";
        for $j (1..20)
        {
          print PARFILE "-----------";
        }
        print PARFILE "\n";
        print PARFILE "\$";
        for $j (1..9)
        {
          print PARFILE "   $j       ";
        }
        for $j (10..20)
        {
          print PARFILE "   $j      ";
        }
        print PARFILE "\n";
        print PARFILE "\$";
        for $j (1..20)
        {
          print PARFILE "-----------";
        }
        print PARFILE "\n";

      }
```

GWSCREEN Input File

```
RHLLW - PA Dose Calculations DOE STD-1196 DCFs WEST SIDE Surface contamination on NRF canisters
1 3 0 2 1                                    (Card 2) imode,itype,idisp,kflag,idil
3 2 1 1 1                                    (Card 3)
imodel,isolve,isolveu,imoist,imoistu
6 13 0.001                                   (Card 4) jstart jmax eps
$ --- When using all pathway dcfs, set ef=1, ed=1 and wi=1000 to
$ --- convert from m**3 to L  units of DCF are rem m**3/Ci
70. 2.555E+04 1000.0  1.  1.  1.0E-3         (Card 5) bw,at,wi,ef,ed,dlim
0.   0.                                      (Card 6) x0,y0
10  25.0  1.0                               (Card 7) l,w,perc
0.001   1.00  0.                             (Card 9) depth,rhou,axu
0.30                                         (Card 9a) thetau
$ --- use ICDF values for ax and ay ay=0.2ax and az=1.16e-3ax as stated in the MEPAS Manual
3.31 0.662  0.00384   76.  15.                   (Card 10) ax,ay,az,b,z(well screen
thickness)
$ --- Aquifer density and porosity from WAG 10 model
$ --- Darcy velocity assumed to be between 10 and 21.9 m/yr based on WAG 10 model. Assume 16 m/yr
for this case
```

```
16.0  0.06  1.900                                      (Card 11) u,phi,rhoa
4                                                      (Card 12a) nrecept
105.  0.                                               (Card 12b) xrec yrec
105.  18.6                                             midway between west and east
105.  24.7
105.  53.6
10                                                      (Card 13a) ntimes
0.      100.   5.                                      (Card 13b) t1 t2 tp
101.    120.   1.0
125.   975.   25
980    1150   1.0
1155   1200.  5.                                      (Card 13b) t1 t2 tp
1100   5000.  50.                                     (Card 13b) t1 t2 tp
5250   10000. 100.                                     (Card 13b) t1 t2 tp
10500  20000. 200.
20750  80000. 1000.
90000. 3.2e5  4000.

36                                                       (ncontam)

$  ------------------------- C-14 ------------------------ 1
 0  5  5  14  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'C14'  5.73E+03  0.0  5.86E+03                               (card14b) cname thalf kda dcf
'../mcmt/vz/C-14.rel'

$  ------------------------- H-3 ------------------------ 2
 0  0.00E+00  0.00E+00  3  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'H3'  12.3  0  1.74E+02                                (card14b) cname thalf kda dcf
'../mcmt/vz/H-3.rel'

$  ------------------------- I-129 ------------------------ 3
 0  1.00E-01  1.00E-01  129  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'I129'  1.57E+07  0.0    6.92E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/I-129.rel'

$  ------------------------- Nb-94 ------------------------ 4
 0  0.00E+00  0.00E+00  3  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'Nb94'  12.3  0   7.47E+04                               (card14b) cname thalf kda dcf
'../mcmt/vz/Nb-94.rel'

$  ------------------------- Ni-59 ------------------------ 5
 0  1.00E+02  1.00E+02  59  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'Ni59'  7.60E+04  0   2.92E+02                                (card14b) cname thalf kda dcf
'../mcmt/vz/Ni-59.rel'

$  ------------------------- Tc-99 ------------------------ 6
 0  2.00E-01  2.00E-01  99  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'Tc99'  2.11E+05  0.0    6.26E+03                                (card14b) cname thalf kda dcf
'../mcmt/vz/Tc-99.rel'

$ Am-241 Decay Chain
$  ------------------------- aAm241 ------------------------ 7
 0  8.00E+00  8.00E+00  241  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'aAm241'  4.32E+02  0.0   6.69E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/aAm-241.rel'

$  ------------------------- aNp237 ------------------------ 8
 0  8.00E+00  8.00E+00  237  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'aNp237'  2.144E+06  0.0   3.53E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/aNp-237.rel'

$  ------------------------- aU233 ------------------------ 9
 0  6.00E+00  6.00E+00  233  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'aU233'  1.59E+05  0.0   1.78E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/aU-233.rel'

$  ------------------------- aTh229 ------------------------ 10
 0  1.00E+02  1.00E+02  229  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'aTh229'  7.34E+03  0  2.52E+06                                (card14b) cname thalf kda dcf
'../mcmt/vz/aTh-229.rel'
```

```
$ -------------------------- Pu-241 decay chain ---------------------------------
$  ------------------------- bPu241 ------------------------ 11
 0  8.00E+00  8.00E+00  241  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'bPu241'  1.44E+01  0.0   1.47E+04                                (card14b) cname thalf kda dcf
'../mcmt/vz/bPu-241.rel'

$  ------------------------- bAm241 ------------------------ 12
 0  8.00E+00  8.00E+00  241  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'bAm241'  4.32E+02  0.0   6.69E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/bAm-241.rel'

$  ------------------------- bNp237 ------------------------ 13
 0  8.00E+00  8.00E+00  237  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'bNp237'  2.144E+06  0.0   3.53E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/bNp-237.rel'

$  ------------------------- bU233 ------------------------ 14
 0  6.00E+00  6.00E+00  233  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'bU233'  1.59E+05  0.0   1.78E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/bU-233.rel'

$  ------------------------- bTh229 ------------------------ 15
 0  1.00E+02  1.00E+02  229  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'bTh229'  7.34E+03  0  2.52E+06                                (card14b) cname thalf kda dcf
'../mcmt/vz/bTh-229.rel'

$  ---------------------------------U-234 decay chain --------------------------------
$  ------------------------- cU234 ------------------------ 16
 0  6.00E+00  6.00E+00  234  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'cU234'  2.45E+05  0.0   1.71E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/cU-234.rel'
$  ------------------------- cTh230 ------------------------ 17
 0  1.00E+02  1.00E+02  230  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'cTh230'  7.54E+04  0  7.11E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/cTh-230.rel'
$  ------------------------- cRa226 ------------------------ 18
 0  1.00E+02  1.00E+02  226  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'cRa226'  1.60E+03  0  1.30E+06                                (card14b) cname thalf kda dcf
'../mcmt/vz/cRa-226.rel'
$  ------------------------- cPb210 ------------------------ 19
 0  1.00E+02  1.00E+02  210  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'cPb210'  2.23E+01  0  7.91E+06                                (card14b) cname thalf kda dcf
'../mcmt/vz/cPb-210.rel'

$  ---------------------------------Pu-240 decay chain --------------------------------
$  ------------------------- dPu240 ------------------------ 20
 0  2.20E+01  2.20E+01  240  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'dPu240'  6560  0.0   8.10E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/dPu-240.rel'
$  ------------------------- dU236 ------------------------ 21
 0  6.00E+00  6.00E+00  236  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'dU236'  2.34E+07  0.0 1.61E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/dU-236.rel'
$  ------------------------- dTh232 ------------------------ 22
 0  1.00E+02  1.00E+02  232  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'dTh232'  1.40E+10  0  7.81E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/dTh-232.rel'
$  ------------------------- dRa228 ------------------------ 23
 0  1.00E+02  1.00E+02  228  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'dRa228'  5.75  0    4.51E+06                                (card14b) cname thalf kda dcf
'../mcmt/vz/dRa-228.rel'
$  ------------------------- dTh228 ------------------------ 24
 0  1.00E+02  1.00E+02  228  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'dTh228'  1.91  0  3.23E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/dTh-228.rel'

$ ----------------------------------- U-235 Decay Chain --------------------------------
$  ------------------------- eU235 ------------------------ 25
 0  6.00E+00  6.00E+00  235  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'eU235'  7.04E+08  0.0   1.63E+05                                (card14b) cname thalf kda dcf
'../mcmt/vz/eU-235.rel'
```

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$  ------------------------- ePa231 ------------------------ 26
 0  5.55E+02  5.55E+02  231  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'ePa231'  3.28E+04   0.0  1.57E+06                              (card14b) cname thalf kda dcf
'../mcmt/vz/ePa-231.rel'
$  ------------------------- eAc227 ------------------------ 27
 0  4.50E+02  4.50E+02  227  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'eAc227'  21.77   0  1.72E+06                               (card14b) cname thalf kda dcf
'../mcmt/vz/eAc-227.rel'

$ ----------------------------------- Pu-238 Decay Chain --------------------------------
$  ------------------------- fPu238 ------------------------ 28
 0  6.00E+00  6.00E+00  238  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'fPu238'  8.77E+01  0.0   7.40E+05                              (card14b) cname thalf kda dcf
'../mcmt/vz/fPu-238.rel'
$  ------------------------- fU234 ------------------------ 29
 0  6.00E+00  6.00E+00  234  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'fU234'  2.45E+05  0.0   1.71E+05                              (card14b) cname thalf kda dcf
'../mcmt/vz/fU-234.rel'
$  ------------------------- fTh230 ------------------------ 30
 0  1.00E+02  1.00E+02  230  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'fTh230'  7.54E+04  0  7.11E+05                              (card14b) cname thalf kda dcf
'../mcmt/vz/fTh-230.rel'
$  ------------------------- fRa226 ------------------------ 31
 0  1.00E+02  1.00E+02  226  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'fRa226'  1.60E+03  0  1.30E+06                              (card14b) cname thalf kda dcf
'../mcmt/vz/fRa-226.rel'
$  ------------------------- fPb210 ------------------------ 32
 0  1.00E+02  1.00E+02  210  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'fPb210'  2.23E+01  0  7.91E+06                              (card14b) cname thalf kda dcf
'../mcmt/vz/fPb-210.rel'

$ ----------------------------------- Pu-239 Decay Chain --------------------------------
$  ------------------------- gPu239 ------------------------ 33
 0  2.20E+01  2.20E+01  239  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'gPu239'  2.41E+04  0.0   8.10E+05                              (card14b) cname thalf kda dcf
'../mcmt/vz/gPu-239.rel'
$  ------------------------- gU235 ------------------------ 34
 0  6.00E+00  6.00E+00  235  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'gU235'  7.04E+08  0.0   1.63E+05                              (card14b) cname thalf kda dcf
'../mcmt/vz/gU-235.rel'
$  ------------------------- gPa231 ------------------------ 35
 0  5.55E+02  5.55E+02  231  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'gPa231'  3.28E+04   0.0  1.57E+06                              (card14b) cname thalf kda dcf
'../mcmt/vz/gPa-231.rel'
$  ------------------------- gAc227 ------------------------ 36
 0  4.50E+02  4.50E+02  227  0  0. 1.00E+09  0.   (card14a) nprog kds kdu zmw qi rmi sl other
'gAc227'  21.77   0  1.72E+06                               (card14b) cname thalf kda dcf
'../mcmt/vz/gAc-227.rel'
```