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Reportable Radionuclides in DWPF Sludge Batch 7a (Macrobatch 8)

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EXECUTIVE SUMMARY

Extensive radionuclide analyses were performed on a Sludge Batch 7a (SB7a) sample collected from Tank 40. Results of these analyses were used to project the radionuclide content of the SB7a waste over the 1100 year time period from calendar year 2015 to 3115. This was done to determine which radionuclides were reportable per the requirements of the Waste Acceptance Product Specifications (WAPS) and the Defense Waste Processing Facility (DWPF).

Twenty-five radionuclides in SB7a waste were identified as being reportable based on the criterion of contributing ≥ 0.01 percent of the total curie content from 2015 to 3115 and having half-lives ≥ 10 years. These twenty-five radionuclides are:

Ni-59	**Ni-63**	**Se-79**	**Sr-90**	**Zr-93**
Nb-93m	**Tc-99**	**Sn-126**	**Cs-137**	**Sm-151**
Th-229	**U-233**	**U-234**	**U-238**	**Np-237**
Pu-238	**Pu-239**	**Pu-240**	**Pu-241**	**Pu-242**
Am-241	**Am-243**	**Cm-244**	**Cm-246**	**Cf-251**

Three of these radionuclides – Th-229, Cm-246, and Cf-251 – are ones that are absent from the list of radionuclides projected to be reportable in the DWPF glass design basis. In contrast, three of the nuclides identified in the DWPF glass design basis – Pd-107, Cs-135, and Th-230 – are ones not found to be reportable based on the SB7a characterization. These deviations should not be considered unique, as they also occurred in several of the previous sludge batches. However, they demonstrate the importance of utilizing laboratory data to test process expectations.

In addition to the twenty-five radionuclides identified above, U-235 and U-236 are also considered reportable – not because of the curie content/half-life criterion – but because of their identification as being always reportable per the requirements of Section 1.6 of the WAPS.

Based on the 2015 to 3115 radionuclides projections, the total curie content of the SB7a waste will decrease three orders of magnitude over the upcoming 1100 year time period. Most of this decrease will occur over the first 400 years, due to the dominance of radionuclides with half-lives of 100 years or less. Specifically, Sr-90 (and its short-lived daughter Y-90), Sm-151, and Pu-238 are the primary radionuclides driving the curie content over the first 400 years (2015 to 2415), and each of these radionuclides has a half-life of 100 years or less. In contrast, Pu-239 (and its short-lived daughter U-235m) and Am-241 will dominate the curie content after 2415, once the majority of the Sr-90, Sm-151, and Pu-238 have decayed away. This should not be considered surprising, given the significantly longer half-lives of Pu-239 and Am-241 (24,000 and 430 years, respectively).

Three of the reportable radionuclides in SB7a (Sn-126, Pu-242, and Cf-251) were identified based upon minimum detection limits, rather than true detectable concentrations. Methodologies for reducing the minimum detection limits of these particular analytes could be pursued in the future, if more accurate projections are needed. This would improve the ability for making a clear determination of whether or not these radionuclides are reportable.

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LIST OF ABBREVIATIONS

DI	de-ionized
DWPF	Defense Waste Processing Facility
FYSF	fission yield scaling factor
HLW	High Level Waste
ICP-AES	inductively coupled plasma – atomic emission spectroscopy
ICP-MS	inductively coupled plasma – mass spectroscopy
LEPS	low energy photon spectroscopy
PHA	pulse height analysis
SB	Sludge Batch
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
t_H	half-life
TTR	Technical Task Request
WAPS	Waste Acceptance Product Specifications
WCP	Waste Form Compliance Plan

1.0 Introduction

The Waste Acceptance Product Specifications (WAPS)[1] 1.2 require that the waste producer "shall report the curie inventory of radionuclides that have half-lives longer than 10 years and that are, or will be, present in concentrations greater than 0.05 percent of the total inventory for each waste type indexed to the years 2015 and 3115." As part of the strategy to meet WAPS 1.2, the Defense Waste Processing Facility (DWPF) will report for each waste type all radionuclides that have half-lives longer than 10 years and contribute greater than 0.01 percent of the total curie inventory from the time of production through the 1100 year period from 2015 through 3115.[2] The initial list of radionuclides to be reported is based on the design-basis glass identified in the Waste Form Compliance Plan (WCP)[2] and Waste Form Qualification Report.[3] However, it is required that the list be expanded if other radionuclides with half-lives greater than 10 years are identified that meet the "greater than 0.01% of the curie inventory" criterion.

Specification 1.6 of the WAPS, International Atomic Energy Agency Safeguards Reporting for High Level Waste (HLW), requires that the ratio by weights of the following uranium and plutonium isotopes be reported: U-233, U-234, U-235, U-236, and U-238; and Pu-238, Pu-239, Pu-240, Pu-241, and Pu-242. Therefore, the complete list of reportable radionuclides must also include these sets of U and Pu isotopes – and the U and Pu isotopic mass distributions must be identified.

The DWPF receives HLW sludge slurry from Savannah River Site (SRS) Tank 40. For Sludge Batch 7a (SB7a), the waste in Tank 40 contained a blend of the heel from Sludge Batch 6 (SB6) and the Sludge Batch 7 (SB7) material transferred to Tank 40 from Tank 51. This sludge blend is also referred to as Macrobatch 8.

Laboratory analyses of a Tank 40 sludge sample were performed to quantify the concentrations of pertinent radionuclides in the SB7a waste. Subsequently, radiological decay and in-growth were calculated over the time period from 2015 to 3115. This provided a basis for characterizing the radionuclide content of SB7a over time and for identifying the "reportable radionuclides." Details of the characterization methodology and the analytical results are the focus of this report.

This work was performed at the request of the Waste Solidification Engineering Department of Savannah River Remediation, initiated via Technical Task Request (TTR) HLW-DWPF-TTR-2010-0031.[4] A minor revision in the reporting requirements was requested via a subsequent email communication.[5] The work was conducted in accordance with the protocols identified in Task Technical and Quality Assurance Plan SRNL-RP-2010-01218[6] and Analytical Study Plan SRNL-RP-2010-01219.[7] All of the raw data related to this scope have been recorded in laboratory notebook SRNL-NB-2011-00061.[8]

2.0 Objectives

The overall goal of this task was to characterize the radionuclide content of the SB7a waste sufficiently to meet the WAPS and DWPF reporting requirements. The specific objectives were:

1) Quantify the current concentrations of all radionuclides impacting (or potentially-impacting) the total curie content between calendar years 2011 and 3115. Also quantify the current concentrations of other radionuclides specifically requested in the TTR or required by the WAPS.

2) Calculate future concentrations of decayed and in-grown radionuclides impacting the total curie content between calendar years 2015 and 3115;

3) Identify as "reportable" all radionuclides contributing ≥ 0.01% of the total curie content from 2015 to 3115 and having half-lives ≥ 10 years.

3.0 Methodology

3.1 Radionuclides Selected for Initial Quantification

Sixty-six radionuclides were chosen for initial quantification, based on the need to: a) accurately access the total curie content of the sludge over the period of the next 1100 years; b) accurately quantify the reportable radionuclides; and c) provide characterization data for specific radionuclides required by the WAPS or otherwise requested in the TTR. The sixty-six radionuclides are identified in Table 3-1, along with their half-lives and association with the WCP Design Basis, WAPS 1.6 Requirements, and/or TTR request. Also identified in the table are the means of quantifying each radionuclide, either by laboratory analysis or by calculation. (Note that summaries of the laboratory analysis methods and calculation assumptions are presented in the following section, and details of the methods are presented in Appendix B).

Omitted from the initial quantification were: H-3, C-14, Nb-94, Zr-96, Cd-113, In-115, La-138, Ce-142, Nd-144, Nd-150, Sm-147, Sm-149, Eu-152, Np-236, and U-232. H-3 and C-14 were omitted due to their volatility during DWPF processing, which prevents their retention in the final glass form. The other nuclides (Nb-94 through U-232) were omitted based on process knowledge indicating their negligibility.[9,10] Note that short-lived decay products contributing less than 0.01% of the total inventory were not included in the initial characterization (since they had negligible impact on the initial total inventory), but were included in the decay and in-growth calculations applicable to years 2015 to 3115. Te-125m, Pa-233, Pa-234m, and isotopes of Tl, Bi, and Po are examples of the short-lived decay products having negligible impact on the current curie content and therefore omitted from the initial quantification.

3.2 SB7a Tank 40 Sample Analyses

Laboratory analyses were performed on aliquots of a 3-liter SB7a slurry sample collected from Tank 40 (HTF-40-11-66) and submitted to SRNL on May 24, 2011. Note that characterization of the stable constituents in the SB7a sample and select radionuclide data needed to support DWPF's Waste Acceptance Criteria compliance assessment have been reported in previous memoranda.[11,12]

A summary of the laboratory methods used for performing the radionuclide analyses (the radionuclide analyses identified in Table 3-1) is given in Table 3-2. Details of the methods are presented in Appendix B. Note that in every case, the laboratory analyses were performed on four separate sample aliquots. As such, the results reported in this document are typically average values based on four measurements, assuming all four of the measurements yielded values above the minimum detection limits. However, in cases where all four analytical results were below the minimum detection limits, the lowest minimum detection limit was reported in this document.

Table 3-1. Radionuclides Selected for Quantification

Nuclide	Half-life, years	In Design Basis	Required by WAPS 1.6	Requested in TTR	Method of Quantification	Nuclide	Half-life, years	In Design Basis	Required by WAPS 1.6	Requested in TTR	Method of Quantification
Cl-36[a]	3.0E+05				Lab analysis	Th-228[c]	1.9E+00				Calculated from Th-232
Co-60[a]	5.3E+00				Lab analysis	Th-229[c]	7.3E+03				Calculated from U-233
Ni-59[a]	7.5E+04	X			Lab analysis	Th-230[c,e]	7.5E+04	X			Process knowledge
Ni-63[a]	1.0E+02	X			Lab analysis	Th-232[d]	1.4E+10				Lab analysis
Se-79[b]	≤6.5E+04	X			Lab analysis	Pa-231[c]	3.3E+04				Calculated fromU-235
Sr-90[b]	2.9E+01	X			Lab analysis	U-233[a]	1.6E+05		X		Lab analysis
Y-90[c]	7.3E-03				Calculated from Sr-90	U-234[c]	2.5E+05	X	X		Lab analysis
Zr-93[b]	1.5E+06	X			Lab analysis	U-235[d]	7.0E+08		X		Lab analysis
Nb-93m[c]	1.4E+01	X			Calculated from Zr-93	U-235m[c]	4.9E-05				Calculated fromPu-239
Tc-99[b]	2.1E+05	X			Lab analysis	U-236[a]	2.3E+07		X		Lab analysis
Ru-106[b]	1.0E+00			X	Lab analysis	U-238[d]	4.5E+09	X	X		Lab analysis
Rh-106[c]	2.5E-04			X	Calculated from Rh-106	Np-237[a]	2.1E+06	X			Lab analysis
Pd-107[b]	6.5E+06	X			Calculated from Pd-105	Pu-238[a]	8.8E+01	X	X		Lab analysis
Cd-113m[b]	1.4E+01				Utilizing FYSF	Pu-239[a]	2.4E+04	X	X		Lab analysis
Sn-121m[b]	5.5E+01				Lab analysis	Pu-240[a]	6.6E+03	X	X		Lab analysis
Sn-126[b]	1.0E+5	X			Lab analysis	Pu-241[a]	1.4E+01	X	X		Lab analysis
Sb-125[b]	2.7E+00				Lab analysis	Pu-242[a]	3.8E+05	X	X		Lab analysis
I-129[b]	1.6E+07				Lab analysis	Pu-244[c]	8.3E+07				Calculated from Cm-248
Cs-134[b]	2.1E+00			X	Lab analysis	Am-241[a]	4.3E+02	X			Lab analysis
Cs-135[b]	3.0E+06	X			Lab analysis	Am-242m[a]	1.4E+02				Lab analysis
Cs-137[b]	3.0E+01	X			Lab analysis	Am-243[a]	7.4E+03	X			Lab analysis
Ba-133[b]	1.1E+01				Lab analysis	Cm-242[a]	4.5E-01				Lab analysis
Ba-137m[c]	4.9E-06				Calculated from Cs-137	Cm-243[a]	2.9E+01				Lab analysis
Ce-144[b]	7.8E-01			X	Lab analysis	Cm-244[a]	1.8E+01	X			Lab analysis
Pr-144[c]	3.3E-05			X	Calculated from Ce-144	Cm-245[a]	8.5E+03				Lab analysis
Pm-147[b]	2.6E+00				Lab analysis	Cm-246[a]	4.7E+03				Lab analysis
Sm-151[b]	9.0E+01	X			Lab analysis	Cm-247[a]	1.6E+07				Lab analysis
Eu-154[b]	8.8E+00				Lab analysis	Cm-248[a]	3.4E+05				Lab analysis
Eu-155[b]	5.0E+00				Lab analysis	Bk-247[a]	1.4E+03				Lab analysis
Pb-210[c]	2.2E+01				Calculated from Th-230, U-234, Pu-238	Cf-249[a]	3.5E+02				Lab analysis
Ra-226[c]	1.6E+03				Calculated from Th-230, U-234, Pu-238	Cf-250[a]	1.3E+01				Lab analysis
Ra-228[c]	5.8E+00				Calculated from Th-232	Cf-251[a]	9.0E+02				Lab analysis
Ac-227[c]	2.2E+01				Calculated from U-235	Cf-252[a]	2.6E+00				Lab analysis

a = activation product; b = fission product; c = decay product; d = naturally occurring nuclide; e = thoria impurity; FYSF = fission yield scaling factor

Table 3-2. Summary of Radioanalytical Laboratory Methods

Radionuclides	PF Digestion	AR Digestion	Other Digestion	Chemical Separation	Measurement Technique	Other Information
Co-60, Ru-106, Sb-125, Sn-126, Ba-133, Ce-144, Eu-154, Eu-155, Am-241	**X**			**X**	γ-PHA	Chemical separation removes Cs
Cl-36, Sr-90, Pm-147, Sm-151, Pu-241	**X**			**X**	LSC	Different chemical separations for Cl, Sr, Pm/Sm, and Pu
Sn-121m	**X**			**X**	LEPS	Chemical separation removes Cs
Cs-135	**X**			**X**	ICP-MS	Chemical separation removes Ba
Zr-93, Tc-99, Th-232, U-233, U-234, U-235, U-236, U-238, Np-237, Pu-239, Pu-240, Pu-242		**X**			ICP-MS	
Se-79			**X**	**X**	LSC	Chemical separation purifies Se
I-129, Cm-243, Cf-249, Cf-251			**X**	**X**	LEPS	Different chemical separations for I and Cm
Cs-134, Cs-137	**X**				γ-PHA	
Pu-238	**X**			**X**	α-PHA	Chemical separation removes Am
Am-242m, Cm-245, Cm-246, Cm-247, Cm-248, Bk-247, Cf-250			**X**	**X**	ICP-MS	
Am-243, Cm-242, Cm-244, Cf-252			**X**	**X**	α-PHA	

PF = peroxide fusion; **AR** = aqua regia; **LSC** = liquid scintillation counting; **γ-PHA** = gamma pulse height analysis; **ICP-MS** = inductively coupled plasma mass spectroscopy; **LEPS** = low energy photon spectroscopy; **α-PHA** = alpha pulse height analysis.

Calculations of the quantities of radioactive decay products (the radioactive decay products identified in Table 3-1) were performed based on the assumption that the waste is currently 50 years old. This age was chosen for conservatism – to assure that the calculated quantities of decay products were not underestimated. (In actuality, the average age of the waste is likely closer to 40 years than 50 years).

In calculating the concentrations of decay products, the first step was to calculate the concentrations of the parent nuclides 50 years ago. Utilizing the standard activity decay relationship,[13] the parent concentration in 1961 was calculated as the product of the current concentration (in 2011) and the term $[\exp(0.693*50/t_H)]$, where t_H is the half-life of the parent nuclide in units of years.

The second step was to determine the decay product concentration in 2011, utilizing a decay/in-growth calculation to quantify the progeny arising from 50 years of decay of the 1961 parent concentration. RadCalc 4.1 software was utilized for these calculations. (RadCalc 4.1 is a software application developed to assist the Department of Energy in performing calculations

consistent with the requirements and methods prescribed by the Department of Energy, the U. S. Nuclear Regulatory Commission, the Environmental Protection Agency, and the International Commission of Radiation Protection).[14] Details of the decay product calculations are given in Appendix B.

Results of the laboratory analyses and the decay product calculations were reported in units of μCi per gram of total solids, curies per gallon of sludge slurry, and weight percent of total solids. These results defined the current radionuclide content of the SB7a waste. They also provided the "input data" for calculating the radionuclide content of the waste between calendar years 2015 and 3115.

Also reported were the weight percent distributions of the uranium and plutonium isotopes. These distributions were determined utilizing the uranium and plutonium concentrations identified through the laboratory analyses.

Unit conversions between "activity per mass of total solids" and "activity per volume of sludge slurry" were performed using the previously published[11] total solids and slurry density values: a) 17.2 wt% total solids; and b) 1.14 grams per mL of slurry.

Unit conversions between "activity per mass of total solids" and "weight percent of total solids" were performed for each radionuclide using the specific activities published in DOE/RW-0006.[15] In the rare cases when a specific activity was not identified in DOE/RW-0006, the specific activity was taken from a 1999 SRS radionuclide data document.[16]

3.3 Calculation of Radionuclide Concentrations Between 2015 and 3115

The RadCalc 4.1 software was utilized to calculate the concentrations of radionuclides present in the waste between calendar years 2015 and 3115. The current radionuclide concentrations (as determined through the 2011 laboratory analyses and 2011 in-growth/decay calculations) provided the source data for 2015-3115 calculations.

Future projections were performed at 100 year intervals starting at the year 2015 and ending at 3115. Thus, twelve sets of output data were generated. All of the projected concentrations were calculated in units of μCi per gram of total solids. For each projection year, the individual radionuclide concentrations were reported along with a sum of the total concentration of activity. Also reported were the percentages of the curie content contributed by each nuclide.

3.4 Identification of Reportable Radionuclides

Any radionuclide contributing ≥ 0.01 percent of the total curie content from years 2015 to 3115 and having a half-life ≥ 10 years was identified as being "reportable."

4.0 Results and Discussion

4.1 Initial Radionuclide Characterization

Current concentrations of radionuclides in the SB7a waste are given in Table 4-1. These results indicate that the total concentration of radioactivity is 3.0E+04 μCi per gram of total solids, or 2.2E+01 Ci per gallon of sludge slurry.

Table 4-1. Initial Radionuclide Characterization (Source Data for 2015 to 3115 Projections)

Nuclide	µCi per gram of total solids	Ci per gallon of sludge slurry	wt% of total solids	Nuclide	µCi per gram of total solids	Ci per gallon of sludge slurry	wt% of total solids
Cl-36	<2.5E-04	<1.9E-07	<7.7E-07	Th-228	1.6E-03	1.2E-06	1.9E-10
Co-60	2.7E+00	2.0E-03	2.3E-07	Th-229	6.3E-04	4.7E-07	3.0E-07
Ni-59	1.5E+00	1.1E-03	1.8E-03	Th-230	3.8E-04	2.8E-07	1.8E-06
Ni-63	2.5E+01	1.8E-02	4.0E-05	Th-232	1.6E-03	1.2E-06	1.4E+00
Se-79	7.6E-03	5.7E-06	1.1E-05	Pa-231	6.8E-07	5.0E-10	1.4E-09
Sr-90	1.4E+04	1.0E+01	1.0E-02	U-233	1.3E-01	9.9E-05	1.4E-03
Y-90	1.4E+04	1.0E+01	2.5E-06	U-234	4.8E-02	3.6E-05	7.7E-04
Zr-93	5.3E-01	3.9E-04	2.1E-02	U-235	6.4E-04	4.7E-07	3.0E-02
Nb-93m	4.6E-01	3.4E-04	1.6E-07	U-235m	1.3E+01	9.3E-03	3.9E-11
Tc-99	1.0E-01	7.7E-05	6.1E-04	U-236	1.1E-03	8.0E-07	1.7E-03
Ru-106	<6.4E-01	<4.7E-04	<1.9E-08	U-238	1.5E-02	1.1E-05	4.5E+00
Rh-106	<6.4E-01	<4.7E-04	<1.8E-14	Np-237	2.2E-02	1.6E-05	3.1E-03
Pd-107	1.2E-03	9.2E-07	2.4E-04	Pu-238	1.8E+02	1.3E-01	1.0E-03
Cd-113m	3.1E+00	2.3E-03	1.4E-06	Pu-239	1.3E+01	9.3E-03	2.0E-02
Sn-121m	<5.7E-02	<4.2E-05	<9.6E-08	Pu-240	4.1E+00	3.1E-03	1.8E-03
Sn-126	<6.4E-01	<4.8E-04	<2.3E-03	Pu-241	5.6E+01	4.2E-02	5.5E-05
Sb-125	<2.4E-01	<1.8E-04	<2.3E-08	Pu-242	<2.3E-02	<1.7E-05	<5.9E-04
I-129	1.7E-03	1.2E-06	9.5E-04	Pu-244	<1.2E-10	<8.9E-14	<6.6E-10
Cs-134	<7.9E-01	<5.9E-04	<6.1E-08	Am-241	3.7E+01	2.8E-02	1.1E-03
Cs-135	2.8E-03	2.1E-06	2.4E-04	Am-242m	3.4E-02	2.7E-05	3.5E-07
Cs-137	5.9E+02	4.4E-01	6.8E-04	Am-243	5.7E-01	4.4E-04	2.8E-04
Ba-133	<2.0E-01	<1.5E-04	<7.9E-08	Cm-242	2.8E-02	2.1E-05	8.6E-10
Ba-137m	5.6E+02	4.1E-01	1.0E-10	Cm-243	<3.9E-01	<2.9E-04	<7.6E-07
Ce-144	<1.3E+00	<9.5E-04	<4.0E-08	Cm-244	1.9E+01	1.5E-02	2.3E-05
Pr-144	<1.3E+00	<9.5E-04	<1.7E-12	Cm-245	2.8E-03	2.2E-06	1.6E-06
Pm-147	<1.6E+02	<1.2E-01	<1.8E-05	Cm-246	7.3E-03	5.6E-06	2.4E-06
Sm-151	2.3E+02	1.7E-01	8.7E-04	Cm-247	<9.2E-08	<7.1E-11	<9.9E-08
Eu-154	1.7E+01	1.3E-02	6.2E-06	Cm-248	<3.1E-04	<2.4E-07	<7.2E-06
Eu-155	2.6E+00	1.9E-03	5.6E-07	Bk-247	<1.0E-03	<7.9E-07	<9.8E-08
Pb-210	3.8E-06	2.8E-09	5.0E-12	Cf-249	<4.0E-03	<3.1E-06	<9.7E-08
Ra-226	7.7E-06	5.7E-09	7.8E-10	Cf-250	<9.6E-05	<7.4E-08	<8.8E-11
Ra-228	1.6E-03	1.2E-06	6.8E-10	Cf-251	<9.2E-03	<7.1E-06	<5.8E-07
Ac-227	3.4E-07	2.5E-10	4.7E-13	Cf-252	<2.8E-02	<2.1E-05	<5.2E-09
Total µCi per gram of total solids = 3.0E+04; Total Ci per gallon of sludge slurry = 2.2E+01; Total wt% of total solids = 6.0E+00							

4.2 Current Distributions of Uranium and Plutonium Isotopes

Uranium and plutonium isotopic distributions are given in Tables 4-2 and 4-3, respectively.

Table 4-2. Uranium Isotope Distribution in SB7a

Isotope	wt% of total solids	% distribution
U-233	1.37E-03	3.04E-02
U-234	7.67E-04	1.70E-02
U-235	2.96E-02	6.58E-01
U-236	1.66E-03	3.69E-02
U-238	4.47E+00	9.93E+01
Total	4.50E+00	1.00E+02

Table 4-3. Plutonium Isotope Distribution in SB7a

Isotope	wt% of total solids	% distribution
Pu-238	1.03E-03	4.35E+00 to 4.46E+00
Pu-239	2.02E-02	8.52E+01 to 8.74E+01
Pu-240	1.81E-03	7.64E+00 to 7.84E+00
Pu-241	5.48E-05	2.31E-01 to 2.37E-01
Pu-242	<5.91E-04	<2.49E+01
Total	2.31E-02 to 2.37E-02	1.00E+2

4.3 Radionuclide Concentrations and Curie Distributions from 2015 to 3115

Radionuclide concentrations between the years of 2015 and 3115 are given in Table 4-4, and a plot of the total concentration of activity as a function of time is given in Figure 4-1. These results show that the total activity concentration drops by three orders of magnitude over the 1100 year period. Specifically, in year 2015 the total activity concentration is 2.7E+04 μCi/g and in year 3115 the concentration has dropped to 4.2E+01 μCi/g. As illustrated in the plot, the most rapid decline in the concentration occurs over the first 300 years (between years 2015 and 2315).

Correspondingly, the percentages of the curie content between years of 2015 and 3115 are given in Table 4-5, and a plot of the percentages contributed by the dominant radionuclides as a function of time is given in Figure 4-2. These results show that: a) Sr-90 (and its short-lived decay product Y-90) will dominate the activity over the first 200 years (from 2015 to 2215); b) Sm-151 and Pu-238 will become significant activity contributors over the next 200 years (from 2215 to 2415); and c) Pu-239 (as well as its short-lived decay product U-235m) and Am-241 will dominate the activity over the final 700 years (from 2415 to 3115).

Table 4-4. Radionuclide Concentrations Between Calendar Years 2015 and 3115

Radionuclide	Radionuclide Concentration, µCi per gram of total solids											
	2015	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
Cl-36	<2.5E-04	<2.5E-04	<2.5E-04	<2.5E-04	<2.5E-04	<2.5E-04	<2.5E-04	<2.5E-04	<2.5E-04	<2.5E-04	<2.5E-04	<2.5E-04
Co-60	1.7E+00	3.3E-06	6.4E-12	0	0	0	0	0	0	0	0	0
Ni-59	1.5E+00	1.5E+00	1.5E+00	1.5E+00	1.5E+00	1.5E+00	1.5E+00	1.5E+00	1.5E+00	1.5E+00	1.5E+00	1.5E+00
Ni-63	2.4E+01	1.2E+01	6.2E+00	3.1E+00	1.6E+00	7.8E-01	3.9E-01	2.0E-01	9.8E-02	4.9E-02	2.5E-02	1.2E-02
Se-79	7.6E-03	7.6E-03	7.6E-03	7.6E-03	7.6E-03	7.6E-03	7.6E-03	7.6E-03	7.6E-03	7.6E-03	7.6E-03	7.6E-03
Sr-90	1.3E+04	1.2E+03	1.0E+02	9.4E+00	8.5E-01	7.5E-02	6.8E-03	6.1E-04	5.5E-05	4.9E-06	4.4E-07	4.0E-08
Y-90	1.3E+04	1.2E+03	1.0E+02	9.4E+00	8.5E-01	7.5E-02	6.8E-03	6.1E-04	5.5E-05	4.9E-06	4.5E-07	4.0E-08
Zr-93	5.3E-01	5.3E-01	5.3E-01	5.3E-01	5.3E-01	5.3E-01	5.3E-01	5.3E-01	5.3E-01	5.3E-01	5.3E-01	5.3E-01
Nb-93m	4.7E-01	5.2E-01	5.2E-01	5.2E-01	5.2E-01	5.2E-01	5.2E-01	5.2E-01	5.2E-01	5.2E-01	5.2E-01	5.2E-01
Tc-99	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01
Ru-106	<5.9E-02	0	0	0	0	0	0	0	0	0	0	0
Rh-106	<5.9E-02	0	0	0	0	0	0	0	0	0	0	0
Pd-107	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03
Cd-113m	2.6E+00	1.9E-02	1.4E-04	1.0E-06	7.5E-09	5.4E-11	3.9E-13	0	0	0	0	0
Sn-121	<4.2E-02	<1.2E-02	<3.4E-03	<9.7E-04	<2.7E-04	<7.7E-05	<2.2E-05	<6.2E-06	<1.8E-06	<5.0E-07	<1.4E-07	<4.0E-08
Sn-121m	<5.5E-02	<1.5E-02	<4.4E-03	<1.2E-03	<3.5E-04	<9.9E-05	<2.8E-05	<8.0E-06	<2.3E-06	<6.4E-07	<1.8E-07	<5.2E-08
Sn-126	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01
Sb-125	<1.0E-01	<1.2E-12	0	0	0	0	0	0	0	0	0	0
Sb-126	<9.0E-02	<9.0E-02	<9.0E-02	<9.0E-02	<8.9E-02	<8.9E-02	<8.9E-02	<8.9E-02	<8.9E-02	<8.9E-02	<8.9E-02	<8.9E-02
Sb-126m	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01	<6.4E-01
Sb-126m2	<4.3E-01	<4.3E-01	<4.3E-01	<4.3E-01	<4.3E-01	<4.3E-01	<4.3E-01	<4.3E-01	<4.3E-01	<4.3E-01	<4.3E-01	<4.3E-01
Te-125m	<2.4E-02	0	0	0	0	0	0	0	0	0	0	0
I-129	1.7E-03	1.7E-03	1.7E-03	1.7E-03	1.7E-03	1.7E-03	1.7E-03	1.7E-03	1.7E-03	1.7E-03	1.7E-03	1.7E-03
Cs-134	<2.4E-01	0	0	0	0	0	0	0	0	0	0	0
Cs-135	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03
Cs-137	5.4E+02	5.4E+01	5.4E+00	5.4E-01	5.3E-02	5.3E-03	5.2E-04	5.2E-05	5.2E-06	5.2E-07	5.1E-08	5.1E-09
Ba-133	<1.6E-01	<2.2E-04	<3.1E-07	<4.3E-10	<6.0E-13	0	0	0	0	0	0	0
Ba-137m	5.1E+02	5.1E+01	5.1E+00	5.1E-01	5.0E-02	5.0E-03	4.9E-04	4.9E-05	4.9E-06	4.9E-07	4.8E-08	4.8E-09
Ce-144	<5.8E-02	0	0	0	0	0	0	0	0	0	0	0
Pr-144	<5.8E-02	0	0	0	0	0	0	0	0	0	0	0
Pr-144m	<8.0E-04	0	0	0	0	0	0	0	0	0	0	0
Nd-144	<4.2E-16	<4.4E-16	<4.4E-16	<4.4E-16	<4.4E-16	<4.4E-16	<4.4E-16	<4.4E-16	<4.4E-16	<4.4E-16	<4.4E-16	<4.4E-16
Pm-147	<6.3E+01	<2.1E-10	0	0	0	0	0	0	0	0	0	0
Sm-147	<1.4E-05	<1.4E-05	<1.4E-05	<1.4E-05	<1.4E-05	<1.4E-05	<1.4E-05	<1.4E-05	<1.4E-05	<1.4E-05	<1.4E-05	<1.4E-05
Sm-151	2.2E+02	1.0E+02	4.8E+01	2.2E+01	1.0E+01	4.7E+00	2.2E+00	1.0E+00	4.7E-01	2.2E-01	1.0E-01	4.7E-02
Eu-154	1.3E+01	4.0E-03	1.3E-06	4.0E-10	1.2E-13	0	0	0	0	0	0	0
Eu-155	1.6E+00	7.2E-07	3.4E-13	0	0	0	0	0	0	0	0	0
Tl-207	3.8E-07	1.7E-06	3.0E-06	4.3E-06	5.7E-06	7.1E-06	8.4E-06	9.7E-06	1.1E-05	1.2E-05	1.4E-05	1.5E-05
Tl-208	5.7E-04	5.7E-04	5.7E-04	5.7E-04	5.7E-04	5.7E-04	5.7E-04	5.7E-04	5.7E-04	5.7E-04	5.7E-04	5.7E-04
Tl-209	1.5E-05	4.1E-05	6.7E-05	9.2E-05	1.2E-04	1.4E-04	1.7E-04	1.9E-04	2.2E-04	2.4E-04	2.7E-04	2.9E-04

Table 4-4. Radionuclide Concentrations Between Calendar Years 2015 and 3115 (continued from previous page)

Radionuclide	Radionuclide Concentration, µCi per gram of total solids											
	2015	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
Tl-210	1.7E-09	5.3E-09	9.4E-09	1.4E-08	2.0E-08	2.6E-08	3.2E-08	4.0E-08	4.8E-08	5.6E-08	6.5E-08	7.5E-08
Pb-209	6.7E-04	1.9E-03	3.1E-03	4.3E-03	5.5E-03	6.6E-03	7.8E-03	8.9E-03	1.0E-02	1.1E-02	1.2E-02	1.3E-02
Pb-210	4.2E-06	2.0E-05	3.8E-05	6.0E-05	8.5E-05	1.1E-04	1.4E-04	1.8E-04	2.1E-04	2.5E-04	3.0E-04	3.4E-04
Pb-211	3.8E-07	1.7E-06	3.0E-06	4.4E-06	5.7E-06	7.1E-06	8.4E-06	9.8E-06	1.1E-05	1.2E-05	1.4E-05	1.5E-05
Pb-212	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03
Pb-214	8.3E-06	2.5E-05	4.5E-05	6.7E-05	9.3E-05	1.2E-04	1.5E-04	1.9E-04	2.3E-04	2.7E-04	3.1E-04	3.6E-04
Bi-210	4.2E-06	2.0E-05	3.8E-05	6.0E-05	8.5E-05	1.1E-04	1.4E-04	1.8E-04	2.1E-04	2.5E-04	3.0E-04	3.4E-04
Bi-211	3.8E-07	1.7E-06	3.0E-06	4.4E-06	5.7E-06	7.1E-06	8.4E-06	9.8E-06	1.1E-05	1.2E-05	1.4E-05	1.5E-05
Bi-212	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03
Bi-213	6.7E-04	1.9E-03	3.1E-03	4.3E-03	5.5E-03	6.6E-03	7.8E-03	8.9E-03	1.0E-02	1.1E-02	1.2E-02	1.3E-02
Bi-214	8.3E-06	2.5E-05	4.5E-05	6.7E-05	9.3E-05	1.2E-04	1.5E-04	1.9E-04	2.3E-04	2.7E-04	3.1E-04	3.6E-04
Po-210	4.2E-06	2.0E-05	3.8E-05	6.0E-05	8.5E-05	1.1E-04	1.4E-04	1.8E-04	2.1E-04	2.5E-04	3.0E-04	3.4E-04
Po-212	1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03
Po-213	6.6E-04	1.8E-03	3.0E-03	4.2E-03	5.3E-03	6.5E-03	7.6E-03	8.7E-03	9.9E-03	1.1E-02	1.2E-02	1.3E-02
Po-214	8.3E-06	2.5E-05	4.5E-05	6.7E-05	9.3E-05	1.2E-04	1.5E-04	1.9E-04	2.3E-04	2.7E-04	3.1E-04	3.6E-04
Po-216	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03
Po-218	8.3E-06	2.5E-05	4.5E-05	6.7E-05	9.3E-05	1.2E-04	1.5E-04	1.9E-04	2.3E-04	2.7E-04	3.1E-04	3.6E-04
At-217	6.7E-04	1.9E-03	3.1E-03	4.3E-03	5.5E-03	6.6E-03	7.8E-03	8.9E-03	1.0E-02	1.1E-02	1.2E-02	1.3E-02
Rn-219	0	0	0	0	5.7E-06	7.1E-06	8.4E-06	9.8E-06	1.1E-05	1.2E-05	1.4E-05	1.5E-05
Rn-220	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03
Rn-222	8.3E-06	2.5E-05	4.5E-05	6.7E-05	9.3E-05	1.2E-04	1.5E-04	1.9E-04	2.3E-04	2.7E-04	3.1E-04	3.6E-04
Fr-221	6.7E-04	1.9E-03	3.1E-03	4.3E-03	5.5E-03	6.6E-03	7.8E-03	8.9E-03	1.0E-02	1.1E-02	1.2E-02	1.3E-02
Fr-223	5.2E-09	2.3E-08	4.2E-08	6.0E-08	7.9E-08	9.8E-08	1.2E-07	1.3E-07	1.5E-07	1.7E-07	1.9E-07	2.1E-07
Ra-223	3.8E-07	1.7E-06	3.0E-06	4.4E-06	5.7E-06	7.1E-06	8.4E-06	9.8E-06	1.1E-05	1.2E-05	1.4E-05	1.5E-05
Ra-224	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03
Ra-225	6.7E-04	1.9E-03	3.1E-03	4.3E-03	5.5E-03	6.6E-03	7.8E-03	8.9E-03	1.0E-02	1.1E-02	1.2E-02	1.3E-02
Ra-226	8.3E-06	2.5E-05	4.5E-05	6.7E-05	9.3E-05	1.2E-04	1.5E-04	1.9E-04	2.3E-04	2.7E-04	3.1E-04	3.6E-04
Ra-228	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03
Ac-225	6.7E-04	1.9E-03	3.1E-03	4.3E-03	5.5E-03	6.6E-03	7.8E-03	8.9E-03	1.0E-02	1.1E-02	1.2E-02	1.3E-02
Ac-227	3.8E-07	1.7E-06	3.0E-06	4.4E-06	5.7E-06	7.1E-06	8.4E-06	9.8E-06	1.1E-05	1.2E-05	1.4E-05	1.5E-05
Ac-228	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03
Th-227	3.7E-07	1.6E-06	3.0E-06	4.3E-06	5.6E-06	7.0E-06	8.3E-06	9.6E-06	1.1E-05	1.2E-05	1.4E-05	1.5E-05
Th-228	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03
Th-229	6.7E-04	1.9E-03	3.1E-03	4.3E-03	5.5E-03	6.6E-03	7.8E-03	8.9E-03	1.0E-02	1.1E-02	1.2E-02	1.3E-02
Th-230	3.8E-04	4.4E-04	5.3E-04	6.2E-04	7.2E-04	8.2E-04	9.3E-04	1.0E-03	1.1E-03	1.2E-03	1.3E-03	1.4E-03
Th-231	6.4E-04	6.4E-04	6.4E-04	6.4E-04	6.5E-04	6.5E-04	6.5E-04	6.5E-04	6.5E-04	6.5E-04	6.5E-04	6.5E-04
Th-232	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03
Th-234	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02
Pa-231	7.3E-07	2.1E-06	3.4E-06	4.8E-06	6.1E-06	7.5E-06	8.8E-06	1.0E-05	1.2E-05	1.3E-05	1.4E-05	1.6E-05
Pa-233	2.2E-02	2.3E-02	2.4E-02	2.5E-02	2.6E-02	2.6E-02	2.7E-02	2.7E-02	2.8E-02	2.8E-02	2.8E-02	2.9E-02

Table 4-4. Radionuclide Concentrations Between Calendar Years 2015 and 3115 (continued from previous page)

Radionuclide	Radionuclide Concentration, μCi per gram of total solids											
	2015	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
Pa-234	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05
Pa-234m	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02
U-233	1.3E-01	1.3E-01	1.3E-01	1.3E-01	1.3E-01	1.3E-01	1.3E-01	1.3E-01	1.3E-01	1.3E-01	1.3E-01	1.3E-01
U-234	5.0E-02	8.4E-02	9.9E-02	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01
U-235	6.4E-04	6.4E-04	6.4E-04	6.4E-04	6.5E-04	6.5E-04	6.5E-04	6.5E-04	6.5E-04	6.5E-04	6.5E-04	6.5E-04
U-235m	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01
U-236	1.1E-03	1.1E-03	1.1E-03	1.1E-03	1.1E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03
U-237	1.2E-03	9.3E-06	1.4E-07	7.0E-08	6.9E-08	6.9E-08	6.8E-08	6.8E-08	6.8E-08	6.7E-08	6.7E-08	6.6E-08
U-238	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02
U-240	0	0	<6.2E-10	<8.7E-10	<1.1E-09	<1.4E-09	<1.6E-09	<1.9E-09	<2.1E-09	<2.3E-09	<2.6E-09	<2.8E-09
Np-237	2.2E-02	2.3E-02	2.4E-02	2.5E-02	2.6E-02	2.6E-02	2.7E-02	2.7E-02	2.8E-02	2.8E-02	2.8E-02	2.9E-02
Np-238	1.5E-04	9.5E-05	5.8E-05	3.5E-05	2.2E-05	1.3E-05	8.1E-06	4.9E-06	3.0E-06	1.9E-06	1.1E-06	6.9E-07
Np-239	5.7E-01	5.6E-01	5.6E-01	5.5E-01	5.5E-01	5.4E-01	5.4E-01	5.3E-01	5.3E-01	5.2E-01	5.2E-01	5.1E-01
Np-240	<1.3E-10	<3.7E-10	<6.2E-10	<8.7E-10	<1.1E-09	<1.4E-09	<1.6E-09	<1.9E-09	<2.1E-09	<2.3E-09	<2.6E-09	<2.8E-09
Pu-238	1.8E+02	7.9E+01	3.6E+01	1.6E+01	7.4E+00	3.4E+00	1.5E+00	6.9E-01	3.1E-01	1.4E-01	6.5E-02	3.0E-02
Pu-239	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01	1.3E+01
Pu-240	4.1E+00	4.1E+00	4.1E+00	4.0E+00	4.0E+00	3.9E+00	3.9E+00	3.9E+00	3.8E+00	3.8E+00	3.7E+00	3.7E+00
Pu-241	4.7E+01	3.8E-01	5.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.7E-03	2.7E-03	2.7E-03
Pu-242	<2.3E-02	<2.3E-02	<2.3E-02	<2.3E-02	<2.3E-02	<2.3E-02	<2.3E-02	<2.3E-02	<2.3E-02	<2.3E-02	<2.3E-02	<2.3E-02
Pu-243	<9.3E-08	<1.3E-07	<1.7E-07	<2.0E-07	<2.3E-07	<2.6E-07	<2.8E-07	<3.1E-07	<3.3E-07	<3.5E-07	<3.7E-07	<3.9E-07
Pu-244	<1.3E-10	<3.8E-10	<6.2E-10	<8.7E-10	<1.1E-09	<1.4E-09	<1.6E-09	<1.9E-09	<2.1E-09	<2.3E-09	<2.6E-09	<2.8E-09
Am-241	3.7E+01	3.3E+01	2.8E+01	2.4E+01	2.0E+01	1.7E+01	1.5E+01	1.3E+01	1.1E+01	9.2E+00	7.8E+00	6.6E+00
Am-242	3.3E-02	2.0E-02	1.2E-02	7.6E-03	4.7E-03	2.8E-03	1.7E-03	1.1E-03	6.5E-04	4.0E-04	2.4E-04	1.5E-04
Am-242m	3.3E-02	2.0E-02	1.3E-02	7.6E-03	4.7E-03	2.9E-03	1.7E-03	1.1E-03	6.5E-04	4.0E-04	2.4E-04	1.5E-04
Am-243	5.7E-01	5.6E-01	5.6E-01	5.5E-01	5.5E-01	5.4E-01	5.4E-01	5.3E-01	5.3E-01	5.2E-01	5.2E-01	5.1E-01
Cm-242	2.8E-02	1.7E-02	1.0E-02	6.4E-03	3.9E-03	2.4E-03	1.5E-03	8.9E-04	5.4E-04	3.3E-04	2.0E-04	1.2E-04
Cm-243	<3.6E-01	<3.6E-02	<3.5E-03	<3.5E-04	<3.5E-05	<3.4E-06	<3.4E-07	<3.4E-08	<3.3E-09	<3.3E-10	<3.3E-11	<3.3E-12
Cm-244	1.7E+01	3.5E-01	7.5E-03	1.6E-04	3.4E-06	7.1E-08	1.5E-09	3.2E-11	6.8E-13	0	0	0
Cm-245	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.7E-03	2.7E-03	2.7E-03	2.7E-03
Cm-246	7.3E-03	7.2E-03	7.1E-03	7.0E-03	6.9E-03	6.8E-03	6.7E-03	6.6E-03	6.5E-03	6.4E-03	6.3E-03	6.2E-03
Cm-247	<9.3E-08	<1.3E-07	<1.7E-07	<2.0E-07	<2.3E-07	<2.6E-07	<2.8E-07	<3.1E-07	<3.3E-07	<3.5E-07	<3.7E-07	<3.9E-07
Cm-248	<3.1E-04	<3.1E-04	<3.1E-04	<3.1E-04	<3.1E-04	<3.1E-04	<3.1E-04	<3.1E-04	<3.1E-04	<3.1E-04	<3.1E-04	<3.1E-04
Bk-247	<1.0E-03	<9.5E-04	<9.0E-04	<8.6E-04	<8.2E-04	<7.8E-04	<7.4E-04	<7.0E-04	<6.7E-04	<6.4E-04	<6.0E-04	<5.7E-04
Cf-249	<4.0E-03	<3.3E-03	<2.7E-03	<2.2E-03	<1.8E-03	<1.5E-03	<1.2E-03	<1.0E-03	<8.2E-04	<6.7E-04	<5.5E-04	<4.5E-04
Cf-250	<8.0E-05	<4.0E-07	<2.0E-09	<9.9E-12	<5.0E-14	0	0	0	0	0	0	0
Cf-251	<9.2E-03	<8.5E-03	<7.9E-03	<7.3E-03	<6.7E-03	<6.2E-03	<5.8E-03	<5.3E-03	<4.9E-03	<4.6E-03	<4.2E-03	<3.9E-03
Cf-252	<1.1E-02	0	0	0	0	0	0	0	0	0	0	0
Sum	2.7E+04	2.7E+03	3.7E+02	1.2E+02	7.7E+01	6.2E+01	5.4E+01	5.0E+01	4.7E+01	4.5E+01	4.3E+01	4.2E+01

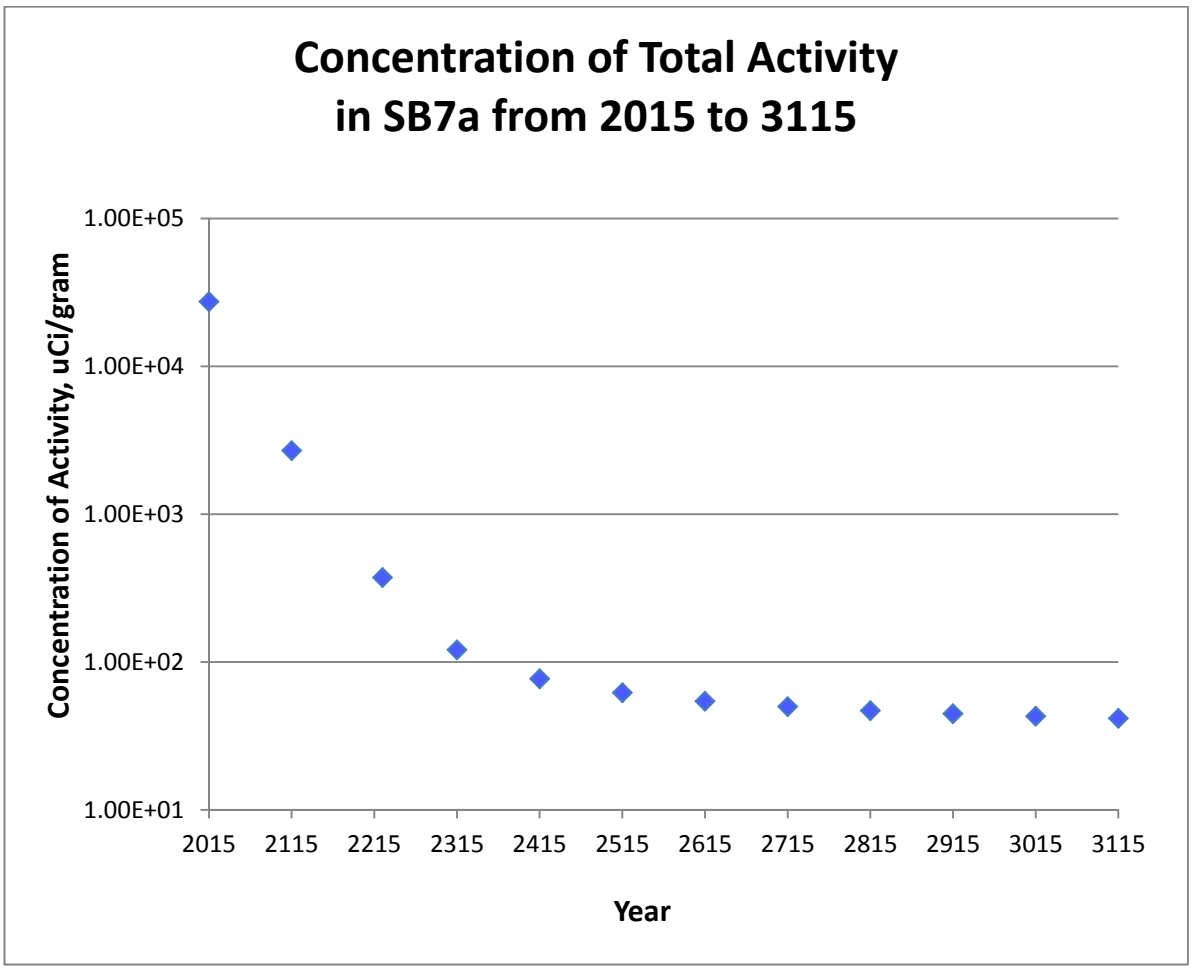

Figure 4-1. Concentration of Total Activity from 2015 to 3115

Table 4-5. Percentages of Curie Content Between Calendar Years 2015 and 3115

Radionuclide	Percentage of Radionuclide Inventory											
	2015	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
Cl-36	<9.1E-07	<9.3E-06	<6.7E-05	<2.1E-04	<3.2E-04	<4.0E-04	<4.6E-04	<5.0E-04	<5.3E-04	<5.6E-04	<5.8E-04	<6.0E-04
Co-60	6.2E-03	1.2E-07	1.7E-12	0	0	0	0	0	0	0	0	0
Ni-59	**5.5E-03**	**5.6E-02**	**4.0E-01**	**1.2E+00**	**1.9E+00**	**2.4E+00**	**2.7E+00**	**3.0E+00**	**3.2E+00**	**3.3E+00**	**3.5E+00**	**3.6E+00**
Ni-63	**8.9E-02**	**4.6E-01**	**1.6E+00**	**2.5E+00**	**2.0E+00**	**1.3E+00**	**7.2E-01**	**3.9E-01**	**2.1E-01**	**1.1E-01**	**5.8E-02**	**3.0E-02**
Se-79	**2.8E-05**	**2.8E-04**	**2.0E-03**	**6.3E-03**	**9.8E-03**	**1.2E-02**	**1.4E-02**	**1.5E-02**	**1.6E-02**	**1.7E-02**	**1.8E-02**	**1.8E-02**
Sr-90	**4.7E+01**	**4.3E+01**	**2.8E+01**	**7.7E+00**	**1.1E+00**	**1.2E-01**	**1.2E-02**	**1.2E-03**	**1.2E-04**	**1.1E-05**	**1.0E-06**	**9.6E-08**
Y-90	4.7E+01	4.3E+01	2.8E+01	7.8E+00	1.1E+00	1.2E-01	1.2E-02	1.2E-03	1.2E-04	1.1E-05	1.0E-06	9.6E-08
Zr-93	**1.9E-03**	**2.0E-02**	**1.4E-01**	**4.4E-01**	**6.9E-01**	**8.6E-01**	**9.7E-01**	**1.1E+00**	**1.1E+00**	**1.2E+00**	**1.2E+00**	**1.3E+00**
Nb-93m	**1.7E-03**	**1.9E-02**	**1.4E-01**	**4.3E-01**	**6.7E-01**	**8.3E-01**	**9.5E-01**	**1.0E+00**	**1.1E+00**	**1.2E+00**	**1.2E+00**	**1.2E+00**
Tc-99	**3.6E-04**	**3.7E-03**	**2.7E-02**	**8.2E-02**	**1.3E-01**	**1.6E-01**	**1.8E-01**	**2.0E-01**	**2.1E-01**	**2.2E-01**	**2.3E-01**	**2.4E-01**
Ru-106	<2.2E-04	0	0	0	0	0	0	0	0	0	0	0
Rh-106	<2.2E-04	0	0	0	0	0	0	0	0	0	0	0
Pd-107	4.4E-06	4.5E-05	3.2E-04	9.9E-04	1.6E-03	1.9E-03	2.2E-03	2.4E-03	2.6E-03	2.7E-03	2.8E-03	2.9E-03
Cd-113m	9.5E-03	7.1E-04	3.8E-05	8.5E-07	9.8E-09	8.7E-11	7.3E-13	0	0	0	0	0
Sn-121	<1.5E-04	<4.5E-04	<9.1E-04	<8.0E-04	<3.5E-04	<1.2E-04	<4.0E-05	<1.2E-05	<3.8E-06	<1.1E-06	<3.3E-07	<9.6E-08
Sn-121m	<2.0E-04	<5.8E-04	<1.2E-03	<1.0E-03	<4.6E-04	<1.6E-04	<5.2E-05	<1.6E-05	<4.8E-06	<1.4E-06	<4.2E-07	<1.2E-07
Sn-126	**<2.3E-03**	**<2.4E-02**	**<1.7E-01**	**<5.3E-01**	**<8.3E-01**	**<1.0E+00**	**<1.2E+00**	**<1.3E+00**	**<1.4E+00**	**<1.4E+00**	**<1.5E+00**	**<1.5E+00**
Sb-125	<3.6E-04	<4.5E-14	0	0	0	0	0	0	0	0	0	0
Sb-126	<3.3E-04	<3.3E-03	<2.4E-02	<7.4E-02	<1.2E-01	<1.4E-01	<1.6E-01	<1.8E-01	<1.9E-01	<2.0E-01	<2.1E-01	<2.1E-01
Sb-126m	<2.3E-03	<2.4E-02	<1.7E-01	<5.3E-01	<8.3E-01	<1.0E+00	<1.2E+00	<1.3E+00	<1.4E+00	<1.4E+00	<1.5E+00	<1.5E+00
Sb-126m2	<1.6E-03	<1.6E-02	<1.1E-01	<3.5E-01	<5.5E-01	<6.9E-01	<7.9E-01	<8.6E-01	<9.1E-01	<9.6E-01	<9.9E-01	<1.0E+00
Te-125m	<8.6E-05	0	0	0	0	0	0	0	0	0	0	0
I-129	6.2E-06	6.3E-05	4.6E-04	1.4E-03	2.2E-03	2.7E-03	3.1E-03	3.4E-03	3.6E-03	3.8E-03	4.0E-03	4.1E-03
Cs-134	<8.9E-04	0	0	0	0	0	0	0	0	0	0	0
Cs-135	1.0E-05	1.0E-04	7.5E-04	2.3E-03	3.6E-03	4.5E-03	5.1E-03	5.6E-03	6.0E-03	6.3E-03	6.5E-03	6.7E-03
Cs-137	**2.0E+00**	**2.0E+00**	**1.4E+00**	**4.4E-01**	**6.9E-02**	**8.5E-03**	**9.6E-04**	**1.0E-04**	**1.1E-05**	**1.2E-06**	**1.2E-07**	**1.2E-08**
Ba-133	<5.8E-04	<8.2E-06	<8.3E-08	<3.5E-10	<7.8E-13	0	0	0	0	0	0	0
Ba-137m	1.9E+00	1.9E+00	1.4E+00	4.2E-01	6.5E-02	8.0E-03	9.1E-04	9.9E-05	1.0E-05	1.1E-06	1.1E-07	1.2E-08
Ce-144	<2.1E-04	0	0	0	0	0	0	0	0	0	0	0
Pr-144	<2.1E-04	0	0	0	0	0	0	0	0	0	0	0
Pr-144m	<2.9E-06	0	0	0	0	0	0	0	0	0	0	0
Nd-144	<1.5E-18	<1.6E-17	<1.2E-16	<3.7E-16	<5.7E-16	<7.1E-16	<8.1E-16	<8.9E-16	<9.5E-16	<9.9E-16	<1.0E-15	<1.1E-15
Pm-147	<2.3E-01	<7.9E-12	0	0	0	0	0	0	0	0	0	0
Sm-147	<5.1E-08	<5.2E-07	<3.7E-06	<1.2E-05	<1.8E-05	<2.3E-05	<2.6E-05	<2.8E-05	<3.0E-05	<3.1E-05	<3.3E-05	<3.4E-05
Sm-151	**8.2E-01**	**3.9E+00**	**1.3E+01**	**1.8E+01**	**1.3E+01**	**7.7E+00**	**4.0E+00**	**2.0E+00**	**1.0E+00**	**4.9E-01**	**2.3E-01**	**1.1E-01**
Eu-154	4.7E-02	1.5E-04	3.4E-07	3.3E-10	1.6E-13	0	0	0	0	0	0	0
Eu-155	5.7E-03	2.7E-08	9.0E-14	0	0	0	0	0	0	0	0	0
Tl-207	1.4E-09	6.1E-08	8.0E-07	3.6E-06	7.4E-06	1.1E-05	1.5E-05	2.0E-05	2.4E-05	2.8E-05	3.2E-05	3.6E-05
Tl-208	2.1E-06	2.1E-05	1.5E-04	4.7E-04	7.5E-04	9.3E-04	1.1E-03	1.2E-03	1.2E-03	1.3E-03	1.3E-03	1.4E-03
Tl-209	5.3E-08	1.5E-06	1.8E-05	7.6E-05	1.5E-04	2.3E-04	3.1E-04	3.9E-04	4.6E-04	5.4E-04	6.2E-04	7.0E-04

Table 4-5. Percentages of Curie Content Between Calendar Years 2015 and 3115 (continued from previous page)

Radionuclide	Percentage of Radionuclide Inventory											
	2015	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
Tl-210	6.3E-12	2.0E-10	2.5E-09	1.2E-08	2.5E-08	4.1E-08	5.9E-08	8.0E-08	1.0E-07	1.3E-07	1.5E-07	1.8E-07
Pb-209	2.4E-06	7.0E-05	8.3E-04	3.5E-03	7.1E-03	1.1E-02	1.4E-02	1.8E-02	2.1E-02	2.5E-02	2.9E-02	3.2E-02
Pb-210	1.5E-08	7.4E-07	1.0E-05	5.0E-05	1.1E-04	1.8E-04	2.6E-04	3.6E-04	4.6E-04	5.7E-04	6.9E-04	8.2E-04
Pb-211	1.4E-09	6.2E-08	8.1E-07	3.6E-06	7.4E-06	1.1E-05	1.5E-05	2.0E-05	2.4E-05	2.8E-05	3.2E-05	3.6E-05
Pb-212	5.8E-06	6.0E-05	4.3E-04	1.3E-03	2.1E-03	2.6E-03	2.9E-03	3.2E-03	3.4E-03	3.6E-03	3.7E-03	3.8E-03
Pb-214	3.0E-08	9.4E-07	1.2E-05	5.6E-05	1.2E-04	2.0E-04	2.8E-04	3.8E-04	4.8E-04	6.0E-04	7.2E-04	8.5E-04
Bi-210	1.5E-08	7.4E-07	1.0E-05	5.0E-05	1.1E-04	1.8E-04	2.6E-04	3.6E-04	4.6E-04	5.7E-04	6.9E-04	8.2E-04
Bi-211	1.4E-09	6.2E-08	8.1E-07	3.6E-06	7.4E-06	1.1E-05	1.5E-05	2.0E-05	2.4E-05	2.8E-05	3.2E-05	3.6E-05
Bi-212	5.8E-06	6.0E-05	4.3E-04	1.3E-03	2.1E-03	2.6E-03	2.9E-03	3.2E-03	3.4E-03	3.6E-03	3.7E-03	3.8E-03
Bi-213	2.4E-06	7.0E-05	8.3E-04	3.5E-03	7.1E-03	1.1E-02	1.4E-02	1.8E-02	2.1E-02	2.5E-02	2.9E-02	3.2E-02
Bi-214	3.0E-08	9.4E-07	1.2E-05	5.6E-05	1.2E-04	2.0E-04	2.8E-04	3.8E-04	4.8E-04	6.0E-04	7.2E-04	8.5E-04
Po-210	1.5E-08	7.3E-07	1.0E-05	4.9E-05	1.1E-04	1.8E-04	2.6E-04	3.6E-04	4.6E-04	5.7E-04	6.9E-04	8.2E-04
Po-212	3.7E-06	3.8E-05	2.7E-04	8.5E-04	1.3E-03	1.7E-03	1.9E-03	2.1E-03	2.2E-03	2.3E-03	2.4E-03	2.5E-03
Po-213	2.4E-06	6.9E-05	8.1E-04	3.5E-03	6.9E-03	1.0E-02	1.4E-02	1.8E-02	2.1E-02	2.5E-02	2.8E-02	3.2E-02
Po-214	3.0E-08	9.4E-07	1.2E-05	5.6E-05	1.2E-04	2.0E-04	2.8E-04	3.8E-04	4.8E-04	6.0E-04	7.2E-04	8.5E-04
Po-216	5.8E-06	6.0E-05	4.3E-04	1.3E-03	2.1E-03	2.6E-03	2.9E-03	3.2E-03	3.4E-03	3.6E-03	3.7E-03	3.8E-03
Po-218	3.0E-08	9.4E-07	1.2E-05	5.6E-05	1.2E-04	2.0E-04	2.8E-04	3.8E-04	4.8E-04	6.0E-04	7.2E-04	8.5E-04
At-217	2.4E-06	7.0E-05	8.3E-04	3.5E-03	7.1E-03	1.1E-02	1.4E-02	1.8E-02	2.1E-02	2.5E-02	2.9E-02	3.2E-02
Rn-219	0	0	0	0	7.4E-06	1.1E-05	1.5E-05	2.0E-05	2.4E-05	2.8E-05	3.2E-05	3.6E-05
Rn-220	5.8E-06	6.0E-05	4.3E-04	1.3E-03	2.1E-03	2.6E-03	2.9E-03	3.2E-03	3.4E-03	3.6E-03	3.7E-03	3.8E-03
Rn-222	3.0E-08	9.4E-07	1.2E-05	5.6E-05	1.2E-04	2.0E-04	2.8E-04	3.8E-04	4.8E-04	6.0E-04	7.2E-04	8.5E-04
Fr-221	2.4E-06	7.0E-05	8.3E-04	3.5E-03	7.1E-03	1.1E-02	1.4E-02	1.8E-02	2.1E-02	2.5E-02	2.9E-02	3.2E-02
Fr-223	1.9E-11	8.5E-10	1.1E-08	5.0E-08	1.0E-07	1.6E-07	2.1E-07	2.7E-07	3.3E-07	3.9E-07	4.4E-07	5.0E-07
Ra-223	1.4E-09	6.2E-08	8.1E-07	3.6E-06	7.4E-06	1.1E-05	1.5E-05	2.0E-05	2.4E-05	2.8E-05	3.2E-05	3.6E-05
Ra-224	5.8E-06	6.0E-05	4.3E-04	1.3E-03	2.1E-03	2.6E-03	2.9E-03	3.2E-03	3.4E-03	3.6E-03	3.7E-03	3.8E-03
Ra-225	2.4E-06	7.0E-05	8.3E-04	3.5E-03	7.1E-03	1.1E-02	1.4E-02	1.8E-02	2.1E-02	2.5E-02	2.9E-02	3.2E-02
Ra-226	3.0E-08	9.4E-07	1.2E-05	5.6E-05	1.2E-04	2.0E-04	2.8E-04	3.8E-04	4.8E-04	6.0E-04	7.2E-04	8.5E-04
Ra-228	5.8E-06	6.0E-05	4.3E-04	1.3E-03	2.1E-03	2.6E-03	2.9E-03	3.2E-03	3.4E-03	3.6E-03	3.7E-03	3.8E-03
Ac-225	2.4E-06	7.0E-05	8.3E-04	3.5E-03	7.1E-03	1.1E-02	1.4E-02	1.8E-02	2.1E-02	2.5E-02	2.9E-02	3.2E-02
Ac-227	1.4E-09	6.2E-08	8.1E-07	3.6E-06	7.4E-06	1.1E-05	1.5E-05	2.0E-05	2.4E-05	2.8E-05	3.2E-05	3.6E-05
Ac-228	5.8E-06	6.0E-05	4.3E-04	1.3E-03	2.1E-03	2.6E-03	2.9E-03	3.2E-03	3.4E-03	3.6E-03	3.7E-03	3.8E-03
Th-227	1.4E-09	6.1E-08	7.9E-07	3.5E-06	7.3E-06	1.1E-05	1.5E-05	1.9E-05	2.3E-05	2.8E-05	3.2E-05	3.6E-05
Th-228	5.8E-06	6.0E-05	4.3E-04	1.3E-03	2.1E-03	2.6E-03	2.9E-03	3.2E-03	3.4E-03	3.6E-03	3.7E-03	3.8E-03
Th-229	**2.5E-06**	**7.0E-05**	**8.3E-04**	**3.5E-03**	**7.1E-03**	**1.1E-02**	**1.4E-02**	**1.8E-02**	**2.1E-02**	**2.5E-02**	**2.9E-02**	**3.2E-02**
Th-230	1.4E-06	1.7E-05	1.4E-04	5.1E-04	9.4E-04	1.3E-03	1.7E-03	2.1E-03	2.4E-03	2.8E-03	3.1E-03	3.4E-03
Th-231	2.3E-06	2.4E-05	1.7E-04	5.3E-04	8.4E-04	1.0E-03	1.2E-03	1.3E-03	1.4E-03	1.5E-03	1.5E-03	1.6E-03
Th-232	5.8E-06	6.0E-05	4.3E-04	1.3E-03	2.1E-03	2.6E-03	2.9E-03	3.2E-03	3.4E-03	3.6E-03	3.7E-03	3.8E-03
Th-234	5.5E-05	5.6E-04	4.0E-03	1.2E-02	1.9E-02	2.4E-02	2.8E-02	3.0E-02	3.2E-02	3.4E-02	3.5E-02	3.6E-02
Pa-231	2.7E-09	7.7E-08	9.2E-07	3.9E-06	8.0E-06	1.2E-05	1.6E-05	2.0E-05	2.5E-05	2.9E-05	3.3E-05	3.7E-05
Pa-233	8.0E-05	8.6E-04	6.5E-03	2.1E-02	3.3E-02	4.3E-02	4.9E-02	5.5E-02	5.9E-02	6.3E-02	6.6E-02	6.9E-02

Table 4-5. Percentages of Curie Content Between Calendar Years 2015 and 3115 (continued from previous page)

Radionuclide	Percentage of Radionuclide Inventory											
	2015	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
Pa-234	8.2E-08	8.4E-07	6.0E-06	1.9E-05	2.9E-05	3.6E-05	4.1E-05	4.5E-05	4.8E-05	5.0E-05	5.2E-05	5.4E-05
Pa-234m	5.5E-05	5.6E-04	4.0E-03	1.2E-02	1.9E-02	2.4E-02	2.8E-02	3.0E-02	3.2E-02	3.4E-02	3.5E-02	3.6E-02
U-233	**4.7E-04**	**4.8E-03**	**3.5E-02**	**1.1E-01**	**1.7E-01**	**2.1E-01**	**2.4E-01**	**2.6E-01**	**2.8E-01**	**2.9E-01**	**3.0E-01**	**3.1E-01**
U-234	**1.8E-04**	**3.1E-03**	**2.7E-02**	**8.8E-02**	**1.4E-01**	**1.8E-01**	**2.1E-01**	**2.2E-01**	**2.4E-01**	**2.5E-01**	**2.6E-01**	**2.7E-01**
U-235	2.3E-06	2.4E-05	1.7E-04	5.3E-04	8.4E-04	1.0E-03	1.2E-03	1.3E-03	1.4E-03	1.5E-03	1.5E-03	1.6E-03
U-235m	4.7E-02	4.8E-01	3.5E+00	1.1E+01	1.7E+01	2.1E+01	2.4E+01	2.6E+01	2.7E+01	2.8E+01	2.9E+01	3.0E+01
U-236	4.0E-06	4.1E-05	3.0E-04	9.4E-04	1.5E-03	1.9E-03	2.2E-03	2.4E-03	2.5E-03	2.7E-03	2.8E-03	2.9E-03
U-237	4.2E-06	3.5E-07	3.8E-08	5.7E-08	8.9E-08	1.1E-07	1.3E-07	1.4E-07	1.4E-07	1.5E-07	1.6E-07	1.6E-07
U-238	**5.5E-05**	**5.6E-04**	**4.0E-03**	**1.2E-02**	**1.9E-02**	**2.4E-02**	**2.8E-02**	**3.0E-02**	**3.2E-02**	**3.4E-02**	**3.5E-02**	**3.6E-02**
U-240	0	0	<1.7E-10	<7.2E-10	<1.4E-09	<2.2E-09	<3.0E-09	<3.7E-09	<4.5E-09	<5.2E-09	<6.0E-09	<6.8E-09
Np-237	**8.0E-05**	**8.6E-04**	**6.5E-03**	**2.1E-02**	**3.3E-02**	**4.3E-02**	**4.9E-02**	**5.5E-02**	**5.9E-02**	**6.3E-02**	**6.6E-02**	**6.9E-02**
Np-238	5.6E-07	3.5E-06	1.6E-05	2.9E-05	2.8E-05	2.1E-05	1.5E-05	9.9E-06	6.5E-06	4.1E-06	2.6E-06	1.7E-06
Np-239	2.1E-03	2.1E-02	1.5E-01	4.6E-01	7.1E-01	8.8E-01	9.9E-01	1.1E+00	1.1E+00	1.2E+00	1.2E+00	1.2E+00
Np-240	<4.7E-13	<1.4E-11	<1.7E-10	<7.2E-10	<1.4E-09	<2.2E-09	<3.0E-09	<3.7E-09	<4.5E-09	<5.2E-09	<6.0E-09	<6.8E-09
Pu-238	**6.4E-01**	**3.0E+00**	**9.7E+00**	**1.3E+01**	**9.6E+00**	**5.4E+00**	**2.8E+00**	**1.4E+00**	**6.7E-01**	**3.2E-01**	**1.5E-01**	**7.1E-02**
Pu-239	**4.7E-02**	**4.8E-01**	**3.5E+00**	**1.1E+01**	**1.7E+01**	**2.1E+01**	**2.4E+01**	**2.6E+01**	**2.7E+01**	**2.8E+01**	**2.9E+01**	**3.0E+01**
Pu-240	**1.5E-02**	**1.5E-01**	**1.1E+00**	**3.3E+00**	**5.2E+00**	**6.4E+00**	**7.2E+00**	**7.7E+00**	**8.1E+00**	**8.4E+00**	**8.7E+00**	**8.9E+00**
Pu-241	**1.7E-01**	**1.4E-02**	**1.5E-03**	**2.3E-03**	**3.6E-03**	**4.5E-03**	**5.1E-03**	**5.5E-03**	**5.9E-03**	**6.1E-03**	**6.3E-03**	**6.5E-03**
Pu-242	**<8.4E-05**	**<8.6E-04**	**<6.2E-03**	**<1.9E-02**	**<3.0E-02**	**<3.7E-02**	**<4.2E-02**	**<4.6E-02**	**<4.9E-02**	**<5.1E-02**	**<5.3E-02**	**<5.5E-02**
Pu-243	<3.4E-10	<4.9E-09	<4.5E-08	<1.6E-07	<3.0E-07	<4.2E-07	<5.2E-07	<6.2E-07	<7.1E-07	<7.9E-07	<8.6E-07	<9.3E-07
Pu-244	<4.7E-13	<1.4E-11	<1.7E-10	<7.2E-10	<1.4E-09	<2.2E-09	<3.0E-09	<3.7E-09	<4.5E-09	<5.3E-09	<6.0E-09	<6.8E-09
Am-241	**1.4E-01**	**1.2E+00**	**7.5E+00**	**2.0E+01**	**2.6E+01**	**2.8E+01**	**2.7E+01**	**2.5E+01**	**2.3E+01**	**2.0E+01**	**1.8E+01**	**1.6E+01**
Am-242	1.2E-04	7.6E-04	3.3E-03	6.3E-03	6.0E-03	4.6E-03	3.2E-03	2.1E-03	1.4E-03	8.9E-04	5.7E-04	3.6E-04
Am-242m	1.2E-04	7.6E-04	3.3E-03	6.3E-03	6.1E-03	4.6E-03	3.2E-03	2.1E-03	1.4E-03	8.9E-04	5.7E-04	3.6E-04
Am-243	**2.1E-03**	**2.1E-02**	**1.5E-01**	**4.6E-01**	**7.1E-01**	**8.8E-01**	**9.9E-01**	**1.1E+00**	**1.1E+00**	**1.2E+00**	**1.2E+00**	**1.2E+00**
Cm-242	1.0E-04	6.3E-04	2.8E-03	5.2E-03	5.0E-03	3.8E-03	2.7E-03	1.8E-03	1.2E-03	7.4E-04	4.7E-04	3.0E-04
Cm-243	<1.3E-03	<1.3E-03	<9.5E-04	<2.9E-04	<4.5E-05	<5.5E-06	<6.2E-07	<6.8E-08	<7.1E-09	<7.4E-10	<7.6E-11	<7.8E-12
Cm-244	**6.0E-02**	**1.3E-02**	**2.0E-03**	**1.3E-04**	**4.4E-06**	**1.1E-07**	**2.8E-09**	**6.4E-11**	**1.5E-12**	**0**	**0**	**0**
Cm-245	1.0E-05	1.0E-04	7.5E-04	2.3E-03	3.6E-03	4.5E-03	5.1E-03	5.5E-03	5.9E-03	6.1E-03	6.3E-03	6.5E-03
Cm-246	**2.7E-05**	**2.7E-04**	**1.9E-03**	**5.8E-03**	**8.9E-03**	**1.1E-02**	**1.2E-02**	**1.3E-02**	**1.4E-02**	**1.4E-02**	**1.5E-02**	**1.5E-02**
Cm-247	<3.4E-10	<4.9E-09	<4.5E-08	<1.6E-07	<3.0E-07	<4.2E-07	<5.2E-07	<6.2E-07	<7.1E-07	<7.9E-07	<8.6E-07	<9.3E-07
Cm-248	<1.1E-06	<1.2E-05	<8.3E-05	<2.6E-04	<4.0E-04	<5.0E-04	<5.7E-04	<6.2E-04	<6.6E-04	<6.9E-04	<7.2E-04	<7.4E-04
Bk-247	<3.6E-06	<3.5E-05	<2.4E-04	<7.1E-04	<1.1E-03	<1.3E-03	<1.4E-03	<1.4E-03	<1.4E-03	<1.4E-03	<1.4E-03	<1.4E-03
Cf-249	<1.4E-05	<1.2E-04	<7.2E-04	<1.8E-03	<2.3E-03	<2.4E-03	<2.2E-03	<2.0E-03	<1.7E-03	<1.5E-03	<1.3E-03	<1.1E-03
Cf-250	<2.9E-07	<1.5E-08	<5.3E-10	<8.2E-12	<6.4E-14	0	0	0	0	0	0	0
Cf-251	**<3.3E-05**	**<3.2E-04**	**<2.1E-03**	**<6.0E-03**	**<8.7E-03**	**<1.0E-02**	**<1.1E-02**	**<1.1E-02**	**<1.1E-02**	**<1.0E-02**	**<9.9E-03**	**<9.4E-03**
Cf-252	<4.1E-05	0	0	0	0	0	0	0	0	0	0	0
Sum	1.00E+02	1.00E+02	1.00E+02	1.00E+02	1.00E+02	1.00E+02	1.00E+02	1.00E+02	1.00E+02	1.00E+02	1.00E+02	1.00E+02

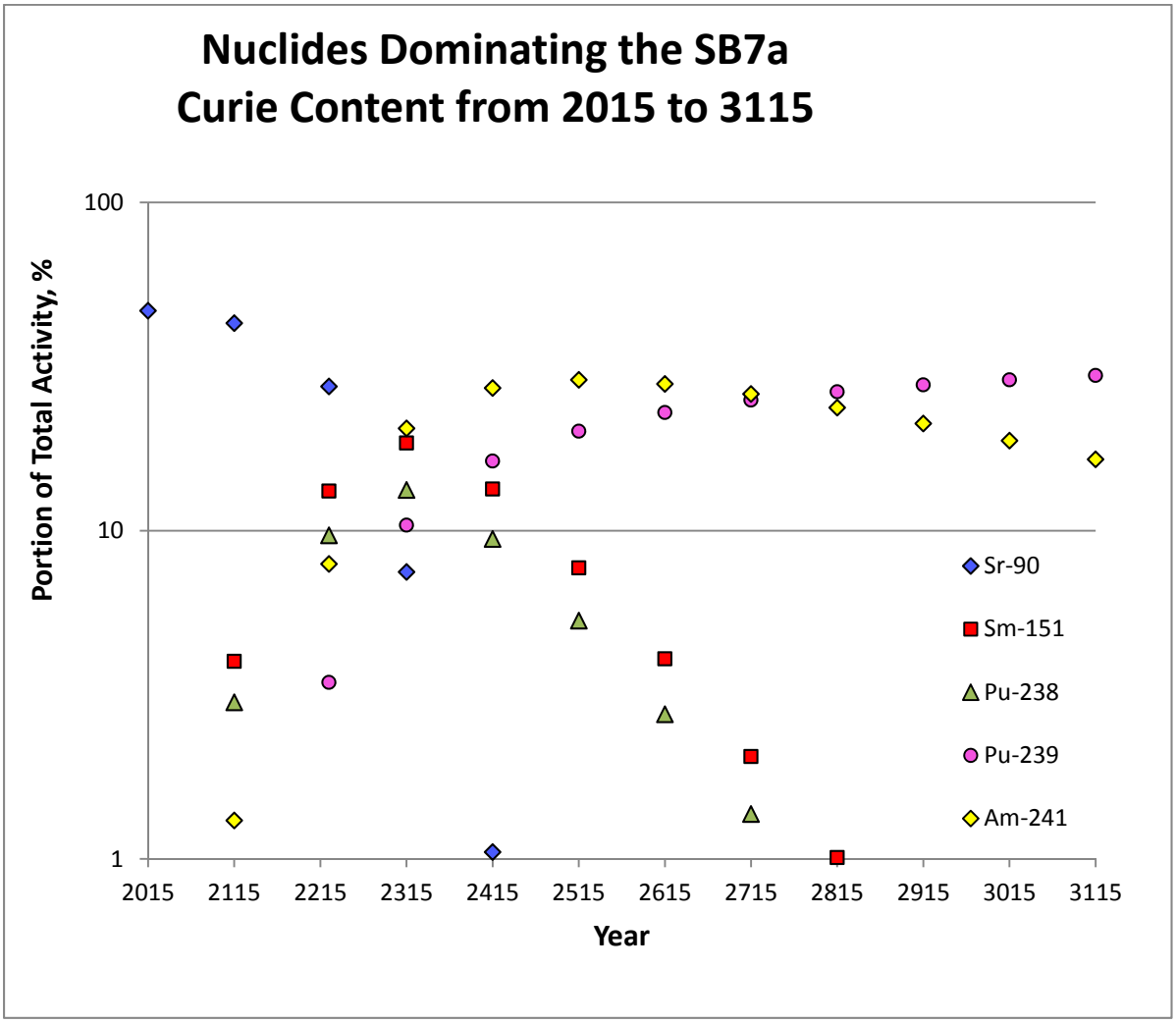

Figure 4-2. Portions of Curie Content Contributed by the Dominant Radionuclides

4.4 Reportable Nuclides

Radionuclides contributing ≥ 0.01 percent of the total curie content and having a half-lives ≥ 10 years have been highlighted in Table 4-5, using bold font and grey-shading. The twenty-five radionuclides meeting these criteria are identified in Table 4-6. Note that three of the nuclides were identified as reportable based on analytical detection limits (versus detected concentrations).

Table 4-6. Radionuclides Contributing ≥ 0.01% of the Curies and Having t_H ≥ 10 years

Ni-59	**Ni-63**	**Se-79**	**Sr-90**	**Zr-93**
Nb-93m	**Tc-99**	**Sn-126***	**Cs-137**	**Sm-151**
Th-229	**U-233**	**U-234**	**U-238**	**Np-237**
Pu-238	**Pu-239**	**Pu-240**	**Pu-241**	**Pu-242***
Am-241	**Am-243**	**Cm-244**	**Cm-246**	**Cf-251***

*These nuclides were identified based on analytical detection limits (rather than detectable concentrations)

With this list of nuclides, it is noted that all of the radionuclides in the Design Basis glass are reportable with the following three exceptions: Pd-107, Cs-135, and Th-230. It is also noted that three of the radionuclides identified as reportable for SB7a are not on the Design Basis list or the U and Pu isotope list identified in WAPS 1.6. Those three radionuclides are Th-229, Cm-246, and Cf-251.

A comparison of the reportable radionuclides for SB7a with those of previous sludge batches is given in Table 4-7. As shown in the table, all of the reportable nuclides in SB7a were ones that had been reportable in two or more previous sludge batches.

Although not identified in Table 4-6 or Table 4-7, U-235 and U-236 are automatically considered reportable per the requirements of WAPS 1.6. Taking these nuclides into account means that the SB7a waste contains a grand total of twenty-seven reportable radionuclides.

Table 4-7. Reportable Radionuclides for Sludge Batches 1B to 7a

Radionuclide	SB1b[17]	SB2[9]	SB3[18]	SB4[19]	SB5[20]	SB6[10]	SB7a
C-14	X	X					
Cl-36					X		
Ni-59	X	X	X	X	X	X	X
Ni-63	X	X	X	X	X	X	X
Se-79	X	X	X	X		X	X
Sr-90	X	X	X	X	X	X	X
Zr-93	X	X	X	X	X	X	X
Nb-93m	X	X	X	X	X	X	X
Tc-99	X	X	X	X	X	X	X
Sn-121m	X	X	X			X	
Sn-126	X	X	X	X	X	X	X
I-129	X						
Cs-137	X	X	X	X	X	X	X
Sm-151	X	X	X	X	X	X	X
Th-229	X					X	X
U-233	X	X	X	X	X	X	X
U-234	X	X	X	X	X	X	X
U-238	X	X	X	X	X	X	X
Np-237	X	X	X	X	X	X	X
Pu-238	X	X	X	X	X	X	X
Pu-239	X	X	X	X	X	X	X
Pu-240	X	X	X	X	X	X	X
Pu-241	X	X	X	X	X	X	X
Pu-242	X	X	X	X	X	X	X
Am-241	X	X	X	X	X	X	X
Am-242m			X	X	X	X	
Am-243	X	X	X	X	X	X	X
Cm-244	X	X	X	X	X	X	X
Cm-245		X	X	X	X	X	
Cm-246	X	X	X	X	X	X	X
Cm-247			X	X			
Cm-248			X	X		X	
Bk-247				X			
Cf-249			X			X	
Cf-251		X	X	X	X	X	X

5.0 Conclusions

1) The reportable radionuclides for SB7a are consistent with those of previous sludge batches. No new reportable radionuclides were found in the SB7a waste. The nuclides contributing ≥ 0.01 percent of the total curie content from 2015 to 3115 and having half-lives ≥ 10 years in the SB7a waste include:

Ni-59	**Ni-63**	**Se-79**	**Sr-90**	**Zr-93**
Nb-93m	**Tc-99**	**Sn-126**	**Cs-137**	**Sm-151**
Th-229	**U-233**	**U-234**	**U-238**	**Np-237**
Pu-238	**Pu-239**	**Pu-240**	**Pu-241**	**Pu-242**
Am-241	**Am-243**	**Cm-244**	**Cm-246**	**Cf-251**

As in other previous sludge batches, Pd-107, Cs-135, and Th-230 were not found to be reportable, despite being identified in the glass design basis. Also as in other previous sludge batches, Th-229, Cm-246, and Cf-251 were found to be reportable despite their absence from the list of radionuclides identified in the glass design basis.

In this and all sludge batches, U-235 and U-236 are considered reportable per the requirements of WAPS 1.6.

2) Between the years of 2015 and 3115, the total curie content of SB7a will drop by three orders of magnitude. Over this period, Sr-90 (and its short-lived decay product Y-90) will be the dominant contributors of activity between 2015 and 2215; Sm-151 and Pu-238 will become significant contributors of activity between 2215 and 2415; and Pu-239 (as well as its short-lived decay product U-235m) and Am-241 will be the dominant contributors of activity between 2415 and 3115.

3) Three of the reportable radionuclides in SB7a were identified based upon minimum detection limits, as opposed to true detectable concentrations. These three nuclides were Sn-126, Pu-242, and Cf-251. Methodologies for reducing the minimum detection limits of these particular analytes could be pursued in the future, if more accurate projections are needed. This would improve the ability for making a clear determination of whether or not these radionuclides are reportable.

6.0 References

1 Office of Environmental Management. *Waste Acceptance Product Specifications for Vitrified High-Level Waste Forms*, DOE/EM-0093, Revision 2, December 1996.

2 Washington Savannah River Company. *DWPF Waste Form Compliance Plan*, WSRC-IM-91-116-0, Revision 8, March 2006.

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4 Bricker, J. M. *Technical Task Request: Sludge Batch 7 Shielded Cells Testing*, Savannah River Remediation, HLW-DWPF-TTR-2010-0031, Revision 0, July 20, 2010.

5 Ray, J. W. *E-mail Revision to HLW-DWPF-TTR-2010-0031*, Savannah River Remediation, Email Message from J. W. Ray to S. H. Reboul, November 15, 2011 (see Appendix A).

6 Pareizs, J. M. *Task Technical and Quality Assurance Plan for Sludge Batch 7 Qualification in the Shielded Cells*, Savannah River National Laboratory, SRNL-RP-2010-01218, Revision 0, August 19, 2010.

7 Pareizs, J. M. *Analytical Study Plan for Sludge Batch 7 Qualification in the Shielded Cells*, Savannah River National Laboratory, SRNL-RP-2010-01219, Revision 0, September 13, 2010.

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Appendix A: TTR Revision

E-mail Revision to HLW-DWPF-TTR-2010-0031
Jeff Ray to: Scott Reboul 11/15/2011 04:41 PM
Cc: Connie Herman, Terri Fellinger, Jonathan Bricker, Amanda Shafer, Herbert Elder

Scott,
Per our phone conversation, see the revised wording for the WAPS Report task in the Sludge Batch 7A Shielded Cells TTR (specifically, Task II, Item 2). As discussed in the TTR, "Additions and/or deletions to Tasks I, II and II, if required, will be communicated via electronic mail."

BEFORE

2. Report the radionuclide composition for waste acceptance purposes. Report radionuclides which have half lives greater than 10 years and those that will be present in greater than 0.01% of the total activity at any time up to 1100 years after production (per WSRC-IM-91-116-4). In addition, report compositions for Ru-106, Rh-106, Cs-134, Ce-144, and Pr-144 (not included in WAPS reporting criteria). All compositions shall be reported in curies per gram (Ci/g) of dried sludge, curies per gal (Ci/gal) of sludge slurry, and weight percent in total dried solids.

AFTER

2. Report the radionuclide composition for waste acceptance purposes. Report radionuclides which have half lives greater than 10 years and those that will be present in greater than 0.01% of the total activity at any time up to 1100 years after production (per WSRC-IM-91-116-4). In addition, report compositions for Ru-106, Rh-106, Cs-134, Ce-144, and Pr-144 (not included in WAPS reporting criteria). For the initial characterization, compositions shall be reported in microcuries per gram (µCi/g) of dried sludge, curies per gal (Ci/gal) of sludge slurry, and weight percent in total dried solids. For the identification of reportable radionuclides through the 1100 year time period, isotopic concentrations shall be reported in µCi/g of dried sludge.

Thanks. Please call if you have any questions.

Jeff
8-7194 / 19101

Appendix B: Descriptions of the Analytical Methods

Direct Methods

ICP-MS
Inductively coupled plasma – mass spectrometry (ICP-MS) was utilized to analyze separate sub-samples of the aqua regia digestions of the Tank 40 – SB7a solids. Measurements were first converted to weight percents on a total solids basis and then converted to activities using the specific activity of each isotope taken from Reference 15. The isotopes obtained from direct ICP-MS measurements included: Zr-93, Tc-99, Th-232, U-233, U-234, U-235, U-236, U-238, Np-237, Pu-239, Pu-240, and Pu-242.

Gamma Counting
Gamma Pulse Height Analysis (PHA) was performed on separate sub-samples of the alkali fusion (also known as "peroxide fusion") digestions of the adjusted Tank 40 – SB7a solids. Detectors were calibrated with known standards. Since detection efficiencies for gamma-rays vary with energy, they were determined for these specific radionuclide energies during the calibration process. The counting geometry was established during calibration and duplicated for these measurements. Samples were diluted as necessary to achieve accurate counting. The isotopes obtained from Gamma PHA counting included: Cs-134 and Cs-137.

Separation Methods

These analytical methods involved separation techniques that enabled low concentrations of radionuclides to be measured more accurately and to have lower minimum detection limits. These techniques are now SRNL AD procedures and will only be summarized here. Aliquots of the alkali fusions or the aqua regia dissolutions were analyzed along with blanks. In all cases, the activity in the blanks did not contribute significant activity to the radionuclides being analyzed.

Cl-36 Method
Aliquots of the SB7a aqua regia digest solution were subjected to multiple resin based decontamination steps. Chlorine was then separated from the non-volatile components of the matrix via steam distillation. Additional resins were used to further decontaminate the distillate. The decontamination steps were followed by AgCl precipitation. The AgCl precipitate was counted using gas flow proportional counter analysis. The AgCl precipitate was then activated by neutron activation analysis to determine Cl losses during the processes. The HCl used to digest the samples was used to trace Cl-36 throughout the processes. The chlorine yields were used to correct Cl-36 results for any losses.

Ni-59/Ni-63 Method
This separation is based on isolation of Ni from the dissolved sludge using a column containing dimethylglyoxime as an extractant that is specific for Ni. Alkali fusion digest solutions of the SB7a solids were spiked with a stable Ni carrier to trace the Ni separation and were then passed through a column containing the Ni extractant. The sorbed Ni was then eluted from each column. The Ni-59 in the eluate was measured by its characteristic X-rays and Ni-63 by its beta radiation. Total Ni in each eluate was measured by ICP-AES. The radiochemical Ni measurements were corrected for the Ni carrier recoveries as measured by ICP-AES.

Se-79 Method
Aliquots of wet sludge slurry were spiked with a known amount of stable Se as a carrier. The samples were digested with concentrated nitric acid. The Fe in the dissolutions was reduced to Fe(II) using ascorbic acid to ensure it would not interfere with subsequent decontamination steps designed to extract Y-90, the lanthanides and the actinides from the Se traced dissolutions. The dissolutions were then treated with resins (Bio-Rad AMP-1, Eichrom Sr, RE, and Actinide resins) to reduce levels of Sr-90, Cs-137, Y-90, the lanthanides and the actinides to levels low enough to allow for their removal from the Shielded Cells. The Se traced dissolutions were then further decontaminated with a Bio-Rad AMP-1, Eichrom Sr and RE resin treatment. The total Se was reduced to Se metal using titanium (III) chloride, hydroxylamine hydrochloride, and ascorbic acid. The precipitated Se metal was then washed repeatedly with deionized water and dilute nitric acid. The Se metal was then dissolved with concentrated HBr, and the resulting $SeBr_4$ was extracted by solvent-solvent extraction using a tri-butyl phosphate/n-paraffin solvent extraction system. The Se was back extracted from the solvent. Aliquots of the purified Se fraction were then analyzed. A portion was neutron activated in a Cf-252 neutron source at SRNL to determine the total amount of Se present in order to calculate the recovery of Se from the radiochemical separation. A second portion was counted by liquid scintillation to determine the Se-79 beta activity. The yields of the stable Se carrier were applied to the Se-79 beta activity result to determine Se-79 activities in the sample aliquots initially treated.

Sr-90 Method
Aliquots of each sample from the alkali fusions were spiked with a stable Sr carrier, and a stable Ce carrier. The Sr carrier was used for separation yielding purposes and the Ce carrier was used to enhance the separation rates of undesirable isotopes such as Y-90, the lanthanides or the actinides. The spiked sample aliquots were initially oxidized using nitric acid. The Sr in the samples was extracted using commercially available Sr extraction resin. This resin also extracts some of the Pu under the conditions used to extract the Sr. The Pu was washed from the resin using an oxalic acid/nitric acid mixture. The Sr was eluted from the resin, and the resulting solution concentrated. A portion of the purified Sr solution was neutron activated in a Cf-252 neutron activation facility at SRNL to determine the total Sr and in order to calculate the fraction of Sr isolated by the procedure. A second portion of each of the Sr fractions was stored for five to seven days to allow Y-90 to grow in. Each fraction was then counted by liquid scintillation analysis to determine the Y-90 activity. The Sr-90 beta activity in each case was calculated from the Y-90 activity. The yields of the stable Sr carriers were applied to the Sr-90 beta activity results to determine Sr-90 activities in the original aliquots of the solutions resulting from the dissolution of the dried sludge slurry samples.

Gamma Counting Following Cs-137 Removal
This method was used to determine Co-60, Ru-106, Sn-121m, Sn-126, Sb-125, Ba-133, Ce-144, Eu-154, Eu-155, and Am-241. These gamma emitters could not be determined directly because of the high Cs-137 activity in the samples. Consequently the Cs-137 was removed. Aliquots of the alkali fusion digest solutions were treated with two batch additions of an ammonium phosphomolybdate resin to selectively remove the Cs-137 from the aliquots. This allowed gammas for isotopes at low concentrations to be detected or allowed lower detection limits to be determined for those isotopes that were not detected. The Cs-137 decontaminated aliquots were then gamma counted in two different detectors. The first was a high purity coaxial germanium detector to measure gamma rays from Co-60, Ru-106, Sn-126, Sb-125, Ba-133, Ce-144, Eu-154, Eu-155, and Am-241. To obtain reliable and lower detection limits for these radionuclides, each of the solutions was counted for four hours or more. The detection limits were used to calculate the maximum activity of each for input to the projection calculations. The second detector was a

Be thin window, semi-planar, high purity germanium detector. This detector has a high counting efficiency for the low energy gamma rays (37.2 keV) that are used to measure Sn-121m. This type of detector if often referred to as a LEPS detector, where LEPS is the acronym for Low Energy Photon Spectroscopy.

I-129 Method

The radionuclide I-129 is a long-lived beta emitting fission product (t_H = 1.6E+07 years) that is in SRS wastes. Aliquots of wet sludge slurry were spiked with a known amount of stable KI to act as an iodine tracer/carrier. The samples were digested with 8M nitric acid. The iodate/iodine in the samples was reduced with sodium sulfite to minimize losses of iodine in the Shielded Cells I-129 procedure. The Fe in the dissolutions was reduced to Fe(II) using ascorbic acid to ensure it would not interfere with subsequent decontamination steps designed to extract Y-90, the lanthanides and the actinides from the KI traced dissolutions. The dissolutions were then treated with resins (Bio-Rad AMP-1, Eichrom Sr, RE, and Actinide resins) to reduce levels of Sr-90, Cs-137, Y-90, the lanthanides and the actinides. The traced samples were then rendered caustic, treated a second time with a sodium sulfite reduction, and filtered to ensure Sr-90 and Y-90 levels were reduced low enough to allow for sample removal from the Shielded Cells. The samples were decontaminated a final time with a resin treatment to remove Cs-137 and the actinide elements. The solution was then treated with $AgNO_3$ in order to precipitate the iodide ion as AgI. The precipitate was analyzed by LEPS to determine the amount of I-129 present. I-129 is detected by its characteristic gamma and x-ray emissions. The precipitate was then neutron activated in a Cf-252 neutron source at SRNL to determine the total amount of iodine present in order to calculate the recovery of I-129 in the radiochemical separation.

Cs-135

Cs-135 is a long-lived beta emitting fission product (t_H = 3.0E+06 years). Due to its long life relative to Cs-137, and its correspondingly lower activity relative to Cs-137, beta counting is incapable of providing an effective means for quantifying Cs-135. Due to the dominance of natural Ba-135 in the waste, ICP-MS can only be used to quantify Cs-135 if the Ba is first removed. Given this situation, a radiochemical separation is performed to isolate Cs prior to measurements. Aliquots of the solids digest solution are alkalized, and then Cs is extracted into BOB-calix extractant. The purified Cs is stripped from the extractant utilizing dilute nitric acid, and the resulting nitric acid solutions are analyzed by ICP-MS. Recoveries of the analyses are monitored one of two ways: 1) by ratioing the post-purification Cs-133 mass signal to the pre-purification Cs-133 mass signal (the 133 mass signal has no isobaric interferences); or 2) performing gamma PHA of the purified aliquot and ratioing the post-purification Cs-137 content to the pre-purification Cs-137 content. The post-purification Cs-135 measurements were adjusted for losses identified by the recoveries.

Pu-238/Pu-241 Method

Pu-241 is a beta-emitting Pu isotope that cannot be measured directly in the dissolved dried sludge slurry solutions because of its low concentration. Pu-241 has a relatively short half-life (15 years). Its concentration, along with that for Pu-238, was determined by isolating the Pu from each solution by a thenoyltrifluoroacetone extraction procedure. The extracted Pu was then analyzed by beta and alpha counting to determine the ratio of beta activity from Pu-241 to the alpha activity from the other isotopes of Pu (Pu-238, Pu-239, Pu-240, and Pu-242). In the original dissolution solutions, the total alpha activity from the Pu isotopes was determined by alpha counting and ICP-MS. Knowing the total alpha activity from Pu in the solutions resulting from the extraction allows the concentration of Pu-241 in the original dissolution solutions to be calculated using the beta/alpha ratio determined in the extracted solution. In the extracted solution, the alpha counting technique also gives the alpha counts due specifically to Pu-238 so

that the total amount of Pu-238 can be determined. The activities of these two radionuclides were then used in the calculations to determine the reportable radionuclides.

Am/Cm Method
This method was used for Am-242m, Cm-242, Am-243, Cm-243, Cm-244, Cm-245, Cm-246, Cm-247, Cm-248, Bk-247, Cf-249, Cf-250, Cf-251, and Cf-252. These radionuclides are neutron activation products produced in the SRS reactors. These isotopes are difficult to measure because of their low concentrations in the sludge slurry and the dilutions necessary to get the dissolved slurry samples out of the Shielded Cells. Of these isotopes, the Am-241 can be easily and accurately analyzed directly by long term gamma counting of the dissolved sludge. For the other radionuclides listed above, a separation method has been has developed by AD for isolating Am, Cm, Bk and Cf from a wet sludge slurry solution. The slurry is digested in the Shielded Cells with concentrated nitric acid. The actinides are then extracted from the dissolution using a commercially available ion exchange resin (Eichrom RE). As Y-90 co-extracts with the trivalent actinides on RE resin, the treated samples were held in the Shielded Cells for nine days to allow the Y-90 to decay. The solutions were purified further with a second RE resin extraction followed by an Eichrom Ln resin extraction. The Am, Cm, Bk, and Cf extracts were then analyzed by alpha and low energy gamma counting techniques as well as by ICP-MS. The radionuclides Cm-242, Am-242m, Cm-244, and Cf-252 were measured by alpha spectroscopy, Am-241, Am-243, Cm-243, Cm-245, Cf-249, and Cf-251 were measured by low energy gamma spectroscopy, and Cm-245, Cm-246, Cm-247, Bk-247, Cm-248 and Cf-250 was measured by ICP-MS. The fraction of each actinide element isolated by this ion exchange technique was determined by comparing the measured concentrations of Am-241 in the eluted solutions with their respective concentration in the original dissolved slurry that was measured by direct gamma counting of Cs-137 removed aliquots of the dissolved slurry.

Pm-147/Sm-151 Method
The alkali fusion digest solutions were spiked with a stable Sm carrier. The Sm carrier was used for separation yielding purposes. The spiked sample aliquots were initially oxidized using nitric acid. The Sm and Pm along with other trivalent species in the samples were extracted using Eichrom RE resin. The Sm and Pm where then extracted from the other radionuclides present using Eichrom Ln resin. A portion of the purified Pm/Sm solution was neutron activated in a Cf-252 neutron activation facility at SRNL to determine the total Sm and in order to calculate the fraction of Sm isolated by the procedure. A second portion of each of the Pm/Sm fractions was then counted by liquid scintillation analysis to determine the Pm-147 and Sm-151 activity. The Pm-147 measurement was conducted using a higher energy beta window which was free of any interference from the low energy Sm-151 beta. The Sm-151 beta result is corrected for any Pm-147 events occurring in its beta counting window when necessary. The yields of the stable Sm carriers were applied to the Sm-151 and the Pm-147 beta activity results to determine Sm-151 and Pm-147 activities in the original aliquots of the solutions resulting from the dissolution of the dried sludge slurry samples. A Pm-147 spiked sample was run through the process to monitor and correct for any slight differences in the chemical recoveries of Sm and Pm.

Calculated Activities of the Other Radionuclides

Pd-107
The noble metal Pd-107 is a pure beta emitter with a very long half-life (6.5E+06 years). This radionuclide could not be detected in the SB7a dissolved dried slurry samples by ICP-MS due to the presence of natural silver. Natural Ag contains the isotope Ag-107, which interferes with the measurement of Pd-107. However, the concentration of Pd-105 could be measured in the solutions, so the concentration of Pd-107 was calculated from the concentration of Pd-105. This

was done by multiplying the ratio of the product of the fission yields and masses for Pd-107 and Pd-105 by the measured wt% for Pd-105 as determined by ICP-MS.

Cd-113m

With a half-life of 13.7 years and specific activity of 217 Ci/g, Cd-113m may also qualify as a WAPS reportable radionuclide. However, Cd-113m primarily decays by moderate energy beta emission and would require extensive radiochemical purification prior to counting measurements. Also, the determination of Cd-113m by ICP-MS is typically not feasible because of the presence of natural Cd in the sludge. Natural Cd is 12.3 % Cd-113 with a half-life greater than 1.1E11 years. This makes its activity negligible at all times. Finally, the fission yield of Cd-113m is very small, 1.66E-04%,[22] and thus its concentration is expected to be very low in HLW.

An upper limit of the mass concentration of Cd-113m can be estimated by using the fission yield scaling factor (FYSF).[23] The FYSF relates the concentration of a fission product in the total solids to the fission yield and the atomic mass of that fission product. The atomic mass of that isotope has to be included in the equation because fission yields are given in terms of atoms produced per 100 fissions of U-235 and not in terms of mass percent of the isotope produced. The equation for the concentration in weight percent is:

$$\text{Concentration (wt\%)} = \text{FYSF} \times \text{fission yield} \times \text{atomic mass} \quad (1)$$

Thus, the FYSF for each measured isotope can be calculated as follows:

$$FYSF_i = wt\%_i / (fy_i \times am_i) \quad (2)$$

Where $FYSF_i \equiv$ the fission yield scaling factor based on isotope i
$wt\%_i \equiv$ the weight per percent of isotope i in the HLW total dried solids
$fy_i \equiv$ the fission yield of isotope i
$am_i \equiv$ the atomic mass of isotope i.

Several of the U-235 fission products have the six critical chemical and nuclear properties that allow calculation of a constant FYSF for a particular sludge. These properties are discussed in Reference 23. In SB7a, there are 14 isotopes that have these six properties. The FYSF's calculated for these 14 isotopes are given below. The measured concentrations were determined by ICP-MS analysis of SB7a solids dissolved by the aqua regia method. The average FYSF based on these fourteen measurements is 7.55E-05.

Calculated Values of FYSF for Fourteen U-235 Fission Products in SB7a

Isotope	Measured	Fission	FYSF
Ru-101	3.87E-02	5.20	7.35E-05
Ru-102	3.55E-02	4.30	8.08E-05
Rh-103	1.93E-02	3.03	6.18E-05
Ru-104	2.00E-02	1.88	1.02E-04
La-139	6.61E-02	6.41	7.42E-05
Ce-140	6.42E-02	6.22	7.37E-05
Pr-141	5.77E-02	5.80	7.06E-05
Ce-142	6.23E-02	5.85	7.50E-05
Nd-143	5.95E-02	5.96	6.98E-05
Nd-144	6.10E-02	5.50	7.70E-05
Nd-145	4.08E-02	3.93	7.16E-05
Nd-146	3.31E-02	3.00	7.56E-05
Sm-147	2.20E-02	2.25	6.65E-05
Sm-148	2.10E-02	1.67	8.50E-05
Average	**NA**	**NA**	**7.55E-05**

Using the FYSF, the maximum possible concentration in terms of weight percent of total solids can be estimated for other U-235 fission products. These estimations provide upper bounds for the other fission products because they do not have all of the necessary six properties. For example, the radionuclide Cd-113m has a very large neutron absorption cross section (20,000 barns[24]), and thus it was transmuted in the reactors at SRS to stable Cd-114 while the reactors were in operation. Consequently, the concentration calculated for Cd-113m with Equation 1 and a fission yield of 1.66E-04% can be considered the maximum concentration and is estimated as:

Concentration Cd-113m (wt%) = 7.55E-05 × 1.66E-04 × 113 = 1.42E-06 wt%.

Th-230

Th-230 is long-lived alpha emitting radionuclide (t_H = 7.5E+04 years) that is a decay product of U-234 and Pu-238. It is also an impurity in Thoria (ThO_2), the source material used for generating U-233. Based on the SRS Thoria specifications,[21] the concentration of Th-230 in Thoria is assumed to be 1 ppm. Coupling this concentration with the mass concentration of Th-232 provides a basis for calculating the concentration of Th-230 introduced by the Thoria. In SB7a, this is the primary source of Th-230. The quantity of Th-230 produced by decay of U-234 and Pu-238 is determined by first back-calculating the concentrations of U-234 and Pu-238 when the waste was new (as described in Section 3.2, the waste is assumed to be 50 years old), and then performing decay/in-growth calculations to determine the quantity of Th-230 that "grows-in" over the 50 year time period. The total concentration of Th-230 in the waste is the sum of the Th-230 due to the Thoria impurities and the Th-230 produced through U-234 and Pu-238 decay.

Decay Products including Y-90, Nb-93m, Rh-106, Ba-137m, Pr-144, Pb-210, Ra-226, Ra-228, Ac-227, Th-228, Th-229, Pa-231, U-235m, and Pu-244

Concentrations of the decay products were calculated based on the concentrations of the principal parent nuclides, as described in Section 3.2. The applicable parent nuclides are: a) Sr-90 (for Y-90); b) Zr-93 (for Nb-93m), c) Ru-106 (for Rh-106); d) Cs-137 (for Ba-137m); e) Ce-144 (for Pr-144); f) Th-230, U-234, and Pu-238 (for Pb-210 and Ra-226); g) Th-232 (for Ra-228 and Th-

228); h) U-235 (for Ac-227 and Pa-231); i) U-233 (for Th-229); j) Pu-239 (for U-235m); and k) Cm-248 (for Pu-244).

Distribution:

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