PNNL-13702

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October 2001

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RL01830

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Summary

This report describes the Hanford Tank S-110 sludge caustic leaching test conducted in FY 2001 at the Pacific Northwest National Laboratory. The data presented here can be used to develop the baseline and alternative flowsheets for pretreating Hanford tank sludge. The U.S. Department of Energy funded the work through the Efficient Separations and Processing Crosscutting Program (ESP; EM-50).

The S-110 sludge sample was first subjected to washing with dilute sodium hydroxide solution at ambient temperature. Following the dilute hydroxide washing, several aliquots of the washed solids were taken for leaching tests. The washed solids were subjected to leaching with 1, 3, or 5 M NaOH at 60, 80, or 100°C for up to 168 h. The leachates were sampled at 4, 8, 24, 72, and 168 h. The leached solids were dried to constant mass at 105°C and then analyzed.

The work presented here indicates caustic leaching to be a very effective method of pretreating Hanford Tank S-110 sludge. Because of the predominance of boehmite in the water-insoluble S-110 solids, high caustic and temperature are required to sufficiently remove Al. It would also be necessary to leach for several days to realize the full benefits of caustic leaching. As expected, Al removal improves with increasing temperature, NaOH concentration, and leaching time. The Cr behavior parallels that of Al.

At a maximum of 0.5 wt% Cr_2O_3 in the high-level waste form, the mass of immobilized high-level waste (IHLW) would be constrained by the Cr content of the leached S-110 solids. Nevertheless, an 80 to 90% reduction in IHLW mass from the S-110 solids should be readily achievable.

The results of this work underscore the need to continue process optimization studies. If subjected to the baseline leaching approach (3 M NaOH, 80 to 90°C, for 8 h), only about 25% of the Al would be leached from the dilute hydroxide-washed S-110 solids. Clearly, this would not be sufficient to adequately reduce the IHLW mass.

Glossary

DOE	U.S. Department of Energy
ESP	Efficient Separations and Processing Crosscutting Program
ESW	enhanced sludge washing
GEA	gamma energy analysis
HDPE	high density polyethylene
HLW	high-level waste
ICP/AES	inductively coupled plasma/atomic emission spectroscopy
IHLW	immobilized high level waste
ILAW	immobilized low-activity waste
LAW	low-activity waste
LLW	low-level waste
NRC	U.S. Nuclear Regulatory Commission
PMP	polymethylpentene
PNNL	Pacific Northwest National Laboratory
PP	polypropylene
REDOX	REDOX process for Pu recovery
TRU	transuranic elements
UV/vis	ultraviolet/visible
WOL	Waste Oxide Loading

Acknowledgments

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Contents

Figures

Tables

1.0 Introduction

Since 1990, the primary mission at the U.S. Department of Energy's Hanford Site has changed from producing plutonium to restoring the environment. Large volumes of high-level radioactive wastes (HLW), generated during past Pu production and other operations, are stored in underground tanks onsite. The current plan for remediating the Hanford tank farms consists of waste retrieval, pretreatment, treatment (immobilization), and disposal. The tank wastes will be partitioned into high-level and low-activity fractions. The low-activity waste (LAW) will be processed to remove ^{137}Cs and ^{99}Tc (and ^{90}Sr and transuranic elements in selected cases), and then it will be immobilized in a glass matrix and disposed of by shallow burial onsite. The HLW will be immobilized in a borosilicate glass matrix; the resulting glass canisters will then be disposed of in a geologic repository (DOE/ORP 2001). Because of the expected high cost of HLW vitrification and geologic disposal, pretreatment processes will be implemented to reduce the volume of immobilized high-level waste (IHLW).

Dilute hydroxide washing is the minimum pretreatment that would be performed on Hanford tank sludges. This method simply involves mixing the sludge with dilute (0.1 M or less) NaOH, then performing some sort of solid/liquid separation. This is meant to remove water-soluble sludge components (mainly sodium salts) from the HLW stream. Dilute hydroxide is used rather than water to maintain the ionic strength high enough that colloidal suspensions are avoided.

Caustic leaching (sometimes referred to as enhanced sludge washing or ESW) represents the baseline method for pretreating Hanford tank sludges. Caustic leaching is expected to remove a large fraction of the Al, which is present in large quantities in Hanford tank sludges. The Al will be removed by converting aluminum oxides/hydroxides to sodium aluminate. For example, boehmite and gibbsite are dissolved according to the following equations (Weber 1982).

$$AlOOH(s) + NaOH(aq) \rightarrow NaAlO_2(aq) + H_2O \quad (1.1)$$

$$Al(OH)_3(s) + NaOH(aq) \rightarrow NaAlO_2(aq) + 2H_2O \quad (1.2)$$

A significant portion of the P is also expected to be removed from the sludge by the metathesis of water-insoluble metal phosphates to insoluble hydroxides and soluble Na_3PO_4. An example of this is shown for iron(III) phosphate in the following equation.

$$FePO_4(s) + 3NaOH(aq) \rightarrow Fe(OH)_3(s) + Na_3PO_4(aq) \quad (1.3)$$

Similar metathesis reactions can also occur for insoluble sulfate salts, allowing the removal of sulfate from the HLW stream.

Based on its known amphoteric behavior (Rai et al. 1987), Cr(III) was expected to be removed by caustic leaching according to the following equation:

$$Cr(OH)_3(s) + NaOH(aq) \rightarrow Na[Cr(OH)_4](aq) \quad (1.4)$$

However, studies conducted at the Pacific Northwest National Laboratory (PNNL) have suggested that the behavior of Cr in the caustic leaching process is more complex (Lumetta et al. 1997).

Results of previous studies of the baseline Hanford sludge-washing and caustic-leaching process have been reported (Lumetta and Rapko 1994; Rapko et al. 1995, Lumetta et al. 1996a and 1996b, 1997, and 1998; Temer and Villarreal 1995, 1996, and 1997). In the initial work, a standard set of test conditions was examined for each sludge. In FY 1998, the focus of the testing effort shifted to performing parametric tests on selected sludge samples (Lumetta et al. 1998). The purpose of the parametric tests is to provide data that process engineers can use to optimize process flowsheets for specific waste types. The parameters being considered are time, temperature, and caustic (NaOH) concentration. This report describes the results of a parametric caustic-leaching tests performed on sludge from Hanford Tank S-110. This tank contains primarily waste from the Reduction Oxidation (REDOX) process for Pu recovery, but also contains evaporator bottoms and a mixture of other miscellaneous wastes (Hill et al. 1995).

2.0 Experimental

2.1 Description of the S-110 Sludge Sample

The S-110 sludge sample used was a composite of segments from two different core samples (Table 2.1). The composite sample was prepared at the Hanford 222-S Laboratory and shipped to PNNL in March 2001.

Table 2.1. Description of S-110 Sludge Composite

Sample ID[(a)]	Core No.	Core Date	Tank Riser	Segment No.	Amount Added, g
S98T001898	240	May 1998	14	9	30.0
S98T001904	240	May 1998	14	10	30.7
S98T001978	241	June 1998	6	2	30.2
S98T001984	241	June 1998	6	3	30.0
S98T001994	241	June 1998	6	4	30.1
S98T002014	241	June 1998	6	7	30.0
S98T002026	241	June 1998	6	8	30.1
				Net Mass, g:	211.1
(a) Unique identifier used at the Hanford 222-S Laboratory.					

2.2 Initial Washing of the S-110 Solids

The 211-g S-110 composite sample was transferred to a 500-mL high-density polyethylene (HDPE) bottle by a combination of scooping with a spatula and sluicing with 0.01 M NaOH. The S-110 sludge was very sticky with a consistency like peanut butter. Dilute (0.01 M) NaOH solution was added to yield a total volume of 400 mL, and then the mixture was shaken overnight. The mixture was allowed to stand for 2 h, after which time there was no indication of solids settling. The wash slurry was split between two centrifuge bottles and was centrifuged for 20 min (at ~1200 G). The wash liquor was decanted from each centrifuge bottle and saved. The centrifuged solids were transferred back into the 500-mL bottle, and the process was repeated. The third and final wash was conducted in the centrifuge bottles. Dilute (0.01 M) NaOH solution was added to each centrifuge bottle containing the centrifuged solids to yield a total volume of ~175 mL in each bottle. The bottles were shaken overnight and then centrifuged. The wash liquor was decanted and combined with the previous wash liquors. The total mass of the combined wash solution was 764.7 g.

The washed solids were transferred to a 1-L HDPE bottle by slurrying with deionized water. The slurry was made to ~1 L with deionized water. The mass of this slurry was 976.6 g. The slurry was mixed with a magnetic stirrer, and two 2-g aliquots were taken for analysis. Two additional 0.5-mL aliquots of the washed solids slurry were taken for potential solids characterization. The two 2-g aliquots were dried to constant weight at 105°C to determine the solids composition of the slurry. The slurry contained 7.72 wt% solids, which translated to a total of 74.96 g of washed solids. The two dried aliquots of washed solids were analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES), gamma energy analysis (GEA), and for total alpha and total beta activity (Table 2.2).

Table 2.2. Composition of the Dilute Hydroxide-Washed S-110 Solids

Component	Concentration, µg/g
Al	325000
B	[135]
Ba	[110]
Bi	1365
Ca	[1200]
Cd	[60]
Cr	23050
Cu	[82]
Fe	14150
La	[160]
Mg	[380]
Mn	5305
Na	30000
Nd	[345]
P	1415
Pb	[595]
Si	[5500]
Sr	1240
Ti	[58]
U	[23500]
Zn	[225]
Zr	[135]
Component	**Concentration, µCi/g**
Total Alpha[(b)]	1.8E+00
Total Beta	1.4E+03
^{137}Cs[(b)]	3.1E+01

(a) Experimental uncertainties are 15%, except for values given in brackets. Values given in brackets are within 10 times the detection limit, and the uncertainties for these values are greater than 15%.

(b) The process blank indicated relatively high total alpha (0.35 µCi/g) and ^{137}Cs (7.61 µCi/g) concentrations. So the reported values should be used with some caution.

2.3 Division of the Washed S-110 Solids

After having stood for 2 to 3 weeks, it was impossible to adequately stir the slurry of washed solids with the magnetic stirrer. A mechanical stirrer was used instead to homogenize the slurry. Nine aliquots, nominally 15 g each, were transferred to 125-mL polypropylene (PP) bottles using a large (23-mL capacity) disposable polyethylene pipette. Table 2.3 lists the bottle labels, the mass of each aliquot, and the amount of solids in each aliquot, based on 7.72 wt% solids in the slurry.

Table 2.3. Mass of Washed S-110 Solids in Each Leaching Aliquot

Bottle ID	Mass Slurry, g	Mass Solids, g
S110-60-1	15.4	1.189
S110-60-3	15.2	1.173
S110-60-5	15.0	1.158
S110-80-1	15.1	1.166
S110-80-3	15.0	1.158
S110-80-5	15.1	1.166
S110-100-1	15.0	1.158
S110-100-3	15.2	1.173
S110-100-5	15.1	1.166

2.4 Caustic Leaching of the Washed S-110 Solids

Table 2.4 summarizes the leaching conditions for each aliquot of washed S-110 solids. A slight excess (0.1 M) of NaOH was added to each reaction vessel to compensate for hydroxide ion consumed in chemical reactions. The aluminum heating block was preheated to the desired temperature. Sodium hydroxide solution (10 M) was added to each aliquot of washed S-110 solids in the following amounts: 11.0 mL to yield 1 M NaOH, 31.0 mL to yield 3 M NaOH, and 51 mL to yield 5 M NaOH. The leaching mixtures were then diluted to 100 mL with deionized water. The ratio of ~80 mL solution per gram of washed S-110 solids was chosen so as to avoid Al solubility limits in any of the test samples.

It was discovered that the 125-mL HDPE bottles containing the nine aliquots would not fit in the aluminum heating block when at temperature. For this reason, it was necessary to transfer the leaching slurries to 125-mL polymethylpentene (PMP) bottles. In all cases, the transfer of the slurry was essentially quantitative, with ≥ 99.8% of the slurry transferred.

The liquid level was marked on each reaction vessel, and each vessel was closed with a cap equipped with a tube-condenser. The leaching mixtures were mixed at temperature with a magnetic stirrer. Evaporation was minimal during the course of the experiment; occasionally, deionized water was added to bring the liquid level up to its original position. The leachates were sampled at intervals of 4, 8, 24, 72, and 168 h. For each sampling, the stirrer was stopped, and the solids were settled at temperature. The transfer pipette and the syringe filter assembly (0.45-µm nylon membrane) were preheated by inserting in a boiling water bath. These were then used to filter ~1 mL of the leachate solution. A 0.5-mL aliquot of the filtered solution was immediately acidified with 15 mL of 0.3 M HNO_3. The remaining filtered solution was added back to the reaction vessel, and the leaching was continued. After 168 h, additional samples were taken for titrimetric (diluted into deionized water) analysis and Cr(VI) analysis by UV spectrophotometry (diluted into 0.1 M NaOH).

At the conclusion of the test, the reaction vessels were centrifuged for 5 min (~1200 G) immediately after removing from the heating block. The leachate was decanted and saved. The leached solids were washed thrice with 30-mL portions of 0.01 M NaOH and then were dried at 105°C. Table 2.5 gives the weights of the leached solids and the weight reductions achieved after leaching for168 h.

Table 2.4. Caustic Leaching Conditions

	[NaOH], M		
Bottle ID	**Target**	**Measured**	**Temperature, °C**
S110-60-1	1	1.0	60
S110-60-3	3	2.8	60
S110-60-5	5	4.8	60
S110-80-1	1	0.9	80
S110-80-3	3	2.7	80
S110-80-5	5	4.6	80
S110-100-1	1	0.8	100
S110-100-3	3	2.7	100
S110-100-5	5	4.6	100

Table 2.5. Mass of the Leached S-110 Solids and the Mass Loss Achieved During Leaching

Bottle ID	Mass of Leached Solids, g	Mass Loss, %
S110-60-1	0.799	33
S110-60-3	0.671	43
S110-60-5	0.598	48
S110-80-1	0.428	63
S110-80-3	0.207	82
S110-80-5	0.143	88
S110-100-1	0.210	82
S110-100-3	0.107	91
S110-100-5	0.099	92

2.5 Determination of Hydroxide Concentration

The free hydroxide concentration in the S-110 caustic leaching solutions was determined by titration with standard HCl. Initially, aliquots of the leaching solutions were diluted with deionized water and titrated directly with HCl. This gave very erratic results, which was believed to be caused by varying amounts of carbonate in the samples. Accordingly, $Ca(NO_3)_2$ was added to precipitate $CaCO_3$ before performing the titration. Aliquots of the leaching solution (0.5 mL for 1 M NaOH, 0.15 mL for 3 M NaOH, or 0.1 mL for 5 M NaOH) were diluted into 10 mL of deionized water. To these analyte solutions was added 0.1 mL of 2 M $Ca(NO_3)_2$. The resulting solutions were then titrated with 0.1 M HCl. The titration was conducted using a Mettler DL-21 automatic titrator equipped with a combination Ross® Electrode (ATI Orion, Boston, Massachusetts). Table 2.4 presents the measured free hydroxide concentrations.

2.6 Determination of Chromium(VI) Concentration

The CrO_4^{2-} concentration in the leaching solutions (after 1 week of leaching) was determined by ultraviolet/visible (UV/vis) spectrophotometry. A calibration curve was generated by measuring the spectra of standard CrO_4^{2-} solutions (in 0.1 M NaOH). The absorption at 372 nm was used. The leaching solutions were diluted with 0.1 M NaOH as needed, and the absorption was measured at 372 nm. The CrO_4^{2-} concentrations were calculated from the measured absorbance and the calibration curve. Table 2.6 compares the measured CrO_4^{2-} values to the total Cr concentrations determined by ICP-AES. In all cases, the Cr(VI) and total Cr concentrations were the same within experimental uncertainty, although the total Cr concentrations were consistently greater than the Cr(VI) concentrations, which might suggest that some Cr(III) was present.

Table 2.6. Comparison of Measured Cr(VI) and Total Cr Concentrations

	Concentration, µg/g	
Solution	**Cr(VI)**	**Total Cr**
1 M NaOH at 60°C	144	154
3 M NaOH at 60°C	190	199
5 M NaOH at 60°C	207	217
1 M NaOH at 80°C	226	237
3 M NaOH at 80°C	236	251
5 M NaOH at 80°C	241	234
1 M NaOH at 100°C	258	265
3 M NaOH at 100°C	256	265
5 M NaOH at 100°C	245	255

3.0 Results and Discussion

Table 3.1 presents the behavior of the various S-110 sludge components during washing of the as-received S-110 sludge sample with 0.01 M NaOH. Besides Na, Al is the dominant element present in the S-110 sludge. Dilute hydroxide washing is ineffectual at removing Al with only 4% reporting to the washing solution. Likewise, Cr removal is poor with only 17% of the total Cr removed by dilute hydroxide washing. In contrast, ~70% of the P is removed by dilute hydroxide washing, suggesting that most of the P is present in the S-110 sludge as water-soluble phosphate salts. As expected, Na is largely removed by dilute hydroxide washing.

Appendix A presents the concentrations of the various S-110 sludge components in the leaching solutions as a function of time, as well as the concentrations in the final washing solutions. Appendix B presents detailed results of the S-110 leaching test in terms of the concentration and mass of each component in the 1) leaching solution (after one week), 2) post-leach washing solution, and 3) the leached solids. Also presented in Appendix B is the concentration of each component in the water-washed solids calculated by summing the mass of each component in the leaching and washing solutions and the residual solids then dividing by the amount of washed solids used in the test. The concentrations determined in this manner are compared to those obtained by direct analysis of the washed solids. Mass recoveries obtained were generally within 15% for the major sludge components (i.e., Al, Cr, Fe, Mn, P, and Sr). Uranium was also a significant component of the sludge. The mass balance for U was generally low (but within 20%), probably because of the relative insensitivity of ICP-AES to U analysis.

Table 3.2 summarizes the removal achieved for the important sludge components Al, Cr, and P by leaching the washed S-110 solids with NaOH for one week. The removal of these elements parallels the mass losses listed in Table 2.4. That is, the removals of Al, Cr, and P increase with increasing temperature or increasing NaOH concentration. A more detailed discussion of Al and Cr dissolution is given in the following sections.[(a)]

Table 3.1. Results of Dilute-Hydroxide Washing of the As-Received S-110 Sludge

	Initial Washing Solution		**Washed Solids**			
	Solution Mass, g	**764.7**	**Solids Mass, g**	**74.96**		
Component	**Conc. μg/g**	**Mass, μg**	**Conc. μg/g**	**Mass, μg**	**Total Mass, μg**	**Removed, %**
Ag						
Al	1410	1077863	325000	24362000	25439863	4%
As						
B			[135]	[10120]	10120	(b)
Ba			[110]	8246	8246	(b)
Be						
Bi			1365	102320	102320	(b)
Ca			[1200]	[89952]	89952	(b)

(a) A detailed discussion of phosphorus removal is not presented because the removal of this element is relatively independent of hydroxide concentration and temperature under the conditions examined, and its concentration in the S-110 solids is not great enough to cause concern.

Table 3.1 (Contd)

	Initial Washing Solution		Washed Solids			
	Solution Mass, g	764.7	Solids Mass, g	74.96		
Component	Conc. μg/g	Mass, μg	Conc. μg/g	Mass, μg	Total Mass, μg	Removed, %
Cd			[60]	[4498]	4498	(b)
Ce						
Co						
Cr	448	342294	23050	1727828	2070122	17%
Cu			[82]	[6147]	6147	(b)
Dy						
Eu						
Fe	[0.6]	452	14150	1060684	1061136	0.04%
K	[124]	94677	N/A	N/A	N/A	N/A
La			[160]	[11994]	11994	(b)
Li						
Mg			[380]	[28485]	28485	(b)
Mn			5305	397663	397663	(b)
Mo	5	3671			3761	100%
Na	27381	20938214	30000	2248800	23187014	91%[(c)]
Nd			[345]	[25861]	25861	(b)
Ni			N/A	N/A	N/A	N/A
P	356	272379	1415	[106068]	378447	72%
Pb			[595]	[44601]	44601	(b)
Pd						
Rh						
Ru						
Sb						
Se						
Si	28	21594	[5500]	[412280]	433874	5%
Sn						
Sr			1240	92950	92950	(b)
Te						
Th						
Ti			[58]	[4348]	4348	(b)
Tl						
U			[23500]	1761560	1761560	(b)
W						
Y						
Zn			[225]	[16866]	16866	(b)
Zr			[135]	10120	10120	(b)

(a) Analyte was below detection limit if left blank. Experimental uncertainties are 15%, except for values given in brackets. Values given in brackets are within 10 times the detection limit and the uncertainties for these values are greater than 15%.
(b) No detectable removal.
(c) Not corrected for Na added as NaOH in washing solution.

Table 3.2. Aluminum, Chromium, and Phosphorus Removal Achieved After One Week of Leaching

		Removed, %		
T, °C	**[NaOH], M**	**Al**	**Cr**	**P**
60	1.0	39	49	90
60	2.8	47	70	92
60	4.8	50	81	94
80	0.9	69	78	92
80	2.7	91	89	97
80	4.6	96	90	99
100	0.8	91	87	83
100	2.7	100	91	95
100	4.5	100	93	99

3.1 Aluminum Dissolution

Figures 3.1, 3.2, and 3.3 illustrate the Al dissolution at 60, 80, and 100°C, respectively. At 60°C, the dissolution of Al was similar at the three hydroxide concentrations examined. There was a fairly rapid (within 8 h) rise in Al concentration to about 700 µg/g, followed by a gradual increase to about 1,800 µg/g after 168 h of leaching. The Al concentration did not appear to reach a steady value after 168 h of leaching at 60°C. The initial rapid rise in Al concentration was probably due to dissolution of gibbsite. The more gradual increase in Al concentration beyond 8 h can be attributed to dissolution of boehmite, which is known to dissolve more slowly than gibbsite. X-ray diffraction analysis of the water-washed S-110 solids indicated that the crystalline forms of Al in the solids consisted of 10 to 20% gibbsite and 80 to 90% boehmite.

At 80°C, Al dissolution was similar in 3 and 5 M NaOH, but Al dissolved to a lesser extent in 1 M NaOH. It is not clear whether the Al concentration reached a constant value after 168 h of leaching at 80°C. On the other hand, a constant Al concentration was reached after leaching for 72 h at 100°C in 3 and 5 M NaOH. Aluminum dissolution was somewhat slower for 1 M NaOH at 100°C, but reached the same end state (approximately 4000 µg/g) as the 3 and 5 M cases after leaching for 168 h.

Figures 3.4, 3.5, and 3.6 illustrate the Al dissolution at 1, 3, and 5 M NaOH, respectively. The data are presented in terms of both the Al concentration and the percentage of Al removed as a function of time. These figures clearly illustrate increased Al dissolution with increasing temperature. They also indicate that various conditions can be chosen to reach the same level of Al removal. For example, leaching the S-110 sludge with 1 M NaOH at 100°C for 1 week removes approximately the same amount of Al as leaching with 3 M NaOH at 100°C for 3 days. One striking feature of these data is that, in terms of Al dissolution, there is no significant advantage in using 5 M NaOH instead of 3 M NaOH. However, there may be an advantage in using 5 M NaOH in terms of solution stability.

The Al solubilities with respect to Gibbsite in 1, 3, and 5 M NaOH at 25°C are approximately 1818, 5885, and 11445 µg/g solution, respectively.[a] Based on this, only the leachates obtained by leaching with 1 M NaOH at 80 and 100°C would be supersaturated when allowed to cool to 25°C. However, the Al solubility in 1 M NaOH at 60°C is approximately 4675 µg/g solution. As the Al solubility increases with increasing temperature and NaOH concentration, this can be viewed as the minimum solubility for the leaching solutions at temperature. Comparison of this value to the measured Al concentrations confirms that in no case was Al removal limited by the Al concentration.

3.2 Chromium Dissolution

Figures 3.7, 3.8, and 3.9 illustrate the Cr dissolution at 60, 80, and 100 °C, respectively. Unlike the Al behavior, increased hydroxide concentration led to higher Cr concentrations at 60°C. But similar to the Al behavior, the Cr concentration did not appear to reach a steady value after 168 h of leaching at 60 °C. At 80°C, Cr dissolution was similar in 3 and 5 M NaOH; Cr dissolution in 1 M NaOH was slower but reached essentially the same final concentration (approximately 225 µg/g) after leaching for 168 h. The Cr behavior at 100°C was similar to that at 80°C except that dissolution was somewhat more rapid.

Figures 3.10, 3.11, and 3.12 illustrate the Cr dissolution at 1, 3, and 5 M NaOH, respectively. The data are presented in terms of both the Cr concentration and the percentage of Cr removed as a function of time. These figures clearly illustrate more rapid Cr dissolution with increasing temperature, but the data also suggest that the same level of Cr removal would probably be reached for all hydroxide concentrations and temperature if sufficient time were allowed.

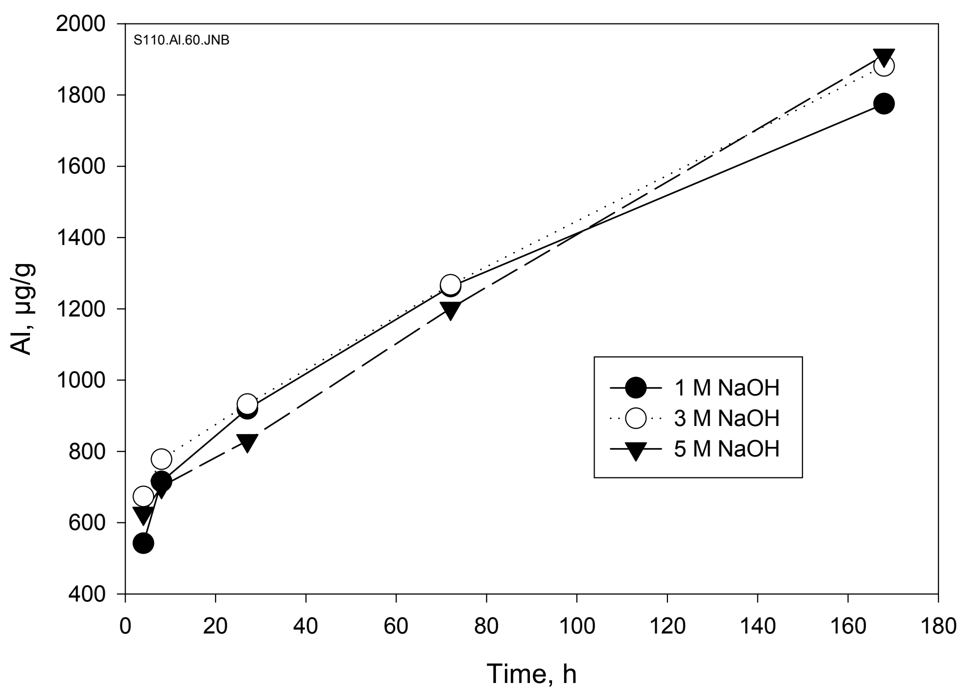

Figure 3.1. Aluminum Concentration as a Function of Time During Leaching of S-110 Solids at 60°C

(a) AR Felmy, Pacific Northwest National Laboratory, personal communication, 2001.

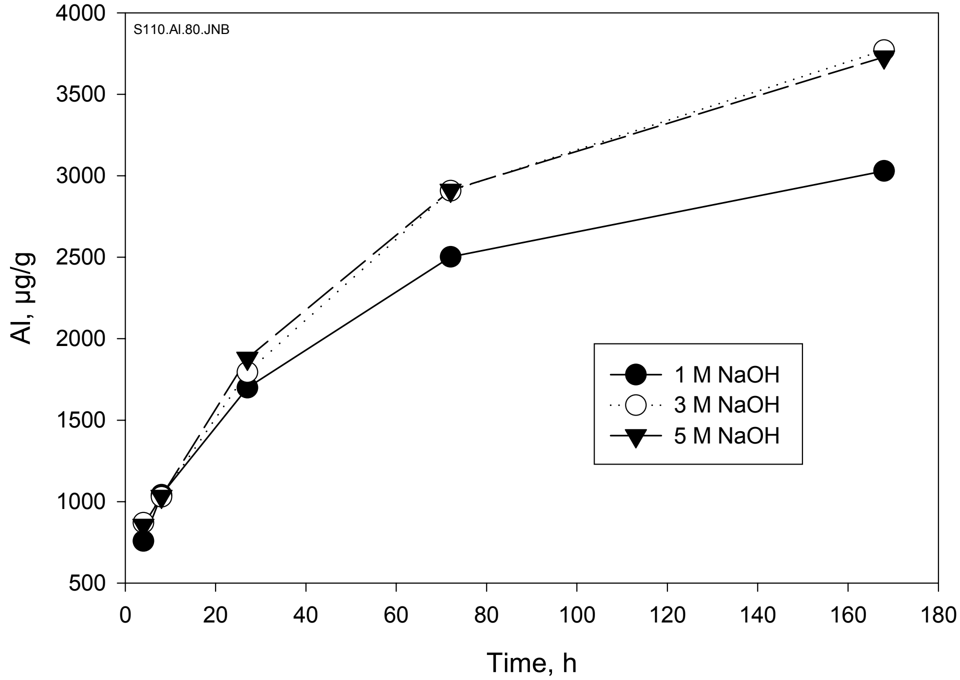

Figure 3.2. Aluminum Concentration as a Function of Time During Leaching of S-110 Solids at 80°C

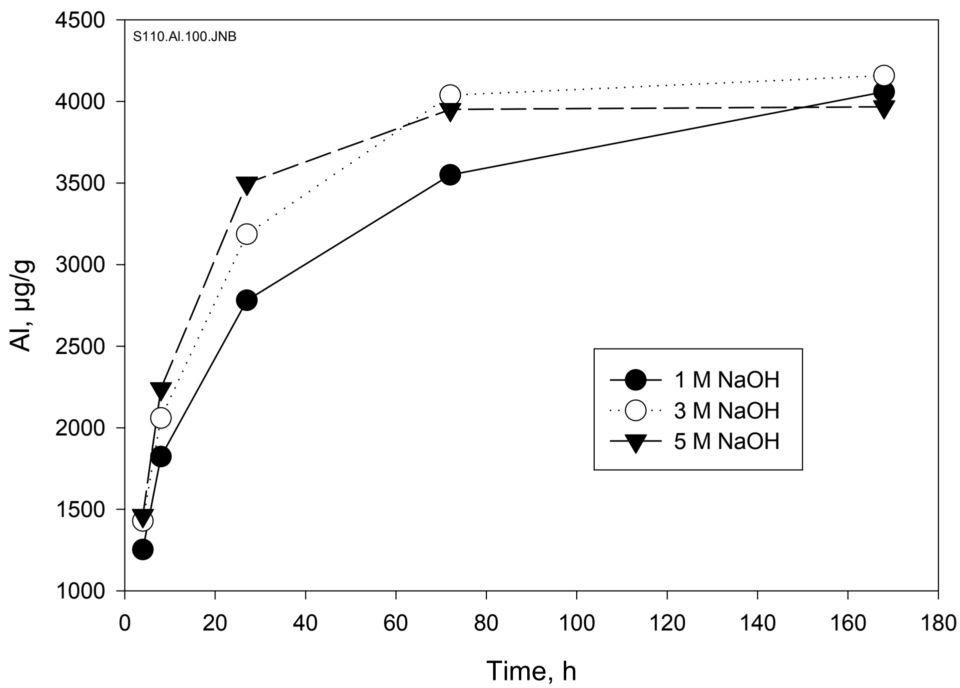

Figure 3.3. Aluminum Concentration as a Function of Time During Leaching of S-110 Solids at 100°C

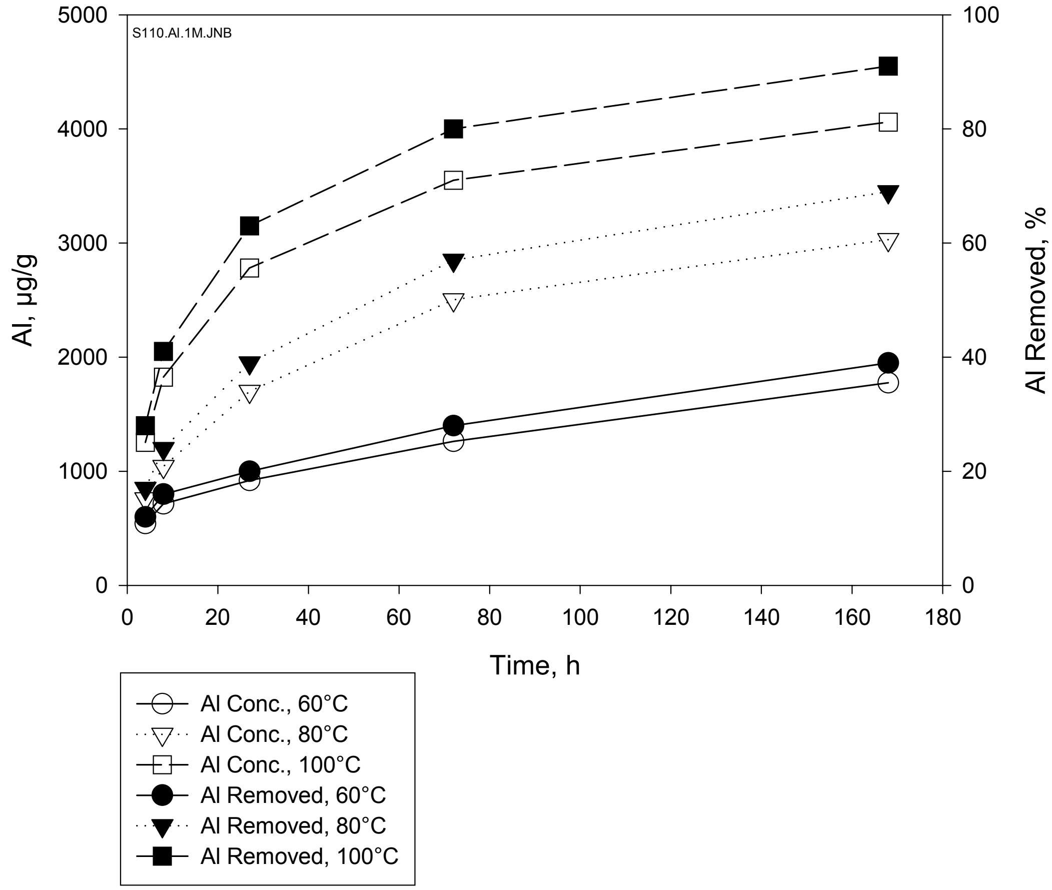

Figure 3.4. Aluminum Concentration and Removal as a Function of Time During Leaching of S-110 Solids at 1 M NaOH

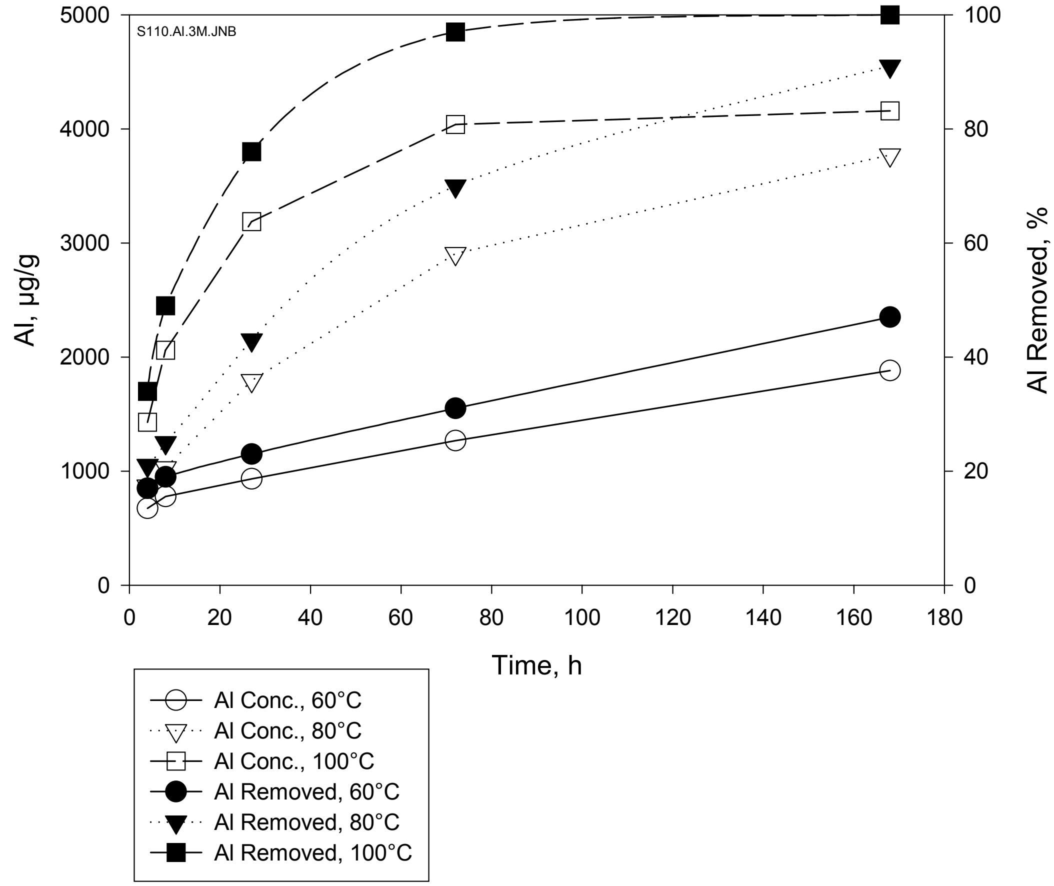

Figure 3.5. Aluminum Concentration and Removal as a Function of Time During Leaching of S-110 Solids at 3 M NaOH

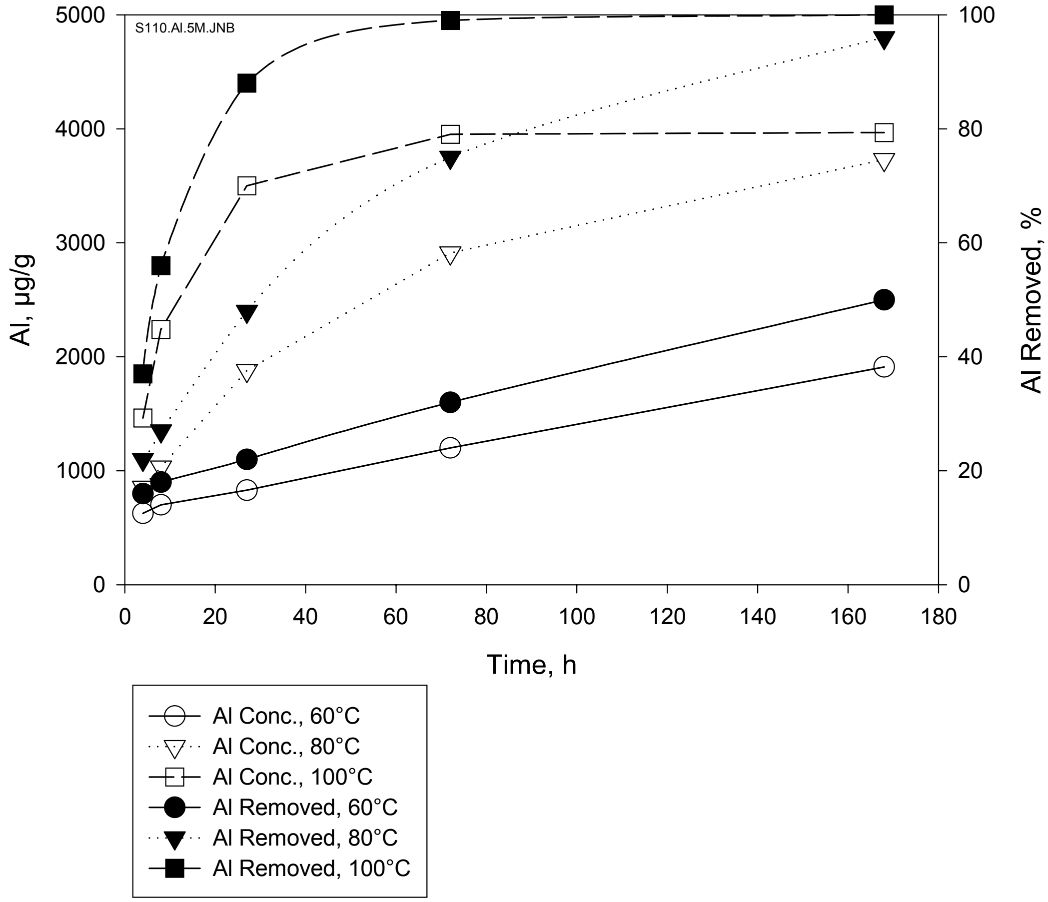

Figure 3.6. Aluminum Concentration and Removal as a Function of Time During Leaching of S-110 Solids at 5 M NaOH

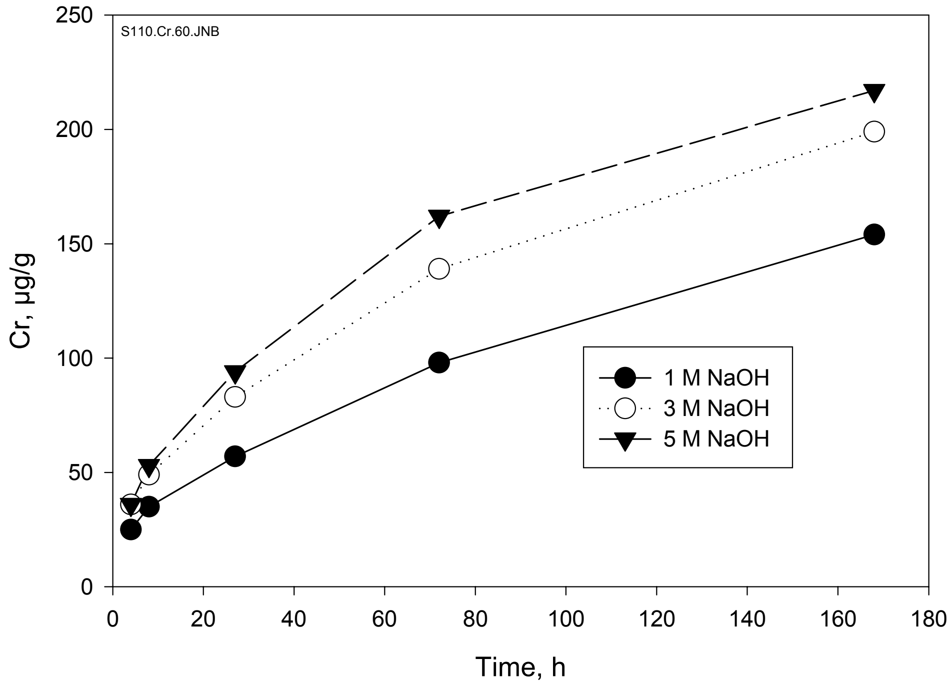

Figure 3.7. Chromium Concentration as a Function of Time During Leaching of S-110 Solids at 60°C

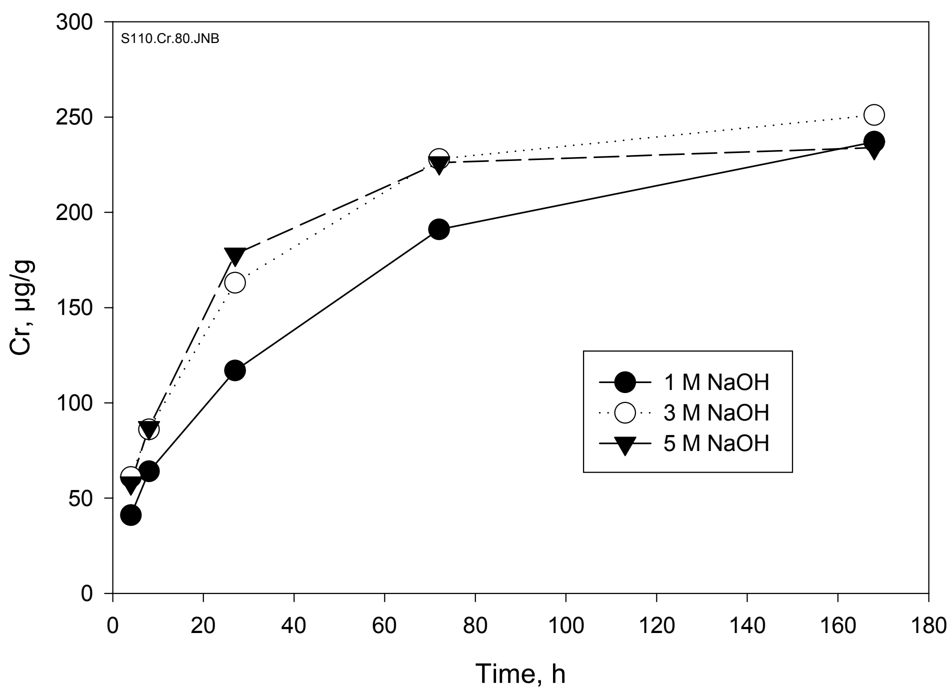

Figure 3.8. Chromium Concentration as a Function of Time During Leaching of S-110 Solids at 80°C

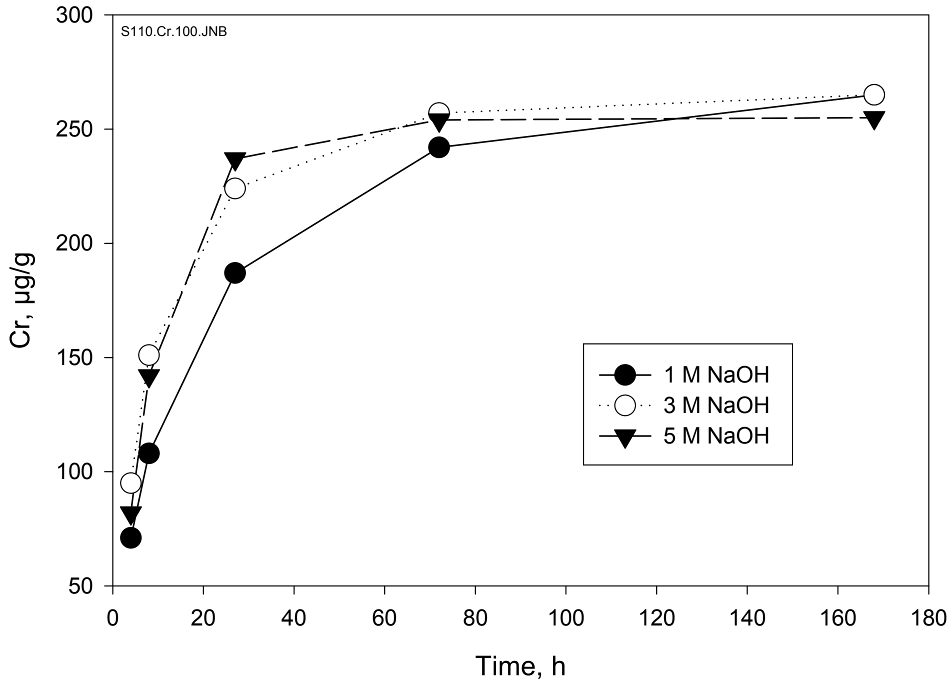

Figure 3.9. Chromium Concentration as a Function of Time During Leaching of S-110 Solids at 100°C

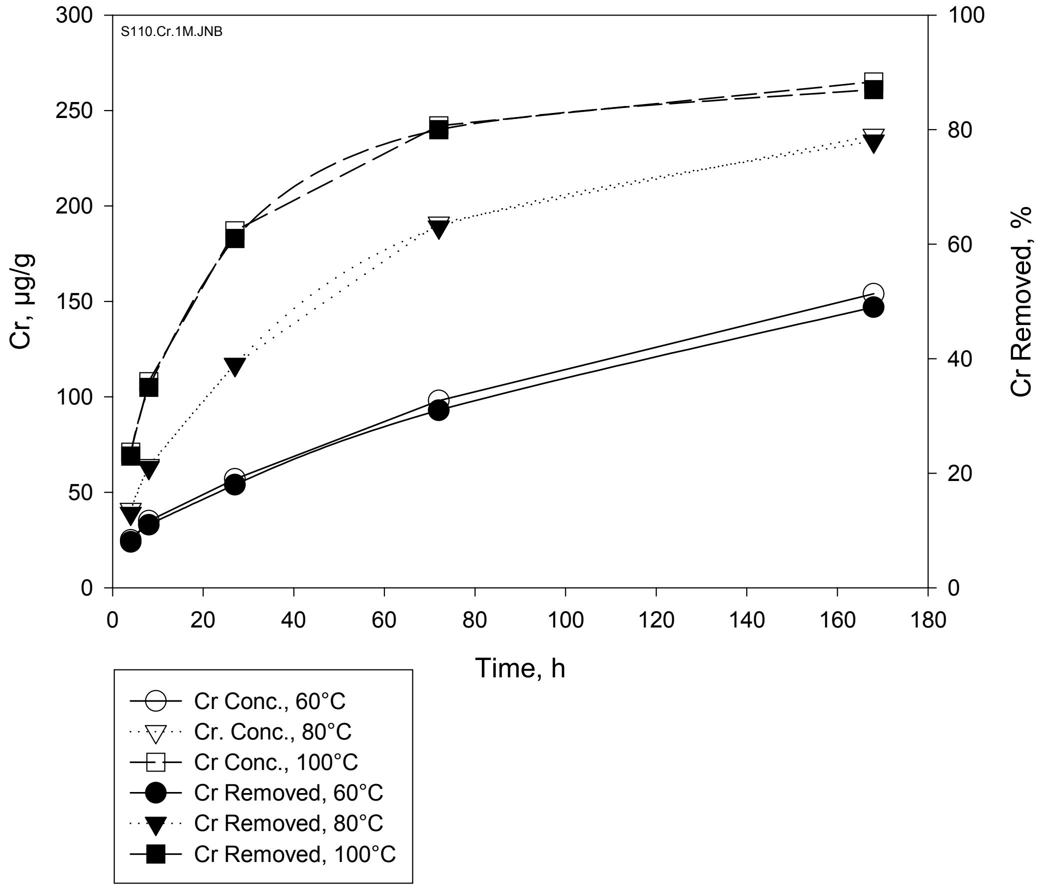

Figure 3.10. Chromium Concentration and Removal as a Function of Time During Leaching of S-110 Solids at 1 M NaOH

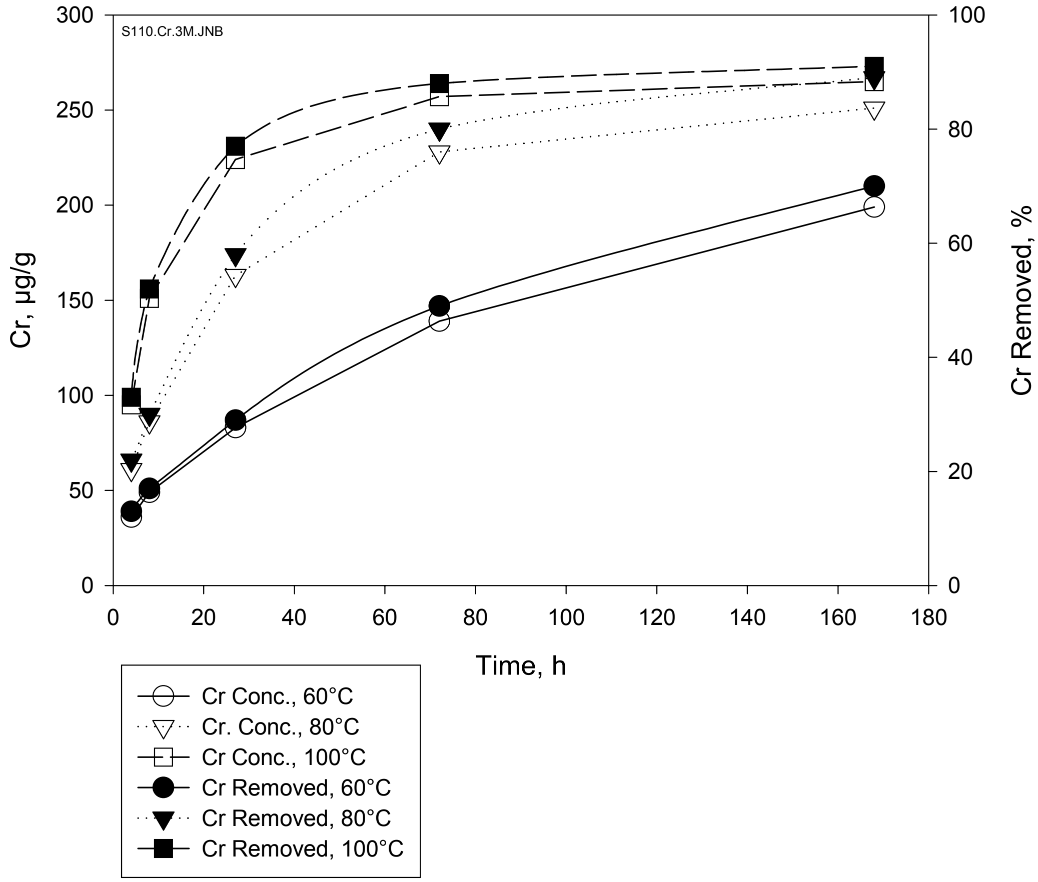

Figure 3.11. Chromium Concentration and Removal as a Function of Time During Leaching of S-110 Solids at 3 M NaOH

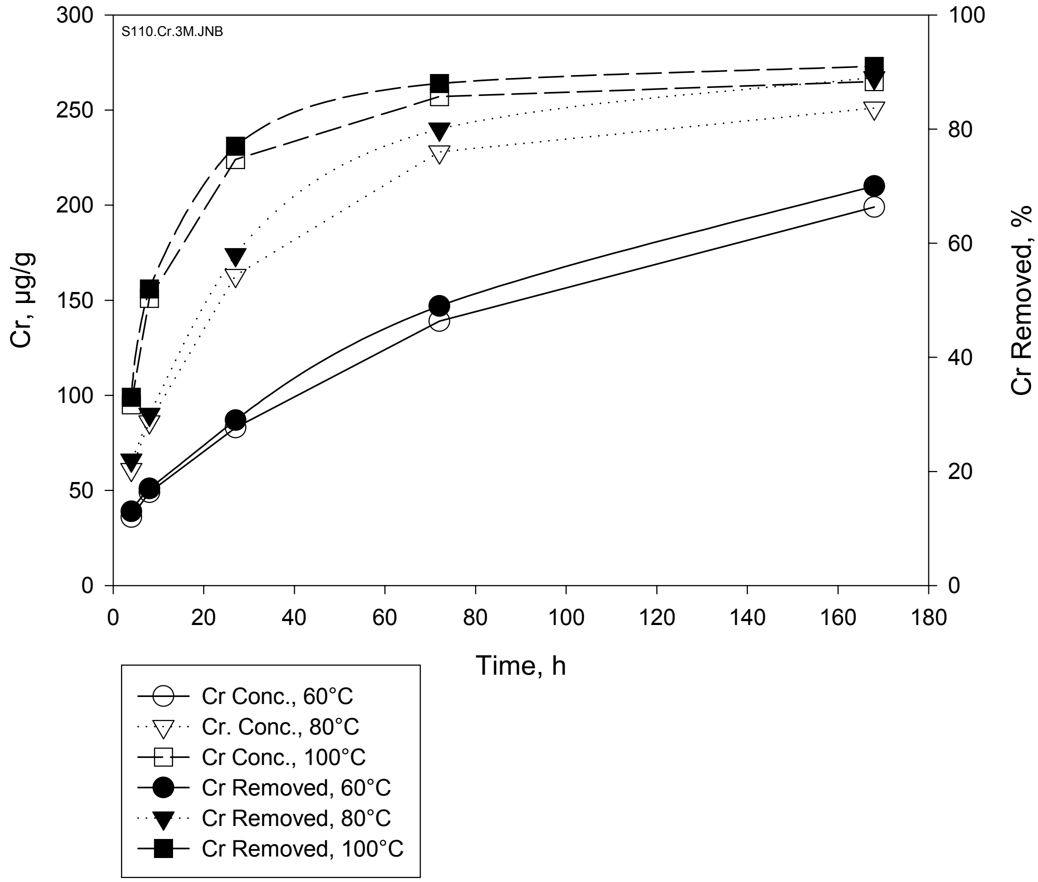

Figure 3.12. Chromium Concentration and Removal as a Function of Time During Leaching of S-110 Solids at 5 M NaOH

3.3 Radionuclide Behavior

Appendix C summarizes the behavior of the radionuclides in the S-110 caustic leaching tests. Under all conditions examined, greater than 90% of the ^{137}Cs reported to the leaching solution. There was no significant effect of temperature upon the ^{137}Cs behavior, but increasing NaOH concentration led to increased ^{137}Cs removal from the S-110 solids. As expected, the lanthanide and actinide isotopes were largely insoluble in the highly alkaline leaching solutions.

The highest transuranic (TRU) concentration in the leachate was ~3.5 x 10^{-4} µCi/g (e.g., for leaching with 5 M NaOH at 60 or 100°C). To assess whether this would lead to an immobilized low-activity waste (ILAW) form exceeding the 10 nCi TRU/g limit for Class A LLW (10 CFR 61. 1988. U.S. Nuclear Regulatory Commission, "Licensing Requirements for Land Disposal of Radioactive Waste." *U.S. Code of Federal Regulations*), we considered a 1 M NaOH leaching solution with a TRU concentration of 3.5 x 10^{-4} µCi/g as a limiting case. Assuming that the ILAW form contains 20 wt% Na_2O, the resulting TRU concentration would be 2.4 nCi/g. Thus, it appears the leaching solutions would not exceed the TRU criteria for LAW.

A similar analysis can be done for ^{137}Cs. In this case, the highest concentration was approximately 0.43 µCi/g. Assuming that the ILAW form contains 20 wt% Na_2O and has a density of 2.7 MT/m^3, immobilization of a 1 M NaOH leachate containing 0.43 µCi/g ^{137}Cs would lead to a waste form with 8 Ci/m^3. This exceeds the U.S. Nuclear Regulatory Commission (NRC) Class A limit of 1 Ci $^{137}Cs/m^3$ (but is well within the Class B limit of 44 Ci $^{137}Cs/m^3$). Thus, if the ILAW waste form is to meet Class A criteria, the ^{137}Cs must be removed from the leaching solutions.

3.4 Impact of Leaching on Immobilized High-Level Waste Glass Mass

To illustrate the effects of caustic leaching on the production of IHLW glass, Table 3.3 shows the concentration of waste oxides in the dilute hydroxide-washed S-110 solids and in the leached S-110 solids. For the sake of discussion, the table also shows the concentrations of waste-derived components that would result from vitrifying these solids at 25 wt% waste oxide loading (WOL), excluding oxides of Na and Si. Two cases are presented—leaching with 3 M NaOH at 80°C and at 100°C for 1 week. The oxide concentrations in the washed and leached solids were determined by converting the elemental concentrations listed in Tables 2.2 (washed solids), B.5, and B.8 (leached solids) to the corresponding oxide concentrations. The oxide concentrations in the IHLW were determined according to the following formula:

$$[C_x]_{IHLW} = WOL \bullet \left(\frac{C_x}{\sum_i C_i} \right) \tag{3.1}$$

where $[C_x]_{IHLW}$ is the concentration of component x oxide (wt%) in the IHLW, C_x is the concentration of component x oxide in the washed or leached solids, and $\sum C_i$ is the sum of the concentration of all the component oxides in the washed or leached solids (excluding Na_2O and SiO_2).

Assuming upper limits of 15, 0.5, and 3.0 wt% for Al, Cr, and P oxides, respectively, in the IHLW, a 25 wt% WOL could not be achieved for the dilute-hydroxide washed S-110 solids. Both Al and Cr exceed the assumed upper limits. Leaching with 3 M NaOH for 1 week at 80 or 100°C would remove enough Al so that Al is not a limiting component. However, even after leaching for 1 week at 100°C, Cr_2O_3 would still exceed the assumed 0.5 wt% limit.

The mass (W_{IHLW}) of IHLW glass produced from 1 g of the washed solids can be calculated as follows:

$$W_{IHLW} = 100 \bullet \frac{\sum_i C_i}{WOL} \tag{3.2}$$

Likewise, the mass of IHLW glass produced from the leached solids derived from 1 g of washed solids can be determined as follows:

$$W_{IHLW} = 100 \bullet \frac{W_L}{W_W} \bullet \frac{\sum_i C_i}{WOL} \qquad (3.3)$$

where W_L is the weight of the leached solids obtained by leaching W_W grams of washed solids. In the case considered here, W_L = 0.207 g and W_W = 1.158 g for the 3 M/80°C test and W_L = 0.107 g and W_W = 1.173 g for the 3 M/100°C test. Setting the upper limit for Cr_2O_3 in the IHLW as 0.5 wt%, it can be derived from Equation 3.1 that the maximum WOL achievable for the washed S-110 solids would be 10.6 wt%. At this WOL, application of Equation 3.2 indicates that 6.74 g IHLW would be produced per gram of washed S-110 solids. Likewise, setting the upper limit for Cr_2O_3 in the IHLW as 0.5 wt%, the maximum WOL that could be achieved for the leached (3 M NaOH at 80°C) S-110 solids would be 15.1 wt%. At this WOL, application of Equation 3.3 indicates that 0.84 g IHLW would be produced per gram of washed S-101 solids. Thus, a reduction in IHLW of 88% could be achieved by leaching the S-101 solids with 3 M NaOH for 1 week at 80°C. Interestingly, applying an upper limit of 0.5 wt% Cr_2O_3 in the IHLW would result in a maximum WOL of only 9.2% for the residue remaining after leaching the S-110 solids with 3 M NaOH at 100°C for 1 week. Because of this, only a marginal improvement (90% reduction in IHLW) would be achieved by leaching at 100°C versus 80°C.

3.5 Conclusions and Recommendations

The work presented here indicates caustic leaching to be a very effective method of pretreating Hanford Tank S-110 sludge. Because of the predominance of boehmite in the water-insoluble S-110 solids, high caustic and temperature are required to sufficiently remove Al. It would also be necessary to leach for several days to realize the full benefits of caustic leaching. Leaching at 60°C only removed ~50% of the Al even after leaching with 5 M NaOH for 1 week. Increasing the temperature led to significant improvements in Al removal. The best Al removal was obtained by leaching with 5 M NaOH at 100°C for 1 week; this led to nearly quantitative removal of Al from the S-110 solids. However, the benefit in using 5 M NaOH instead of 3 M NaOH is marginal. The Cr behavior parallels that of Al, with increasing removal obtained with increasing [NaOH], temperature, or leaching time.

At a maximum of 0.5 wt% Cr_2O_3 in the HLW form, the mass of IHLW would be constrained by the Cr content of the leached S-110 solids. Nevertheless, an 80 to 90% reduction in IHLW mass from the S-110 solids should be readily achievable.

The results of this work underscore the need to continue process optimization studies. If subjected to the baseline leaching approach (3 M NaOH, 80 to 90°C, for 8 h), only about 25% of the Al would be leached from the dilute hydroxide-washed S-110 solids. Clearly, this would not be sufficient to adequately reduce the IHLW mass.

Table 3.3. Estimated Concentrations of Waste-Derived Components in the IHLW Glass from S-110 Waste

	Washed Solids	
Component	**g oxide/g solids**	**Conc. in IHLW, wt%[(a)]**
Al_2O_3	0.6143	21.5
BaO	0.0001	0.00
Bi_2O_3	0.0015	0.05
CaO	0.0017	0.1
Cr_2O_3	0.0337	1.2
Fe_2O_3	0.0202	0.7
MgO	0.0006	0.0
MnO_2	0.0084	0.3
P_2O_5	0.0032	0.1
SrO	0.0015	0.05
UO_3	0.0282	1.0
ZnO	0.0003	0.01
ZrO_2	0.0002	0.01
	Leached Solids (3 M NaOH/80°C/168 h)	
Component	**g oxide/g solids**	**Conc. in IHLW, wt%[(a)]**
Al_2O_3	0.3644	12.8
BaO	0.0009	0.03
Bi_2O_3	0.0051	0.18
CaO	0.0085	0.3
Cr_2O_3	0.0236	0.8
Fe_2O_3	0.1089	3.8
MgO	0.0032	0.1
MnO_2	0.0476	1.7
P_2O_5	0.0007	0.0
SrO	0.0088	0.31
UO_3	0.1380	4.8
ZnO	0.0007	0.02
ZrO_2	0.0013	0.04
	Leached Solids (3M NaOH/100°C/168 h)	
Component	**g oxide/g solids**	**Conc. in IHLW, wt%[(a)]**
Al_2O_3	0.0248	0.9
BaO	0.0018	0.07
Bi_2O_3	0.0092	0.34
CaO	0.0167	0.6
Cr_2O_3	0.0363	1.4
Fe_2O_3	0.2000	7.5
MgO	0.0062	0.2
MnO_2	0.0909	3.4
P_2O_5	0.0018	0.1
SrO	0.0172	0.64
UO_3	0.2618	9.8
ZnO	0.0009	0.03
ZrO_2	0.0023	0.09

(a) Based on 25 wt% waste oxide loading (excluding NaO_2 and SiO_2).

4.0 References

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Appendix A

Solution Concentrations as a Function of Time

Appendix A: Solution Concentrations as a Function of Time

Table A.1. Component Concentrations As a Function of Time For Leaching of S-110 Solids With 1 M NaOH at 60°C

	Concentration, μg/g[(a)]						
Time, h:	4	8	24	72	168	168	Final Wash
Ag							
Al	542	715	919	1262	1811	1739	178
As							
B							
Ba							
Be							
Bi							
Ca	[12]	[11]	[9]	[11]	[10]	[10]	[6]
Cd							
Ce							
Co							
Cr	25	35	57	98	157	151	16
Cu							
Dy							
Eu							
Fe	[1]	[1]	[1]	[1]	[1]	[2]	[0]
K							
La							
Li							
Mg							
Mn							
Mo							
Na	24855	25056	24870	25040	25942	24872	2950
Nd							
Ni	[1]	[1]	[1]	[1]	[1]	[1]	[1]
P	[13]	[14]	[15]	[15]	[16]	[16]	[3]
Pb							
Pd							
Rh							
Ru							
Sb							
Se							
Si	[47]	[48]	[46]	[44]	[42]	[41]	[20]
Sn							
Sr							
Te							
Th							
Ti							
Tl							
U							
V							
W							
Y							
Zn							
Zr							

(a) Analyte was below detection limit if left blank. Experimental uncertainties are 15%, except for values given in brackets. Values given in brackets are within 10 times the detection limit and the uncertainties for these values are greater than 15%.

Table A.2. Component Concentrations As a Function of Time For Leaching of S-110 Solids With 3 M NaOH at 60°C

	Concentration, µg/g[(a)]						
Time, h:	4	8	24	72	168	168	Final Wash
Ag							
Al	673	778	932	1267	1892	1870	139
As							
B							
Ba							
Be							
Bi							
Ca	[9]	[9]	[11]	[11]	[10]	[9]	[6]
Cd							
Ce							
Co							
Cr	36	49	83	139	200	198	15
Cu							
Dy							
Eu							
Fe	[3]	[3]	[4]	[4]	[6]	[6]	[0]
K							
La							
Li							
Mg							
Mn							
Mo							
Na	60354	64166	66551	65173	65867	65144	5040
Nd							
Ni	[1]	[1]	[1]	[1]	[1]	[1]	[1]
P	[16]	[15]	[15]	[15]	[15]	[16]	[2]
Pb	[4]	[3]	[3]	[4]	[4]	[4]	
Pd							
Rh							
Ru							
Sb							
Se							
Si	[58]	[61]	[66]	[64]	[65]	[64]	[22]
Sn							
Sr							
Te							
Th							
Ti							
Tl							
U							
V							
W							
Y							
Zn	[1]	[2]	[2]	[2]	[2]	[2]	
Zr							

(a) Analyte was below detection limit if left blank. Experimental uncertainties are 15%, except for values given in brackets. Values given in brackets are within 10 times the detection limit and the uncertainties for these values are greater than 15%.

Table A.3. Component Concentrations As a Function of Time For Leaching of S-110 Solids With 5 M NaOH at 60°C

	Concentration, µg/g(a)						
Time, h:	4	8	24	72	168	168	Final Wash
Ag							
Al	626	701	830	1201	1926	1896	203
As							
B							
Ba							
Be							
Bi							
Ca	[8]	[11]	[10]	[10]	[12]	[11]	[5]
Cd							
Ce							
Co							
Cr	36	53	94	162	220	215	23
Cu							
Dy							
Eu							
Fe	[4]	[6]	[7]	[14]	[19]	[16]	
K	[54]	[124]	[79]	[68]		[64]	
La							
Li							
Mg							
Mn							
Mo							
Na	88464	95649	94341	97723	97460	98280	10609
Nd							
Ni	[1]	[2]	[2]	[3]	[1]	[1]	[1]
P	[15]	[19]	[17]	[17]	[16]	[17]	[2]
Pb	[4]	[6]	[6]	[6]	[4]	[5]	
Pd							
Rh							
Ru							
Sb							
Se							
Si	[51]	[62]	[61]	[63]	[66]	[64]	[24]
Sn							
Sr							
Te							
Th							
Ti							
Tl							
U		[75]	[57]				
V							
W							
Y							
Zn	[1]	[2]	[3]	[2]	[3]	[2]	
Zr							

(a) Analyte was below detection limit if left blank. Experimental uncertainties are 15%, except for values given in brackets. Values given in brackets are within 10 times the detection limit and the uncertainties for these values are greater than 15%.

Table A.4. Component Concentrations As a Function of Time For Leaching of S-110 Solids With 1 M NaOH at 80°C

	Concentration, μg/g[(a)]						
Time, h:	4	8	24	72	168	168	Final Wash
Ag							
Al	758	1042	1699	2502	3003	3056	137
As							
B							
Ba							
Be							
Bi			[4]			[3]	
Ca	[10]	[11]	[12]	[10]	[9]	[10]	[0]
Cd							
Ce							
Co							
Cr	[41]	64	117	191	234	241	11
Cu							
Dy							
Eu							
Fe	[1]	[1]	[4]	[2]	[2]	[2]	[1]
K							
La							
Li							
Mg							
Mn							
Mo							
Na	20253	22867	23620	23158	22657	23084	1538
Nd							
Ni	[1]	[1]	[2]	[1]	[1]	[1]	
P	[12]	[15]	[19]	[16]	[16]	[17]	[2]
Pb						[3]	
Pd							
Rh							
Ru							
Sb							
Se							
Si	[39]	[47]	[45]	[41]	[35]	[36]	[13]
Sn							
Sr							
Te							
Th							
Ti							
Tl							
U							
V							
W							
Y							
Zn			[2]	[1]	[1]	[1]	
Zr							

(a) Analyte was below detection limit if left blank. Experimental uncertainties are 15%, except for values given in brackets. Values given in brackets are within 10 times the detection limit and the uncertainties for these values are greater than 15%.

Table A.5. Component Concentrations As a Function of Time For Leaching of S-110 Solids With 3 M NaOH at 80°C

	Concentration, µg/g(a)						
Time, h:	4	8	24	72	168	168	Final Wash
Ag							
Al	870	1029	1794	2907	3757	3786	186
As							
B							
Ba							
Be							
Bi	[6]	[7]	[7]	[7]	[7]	[15]	
Ca	[11]	[12]	[10]	[12]	[11]	[14]	
Cd							
Ce							
Co							
Cr	61	86	163	228	252	250	12
Cu							
Dy							
Eu							
Fe	[4]	[4]	7	11	9	16	[0.5]
K	[94]	[122]	[68]	[87]	[74]	[53]	
La							
Li	[1]	[1]					
Mg							
Mn							
Mo							
Na	58860	57233	62592	60966	62258	62423	3681
Nd		[3]					
Ni	[1]	[1]	[1]	[1]	[1]	[4]	
P	[16]	[16]	[16]	[18]	[18]	[25]	
Pb	[4]	[5]	[4]	[5]	[5]	[4]	
Pd							
Rh							
Ru							
Sb							
Se							
Si	[65]	[65]	[65]	[65]	[66]	[65]	[14]
Sn							
Sr						[0.5]	
Te							
Th							
Ti							
Tl							
U		[65]					
V							
W							
Y							
Zn	[2]	[2]	[2]	[2]	[2]	[2]	
Zr							

(a) Analyte was below detection limit if left blank. Experimental uncertainties are 15%, except for values given in brackets. Values given in brackets are within 10 times the detection limit and the uncertainties for these values are greater than 15%.

Table A.6. Component Concentrations As a Function of Time For Leaching of S-110 Solids With 5 M NaOH at 80°C

	Concentration, µg/g(a)						
Time, h:	4	8	24	72	168	168	Final Wash
Ag							
Al	855	1032	1880	2911	3788	3670	178
As							
B							[1]
Ba							
Be							
Bi	[12]	[14]	[11]	[10]	[11]	[10]	
Ca	[13]	[20]	[14]	[11]	[11]	[10]	[5]
Cd			[0.5]		[0.5]	[0.5]	
Ce							
Co							
Cr	58	87	178	214	239	230	11
Cu							
Dy							
Eu							
Fe	7	15	17	21	16	15	
K	[89]		[92]		[76]	[71]	
La							
Li							
Mg							
Mn							
Mo							
Na	93933	88678	95900	93104	95229	89978	4953
Nd			[3]				
Ni	[3]	[4]	[2]	[2]	[1]	[1]	[1]
P	[17]	[22]	[18]	[16]	[17]	[17]	
Pb	[5]	[3]	[5]	[4]	[5]	[5]	
Pd							
Rh							
Ru							
Sb							
Se							
Si	[62]	[60]	[65]	[60]	[62]	[59]	[20]
Sn							
Sr				[1]	[1]	[1]	
Te							
Th							
Ti							
Tl							
U			[54]				
V							
W							
Y							
Zn	[2]	[2]	[2]	[2]	[2]	[2]	
Zr							

(a) Analyte was below detection limit if left blank. Experimental uncertainties are 15%, except for values given in brackets. Values given in brackets are within 10 times the detection limit and the uncertainties for these values are greater than 15%.

Table A.7. Component Concentrations As a Function of Time For Leaching of S-110 Solids With 1 M NaOH at 100°C

	Concentration, µg/g[(a)]						
Time, h:	4	8	24	72	168	168	Final Wash
Ag							
Al	1253	1823	2781	3550	4087	4031	139
As							
B							
Ba							
Be							
Bi		[3]	[3]	[3]	[3]	[3]	[0]
Ca	[11]	[11]	[13]	[9]	[11]	[9]	[5]
Cd							
Ce							
Co							
Cr	71	108	187	242	268	263	9
Cu							
Dy							
Eu							
Fe	[1]	[2]	[3]	[3]	[2]	[2]	
K							
La							
Li							
Mg							
Mn							
Mo							
Na	22078	22217	22577	22443	23002	22626	1544
Nd							
Ni	[1]	[1]	[1]	[1]	[1]	[1]	[1]
P	[14]	[15]	[16]	[15]	[15]	[15]	
Pb			[3]			[3]	
Pd							
Rh							
Ru							
Sb							
Se							
Si	[44]	[40]	[38]	[35]	[33]	[31]	[18]
Sn							
Sr							
Te							
Th							
Ti							
Tl							
U							
V							
W							
Y							
Zn	[0]	[1]	[2]	[1]	[2]	[2]	[0]
Zr							

(a) Analyte was below detection limit if left blank. Experimental uncertainties are 15%, except for values given in brackets. Values given in brackets are within 10 times the detection limit and the uncertainties for these values are greater than 15%.

Table A.8. Component Concentrations As a Function of Time For Leaching of S-110 Solids With 3 M NaOH at 100°C

	Concentration, µg/g(a)						
Time, h:	4	8	24	72	168	168	Final Wash
Ag							
Al	1428	2059	3186	4038	4167	4150	138
As							
B							[0.2]
Ba							
Be							
Bi	[7]	[7]	[8]	[8]	[8]	[7]	
Ca	[10]	[11]	[12]	[11]	[10]	[9]	[6]
Cd							
Ce							
Co							
Cr	95	151	224	257	266	263	9
Cu							
Dy							
Eu							
Fe	[6]	9	13	10	8	8	
K	[60]	[67]	[73]	[65]	[73]	[57]	
La							
Li	[1]						
Mg							
Mn							
Mo							
Na	57912	57804	58413	59718	60536	59519	2458
Nd					[3]		
Ni	[2]	[1]	[2]	[2]	[1]	[1]	[1]
P	[16]	[16]	[18]	[18]	[19]	[17]	
Pb	[5]	[5]	[6]	[6]	[6]	[5]	
Pd							
Rh							
Ru							
Sb							
Se							
Si	[63]	[64]	[64]	[65]	[65]	[62]	[20]
Sn							
Sr				[1]	[1]	[0.5]	
Te							
Th							
Ti							
Tl							
U							
V							
W							
Y							
Zn	[2]	[2]	[2]	[2]	[3]	[2]	
Zr							

(a) Analyte was below detection limit if left blank. Experimental uncertainties are 15%, except for values given in brackets. Values given in brackets are within 10 times the detection limit and the uncertainties for these values are greater than 15%.

Table A.9. Component Concentrations As a Function of Time For Leaching of S-110 Solids With 5 M NaOH at 100°C

	Concentration, μg/g(a)						
Time, h:	4	8	24	72	168	168	Final Wash
Ag							
Al	1462	2239	3499	3951	3891	4043	134
As							
B	[5]						[2]
Ba	[0.3]	[0.3]	[0.2]	[0.3]	[0.3]	[0.2]	
Be							
Bi	[8]	[9]	[11]	[11]	[10]	[11]	
Ca	[12]	[12]	[12]	[12]	[10]	[10]	[6]
Cd						[0.5]	
Ce							
Co							
Cr	82	142	237	254	252	259	9
Cu							
Dy							
Eu							
Fe	[11]	[19]	[28]	[20]	[16]	[17]	
K	[60]	[61]	[54]			[86]	
La							
Li			[1]			[1]	
Mg							
Mn	[3]						
Mo							
Na	88862	91087	95312	96808	95866	100544	3757
Nd						[3]	
Ni	[2]	[3]	[2]	[2]	[2]	[2]	[1]
P	[15]	[16]	[17]	[18]	[17]	[19]	
Pb	[5]	[5]	[6]	[6]	[6]	[7]	
Pd							
Rh							
Ru							
Sb							
Se							
Si	[63]	[61]	[63]	[63]	[64]	[65]	[22]
Sn							
Sr			[1]	[1]	[1]	[1]	
Te							
Th							
Ti							
Tl							
U						[55]	
V							
W							
Y							
Zn	[2]	[2]	[2]	[3]	[3]	[3]	
Zr							

(a) Analyte was below detection limit if left blank. Experimental uncertainties are 15%, except for values given in brackets. Values given in brackets are within 10 times the detection limit and the uncertainties for these values are greater than 15%.

Appendix B

Leaching Results in Terms of Percent Component Removed

Appendix B: Leaching Results in Terms of Percent Component Removed

Table B.1. Results of Leaching S-110 Sludge With 1 M NaOH At 60°C

	Leaching Solution		*Washing Solution*		*Leached Solids*						
	Solution Mass, g:	87.77	Solution Mass, g:	90.98	Solids Mass, g:	0.799					
Component	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Total Mass, µg	Removed, %	Calc. Conc. In Washed Solids, µg/g	Measured Conc. In Washed Solids, µg/g	Recovery %
Ag											
Al	1775	155819	178	16167	331800	265108	437094	39%	367615	325000	113%
As					[270]	[216]	[216]	(a)	[181]		
B					[76]	[61]	[61]	(a)	[51]	[135]	38%
Ba					233	186	186	(a)	156	[110]	142%
Be											
Bi					1865	1490	1490	(a)	1253	1365	92%
Ca	[10]	[887]	[6]	[549]	[1420]	[1135]	[2571]	56%	[2162]	[1200]	180%
Cd					[96]	[76]	[76]	(a)	[64]	[60]	107%
Ce					[215]	[172]	[172]	(a)	[144]		
Co											
Cr	154	13520	16	1418	19458	15547	30486	49%	25640	23050	111%
Cu										[82]	0%
Dy											
Eu											
Fe	[2]	[137]			21780	17402	17539	1%	14751	14150	104%
K					N/A	N/A	N/A	N/A	N/A	N/A	N/A
La					[240]	[192]	[192]	(a)	[161]	[160]	101%
Li					[43]	[34]	[34]	(a)	[29]		
Mg					[480]	[384]	[384]	(a)	[323]	[380]	85%
Mn					8305	6636	6636	(a)	5581	5305	105%
Mo											
Na	25407	2229993	2950	268428	14250	11386	2509806	N/A	N/A	N/A	N/A
Nd					[260]	[208]	[208]	(a)	[175]	[345]	51%
Ni	[1]	[100]	[1]	[61]	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P	[16]	[1423]	[3]	[305]	[250]	[200]	[1928]	90%	[1621]	1415	115%
Pb					[465]	[372]	[372]	(a)	[312]	[595]	53%
Pd											
Rh											
Ru											
Sb											
Se											
Si	[41]	[3620]	[20]	[1830]	[5120]	[4091]	[9541]	57%	[8025]	[5500]	146%
Sn											
Sr					2090	1670	1670	(a)	1404	1240	113%
Te											
Th											
Ti					[68]	[54]	[54]	(a)	[46]	[58]	79%
Tl											
U					30700	24529	24529	(a)	20630	[23500]	88%
V											
W											
Y					[56]	[45]	[45]	(a)	[38]		
Zn					[270]	[216]	[216]	(a)	[181]	[225]	81%
Zr					[245]	[196]	[196]	(a)	[165]	[135]	122%

(a) No detectable removal.

Table B.2. Results of Leaching S-110 Sludge With 3 M NaOH At 60°C

	Leaching Solution		***Washing Solution***		***Leached Solids***						
	Solution Mass, g:	98.066	Solution Mass, g:	90.345	Solids Mass, g:	0.671					
Component	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Total Mass, µg	Removed, %	Calc. Conc. In Washed Solids, µg/g	Measured Conc. In Washed Solids, µg/g	Recovery %
Ag											
Al	1881	184459	139	12549	334800	224651	421659	47%	359470	325000	111%
As					[290]	[195]	[195]	(a)	[166]		
B					[66]	[44]	[44]	(a)	[38]	[135]	28%
Ba					263	176	176	(a)	150	[110]	137%
Be											
Bi					1590	1067	1067	(a)	910	1365	67%
Ca			[6]	[520]	[1670]	[1121]	[1641]	32%	[1399]	[1200]	117%
Cd					[98]	[66]	[66]	(a)	[56]	[60]	93%
Ce					[240]	[161]	[161]	(a)	[137]		
Co					[50]	[34]	[34]	(a)	[29]		
Cr	199	19547	15	1349	13158	8829	29725	70%	25341	23050	110%
Cu					943	633	633	(a)	539	[82]	658%
Dy											
Eu											
Fe	[6]	[629]			25030	16795	17425	4%	14855	14150	105%
K					N/A	N/A	N/A	N/A	N/A	N/A	N/A
La					[260]	[174]	[174]	(a)	[149]	[160]	93%
Li					[40]	[27]	[27]	(a)	[23]		
Mg					[570]	[382]	[382]	(a)	[326]	[380]	86%
Mn					9420	6321	6321	(a)	5389	5305	102%
Mo					[47]	[32]	[32]	(a)	[27]		
Na	65506	6423897	5040	455309	4000	2684	6881890	N/A	N/A	N/A	N/A
Nd					[280]	[188]	[188]	(a)	[160]	[345]	46%
Ni	[1]	[105]	[1]	[56]	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P	[15]	[1506]	[2]	[183]	[210]	[141]	[1830]	92%	[1560]	1415	110%
Pb	[4]	[367]			[380]	[255]	[622]	59%	[530]	[595]	89%
Pd											
Rh											
Ru											
Sb											
Se											
Si	[64]	[6294]	[22]	[1967]	[2300]	[1543]	[9805]	84%	[8358]	[5500]	152%
Sn											
Sr					2360	1584	1584	(a)	1350	1240	109%
Te											
Th											
Ti					[85]	[57]	[57]	(a)	[49]	[58]	84%
Tl											
U					34600	23217	23217	(a)	19792	[23500]	84%
V											
W											
Y					[61]	[41]	[41]	(a)	[35]		
Zn	[2]	[184]			1010	678	862	21%	735	[225]	326%
Zr					[230]	[154]	[154]	(a)	[132]	[135]	97%

(a) No detectable removal.

Table B.3. Results of Leaching S-110 Sludge With 5 M NaOH At 60°C

	Leaching Solution		*Washing Solution*		*Leached Solids*						
	Solution Mass, g:	98.896	Solution Mass, g:	93.136	Solids Mass, g:	0.598					
Component	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Total Mass, µg	Removed, %	Calc. Conc. In Washed Solids, µg/g	Measured Conc. In Washed Solids, µg/g	Recovery %
Ag											
Al	1911	188989	203	18882	343800	205592	413463	50%	357049	325000	110%
As					[300]	[179]	[179]	(a)	[155]		
B					[82]	[49]	[49]	(a)	[42]	[135]	31%
Ba					300	179	179	(a)	155	[110]	141%
Be											
Bi					1290	771	771	(a)	666	1365	49%
Ca	[11]	[1114]	[5]	[497]	[1570]	[939]	[2550]	63%	[2202]	[1200]	183%
Cd					[84]	[50]	[50]	(a)	[43]	[60]	72%
Ce					[250]	[150]	[150]	(a)	[129]		
Co											
Cr	218	21525	23	2158	9168	5482	29165	81%	25186	23050	109%
Cu										[82]	0%
Dy											
Eu											
Fe	[17]	[1715]			25630	15327	17042	10%	14716	14150	104%
K					N/A	N/A	N/A	N/A	N/A	N/A	N/A
La					[290]	[173]	[173]	(a)	[150]	[160]	94%
Li					[40]	[24]	[24]	(a)	[21]		
Mg					[650]	[389]	[389]	(a)	[336]	[380]	88%
Mn					10400	6219	6219	(a)	5371	5305	101%
Mo											
Na	97870	9678935	10609	988098	9500	5681	10672715	N/A	N/A	N/A	N/A
Nd					[330]	[197]	[197]	(a)	[170]	[345]	49%
Ni	[1]	[111]	[1]	[57]	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P	[16]	[1631]	[2]	[170]	[200]	[120]	[1921]	94%	[1659]	1415	117%
Pb	[4]	[430]			[300]	[179]	[609]	71%	[526]	[595]	88%
Pd											
Rh											
Ru											
Sb											
Se											
Si	[65]	[6432]	[24]	[2271]	[2000]	[1196]	[9900]	88%	[8549]	[5500]	155%
Sn											
Sr					2620	1567	1567	(a)	1353	1240	109%
Te											
Th											
Ti					[92]	[55]	[55]	(a)	[48]	[58]	82%
Tl											
U					38400	22963	22963	(a)	19830	[23500]	84%
V											
W											
Y					[66]	[39]	[39]	(a)	[34]		
Zn	[3]	[249]			[220]	[132]	[381]	65%	[329]	[225]	146%
Zr					[260]	[155]	[155]	(a)	[134]	[135]	99%

(a) No detectable removal.

Table B.4. Results of Leaching S-110 Sludge With 1 M NaOH At 80°C

	Leaching Solution		***Washing Solution***		***Leached Solids***						
	Solution Mass, g:	90.105	Solution Mass, g:	86.262	Solids Mass, g:	0.423					
Component	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Total Mass, µg	Removed, %	Calc. Conc. In Washed Solids, µg/g	Measured Conc. In Washed Solids, µg/g	Recovery %
Ag					[25]	[11]	[11]	(a)	[9]		
Al	3029	272961	137	11833	299800	126815	411609	69%	353010	325000	109%
As					[320]	[135]	[135]	(a)	[116]		
B					[66]	[28]	[28]	(a)	[24]	[135]	18%
Ba					417	176	176	(a)	151	[110]	138%
Be											
Bi					3140	1328	1328	(a)	1139	1365	83%
Ca	[10]	[886]			3130	1324	2210	40%	[1895]	[1200]	158%
Cd					163	69	69	(a)	[59]	[60]	99%
Ce					[420]	[178]	[178]	(a)	[152]		
Co					[50]	[21]	[21]	(a)	18		
Cr	238	21408	11	940	14558	6158	28506	78%	24448	23050	106%
Cu										[82]	0%
Dy											
Eu											
Fe	[2]	[197]			37730	15960	16157	1%	13856	14150	98%
K						N/A	N/A	N/A	N/A	N/A	N/A
La					[460]	[195]	[195]	(a)	[167]	[160]	104%
Li					[66]	[28]	[28]	(a)	[24]		
Mg					[940]	[398]	[398]	(a)	[341]	[380]	90%
Mn					14800	6260	6260	(a)	5369	5305	101%
Mo											
Na	22871	2060757	1538	132704	22600	9560	2203021	N/A	N/A	N/A	N/A
Nd					580	245	245	(a)	[210]	[345]	61%
Ni	[1]	[111]	[0]	[0]	0	N/A	N/A	N/A	N/A	N/A	N/A
P	[16]	[1476]	[2]	[180]	330	140	1795	92%	[1540]	1415	109%
Pb					710	300	300	(a)	[258]	[595]	43%
Pd											
Rh											
Ru											
Sb											
Se											
Si	[35]	[3197]	[13]	[1092]	9600	4061	8350	51%	[7161]	[5500]	130%
Sn											
Sr					3800	1607	1607	(a)	1379	1240	111%
Te											
Th											
Ti					[120]	[51]	[51]	(a)	[44]	[58]	75%
Tl											
U					55500	23477	23477	(a)	20134	[23500]	86%
V											
W											
Y					[100]	[42]	[42]	(a)	[36]		
Zn					[440]	[186]	[186]	(a)	[160]	[225]	71%
Zr					[490]	[207]	[207]	(a)	[178]	[135]	132%

(a) No detectable removal.

Table B.5. Results of Leaching S-110 Sludge With 3 M NaOH At 80°C

	Leaching Solution		***Washing Solution***		***Leached Solids***						
	Solution Mass, g:	99.177	Solution Mass, g:	87.325	Solids Mass, g:	0.207					
Component	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Total Mass, µg	Removed, %	Calc. Conc. In Washed Solids, µg/g	Measured Conc. In Washed Solids, µg/g	Recovery %
Ag					[41]	[8]	[8]	(a)	[7]		
Al	3771	374041	186	16285	192800	39910	430235	91%	371533	325000	114%
As					[260]	[54]	[54]	(a)	[46]		
B					[91]	[19]	[19]	(a)	[16]	[135]	12%
Ba					844	175	175	(a)	151	[110]	137%
Be											
Bi					4580	948	948	(a)	819	1365	60%
Ca					6050	1252	1252	(a)	1081	[1200]	90%
Cd					286	59	59	(a)	51	[60]	85%
Ce					[800]	[166]	[166]	(a)	[143]		
Co					[79]	[16]	[16]	(a)	[14]		
Cr	251	24893	12	1090	16158	3345	29328	89%	25326	23050	110%
Cu										[82]	0%
Dy											
Eu											
Fe	[13]	[1257]			76130	15759	17016	7%	14694	14150	104%
K					N/A	N/A	N/A	N/A	N/A	N/A	N/A
La					890	184	184	(a)	159	[160]	99%
Li					[100]	[21]	[21]	(a)	[18]		
Mg					1940	402	402	(a)	347	[380]	91%
Mn					30100	6231	6231	(a)	5381	5305	101%
Mo											
Na	62340	6182727	3681	321448	24800	5134	6509308	N/A	N/A	N/A	N/A
Nd					1260	261	261	(a)	225	[345]	65%
Ni	[3]	[254]			N/A	N/A	N/A	N/A	N/A	N/A	N/A
P	[21]	[2116]			[300]	[62]	[2178]	97%	[1881]	1415	133%
Pb	[4]	[430]			880	182	612	70%	[529]	[595]	89%
Pd					[770]	[159]	[159]	(a)	[138]		
Rh											
Ru											
Sb											
Se											
Si	[66]	[6496]	[14]	[1204]	5520	1143	8843	87%	[7636]	[5500]	139%
Sn											
Sr					7480	1548	1548	(a)	1337	1240	108%
Te											
Th											
Ti					[220]	[46]	[46]	(a)	[39]	[58]	68%
Tl											
U					114800	23764	23764	(a)	20521	[23500]	87%
V											
W											
Y					[200]	[41]	[41]	(a)	[36]		
Zn	[2]				562	116	116	(a)	[100]	[225]	45%
Zr					938	194	194	(a)	[168]	[135]	124%

(a) No detectable removal.

Table B.6. Results of Leaching S-110 Sludge With 5 M NaOH At 80°C

	Leaching Solution		***Washing Solution***		***Leached Solids***						
	Solution Mass, g:	105.547	Solution Mass, g:	86.46	Solids Mass, g:	0.143					
Component	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Total Mass, µg	Removed, %	Calc. Conc. In Washed Solids, µg/g	Measured Conc. In Washed Solids, µg/g	Recovery %
Ag					[48]	[7]	[7]	(a)	[6]		
Al	3729	393569	178	15379	122800	17560	426508	96%	365788	325000	113%
As											
B					[200]	[29]	[29]	(a)	[25]	[135]	18%
Ba					1300	186	186	(a)	159	[110]	145%
Be											
Bi					4650	665	665	(a)	570	1365	42%
Ca	[11]	[1110]	[5]	[398]	9570	1369	2876	52%	2467	[1200]	206%
Cd					318	45	45	(a)	39	[60]	65%
Ce					[1200]	[172]	[172]	(a)	[147]		
Co					[120]	[17]	[17]	(a)	[15]		
Cr	235	24781	11	981	20558	2940	28702	90%	24616	23050	107%
Cu										[82]	0%
Dy											
Eu											
Fe	[15]	[1628]			105830	15134	16762	10%	14375	14150	102%
K					N/A	N/A	N/A	N/A	N/A	N/A	N/A
La					1340	192	192	(a)	164	[160]	103%
Li					[120]	[17]	[17]	(a)	[15]		
Mg					2740	392	392	(a)	336	[380]	88%
Mn					46800	6692	6692	(a)	5740	5305	108%
Mo											
Na	92604	9774048	4953	428235	40900	5849	10208131	N/A	N/A	N/A	N/A
Nd					1950	279	279	(a)	239	[345]	69%
Ni	[1]	[107]	[1]	[53]	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P	[17]	[1774]	[0]	[0]	[180]	[26]	[1800]	99%	[1544]	1415	109%
Pb	[5]	[532]			700	100	632	84%	542	[595]	91%
Pd											
Rh											
Ru											
Sb											
Se											
Si	[61]	[6408]	[20]	[1724]	6520	932	9064	90%	7773	[5500]	141%
Sn											
Sr					11200	1602	1602	(a)	1374	1240	111%
Te											
Th											
Ti					322	46	46	(a)	39	[58]	68%
Tl											
U					168800	24138	24138	(a)	20702	[23500]	88%
V											
W											
Y					[290]	[41]	[41]	(a)	[36]		
Zn	[2]	[253]			555	79	333	76%	285	[225]	127%
Zr					1270	182	182	(a)	156	[135]	115%

(a) No detectable removal.

Table B.7. Results of Leaching S-110 Sludge With 1 M NaOH At 100°C

	Leaching Solution		***Washing Solution***		***Leached Solids***						
	Solution Mass, g:	94.577	Solution Mass, g:	87.026	Solids Mass, g:	0.210					
Component	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Total Mass, µg	Removed, %	Calc. Conc. In Washed Solids, µg/g	Measured Conc. In Washed Solids, µg/g	Recovery %
Ag					[39]	[8]	[8]	(a)	[7]		
Al	4059	383902	139	12130	176800	37128	433159	91%	374058	325000	115%
As											
B					[140]	[29]	[29]	(a)	[25]	[135]	19%
Ba					899	189	189	(a)	163	[110]	148%
Be											
Bi					6660	1399	1399	(a)	1208	1365	88%
Ca	[10]	[951]	[5]	[395]	7040	1478	2824	48%	2439	[1200]	203%
Cd					341	72	72	(a)	62	[60]	103%
Ce					[820]	[172]	[172]	(a)	[149]		
Co					[86]	[18]	[18]	(a)	[16]		
Cr	265	25104	9	803	17858	3750	29658	87%	25611	23050	111%
Cu					[67]	[14]	[14]	(a)	[12]	[82]	15%
Dy											
Eu											
Fe	[2]	[224]			77930	16365	16589	1%	14325	14150	101%
K					N/A	N/A	N/A	N/A	N/A	N/A	N/A
La					916	192	192	(a)	166	[160]	104%
Li					[120]	[25]	[25]	(a)	[22]		
Mg					2030	426	426	(a)	368	[380]	97%
Mn					32300	6783	6783	(a)	5858	5305	110%
Mo					[66]	[14]	[14]	(a)	[12]		
Na	22814	2157670	1544	134336	37900	7959	2299964	N/A	N/A	N/A	N/A
Nd					1320	277	277	(a)	239	[345]	69%
Ni	[1]	[106]	[1]	[53]	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P	[15]	[1405]	[0]	[0]	1360	286	1690	83%	1460	1415	103%
Pb					1380	290	290	(a)	250	[595]	42%
Pd					[750]	[158]	[158]	(a)	[136]		
Rh											
Ru											
Sb											
Se											
Si	[32]	[3028]	[18]	[1580]	20000	4200	8808	52%	7606	[5500]	138%
Sn											
Sr					8300	1743	1743	(a)	1505	1240	121%
Te											
Th											
Ti					[220]	[46]	[46]	(a)	[40]	[58]	69%
Tl											
U					119800	25158	25158	(a)	21725	[23500]	92%
V											
W											
Y					[210]	[44]	[44]	(a)	[38]		
Zn					894	188	188	(a)	162	[225]	72%
Zr					993	209	209	(a)	180	[135]	133%

(a) No detectable removal.

Table B.8. Results of Leaching S-110 Sludge With 3 M NaOH At 100°C

	Leaching Solution		***Washing Solution***		***Leached Solids***						
	Solution Mass, g:	99.957	Solution Mass, g:	84.813	Solids Mass, g:	0.107					
Component	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Total Mass, µg	Removed, %	Calc. Conc. In Washed Solids, µg/g	Measured Conc. In Washed Solids, µg/g	Recovery %
Ag					[66]	[7]	[7]	(a)	[6]		
Al	4158	415665	9	762	13100	1402	417829	100%	356205	325000	110%
As											
B					546	58	58	(a)	50	[135]	37%
Ba					1620	173	173	(a)	148	[110]	134%
Be											
Bi					8240	882	882	(a)	752	1365	55%
Ca					11970	1281	1281	(a)	1092	[1200]	91%
Cd					498	53	53	(a)	45	[60]	76%
Ce					[1400]	[150]	[150]	(a)	[128]		
Co					[140]	[15]	[15]	(a)	[13]		
Cr	264	26425	1	49	24858	2660	29134	91%	24837	23050	108%
Cu					[37]	[4]	[4]	(a)	[3]	[82]	4%
Dy											
Eu											
Fe	[8]	[759]			139830	14962	15721	5%	13402	14150	95%
K					N/A	N/A	N/A	N/A	N/A	N/A	N/A
La					1680	180	180	(a)	153	[160]	96%
Li					[180]	[19]	[19]	(a)	[16]		
Mg					3730	399	399	(a)	340	[380]	90%
Mn					57400	6142	6142	(a)	5236	5305	99%
Mo					[58]	[6]	[6]	(a)	[5]		
Na	60028	6000174	160	13570	62900	6730	6020474	N/A	N/A	N/A	N/A
Nd					2470	264	264	(a)	225	[345]	65%
Ni	[1]	[141]			N/A	N/A	N/A	N/A	N/A	N/A	N/A
P	[18]	[1798]			[770]	[82]	[1881]	96%	[1603]	1415	113%
Pb	[6]	[596]			1480	158	755	79%	643	[595]	108%
Pd					[1200]	[128]	[128]	(a)	[109]		
Rh											
Ru											
Sb											
Se											
Si	[63]	[6318]	[1]	[110]	11800	1263	7691	84%	6556	[5500]	119%
Sn											
Sr					14500	1552	1552	(a)	1323	1240	107%
Te											
Th					[1300]	[139]	[139]	(a)	[119]		
Ti					392	42	42	(a)	36	[58]	62%
Tl											
U					217800	23305	23305	(a)	19868	[23500]	85%
V					[68]	[7]	[7]	(a)	[6]		
W											
Y					[370]	[40]	[40]	(a)	[34]		
Zn	[2]	[245]			753	81	326	75%	278	[225]	123%
Zr					1720	184	184	(a)	157	[135]	116%

(a) No detectable removal.

Table B.9. Results of Leaching S-110 Sludge With 5 M NaOH At 100°C

	Leaching Solution		***Washing Solution***		***Leached Solids***						
	Solution Mass, g:	106.523	Solution Mass, g:	88.233	Solids Mass, g:	0.099					
Component	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Conc., µg/g	Mass, µg	Total Mass, µg	Removed, %	Calc. Conc. In Washed Solids, µg/g	Measured Conc. In Washed Solids, µg/g	Recovery %
Ag					[73]	[7]	[7]	(a)	[6]		
Al	3967	422563	134	11862	8840	875	435301	100%	373328	325000	115%
As											
B					[380]	[38]	[38]	(a)	[32]	[135]	24%
Ba					1750	173	173	(a)	149	[110]	135%
Be											
Bi					5440	539	539	(a)	462	1365	34%
Ca	[10]	[1050]	[6]	[562]	12670	1254	2865	56%	2458	[1200]	205%
Cd					355	35	35	(a)	30	[60]	50%
Ce					[1500]	[149]	[149]	(a)	[127]		
Co					[160]	[16]	[16]	(a)	[14]		
Cr	255	27203	9	781	22358	2213	30197	93%	25898	23050	112%
Cu										[82]	0%
Dy											
Eu											
Fe	[17]	[1758]			144830	14338	16096	11%	13805	14150	98%
K					N/A	N/A	N/A	N/A	N/A	N/A	N/A
La					1780	176	176	(a)	151	[160]	94%
Li					[140]	[14]	[14]	(a)	[12]		
Mg					3960	392	392	(a)	336	[380]	88%
Mn					61200	6059	6059	(a)	5196	5305	98%
Mo											
Na	98205	10461099	3757	331485	67900	6722	10799306	N/A	N/A	N/A	N/A
Nd					2590	256	256	(a)	220	[345]	64%
Ni	[2]	[246]	[1]	[110]	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P	[18]	[1927]			[250]	[25]	[1951]	99%	[1674]	1415	118%
Pb	[6]	[672]			1010	100	772	87%	662	[595]	111%
Pd											
Rh											
Ru											
Sb											
Se											
Si	[64]	[6869]	[22]	[1918]	9450	936	9722	90%	8338	[5500]	152%
Sn											
Sr					15400	1525	1525	(a)	1308	1240	105%
Te											
Th											
Ti					427	42	42	(a)	36	[58]	63%
Tl											
U					232800	23047	23047	(a)	19766	[23500]	84%
V											
W											
Y					[380]	[38]	[38]	(a)	[32]		
Zn	[3]	[298]			450	45	343	87%	294	[225]	131%
Zr					1740	172	172	(a)	148	[135]	109%

(a) No detectable removal.

Appendix C

Radionuclide Behavior

Appendix C: Radionuclide Behavior

Table C.1. Radionuclide Behavior During Leaching of S-110 Solids at 60°C[(a)]

Leaching With 1 M NaOH at 60°

	Leaching Solution		*Washing Solution*		*Leached Solids*					
	Solution Mass, g:	87.77	Solution Mass, g:	90.98	Solids Mass, g:	0.799				
	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Total Activity, µCi	Removed, %	Calc. Conc. In Washed Solids, µCi/g	Measured Conc. In Washed Solids, µCi/g
Cs-137	4.32E-01	3.79E+01	3.81E-02	3.46E+00	5.91E+00	4.73E+00	4.61E+01	90%	3.88E+01	3.11E+01
Co-60					<6E-02	4.79E-02	4.79E-02	(b)	4.03E-02	
Eu-154					9.33E-01	7.45E-01	7.45E-01	(b)	6.27E-01	
Eu-155					4.02E-01	3.21E-01	3.21E-01	(b)	2.70E-01	
Am-241(γ)					1.26E+00	1.00E+00	1.00E+00	(b)	8.43E-01	
U-238	2.86E-06	2.51E-04	1.81E-07	1.65E-05	1.45E-02	1.15E-02	1.18E-02	2%	9.94E-03	Not Determined
U-234	4.23E-06	3.71E-04	3.79E-07	3.45E-05	3.40E-02	2.72E-02	2.76E-02	1%	2.32E-02	Not Determined
Pu-239/240	2.55E-05	2.24E-03	7.09E-07	6.45E-05	1.95E+00	1.56E+00	1.56E+00	(b)	1.32E+00	Not Determined
Am-241+Pu-238	1.30E-06	1.14E-04	4.46E-07	4.06E-05	1.37E+00	1.10E+00	1.10E+00	(b)	9.23E-01	Not Determined
Cm-243/244					1.36E-02	1.09E-02	1.09E-02	(b)	9.14E-03	Not Determined
Cm-242										Not Determined
Total Alpha	3.39E-05	2.97E-03	1.71E-06	1.56E-04	3.38E+00	2.70E+00	2.71E+00	(b)	2.28E+00	1.83E+00

Leaching With 3 M NaOH at 60°

	Leaching Solution		*Washing Solution*		*Leached Solids*					
	Solution Mass, g:	98.066	Solution Mass, g:	90.345	Solids Mass, g:	0.671				
	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Total Activity, µCi	Removed, %	Calc. Conc. In Washed Solids, µCi/g	Measured Conc. In Washed Solids, µCi/g
Cs-137	4.03E-01	3.95E+01	2.80E-02	2.53E+00	1.10E+00	7.37E-01	4.27E+01	98%	3.64E+01	3.11E+01
Co-60					7.99E-02	5.36E-02	5.36E-02	(b)	4.57E-02	
Eu-154					1.01E+00	6.78E-01	6.78E-01	(b)	5.78E-01	
Eu-155					4.34E-01	2.91E-01	2.91E-01	(b)	2.48E-01	
Am-241(γ)					1.45E+00	9.73E-01	9.73E-01	(b)	8.29E-01	
U-238	2.68E-06	2.63E-04	1.82E-07	1.64E-05	1.46E-02	9.80E-03	1.01E-02	3%	8.59E-03	Not Determined
U-234	7.35E-06	7.20E-04	2.43E-07	2.19E-05	3.40E-02	2.28E-02	2.36E-02	3%	2.01E-02	Not Determined
Pu-239/240	1.76E-04	1.73E-02	7.48E-07	6.76E-05	2.01E+00	1.35E+00	1.37E+00	1%	1.16E+00	Not Determined
Am-241+Pu-238	9.23E-06	9.05E-04	6.27E-07	5.66E-05	1.52E+00	1.02E+00	1.02E+00	0.1%	8.70E-01	Not Determined
Cm-243/244										Not Determined
Cm-242										Not Determined
Total Alpha	1.95E-04	1.92E-02	1.80E-06	1.63E-04	3.58E+00	2.40E+00	2.42E+00	1%	2.06E+00	1.83E+00

Leaching With 5 M NaOH at 60°

	Leaching Solution		*Washing Solution*		*Leached Solids*					
	Solution Mass, g:	98.896	Solution Mass, g:	93.136	Solids Mass, g:	0.598				
	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Total Activity, µCi	Removed, %	Calc. Conc. In Washed Solids, µCi/g	Measured Conc. In Washed Solids, µCi/g
Cs-137	3.78E-01	3.74E+01	3.90E-02	3.63E+00	6.79E-01	4.06E-01	4.15E+01	99%	3.58E+01	3.11E+01
Co-60					1.09E-01	6.52E-02	6.52E-02	(b)	5.63E-02	
Eu-154					1.28E+00	7.65E-01	7.65E-01	(b)	6.61E-01	
Eu-155					6.41E-01	3.83E-01	3.83E-01	(b)	3.31E-01	
Am-241(γ)					9.25E-01	5.53E-01	5.53E-01	(b)	4.78E-01	
U-238	2.99E-06	2.96E-04	2.80E-07	2.61E-05	2.17E-02	1.30E-02	1.33E-02	2%	1.15E-02	Not Determined
U-234	6.59E-06	6.52E-04	7.62E-07	7.10E-05	2.17E-02	1.30E-02	1.37E-02	5%	1.18E-02	Not Determined
Pu-239/240	3.20E-04	3.17E-02	1.42E-06	1.33E-04	2.37E+00	1.42E+00	1.45E+00	2%	1.25E+00	Not Determined
Am-241+Pu-238	1.70E-05	1.69E-03			1.62E+00	9.68E-01	9.70E-01	0.2%	8.37E-01	Not Determined
Cm-243/244					1.97E-02	1.18E-02	1.18E-02	(b)	1.01E-02	Not Determined
Cm-242										Not Determined
Total Alpha	3.47E-04	3.43E-02	2.47E-06	2.30E-04	4.05E+00	2.42E+00	2.46E+00	1%	2.12E+00	1.83E+00

(a) Analyte was below detection limit if left blank.
(b) No detectable removal.

Table C.2. Radionuclide Behavior During Leaching of S-110 Solids at 80°C[(a)]

Leaching With 1 M NaOH at 80°

	Leaching Solution		***Washing Solution***		***Leached Solids***					
	Solution Mass, g:	90.105	Solution Mass, g:	86.262	Solids Mass, g:	0.423				
	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Total Activity, µCi	Removed, %	Calc. Conc. In Washed Solids, µCi/g	Measured Conc. In Washed Solids, µCi/g
Cs-137	4.38E-01	3.95E+01	1.69E-02	1.46E+00	9.76E+00	4.13E+00	4.50E+01	91%	3.86E+01	3.11E+01
Co-60					1.25E-01	5.29E-02	5.29E-02	(b)	4.53E-02	
Eu-154					1.75E+00	7.40E-01	7.40E-01	(b)	6.35E-01	
Eu-155					1.04E+00	4.40E-01	4.40E-01	(b)	3.77E-01	
Am-241(γ)					2.35E+00	9.94E-01	9.94E-01	(b)	8.53E-01	
U-238	2.57E-06	2.32E-04	1.14E-07	9.82E-06	2.52E-02	1.07E-02	1.09E-02	2%	9.35E-03	Not Determined
U-234	4.68E-06	4.22E-04	2.56E-07	2.21E-05	4.34E-02	1.84E-02	1.88E-02	2%	1.61E-02	Not Determined
Pu-239/240	1.67E-05	1.51E-03			3.46E+00	1.46E+00	1.46E+00	0.1%	1.26E+00	Not Determined
Am-241+Pu-238	1.66E-06	1.50E-04			2.43E+00	1.03E+00	1.03E+00	0.01%	8.81E-01	Not Determined
Cm-243/244					2.07E-02	8.74E-03	8.74E-03	(b)	7.49E-03	Not Determined
Cm-242					5.05E-03	2.14E-03	2.14E-03	(b)	1.83E-03	Not Determined
Total Alpha	2.56E-05	2.31E-03			5.98E+00	2.53E+00	2.53E+00	0.09%	2.17E+00	1.83E+00

Leaching With 3 M NaOH at 80°

	Leaching Solution		***Washing Solution***		***Leached Solids***					
	Solution Mass, g:	99.177	Solution Mass, g:	87.325	Solids Mass, g:	0.207				
	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Total Activity, µCi	Removed, %	Calc. Conc. In Washed Solids, µCi/g	Measured Conc. In Washed Solids, µCi/g
Cs-137	4.19E-01	4.16E+01	1.84E-02	1.60E+00	2.49E+00	5.15E-01	4.37E+01	99%	3.77E+01	3.11E+01
Co-60					2.78E-01	5.75E-02	5.75E-02	(b)	4.97E-02	
Eu-154					3.50E+00	7.25E-01	7.25E-01	(b)	6.26E-01	
Eu-155					1.79E+00	3.71E-01	3.71E-01	(b)	3.20E-01	
Am-241(γ)					4.16E+00	8.61E-01	8.61E-01	(b)	7.44E-01	
U-238	3.32E-06	3.29E-04	2.64E-07	2.31E-05	4.02E-02	8.32E-03	8.67E-03	4%	7.49E-03	Not Determined
U-234	6.08E-06	6.03E-04	4.34E-07	3.79E-05	6.93E-02	1.43E-02	1.50E-02	4%	1.29E-02	Not Determined
Pu-239/240	9.26E-05	9.18E-03	4.03E-07	3.52E-05	6.67E+00	1.38E+00	1.39E+00	1%	1.20E+00	Not Determined
Am-241+Pu-238	4.53E-06	4.49E-04	7.76E-08	6.78E-06	4.66E+00	9.64E-01	9.65E-01	0.05%	8.33E-01	Not Determined
Cm-243/244					6.73E-02	1.39E-02	1.39E-02	(b)	1.20E-02	Not Determined
Cm-242					6.11E-03	1.26E-03	1.26E-03	(b)	1.09E-03	Not Determined
Total Alpha	1.07E-04	1.06E-02	1.18E-06	1.03E-04	1.15E+01	2.38E+00	2.39E+00	0.4%	2.06E+00	1.83E+00

Leaching With 5 M NaOH at 80°

	Leaching Solution		***Washing Solution***		***Leached Solids***					
	Solution Mass, g:	105.547	Solution Mass, g:	86.46	Solids Mass, g:	0.143				
	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Total Activity, µCi	Removed, %	Calc. Conc. In Washed Solids, µCi/g	Measured Conc. In Washed Solids, µCi/g
Cs-137	3.81E-01	4.02E+01	1.80E-02	1.56E+00	1.09E+00	1.56E-01	4.19E+01	100%	3.59E+01	3.11E+01
Co-60					3.81E-01	5.45E-02	5.45E-02	(b)	4.67E-02	
Eu-154					5.38E+00	7.69E-01	7.69E-01	(b)	6.60E-01	
Eu-155					2.75E+00	3.93E-01	3.93E-01	(b)	3.37E-01	
Am-241(γ)					6.38E+00	9.12E-01	9.12E-01	(b)	7.82E-01	
U-238	2.08E-06	2.19E-04	1.19E-07	1.03E-05	6.30E-02	9.01E-03	9.24E-03	2%	7.92E-03	Not Determined
U-234	5.33E-06	5.63E-04	3.86E-07	3.33E-05	1.07E-01	1.53E-02	1.59E-02	4%	1.36E-02	Not Determined
Pu-239/240	2.06E-04	2.17E-02	4.89E-07	4.23E-05	9.76E+00	1.40E+00	1.42E+00	2%	1.22E+00	Not Determined
Am-241+Pu-238	1.18E-05	1.24E-03	1.04E-07	8.98E-06	7.00E+00	1.00E+00	1.00E+00	0.1%	8.59E-01	Not Determined
Cm-243/244					6.84E-02	9.77E-03	9.77E-03	(b)	8.38E-03	Not Determined
Cm-242					1.18E-02	1.69E-03	1.69E-03	(b)	1.45E-03	Not Determined
Total Alpha	2.25E-04	2.38E-02	1.10E-06	9.49E-05	1.70E+01	2.43E+00	2.45E+00	1%	2.11E+00	1.83E+00

(a) Analyte was below detection limit if left blank.
(b) No detectable removal.

Table C.3. Radionuclide Behavior During Leaching of S-110 Solids at 100°C[(a)]

Leaching With 1 M NaOH at 100°

	Leaching Solution		*Washing Solution*		*Leached Solids*					
	Solution Mass, g:	94.577	Solution Mass, g:	87.026	Solids Mass, g:	0.21				
	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Total Activity, µCi	Removed, %	Calc. Conc. In Washed Solids, µCi/g	Measured Conc. In Washed Solids, µCi/g
Cs-137	4.08E-01	3.86E+01	1.49E-02	1.30E+00	1.84E+01	3.86E+00	4.37E+01	91%	3.78E+01	3.11E+01
Co-60					2.80E-01	5.88E-02	5.88E-02	(b)	5.08E-02	
Eu-154					3.97E+00	8.34E-01	8.34E-01	(b)	7.20E-01	
Eu-155					1.87E+00	3.93E-01	3.93E-01	(b)	3.39E-01	
Am-241(γ)					4.14E+00	8.69E-01	8.69E-01	(b)	7.51E-01	
U-238	6.72E-06	6.35E-04	8.23E-07	7.16E-05	5.52E-02	1.16E-02	1.23E-02	6%	1.06E-02	Not Determined
U-234	1.13E-05	1.07E-03	8.65E-07	7.53E-05	8.80E-02	1.85E-02	1.96E-02	6%	1.69E-02	Not Determined
Pu-239/240	5.16E-05	4.88E-03	1.69E-06	1.47E-04	6.92E+00	1.45E+00	1.46E+00	0.3%	1.26E+00	Not Determined
Am-241+Pu-238	2.60E-06	2.46E-04	0.00E+00	0.00E+00	4.98E+00	1.05E+00	1.05E+00	0.02%	9.03E-01	Not Determined
Cm-243/244					2.88E-02	6.04E-03	6.04E-03	(b)	5.21E-03	Not Determined
Cm-242										Not Determined
Total Alpha	7.23E-05	6.84E-03	3.39E-06	2.95E-04	1.21E+01	2.54E+00	2.55E+00	0.3%	2.20E+00	1.83E+00

Leaching With 3 M NaOH at 100°

	Leaching Solution		*Washing Solution*		*Leached Solids*					
	Solution Mass, g:	99.957	Solution Mass, g:	84.813	Solids Mass, g:	0.107				
	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Total Activity, µCi	Removed, %	Calc. Conc. In Washed Solids, µCi/g	Measured Conc. In Washed Solids, µCi/g
Cs-137	4.31E-01	4.30E+01	1.37E-02	1.16E+00	2.21E+00	2.36E-01	4.44E+01	99%	3.79E+01	3.11E+01
Co-60					5.30E-01	5.67E-02	5.67E-02	(b)	4.83E-02	
Eu-154					7.05E+00	7.54E-01	7.54E-01	(b)	6.43E-01	
Eu-155					3.51E+00	3.76E-01	3.76E-01	(b)	3.20E-01	
Am-241(γ)					8.25E+00	8.83E-01	8.83E-01	(b)	7.53E-01	
U-238	8.47E-06	8.47E-04	5.21E-07	4.42E-05	1.06E-01	1.13E-02	1.22E-02	7%	1.04E-02	Not Determined
U-234	1.32E-05	1.32E-03	9.80E-07	8.31E-05	9.34E-02	9.99E-03	1.14E-02	12%	9.72E-03	Not Determined
Pu-239/240	1.98E-04	1.98E-02	5.82E-07	4.93E-05	1.33E+01	1.42E+00	1.44E+00	1%	1.23E+00	Not Determined
Am-241+Pu-238	9.99E-06	9.99E-04	0.00E+00	0.00E+00	9.39E+00	1.00E+00	1.01E+00	0.1%	8.57E-01	Not Determined
Cm-243/244					8.11E-02	8.67E-03	8.67E-03	(b)	7.39E-03	Not Determined
Cm-242										Not Determined
Total Alpha	2.29E-04	2.29E-02	2.08E-06	1.77E-04	2.30E+01	2.46E+00	2.48E+00	1%	2.12E+00	1.83E+00

Leaching With 5 M NaOH at 100°

	Leaching Solution		*Washing Solution*		*Leached Solids*					
	Solution Mass, g:	106.523	Solution Mass, g:	88.233	Solids Mass, g:	0.099				
	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Conc., µCi/g	Activity, µCi	Total Activity, µCi	Removed, %	Calc. Conc. In Washed Solids, µCi/g	Measured Conc. In Washed Solids, µCi/g
Cs-137	3.84E-01	4.09E+01	1.22E-02	1.08E+00	1.19E+00	1.18E-01	4.21E+01	100%	3.61E+01	3.11E+01
Co-60					5.93E-01	5.87E-02	5.87E-02	(b)	5.03E-02	
Eu-154					7.29E+00	7.22E-01	7.22E-01	(b)	6.19E-01	
Eu-155					3.78E+00	3.74E-01	3.74E-01	(b)	3.21E-01	
Am-241(γ)					8.49E+00	8.41E-01	8.41E-01	(b)	7.21E-01	
U-238	5.46E-06	5.82E-04	2.77E-07	2.45E-05	8.89E-02	8.80E-03	9.41E-03	6%	8.07E-03	Not Determined
U-234	1.04E-05	1.11E-03	7.93E-07	6.99E-05	1.34E-01	1.33E-02	1.44E-02	8%	1.24E-02	Not Determined
Pu-239/240	3.31E-04	3.53E-02	4.76E-07	4.20E-05	1.32E+01	1.31E+00	1.34E+00	3%	1.15E+00	Not Determined
Am-241+Pu-238	1.67E-05	1.78E-03			9.09E+00	9.00E-01	9.02E-01	0.2%	7.73E-01	Not Determined
Cm-243/244					1.00E-01	9.94E-03	9.94E-03	(b)	8.53E-03	Not Determined
Cm-242					2.00E-02	1.98E-03	1.98E-03	(b)	1.70E-03	Not Determined
Total Alpha	3.63E-04	3.86E-02	1.54E-06	1.36E-04	2.26E+01	2.24E+00	2.28E+00	2%	1.95E+00	1.83E+00

(a) Analyte was below detection limit if left blank.
(b) No detectable removal.

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