21

Application of Engineered Sorbent Barriers Summary of Laboratory Data for FY 1988

**H. D. Freeman
E. O. Jones**

September 1989

**Prepared for the U.S. Department of Energy
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**Pacific Northwest Laboratory
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Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

Laboratory studies were conducted in FY 1988 by Pacific Northwest Laboratory to determine the effect of contact time, pH, solution to solid ratio, and particle size on the performance of a number of materials in adsorbing radioactive cobalt, strontium, and cesium. The laboratory studies were conducted to provide background information useful in designing an engineered sorbent barrier, which restricts the migration of radionuclides from low-level waste sites. Understanding how the variables affect the adsorption of ions on the sorbent materials is the key to estimating the performance of sorbent barriers under a variety of conditions.

The scope of the studies was limited to three radionuclides and four sorbent materials, but the general approach can be used to evaluate other radionuclides and conditions. The sorbent materials evaluated in this study included clinoptilolite, activated carbon, bentonite clay, and Savannah River soil. The clinoptilolite and activated carbon were identified in previous studies as the most cost-effective materials for sorption of the three radionuclides under consideration. The bentonite clay was evaluated as a component of the barrier that could be used to modify the permeability of the barrier system. The Savannah River soil was used to represent soil from a humid site.

The laboratory studies showed that for the materials being evaluated, adsorption kinetics are not very fast, which can impact the proper design of both batch and flowthrough column tests. For the same materials, the initial pH of the leachate did not significantly affect the distribution coefficient (K_d) above a pH of 1. The natural buffering capacity of the sorbent materials was the primary reason for this insensitivity to pH. The solution to solid ratio used in the studies affected the measured K_d s by up to a factor of 7. Decreasing the particle size did not have an important effect on the adsorption rate of the materials tested.

CONTENTS

SUMMARY.	iii
INTRODUCTION	1
LABORATORY STUDIES	3
DESCRIPTION OF SORBENT MATERIALS.	3
BATCH CONTACT TESTS	4
Test Procedures.	5
Results.	6
CONCLUSIONS.	19
REFERENCES	21
APPENDIX - SUMMARY OF BATCH CONTACT DATA	A.1

FIGURES

1	Effect of Contact Time on the Distribution Coefficients for -5 Mesh Clinoptilolite.	8
2	Effect of Contact Time on the Distribution Coefficients for -5 Mesh +35 Mesh Clinoptilolite	8
3	Effect of Contact Time on the Distribution Coefficients for Activated Carbon.	9
4	Effect of Contact Time on the Distribution Coefficients for Granular Bentonite Clay	9
5	Effect of Contact Time on the Distribution Coefficients for Powdered Bentonite Clay	10
6	Effect of pH on the Distribution Coefficients for Clinoptilolite.	12
7	Effect of pH on the Distribution Coefficients for Activated Carbon.	12
8	Effect of pH on the Distribution Coefficients for Bentonite Clay.	13
9	Effect of pH on the Distribution Coefficients for Savannah River Soil.	13
10	Effect of Solution:Solid Ratio on the Distribution Coefficients for -5 Mesh Clinoptilolite.	14
11	Effect of Solution:Solid Ratio on the Cobalt Distribution Coefficient for Activated Carbon.	14
12	Effect of Solution:Solid Ratio on the Cesium Distribution Coefficient for Savannah River Soil	15
13	Effect of Particle Size on the Distribution Coefficient and Rate of Adsorption for Clinoptilolite	16
14	Effect of Particle Size on the Cobalt Distribution Coefficient and Rate of Adsorption for Activated Carbon	16

TABLE

1	Results of 1988 Benchmark Tests and Comparison with 1986 Data. . .	6
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INTRODUCTION

The Engineered Sorbent Barrier (ESB) technology was developed by Pacific Northwest Laboratory (PNL)^(a) as part of the Low-Level Waste Management Program, sponsored by the U.S. Department of Energy (DOE). During the program, a number of sorbent materials were evaluated and laboratory studies conducted to develop an effective method to limit radionuclide migration from low-level waste (LLW) sites (Freeman, Mitchell, and Buelte 1986; Jones and Freeman 1988). The studies showed that applying an ESB to a particular site must take into account specific site conditions.

An ESB is created by lining a trench or surrounding a vault with sorptive material such as activated carbon or natural zeolites. With the barrier in place, infiltrating water can pass through the bottom of the trench while any radionuclides leached from the waste are adsorbed by the barrier material. The sorbent barrier can be designed to retard the migration of radionuclides such as ^{90}Sr , ^{60}Co , and ^{137}Cs long enough to allow decay to a safe level.

Designing an ESB to remain effective for several hundred years requires that the relationship of variables such as pH, competing ions, and adsorption kinetics be understood in terms of adsorption of ions on the sorbent materials. A number of batch contact tests were conducted in this study to determine these relationships. Some of the results were used as examples in a separate report, "Technology Assessment Guide for Application of Engineered Sorbent Barriers to Low-Level Waste Sites" (Freeman, Jones, and Depner 1989). The data presented in the following text summarizes the laboratory studies conducted in FY 1988.

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LABORATORY STUDIES

The laboratory testing in FY 1988 focused on the adsorption behavior of clinoptilolite, bentonite clay, and activated carbon with a simulated LLW leachate. Specifically, the studies concentrated on batch contact testing to determine the distribution coefficients (K_d) of the three sorbent materials. The K_d is the ratio of the ion concentration in the solids to the concentration in the interstitial water at equilibrium:

$$K_d = C_s/C_{sol} \quad (1)$$

Consequently, the K_d can be used to measure the effectiveness of a material in adsorbing a particular ion from solution. The K_d can also be determined using flowthrough column tests; however, the batch contact tests showed that results from column tests could not readily be obtained within the study period.

The three materials used in the study were chosen because adsorption performance was good and the cost was relatively low (Freeman, Mitchell, and Buel 1986). A limited number of tests were also performed on Savannah River soil to represent a typical soil from a humid climate. The simulated leachate used in the majority of the tests contained the standard composition of 1 $\mu\text{Ci/L}$ each of ^{85}Sr , ^{60}Co , and ^{137}Cs ; 100 ppm each of Ca, Na, and Mg ions; 1 ppm of EDTA as a complexing agent; with an adjusted solution pH of 5. The nonradioactive ions were added to simulate the ions expected to be present from leaching of the natural soil and waste forms. EDTA was added to simulate the presence of a complexant that mobilizes ^{60}Co , normally not a very mobile ion. In some of the tests, the standard conditions were altered to allow the effect of variables to be assessed. A summary of the data obtained in these tests is presented in the appendix.

DESCRIPTION OF SORBENT MATERIALS

The materials used for the FY 1988 studies were similar to materials used in the tests reported in Freeman, Mitchell, and Buel (1986). The clinoptilolite, a natural zeolite, was obtained from Teague Minerals in

Adrian, Oregon. Materials from two different deposits, designated as the CH and XY deposit, were tested although only one set of tests was performed on the XY deposit. Because material from the XY deposit was found to be less effective in adsorbing the radionuclides of interest and more costly than the CH deposit, the remainder of the tests were performed on two different size fractions of the CH deposit. The first size fraction was a -5 mesh material, which represented material as produced by the crusher (sample ID prefix of CH1). This material contained a significant fraction of fines. The second size distribution contained material in the size range -5 mesh +35 mesh (sample ID prefix of CH2). This distribution represented a relatively coarse material with a more reproducible size range that could provide the basis for material specifications. Because of its lower cost, the -5 mesh material was used more extensively.

Bentonite, a swelling clay, was tested because it may be used to adjust the permeability of the barrier mixture to optimize residence time of the leachate in the sorbent layer. The bentonite clay used for these tests was also obtained from Teague Minerals. A granular material (sample ID prefix of BE1) and a fine material (sample ID prefix of BE2) were tested.

The activated carbon, which is used to adsorb the organic complexed species that can be found in LLW leachate, was obtained from the Calgon Corporation. The material, as received, was sized as -6 +16 mesh.

BATCH CONTACT TESTS

Test conditions were varied in the batch contact tests to provide information useful in estimating the long-term performance of sorbent barriers. The variations in the tests included:

- length of batch contact time - to determine the rate of adsorption
- solution pH and solution:solid ratio - to determine how they affect adsorption
- adsorbent particle size - to alter the rate of adsorption.

This section gives the procedures used for the tests, the equation used for data analysis, and the results of the tests.

Test Procedures

Before the tests, the solids were dried at 110°C for 24 h and allowed to cool to room temperature. If the material was not used immediately, it was sealed in an airtight container or bag. Next, a batch of the simulated leachate was prepared and adjusted to the appropriate pH (pH expected in the trench).

Duplicate samples were prepared for each test by weighing the desired amount of solid and placing it in a 250-mL polyethylene wide-mouth bottle. Two hundred milliliters of simulated leachate were added to the bottle, and the bottle was sealed. One sample was prepared as a blank without sorbent material in case a particular radionuclide tended to adsorb on the surface of the container.

The bottles were gently agitated with a shaker platform for various times ranging from 1/2 to 256 h. The solutions were then filtered with a 0.45 μm filter to remove the solids. Twenty milliliters of the filtrate from each sample were analyzed for all ions of interest. A sample of the simulated leachate used in each series of tests was also analyzed. Most of the samples were only analyzed for radionuclide content using gamma spectroscopy. In some instances, nonradioactive ions were evaluated with inductively coupled plasma analysis.

The K_d was calculated for each radionuclide from the gamma spectroscopy analyses using the following equation:

$$K_d = \frac{(L_v) (\text{Initial} - \text{Final})}{(S_w) (\text{Final})} \quad (2)$$

where K_d = distribution coefficient, mL/g

L_v = liquid volume, mL

S_w = weight of solids, g

Initial = initial counts in simulated leachate before contacting with solids

Final = final counts in solution after contacting with solids.

Results

The test results include data from benchmark tests and data on the effect of contact time, leachate solution pH, solution to solid ratio, and particle size.

Benchmark Tests

Benchmark tests were performed to compare the effectiveness of materials used for this study against materials tested in earlier studies. Previously tested materials included clinoptilolite from the CH deposit and activated carbon. In addition, two different size fractions of two new materials, clinoptilolite from the XY deposit and bentonite clay, were included to determine their relative effectiveness. The test conditions were similar to tests run in 1986 (Freeman, Mitchell, and Buelte 1986). The simulated leachate for the benchmark tests contained the standard composition described in this report. This leachate composition differed from the 1986 study in that it contained 100 ppm Mg and Na instead of 1000 ppm. The materials were contacted for 72 h to match the contact time of earlier studies. The results of the 1986 and 1988 measurements are compared in Table 1.

TABLE 1. Results of 1988 Benchmark Tests and Comparison with 1986 Data

Material	Distribution Coefficient, mL/g					
	1988			1986		
	⁸⁵ Sr	¹³⁷ Cs	⁶⁰ Co	⁸⁵ Sr	¹³⁷ Cs	⁶⁰ Co
Clinoptilolite, CH -5 mesh	1090	3860	0.5	NA	NA	NA
Clinoptilolite, CH -5 +35 mesh	1100	3340	-0.3	165	1130	66.4
Clinoptilolite, XY -5 mesh	553	4900	-1.2	NA	NA	NA
Clinoptilolite, XY -5 +35 mesh	564	5370	1.2	NA	NA	NA
Activated Carbon	13.0	25.1	681	27.1	28.5	611
Bentonite Clay, Granular	67.7	2080	2.0	NA	NA	NA
Bentonite Clay, Powder	72.8	2770	3.0	NA	NA	NA

The results of the CH deposit clinoptilolite do not compare well between the 1988 and 1986 data. The material received in 1988 appears to be more effective in adsorbing Sr and Cs but less effective in sorbing Co. This difference could be due to the higher Na and Mg concentration in the 1986 tests or to differences in the materials within the deposit. The data for the activated carbon, on the other hand, compare very closely. The differences in the data emphasize the need for a good quality assurance program during construction of an ESB.

Table 1 also shows that the XY deposit is not as effective in adsorbing Sr as the less expensive CH deposit material. The XY deposit was not evaluated in any further tests. The bentonite clay has a moderate K_d for Sr and a good K_d for Cs. If bentonite is used in a barrier formulation, its adsorption effectiveness should be incorporated into the performance assessment.

Effect of Contact Time

Typically, when adsorption of ions on materials is simulated in radionuclide transport models, it is assumed that the adsorption reaction reaches equilibrium in a short time period. This assumption is probably valid for cases where the leachate moves through the solids at a slow rate. However, in laboratory flowthrough column tests, where the leachate travels through the column at relatively high velocities, the assumption of fast kinetics may lead to errors in measuring the K_d . Therefore, a series of tests were performed to investigate the effect of contact time on the sorbent material K_d . The tests were conducted using the standard simulated leachate at a 200 to 1 solution to solid ratio. The contact times included 1/2, 1, 2, 4, 16, 72, 120, and 256 h. The results of these tests are shown in Figures 1 through 5.

When plotted on a log-log scale, most of the data follows a linear relationship. This implies that the kinetics of adsorption follow a power law relationship:

$$K_d(t) = K \cdot t^b \quad (3)$$

FIGURE 1. Effect of Contact Time on the Distribution Coefficients for -5 Mesh Clinoptilolite

FIGURE 2. Effect of Contact Time on the Distribution Coefficients for -5 Mesh +35 Mesh Clinoptilolite

FIGURE 3. Effect of Contact Time on the Distribution Coefficients for Activated Carbon

FIGURE 4. Effect of Contact Time on the Distribution Coefficients for Granular Bentonite Clay

FIGURE 5. Effect of Contact Time on the Distribution Coefficients for Powdered Bentonite Clay

where $K_d(t)$ = distribution coefficient at time t , mL/g

K = constant

t = contact time, h

b = exponent

or, taking the log of both sides:

$$\text{Log}(K_d) = \log(K) + b \cdot \log(t) \quad (4)$$

Thus if the K_d is plotted on the y axis and time on the x axis, a straight line with intercept of $\log(K)$ and slope of b should be obtained. Materials with fast adsorption rates, such as the bentonite clay, will have a slope near zero, while materials that have slower adsorption will have more positive slopes.

The data in Figures 1 through 5 show that the adsorption of radionuclides on clinoptilolite and activated carbon requires at least 120 h to reach equilibrium. Adsorption rates on bentonite clay, however, are much faster.

The slow adsorption kinetics for clinoptilolite and activated carbon requires that any flowthrough column tests be run at extremely slow flow rates if equilibrium is to be obtained between the solids and leachate. This requirement would preclude the use of accelerated exposure tests designed to simulate many years of infiltration in a few weeks or months.

Effect of Leachate Solution pH

The effectiveness of sorbent materials in adsorbing ions can be highly dependent on the pH of the liquid phase. In many cases the solid phase has a natural buffering capacity that minimizes the impact of changes in pH which may occur in the liquid phase. Because of this natural buffering capacity, the tests to determine the effect of pH were performed by changing the pH of the simulated leachate rather than by adjusting the pH of the solution after contacting the solids. The tests covered a pH range of 1 to 9, the expected range for a typical humid LLW site. The tests were conducted using a solution to solid ratio of 200 to 1 with an exposure time of 120 h.

Figures 6 through 9 show the effect of pH on the K_d for ^{85}Sr , ^{137}Cs , and ^{60}Co on clinoptilolite, activated carbon, bentonite clay, and Savannah River soil, respectively. These figures show that the K_d for the first three materials is not highly dependent on the initial pH of the leachate above a pH of 1. Although the scope of the project did not include it, the total buffering capacity of the solids should be measured to determine how long the solids will be able to buffer the leachate passing through the barrier.

Effect of Solution to Solid Ratio

Batch contact tests are generally performed at a relatively high solution to solid ratio, especially for materials with large K_d s. A number of tests were performed to determine if the solution to solid ratio has an effect on the measured K_d of a material. The tests were performed over a solution to solid ratio of 20 to 1000 for activated carbon and clinoptilolite, and 20 to 400 for Savannah River soil. Tests were performed using the standard simulated leachate composition with an exposure time of 120 h. Results of these tests are shown in Figures 10 through 12.

FIGURE 6. Effect of pH on the Distribution Coefficients for Clinoptilolite

FIGURE 7. Effect of pH on the Distribution Coefficients for Activated Carbon

FIGURE 8. Effect of pH on the Distribution Coefficients for Bentonite Clay

FIGURE 9. Effect of pH on the Distribution Coefficients for Savannah River Soil

FIGURE 10. Effect of Solution:Solid Ratio on the Distribution Coefficients for -5 Mesh Clinoptilolite

FIGURE 11. Effect of Solution:Solid Ratio on the Cobalt Distribution Coefficient for Activated Carbon

FIGURE 12. Effect of Solution:Solid Ratio on the Cesium Distribution Coefficient for Savannah River Soil

Effect of Particle Size

One technique for accelerating column tests, used by manufacturers of activated carbon, is to use very small particles of adsorbent. The fine particles reduce the path length for interparticle diffusion. The rate of adsorption is increased if the interparticle diffusion controls the overall rate of adsorption. If chemical kinetics are controlling, then reducing the particle size will not increase the adsorption rate.

Batch contact tests were completed with ground and standard-sized clinoptilolite and with ground and standard-sized activated carbon at different solution to solid ratios and contact times. Figures 13 and 14 show the effect of particle size on the rate of adsorption on clinoptilolite and activated carbon, respectively. The ground activated carbon (-200 mesh) had a slightly faster adsorption rate than standard-sized activated carbon. The implication is that the interparticle diffusion is a controlling mechanism for adsorption of ^{60}Co onto activated carbon, although the relationship is not strong enough to imply that it is the rate-limiting step.

FIGURE 13. Effect of Particle Size on the Distribution Coefficient and Rate of Adsorption for Clinoptilolite

FIGURE 14. Effect of Particle Size on the Cobalt Distribution Coefficient and Rate of Adsorption for Activated Carbon

The adsorption rate of ^{85}Sr on ground clinoptilolite (-200 mesh) was not altered by the particle size, an indication that the rate of chemical reactions is limiting the adsorption. Possibly, the adsorption of ^{85}Sr onto clinoptilolite follows a series of faster competing ionic adsorption; the adsorption of ^{85}Sr is thermodynamically more stable but occurs at a slower kinetic rate than other competing adsorption. The increased adsorption rate for activated carbon was not high enough to recommend this technique be used for flowthrough column tests for these materials.

CONCLUSIONS

The results of the batch contact tests led to the following conclusions:

- Adsorption kinetics is an important parameter that should be investigated first in the sorbent material performance studies to determine the optimum contact time for the remainder of the tests.
- For the conditions under investigation in this study, pH did not have a significant impact on the K_d above a pH of 1. However, the effect of pH can be important in some instances and, therefore, should be included in all investigations of sorbent material effectiveness.
- The solution to solid ratio used in the batch contact tests affected the measured distribution coefficients by up to a factor of 7.
- Decreasing particle size did not increase the rate of adsorption of strontium on clinoptilolite and only had a moderate effect for adsorption of cobalt on activated carbon.

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APPENDIX

SUMMARY OF BATCH CONTACT DATA

APPENDIX

SUMMARY OF BATCH CONTACT DATA

Sample ID	Material Type	Contact Time, h	Soln/Solid Ratio	Leachate Ions	K _d , mL/g			Solution Counts, c/20 min			Initial pH	Final pH
					85 Sr	137 Cs	60 Co	85 Sr	137 Cs	60 Co		
BENCHMARK TESTS												
Batch01	SIM	-	-	STD	-	-	-	19144	11184	8145	5.0	5.0
ACT-01-A	ACT	72.0	200.0	STD	13.1	23.9	726.6	17966	9990	1758	5.0	8.5
ACT-01-B	ACT	72.0	200.0	STD	12.9	26.3	634.5	17983	9884	1952	5.0	8.5
BE1-01-A	BC1	72.0	200.0	STD	69.2	2122.7	2.7	14225	963	8036	5.0	6.4
BE1-01-B	BC1	72.0	200.0	STD	66.3	2039.0	1.4	14380	999	8090	5.0	6.4
BE2-01-A	BC2	72.0	200.0	STD	72.4	2774.5	-0.4	14056	752	8163	5.0	7.1
BE2-01-B	BC2	72.0	200.0	STD	73.1	2762.7	6.4	14020	755	7891	5.0	7.2
BLK-01-A	BLK	72.0	200.0	STD	1.0	1.6	1.4	19051	11097	8087	5.0	5.1
BLK-01-B	BLK	72.0	200.0	STD	0.4	3.6	1.0	19107	10984	8186	5.0	5.0
CH1-01-A	CL1	72.0	200.0	STD	1101.9	3794.3	1.4	2941	560	8088	5.0	6.4
CH1-01-B	CL1	72.0	200.0	STD	1078.8	3926.9	-0.3	2994	542	8158	5.0	6.4
CH2-01-A	CL2	72.0	200.0	STD	1103.6	3503.3	0.1	2937	604	8141	5.0	5.6
CH2-01-B	CL2	72.0	200.0	STD	1097.0	3178.9	-0.7	2952	662	8173	5.0	5.6
XY1-01-A	CL3	72.0	200.0	STD	601.7	5075.5	2.3	4776	424	8054	5.0	5.7
XY1-01-B	CL3	72.0	200.0	STD	504.0	4726.9	-4.6	5439	454	8338	5.0	5.8
XY2-01-A	CL4	72.0	200.0	STD	543.8	5861.8	-0.4	5148	369	8162	5.0	5.7
XY2-01-B	CL4	72.0	200.0	STD	584.6	4883.6	2.7	4880	440	8035	5.0	5.8
EFFECT OF CONTACT TIME												
BATCH02	SIM	-	-	STD	0.0	0.0	0.0	21214	8708	7757	5.0	5.0
ACT-02-A	ACT	0.5	200.0	STD	11.0	16.3	59.0	20109	8053	5989	5.0	9.6
ACT-02-B	ACT	0.5	200.0	STD	9.4	18.3	55.6	20263	7978	6069	5.0	9.6
BE1-02-A	BC1	0.5	200.0	STD	72.1	2828.9	1.1	15592	575	7715	5.0	6.8
BE1-02-B	BC1	0.5	200.0	STD	71.2	2521.3	-3.1	15646	640	7880	5.0	6.8
BE2-02-A	BC2	0.5	200.0	STD	74.3	2547.0	-2.3	15468	634	7848	5.0	7.2
BE2-02-B	BC2	0.5	200.0	STD	75.4	2273.9	-7.5	15406	704	8059	5.0	7.3
BLK-02-A	BLK	0.5	200.0	STD	5.9	-19.5	-3.9	20609	9650	7913	5.0	5.1
BLK-02-B	BLK	0.5	200.0	STD	5.3	1.3	0.3	20670	8650	7747	5.0	5.1
CH1-02-A	CL1	0.5	200.0	STD	89.9	2538.4	6.4	14636	636	7518	5.0	5.8

Appendix (contd)

Sample ID	Material Type	Contact Time, h	Soln/Solid Ratio	Leachate Ions	K _d , mL/g			Solution Counts, c/20 min			Initial pH	Final pH
					85 Sr	137 Cs	60 Co	85 Sr	137 Cs	60 Co		
CH1-02-B	CL1	0.5	200.0	STD	90.2	2645.8	-0.9	14621	612	7793	5.0	5.9
CH2-02-A	CL2	0.5	200.0	STD	71.0	900.2	-0.3	15658	1583	7768	5.0	5.8
CH2-02-B	CL2	0.5	200.0	STD	59.9	826.3	-4.0	16325	1697	7914	5.0	5.7
BATCH03	SIM	0.0	0.0	STD	0.0	0.0	0.0	21217	8519	7777	5.1	5.1
ACT-03-A	ACT	1.0	200.0	STD	12.9	22.9	91.4	19929	7643	5338	5.1	9.7
ACT-03-B	ACT	1.0	200.0	STD	13.2	20.7	72.5	19908	7721	5709	5.1	9.8
BE1-03-A	BC1	1.0	200.0	STD	80.2	2697.6	7.8	15145	588	7487	5.1	6.9
BE1-03-B	BC1	1.0	200.0	STD	76.6	2425.3	0.3	15339	649	7766	5.1	6.9
BE2-03-A	BC2	1.0	200.0	STD	76.2	2949.4	1.5	15363	541	7718	5.1	7.4
BE2-03-B	BC2	1.0	200.0	STD	82.1	3134.3	-3.2	15042	511	7904	5.1	7.4
BLK-03-A	BLK	1.0	200.0	STD	8.1	1.6	2.2	20387	8453	7692	5.1	5.1
BLK-03-B	BLK	1.0	200.0	STD	8.6	1.6	2.3	20346	8451	7690	5.1	5.1
CH1-03-A	CL1	1.0	200.0	STD	153.2	2897.8	-1.9	12013	550	7851	5.1	6.0
CH1-03-B	CL1	1.0	200.0	STD	138.3	2869.9	-2.9	12545	555	7890	5.1	6.0
CH2-03-A	CL2	1.0	200.0	STD	108.1	1109.6	-5.8	13772	1301	8009	5.1	5.8
CH2-03-B	CL2	1.0	200.0	STD	93.5	859.6	-1.6	14459	1608	7840	5.1	5.8
BATCH04	SIM	0.0	0.0	STD	0.0	0.0	0.0	19994	9218	7789	5.1	5.1
ACT-04-A	ACT	2.0	200.0	STD	4.0	47.8	168.5	19600	7439	4227	5.1	9.7
ACT-04-B	ACT	2.0	200.0	STD	8.4	26.1	169.0	19192	8155	4222	5.1	9.8
BE1-04-A	BC1	2.0	200.0	STD	73.7	2792.9	-0.4	14612	616	7803	5.1	6.8
BE1-04-B	BC1	2.0	200.0	STD	67.1	2935.4	0.5	14974	588	7768	5.1	6.9
BE2-04-A	BC2	2.0	200.0	STD	74.5	3436.3	-0.1	14568	507	7792	5.1	7.4
BE2-04-B	BC2	2.0	200.0	STD	70.1	3450.7	3.4	14803	505	7660	5.1	7.5
BLK-04-A	BLK	2.0	200.0	STD	0.8	19.4	2.9	19910	8402	7679	5.1	5.4
BLK-04-B	BLK	2.0	200.0	STD	1.4	14.1	0.5	19857	8613	7769	5.1	5.2
CH1-04-A	CL1	2.0	200.0	STD	181.1	3207.8	0.6	10493	541	7767	5.1	6.1
CH1-04-B	CL1	2.0	200.0	STD	211.6	4409.0	-2.7	9716	400	7895	5.1	6.1
CH2-04-A	CL2	2.0	200.0	STD	134.6	1032.4	-2.0	11952	1496	7867	5.1	5.8
CH2-04-B	CL2	2.0	200.0	STD	153.5	1750.9	0.6	11312	945	7765	5.1	5.9
BATCH05	SIM	0.0	0.0	STD	0.0	0.0	0.0	19950	8701	7708	5.0	5.0
ACT-05-A	ACT	4.0	200.0	STD	12.5	31.4	249.2	18773	7520	3432	5.0	9.7

Appendix (contd)

Sample ID	Material Type	Contact Time, h	Soln/Solid Ratio	Leachate Ions	K _d , mL/g			Solution Counts, c/20 min			Initial pH	Final pH
					85 Sr	137 Cs	60 Co	85 Sr	137 Cs	60 Co		
ACT-05-B	ACT	4.0	200.0	STD	11.4	31.9	211.0	18876	7505	3751	5.0	9.7
BE1-05-A	BC1	4.0	200.0	STD	73.6	2759.5	5.5	14586	588	7502	5.0	6.8
BE1-05-B	BC1	4.0	200.0	STD	74.0	3040.6	5.1	14563	537	7518	5.0	6.8
BE2-05-A	BC2	4.0	200.0	STD	80.4	4013.6	7.9	14232	413	7415	5.0	7.5
BE2-05-B	BC2	4.0	200.0	STD	77.3	3675.7	11.5	14391	449	7289	5.0	7.5
BLK-05-A	BLK	4.0	200.0	STD	6.0	17.0	2.4	19371	8018	7615	5.0	5.1
BLK-05-B	BLK	4.0	200.0	STD	5.9	18.5	-0.3	19378	7965	7718	5.0	5.1
CH1-05-A	CL1	4.0	200.0	STD	311.9	4139.7	-2.0	7794	401	7785	5.0	6.1
CH1-05-B	CL1	4.0	200.0	STD	319.9	4403.7	-1.0	7674	378	7747	5.0	6.1
CH2-05-A	CL2	4.0	200.0	STD	221.2	2065.9	1.9	9472	768	7636	5.0	5.9
CH2-05-B	CL2	4.0	200.0	STD	213.0	1986.2	5.3	9661	796	7511	5.0	5.9
BATCH06	SIM	0.0	0.0	STD	0.0	0.0	0.0	20920	8440	7685	5.0	5.0
ACT-06-A	ACT	16.0	200.0	STD	16.5	23.1	343.1	19325	7566	2830	5.0	9.4
ACT-06-B	ACT	16.0	200.0	STD	12.8	48.2	338.2	19659	6800	2856	5.0	9.5
BE1-06-A	BC1	16.0	200.0	STD	70.6	2389.0	1.4	15461	652	7630	5.0	6.8
BE1-06-B	BC1	16.0	200.0	STD	75.6	2470.9	4.6	15182	632	7513	5.0	6.8
BE2-06-A	BC2	16.0	200.0	STD	72.8	2943.4	7.0	15336	537	7425	5.0	7.5
BE2-06-B	BC2	16.0	200.0	STD	76.4	2841.4	3.1	15140	555	7569	5.0	7.5
BLK-06-A	BLK	16.0	200.0	STD	4.8	13.3	-2.2	20428	7915	7770	5.0	5.3
BLK-06-B	BLK	16.0	200.0	STD	3.8	9.5	1.5	20532	8057	7627	5.0	4.9
CH1-06-A	CL1	16.0	200.0	STD	500.8	4581.9	5.2	5970	353	7490	5.0	6.1
CH1-06-B	CL1	16.0	200.0	STD	434.4	3601.8	-2.0	6595	444	7763	5.0	6.0
CH2-06-A	CL2	16.0	200.0	STD	362.8	2745.9	3.0	7434	573	7570	5.0	5.9
CH2-06-B	CL2	16.0	200.0	STD	344.1	2576.3	3.1	7690	608	7568	5.0	6.0
BATCH07	SIM	0.0	0.0	STD	0.0	0.0	0.0	19684	7970	7442	5.0	5.0
ACT-07-A	ACT	120.0	200.0	STD	19.6	23.7	1023.0	17929	7127	1217	5.0	8.5
ACT-07-B	ACT	120.0	200.0	STD	17.3	26.6	966.5	18116	7034	1276	5.0	8.7
BE1-07-A	BC1	120.0	200.0	STD	69.0	2543.6	0.5	14635	581	7423	5.0	6.8
BE1-07-B	BC1	120.0	200.0	STD	71.4	2601.4	-0.8	14508	569	7473	5.0	6.8
BE2-07-A	BC2	120.0	200.0	STD	76.1	2830.4	4.4	14259	526	7282	5.0	7.4
BE2-07-B	BC2	120.0	200.0	STD	79.7	2901.2	-3.3	14077	514	7567	5.0	7.4

Appendix (contd)

Sample ID	Material Type	Contact Time, h	Soln/Solid Ratio	Leachate Ions	K _d , mL/g			Solution Counts, c/20 min			Initial pH	Final pH
					85 Sr	137 Cs	60 Co	85 Sr	137 Cs	60 Co		
BLK-07-A	BLK	120.0	200.0	STD	-0.6	4.0	-6.5	19747	7815	7691	5.0	5.1
BLK-07-B	BLK	120.0	200.0	STD	3.4	3.0	0.2	19360	7852	7433	5.0	5.1
CH1-07-A	CL1	120.0	200.0	STD	1269.0	5026.2	3.0	2680	305	7334	5.0	6.1
CH1-07-B	CL1	120.0	200.0	STD	1163.2	5354.0	3.7	2888	287	7307	5.0	6.1
CH2-07-A	CL2	120.0	200.0	STD	1333.6	4393.7	-2.1	2567	347	7522	5.0	6.1
CH2-07-B	CL2	120.0	200.0	STD	1294.0	4558.2	-5.1	2635	335	7635	5.0	6.1
BATCH08	SIM	0.0	0.0	STD	0.0	0.0	0.0	18477	6859	7302	5.0	5.0
ACT-08-A	ACT	256.0	200.0	STD	15.4	23.4	1287.2	17157	6141	982	5.1	8.3
ACT-08-B	ACT	256.0	200.0	STD	17.0	25.7	1133.7	17030	6077	1095	5.1	8.3
BE1-08-A	BC1	256.0	200.0	STD	72.4	2521.8	1.1	13566	504	7264	5.1	6.7
BE1-08-B	BC1	256.0	200.0	STD	73.0	2468.9	0.6	13537	514	7282	5.1	6.7
BE2-08-A	BC2	256.0	200.0	STD	78.3	2932.0	0.6	13279	438	7158	5.1	7.3
BE2-08-B	BC2	256.0	200.0	STD	77.6	3600.0	4.3	13311	361	7149	5.1	7.3
BLK-08-A	BLK	256.0	200.0	STD	5.3	0.6	4.3	18003	6839	7150	5.1	5.1
BLK-08-B	BLK	256.0	200.0	STD	1.9	-1.6	-0.6	18305	6915	7324	5.1	5.1
CH1-08-A	CL1	256.0	200.0	STD	1266.4	5468.6	3.7	2520	242	7171	5.1	6.1
CH1-08-B	CL1	256.0	200.0	STD	1134.1	5563.9	1.1	2770	238	7262	5.1	6.1
CH2-08-A	CL2	256.0	200.0	STD	1348.1	5200.8	1.6	2387	254	7245	5.1	6.1
CH2-08-B	CL2	256.0	200.0	STD	1376.5	5738.5	2.0	2344	231	7230	5.1	6.1
EFFECT OF pH												
BATCH09	SIM	0.0	0.0	STD	0.0	0.0	0.0	18797	7377	7242	0.9	0.9
ACT-09-A	ACT	120.0	200.0	STD	0.0	20.7	7.1	18799	6685	6994	0.9	1.0
ACT-09-B	ACT	120.0	200.0	STD	2.5	28.3	7.3	18562	6462	6986	0.9	1.0
BE1-09-A	BC1	120.0	200.0	STD	10.4	194.3	8.7	17868	3742	6939	0.9	1.0
BE1-09-B	BC1	120.0	200.0	STD	10.4	215.0	6.6	17869	3555	7011	0.9	0.9
BLK-09-A	BLK	120.0	200.0	STD	3.4	27.4	4.7	18487	6487	7075	0.9	0.9
BLK-09-B	BLK	120.0	200.0	STD	0.1	25.8	3.7	18792	6535	7111	0.9	0.9
CH1-09-A	CL1	120.0	200.0	STD	24.3	935.8	2.2	16761	1299	7162	0.9	1.0
CH1-09-B	CL1	120.0	200.0	STD	21.1	818.9	13.4	17000	1448	6788	0.9	1.0
BATCH10	SIM	0.0	0.0	STD	0.0	0.0	0.0	19131	7444	7329	3.0	3.0
ACT-10-A	ACT	120.0	200.0	STD	12.7	31.2	475.2	17990	6439	2171	3.0	7.1

Appendix (contd)

Sample ID	Material Type	Contact Time, h	Soln/Solid Ratio	Leachate Ions	K _d , mL/g			Solution Counts, c/20 min			Initial pH	Final pH
					⁸⁵ Sr	¹³⁷ Cs	⁶⁰ Co	⁸⁵ Sr	¹³⁷ Cs	⁶⁰ Co		
ACT-10-B	ACT	120.0	200.0	STD	10.8	38.3	510.9	18152	6249	2062	3.0	7.2
BE1-10-A	BC1	120.0	200.0	STD	62.1	1876.4	3.1	14599	717	7219	3.0	4.5
BE1-10-B	BC1	120.0	200.0	STD	65.3	2137.2	-1.4	14420	637	7382	3.0	4.7
BLK-10-A	BLK	120.0	200.0	STD	-0.5	3.0	-1.5	19182	7334	7385	3.0	2.9
BLK-10-B	BLK	120.0	200.0	STD	-4.9	2.0	-0.1	19615	7370	7334	3.0	2.9
CH1-10-A	CL1	120.0	200.0	STD	1144.9	1423.6	0.4	2845	917	7313	3.0	3.4
CH1-10-B	CL1	120.0	200.0	STD	1097.9	4762.7	0.6	2948	300	7309	3.0	3.4
BATCH11	SIM	0.0	0.0	STD	0.0	0.0	0.0	19226	7600	7373	7.1	7.1
ACT-11-A	ACT	120.0	200.0	STD	17.0	20.4	1059.3	17720	6897	1171	7.1	8.6
ACT-11-B	ACT	120.0	200.0	STD	19.2	25.5	1029.9	17546	6742	1199	7.1	8.6
BE1-11-A	BC1	120.0	200.0	STD	74.5	2462.0	-0.2	14006	571	7382	7.1	6.9
BE1-11-B	BC1	120.0	200.0	STD	70.8	2528.9	3.2	14199	557	7256	7.1	6.9
BLK-11-A	BLK	120.0	200.0	STD	-0.2	14.8	-7.8	19240	7075	7673	7.1	6.9
BLK-11-B	BLK	120.0	200.0	STD	0.8	16.6	-0.4	19148	7017	7388	7.1	6.8
CH1-11-A	CL1	120.0	200.0	STD	1211.6	4671.8	-1.1	2724	312	7415	7.1	6.4
CH1-11-B	CL1	120.0	200.0	STD	1168.4	4783.6	3.9	2810	305	7231	7.1	6.5
BATCH12	SIM	0.0	0.0	STD	0.0	0.0	0.0	16948	7145	7199	9.1	9.1
ACT-12-A	ACT	120.0	200.0	STD	19.6	41.5	1106.5	15433	5917	1102	9.1	8.9
ACT-12-B	ACT	120.0	200.0	STD	21.2	29.8	1195.2	15322	6218	1032	9.1	8.9
BE1-12-A	BC1	120.0	200.0	STD	78.2	2777.1	0.1	12185	480	7197	9.1	7.4
BE1-12-B	BC1	120.0	200.0	STD	86.0	3560.5	12.6	11851	380	6772	9.1	7.4
BLK-12-A	BLK	120.0	200.0	STD	7.9	11.4	1.6	16301	6761	7142	9.1	8.7
BLK-12-B	BLK	120.0	200.0	STD	8.7	15.7	5.3	16245	6624	7013	9.1	8.7
CH1-12-A	CL1	120.0	200.0	STD	883.3	6179.5	8.1	3129	224	6920	9.1	7.3
CH1-12-B	CL1	120.0	200.0	STD	1064.3	5015.3	2.7	2681	274	7102	9.1	7.5
BATCH13	SIM	0.0	0.0	STD	0.0	0.0	0.0	17363	6990	7194	4.9	4.9
ACT-13-A	ACT	120.0	20.0	STD	14.5	10.0	1756.3	10063	4656	81	4.9	7.0
ACT-13-B	ACT	120.0	20.0	STD	16.5	7.2	1510.6	9518	5148	94	4.9	7.0
BE1-13-A	BC1	120.0	20.0	STD	91.7	1378.0	0.1	3108	100	7171	4.9	8.5
BE1-13-B	BC1	120.0	20.0	STD	93.5	1154.8	0.3	3059	119	7073	4.9	8.7
CH1-13-A	CL1	120.0	20.0	STD	723.6	3019.1	-0.3	467	46	7287	4.9	6.5

Appendix (contd)

Sample ID	Material Type	Contact Time, h	Soln/Solid Ratio	Leachate Ions	K _d , mL/g			Solution Counts, c/20 min			Initial pH	Final pH
					85 Sr	137 Cs	60 Co	85 Sr	137 Cs	60 Co		
CH1-13-B	CL1	120.0	20.0	STD	472.6	2617.7	-0.2	705	53	7276	4.9	6.4
BATCH14	SIM	0.0	0.0	STD	0.0	0.0	0.0	17137	7197	7518	4.9	4.9
ACT-14-A	ACT	120.0	8.0	STD	35.4	6.5	2607.0	3158	3980	23	4.9	8.5
ACT-14-B	ACT	120.0	8.0	STD	32.0	6.2	1760.9	3432	4043	34	4.9	8.5
CH1-14-A	CL1	120.0	8.0	STD	289.4	2206.5	0.5	461	26	7079	4.9	6.6
CH1-14-B	CL1	120.0	8.0	STD	353.7	1191.5	0.6	379	48	7008	4.9	6.6
EFFECT OF PARTICLE SIZE												
BATCH15	SIM	.0	0.0	STD	0.0	0.0	0.0	19377	7920	7174	5.0	5.0
AG1.0-15A	AC	4.0	20.0	STD	22.6	38.2	962.7	17411	6650	1234	5.0	9.3
AG1.0-15B	ACG	4.0	200.0	STD	24.0	46.2	982.9	17300	6434	1213	5.0	9.3
CG1.0-15A	CLG	4.0	200.0	STD	399.5	7201.9	10.4	6464	214	6820	5.0	6.3
CG1.0-15B	CLG	4.0	200.0	STD	389.2	7099.5	8.2	6578	217	6892	5.0	6.3
BATCH16	SIM	0.0	0.0	STD	0.0	0.0	0.0	19028	7297	6898	5.1	5.1
AC1.0-16A	ACT	16.0	200.0	Std	10.7	12.0	588.8	18058	6885	1749	5.1	9.2
AC0.6-16A	ACT	16.0	333.3	Std	10.2	33.0	477.7	18464	6640	2835	5.1	9.0
AC0.2-16A	ACT	16.0	1000.0	Std	8.3	81.8	377.7	18872	6745	5007	5.1	8.4
AG1.0-16A	ACG	16.0	200.0	Std	24.9	41.5	911.7	16925	6042	1241	5.1	9.3
AG0.6-16A	ACG	16.0	333.3	Std	20.8	49.5	793.8	17911	6354	2040	5.1	9.1
AG0.2-16A	ACG	16.0	1000.0	Std	17.7	144.8	715.9	18698	6374	4020	5.1	8.5
CH1.0-16A	CL1	16.0	200.0	Std	721.5	3325.1	3.2	4130	414	6788	5.1	6.0
CH0.6-16A	CL1	16.0	333.3	Std	660.0	3217.5	-1.6	6385	685	6932	5.1	5.8
CH0.2-16A	CL1	16.0	1000.0	Std	638.2	4029.0	-11.3	11615	1451	6977	5.1	5.7
CG1.0-16A	CLG	16.0	200.0	Std	884.8	4902.8	1.3	3508	286	6853	5.1	6.3
CG0.6-16A	CLG	16.0	333.3	Std	757.6	5120.3	-7.9	5814	446	7065	5.1	6.2
CG0.2-16A	CLG	16.0	1000.0	Std	991.4	8403.4	-6.3	9555	776	6942	5.1	5.8
BATCH17	SIM	0.0	0.0	Std	0.0	0.0	0.0	18800	6502	6749	5.0	5.0
AC1.0-17A	ACT	120.0	200.0	Std	19.9	20.1	1197.3	17100	5908	966	5.0	8.5
AC0.6-17A	ACT	120.0	333.3	Std	20.3	20.2	878.1	17723	6130	1857	5.0	8.2
AC0.2-17A	ACT	120.0	1000.0	Std	24.1	-43.5	729.2	18357	6798	3903	5.0	7.8
AG1.0-17A	ACG	120.0	200.0	Std	29.8	43.1	1180.2	16365	5349	978	5.0	8.7
AG0.6-17A	ACG	120.0	333.3	Std	32.8	25.6	1043.5	17118	6039	1634	5.0	8.6

Appendix (contd)

Sample ID	Material Type	Contact Time, h	Soln/Solid Ratio	Leachate Ions	K _d , mL/g			Solution Counts, c/20 min			Initial pH	Final pH
					⁸⁵ Sr	¹³⁷ Cs	⁶⁰ Co	⁸⁵ Sr	¹³⁷ Cs	⁶⁰ Co		
AG0.2-17A	ACG	120.0	1000.0	Std	51.0	15.0	923.3	17887	6601	3509	5.0	8.2
CH1.0-17A	CL1	120.0	200.0	Std	1316.7	5429.4	17.7	2479	231	6201	5.0	6.1
CH0.6-17A	CL1	120.0	333.3	Std	1472.1	4839.3	14.1	3471	419	6476	5.0	6.1
CH0.2-17A	CL1	120.0	1000.0	Std	1614.4	5917.0	-0.2	7191	940	6750	5.0	6.2
CG1.0-17A	CLG	120.0	200.0	Std	1313.1	6644.2	10.4	2485	190	6415	5.0	6.7
CG0.6-17A	CLG	120.0	333.3	Std	1424.5	5209.7	11.9	3565	391	6517	5.0	6.2
CG0.2-17A	CLG	120.0	1000.0	Std	1654.2	7240.8	10.8	7083	789	6677	5.0	6.1
BATCH19	SIM	0.0	0.0	NRI	0.0	0.0	0.0	20718	7958	7073	5.0	5.0
AC-05-19A	ACT	1.0	40.0	NRI	5.0	64.1	48.2	18426	3057	3208	5.0	6.6
AC-05-19B	ACT	1.0	40.0	NRI	5.5	62.3	48.4	18223	3111	3199	5.0	6.6
AC-02-19A	ACT	1.0	100.0	NRI	7.0	103.8	45.4	19360	3905	4865	5.0	6.2
AC-02-19B	ACT	1.0	100.0	NRI	6.5	90.3	41.4	19455	4183	5003	5.0	6.2
BLK-19A	BLK	1.0	0.0	NRI	0.0	0.0	0.0	17991	1031	3985	5.0	5.2
BLK-19B	BLK	1.0	0.0	NRI	0.0	0.0	0.0	17758	968	4113	5.0	5.0
CH-05-19A	CL1	1.0	40.0	NRI	23.3	808.9	13.0	13095	375	5336	5.0	5.2
CH-05-19B	CL1	1.0	40.0	NRI	25.0	802.1	12.9	12756	378	5351	5.0	5.2
CH-02-19A	CL1	1.0	100.0	NRI	31.8	1196.1	27.0	15714	614	5569	5.0	5.1
CH-02-19B	CL1	1.0	100.0	NRI	28.2	1055.0	26.5	16156	689	5592	5.0	5.1
AC-01-19A	CL1	1.0	200.0	NRI	7.2	149.3	62.8	19995	4557	5382	5.0	6.0
CH-01-19A	CL1	1.0	200.0	NRI	37.7	1326.0	49.1	17433	1043	5679	5.0	5.2
SAVANNAH RIVER SOIL TESTS												
BATCH20	SIM	.0	0.0	COM	0.0	0.0	0.0	20820	12876	8893	5.1	5.1
A120H-20A	ACT	.0	200.0	COM	3.2	15.9	69.8	20488	11928	6592	5.1	6.3
A120H-20B	ACT	120.0	20.0	COM	7.8	14.9	71.4	20040	11982	6553	5.1	6.3
C120H-20A	CL1	120.0	200.0	COM	478.8	1029.8	2.1	6134	2094	8802	5.1	5.5
C120H-20B	CL1	120.0	200.0	COM	468.1	1073.6	2.9	6233	2022	8764	5.1	5.3
BLK-20A	SRS	120.0	0.0	COM	2.5	2.0	-3.3	20561	12749	9044	5.1	5.0
BLK-20B	SRS	120.0	0.0	COM	2.4	1.3	-3.5	20575	12793	9050	5.1	5.0
S10G-20A	SRS	120.0	20.0	COM	0.6	65.2	2.9	20229	3021	7753	5.1	4.0
S10G-20B	SRS	120.0	20.0	COM	0.8	62.7	3.4	20065	3115	7617	5.1	4.0
S5G-20A	SRS	120.0	40.0	COM	0.6	105.9	3.1	20497	3530	8258	5.1	4.1

Appendix (contd)

Sample ID	Material Type	Contact Time, h	Soln/Solid Ratio	Leachate Ions	K _d , mL/g			Solution Counts, c/20 min			Initial pH	Final pH
					85 Sr	137 Cs	60 Co	85 Sr	137 Cs	60 Co		
S5G-20B	SRS	120.0	40.0	COM	0.6	114.7	3.6	20523	3330	8156	5.1	4.1
S1P-20A	SRS	120.0	200.0	COM	20.6	54.6	19.2	18878	10113	8113	1.0	1.0
S1P-20B	SRS	120.0	200.0	COM	22.0	48.2	23.8	18754	10377	7946	1.0	1.0
S3P-20A	SRS	120.0	200.0	COM	-2.6	77.1	2.3	21091	9295	8793	3.0	3.0
S3P-20B	SRS	120.0	200.0	COM	-1.5	192.3	-2.2	20982	6565	8991	3.0	3.0
S5P-20A	SRS	120.0	200.0	COM	-0.2	259.5	-3.7	20844	5604	9061	5.1	4.3
S5P-20B	SRS	120.0	200.0	COM	1.2	284.2	-2.3	20701	5318	8995	5.1	4.3
S.5G-20A	SRS	120.0	400.0	COM	-2.4	403.2	-2.1	20943	6412	8940	5.1	4.5
S.5G-20B	SRS	120.0	400.0	COM	3.8	394.6	-6.0	20626	6482	9029	5.1	4.5
BATCH21A7	SIM	0.0	0.0	STD	0.0	0.0	0.0	20870	13097	8870	7.0	7.0
BATCH21A9	SIM	0.0	0.0	STD	0.0	0.0	0.0	20771	12928	8988	9.0	9.0
S7P-21A	SRS	120.0	200.0	STD	7.9	625.5	-3.8	20079	3173	9041	7.0	5.3
S7P-21B	SRS	120.0	200.0	STD	5.6	545.4	-0.3	20300	3514	8884	7.0	5.5
S9P-21A	SRS	120.0	200.0	STD	9.6	646.9	1.0	19919	3093	8827	9.0	5.9
S9P-21B	SRS	120.0	200.0	STD	2.4	647.4	-3.5	20622	3091	9027	9.0	5.9

ACT = Activated Carbon

BC1 = Granular Bentonite Clay

BC2 = Powdered Bentonite Clay

CL1 = -5 mesh CH Clinoptilolite

CL2 = -5 +35 CH mesh Clinoptilolite

CL3 = -5 mesh XY Clinoptilolite

CL4 = -5 +35 mesh XY Clinoptilolite

SRS = Savannah River Soil

SIM = Simulated Leachate

STD = Standard Composition

RI = Nonradioactive model ions

COM = Combination radioactive & model ions

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