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Comparison of Inorganic Ion Exchange Materials for Removing Cesium, Strontium, and Transuranic Elements from K-Basin Water

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Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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Summary

The work presented in this report was conducted by the Pacific Northwest National Laboratory (PNNL) under the Efficient Separations and Crosscutting Program (ESP), Office of Science and Technology, U.S. Department of Energy (DOE). The objective of this work was to investigate radionuclide uptake by several newly produced ion exchange materials under actual waste conditions, and to compare the performance of those materials with that of commercially available ion exchangers. The equilibrium uptake data presented in this report are useful for identifying potential materials that are capable of removing cesium and strontium from 105-KE Basin water. The data show the relative selectivities of the ion exchange materials under similar operating conditions. Additional flow studies are needed to predict material capacities and to develop complete ion exchange process flow sheets.

The materials investigated in this study include commercially available ion exchangers such as IONSIV® IE-911 (manufactured by UOP), clinoptilolite (a naturally occurring zeolite), and materials produced on an experimental basis by AlliedSignal (biotites and nonatitanates), 3M (hexacyanoferrates), Selion Technologies, Inc. (hexacyanoferrates and titanates), and Texas A&M University (pharmacosiderites, biotites, and nonatitanates). In all, the performance of 14 ion exchange materials was evaluated at two solution-to-exchanger mass ratios (i.e., 10^4 and 10^5) using actual 105-KE Basin water. Evaluation consisted of determining cesium and strontium batch distribution coefficients, loading, and decontamination factors.

Actual 105-KE Basin water was obtained from a sample collected during the sludge dissolution work conducted by PNNL in FY 1996. This sample was taken from the bottom of the basin and contained significantly higher concentrations of the radioactive constituents than do samples taken from the top of the basin. Also, the sample contained large quantities of sludge and fuel pellets that had to be filtered prior to the batch contact testing. Filtration of the 105-KE Basin water resulted in removal of the transuranic (TRU) elements to below the detection limit. Therefore, the exchangers' performance in removing TRU elements could not be assessed in this study.

For ^{137}Cs removal, the 3M hexacyanoferrate and Texas A&M SZ-72 (modified zirconate) exhibited the best performance by removing over 99% of the ^{137}Cs from the 105-KE Basin water at a phase ratio of 10^4 . The performance of the hexacyanoferrate was better than IONSIV® IE-911 and clinoptilolite by one order and six orders of magnitude, respectively, in the neutral pH 105-KE Basin water. SZ-72 also exhibited similar improved performance over the commercial exchangers for cesium removal. For ^{90}Sr removal, in contrast, the pharmacosiderite and sodium nonatitanate ion exchange materials, both developed by Texas A&M, exhibited the best performance by removing over 99% of the ^{90}Sr at a phase ratio of 10^4 .

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1.0 Introduction

Ever since the U.S. Department Energy (DOE) discontinued fuel-processing operations at Hanford in 1989, its spent nuclear fuel (SNF) has been stored in water-filled pools designated as the K-Basins. These basins are located within the 100-K Area on DOE's Hanford Site, approximately 25 miles northwest of Richland, Washington. Two fuel storage basins, 105-KE and 105-KW, comprise the K-Basins. Both were originally designed to temporarily store spent fuel from the K reactors in the 100-K Area at Hanford. The cladding that surrounds the SNF assemblies stored in the K-Basins has severely corroded because of extended storage and material incompatibilities, resulting in significant releases of radionuclides and fissile materials into the basin water. DOE, federal, and state agencies involved in the Hanford Site cleanup are concerned about possible leakage of radioactively contaminated basin water into the Columbia River and the groundwater table and the effects of such releases on the environment. Under the Hanford Federal Facility Agreement and Consent Order (Tri-Party Agreement) established between the local and state government and DOE, the goal is to reduce the source of groundwater contamination from the radioactive materials that have leached into the water in the most problematic of the two basins, the 105-KE Basin.

In accord with DOE's goals and objectives, experimental ion exchange studies are being conducted by the Pacific Northwest National Laboratory (PNNL)^(a) under the Efficient Separations and Processing (ESP) Crosscutting Program to evaluate newly emerging materials and technologies for removing cesium, strontium, cobalt, technetium, and transuranic (TRU) elements from simulated and actual wastes at Hanford (Bray et al. 1990 and 1993; Brown et al. 1995a-c and 1996a and b). Although the majority of the previous work was focussed on treatment of high-level alkaline tank wastes (Bray et al. 1984; Kurath et al. 1995; Brown et al. 1995a-c, 1996a and b, and 1997), many of these technologies can be used for process and groundwater remediation (Herbst et al. 1995; Brown et al. 1996b and 1997).

1.1 K-Basins: History and Background

Fuel from the K reactors was stored in the K-Basins (basins 105-KE and 105-KW) until the decommissioning of the K reactors in 1971. After that time, most of the fuel stored in the K-Basins was removed and shipped to the 200 East Area for processing. In the mid-1970s and early 1980s, the two basins were repaired and modified to provide temporary storage for the spent fuel from the N Reactor until the fuel could be processed at the Plutonium-Uranium Extraction (PUREX) plant. In 1989, all the fuel assemblies in the N-Basin, the fuel storage basin at the N Reactor, were encapsulated and shipped to the K-Basins. No fuel shipments to the K-Basins were made after 1989. Although the K-Basins were intended to provide temporary storage for spent N Reactor fuel before its reprocessing at the PUREX plant, two shutdowns of the PUREX plant in 1982 and 1992 have led to extended underwater storage of the fuel in the 105-KE and -KW Basins.

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The 105-KE and -KW Basins have a single tier fuel storage rack, a 1-M-gal (3.8-M-L) water-cooling and shielding system, a fuel loading and transport system, and a water makeup/treatment system (Watson et al. 1991; WHC 1994). The basin water levels are kept at least 10 ft above the fuel height to provide radiological shielding to personnel working in the 100-K Area fuel storage facilities. The floor drains in the pool are sealed with concrete to ensure against water loss. In the KW Basin, a pliable epoxy coating on the walls and floor of the pool provides additional protection. The only escape (other than evaporation) for the water from the basins is through overflow weirs located about 2.5 ft above the pool water level. Water is continuously added to the basins to make up for that lost due to evaporation. The basins were designed to operate with a maximum water temperature of 38°C (or 100°F). The temperature of the water is maintained below 38°C by continuously recirculating the water through a cooling system. One of the primary functions of the cooling system is to remove the decay heat generated by the irradiated fuel stored in the basin. This is accomplished by circulating the basin water through water chillers where the heat is transferred to a secondary water system and then released into the Columbia River. Provisions are also made to remove the water-soluble radionuclides from the basin water via an ion exchange system that contains a mixed-bed ion exchanger. K-Basin water entering the ion exchange system is first passed through sand pits to remove any solid particles from the water. To protect against corrosion, the pH of the basin water is maintained between 5.0 and 9.0.

The 105-KE Basin contains 3668 open-top canisters filled with zirconium-clad fuel from the N Reactor and two baskets (an equivalent of 5 canisters) of aluminum-clad fuel from the K Reactor. During the discharge of the spent fuel elements from the reactors and their subsequent handling and transport to the 105-KE Basin, the cladding integrity was breached. The loss of cladding integrity ranged from cracks to separation of the fuel element from the cladding. The breach of the cladding integrity has allowed water to gain access to the fuel rods, thereby starting the corrosion of the metallic uranium and leaching of the fission products into the basin cooling water. It is currently estimated that 7% of the fuel stored in this basin has ruptured. Corrosion of the fuel and the canisters also has caused significant amounts of sludge to accumulate on the bottom of the basin. Additional sources of sludge materials include 1) concrete from the deterioration of the basin walls, 2) sand from the back washing of the sand filters, 3) dust from the surrounding environment, and 4) zeolite materials from the ion exchange system. The 105-KE Basin contains approximately 3.8 M L of water. Table 1.1 lists the primary radioactive constituents present in the basin water. The continuing contamination of the cooling water from corrosion and leaching of the fission products is of significant environmental concern because the 105-KE Basin has leaked in the past and the basin is located near the Columbia River. The basin, however, has not leaked since it was last repaired in 1980.

The 105-KW Basin contains 3821 sealed canisters filled with zirconium-clad fuel from the N Reactor. As was the case with the fuel elements in the 105-KE Basin, the cladding integrity of some of the fuel elements was breached during the elements' discharge from the N Reactor and their subsequent transport to the basin. It is estimated that 7% of the fuel stored in this basin has ruptured. However, since the fuel is stored in sealed canisters that provide the primary barrier for the escape of the fission products into the basin cooling water, the radioactive contamination of the 105-KW Basin water

Table 1.1. Radionuclide Analysis of the 105-KE and -KW Basin Water Based on Samples Collected in February 1997

Radionuclide	Activity ($\mu\text{Ci/L}$)	
	105-KE Basin	105-KW Basin
Total Alpha	1.39×10^{-2}	Not Detected
^{241}Am	3.74×10^{-3}	Not Detected
^{137}Cs	2.46	5.0×10^{-2}
$^{239/240}\text{Pu}$	8.32×10^{-3}	Not Detected
^{90}Sr	0.993	4.0×10^{-3}
^3H	2.61	7.0×10^{-2}
U (All Species; g/L)	1.35×10^{-5}	Not Detected

is not as high as that of the 105-KE Basin water, as can be seen from the radionuclide activity data in Table 1.1. The 105-KW Basin contains almost no sludge. The volume of water in the basin is estimated to be about 3.8 M L.

1.2 Fate of the K-Basin Water

Of the two basins, the radioactively contaminated water in the 105-KE Basin represents a major environmental concern to DOE and the Department of Ecology primarily because of the high concentration of radionuclides in the water (cf. Table 1.1) and the state of the canisters. Milestone M-34-01 of the Tri-Party Agreement (WHC 1994 and Appendix A) requires the removal, replacement, or treatment of the 105-KE Basin water. The timing of this action is to be coordinated with the encapsulation and removal of the fuel and sludge present in the basin. The disposition of the contaminated water is to be in accordance with reasonable treatment and/or disposal processes available for the Hanford Site at the time of the action. In this context, several options have been considered for the disposition of the 105-KE Basin water. For example, in an engineering study conducted by Westinghouse Hanford Company (WHC 1994), three options—river discharge, soil discharge, and solar evaporation—were evaluated as possible treatment alternatives for the disposition of the 105-KE Basin water. Another option, which is similar to the option being considered for the disposition of the N-Basin liquid effluent (BHI 1994 and 1995), is to dispose the waste at the 200 Area Effluent Treatment Facility (ETF). All options for disposing the 105-KE Basin water require that the water be processed further to reduce the levels of radioactive and nonradioactive contaminants in order to meet regulations put forth by the U.S. Environmental Protection Agency (EPA), Department of Ecology, federal, and state government on the quantities of radioactive elements that can be disposed into the ETF, the Columbia river, soil, or air (see Appendix B).

The most recent scenario for treating the 105-KE Basin water appears to consist of these steps: 1) filtration to remove suspended solids and transuranic particles and 2) ion exchange to remove ^{137}Cs and ^{90}Sr . The filtrate, spent ion exchange resins, and the treated basin water are expected to be disposed

at the 200 Area tank farms, the solid waste burials, and the 200 Area ETF, respectively. In order to identify the decontamination factors required to dispose the 105-KE Basin water at the 200 Area ETF, Table 1.2 lists a comparison of the radionuclide concentrations in the untreated basin water to the effluent activity limit criteria of the 200 Area ETF (all calculations are based on an assumed 1 M gal of water in the basin).

Using an ETF limit of 1 for the Sum [(Effluent Act)_n / (ETF Limit)_n] data in Table 1.2, it would appear that the 105-KE Basin water would not require further treatment by ion exchange once the canisters, sludge, and suspended particles are removed from the basin. However, the calculations in Table 1.2 are based on the radionuclide concentrations determined from samples taken at the top of the basin water. It is expected that once the open canisters are drained and the water in the basin stirred during the removal of the fuel elements and the sludge, the radioactive concentration in the basin water could be a factor of 1000 or more greater than that listed in Table 1.2. This increase in the concentrations would far exceed the ETF limits for ¹³⁷Cs and ⁹⁰Sr as can be seen from the calculations in Table 1.3, which are based on a sample taken from the bottom of the 105-KE Basin. This scenario would require that the 105-KE Basin water be treated prior to its final disposal at the 200 Area ETF.

1.3 Objectives

The work described in this report is a subtask of the project "Develop and Test Sorbents; Industrial Contracts," which is funded by the Efficient Separations and Processing (ESP) Crosscutting Program. The overall objective of this project is to both identify and develop novel sequestering agents and substrates prepared by industrial and university participants. *Identification* involves performing

Table 1.2. Comparison of the Radionuclide Concentrations in the 105-KE Basin to the Activity Limit Criteria of the ETF Based on a Sample from the Top of the Basin

Radionuclide	Total Activity (Ci) ^(a)	ETF Limit (Ci) ^(b)	Eff. Act/ETF Lt.
²⁴¹ Am	3.74E-02	5.20E-01	0.07
¹³⁷ Cs	9.35E+00	6.00E+01	0.16
^{239/240} Pu	3.16E-02	5.20E-01	0.06
⁹⁰ Sr	3.37E+00	1.60E+01	0.21
³ H	9.92E+00	1.00E+03	0.01
U (Total)	5.13E-05	4.20E+00	0.00
		Sum [(Effluent Act) _n / (ETF Limit) _n] = 0.51	

(a) Total Activity (Ci) = Activity (Ci/L from Table 1.1) x 3.8 x 10⁶ L.

(b) For EFT limits, see Appendix B and BHI (1995).

Table 1.3. Comparison of the Radionuclide Concentrations in the 105-KE Basin to the Activity Limit Criteria of the ETF Based on a Sample from the Bottom of the Basin

Radionuclide	Total Activity (Ci) ^(a)	ETF Limit (Ci) ^(b)	Eff. Act/ETF Lt.
¹³⁷ Cs	9.00E+03	6.00E+01	150
⁹⁰ Sr	1.02E+04	1.60E+01	636
		Sum [(Effluent Act) _n / (ETF Limit) _n] = 786	

(a) Activities measured in the 105-KE Basin sample used in this study. See Section 2.5.1 for more information. Total Activity (Ci) = Activity (Ci/L from Table 2.2) x 3.8 x 10⁶ L.

(b) For EFT limits, see Appendix B and BHI (1995).

screening tests on materials with some level of selectivity for the targeted metal ions. *Development* includes testing the capacity, selectivity, and stability of selected sequestering agents in simulated and actual waste streams to determine the physical, chemical, and radiation stability of the newly developed sequestering agents and substrates. Under this project, a collaborative effort between PNNL and industries and universities has been established to investigate new solid sorbent materials for removing various radionuclides from process waste streams. In this context, subcontracts have been made with Texas A&M University to investigate new sorbents and with AlliedSignal to collaborate and develop engineered forms of these materials. The role of PNNL is to evaluate the performance of these materials using either simulated or actual process waste streams.

The objective of the work described in this report is to evaluate the equilibrium performance of several ion exchange materials developed by Texas A&M and AlliedSignal using actual 105-KE Basin water. The experimental objectives were to determine the cesium, strontium, and transuranic element batch distribution coefficients (K_d); to identify and establish performance characteristics of the newly developed ion exchange materials; and to compare the performance of those materials to clinoptilolite, a naturally occurring zeolite, and IONSIV® IE-911, a crystalline silicotitanate ion exchange material manufactured by UOP.

1.4 Scope

The scope of the work described in this report includes the experimental measurements of equilibrium batch distribution coefficients using actual 105-KE Basin water and 14 ion exchange materials at two different exchanger/solution mass ratios. The ion exchangers tested include clinoptilolite (a naturally occurring zeolite), IONSIV® IE-911 crystalline silicotitanate (CST), potassium cobalt hexacyanoferrate (KCoHex; engineered form developed by 3M), six new materials developed at Texas A&M, three ion exchange materials developed by AlliedSignal, and two ion exchange materials developed by Selion Technologies, Inc. (Meriden, Connecticut).

2.0 Theory

2.1 Batch Distribution Coefficient: K_d

The batch distribution coefficient, K_d , of a particular ionic species is defined as the ratio of the concentration of the ionic species in the exchanger phase to that in the solution phase under equilibrium conditions. K_d is an equilibrium measure of the overall ability of the solid phase ion exchange material to remove an ion from solution under the experimental conditions that exist during contact. The batch K_d is not necessarily only a measure of the affinity of a material for a particular ion, but also can be used as an indicator of the selectivity and capacity of the ion exchanger to a particular ion in the presence of a complex matrix of interfering ions. However, K_d does not provide information about ion exchange kinetics and is useful only for measuring the ion exchanger selectivities under the particular conditions of the test. The determination of K_d by adding a small quantity of ion exchange material into a small volume of supernatant solution is an extremely rapid and cost-effective method for comparing the performance of many ion exchange materials. Accurate comparison of K_d results requires identical experimental conditions (i.e., ratio of the exchanger mass to solution volume, equilibrium solution composition, material pretreatment, temperature) because all of these factors are known to affect K_d .

In most K_d determination tests, a known quantity of the ion exchange material is contacted with a predetermined volume or weight of solution containing the ions of interest. The material is allowed to equilibrate with the solution for a known time at a constant temperature. After equilibration, the solid ion exchanger and liquid supernate are separated. The concentration of the species of interest is determined in the solution and in the solid exchanger phase.

In this study, the ion concentrations in the solid exchanger phase were determined from the difference in the measured concentration in the solution phase before and after contact. The equation for determining the batch distribution, in this case, is expressed as (Kurath et al. 1994)

$$K_d = \frac{C_i - C_f}{C_f} \frac{V}{MF} \quad (2.1)$$

where C_i = the initial activity of the ion of interest in the feed solution prior to contact

C_f = the activity after contact

V = the solution volume

M = the exchanger mass.

The term F , also known as the F-factor, is defined as the mass of the completely dry ion exchanger divided by its mass as received. This term accounts for the sorption of water into the exchanger phase during prolonged storage. The batch K_d , with units of mL of solution per gram of dry exchanger (mL/g), represents the theoretical volume of solution that can be processed per unit mass of exchanger under equilibrium conditions.

The usefulness of the K_d measurements is that they are also a relative measure of the amount of cesium removed from the solution phase. For example, when the K_d of a particular ionic species is equal to the phase ratio (i.e., the term V/MF in Equation 2.1), from Equation 2.1, a back calculation shows that 50% of that ion is removed from the solution. Similarly, when the measured K_d is a factor of 10, 100, and 1000 greater than the phase ratio, then 91%, 99%, and 99.9% of the ion, respectively, is removed from the solution in a batch-type operation. Using the same analogy, when the measured K_d is a factor of 10 and 100 less than the phase ratio, then 9% and 1%, respectively, of the ion is removed from the solution.

2.2 Column Distribution Coefficient: Lambda

The column distribution coefficient, λ (i.e., the theoretical number of bed volumes of solution that can be processed per unit volume of the exchanger), is obtained by multiplying K_d by the exchanger bed density, ρ_b (grams of dry exchanger per unit volume (mL) of the resin in a column), as shown in Equation 2.2:

$$\lambda = K_d \rho_b \quad (2.2)$$

The column distribution λ is an important parameter in comparing the performance of ion exchangers during a column operation. In order to compare the column performance of an exchanger based on its λ value, it is essential that K_d and ρ_b be determined at the compositions that are prevalent in the feed solution. During a batch contact experiment, as the ionic species of interest is loaded onto the exchanger, its concentration decreases. For this reason, at any particular phase ratio, the K_d values are determined at several concentrations of the species of interest by spiking the feed solution with the ionic species and interpolating to determine K_d at the concentration of interest.

2.3 Ion Exchanger Loading and Decontamination Factor

The ion exchanger loading and decontamination factor (DF) are two additional parameters that are important in comparing ion exchanger performance. The loading of the ion exchanger, defined as the moles of the ionic species that can be absorbed on the exchanger per unit weight of the exchanger, is a convenient measure of the utilization of the ion exchange capacity of the exchanger. When the initial and final concentration of the ionic species of interest are measured only in the solution phase, the loading in units of mmol/g is given by

$$\text{Loading} = \frac{|C_i - C_f| 1000 V}{MF} \quad (2.3)$$

The decontamination factor (DF) is defined as the ratio of the activity or concentration of the ionic species of interest in the solution phase before and after contact, i.e.,

$$DF = \frac{C_i}{C_f} \quad (2.4)$$

3.0 Experimental Description

3.1 Properties of Ion Exchange Materials

Table 3.1 lists the ion exchange materials examined in this study, along with selected general information. Several of these material are still under development and may not be in their optimal form. Also, some of the materials were specifically designed for removing cesium and strontium from highly caustic or high ionic strength solutions (e.g., from Hanford tank wastes) and, therefore, may not perform to their maximum capacity in the neutral pH water of the 105-KE Basin.

Table 3.1. Selected Properties of the Ion Exchange Materials Used in This Study

Ion Exchange Material	ID	Manufacturer	Batch No.	ρ_b	F-Factor
IONSIV® IE-911	A	UOP	999096810002	0.85	0.8499
Clinoptilolite	B	Natural Zeolite		0.95	0.9540
Potassium Cobalt Hexacyanoferrate (KCoHex)	C	3M	2999-14	--(a)	0.9655
SFT	D	Texas A&M	SFT	--(a)	0.8516
Pharmacosiderite	E	Texas A&M	E-B Pharm-1	--(a)	0.8641 ^(a,b)
Sodium Biotite	G	AlliedSignal	8212-15D	--(a)	0.8811 ^(a,b)
Sodium Biotite	H	AlliedSignal	8212-32A	--(a)	0.7781 ^(a,b)
Sodium Nonatitanate	I	AlliedSignal	8212-152	0.84	0.9628
Cs-Treat	J	Selion Technologies, Inc.	H58	0.52	0.9558
Sr-Treat	L	Selion Technologies, Inc.	H18	0.71	0.9027
Modified Mica	M	Texas A&M	M-275	--(a)	0.9449
Sodium Zirconate	N	Texas A&M	SZ-72	--(a)	0.9013
Pharmacosiderite	P	Texas A&M	AIB-TS255	--(a)	--(a)
Sodium Nonatitanate	Q	Texas A&M	GMG-3-1	--(a)	--(a)
(a) Because of an insufficient amount of sample for measurement, the bed densities and F-factor for these ion exchange materials were not measured.					
(b) Data taken from Brown et al. (1997).					

IONSIV® IE-911 is the engineered version of the crystalline silicotitanate (CST) produced by UOP (Des Plaines, Illinois). The engineered CST was developed by UOP under a Cooperative Research and Development Agreement (CRADA) with Sandia National Laboratory (SNL). Potassium cobalt hexacyanoferrate (KCoHex) is an inorganic ion exchange material produced by 3M on an experimental basis for incorporation into their proprietary web-like membranes (e.g., Empore™ and other materials). Clinoptilolite is a natural zeolite that is currently being used to treat the N-Springs water at Hanford. It was obtained from Mr. Abdul Dada (Bechtel Hanford Inc., Richland, Washington). In collaboration with researchers from AlliedSignal, the pharmacosiderites (E-B Pharm-1 and AIB-TS255), biotites, and sodium nonatitanate materials are being developed by Professor Abraham Clearfield and coworkers at Texas A&M for removing cesium and strontium from several waste matrices. Engineered forms of the biotite and sodium nonatitanate materials were developed by AlliedSignal. Cs-Treat and Sr-Treat are cesium and strontium selective ion exchangers, respectively, developed by Selion Technologies, Inc.

All materials were used as received without any additional processing. Because of the different manufacturing conditions, the ion exchange materials do not contain the same counter ion when received from the university or industrial contact. The variation in the counter ion form and the differences in the ion exchange capacity of these materials could cause the contact solution composition to change because of the desorption of the counter ions from the exchanger during a batch contact experiment. However, since the solution volume-to-exchanger mass ratios examined in this study are extremely high (approximately 10^4 and 10^5), we believe that small changes in the solution composition stemming from the desorption of the exchanger counter ions will only negligibly affect the measured batch distribution coefficients. Another important variable is the ion exchange particle size distribution, which is known to affect the measured K_d value. For example, smaller particle sodium nonatitanates (GMG-3-1), produced by Texas A&M, will show higher K_d s than the larger engineered particles (8212-152) produced by AlliedSignal.

3.2 Experimental Procedures

The actual 105-KE Basin water used in this study was obtained from the Sludge Dissolution Study Program conducted by PNNL in FY 1996. This sample, taken from the bottom of the basin, contains significant quantities of solids primarily as TRU elements. Filtration of the water removes 99.9% of the TRU and also changes the measured activities of ^{137}Cs and ^{90}Sr , as shown by the pre- and post-filtration compositions listed in Table 3.2. Since measured K_d , λ , loading, and DF values for ^{137}Cs , ^{90}Sr , and TRU elements will be influenced by the changes in measured activities resulting from filtration of solid particles, the 105-KE Basin water was filtered before any batch contact experiments were conducted. The water was filtered by passing it through a $0.45\text{-}\mu\text{m}$ filter and pulling the liquid through by vacuum.

In the batch contact experiments conducted in this study, a predetermined amount of the ion exchanger (0.1 g for a phase ratio of 10,000 and 0.01 g for a phase ratio of 100,000) was weighed out in a 1000-mL glass bottle with a screw-top cap. To this, approximately 1000 mL of filtered 105-KE Basin water was added. The exact amount of basin water taken was obtained from the difference in the measured weight of the sample bottle before and after the water was added. The exchanger was allowed to equilibrate with the water for 7 to 10 days, during which time the bottles were periodically shaken. An

Table 3.2. Radioactive Ion Activities^(a) in the 105-KE Basin Water Before and After Filtration

Sample ID	Measured Activities ($\mu\text{Ci/mL}$)		
	Total α	^{90}Sr	^{137}Cs
105-KE Basin Water (Unfiltered)	2.21×10^{-2}	2.68	2.37
105-KE Basin Water (Filtered)	$< 2. \times 10^{-4}$	2.39	3.29
<p>(a) The data listed here indicate that the activities of the ions in the 105-KE Basin water sample are a factor of 1000 greater than the activities reported previously in Table 1.1. The difference is due to the fact that the water sample used in this study was taken from the bottom of the basin, where a significant concentration of radioactive sludge is present. The samples used to obtain the data in Table 1.1 were taken from the top of the basin water. The effects of these differences can be understood by examining the activity of the radioactive sludge in the 105-KE Basin, which indicates that the total activity of the sludge ranges between 110 to 200 $\mu\text{Ci/mL}$ (data from K. M. Tominey, "SE Support for SNF Characterization: Baseline Characteristics of KE-Spent Nuclear Fuel for Use in Planning for Receipt and Management of K-Basin Fuel," memo dated August 3, 1994 to Distribution, Battelle Pacific Northwest Laboratory, Richland, Washington).</p>			

equilibration period of over 7 days was chosen to ensure that complete equilibrium between the exchanger and the water was attained. All solid/liquid contact experiments were conducted in a shielded hot cell without temperature controllers. The temperature was recorded periodically throughout the experiments, but no attempts were made to control the temperature. All experiments were conducted in duplicate to ensure reproducibility. Blank tests were conducted to check for changes in the activities resulting from natural decay processes, absorption of the ions to the walls of the containers, filtration, and other uncontrolled experimental conditions.

After equilibration, a sample of the supernatant liquid was filtered through a 0.45- μm syringe filter to separate the ion exchanger phase. The changes in the activities of ^{137}Cs , ^{90}Sr , and TRU elements in the 105-KE Basin water solutions before and after contact were determined by GEA (gamma energy analysis), ^{90}Sr , and AT (total alpha) analysis, respectively.

To determine K_d , λ , and loading using Equations 2.1 through 2.3, F , the F-factor, must be determined. The F-factor accounts for the sorption of water into the exchanger phase during prolonged storage. For the typical F-factor determination test conducted in this study, a known amount of the ion exchange material (typically 0.5 g) was added to a glass vial and the vial was placed in a 105°C oven for 24 hours, after which the sample was weighed again. A drying period of 24 hours was chosen because previous experimental studies have shown that within 24 hours all of the free water is desorbed from the exchanger. The F-factor was calculated using the following equation:

$$F = \frac{\text{Weight of Ion Exchanger after Drying}}{\text{Weight of Ion Exchanger before Drying}} \quad (3.1)$$

The experimentally determined F-factors for the ion exchange materials used in these tests also are listed in Table 3.1. Because of insufficient amounts of the pharmacosiderite (batch no. E-B Pharm-1) and biotite (batch no. 8812-15D and 8812-32A) samples, the F-factor data reported in Table 3.1 were taken from Brown et al. (1997). The F-factor correction was omitted (i.e., F was set equal to 1) for the pharmacosiderite, sodium nonatitanate, M-275, and SZ-72 materials developed by Texas A&M because of an insufficient amount of sample and lack of previous experimental data.

In order to use Equation 2.2 to determine λ , the bed density, ρ_b , of the ion exchange material must be determined. For the typical bed density determination test conducted in this study, a known amount of the ion exchange material (typically 4 g) was placed in a 10-mL graduated cylinder filled with about 5 mL of deionized water (here, deionized water was taken to be a typical representation of the 105-KE Basin water because of the extremely low concentration of the ionic species in the basin water). The ion exchange material was allowed to equilibrate with the water for 24 hours, after which the volume of the ion exchange bed was recorded. The bed density was calculated using the following relationship:

$$\rho_b = \frac{(\text{Weight of Ion Exchanger Taken}) F}{\text{Volume of the Ion Exchange Bed in DI Water}} \quad (3.2)$$

Once again, because an insufficient amount of sample was available for the bed density measurement, the bed densities were determined for only 5 of the 14 ion exchangers tested. These data are also listed in Table 3.1.

3.3 Experimental Results

In this study, only the radioactive cesium and strontium concentrations rather than their total concentration (i.e., the radioactive and nonradioactive concentrations) were measured. Not measuring the nonradioactive concentration does not affect the K_d , λ , and DF results. However, it does influence the loading data since the loading (or exchanger utilization) will be higher because both radioactive and nonradioactive cesium and strontium are loaded onto the exchanger. For the purpose of calculating exchanger loading, 100% of the cesium and strontium was assumed to be radioactive ^{137}Cs and ^{90}Sr , respectively. The averaged data for the computed K_d , DF, and loading of the cesium and strontium ions are listed in Tables 3.3 through 3.6. The complete data, including weight of the ion exchanger and 105-KE Basin water; the activities of the radionuclides measured in the samples before and after contact; and the computed values of the batch distribution coefficients, loading, and DF for each individual ion exchanger/test are listed in Appendix C.

Table 3.3. Average K_d , Loading, and DF Data for ^{137}Cs Uptake from 105-KE Basin Water at a Phase Ratio of 10^4

Ion Exchanger	ID	K_d (mL/g)	Loading (mmol/g)	DF
IONSIV® IE-911	A	1.41E+05	1.88E-03	1.31E+01
Clinoptilolite	B	2.81E+04	1.31E-03	3.91E+00
Potassium Cobalt Hexacyanoferrate (KCoHex)	C	1.67E+06	1.69E-03	1.79E+02
SFT	D	2.68E+04	1.44E-03	3.37E+00
Pharmacosiderite	E	9.81E+04	1.72E-03	1.04E+01
Sodium Biotite	G	3.62E+04	1.51E-03	4.37E+00
Sodium Biotite	H	2.94E+04	1.50E-03	3.50E+00
Sodium Nonatitanate	I	7.34E+03	7.40E-04	1.75E+00
Cs-Treat	J	4.24E+05	1.70E-03	4.58E+01
Sr-Treat	L	1.84E+04	1.23E-03	2.71E+00
Modified Mica	M	2.90E+04	1.36E-03	3.90E+00
Sodium Zirconate	N	1.28E+06	1.82E-03	1.28E+02
Pharmacosiderite	P	4.06E+05	1.61E-03	4.64E+01
Sodium Nonatitanate	Q	5.42E+04	1.40E-03	7.04E+00

Table 3.4. Average K_d , Loading, and DF Data for ^{137}Cs Uptake from 105-KE Basin Water at a Phase Ratio of 10^5

Ion Exchanger	ID	K_d (mL/g)	Loading (mmol/g)	DF
IONSIV® IE-911	A	1.70E+05	1.19E-02	2.60E+00
Clinoptilolite	B	7.68E+04	8.02E-03	1.75E+00
Potassium Cobalt Hexacyanoferrate (KCoHex)	C	3.87E+05	1.33E-02	5.21E+00
SFT	D	7.41E+04	7.59E-03	1.79E+00
Pharmacosiderite	E	2.07E+05	1.23E-02	3.07E+00
Sodium Biotite	G	4.58E+04	5.77E-03	1.45E+00
Sodium Biotite	H	1.82E+04	2.88E-03	1.16E+00
Sodium Nonatitanate	I	4.82E+04	5.57E-03	1.57E+00
Cs-Treat	J	1.85E+05	1.19E-02	2.84E+00
Sr-Treat	L	2.04E+04	3.08E-03	1.21E+00
Modified Mica	M	4.80E+04	5.64E-03	1.54E+00
Sodium Zirconate	N	2.20E+05	1.18E-02	3.43E+00
Pharmacosiderite	P	4.31E+05	1.43E-02	5.48E+00
Sodium Nonatitanate	Q	2.88E+04	3.87E-03	1.30E+00

Table 3.5. Average K_d , Loading, and DF Data for ^{90}Sr Uptake from 105-KE Basin Water at a Phase Ratio of 10^4

Ion Exchanger	ID	K_d (mL/g)	Loading (mmol/g)	DF
IONSIV® IE-911	A	9.72E+04	2.00E-03	9.32E+00
Clinoptilolite	B	9.03E+04	1.67E-03	1.03E+01
Potassium Cobalt Hexacyanoferrate (KCoHex)	C	2.35E+04	1.28E-03	3.52E+00
SFT	D	1.73E+05	2.03E-03	1.63E+01
Pharmacosiderite	E	6.44E+05	1.97E-03	6.27E+01
Sodium Biotite	G	6.96E+04	1.79E-03	7.45E+00
Sodium Biotite	H	4.89E+04	1.82E-03	5.15E+00
Sodium Nonatitanate	I	4.80E+04	1.53E-03	5.99E+00
Cs-Treat	J	2.17E+04	1.27E-03	3.30E+00
Sr-Treat	L	9.10E+04	1.85E-03	9.45E+00
Modified Mica	M	1.39E+05	1.79E-03	1.49E+01
Sodium Zirconate	N	3.99E+05	1.88E-03	4.07E+01
Pharmacosiderite	P	4.77E+06	1.73E-03	5.48E+02
Sodium Nonatitanate	Q	1.83E+06	1.71E-03	2.08E+02

Table 3.6. Average K_d , Loading, and DF Data for ^{90}Sr Uptake from 105-KE Basin Water at a Phase Ratio of 10^5

Ion Exchanger	ID	K_d (mL/g)	Loading (mmol/g)	DF
IONSIV® IE-911	A	3.63E+05	1.58E-02	4.39E+00
Clinoptilolite	B	3.16E+05	1.49E-02	4.08E+00
Potassium Cobalt Hexacyanoferrate (KCoHex)	C	2.61E+05	1.27E-02	3.84E+00
SFT	D	6.57E+05	1.59E-02	7.75E+00
Pharmacosiderite	E	2.87E+05	1.42E-02	3.87E+00
Sodium Biotite	G	2.25E+05	1.35E-02	3.21E+00
Sodium Biotite	H	2.88E+05	1.59E-02	3.47E+00
Sodium Nonatitanate	I	2.97E+05	1.24E-02	4.47E+00
Cs-Treat	J	1.83E+05	1.25E-02	2.80E+00
Sr-Treat	L	2.96E+05	1.39E-02	4.07E+00
Modified Mica	M	2.55E+05	1.28E-02	3.82E+00
Sodium Zirconate	N	3.71E+05	1.41E-02	5.09E+00
Pharmacosiderite	P	3.69E+05	1.46E-02	4.84E+00
Sodium Nonatitanate	Q	3.69E+05	1.45E-02	4.87E+00

4.0 Results and Discussion

4.1 Cesium Uptake Results

The following sections compare the performance of the ion exchangers for ^{137}Cs removal from 105-KE Basin water in terms of the batch distribution coefficients (K_d and λ) and ion loading.

4.1.1 Cesium Batch K_d

The cesium K_d data for all the ion exchangers (including duplicate measurements) plotted as a function of the final ^{137}Cs concentration are shown in Figure 4.1^(a) for the two phase ratios examined in this study. The data in Figure 4.1 show trends that are typical of ion exchange K_d measurement tests, i.e., as the ^{137}Cs concentration in the solution decreases as a result of cesium ion uptake by the exchanger, the K_d increases.

Using the analogy presented in Section 2.1 for interpreting the K_d data, it can be seen from Figure 4.1 that at a phase ratio of 10^4 , all exchangers remove more than 50% of the cesium in the 105-KE Basin water, while several remove 90% and two exchangers showed over 99% removal efficiency. The

Figure 4.1. Cesium-137 Batch K_d as a Function of the Final ^{137}Cs Concentration in the Contact Solution Following the Batch Equilibrium Test

(a) The material identification letters listed in the legend on this figure and used on all subsequent figures in Section 4.0 correspond to the material identification letters in Table 3.1 (see page 3.1).

performance of all exchangers was diminished at the higher phase ratio of 10^5 . In this situation, none of the ion exchangers removed more than 90% of the cesium from the solution, although several of the ion exchangers showed over 50% removal efficiency. The data in Figure 4.1 suggest that, for a given exchanger, an increase in the phase ratio results in a decrease in the amount of cesium removed from the solution. This result is intuitive, because for a given mass of solution, as the amount of exchanger decreases (i.e., the phase ratio increases), there are fewer sites for ion exchange and therefore the amount of cesium removed from the solution decreases.

One additional interesting feature of the data in Figure 4.1 is that for a phase ratio of 10^4 , the K_d values show a broad range of variation (the K_d increases over three orders of magnitude). However, at the higher phase ratio of 10^5 , all the experimentally measured K_d values exhibit a significantly compressed behavior (the K_d values lying between 10^4 and 5×10^5). Also, by examining the data closely, it can be seen that with decreasing phase ratio, the K_d values for some exchangers increases, for others remains constant, and for others decreases. Such exchanger behavior can be partially explained by examining the K_d relationship (Equation 2.1), which is a product of the $(C_i - C_f)/C_f$ or $(C_i/C_f - 1)$ term and the phase ratio term (V/MF) . In an ideal case, the cesium K_d should be independent of the phase ratio, i.e., with decreasing phase ratio, the final solution concentration of cesium should also decrease accordingly to keep K_d constant. For very cesium-selective ion exchangers, at the lower phase ratios there is essentially no cesium in the solution to saturate the ion exchange sites (i.e., $C_f \rightarrow 0$) and the increase in the $(C_i - C_f)/C_f$ becomes larger than the decrease in the phase ratio. Therefore, for these exchangers, the K_d appears to increase with decreasing phase ratio. The apparent decrease in the K_d with decreasing phase ratio for noncesium-selective exchangers may be attributed to errors in measuring small changes in the cesium ion concentration in the solution phase before and after contact.

Although the data in Figure 4.1 show the general trends in the K_d profiles, it is difficult to clearly delineate each exchanger performance from the others because of 1) cluttering of the data in the figures and 2) slight differences in the measured K_d data for the duplicate experiments resulting from slight variations in the experimental conditions (i.e., volume of the basin water and weight of the ion exchanger taken).

To illustrate the comparative performance of the exchangers, the averaged and sorted K_d data are presented as bar graphs in Figures 4.2 and 4.3 for the phase ratios of 10^4 and 10^5 , respectively. The data in Figure 4.2 indicate that for a phase ratio of 10^4 , the KCoHex material developed by 3M shows the best performance (average $K_d = 1.7 \times 10^6$), followed by the SZ-72 ion exchange material (average $K_d = 1.3 \times 10^6$) developed by Texas A&M. Intermediate performance was observed with the pharmacosiderite (AIB-TS255; Texas A&M) and Cs-Treat (Selion Technologies, Inc.) ion exchangers, whereas all other materials showed relatively lower selectivities for removing cesium from the 105-KE Basin water. For the higher phase ratio tests (see Figure 4.3), in contrast, the pharmacosiderite (AIB-TS255; Texas A&M) shows the best performance, followed by the KCoHex material developed by 3M. Intermediate performance was shown by SZ-72 (Texas A&M), pharmacosiderite (EB-Pharm-1; Texas A&M), Cs-Treat (Selion Technologies, Inc.), and IONSIV® IE-911, with all other materials exhibiting average to poor performance.

Figure 4.2. Comparative Performance of Ion Exchangers in Removing ^{137}Cs from 105-KE Basin Water at a Phase Ratio of 10^4

Figure 4.3. Comparative Performance of Ion Exchangers in Removing ^{137}Cs from 105-KE Basin Water at a Phase Ratio of 10^5

4.1.2 Cesium Loading

As mentioned in the experimental section, only the radioactive cesium concentration rather than the total cesium concentration (i.e., the radioactive and the nonradioactive cesium concentrations) was measured. Therefore, this discussion of the amount of cesium loaded on the exchanger and the exchanger active site utilization is based on only the ^{137}Cs concentration. The actual utilization of the exchanger sites for cesium removal will be greater by the same magnitude as the ratio of the total cesium and the ^{137}Cs concentrations. Historical cesium decay suggests that this ratio may be between 3:1 and 2:1. The average ^{137}Cs loadings at the phase ratios 10^4 and 10^5 are shown in Figures 4.4 and 4.5, respectively. The data in both figures show a "boomerang" type profile, indicating that although the ^{137}Cs concentration in the solution phase decreases, the extent of exchanger loading is not significantly affected. This is due to the fact that the $(C_i - C_f)$ term in the loading equation (Equation 2.3) approaches C_i as C_f becomes very small. If one assumes a typical ion exchange capacity of 1 mmol/g for the exchangers, from Figures 4.4 and 4.5 it appears that the maximum amount of ^{137}Cs loaded on the exchangers is less than 0.1% and 1% of the total ion exchange capacity at the phase ratios of 10^4 and 10^5 , respectively. This is due to the fact that although the ion exchange capacity of the exchanger may be high, the ^{137}Cs loading cannot exceed C_i times the phase ratio.

4.1.3 Cesium Lambda

The computed ^{137}Cs λ values of the few ion exchange materials for which the bed densities were measured are listed in Tables 4.1 and 4.2 at the phase ratios of 10^4 and 10^5 , respectively. The computed

Figure 4.4. Cesium-137 Loading on Exchangers at a Phase Ratio of 10^4 as a Function of the Final ^{137}Cs Concentration in the Contact Solution Following the Batch Equilibrium Test

Figure 4.5. Cesium-137 Loading on Exchangers at a Phase Ratio of 10^5 as a Function of the Final ^{137}Cs Concentration in the Contact Solution Following the Batch Equilibrium Test

values are based on the average values of K_d obtained from the duplicate runs. As mentioned in Section 2.2, the cesium λ values in Tables 4.1 and 4.2 should be used for comparison purposes only, as the final ^{137}Cs concentration for all ion exchangers is less than the initial concentration of $1.87 \times 10^{-7} \text{ M}$. The data in the tables indicate that cesium-selective ion exchangers such as IONSIV® IE-911 and Cs-Treat could typically process 10^5 volumes of the 105-KE Basin water per unit volume of the ion exchanger bed. The performance of noncesium-selective ion exchangers such as clinoptilolite, Sr-Treat, and sodium nonatitanate, by contrast, is less by an order of magnitude.

Table 4.1. Experimentally Determined ^{137}Cs λ at a Phase Ratio of 10^4

Ion Exchanger	Final ^{137}Cs Conc. [M]	Avg. ^{137}Cs K_d [mL/g]	Bed Density [g/mL]	^{137}Cs λ [mL/mL]
IONSIV® IE -911	2.19E-08	1.41E05	8.50E-01	1.19E05
Clinoptilolite	4.67E-08	2.81E04	9.50E-01	2.67E04
Cs-Treat	4.04E-09	4.24E05	5.20E-01	2.21E05
Sr-Treat	6.81E-08	1.84E04	7.10E-01	1.31E04
Sodium Nonatitanate (Texas A&M)	2.59E-08	5.42E04	8.40E-01	4.55E04

Table 4.2. Experimentally Determined ^{137}Cs λ at a Phase Ratio of 10^5

Ion Exchanger	Final ^{137}Cs Conc. [M]	Avg. ^{137}Cs K_d [mL/g]	Bed Density [g/mL]	^{137}Cs λ [mL/mL]
IONSIV® IE -911	7.14E-08	1.70E05	8.50E-01	1.44E05
Clinoptilolite	1.04E-07	7.68E04	9.50E-01	7.29E04
Cs-Treat	6.49E-08	1.85E05	5.20E-01	9.61E04
Sr-Treat	1.51E-07	2.04E04	7.10E-01	1.45E04
Sodium Nonatitanate (Texas A&M)	1.42E-07	2.88E04	8.40E-01	2.42E04

4.2 Strontium Uptake Results

The following sections compare the performance of the ion exchangers for ^{90}Sr removal from 105-KE Basin water in terms of the batch distribution coefficients (K_d and λ) and ion loading.

4.2.1 Strontium Batch K_d

The ^{90}Sr K_d data for all of the ion exchangers (including duplicate measurements) are shown in Figure 4.6 for the two different phase ratios that were examined in this study. As was the case with the ^{137}Cs K_d results, the ^{90}Sr K_d values also increase with decreasing ^{90}Sr concentration in the contact solution phase.

Using the same analogy presented in Section 2.1 for interpreting the K_d data, it can be seen from Figure 4.6 that at a phase ratio of 10^4 , all exchangers remove over 50% of the ^{90}Sr from the solution. The efficiency of ^{90}Sr removal in some cases exceeded 99%. As was the case with the ^{137}Cs K_d results, the effectiveness of the ion exchanger decreases with increasing phase ratio. However, unlike the ^{137}Cs case where the performance of several ion exchangers at the higher phase ratio fell below 50% removal efficiency, all ion exchangers still exhibited over 50% ^{90}Sr removal.

To illustrate the comparative performance of the ion exchangers for ^{90}Sr removal, the averaged and sorted K_d data are presented as bar charts in Figures 4.7 and 4.8 for the phase ratios of 10^4 and 10^5 , respectively. The ^{90}Sr K_d data in Figure 4.7 indicates that for a phase ratio of 10^4 , the pharmacosiderite (AIB-TS255) ion exchanger developed by Texas A&M shows the best performance (average $K_d = 4.8 \times 10^6$), removing over 99% of the ^{90}Sr from the solution. The second best-performing ion exchanger for ^{90}Sr removal was the sodium nonatitanate material (average $K_d = 1.8 \times 10^6$), also developed by Texas A&M. Intermediate performance was observed with pharmacosiderite (E-B Pharm-1), SZ-72, SFT, and M-275 ion exchange materials (all developed by Texas A&M), which removed over 90% of the ^{90}Sr from the solution. All other ion exchange materials showed relatively lower selectivities for ^{90}Sr removal from the 105-KE Basin water. At the higher phase ratio of 10^5 , the data in Figure 4.8 suggest that

Figure 4.6. Strontium-90 Batch K_d as a Function of the Final ^{90}Sr Concentration in the Contact Solution Following the Batch Equilibrium Test

Figure 4.7. Comparative Performance of Ion Exchangers in Removing ^{90}Sr from 105-KE Basin Water at a Phase Ratio of 10^4

Figure 4.8. Comparative Performance of Ion Exchangers in Removing ^{90}Sr from 105-KE Basin Water at a Phase Ratio of 10^5

except for the SFT material, the performance of all other ion exchangers was similar. It is rather surprising to find that the SFT material showed the best performance at the higher phase ratio, while its performance was intermediate at the lower phase ratio of 10^4 . This result may be due to an operator error in which the sample from the pharmacosiderite (ID No. P) batch contact test was mistakenly stored in the sample vial for the SFT material (ID No. D) because of poor lighting conditions in the hot cell where the experiments were conducted. The reason for this presumption is that pharmacosiderite, which exhibited extremely high selectivity for ^{90}Sr at the low phase ratio, was found to be the third best at the high phase ratio. The pharmacosiderite is an ion exchange material specifically developed by Texas A&M for ^{90}Sr removal.

4.2.2 Strontium Loading

The average ^{90}Sr loading at the phase ratios 10^4 and 10^5 are shown in Figures 4.9 and 4.10, respectively, for all the ion exchangers examined in this study. The data in both figures, as was the case with the cesium data, show a “boomerang” type profile, indicating that although the strontium concentration in the solution phase decreases, the extent of loading of the exchangers is not significantly affected. The explanation for this behavior is the same as that presented earlier for the cesium ion loading data. If one assumes a typical ion exchange capacity of 1 mmol/g for the exchangers, from Figures 4.4 and 4.5 it appears that the maximum amount of ^{90}Sr loaded on the exchangers is less than 0.1% and 1% of the total ion exchange capacity at the phase ratios of 10^4 and 10^5 , respectively. This is due to the fact that although the ion exchange capacity of the exchanger may be high, the ^{90}Sr loading cannot exceed C_i times the phase ratio. This condition was the same with the cesium ion uptake.

Figure 4.9. Strontium-90 Loading on Exchangers at a Phase Ratio of 10^4 as a Function of the Final ^{90}Sr Concentration in the Contact Solution Following the Batch Equilibrium Test

Figure 4.10. Strontium-90 Loading on Exchangers at a Phase Ratio of 10^5 as a Function of the Final ^{90}Sr Concentration in the Contact Solution Following the Batch Equilibrium Test

4.2.3 Strontium Lambda

The computed ^{90}Sr λ values of the few ion exchange materials for which the bed densities were measured are listed in Tables 4.3 and 4.4 at the two different phase ratios of 10^4 and 10^5 , respectively. The computed values in these tables are based on the average values of K_d obtained from the duplicate runs. As with the cesium lambda data, the data in these tables are for comparison purposes only and should not be used for process flowsheet development. At a phase ratio of 10^4 , the ^{90}Sr λ data in Table 4.3 indicate that the sodium nonatitanate material (Texas A&M) shows the best performance, processing over 10^6 volumes of the K-Basin water per unit volume of the exchanger bed. The performance of all other exchangers is close to two orders of magnitude smaller. The data in Table 4.4, in contrast, shows a smaller delineation in the ^{90}Sr λ values, with all values (except for sodium nonatitanate)

Table 4.3. Experimentally Determined ^{90}Sr λ at a Phase Ratio of 10^4

Ion Exchanger	Final ^{90}Sr Conc. [M]	Avg. ^{90}Sr K_d [mL Sol/g Exch.]	Bed Density [g Exch/mL of Exch. Bed]	^{90}Sr λ [mL Sol/mL of Exch. Bed]
IONSIV® IE -911	2.06E-08	9.72E04	8.50E-01	8.26E04
Clinoptilolite	1.92E-08	9.03E04	9.50E-01	8.58E04
Cs-Treat	5.86E-08	2.17E04	5.20E-01	1.13E04
Sr-Treat	2.04E-08	9.10E04	7.10E-01	6.46E04
Sodium Nonatitanate (Texas A&M)	1.03E-09	1.83E06	8.40E-01	1.54E06

Table 4.4. Experimentally Determined ^{90}Sr λ at a Phase Ratio of 10^5

Ion Exchanger	Final ^{90}Sr Conc. [M]	Avg. ^{90}Sr K_d [mL Sol/g Exch.]	Bed Density [g Exch/mL of Exch. Bed]	^{90}Sr λ [mL Sol/mL of Exch. Bed]
IONSIV® IE -911	4.39E-08	3.63E05	8.50E-01	3.08E05
Clinoptilolite	4.72E-08	3.16E05	9.50E-01	3.00E05
Cs-Treat	6.85E-08	1.83E05	5.20E-01	9.49E04
Sr-Treat	4.72E-08	2.96E05	7.10E-01	2.10E05
Sodium Nonatitanate (Texas A&M)	3.95E-08	3.69E05	8.40E-01	3.10E05

being greater than the corresponding data in Table 4.3. Such anomalous behavior is attributed to the strong dependence of the K_d data on the phase ratio, as discussed in Section 4.2.1.

4.3 Transuranic Element Uptake Results

Filtrating the 105-KE Basin water prior to the batch contact tests caused the transuranic element concentrations to be below the detection limit. Therefore, the exchangers' performance in removing TRU elements could not be assessed in this study.

5.0 Conclusions

This report evaluates 14 inorganic ion exchange materials for their performance in removing cesium, strontium, and TRU elements from actual 105-KE Basin water. The water used in this study was obtained from the bottom of the 105-KE Basin and contained significant quantities of sludge and fuel pellets that were filtered before conducting the batch contact testing. The water also contained significantly higher concentrations of radioactive cesium and strontium as compared to the samples taken from the top of the 105-KE Basin.

For ^{137}Cs removal, the KCoHex (potassium cobalt hexacyanoferrate) and SZ-72 (modified zirconate) ion exchange materials, developed by 3M and Texas A&M, respectively, showed the best performance by removing over 99% of the ^{137}Cs from the 105-KE Basin water at a phase ratio of 10^4 . In comparison to the commercial materials used for cesium removal, the performance of KCoHex was better than the IONSIV® IE-911 and clinoptilolite by one order and six orders of magnitude, respectively, in the neutral pH 105-KE Basin water. The modified zirconate (SZ-72) material developed by Texas A&M also performed better than the commercial exchangers in removing cesium from 105-KE Basin water. For ^{90}Sr removal, in contrast, the pharmacosiderite and sodium nonatitanate ion exchange materials, both developed by Texas A&M, showed the best performance by removing over 99% of the strontium at a phase ratio of 10^4 . Presently, no commercial materials for strontium removal have been identified for comparison to the performance of the newly developed materials. Filtrating the 105-KE Basin water before conducting the batch contact tests caused the transuranic element concentrations to be below the detection limit. Therefore, the exchangers' performance in removing the TRU elements could not be assessed in this study.

The data presented in this report are useful for identifying materials with the potential to remove cesium and strontium from 105-KE Basin water. The data show the relative selectivities of the ion exchange materials under similar operating conditions. Additional flow studies are needed to predict the materials' capacities and to develop complete ion exchange process flow sheets.

6.0 References

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Appendix A

K-Basin Milestones from the Hanford Federal Facility Agreement and Consent Order

Appendix A

K-Basin Milestones from the Hanford Federal Facility Agreement and Consent Order

Table A.1 lists Hanford Federal Facility Agreement and Consent Order (Tri-Party Agreement) milestones associated with the K-Basins and their due dates for completion.

Table A.1. Major and Interim Milestones

Number	Milestone	Due Date
M-34-00	Complete actions specified by agreed interim milestones related to remediation of K-East Basin.	TBD
M-34-00-T01	Issue Notice of Intent for N-Reactor fuel EIS.	06/30/1994
M-34-00-T02	Initiate K-East Basin fuel encapsulation.	06/30/1994
M-34-00-T03	Submit an engineering study to determine the feasibility of moving and temporarily storing K-East fuel and sludge (once encapsulated) to the K-West basin.	09/30/1994
M-34-00-T04	Submit a schedule describing activities for the final disposition of contaminated K-East basin water for planning purposes to support the 100-KR-4 record of decision.	10/31/1994
M-34-00-T05	DOE shall provide a schedule for fuel and sludge encapsulation and contaminated water removal or replacement to Ecology and EPA that supports the TPA milestone.	03/31/1995
M-34-00-T06	Initiate K-East Basin sludge encapsulation.	06/30/1996
M-34-00-T07	Complete encapsulation of the fuel and sludge within K-East Basin.	12/31/1998
M-34-00-T08	Remove all fuel and sludge from K-East and K-West Basins in an encapsulated form.	12/31/2002

Table A.1. (contd)

Number	Milestone	Due Date
M-34-01	<p>Contaminated K-East Basin water will be removed, replaced, or treated. The timing of this action must be coordinated with the cleaning of the residual contamination in the basin and (as noted below) the alternative is dependant on the feasibility of moving encapsulated K-East Basin fuel and sludge to the K-West Basin. The contaminated water will be dispositioned in accordance with reasonable available Hanford Site treatment and/or disposal processes and methods, available at the time of this action. Unless a better option becomes available, the water will be trucked to C-018 (ETF) for disposal. If the K-East fuel and sludge, once encapsulated, can be moved to the K-West Basin (determined through a September 1994 engineering study target date) the removal and disposal of the contaminated water will be completed by September 2000. This date is an eighteen month action starting March 1999, three months after the fuel and sludge encapsulation is completed. If the transfer of the encapsulated K-East basin fuel to the K-West Basin is infeasible, contaminated K-East Basin water will be replaced by fresh water, starting September 1996 at a rate of 2 million gallons per year and will continue until such time that the tritium concentration in the basin is decreased and is maintained at or below 300,000 pCi/L (the goal is to reduce the tritium concentration in the basin such that resulting ground water tritium concentration meet drinking water standards, recognizing a lag between basin and groundwater concentrations).</p>	TBD
M-34-02	<p>Initiated negotiations with Ecology and EPA on incorporation of transition activities including stabilization of the basins, consistent with Section 3.1 of the agreement (as amended) and the record of decision regarding long term storage and ultimate disposition of the irradiated fuel. DOE will submit a signed Tri-Party Agreement Change Request milestones for: 1) the completion of removal of fuel and sludge from the k-basins and 2) the completion of stabilization of the basins.</p>	06/30/1996

Appendix B

Water and Air Quality Standards and Guidelines

Appendix B

Water and Air Quality Standards and Guidelines

This appendix presents the water and air quality standards, criteria, and guidelines that may be applicable for disposing of the treated K-Basin water to the ETF, Columbia River, soil or air. The guidelines reported here for disposing of the K-Basin water at the ETF are taken from reports prepared by Bechtel Hanford Incorporated for the U.S. Department of Energy (DOE) (BHI 1994 and 1995); and those for disposing of the K-Basin water into the Columbia River, ground, or air were taken from a report prepared by Westinghouse Hanford Company, also for DOE (WHC 1994). Also, since the K-Basin water contains very little or no organic contaminants (WHC 1994) and the primary concern of this study is the ion exchange of the radioactive constituents, only the limits for the radioactive contaminants are presented. Table B.1 lists the guidelines for disposing of the K-Basin water to the ETF, Columbia River, ground, or air.

Table B.1. Maximum Acceptable Radionuclide Concentrations at Various Discharge Locations

Contaminant	200 Area ETF ^(a)	River Discharge Levels ^(c)		Soil Discharge ^(c,f)	Air Discharge ^(c,g)
		Chronic ^(d)	Ambient ^(e)		
	Conc. (Ci) ^(b)	Conc. (pCi/L)	Conc. (pCi/L)	Conc. (pCi/g)	Conc. (Ci/m ³)
²⁴¹ Am	5.20E-01	3.00E+01		1.20E+00	2.00E-15
²⁴² Cm		1.00E+03		4.00E+01	
²⁴⁴ Cm	1.00E+00	6.00E+01		2.40E+02	
⁶⁰ Co	2.80E+02	1.00E+04		4.00E+02	8.00E-12
¹³⁴ Cs	4.20E+01	2.00E+03		8.00E+01	2.00E-11
¹³⁷ Cs	6.00E+01	3.00E+03		1.20E+02	4.00E-11
³ H	1.00E+03	2.00E+06	3.74E+02	2.00E+04	1.00E-08
⁴⁰ K	1.70E+02	7.00E+03		2.80E+02	9.00E-11
⁵⁴ Mn	8.80E+02	5.00E+04		2.00E+03	2.00E-10
²¹⁰ Pb		3.00E+00		1.20E+00	9.00E-14
²³⁸ Pu	6.20E-01	4.00E+01	1.32E-01	1.60E+00	3.00E-15

Table B.1. (contd)

Contaminant	200 Area ETF ^(a)	River Discharge Levels ^(c)		Soil Discharge ^(c,f)	Air Discharge ^(c,g)
		Chronic ^(d)	Ambient ^(e)		
	Conc. (Ci) ^(b)	Conc. (pCi/L)	Conc. (pCi/L)	Conc. (pCi/g)	Conc. (Ci/m ³)
^{239/240} Pu	5.20E-01	3.00E+01	7.00E-02	1.20E+00	2.00E-15
Radium		1.00E+02	1.42E-01	4.00E+00	1.00E-13
¹⁰⁶ Ru	1.00E+02	6.00E+03		2.40E+02	3.00E-12
¹²⁵ Sb	1.20E+02	5.00E+04		2.00E+03	1.00E-10
⁹⁰ Sr	1.60E+01	1.00E+03	3.48E-01	5.00E+00	9.00E-12
²³⁴ U	4.20E+00	5.00E+02		2.00E+01	9.00E-15
²³⁵ U	4.20E+00	6.00E+02		2.00E+01	9.00E-15
²³⁸ U	4.20E+00	6.00E+02		2.40E+01	1.00E-14

(a) From BHI (1994 and 1995).

(b) The limit indicates the maximum allowable activity of the species in the total ETF inventory. For inventories of multiple isotopes, DOE-RL Waste Management Program requires that the sum of the ratios of the isotopes in the inventory to the limits in Table B.1 not exceed 1.0.

(c) From WHC (1994).

(d) Chronic concentrations indicate concentration limits that produce long-term effects in aquatic life and humans. Many of the chronic toxic criteria are based on the Lowest Observed Effects Level (LOEL) for sensitive aquatic species.

(e) The Department of Ecology and the EPA have developed ambient surface Water Quality Criteria (WQC) designed to prevent adverse effects to aquatic organisms and to humans who may be consuming the aquatic organisms or surface water. Ecology has promulgated surface water regulations pursuant to Chapter 90.48 of the Revised Code of Washington (RCW) Water Pollution Control Act (WPCA). The EPA has established WQC pursuant to its authority under the Clean Water Act of 1977.

(f) Ecology has adopted regulations (WAC 173-200) pursuant to WPCA that set forth standards for protection of groundwater. The purpose of these standards is to establish criteria that must not be exceeded to protect existing and potential future uses of groundwater.

(g) Air emissions of radionuclides at the Hanford Site are regulated under 40 CFR Part 61, Subpart H (EPA 1989). These regulations specify that the combined effective dose to the maximally exposed member of the public from all sources of emissions at each DOE facility must be less than 10 mrem/year, paralleling the standard established by DOE under DOE Order 5400.5.

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Appendix C

105-K East Basin Batch Test Raw Data at Variable Phase Ratios

105-K East Basin Batch Test Raw Data at Variable Phase Ratios

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Appendix C
105-K East Basin Batch Test Raw Data at Variable Phase Ratios
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Batch Distribution Data Collection Sheet
Prepared by GN Brown: 9/30/97 1:54 PM

Ion Exchanger ID Number	D	D	D	D	E	E	E	E	G	G	G	G
Material	SFT	SFT	SFT	SFT	EB-Ph-1	EB-Ph-1	EB-Ph-1	EB-Ph-1	Biotite #15D	Biotite #15D	Biotite #15D	Biotite #15D
Vendor/Supplier	TAMU	TAMU	TAMU	TAMU	TAMU	TAMU	TAMU	TAMU	AlliedSignal	AlliedSignal	AlliedSignal	AlliedSignal
LRB ID Number	AN-01-D1	AN-01-D2	AN-02-D1	AN-02-D2	AN-01-E1	AN-01-E2	AN-02-E1	AN-02-E2	AN-01-G1	AN-01-G2	AN-02-G1	AN-02-G2
Analytical Method	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90
Waste Solution	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin
Solution ID	KE-Basin Water				KE-Basin Water				KE-Basin Water			
Analysis Date	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97
Start date	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97
Stop date	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97
Total time, Days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days
Volume, mL or g	970.43	946.64	985.17	1002.63	947.66	947.38	914.98	897.08	940.01	972.09	947.94	975.78
Temperature, °C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C
F-Factor, dry/wet	0.8516	0.8516	0.8516	0.8516	0.8641	0.8641	0.8641	0.8641	0.8811	0.8811	0.8811	0.8811
Sample Weight, g	1.00E-02	1.46E-02	1.06E-01	1.02E-01	1.14E-02	1.06E-02	1.01E-01	9.97E-02	1.06E-02	1.07E-02	1.02E-01	1.01E-01
Phase Ratio	9.68E+04	6.48E+04	9.31E+03	9.87E+03	8.29E+04	8.98E+04	9.06E+03	9.00E+03	8.84E+04	9.11E+04	9.30E+03	9.67E+03
Sr-90 Initial, uCi/mL	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00
Sr-90 Final, uCi/mL	2.78E-01	3.50E-01	1.47E-01	1.47E-01	6.29E-01	6.12E-01	4.45E-02	3.36E-02	7.31E-01	7.64E-01	3.53E-01	2.96E-01
[Sr-90] Initial, mol/L	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07
[Sr-90] Final, mol/L	2.22E-08	2.80E-08	1.18E-08	1.18E-08	5.03E-08	4.89E-08	3.56E-09	2.69E-09	5.84E-08	6.11E-08	2.82E-08	2.37E-08
Sr Batch Kd, mL/g	8.67E+05	4.46E+05	1.68E+05	1.78E+05	2.70E+05	3.04E+05	5.55E+05	7.33E+05	2.29E+05	2.21E+05	6.12E+04	7.80E+04
Sr-90 Loading, mmol/g	1.93E-02	1.25E-02	1.97E-03	2.09E-03	1.36E-02	1.49E-02	1.97E-03	1.97E-03	1.34E-02	1.35E-02	1.73E-03	1.85E-03
Sr DF, Initial/Final	8.63E+00	6.86E+00	1.63E+01	1.63E+01	3.82E+00	3.92E+00	5.39E+01	7.14E+01	3.28E+00	3.14E+00	6.80E+00	8.11E+00
Cs-137 Initial, uCi/mL	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00
Cs-137 Final, uCi/mL	1.25E+00	1.18E+00	6.99E-01	5.98E-01	7.03E-01	7.12E-01	2.56E-01	1.77E-01	1.48E+00	1.52E+00	4.88E-01	5.09E-01
[Cs-137] Initial, mol/L	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07
[Cs-137] Final, mol/L	1.05E-07	9.90E-08	5.86E-08	5.02E-08	5.90E-08	5.97E-08	2.15E-08	1.49E-08	1.24E-07	1.28E-07	4.09E-08	4.27E-08
Cs Batch Kd, mL/g	8.41E+04	6.42E+04	2.31E+04	3.06E+04	2.01E+05	2.14E+05	7.86E+04	1.18E+05	4.71E+04	4.46E+04	3.65E+04	3.59E+04
Cs-137 Loading, mmol/g	8.82E-03	6.36E-03	1.35E-03	1.53E-03	1.18E-02	1.28E-02	1.69E-03	1.75E-03	5.85E-03	5.68E-03	1.49E-03	1.53E-03
Cs DF, Initial/Final	1.74E+00	1.84E+00	3.11E+00	3.64E+00	3.09E+00	3.05E+00	8.50E+00	1.23E+01	1.47E+00	1.43E+00	4.46E+00	4.27E+00
Cs-134 Initial, uCi/mL	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04
Cs-134 Final, uCi/mL	2.60E-04	2.31E-04	1.58E-04	1.15E-04	1.15E-04	1.23E-04	6.00E-05	5.27E-05	3.44E-04	2.91E-04	1.07E-04	1.23E-04
[Cs] Initial, mol/L	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12
[Cs] Final, mol/L	3.73E-12	3.32E-12	2.27E-12	1.65E-12	1.65E-12	1.77E-12	8.61E-13	7.56E-13	4.94E-12	4.18E-12	1.54E-12	1.77E-12
Cs Batch Kd, mL/g	5.40E+04	5.03E+04	1.56E+04	2.71E+04	2.24E+05	2.20E+05	5.65E+04	6.53E+04	1.15E+04	3.29E+04	2.73E+04	2.33E+04
Cs Loading, mmol/g	2.01E-07	1.87E-07	3.54E-08	4.47E-08	3.70E-07	3.89E-07	4.87E-08	4.94E-08	5.69E-08	1.37E-07	4.19E-08	4.10E-08
Cs DF, Initial/Final	1.48E+00	1.66E+00	2.43E+00	3.33E+00	3.33E+00	3.12E+00	6.39E+00	7.28E+00	1.11E+00	1.32E+00	3.58E+00	3.12E+00
Co-60 Initial, uCi/mL	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04
Co-60 Final, uCi/mL	1.42E-04	1.66E-04	6.95E-05	6.30E-05	1.64E-04	1.43E-04	4.00E-05	3.00E-05	1.30E-04	1.49E-04	5.24E-05	4.94E-05
[Co] Initial, mol/L	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12
[Co] Final, mol/L	2.08E-12	2.43E-12	1.02E-12	9.21E-13	2.40E-12	2.09E-12	5.85E-13	4.39E-13	1.90E-12	2.18E-12	7.66E-13	7.22E-13
Co Batch Kd, mL/g	-2.21E-11	-1.10E+04	1.14E+04	1.45E+04	-1.29E+04	-7.27E+02	2.67E+04	3.89E+04	9.26E+03	-4.86E+03	1.81E+04	2.06E+04
Co Loading, mmol/g	-4.59E-23	-2.67E-08	1.16E-08	1.34E-08	-3.09E-08	-1.52E-09	1.56E-08	1.70E-08	1.76E-08	-1.06E-08	1.38E-08	1.49E-08
Co DF, Initial/Final	1.00E+00	8.55E-01	2.04E+00	2.25E+00	8.66E-01	9.93E-01	3.55E+00	4.73E+00	1.09E+00	9.53E-01	2.71E+00	2.87E+00

Appendix C
105-K East Basin Batch Test Raw Data at Variable Phase Ratios

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Batch Distribution Data Collection Sheet
 Prepared by GN Brown: 9/30/97 1:54 PM

Ion Exchanger ID Number	H	H	H	H	I	I	I	I	J	J	J	J
Material	Biotite #32A	Biotite #32A	Biotite #32A	Biotite #32A	NaTi #152	NaTi #152	NaTi #152	NaTi #152	CsTreat	CsTreat	CsTreat	CsTreat
Vendor/Supplier	AlliedSignal	AlliedSignal	AlliedSignal	AlliedSignal	AlliedSignal	AlliedSignal	AlliedSignal	AlliedSignal	Selion	Selion	Selion	Selion
LRB ID Number	AN-01-H1	AN-01-H2	AN-02-H1	AN-02-H2	AN-01-I1	AN-01-I2	AN-02-I1	AN-02-I2	AN-01-J1	AN-01-J2	AN-02-J1	AN-02-J2
Analytical Method	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90
Waste Solution	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin
Solution ID	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water
Analysis Date	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97
Start date	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97
Stop date	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97
Total time, Days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days
Volume, mL or g	921.41	932.55	941.68	940.81	1008.24	1056.23	1042.56	920.91	986.65	968.69	965.67	873.02
Temperature, °C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C
F-Factor, dry/wet	0.7781	0.7781	0.7781	0.7781	0.9628	0.9628	0.9628	0.9628	0.9558	0.9558	0.9558	0.9558
Sample Weight, g	9.94E-03	1.06E-02	1.02E-01	1.03E-01	1.39E-02	1.19E-02	1.07E-01	1.05E-01	9.54E-03	1.07E-02	1.00E-01	1.02E-01
Phase Ratio	9.27E+04	8.82E+04	9.21E+03	9.10E+03	7.26E+04	8.85E+04	9.72E+03	8.76E+03	1.03E+05	9.03E+04	9.63E+03	8.59E+03
Sr-90 Initial, uCi/mL	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00
Sr-90 Final, uCi/mL	6.59E-01	7.26E-01	4.75E-01	4.57E-01	6.52E-01	4.56E-01	3.88E-01	4.14E-01	8.53E-01	8.61E-01	7.97E-01	6.70E-01
[Sr-90] Initial, mol/L	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07
[Sr-90] Final, mol/L	5.27E-08	5.80E-08	3.80E-08	3.65E-08	5.21E-08	3.65E-08	3.10E-08	3.31E-08	6.82E-08	6.88E-08	6.37E-08	5.36E-08
Sr Batch Kd, mL/g	3.15E+05	2.61E+05	4.80E+04	4.97E+04	2.02E+05	3.92E+05	5.23E+04	4.36E+04	1.96E+05	1.69E+05	2.03E+04	2.32E+04
Sr-90 Loading, mmol/g	1.66E-02	1.52E-02	1.82E-03	1.82E-03	1.05E-02	1.43E-02	1.62E-03	1.44E-03	1.34E-02	1.16E-02	1.29E-03	1.24E-03
Sr DF, Initial/Final	3.64E+00	3.31E+00	5.05E+00	5.25E+00	3.68E+00	5.26E+00	6.19E+00	5.80E+00	2.81E+00	2.79E+00	3.01E+00	3.58E+00
Cs-137 Initial, uCi/mL	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00
Cs-137 Final, uCi/mL	1.88E+00	1.88E+00	7.91E-01	5.12E-01	1.42E+00	1.35E+00	1.09E+00	1.44E+00	8.54E-01	6.92E-01	5.38E-02	4.25E-02
[Cs-137] Initial, mol/L	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07
[Cs-137] Final, mol/L	1.58E-07	1.58E-07	6.64E-08	4.30E-08	1.19E-07	1.13E-07	9.15E-08	1.21E-07	7.17E-08	5.81E-08	4.51E-09	3.57E-09
Cs Batch Kd, mL/g	1.87E+04	1.78E+04	2.07E+04	3.80E+04	4.01E+04	5.62E+04	1.00E+04	4.64E+03	1.67E+05	2.02E+05	3.97E+05	4.51E+05
Cs-137 Loading, mmol/g	2.95E-03	2.81E-03	1.38E-03	1.63E-03	4.78E-03	6.36E-03	9.19E-04	5.61E-04	1.20E-02	1.18E-02	1.79E-03	1.61E-03
Cs DF, Initial/Final	1.16E+00	1.16E+00	2.75E+00	4.25E+00	1.53E+00	1.61E+00	2.00E+00	1.51E+00	2.55E+00	3.14E+00	4.04E+01	5.12E+01
Cs-134 Initial, uCi/mL	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04
Cs-134 Final, uCi/mL	3.70E-04	2.00E-04	1.24E-04	1.01E-04	2.85E-04	3.09E-04	2.72E-04	2.87E-04	1.87E-04	1.04E-04	3.00E-05	3.00E-05
[Cs] Initial, mol/L	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12
[Cs] Final, mol/L	5.31E-12	2.87E-12	1.78E-12	1.45E-12	4.09E-12	4.43E-12	3.90E-12	4.12E-12	2.68E-12	1.49E-12	4.31E-13	4.31E-13
Cs Batch Kd, mL/g	4.35E+03	1.04E+05	2.48E+04	3.27E+04	2.61E+04	2.22E+04	4.14E+03	3.08E+03	1.14E+05	2.54E+05	1.19E+05	1.06E+05
Cs Loading, mmol/g	2.31E-08	2.99E-07	4.41E-08	4.74E-08	1.07E-07	9.83E-08	1.62E-08	1.26E-08	3.05E-07	3.79E-07	5.11E-08	4.56E-08
Cs DF, Initial/Final	1.04E+00	1.92E+00	3.09E+00	3.80E+00	1.35E+00	1.24E+00	1.41E+00	1.34E+00	2.05E+00	3.69E+00	1.28E+01	1.28E+01
Co-60 Initial, uCi/mL	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04
Co-60 Final, uCi/mL	1.37E-04	1.51E-04	9.20E-05	9.14E-05	1.96E-04	9.97E-05	7.00E-05	1.33E-04	1.48E-04	1.37E-04	6.33E-05	4.00E-05
[Co] Initial, mol/L	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12
[Co] Final, mol/L	2.00E-12	2.21E-12	1.35E-12	1.34E-12	2.87E-12	1.46E-12	1.02E-12	1.94E-12	2.16E-12	2.00E-12	9.25E-13	5.85E-13
Co Batch Kd, mL/g	4.35E+03	-6.76E+03	6.44E+03	6.48E+03	-2.08E+04	3.90E+04	1.04E+04	6.15E+02	-4.39E+03	3.45E+03	1.25E+04	2.29E+04
Co Loading, mmol/g	8.71E-09	-1.49E-08	8.66E-09	8.66E-09	-5.96E-08	5.69E-08	1.06E-08	1.20E-09	-9.49E-09	6.90E-09	1.16E-08	1.34E-08
Co DF, Initial/Final	1.04E+00	9.40E-01	1.54E+00	1.55E+00	7.24E-01	1.42E+00	2.03E+00	1.07E+00	9.59E-01	1.04E+00	2.24E+00	3.55E+00

Appendix C
105-K East Basin Batch Test Raw Data at Variable Phase Ratios
Page C.4 of C.5

Batch Distribution Data Collection Sheet
Prepared by GN Brown: 9/30/97 1:54 PM

C.4

Ion Exchanger ID Number	L	L	L	L	M	M	M	M	N	N	N	N
Material	SrTreat	SrTreat	SrTreat	SrTreat	M275	M275	M275	M275	SZ-72	SZ-72	SZ-72	SZ-72
Vendor/Supplier	Selion	Selion	Selion	Selion	TAMU	TAMU	TAMU	TAMU	TAMU	TAMU	TAMU	TAMU
LRB ID Number	AN-01-L1	AN-01-L2	AN-02-L1	AN-02-L2	AN-01-M1	AN-01-M2	AN-02-M1	AN-02-M2	AN-01-N1	AN-01-N2	AN-02-N1	AN-02-N2
Analytical Method	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90
Waste Solution	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin
Solution ID	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water	KE-Basin Water
Analysis Date	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97
Start date	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97
Stop date	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97
Total time, Days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days
Volume, mL or g	973.52	974.32	1001.55	980.93	941.22	945.41	975.28	965.46	979.05	968.83	949.10	949.41
Temperature, °C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C
F-Factor, dry/wet	0.9027	0.9027	0.9027	0.9027	0.9449	0.9449	0.9449	0.9449	0.9013	0.9013	0.9013	0.9013
Sample Weight, g	1.13E-02	1.11E-02	1.04E-01	1.00E-01	1.17E-02	1.04E-02	1.02E-01	1.03E-01	1.06E-02	1.32E-02	1.04E-01	1.05E-01
Phase Ratio	8.60E+04	8.80E+04	9.68E+03	9.77E+03	8.03E+04	9.07E+04	9.57E+03	9.34E+03	9.23E+04	7.34E+04	9.12E+03	9.02E+03
Sr-90 Initial, uCi/mL	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00
Sr-90 Final, uCi/mL	5.79E-01	6.01E-01	2.35E-01	2.76E-01	6.39E-01	6.19E-01	1.99E-01	1.36E-01	5.20E-01	4.32E-01	6.56E-02	5.35E-02
[Sr-90] Initial, mol/L	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07
[Sr-90] Final, mol/L	4.63E-08	4.80E-08	1.88E-08	2.21E-08	5.11E-08	4.95E-08	1.59E-08	1.08E-08	4.16E-08	3.45E-08	5.24E-09	4.28E-09
Sr Batch Kd, mL/g	3.00E+05	2.92E+05	9.87E+04	8.33E+04	2.34E+05	2.76E+05	1.12E+05	1.65E+05	3.70E+05	3.71E+05	3.60E+05	4.39E+05
Sr-90 Loading, mmol/g	1.39E-02	1.40E-02	1.86E-03	1.84E-03	1.20E-02	1.37E-02	1.78E-03	1.79E-03	1.54E-02	1.28E-02	1.89E-03	1.88E-03
Sr DF, Initial/Final	4.15E+00	3.99E+00	1.02E+01	8.70E+00	3.76E+00	3.88E+00	1.21E+01	1.77E+01	4.62E+00	5.56E+00	3.66E+01	4.49E+01
Cs-137 Initial, uCi/mL	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00
Cs-137 Final, uCi/mL	1.82E+00	1.77E+00	7.26E-01	8.97E-01	1.30E+00	1.55E+00	5.67E-01	5.50E-01	6.99E-01	5.81E-01	1.64E-02	1.75E-02
[Cs-137] Initial, mol/L	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07
[Cs-137] Final, mol/L	1.53E-07	1.49E-07	6.09E-08	7.53E-08	1.09E-07	1.30E-07	4.76E-08	4.61E-08	5.86E-08	4.87E-08	1.38E-09	1.47E-09
Cs Batch Kd, mL/g	1.86E+04	2.23E+04	2.14E+04	1.54E+04	5.72E+04	3.87E+04	2.87E+04	2.92E+04	2.16E+05	2.23E+05	1.33E+06	1.23E+06
Cs-137 Loading, mmol/g	2.84E-03	3.31E-03	1.30E-03	1.16E-03	6.24E-03	5.04E-03	1.37E-03	1.35E-03	1.27E-02	1.09E-02	1.83E-03	1.81E-03
Cs DF, Initial/Final	1.20E+00	1.23E+00	3.00E+00	2.42E+00	1.67E+00	1.40E+00	3.84E+00	3.95E+00	3.11E+00	3.74E+00	1.33E+02	1.24E+02
Cs-134 Initial, uCi/mL	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04
Cs-134 Final, uCi/mL	2.22E-04	2.77E-04	1.08E-04	1.36E-04	2.75E-04	2.17E-04	9.18E-05	7.79E-05	1.06E-04	1.05E-04	2.00E-05	2.00E-05
[Cs] Initial, mol/L	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12
[Cs] Final, mol/L	3.19E-12	3.98E-12	1.55E-12	1.95E-12	3.95E-12	3.11E-12	1.31E-12	1.12E-12	1.52E-12	1.51E-12	2.87E-13	2.87E-13
Cs Batch Kd, mL/g	6.93E+04	3.75E+04	2.73E+04	1.97E+04	3.35E+04	7.37E+04	3.23E+04	3.88E+04	2.68E+05	2.16E+05	1.84E+05	1.82E+05
Cs Loading, mmol/g	2.21E-07	1.49E-07	4.24E-08	3.84E-08	1.32E-07	2.29E-07	4.24E-08	4.33E-08	4.08E-07	3.25E-07	5.28E-08	5.22E-08
Cs DF, Initial/Final	1.73E+00	1.38E+00	3.55E+00	2.82E+00	1.39E+00	1.77E+00	4.19E+00	4.92E+00	3.62E+00	3.65E+00	1.92E+01	1.92E+01
Co-60 Initial, uCi/mL	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04
Co-60 Final, uCi/mL	1.51E-04	1.49E-04	1.01E-04	1.01E-04	1.26E-04	1.25E-04	3.00E-05	3.00E-05	1.51E-04	1.11E-04	2.00E-05	2.00E-05
[Co] Initial, mol/L	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12
[Co] Final, mol/L	2.21E-12	2.18E-12	1.48E-12	1.48E-12	1.84E-12	1.83E-12	4.39E-13	4.39E-13	2.21E-12	1.62E-12	2.92E-13	2.92E-13
Co Batch Kd, mL/g	-5.68E+03	-4.58E+03	4.35E+03	4.39E+03	1.08E+04	1.31E+04	3.78E+04	3.69E+04	-6.10E+03	2.27E+04	6.17E+04	6.10E+04
Co Loading, mmol/g	-1.25E-08	-9.98E-09	6.43E-09	6.49E-09	1.99E-08	2.39E-08	1.66E-08	1.62E-08	-1.35E-08	3.69E-08	1.80E-08	1.78E-08
Co DF, Initial/Final	9.40E-01	9.53E-01	1.41E+00	1.41E+00	1.13E+00	1.14E+00	4.73E+00	4.73E+00	9.40E-01	1.28E+00	7.10E+00	7.10E+00

Appendix C
105-K East Basin Batch Test Raw Data at Variable Phase Ratios
Page C.5 of C.5

Batch Distribution Data Collection Sheet
Prepared by GN Brown: 9/30/97 1:54 PM

Ion Exchanger ID Number	P	P	P	P	Q	Q	Q	Q
Material	Pharm AIB-TS255		Pharm AIB-TS255		NaTi #GMG-1-1		NaTi #GMG-1-1	
Vendor/Supplier	TAMU	TAMU	TAMU	TAMU	TAMU	TAMU	TAMU	TAMU
LRB ID Number	AN-01-P1	AN-01-P2	AN-02-P1	AN-02-P2	AN-01-Q1	AN-01-Q2	AN-02-Q1	AN-02-Q2
Analytical Method	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90	GEA, Sr-90
Waste Solution	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin	KE-Basin
Solution ID	KE-Basin Water		KE-Basin Water		KE-Basin Water		KE-Basin Water	
Analysis Date	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97	4/10/97
Start date	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97	3/8/97
Stop date	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97	3/20/97
Total time, Days	12 days	12 days	12 days	12 days	12 days	12 days	12 days	12 days
Volume, mL or g	937.03	968.10	883.51	1033.65	975.79	1020.65	914.23	970.33
Temperature, °C	23°C	23°C	23°C	23°C	23°C	23°C	23°C	23°C
F-Factor, dry/wet	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Sample Weight, g	9.69E-03	1.01E-02	1.07E-01	1.05E-01	1.04E-02	1.05E-02	1.06E-01	1.04E-01
Phase Ratio	9.67E+04	9.57E+04	8.24E+03	9.81E+03	9.39E+04	9.71E+04	8.66E+03	9.29E+03
Sr-90 Initial, uCi/mL	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00
Sr-90 Final, uCi/mL	5.38E-01	4.60E-01	3.17E-03	7.08E-03	4.69E-01	5.20E-01	8.77E-03	1.69E-02
[Sr-90] Initial, mol/L	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07	1.92E-07
[Sr-90] Final, mol/L	4.30E-08	3.68E-08	2.53E-10	5.66E-10	3.75E-08	4.16E-08	7.01E-10	1.35E-09
Sr Batch Kd, mL/g	3.35E+05	4.03E+05	6.23E+06	3.31E+06	3.87E+05	3.51E+05	2.36E+06	1.31E+06
Sr-90 Loading, mmol/g	1.44E-02	1.48E-02	1.58E-03	1.88E-03	1.45E-02	1.46E-02	1.65E-03	1.77E-03
Sr DF, Initial/Final	4.46E+00	5.22E+00	7.57E+02	3.39E+02	5.12E+00	4.62E+00	2.74E+02	1.42E+02
Cs-137 Initial, uCi/mL	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00	2.18E+00
Cs-137 Final, uCi/mL	4.51E-01	3.54E-01	4.29E-02	5.17E-02	1.88E+00	1.51E+00	3.08E-01	3.10E-01
[Cs-137] Initial, mol/L	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07	1.82E-07
[Cs-137] Final, mol/L	3.78E-08	2.97E-08	3.60E-09	4.34E-09	1.58E-07	1.27E-07	2.58E-08	2.60E-08
Cs Batch Kd, mL/g	3.70E+05	4.92E+05	4.09E+05	4.03E+05	1.47E+04	4.28E+04	5.25E+04	5.59E+04
Cs-137 Loading, mmol/g	1.40E-02	1.46E-02	1.47E-03	1.75E-03	2.32E-03	5.42E-03	1.36E-03	1.45E-03
Cs DF, Initial/Final	4.82E+00	6.14E+00	5.07E+01	4.21E+01	1.16E+00	1.44E+00	7.06E+00	7.02E+00
Cs-134 Initial, uCi/mL	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04	3.84E-04
Cs-134 Final, uCi/mL	8.95E-05	6.48E-05	2.00E-05	3.00E-05	3.56E-04	3.54E-04	4.00E-05	5.42E-05
[Cs] Initial, mol/L	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12	5.50E-12
[Cs] Final, mol/L	1.28E-12	9.30E-13	2.87E-13	4.31E-13	5.11E-12	5.08E-12	5.74E-13	7.78E-13
Cs Batch Kd, mL/g	3.18E+05	4.70E+05	1.50E+05	1.16E+05	7.25E+03	8.09E+03	7.43E+04	5.64E+04
Cs Loading, mmol/g	4.08E-07	4.38E-07	4.30E-08	4.97E-08	3.71E-08	4.11E-08	4.27E-08	4.39E-08
Cs DF, Initial/Final	4.28E+00	5.92E+00	1.92E+01	1.28E+01	1.08E+00	1.08E+00	9.59E+00	7.08E+00
Co-60 Initial, uCi/mL	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04	1.42E-04
Co-60 Final, uCi/mL	1.49E-04	1.20E-04	2.00E-05	2.00E-05	6.18E-05	9.00E-05	4.00E-05	7.62E-05
[Co] Initial, mol/L	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12	2.08E-12
[Co] Final, mol/L	2.18E-12	1.75E-12	2.92E-13	2.92E-13	9.04E-13	1.32E-12	5.85E-13	1.11E-12
Co Batch Kd, mL/g	-4.54E+03	1.75E+04	5.02E+04	5.98E+04	1.22E+05	5.81E+04	2.21E+04	8.02E+03
Co Loading, mmol/g	-9.90E-09	3.08E-08	1.47E-08	1.75E-08	1.10E-07	7.38E-08	1.29E-08	8.94E-09
Co DF, Initial/Final	9.53E-01	1.18E+00	7.10E+00	7.10E+00	2.30E+00	1.58E+00	3.55E+00	1.86E+00

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