WSRC-TR-2002-00257
SRT-RPP-2002-00133

KEYWORDS:
Hanford River Protection Project
Cesium
SuperLig
Residence time

Evaluating Residence Time for SuperLig ® 644 Columns with Simulated LAW Envelope C (AN-107) Solution (U)

SAVANNAH RIVER TECHNOLOGY CENTER

Neguib M. Hassan
Charles A. Nash

Publication Date: October 15, 2002

Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

Prepared for the U.S. Department of Energy under Contract No. DE-AC09-96SR18500

This page intentionally left blank

Contents

List of Tables

List of Figures

Abstract

A series of batch contact and column tests were conducted with new and aged Envelope C (AN-107) simulant using SuperLig® 644 resin. In addition to the batch contact tests, four column loading and elution tests were performed with aged Envelope C (AN-107) simulant to evaluate the effects of volumetric flow rate on cesium sorption. A single-column (2.7 cm i.d.) containing ~ 100 mL of SuperLig 644® resin was used. The column test results show more than 100 BVs of simulated AN-107 feed can be processed at nominal flow rate of 3 BV/h before reaching 50% cesium breakthrough at the column outlet. The results from the column tests also revealed that iron was loaded onto the SuperLig® 644 resin. Since only small quantity of iron (~ 26 ppm) is present in AN-107 simulant, the presence of iron had obviously no impact on the cesium loading on SuperLig® 644 resin. Further monitoring of iron loading in the full-height pilot testing is recommended to understand the long-term impact of residual iron on resin stability.

The first series of batch contact tests were aimed to determine the distribution coefficients (K_d) for cesium at various concentration levels (10.4, 74, and 131 mg/L). The lower concentration (10.4 mg/L) was likely to be encountered based on Best Basis Inventory data for Envelope C (AN-107) supernates. The high cesium concentrations (~74 and 131 mg/L) were selected with the purpose of promoting particle diffusion control. The results showed that the cesium K_d values generally decreased with increasing initial concentration levels.

A second series of batch contact tests were performed with fresh AN-107 simulant to determine the impact of AN-107 post-Sr/TRU filtration precipitation solids formation on the cesium ion exchange. The cesium K_ds for the fresh simulant were comparable to those of the aged AN-107 in the same concentration ranges. The test results, therefore, did not reveal an impact of post-filtration solids formation on the cesium sorption.

The final series of the batch contact tests were conducted to evaluate the extent of co-sorption of uranium on the resin. The results from the present tests revealed that the uranium is sorbed onto the SuperLig® 644 resin. The ^{238}U K_d for AN-107 simulant containing 3.7 mg/L of ^{238}U at cesium concentration levels of 10.4 and 68 mg/L were 540 and 708 mL/g, respectively. The cause of the increase in ^{238}U K_d at higher cesium concentration is unknown. Further monitoring of uranium sorption on SuperLig® 644 resin during AW-101 processing is recommended.
.

Nomenclature

AN-107	Hanford Site Tank 241-AN-107
ADS	Analytical Development Section
BV	Bed volume
C/Co	Metal concentration in the column effluent divided by the metal concentration in feed
DF	Decontamination factors
DI	De-ionized water
F-Factor	Mass of oven-dry resin divided by the mass of air-dry resin
IV29	SuperLig® 644 batch # 991022SMC-IV29
IC	Ion chromatography
ICP-AES	Inductively coupled plasma/atomic emission spectroscopy
ICP-MS	Inductively coupled plasma/mass spectroscopy
K_d	Equilibrium distribution coefficient
PNNL	Pacific Northwest National Laboratory
RPP-WTP	River Protection Project – Waste Treatment Plant
RSD	Relative standard deviation
SRTC	Savannah River Technology Section
TAV	Total apparatus volume
TIC	Total inorganic carbon
TOC	Total organic carbon

1.0 Summary of Results

1.1 Objectives: The objectives of this test were the following:

- Evaluate the ion exchange column performance of SuperLig® 644 resin with Envelope C (AN-107) simulant at three volumetric flow rates.
- Determine the extent of uranium (added depleted uranium as uranyl nitrate $UO_2(NO_3)_2$) co-sorption by SuperLig® 644 during the cesium ion exchange process.
- Assess the potential impact of post-filtration solids on the ion exchange process using Envelope C (AN-107) simulant solution derived from the strontium and transuranic precipitation process

1.2 Conduct of Tests

The experiments consisted of batch contact and column tests. Column tests were performed at three volumetric flow rates (1.5, 3, and 18 BV/h) to examine the impact of residence time on the column loading. The approximate (relative) residence times corresponding to the flow rates of 1.5, 3, and 18 BV/h or superficial velocities 0.44, 0.87, and 5.2 cm/min were 40, 20, and 3.3 minutes at ~100 ml bed.

The batch contact tests were performed with two batches of dry, H-form SuperLig® 644 resin (batch # 991022SMC-IV29 and "50 Liter" batch) and aged Envelope C simulant at three cesium concentrations (~ 10.4, 74, and 131 mg/L). Two additional series batch contact tests were performed with aged and fresh Envelope C simulants. The series of batch contact tests with fresh AN-107 simulant was aimed to assess the potential impact of post-filtration solids. The other series of batch contact tests with aged simulant were performed to determine the extent of uranium co-sorption during cesium ion exchange.

The experiments were performed according to the "Task Technical and Quality Assurance Plan for Evaluating the Residence Time for SuperLig® 644 and SuperLig® 639 Columns with Simulated Envelope C Solution" (WSRC-TR-2001-00465, SRT-RPP-2000-00163, Rev. 0). The Task Plan was generated from the "Task Specification for Evaluating Residence Time for SuperLig® 639 and 644 Columns with Simulated Envelope C Solution" (TSP-W375-01-00022, Rev. 0).

1.3 Results and Performance against Objectives

The first test objective was to evaluate the ion exchange column performance of SuperLig® 644 resin with Envelope C (AN-107) simulant at three different flow rates. The ion exchange column tests determined that the cesium adsorption by SuperLig® 644 resin is dependent on the volumetric flow rate of simulated AN-107 solution. At low flow rates of 1.5 and 3 BV/h (i.e. superficial velocities 0.44 and 0.87 cm/min), more than 100 BVs of the AN-107 simulant was processed before 50% breakthrough of cesium was reached at the column outlet. At the highest

flow rate of 18 BV/h (5.2 cm/min), less than 50 BVs of the simulated AN-107 solution were processed before 50% breakthrough of cesium was reached. Thus, the SuperLig®644 resin column loading was adequate at the nominal flow rate of 3 BV/h (relative residence time 20 min.) and only marginal improvement was achieved at the lower flow rate of 1.5 BV/h. At the highest flow rate of 18 BV/h (relative residence time 3.3 min), the cesium loading on the column deteriorated significantly. The data from these tests will be used in the computer model effort at SRTC to determine if the Envelope C design performance criteria is met and to predict the exit concentration in a carousel of two or three columns.

The second objective was to determine the extent of uranium (added as depleted uranium) co-sorption by SuperLig® 644 during the cesium ion exchange process. The results of this series of batch contact tests determined that the SuperLig® 644 resin has a weaker affinity to complex uranium (UO_2^{2+} ion) as compared to cesium (Cs^+ ion). The average K_d of ^{238}U in AN-107 simulant containing 10.4 mg/L cesium was ~ 540 mL/g vs. cesium K_d value of 1849 mL/g. The ^{238}U K_d increased unexpectedly to 708 mL/g when the concentration of cesium in the simulant was increased to 68 mg/L. Uranium monitoring during multi-cycle AW-101 column loading tests is recommended to determine the impact of uranium co-sorption on SuperLig® 644 resin in full-scale plant columns.

The third objective was to assess the potential impact of post-filtration solids derived from the strontium and transuranic precipitation process on the ion exchange process. The results from this set of batch contact experiments revealed that the cesium K_d values for the fresh and aged AN-107 simulants were 1983 and 1849 mL/g, respectively. Apparently, there was no effect of post-filtration solids in the simulant on the cesium sorption on the SuperLig® 644 resin.

1.4 Quality Requirements

This work was conducted in accordance with the RPP-WTP QA requirements specified for work conducted by SRTC as identified in DOE-IWO MOSRLE60. SRTC has provided matrices to WTP demonstrating compliance of the SRTC QA program with the requirements specified by WTP. Specific information regarding the compliance of the SRTC QA program with RW-0333P, Revision 10, NQA-1 1989, Part 1, Basic and Supplementary Requirements and NQA-2a 1990, Subpart 2.7 is contained in these matrices. The QA requirements were specified in the Task Technical and Quality Assurance Plan for Evaluating Effects of Resin Particle Size and Solution Temperature on SuperLig® 644 and SuperLig® 639 Resins Performance with LAW Envelope C Simulant" (WSRC-TR-2001-00465, SRT-RPP-2000-00163, Rev. 0). Data verification was conducted through independent technical review of the final data report.

2.0 Introduction

SuperLig® 644 (Trademark of IBC Advanced Technologies, American Fork, Utah) was selected as the baseline ion exchange material by River Protection Project Waste Treatment Plant (RPP-WTP) for cesium removal from Hanford tank waste solutions. Earlier work at Battelle Pacific Northwest found the resin has adequate density and low-cycle physical durability[1], sufficient chemical stability[2], and sufficient cesium sorption capacity and selectivity[3]. Recent work[4,5] at Savannah River Technology Center (SRTC) with LAW Envelope A (AN-103) simulant indicated that cesium adsorption by SuperLig® 644 is dependent on liquid superficial velocity during column loading. Acceptable lead column performance (50% breakthrough at 100 column volumes) was attained for this resin at maximum RPP-WTP design basis superficial velocities, but the results indicated that sorption kinetics could be limiting. As a follow-up to this previous work, low activity waste Envelope C (AN-107) simulant derived from the strontium and transuranic precipitation process was tested to verify column operability within the design basis. The residence time of loading solutions in the ion exchange column generally affects uptake whereas the liquid superficial velocity affects kinetics. Therefore, a compromise experimental strategy was taken to match both residence time and superficial velocity in a bench scale experiment. A column of manageable size (~ 100 mL) of suitable diameter (2.7 cm, for a column/particle diameter ratio >30) was selected to meet both design nominal residence times (20 minutes per bed) and nominal superficial velocity (5.92 cm/min).

The strontium/transuranics (Sr/TRU) precipitation step prior to ion exchange has shown the generation of post-filtration precipitate in both AN-107 actual and simulated waste filtrate within 24 hours after filtration.[6] As the solids have generally tended to form on polymer storage bottle walls,[7] concern has arisen that during the post-filtration precipitation process deposits could preferentially form on the organic SuperLig® 644 resin and severely hinder cesium ion exchange capability. In addition, uranium detected in SuperLig® 644 column acid eluates from testing with actual tank 241-AN-102 (Envelope C) solutions suggests the resin has some affinity for uranium, which could potentially compete with cesium for resin adsorption.[8,9]. Similar work for uranium co-sorption studies with Envelopes A and B was regarded as unnecessary due to significantly lower uranium concentrations in those tank solutions.

3.0 Experimental

3.1 Materials

The Envelope C simulant used in the batch contact and column loading tests mimics the composition of Tank 241-AN-107 at the Hanford Site. The simulant was derived from 1999 pilot-scale crossflow filtration tests of the strontium and transuranic precipitation process. Forty-five liters of the produced filtrate were used in the tests. A separate one liter volume of the Envelope C (AN-107) simulate at 5.0M sodium concentration was prepared following the instructions provided by Eibling.[10] The Sr/TRU precipitation was conducted per the Bannochie

documented method.[11] In this method, the simulant was treated with sodium hydroxide, sodium permanganate, and strontium nitrate solutions, then filtered. The post-precipitation filtrate solution was aged for one week, then filtered through a 0.45-μm filter before use in batch contact tests. Duplicate sub-samples of the simulant were analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) to determine concentrations of metal constituents. The compositions of the fresh and aged AN-107 simulants are shown in Table 1.

The ion exchange resin used for the cesium removal from Envelope C (AN-107) simulant in column tests was SuperLig® 644 resin (Trademark of IBC Advanced Technologies, American Fort, Utah). This resin batch (# 991022SMC-IV29) was received in potassium form as 20-70 mesh granules. It was pretreated to remove potassium and other impurities that may have been left from the resin manufacturing process. The resin was then converted into hydrogen form. A mass correction factor (F-factor) was determined for an oven-dried hydrogen form of the resin. A second batch designated as the "50-Liter batch" was also used in batch contact tests to compare the data from the # 991022SMC-IV29 batch. The "50-Liter" batch was received in hydrogen form and stored wet in de-ionized water. The resin was air-dried prior to the K_d tests. Batch contact tests for both resin batches were performed as prescribed by the "Task Technical and Quality Assurance Plan for Evaluating the Residence Time for SuperLig® 639 and 644 Columns with Simulated Envelope C Solution (U)" (WSRC-TR-2001-00465, SRT-RPP-2000-00163, Rev. 0).[12] The Task Plan was generated from the "Task Specification for Evaluating Residence Time for SuperLig® 639 and 644 Columns with Simulated Envelope C Solution" (TSP-W375-01-00022, Rev. 0).[13]

3.2 Equipment

The equipment used for batch contact tests consisted of a benchtop incubator shaker (model C24) supplied by New Brunswick Scientific Co., Edison New Jersey, Nalgene® filter units supplied by Nalgene Nunc International, Rochester, New York, and an analytical balance, (model AG285) obtained from Mettler Toledo. The analytical balance was accurate to ± 0.001 g. A high precision (0.01 ^{o}C) thermometer traceable to NIST calibration was mounted in polyethylene bottles containing de-ionized water to record the temperature in the incubator shaker environment. A house-supplied vacuum and a trap assembly were used during sample filtration. All experiments were performed in a chemical hood.

The equipment for ion exchange column tests consisted of a single glass column, a positive displacement pump, an automatic fraction collector, and a water circulator. The column was constructed from borosilicate glass tubing with 2.7-cm i.d., and a total length of 30 cm. The outside of the column walls was coated with a layer of clear polyvinylchloride to reduce hazards associated with potentially pressurizing the apparatus. The column top assemblies had a fill reservoir, a pressure gauge, a pressure relief valve, and a feed inlet port. The fill reservoir on column top assemblies also served as a vent. The top assembly was connected to the lower section by a ground glass joint and was tightly fitted by a screw cap. A ruler affixed to the column wall was used to allow observation of resin bed height and liquid level changes. All tubing connections were made of polypropylene lines that had Teflon® quick-connect fittings

attached to each end. A 3-way, 6 mm bore Teflon® stopcock was attached to the bottom of the column. The column head was attached to the column using a Rudivis ground-glass joint. Two 2-way, 6 mm bore stopcocks were attached on opposite sides of the column head to serve as feed ports. The column head also contained a pressure gauge, a pressure relief valve, and a fill reservoir that also served as a vent. All solutions were passed as down flow through the column using a Fluid Metering Incorporated (FMI) positive displacement pump. Scilog Inc. Middletown, Wisconsin supplied the pump head (model RH00). It was made of a stainless steel (1/8" i.d.) piston that is driven by a 450 rpm optically encoded, servo-controlled motor. The flow rate range for the pump head/piston configuration was 0-23 mL/min. Samples were collected either manually or using a Spectrum Chromatography IS-95 Interval Sampler.

3.3 Procedure

3.3.1 Resin Pretreatment & F-factor determination

To remove any water-soluble residues, or undesired cations remaining on the resin after the manufacturing process, the resin samples were subjected to pre-treatment. For this purpose the resin was converted by acid-caustic cycles from sodium or potassium to hydrogen form. Approximately 50 grams (± 0.01 g) of SuperLig® 644 (batch # 991022SMC-IV29) was weighed in a high density polyethylene (HDPE) bottle and soaked in a 10:1 phase ratio of 1.0M sodium hydroxide solution for 2 hrs. The resin and sodium hydroxide solution mixture was gently swirled several times. No magnetic bar or mechanical stirrer was used to shake the mixture. This was to avoid breaking up the resin particles and generating fines. The sodium hydroxide solution and resin mixture was slurried into a 1-inch diameter glass column. The excess sodium hydroxide solution was drained and discarded. The resin in the column was washed with 3 bed volumes (BVs) of de-ionized water, followed by 15 BVs of 0.5M nitric acid and 10 BVs of de-ionized water. The resin was removed from the column and dried in a vacuum oven at 50 ± 5 ^{o}C and 24 in Hg. The dry mass of the pretreated resin in hydrogen form was approximately 20 grams.

3.3.2 Batch Contact Tests

The batch contact tests were conducted with simulated Envelope C simulant at three concentration levels (10.4, 74, 131 mg/L). A known volume (~15 ml) of simulated Envelope C (AN-107) solution at each cesium concentration level was added into polyethylene bottles containing a known quantity (~0.15 g) of pretreated, oven-dried, SuperLig® 644 resin in hydrogen form. The batch equilibration tests were conducted in duplicate at 25 ^{o}C using SuperLig® 644 resin, batch # 991022SMC-IV29. The tests were all conducted in duplicate for 24 ± 1 hr. Laboratory control samples (~ i.e. 15 mL of simulant solution in which no resin was added) was treated in identical process steps as the simulant test samples. The concentrations of cesium in the control samples were used as initial concentrations for determination of equilibrium distribution coefficient (K_d values). Sub-samples of the simulant in contact with the resin were removed from the solution after 24 hours and filtered using a 0.45-micron filter. The

samples were analyzed by ICP-MS to determine the concentration of total cesium and by ICP-AES to determine the concentrations of metal cations.

In addition, a second test at 10:1 phase ratio was simultaneously conducted in duplicate with the lowest cesium concentration (~10.4 mg/L). A 10 ± 0.1-mL sample of freshly precipitated and filtered AN-107 (Envelope C) simulant solution was contacted with 1.0 ± 0.01-gram of the "50 liter batch" SuperLig® 644 resin for 120 ± 1 hours at 25 ± 1°C. After 120 ± 1 hours of contacting, the mixture was filtered using a 0.45-μm filter. Small aliquots (100 μL) of the filtrate were withdrawn at 24, 48, 72, and 120 hours and submitted for analysis for Na, K, Cs, and transition metals.

Additional tests were conducted with SuperLig® 644 batch designated as "50 liter batch". IBC Advanced Technologies prepared this batch in May-August 2000 as part of a 150-liter production-scale batch. The bottles containing the solution and the resin were placed in an incubator- shaker. Approximately 15 mL of the simulant was contacted with ~0.15 g of air -dried resin. The batch tests were all conducted in duplicate for 48 ± 1 hr. Laboratory control samples (~ i.e. 15 mL simulant), which contained no resin, were treated in identical process steps as the simulant test samples.

3.3.3 Post-filtration Precipitation Effect- Fresh Simulant

Approximately ~1 L of un-precipitated AN-107 supernate simulant was prepared per the Eibling recipe in WSRC-TR-2000-00338 (SRT-RPP-2000-00017) to a 5 M Na concentration, excluding toxic metals lead and chromium.[10] The simulant was aged for one week at ambient conditions. The day prior to start of batch contacting tests, the simulant was precipitated by adding at 50°C to existing levels: 0.875 M free hydroxide, 0.075 M strontium and 0.05 M sodium permanganate. After allowing the solution to stir for 4 hours at 50°C, a freshly precipitated filtrate was generated by dead-end filtration using a 0.45-μm filter. The filtration was complete in 30 minutes. Additional cesium was spiked into the filtrate to achieve elevated concentrations. The mixture was stirred for 30 minutes, and no solids were observed.

Within 24 hours after filtration, 15 ± 0.1-ml of the fresh precipitated and filtered AN-107 (Envelope C) simulant solution was contacted with 0.15 ± 0.01-gram of SuperLig® resin (50 Liter batch) for 24, 48, 72, and 120 ± 1 hours at 25 ± 2°C. The tests with fresh AN-107 simulant were conducted in duplicate for each of three cesium concentrations namely, 11.9, 63.3, and 124 mg/L. Cesium nitrate was spiked into the fresh simulant to achieve the higher cesium concentration levels (63.3 and 124 mg/L). The container headspace was purged with nitrogen prior to beginning of each test solution. Small aliquots (100 μL) were withdrawn from each sample after 24, 48, 72, and 120 ± 1 hours into vials containing approximately 2 g of de-ionized water. This minimized change to liquid-solid phase ratios and provided sufficient solution for elemental and ion analysis.

Table 1. Composition of aged AN-107 simulant

Analyte	avg. value
Cs, mg/L	10.8
Total carbon, mg/L	707.5
TIC, mg/L	260.5
TOC, mg/L	447
Free OH-, M	1.26
IC (anions), M	
Cl-	3.37E-02
F-	1.08E-01
HCOO-	1.33E-01
NO3-	1.35E+00
NO2-	7.26E-01
H(COO)2-	1.04E-02
PO4-	1.45E-02
SO4-	5.22E-02
ICP-ES, mg/L	
Al	260.5
B	36.4
Ca	148
Cr	0.33
Cu	14.0
Fe	26.1
Na	130000
Ni	313
P	301
Sr	91.1
K	1380
$[Na^+]/[Cs^+]$	1.20E+04
[K+]/[Cs+]	1.28E+02

3.3.4 Uranyl Co-sorption on SuperLig 644 resin

A series of batch contact tests using Envelope C (AN-107) simulant spiked with depleted uranium were performed in a radiochemical hood per SRTC procedures.[14] The simulant was 1999 pre-prepared filtrate from pilot-scale cross flow filtration tests of the strontium and transuranic precipitation process. In the first set of this batch contact tests, a series of aged Envelope C (AN-107) simulants with cesium concentration at pre-existing level (i.e 10.4 mg/L) were spiked with depleted uranium. After spiking, the simulants were stirred for several days to achieve the desired concentration levels. Due to uranium solubility limits in alkaline solution, the three uranium concentration levels achieved in the simulant were 3.7, 30.7, and 341 mg/L. In a second set of the tests, the cesium concentration in the aged simulant was increased to 63 mg/L, then desire amounts of uranyl nitrate solution were each spiked to the same concentration levels as the prior set.

The phase ratio for the batch contact tests was typically 100:1 (i.e. 15 ± 0.1-ml of the simulant solution was contacted with 0.15 ± 0.01-gram). However, three single tests with a 10:1 phase ratio (i.e. 10 ± 0.1-mL of the simulant solution was contacted with 1.0 ± 0.01-gram) were performed with simulant containing 3.7, 30.7, and 341 mg/L uranium at two cesium concentrations 10.9 and 63 mg/L. These tests were done to better quantify small (~5-10%) uptake of competing ions that would typically be lost in the sample analytical uncertainty (~10%). The tests were conducted at ambient temperature for a contact times of 48 ±1 h.

3.3.5 Small-Scale Column Tests

A known mass (~ 20 g) of pretreated SuperLig® 644 (batch # 991022SMC-IV29) resin was slurried into a 2.7 cm (~1-inch) i.d. glass column using de-ionized water. The outside walls of the column were tapped while the resin was being slurried into column to ensure uniform packing of the resin bed. The initial height of the resin bed in de-ionized water was approximately 8.7-cm (~3.4-inches), yielding a column that contains ~50-mL of resin in hydrogen form. The temperature of the water-bath circulator and the column jacket were adjusted at 25 ^{o}C. The temperature of the liquid above the resin bed was periodically measured and recorded during the tests. Twelve bed volumes (BVs) of 0.25M sodium hydroxide solution was pumped as down flow into the column at approximately 3 bed volume per hour (BV/h). The resin was stored overnight in the sodium hydroxide solution to allow maximum swelling of the resin bed. After overnight storage, the NaOH liquid level was adjusted so that the height of liquid above the resin bed was approximately 2 cm. The height of the resin bed was approximately 25.7-cm (8.57-inches), yielding a column that contained ~ 147-mL (i.e. 5.74 cross-section area of the column x 25.7 resin bed height) of swollen resin in sodium form. The preconditioning solution (0.25M NaOH) that remained above the resin bed and in the feed tubing was approximately 1 BV; the total apparatus volume (TAV) was, therefore, equal to 2 BV. Thus, the first 111-mL (i.e. resin bed volume in simulant) of simulant that was fed into the column at the beginning of the loading cycle was diluted by a factor of 2. Likewise, the post-feed water wash and the eluting solutions were allowed to mix with the liquid head left above the resin from the

previous cycle. No attempt was made to correct for mixing of solutions in the column headspace when calculating the number of bed volumes of feed, wash, or eluate processed.

The loading cycle was carried out at 25 ^{o}C. The loading cycle was considered to start at the moment that the AN-107 simulant contacted the resin bed. The simulant was pumped as down flow through the column at ~ 1.5 BV/h. The first 3 BV of effluent was discarded to prevent dilution of the effluent by residual sodium hydroxide solution. Sub-samples of the column effluent were collected after 5 BV of solution had passed through the column and at intervals of approximately 10 BVs, until approximately 150-BVs of simulant had been processed. The samples were collected using a Spectrum Chromatography IS-95 Interval Sampler. Periodically (during sample collection except off-shift hours), the heights of the resin bed and the liquid above the resin were recorded. Similarly, the temperatures of the water-bath circulator and the resin bed were measured and recorded. Each of the column effluent samples was analyzed to determine the concentrations of Na, K, and Cs.

At the conclusion of the first loading cycle at 1.5 BV/h (0.44 cm/min), the simulant was displaced from the column using 6 BVs (2 total apparatus volumes) of 0.1M sodium hydroxide solution. The dilute sodium hydroxide solution was pumped as down flow into the column at 3 BV/h. The resin bed was then flushed with 6 BVs (2 total apparatus volumes) of de-ionized water at the same flow rate (3 BV/h). The dilute sodium hydroxide was used in order to prevent aluminum hydroxide precipitation that could foul the resin bed and the water rinse served to displace residual sodium hydroxide solution from the columns prior to elution. The column was eluted using 16 BV of 0.5M nitric acid solution at 1.0 BV/h. Sub-samples of the column eluate were collected in 2-BV increments. ICP-MS and ICP-AES were used to analyze the sub-samples for total cesium and elemental (metal) constituents, respectively. Composite eluate solutions were also analyzed for total cesium (ICP-MS), elemental constituents (ICP-AES), anions (IC), and total organic and inorganic carbon (TIC/TOC). After the elution cycle, the residual nitric acid solution was displaced from the column by pumping 6 BVs (2 total apparatus volumes) of de-ionized water through the column at 1.0 BV/h. The column was stored in the de-ionized water for 2 days before the second column test at 3 BV/h was initiated.

The second column test was carried out at ~ 3 BV/h (0.87 cm/min) using a fresh batch of the AN-107 simulant. The column was regenerated using a 0.25M NaOH solution. The resin was regenerated at 25 ^{o}C by pumping as down flow 12 BVs of 0.25M sodium hydroxide solution at 3 BV/hr through the column. The simulant was pumped as down flow through the column and the first 3 BV of the effluent was discarded. Sub-samples of the column effluent were collected after 5 BVs of solution was processed and at intervals of approximately 10 BVs, until approximately of 100-BVs of the simulant had been processed.

Upon completion of the second loading cycle, 6 BVs of 0.1M sodium hydroxide at 3 BV/h was used to displace the simulant from column. The dilute sodium hydroxide was rinsed from column with 6 BVs of de-ionized water at 3 BV/h. The column was eluted using 16 BV of 0.5M nitric acid solution at 1 BV/h. Sub-samples of the column eluate were collected in 1-BV increments for the first 8 BVs and 2-BV increments, thereafter until 16 BVs of eluent had been processed. The eluate sub-samples were analyzed for total cesium and the eluate composite

solution was analyzed for both cesium and metal constituents. The column was stored in de-ionized water at ambient temperature for 2 days before a third column test was initiated.

The third column test was carried out at 18 BV/h. The column was regenerated by transferring 12 BVs of 0.25M sodium hydroxide solution through the column at 3 BV/h. The simulated Envelope C solution was then pumped as down flow through the column at 18 BV/h (5.2 cm/min). After discarding the first 3 BVs of the effluent, sub-samples were collected after 5 BVs of solution was processed, and at intervals of approximately 10 BVs thereafter, until approximately 100 BVs of simulant had been processed. At the conclusion of the loading cycle, the simulant was displaced from column by transferring 6 BVs of 0.1M sodium hydroxide at 3 BV/h, followed by 6 BVs of de-ionized water to rinse the dilute sodium hydroxide off the resin. The column was eluted using 16 BVs of 0.5M nitric acid solution at 1 BV/h. Sub-samples of the eluate were collected in 1-BV increments for the first 8 BVs and in 2-BV increments thereafter until a total of 16 BVs of eluent had passed through the column.

The fourth column test was carried out at 3 BV/h (0.87 cm/min). This test was performed under the same experimental conditions as the second test. This was done to compare the performance of the resin before and after the resin was exposed to a high volumetric flow rate. In this test, the column was regenerated by transferring 12 BVs of 0.25M sodium hydroxide as down flow at 3 BV/h. The conditions (i.e. flow rate, temperature) during column loading, displacement, rinsing, and elution were identical to that of the second column test at 3 BV/h. Sub-samples of the column effluent were collected after processing 5 BVs of simulant, and at intervals of approximately 10 BVs thereafter, until approximately 100 BVs of simulant had been processed.

4.0 Results and Discussion

4.1 Batch Distribution Coefficients for Cesium

Batch contact tests are used to measure of distribution coefficients or K_d values. The K_d values, defined as the ratio of the molal concentrations of cesium in the resin to the molar concentrations in the solution, are calculated using the following equation:

$$K_d = \left[\left(\frac{C_{init}}{C_{final}}\right) - 1\right]\left[\frac{V}{M * F}\right] \qquad \textbf{(1)}$$

where C_{init} and C_{final} are the cesium concentration before and after contact with resin, V is the volume of solution used, M is the mass of resin used, and F is the F-factor or the ratio of oven-dry resin mass to air-dry mass. Typically, the distribution coefficients are measured at equilibrium so the data represents one point on the equilibrium isotherm. In previous SRTC studies, a sequential batch technique was used as means to obtain an adsorption isotherm over the expected range of cesium concentrations encountered in ion exchange columns. For this work, a

more broad and higher range of concentrations representative of all wastes and representing possible process variances was examined. For batch contact testing except the post-filtration precipitation effects study, a simulated Envelope C (AN-107) solution derived from year 1999 pilot-scale cross flow filtration tests of the strontium and transuranic precipitation process was used. To construct the adsorption isotherm, higher initial cesium concentrations were prepared by adding additional cesium nitrate to the simulant.

The distribution coefficients of cesium were obtained at three different cesium concentrations (10.4, 74.3, 131 mg/L) for the 50 liter batch and pretreated batch # 991022SMC-IV29. For the used or spent resin, the K_ds were obtained at higher concentrations (63.1, 145, and 682 mg/L). All K_d measurements were carried out using aged AN-107 simulant. The K_d measurements for each cesium concentration were performed in duplicate. The results were reported as average of two separate measurements. Tables 2a, 2b, and 2c show average cesium K_d values and percent relative standard deviations for the "50 Liter" batch, the pretreated # 991022SMC-IV29 batch, and the used # 991022SMC-IV29 batch, respectively. The contact time for the pretreated 991022SMC-IV29 resin batch was 24 h. It was later determined as shown by the results reported in section 4.2 that 24 h was insufficient to achieve equilibrium under experimental conditions employed for these tests. Thus, a contact time of 48 h was used for the K_d measurements with "50 Liter" batch.

Table 2 (a): Cesium K_ds for 50 Liter batch (air-dried, H-form), contact time = 48-h

Expt. #	phase ratio	$[Cs]_o$, mg/L	$[Cs]_{eq}$, mg/L	avg. K_d, mL/g	% RSD
1	10	10.4	0.05	2302	2.0
2	97	10.4	0.56	1849	0.4
3	99	74.3	10	681	1.1
4	99	131	25.5	444	0.04

Table 2 (b): Cesium K_ds for batch #991022SMC-IV29 (oven-dried; H-form), contact time = 24 h

Expt. #	phase ratio	$[Cs]_o$, mg/L	$[Cs]_{eq}$, mg/L	avg. K_d, mL/g	% RSD
1	10	10.4	0.08	1320	9.9
2	102	10.4	0.89	1100	2.1
3	101	74.3	17.2	341	4.5
4	102	131	44.1	205	10.2

Table 2 (c): Cesium K_ds for spent resin, batch #991022SMC-IV29 (oven-dried, H-form)

Expt. #	phase ratio	$[Cs]_o$, mg/L	$[Cs]_{eq}$, mg/L	avg. K_d, mL/g	% RSD
1	102	63.1	10.6	490	8.5
2	101	145	46.9	208	16
3	102	682	444	53	5.2

Contact time = 24 h

Figure 1 shows plots of cesium K_d values as a function of equilibrium concentration for the two resin batches. The single data to the left of the inflection points in the curves represent a phase ratio of 10; all other data points had a phase ratio of 100. The results show that the cesium K_d values decreased as the cesium concentration in the simulant was increased. It should be noted that the higher K_d for the "50 Liter" vs. #991022SMC-IV29 batch is partly due to the difference in the contact times the "50 Liter" batch was contacted with the simulant for 48 ± 1h vs. 24 ± 1-h contact for the #991022SMC-IV29 batch. In addition, there was some difference in the resin handling prior to the batch contact tests. The batch #991022SMC-IV29 was originally received in potassium form and it had to be pretreated to remove the potassium bicarbonate impurities. After pretreatment and before using the resin in the batch tests, it was oven-dried at 45 ± 5 ^oC under vacuum. The "50 Liter" batch was originally received wet in hydrogen form and prior to the batch contact it was air-dried at at 25 ± 1 ^oC. Although the resins were handled in slightly different ways (i.e. contact time and drying method), the source of the large difference observed in the K_d values owes primarily to batch variability of SuperLig® 644 resin. A separate test program is underway to investigate the physical and chemical variability of the resin.

Figure 2 shows the batch contact data plotted as an isotherm (i.e. cesium concentration on the resin vs. equilibrium cesium concentration in the solution). The development of the isotherm depicts that the equilibrium loading increased with increasing cesium concentration in the simulant. With the exception of the first data point (obtained at a phase ratio of 10) to the left, the isotherms have slightly negative curvature.

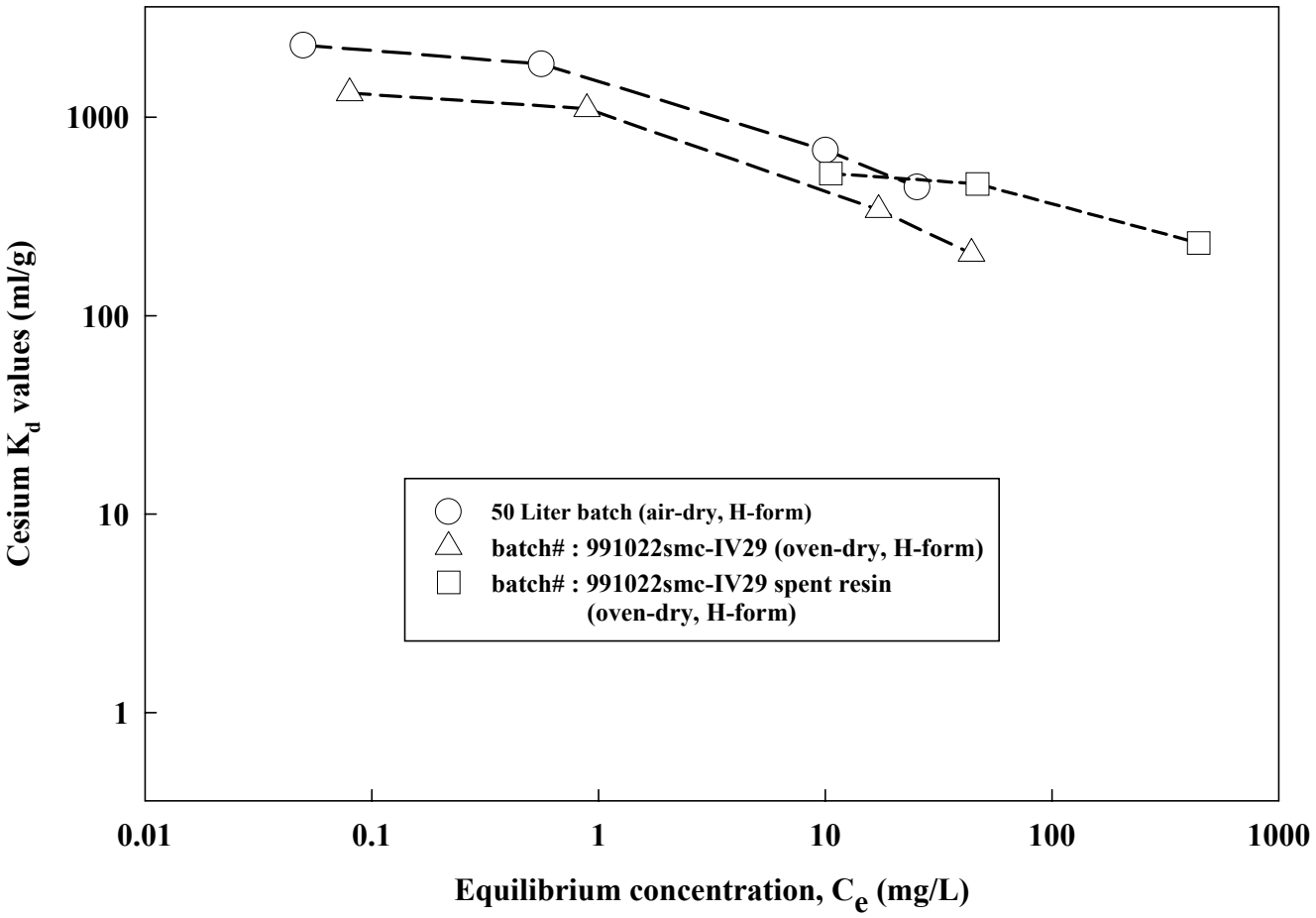

Figure 1. Cesium K_ds vs. equilibrium concentration

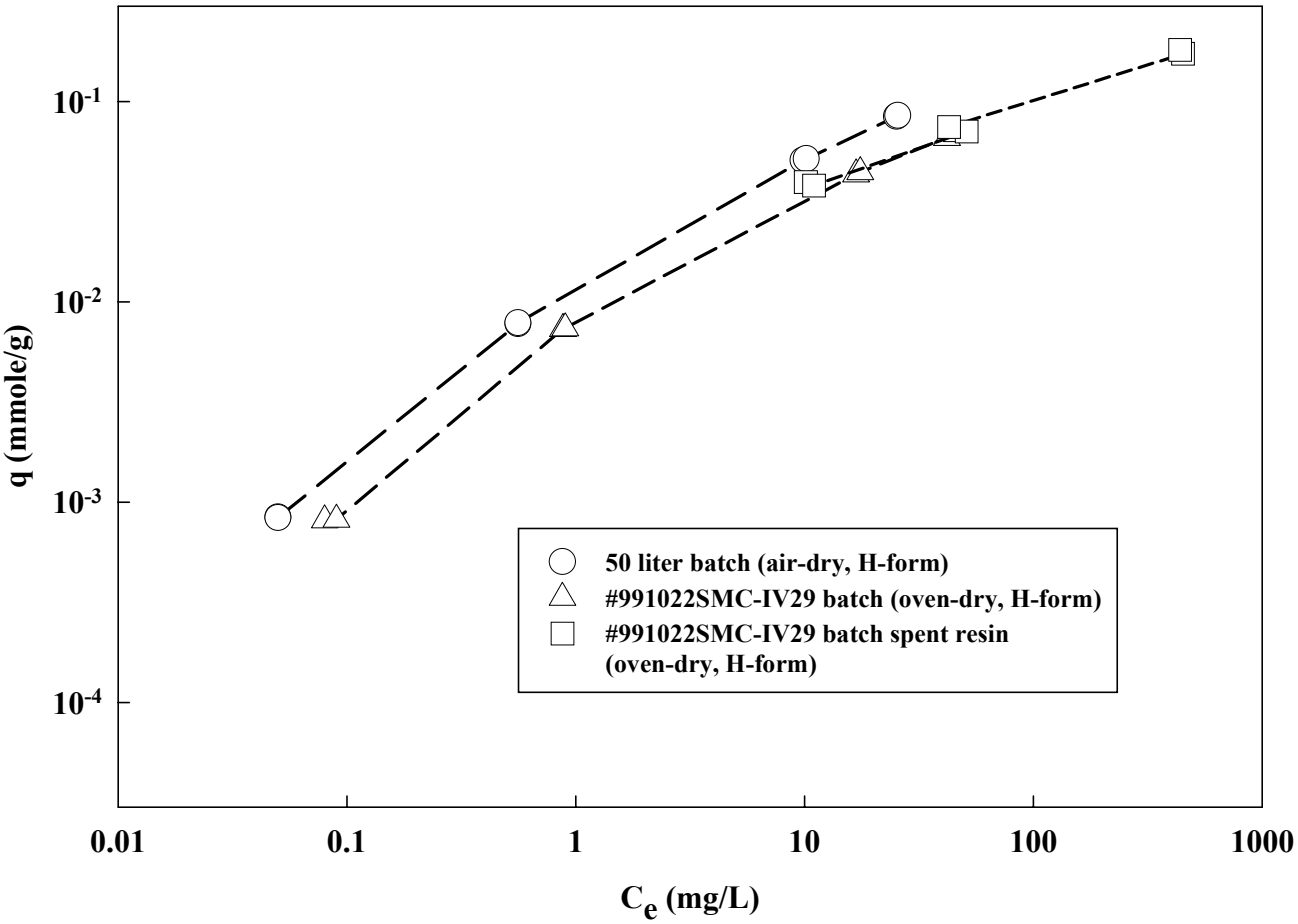

Figure 2. Equilibrium loading of cesium on SuperLig 644 Resin

4.2 Effect of Post-filtration Precipitation on Cesium K_d Values

In this set of batch contact tests, the cesium K_d values were measured as a function of time using fresh AN-107 simulant. The simulant was aged only for one week after precipitation and filtration, then was contacted with the resin samples from the "50 Liter" batch. The cesium concentration levels in the simulant were 11.9, 63, and 124 mg/L. Sub-samples (100 μL) of the test solutions were withdrawn at varying intervals (24, 48, 72, and 120 h) and analyzed for cesium by ICP-MS. The results of the kinetic measurements are presented in Figure 3. It is noted that K_d reached a maximum at contact times of approximately 48 h and decreased for contact times in excess of 48 hours. The observation of decreasing K_d value at prolonged contact times was reported in a recent Battelle-Pacific Northwest study.[14] Although no clear explanation is presently available, one could speculate that resin degradation occurred at prolonged contact times with alkaline solution.

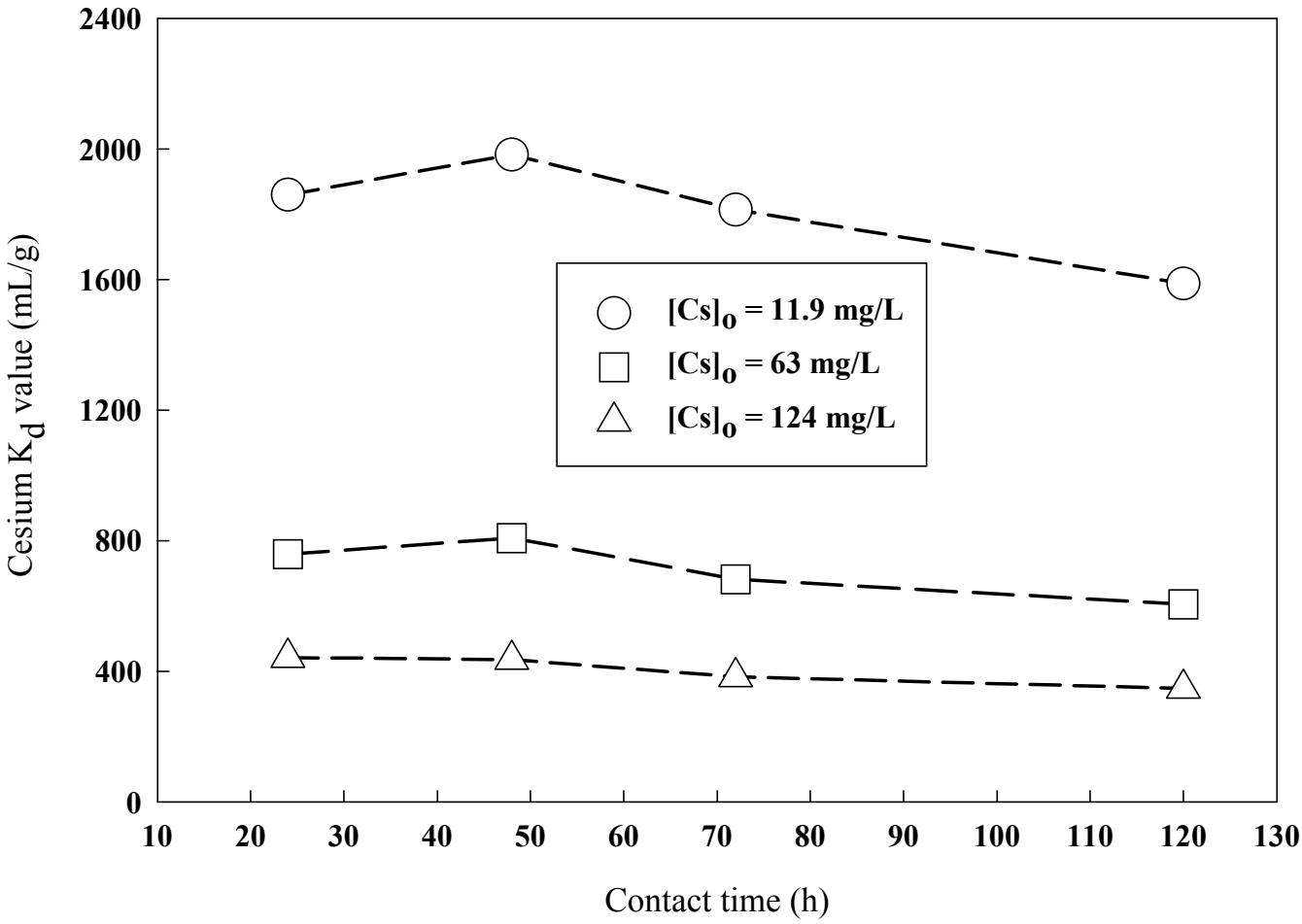

Figure 3. Cesium K_ds vs. contact time for fresh AN-107 simulant

The cesium K_d values for the fresh AN-107 simulant were generally comparable to those obtained with aged simulant under the same experimental conditions (i.e. 25 ± 1 ^oC with contact times of 48 h). The average cesium K_ds for fresh AN-107 simulant were 1983, 808, and 436 mL/g for the initial cesium concentrations of 11.9, 68, 123.5 mg/L, respectively. These values compare reasonably well with the results for the aged simulant (1849, 681, and 444 mL/g) at comparable initial cesium concentrations (10.4, 74.3, and 131 mg/L). The comparison can be made more obvious if the data for cesium in the fresh and aged AN-107 simulants are plotted as isotherms as shown in Figure 4. It can be seen the shape of the isotherms is nearly the same, both linearly increasing with equilibrium concentration. A slight shift between the curves is noted at the lowest cesium concentration.

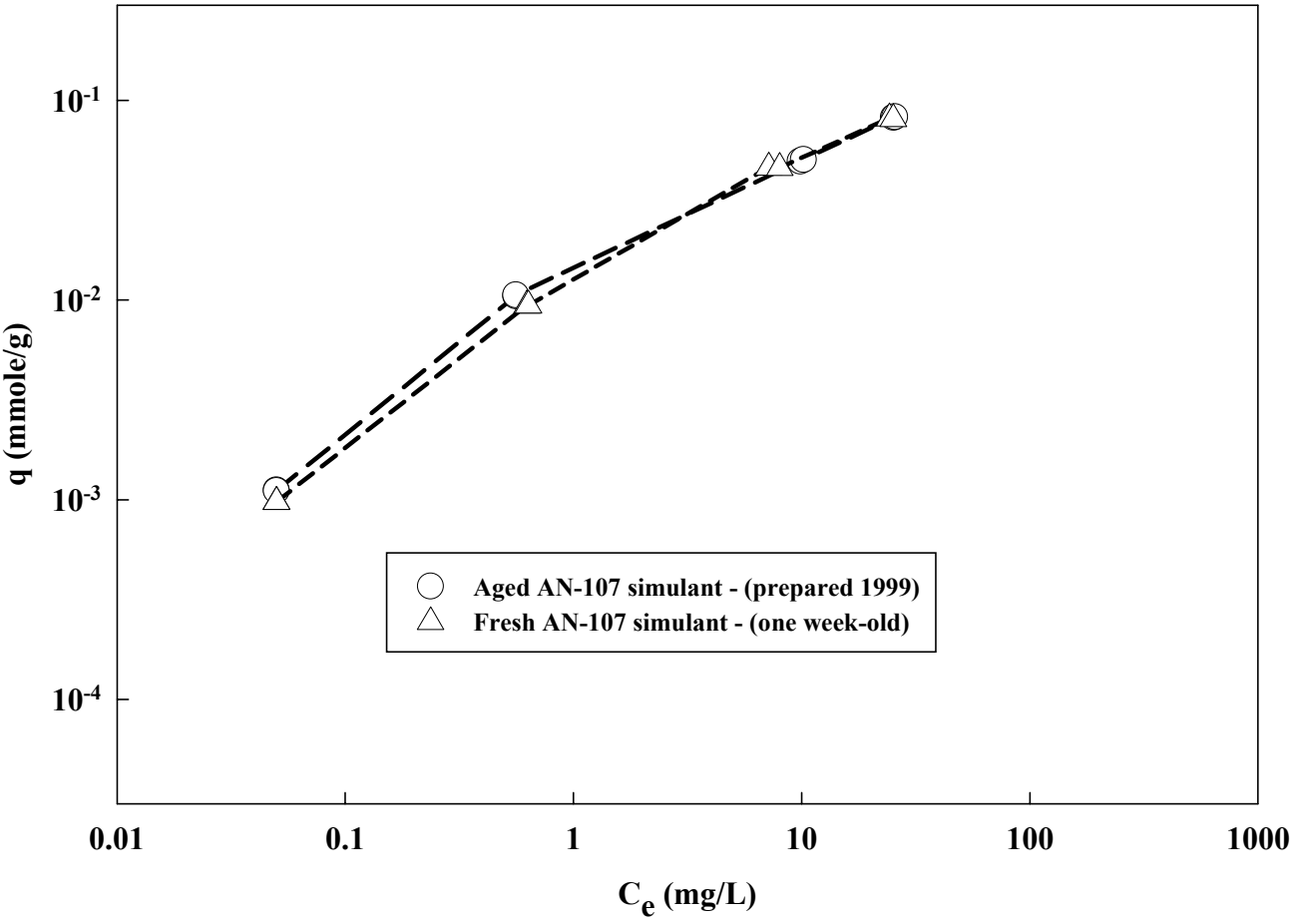

Figure 4. Equilibrium loading of cesium on SuperLig 644 Resin

4.3 Co-sorption of Uranium and Cesium on SuperLig® Resin

In a previous SRTC study, uranium was detected in SuperLig® 644 column acid eluates of Hanford actual tank waste (AN-107).[8] This finding suggested that the resin has some affinity to complex uranium. Resin affinity for uranium is supported by a Battelle- Pacific Northwest study with a solution containing 1M total [Na^+] and 0.25M [OH^-].[15] This study reported ^{238}U K_d value of ~ 4000 mL/g for contact times of 168 h. Although the extent of uranium binding affinity by the SuperLig® resin is not known, it is anticipated to be significantly less than that of cesium.

In this set of experiments, aged simulant (AN-107) was spiked with depleted uranium (^{238}U). The spiked stock solution was uranyl nitrate ($UO_2(NO_3)_2$) in 1M dilute nitric acid solution. Because of the poor solubility of uranyl ion in caustic solution (5M Na^+), the spiked solutions were stirred for several days at ambient conditions. The initial ^{238}U concentrations in the aged simulant were 3.7, 30.7, and 341 mg/L. Two sets of batch contact tests were performed. In the first set, the various uranium concentrations were each spiked into the aged simulant with cesium concentration at pre-existing level (i.e 10.4 mg/L). In the second set, the cesium concentration in the simulant was increased to 68 mg/L, and then various uranium concentrations were each spiked to the same levels as the prior set.

The results of uranium sorption on SuperLig® 644 resin are presented in Tables 3(a) and 3(b). Table 3(a) shows the average K_d values of ^{238}U in AN-107 simulant containing 10.4 mg/L cesium. It is important to note that there was little change in the K_d as the initial uranium concentration in the simulant was increased from 3.7 to 30.7 mg/L. However, further increase of uranium concentration in the simulant to 341 mg/L resulted in a significant drop of the ^{238}U K_d. At high cesium concentration in the simulant (68 mg/L), the ^{238}U K_d values were slightly higher as shown in Table 3(a). The trend of the data from the two tests was same. A 10-fold increase in the initial uranium concentration in the simulant caused little change in the ^{238}U K_d, but a 100-fold increase resulted in a significant drop of the K_d. The reason for sharp drop in the 238U K_d is unknown.

Table 3 (a): Uranium Kd for aged simulant (AN-107) containing 10.4 mg/L cesium

Test #	Phase ratio	$[^{238}U]_o$, (initial)	$[^{238}U]^*_{eq}$, (Sample 1)	$[^{238}U]^*_{eq}$, (Sample 2)	^{238}U K_d, (Sample 1)	^{238}U K_d, (Sample 2)	avg. K_d, (mL/g)	% RSD
1	98	3.7	0.588	0.635	570	510	540	7.8
2	99	30.7	5.75	5.59	527	481	504	6.5
3**	99	341	93	93	301	313	307	2.7

* K_d (mg/L); RSD = relative standard deviation

Table 3 (b): Uranium K_d for Aged Simulant (AN-107) Containing 68 mg/L Cesium

Test #	Phase ratio	$[^{238}U]_o$, (initial)	$[^{238}U]^*_{eq}$, (Sample 1)	$[^{238}U]^*_{eq}$, (Sample 2)	^{238}U K_d, (Sample 1)	^{238}U K_d, (Sample 2)	avg. K_d, (mL/g)	% RSD
1	98	3.7	0.527	0.44	635	780	708	14.5
2	99	30.7	4.04	3.87	696	739	717	4.3
3**	99	341	75	77	403	390	396	2.3

* K_d (mg/L); RSD = relative standard deviation; contact time 48 h (test # 3**) contact time 72 h

4.4 Simulant Column Tests with SuperLig® 644

The column tests with Envelope C (AN-107) simulant were carried out at three volumetric flow rates of 1.5, 3, and 18 BV/h (0.44, 0.87, and 5.2 cm/min). A single-column (2.7-cm inside diameter) containing ~ 100 mL of hydrogen form SuperLig® 664 resin was used. The simulant mimics the composition of low-activity waste solution from Tank 241-AN-107 supernate. Table 4 shows a summary of the column test results. It should be noted that at the flow rate 3 BV/h (0.44 cm/min) approximately 130 BVs of the simulant was processed before 50% breakthrough was reached. At 1.5 BV/h, it was projected to process 160 BVs of the simulant (0.87 cm/min) before reaching 50% breakthrough. Therefore, only a marginal improvement in the column loading was achieved at the lower flow rate (1.5 BV/h). The amount of simulant processed at highest flow rate (18 BV/h) sharply dropped to 50 BVs at 50% breakthrough.

Table 4. Summary of column performances

	Height/Dia.	Feed loading		Residence	Breakthrough
Test #	(cm/cm)	BV/h	cm/min	time (min)	# BV @ 50%
1	17.7/2.7	1.5	0.44	40	130
2	17.8/2.7	3	0.89	20	~ 160*
3	16.3/2.7	18	4.89	3.3	50
4	17.3/2.7	3	0.87	20	105

Initial mass in the column = 20.0 g;
* Projected at 50% breakthrough

Table 5 shows a summary of the swelling and shrinking history of the resin bed during the column tests. Data collected on the height of resin bed during column tests show that the average specific volume during regeneration, loading, and elution cycles was ~ 7.3, 6.0, and 4.5 ml/g, respectively. The volume change of the resin bed between elution and regeneration cycles was significant. A slight reduction of the resin bed volume was noted during column loading with simulant. The volume reduction during loading is probably due to exchange of large hydrated sodium ions on the solid phase (resin) with smaller hydrated cesium ions from the liquid phase (simulant). During this exchange, the resin loses significant amounts of water associated with hydrated sodium ions and, a result begins to contract. Generally, some swelling of the resin is desirable for the ion exchange process to take place. When the resin is swollen, it allows faster mass transfer by reducing intraparticle resistance. Resin swelling and shrinking, however, can become undesirable from operation's point of view since excessive swelling could potentially cause hydraulic problems and channeling.

Table 5. Resin Bed Swelling and Shrinking History (values in mL)

Test #	Flow rate (BV/h)	0.25M NaOH	5M Na^+ Simulant	0.1M NaOH	0.5M HNO3
1	1.5	138	101	117	72.2
2	3	132	102	128	71.6
3	18	127	93.4	124	71.6
4	3	127	99	134	72.2

Figure 5 shows The cesium loading data for simulated Envelope C (AN-107) at different flow rates. The plots (Figure 5) show the cesium concentration profile (i.e. cesium concentration in the effluent divided by the initial concentration in the feed) as a function of the volume of simulant processed. The shape of the breakthrough curves is similar for the 1.5 and 3 BV/h. The shallowness of the breakthrough curves at these flow rates suggests a large mass transfer zone in the column and hence a relatively adequate breakthrough capacity. The effect of flow rate is relatively large, with the faster flow rate of 18 BV/h (5.2 cm/min) yielding faster breakthrough.

Figure 6 shows the elution curves for cesium from SuperLig® 644 resin. The column was eluted at ~ 1 BV/h using 14 BVs of 0.5M nitric acid solution. The elution curves generally consist of three sections. The first section corresponds to the initial portion of the elution and includes the displacement of the liquid in the bed from the previous water rinse cycle. The next section contains a sharp peak where the major portion of the cesium is eluted from the resin. In this section, the cesium concentration in the eluate reached its maximum. The last section of the curve shows the elution tailing. The effects of resin bed shrinking during the elution are not known. It is important to note that cesium concentration peaks for the first three tests occurred only after 2 BVs of 0.5M HNO_3 had passed through the column. The cesium concentration peak for the fourth test had occurred after 3 BVs. The area under the each peak corresponds to the amount of cesium loaded into the column. A short elution tailing was generally observed following the cesium concentration peaks. The elution was complete (i.e. residual cesium concentration in the column was less than 1% of its concentration in the feed) after 14 BVs.

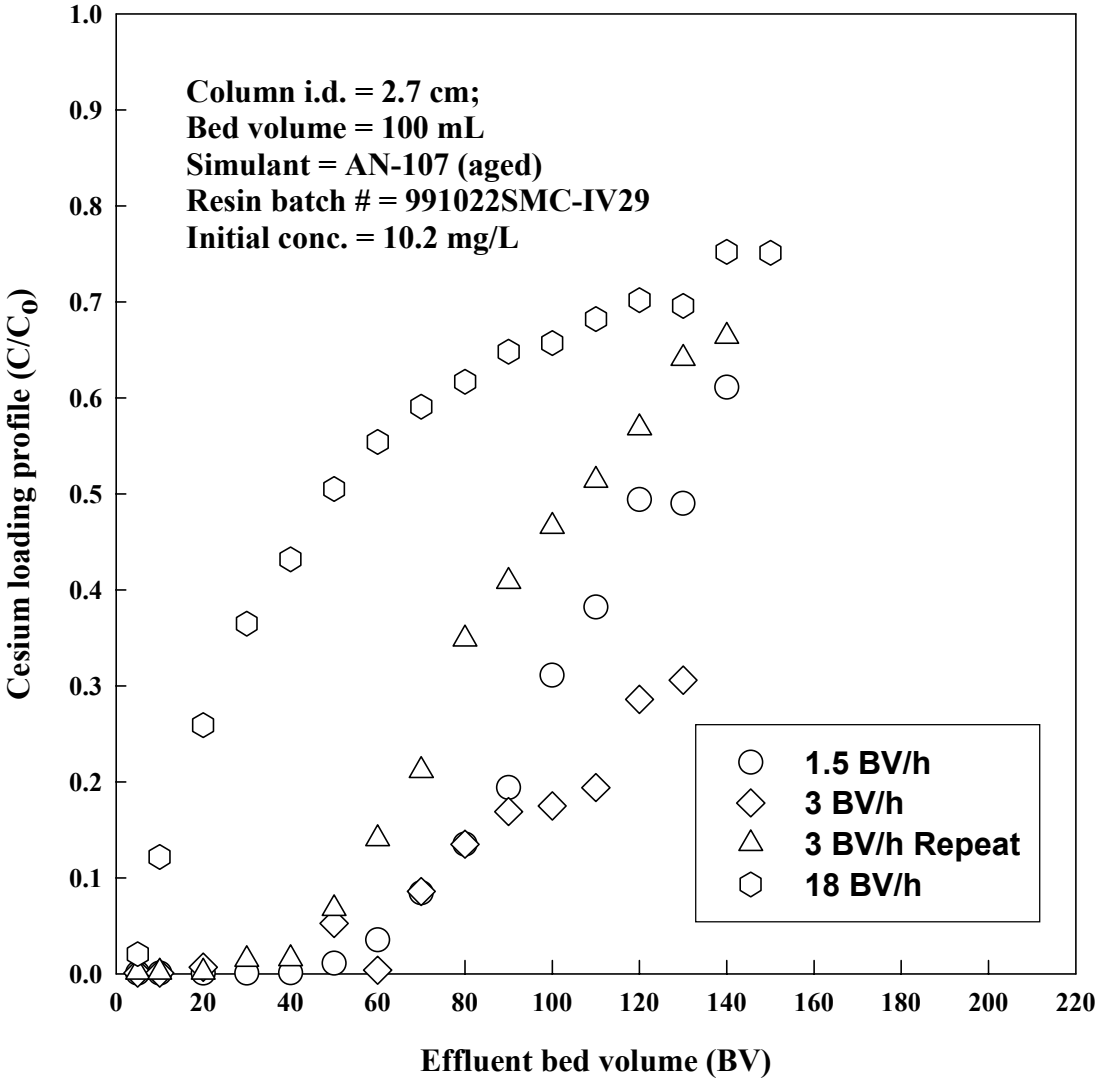

Figure 5. Cesium breakthrough curves at different flow rates

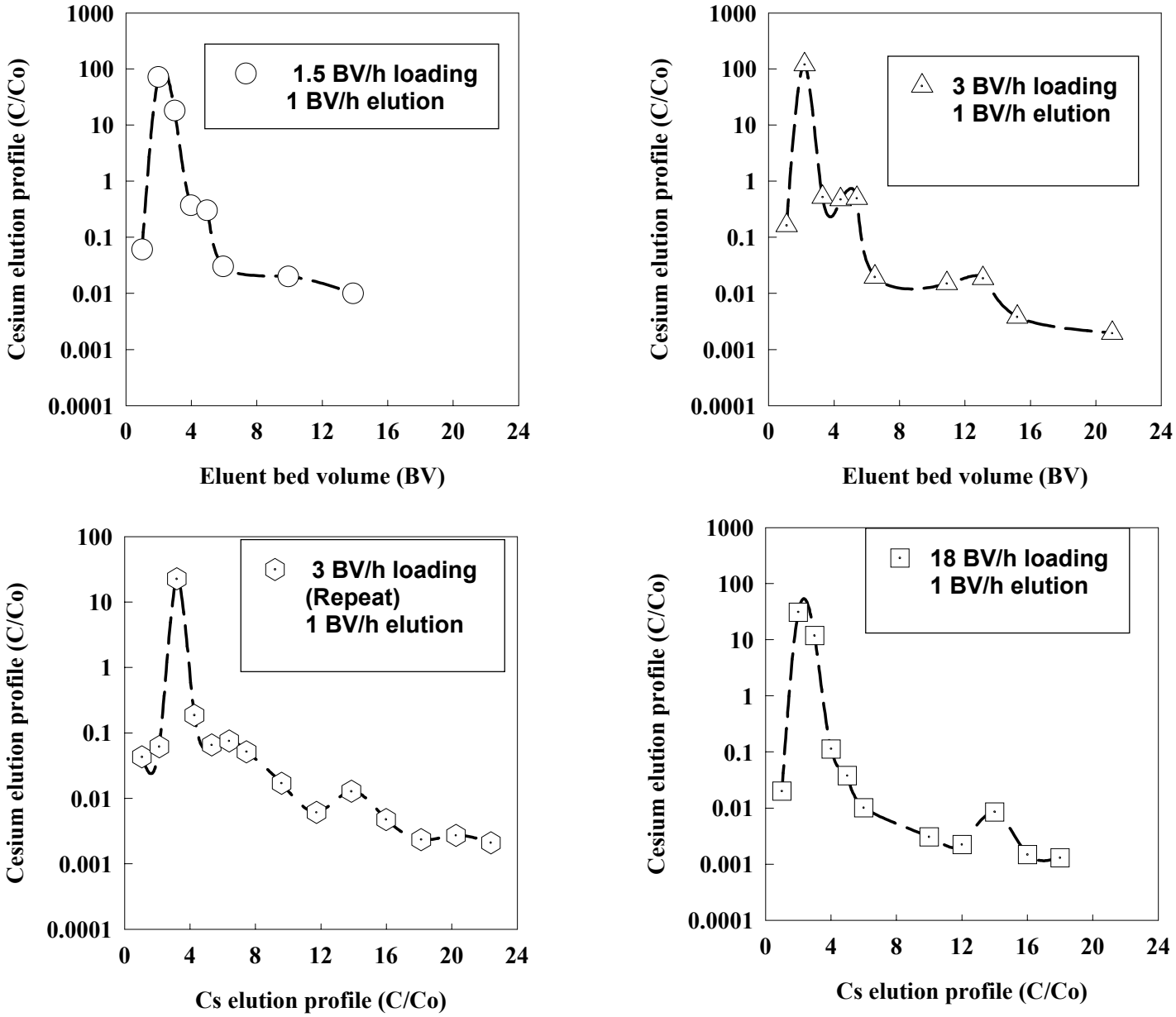

Figure 6. Cesium elution curves

Figure 7 shows the breakthrough curves for iron at three flow rates. The shape of the curves was generally linear, indicating rapid breakthrough of iron from the column. In a previous study at SRTC, we noted that SuperLig® 644 resin had slight affinities Cr, Cd, Fe, and Pb (minor competitors).[16] The early breakthrough of iron from the column could be due to poor diffusion-controlled column kinetics.

Figure 8 shows the elution curves of iron measured at low flow rates (1.5 and 3 BV/h). The elution was performed with 0.5M nitric acid at 1 BV/h. It can be seen that the elution peaks, which correspond to the maximum iron concentration in the eluate, occurred after only 2 BVs of eluent had passed through the resin bed. The elution tailing of iron was long and persistent, indicating that iron could not be easily eluted from the resin. It should be noted that significant amount of iron remained on the resin bed after 16 BVs of eluent had passed the through column.

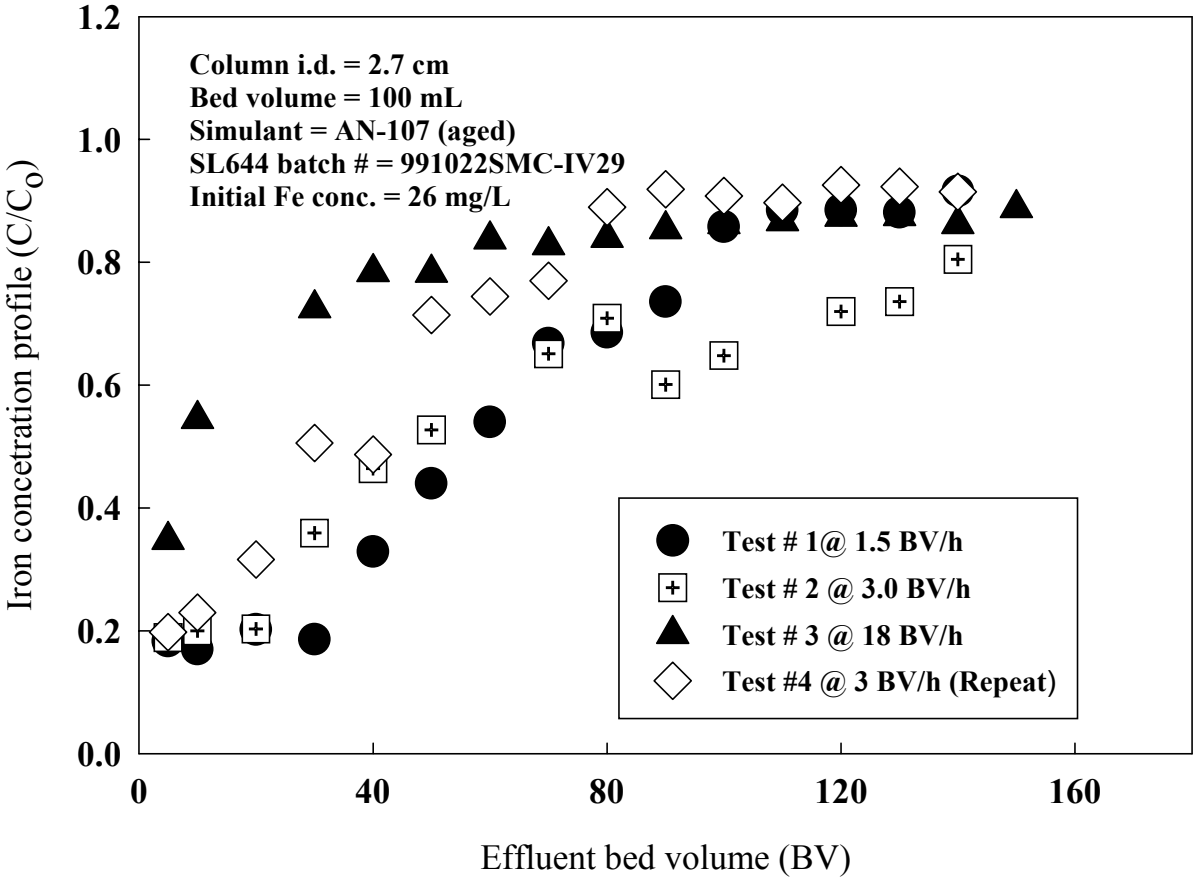

Figure 7. Iron breakthrough curves at different flow rates

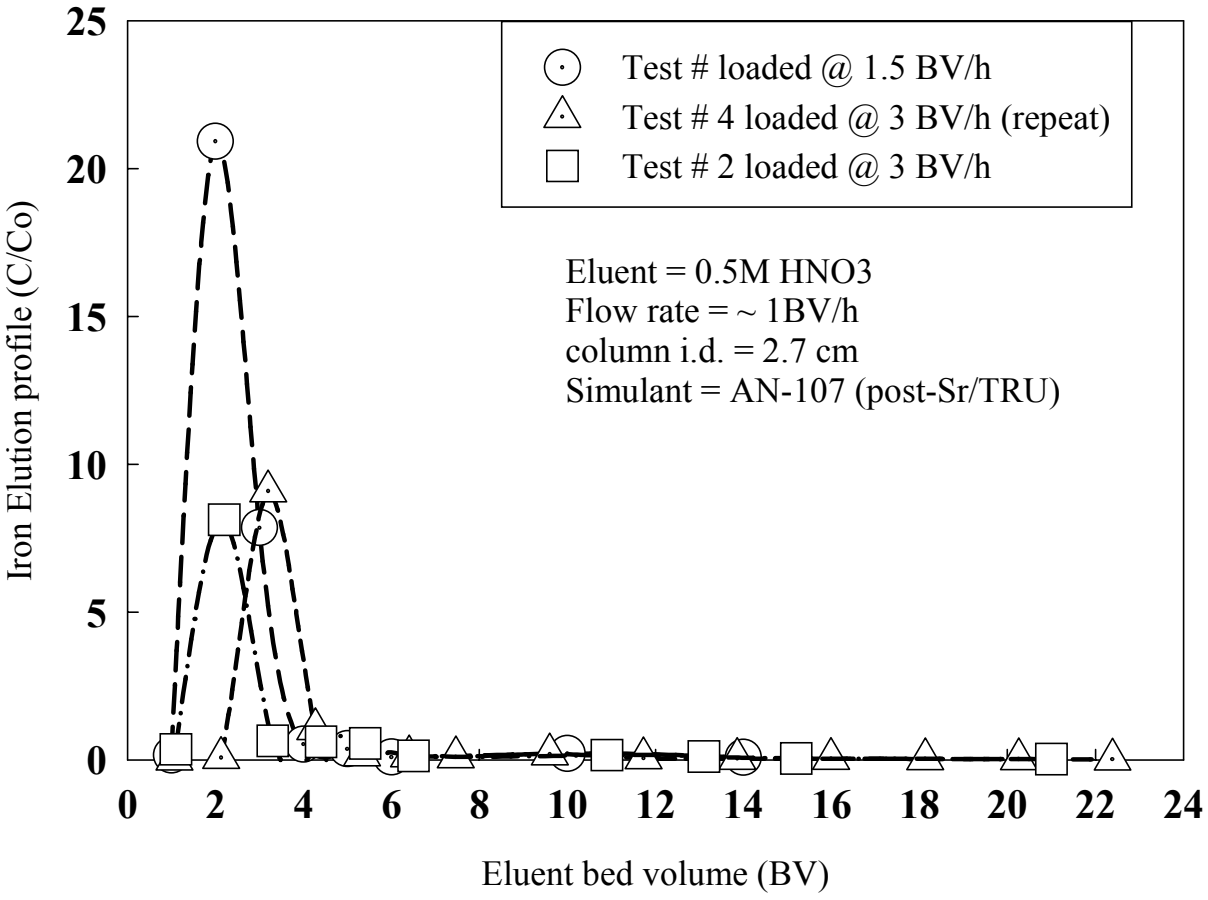

Figure 8. Iron elution curves

5. Conclusion

This experimental investigation consisted of batch contact and column loading tests. The batch contact tests were conducted at three different cesium concentrations (10.4, 74.3, 131 mg/L) using aged Envelope C (AN-107) simulant solutions and SuperLig® 644 resin. The batch tests with fresh Envelope C (AN-107) simulant were performed to determine the potential impact of post-filtration precipitation solids on the ion exchange process. Additional sets of batch contact tests were conducted using the aged simulants spiked with depleted uranium to determine the extent of uranium (UO_2^{2+} ion) co-sorption by SuperLig® 644 resin during the cesium ion exchange process. Two batches of the SuperLig® resin namely # 991022SMC-IV29 and "50 liter batch" was used in the tests.

The column loading tests were conducted to evaluate the ion exchange column performance of SuperLig® 644 with Envelope C (AN-107) solution at three different flow rates. A single column (2.7-cm i.d.) containing 100 mL (~20 g) of the resin was used with simulated Envelope C (AN-107) derived from Sr/TRU precipitation process. The three flow rates were 1.5, 3, and 18 BV/h. The highest flow rate of 18 BV/h was selected to meet RPP-WTP design nominal superficial velocity (5.92 cm/min). The intermediate flow rate of 3 BV/h represented RPP-WTP design nominal residence time (~ 20 minutes per bed). The lowest flow rate of 1.5 BV/h was selected to evaluate less than optimal flow conditions in the plant. The range of the flow rates is consistent with the River Protection Project design for the waste treatment plant (WTP) columns, which will operate at a flow rate between 1.5 to 3 bed volumes per hour.

This work revealed that slight uptake of minor competitors (i.e. Fe and U) by the SuperLig® 644 resin. The affinity of resin for the iron and uranium metals showed no impact on cesium sorption loading onto the resin. It was, therefore, recommended to monitor the iron loading in the full-height pilot testing with Envelope B to understand the long-term impact of residual iron on resin stability. Similarly, monitoring of uranium sorption on SuperLig® 644 resin during AW-101 processing is recommended.

.

6.0 References

1. Brown, G. N., Bray, L. and Elovich, R. J., "Evaluation and Comparison of SuperLig® 644, Resorcinol-Formaldehyde and Cs-100 Ion Exchange Materials for the removal of Cesium from Simulated Alkaline Supernate", PNL-10486, Pacific Northwest Laboratory, Richland, WA, March, 1995.

2. Brown, G. N., Adami, S. R., Bray, L. A, Bryan, S. A., Carlson, C. D., Carson, K. J., Deschane, J. R., Elovich, R. J., Forbes, S. J., Franz, J. A., Linehan, J. C., Shaw, W. J., Tanaka, P. K.and Telander, M. R., "Chemical and Radiological Stability of SuperLig® 644, Resorcinol-Formaldehyde and Cs-100 Cesium Ion Exchange Materials", PNL-10722, Pacific Northwest Laboratory, Richland, WA, September, 1995.

3. Brown, G. N., Bray, L.A., Carlson, C. D., Carson, K. J., Deschane, J. R., Elovich, R. J., Hoopes, V. F., Kurath, D. E., Nenninger, L. L. and Tanaka, P. K., "Comparison of organic and inorganic Ion Exchangers for Removal of Cesium and Strontium from Simulated and Actual Hanford 241-AW-101 DSSF Tank Waste", PNL-10920, Pacific Northwest National Laboratory, 1996.

4. Hassan, N. M., King, W. D. and McCabe, D. J., "Small-Scale Ion Exchange Removal of Cesium and Technetium from Hanford Tank 241-AN-103", BNF-003-98-0146, Rev.1, Westinghouse Savannah River Company, August, 1999

5. Hassan, N. M, McCabe, D. J., King, W. D. and Crowder, M. L., " Small-Scale Ion Exchange Removal of Cesium and Technetium from Hanford Tank 241-AN-102 (U)", BNF-003-98-0219, Rev. 0, Westinghouse Savannah River Company, Marh, 2000.

6. Hallen, R., PNWD-3035, BNFL-RPT-027, Combined Entrained Solids and Sr/TRU Removal from AN-107 Diluted Feed, Pacific Northwest National Laboratory, Richland, WA, August, 2000.

7. Nash, C.A., Saito, H.H., Strontium-Transuranic Precipitation and Crossflow Filtration of 241-AN-102 Large C, WSRC-TR-2000-00506, Rev. 0, Westinghouse Savannah River Company, April, 2001.

8. Hassan, N. M. and McCabe, D. J., "Hanford Envelope C Tank Waste Ion Exchange Column Study (U)", SRTC-BNFL-018, Rev. 0, Westinghouse Savannah River Company, October 24, 1997.

9. King, W. D, Hassan, N. M. and McCabe, D. J., "Intermediate-Scale Ion Exchange Removal of Cesium and Technetium from Hanford Tank 241-AN-102", WSRC-TR-2000-00420, SRT-RPP-2000-00014, Rev.0, Westinghouse Savannah River Company, December 2000.

10. Eibling, R.E., Nash, C.A., "Hanford Waste Simulants Created to Support the Research and Development on the River Protection Project – Waste Treatment Plant", WSRC-TR-2000-00338, SRT-RPP-2000-00017, Westinghouse Savannah River Company, March, *2001.*

11. Bannochie, C. "Standardized Baseline Precipitation Procedure for Handford RPP Studies", WSRC-TR-2002-00138, Rev. 0, 19 March 2002.

12. Saito, H. H., Nash, C. A., "Task Technical and Quality Assurance Plan for Evaluating the Residence Time for SuperLig® 639 and 644 Columns with Simulated Envelope C Solution (U)", WSRC-TR-2001-00465, SRT-RPP-2000-00163, Rev. 0, Westinghouse Savannah River Company, January 9, 2002.

13. Johnson, M. E., "Task Specification for Evaluating Residence Time for SuperLig® 639 and 644 Columns with Simulated LAW Envelope C Solution", TSP-W375-01-00022, Rev. 0, February 20, 2001.

14. Rapko, B. M., Blanchard, D. L., Carson, K. J., DesChane, J. R., Sell, R. L., Swoboda, R. G., "Batch Contact Testing of SuperLig® 644", WTP-RPT-037, Rev.0, Battele Pacific Northwest, April 2002.

15. Hassan, N. M., Nash, C. A., "Effects of Resin Particle Size and Solution Temperature on SuperLig® 644 Resin Performance with AN-105 Simulant", WSRC-TR-2001-00606, Rev. 0, Westinghouse Savannah River Company, March 28, 2002.

16. Kunin, R., Myers, R. J., Ion Exchange Resins, 2nd. Edition, John Wiley & Sons, Inc. New York (1958)

Appendix-A

Tank 241-AN-107 (Envelope C) Simulant Preparation

Appendix A-1: Preparation of Tank-241-AN-107 (Envelope C) Simulant

Compounds	Formula	Formula weight	Mass needed, g	Mass used (g)	Molarity (M)
Aluminum nitrate	Al(NO3)3.9H2O	371.15	5.370	5.373	1.45E-02
Boric Acid	H3BO3	61.83	0.200	0.2053	3.32E-03
Cerium nitrate	Ce(NO3)3.6H2O	434.23	0.160	0.1605	3.70E-04
Calcium Nitrate	Ca(NO3)2.4H2O	308.16	3.480	3.478	1.13E-02
Cesium Nitrate	CsNO3	194.02	0.027	0.277	1.43E-03
Copper Nitrate	Cu(NO3)2.2.5H2O	232.59	0.110	0.1105	4.75E-04
Ferric Nitrate	Fe(NO3)3.9H2O	404.02	12.230	12.2308	3.03E-02
Lanthanum Nitrate	La(NO3)3.6H2O	433.03	0.140	0.1405	3.24E-04
Lead Nitrate	Pb(NO3)2	331.2	0.620	0.6207	1.87E-03
Magnesium Nitrate	Mg(NO3)2.6H2O	256.4	0.260	0.2601	1.01E-03
Manganous Chloride	MnCl2.4H2O	197.9	2.030	2.0297	1.03E-02
Potassium Molybdate	K2MoO4	238.14	0.090	0.0904	3.80E-04
Neodymium Nitrate	Nd(NO3)3.6H2O	438.35	0.290	0.2911	6.64E-04
Nickel Nitrate	Ni(NO3)2.6H2O	290.8	2.630	2.6296	9.04E-03
Nitrilotriacetic Acid		188.116	0.570	0.5709	3.03E-03
Potassium Nitrate	KNO3	101.1	4.600	4.6005	4.55E-02
Strontium Nitrate	Sr(NO3)2	211.65	0.0160	0.0165	7.80E-05

Zinc Nitrate	Zn(NO3)2.6H2O	297.47	0.210	0.2129	7.16E-04
Zirconyl Nitrate	ZrO(NO3)2.xH2O	249.23	0.190	0.1903	7.64E-04
Sodium Acetate	NaCH3COO.3H2O	136.08	2.370	2.3714	1.74E-02
Disodium Ethylenediaminetetraacet	Na2C10H14N2O8.2H2O	372.24	7.260	7.2611	1.95E-02
Iminodiacetic Acid	HN(CH2CO2H)2	133.1	6.040	6.0424	4.54E-02
Citric Acid	C6H8O7.H2O	210.14	9.440	9.44	4.49E-02
Sodium Chloride	NaCl	58.45	1.820	1.8201	3.11E-02
Sodium Fluoride	NaF	41.99	0.290	0.2897	6.90E-03
Sodium Sulfate	Na2SO4	142.05	12.200	12.2037	8.59E-02
Sodium Hydroxide	NaOH	40	25.260	25.2624	6.32E-01
Sodium Formate	HCOONa	68.01	15.710	15.7105	2.31E-01
Sodium Glycolate	HOCH2COONa	218.14	3.930	3.9308	1.80E-02
Sodium Oxalate	Na2C2O4	134	1.260	1.2602	9.40E-03
Sodium Phosphate	Na3PO4.12H2O	380.12	4.440	4.4405	1.17E-02
Sodium Chromate	Na2CrO4	161.97	0.550	0.5507	3.40E-03
Sodium Carbonate	Na2CO3	105.99	148.250	148.2539	1.40E+00
Sodium Nitrate	NaNO3	84.99	297.290	297.2906	3.50E+00
Sodium Nitrite	NaNO2	69	91.490	91.4884	1.33E+00

Appendix-B

Cesium Batch Contact Data

Appendix B-1:Cesium Batch Data

Envelope C (Tank 241-AN-107) simulant-aged (Prepared 1999)
Resin batch # 991022smc-IV29 (pretreated, oven-dry H-form)

Sample ID	LIMS #	Solution mass (g)	Resin mass (g)	Solution vol. (mL)	phase ratio	F-factor	$[Cs]_e$ (mg/L)	uptake, K_d (mL/g)	loading, q (mmole/g)
SL644IV-7E-05-1	3-176430	18.9663	0.152	15.42	101	0.98	0.90	1084	8.12E-04
SL644IV-7E-05-1D	3-176431	18.9129	0.1504	15.38	102	0.98	0.88	1116	8.18E-04
SL644IV-5E-04-1	3-176432	18.7743	0.1525	15.26	100	0.98	17.5	330	7.33E-03
SL644IV-5E-04-1D	3-176433	18.9557	0.1523	15.41	101	0.98	16.8	352	7.40E-03
SL644IV-1E-03-1	3-176434	19.1148	0.1524	15.54	102	0.98	46.3	190	4.34E-02
SL644IV-1E-03-1D	3-176435	18.9676	0.1521	15.42	101	0.98	41.9	219	4.45E-02
SL644IV-7E-05-2	3-176436	12.758	1.0028	10.37	10	0.98	0.09	1227	6.61E-02
SL644IV-7E-05-2D	3-176437	12.8423	1.0031	10.44	10	0.98	0.08	1413	6.91E-02
AN107-7E-05, CTR #1	3-176438	11.9567	na	9.72	na	na	10.40		
AN107-7E-05, CTR #1-D	3-176893	11.9567	na	9.39	na	na	10.3		
AN107-5E-04, CTR #2	3-176439	12.9433	na	10.52			75.9		
AN107-5E-04, CTR #2-D	3-176894	12.9433	na	10.17	na	na	72.6		
AN107-1E-03, CTR #3-D	3-176440	12.382	na	10.07			134		
AN107-1E-03, CTR #3-D	3-176895	12.382	na	9.73	na	na	128		

Appendix B-2: Cesium Batch Data

Envelope C (Tank 241-AN-107) simulant-aged (Prepared 1999)

Resin batch # 991022smc-IV29 (Spent resin, oven-dry H-form)

Sample ID	LIMS #	Solution mass (g)	Resin mass (g)	Solution vol. (mL)	phase ratio	F-factor	$[Cs]_e$ (mg/L)	uptake, K_d (mL/g)	loading, q (mmole/g)
SL644SP-1E-04-1	3-174910	12.3619	0.1019	10.050	99	0.98	10.14	519	3.96E-02
SL644SP-1E-04-1D	3-174911	12.2924	0.1037	9.994	96	0.98	11.00	460	3.81E-02
SL644SP-1E-03-1	3-174912	12.3343	0.1008	10.028	99	0.98	51.00	185	7.09E-02
SL644SP-1E-03-1D	3-174913	12.3122	0.1038	10.010	96	0.98	42.80	232	7.47E-02
SL644SP-5E-03-1	3-174914	12.2862	0.1017	9.989	98	0.98	450.00	51	1.73E-01
SL644SP-5E-03-1D	3-174915	12.2216	0.1022	9.936	97	0.98	437.00	55	1.81E-01
AN107-IVSP, LCS #1E-04	3-174916	12.3569		10.046			63.1		
AN107-IVSP, LCS #1E-03	3-174917	12.326		10.021			145		
AN107-IVSP, LCS #5E-03	3-174918	12.3201		10.016			682		

Appendix B-3: Cesium Batch Data

Envelope C (Tank 241-AN-107) simulant- aged (Prepared 1999)

Resin batch # 50 Liter 50-Liter batch, air-dry (H-form)

Sample ID	LIMS #	Solution mass (g)	Resin mass (g)	Solution vol. (mL)	phase ratio	F-factor	$[Cs]_e$ (mg/L)	uptake, K_d (mL/g)	loading, q (mmole/g)
AN107-SL50L-7E-05-1	3-176885	18.9486	0.1536	14.88	97	0.92	0.56	2481	1.05E-02
AN107-SL50L-7E-05-1D	3-176886	19.0164	0.1527	14.94	98	0.92	0.56	2495	1.06E-02
AN107-SL50L-5E-04-1	3-176887	18.9449	0.1538	14.88	97	0.92	9.87	668	4.96E-02
AN107-SL50L-5E-04-1D	3-176888	18.9137	0.1501	14.86	99	0.92	10.2	658	5.05E-02
AN107-SL50L-1E-03-1	3-176889	18.9695	0.1525	14.90	98	0.92	25.3	431	8.20E-02
AN107-SL50L-1E-03-1D	3-176890	18.9215	0.15	14.86	99	0.92	25.6	431	8.29E-02
AN107-SL50L-7E-05-2	3-176891	12.6866	1.0005	9.97	10	0.92	0.05	3102	1.12E-03
AN107-SL50L-7E-05-2D	3-176892	12.6284	1.0035	9.92	10	0.92	0.05	3015	1.11E-03
AN107-7E-05, CTR #1	3-176893	11.9567	na	9.39	na	na	13.8		
AN107-5E-04, CTR #2	3-176894	12.9433	na	10.17	na	na	72.6		
AN107-1E-03, CTR #3	3-176895	12.382	na	9.73	na	na	128		

Appendix B-4: Cesium Batch Data
Envelope C (Tank 241-AN-107) simulant- fresh (One Week Old)
Resin batch # 50 Liter 50-Liter batch, air-dry (H-form)

Sample ID	LIMS #	Solution mass (g)	Resin mass (g)	Solution vol. (mL)	phase ratio	F-factor	$[Cs]_e$ (mg/L)	uptake, K_d (mL/g)	loading, q (mmole/g)
AN107-SL50L-7E-05-24h	3-177694	19.4662	0.1496	15.29	102	0.92	0.663	1883	9.39E-03
AN107-SL50L-7E-05-24-D	3-177695	19.4164	0.1497	15.25	102	0.92	0.677	1836	9.35E-03
AN107-SL50L-7E-05-48h	3-177696	19.4662	0.1496	15.29	102	0.92	0.635	1971	9.41E-03
AN107-SL50L-7E-05-48h-D	3-177697	19.4164	0.1497	15.25	102	0.92	0.626	1995	9.39E-03
AN107-SL50L-7E-05-72h	3-177698	19.4662	0.1496	15.29	102	0.92	0.712	1746	9.35E-03
AN107-SL50L-7E-05-72h-D	3-177699	19.4164	0.1497	15.25	102	0.92	0.661	1883	9.36E-03
AN107-SL50L-7E-05-120h	3-177700	19.4662	0.1496	15.29	102	0.92	0.755	1640	9.31E-03
AN107-SL50L-7E-05-120h-D	3-177701	19.4164	0.1497	15.25	102	0.92	0.800	1537	9.24E-03
AN107-SL50L-7E-05-2-24h	3-177702	12.8485		10.09			0.05	2496	9.76E-04
AN107-SL50L-7E-05-2-48h	3-177703	12.8485		10.09			0.05	2886	9.77E-04
AN107-SL50L-7E-05-2-72h	3-177704	12.8485		10.09			0.04	2952	9.77E-04
AN107-SL50L-7E-05-2-120h	3-177705	12.8485		10.09			0.05	2705	9.76E-04
RPP-AN107-7E-05, LCS #1	3-177706						11.90		
RPP-AN107-7E-05,LCS #1D	3-177707						11.90		

Appendix B-5: Cesium Batch Data
Envelope C (Tank 241-AN-107) simulant- fresh (One Week Old)
Resin batch # 50 Liter 50-Liter batch, air-dry (H-form)

Sample ID	LIMS #	Solution mass (g)	Resin mass (g)	Solution vol. (mL)	phase ratio	F-factor	$[Cs]_e$ (mg/L)	uptake, K_d (mL/g)	loading, q (mmole/g)
AN107-SL50L-5E-04-24h	3-177708	19.3867	0.1500	15.23	102	0.92	8.03	760	4.59E-02
AN107-SL50L-5E-04-24h-D	3-177709	19.2585	0.1501	15.13	101	0.92	7.99	758	4.56E-02
AN107-SL50L-5E-04-48h	3-177710	19.3867	0.1500	15.23	102	0.92	8.02	761	4.59E-02
AN107-SL50L-5E-04-48h-D	3-177711	19.2585	0.1501	15.13	101	0.92	7.18	856	4.62E-02
AN107-SL50L-5E-04-72h	3-177712	19.3867	0.1500	15.23	102	0.92	8.85	679	4.52E-02
AN107-SL50L-5E-04-72h-D	3-177713	19.2585	0.1501	15.13	101	0.92	8.72	686	4.50E-02
AN107-SL50L-5E-04-120h	3-177714	19.3867	0.1500	15.23	102	0.92	9.73	608	4.44E-02
AN107-SL50L-5E-04-120h-D	3-177715	19.2585	0.1501	15.13	101	0.92	9.74	602	4.41E-02
RPP-AN107-5E-04, LCS #1	3-177716						63.3		
RPP-AN107-5E-04, LCS #2	3-177717						63.4		

Appendix B-6: Cesium Batch Data
Envelope C (Tank 241-AN-107) simulant- fresh (One Week Old)
Resin batch # 50 Liter 50-Liter batch, air-dry (H-form)

Sample ID	LIMS #	Solution mass (g)	Resin mass (g)	Solution vol. (mL)	phase ratio	F-factor	$[Cs]_e$ (mg/L)	uptake, K_d (mL/g)	loading, q (mmole/g)
AN107-SL50L-1E-03-24h	3-177718	19.2746	0.1507	15.14	100	0.92	24.8	435	8.10E-02
AN107-SL50L-1E-03-24h-D	3-177719	19.2765	0.1508	15.14	100	0.92	24.1	450	8.16E-02
AN107-SL50L-1E-03-48h	3-177720	19.2746	0.1507	15.14	100	0.92	25.2	426	8.07E-02
AN107-SL50L-1E-03-48h-D	3-177721	19.2765	0.1508	15.14	100	0.92	24.3	446	8.14E-02
AN107-SL50L-1E-03-72h	3-177722	19.2746	0.1507	15.14	100	0.92	27.3	385	7.90E-02
AN107-SL50L-1E-03-72h-D	3-177723	19.2765	0.1508	15.14	100	0.92	27.5	381	7.88E-02
AN107-SL50L-1E-03-120h	3-177724	19.2746	0.1507	15.14	100	0.92	30.5	333	7.64E-02
AN107-SL50L-1E-03-120h-D	3-177725	19.2765	0.1508	15.14	100	0.92	28.70	361	7.78E-02
RPP-AN107-1E-03, LCS #1	3-177726						123		
RPP-AN107-1E-03,LCS #2	3-177727						124		

Appendix B-7: Uranyl Batch Data
Envelope C (Tank 241-AN-107) simulant- aged (prepared 1999)
Resin batch # 50-Liter batch, air-dry (H-form)
Initial Cs concentration, $[Cs]_o$ = 10.4 mg/L

Sample ID	LIMS #	Solution mass (g)	Resin mass (g)	Solution vol. (mL)	phase ratio	F-factor	$[Cs]_e$ (μg/L)	uptake, K_d (mL/g)	loading, q (mmole/g)
AN107-SL50L-E-05U/7E-05Cs-1	3-178156	18.8725	0.1498	14.83	99	0.92	5.88E+02	570	2.52E-03
AN107-SL50L-E-05U/7E-05Cs-1D	3-178157	18.8147	0.152	14.78	97	0.92	6.35E+02	510	2.44E-03
AN107-SL50L-E-04U/7E-05Cs-1	3-178160	18.8261	0.1514	14.79	98	0.92	5.15E+03	527	2.04E-02
AN107-SL50L-E-04U/7E-05Cs-1D	3-178161	18.835	0.1502	14.80	99	0.92	5.59E+03	481	2.02E-02
SL50L-1E-04U/7E-05Cs72-1	3-179873	18.8255	0.1508	14.79	98	0.92	9.30E+04	301	2.11E-04
SL50L-1E-04U/7E-05Cs72-1D	3-179874	18.7522	0.1498	14.73	98	0.92	9.10E+04	313	2.14E-04
AN107-E-04M U, CTR-1	3-178147	12.5281		9.84			3.70E+03		
AN107-E-05M U, CTR-1	3-178148	12.5281		9.84			3.07E+04		
AN107-E-03M U/5E-04Cs, CTR-1	3-178876	12.4877		9.81			3.57E+05		
AN107-E-03M U/7E-05Cs, CTR-1D	3-179883	12.701		9.98			3.25E+05		

Appendix B-8: Uranyl Batch Data
Envelope C (Tank 241-AN-107) simulant- aged (prepared 1999)
Resin batch # 50 Liter batch, air-dry (H-form)
Initial Cs concentration, $[Cs]_o$ = 68 mg/L

Sample ID	LIMS #	Solution mass (g)	Resin mass (g)	Solution vol. (mL)	phase ratio	F-factor	$[Cs]_e$ (μg/L)	uptake, K_d (mL/g)	loading, q (mmole/g)
AN107-SL50L-E-05U/5E-04Cs-1	3-178162	18.7593	0.152	14.74	97	0.92	5.27E+02	635	2.52E-03
AN107-SL50L-E-05U/5E-04Cs-1D	3-178163	18.7208	0.1519	14.71	97	0.92	4.40E+02	780	2.58E-03
AN107-SL50L-E-04U/5E-04Cs-1	3-178166	18.7793	0.1523	14.75	97	0.92	4.04E+03	696	2.11E-02
AN107-SL50L-E-04U/5E-04Cs-1D	3-178167	18.873	0.152	14.83	98	0.92	3.86E+03	739	2.14E-02
SL50L-E-03U/5E-04Cs72-1	3-179880	19.1837	0.1522	15.07	99	0.92	7.50E+04	403	2.28E-04
SL50L-E-03U/5E-04Cs72-1D	3-179881	19.0884	0.1529	14.99	98	0.92	7.70E+04	390	2.25E-04
AN107-E-05M U, CTR-1	3-178147	12.5281		9.84			3.70E+03		
AN107-E-04M U, CTR-1	3-178148	12.5281		9.84			3.07E+04		
AN107-E-03M U, CTR-1	3-178876	12.4877		9.81			3.57E+05		
AN107-E-03M U, CTR-1D	3-179883	12.701		9.98			3.25E+05		

Appendix-C

Cesium Column Loading and Elution Data

Appendix C-1: Cesium Column Loading at 1.5 BV/h; Aged AN-107 Simulant and Resin batch # 991022smc-IV29

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Cs]_{eff}$ (ug/L)	Cs profile [C/Co]
CR1.5-L5	3-175446	17.7	2.53	1.5	5	10	9.62E-04
CR1.5-L10	3-175447	17.7	2.53	1.5	10	10	9.62E-04
CR1.5-20	3-175448	17.7	2.53	1.5	20	10	9.62E-04
CR1.5-L30	3-175449	17.7	2.53	1.5	30	10	9.62E-04
CR1.5-L40	3-175450	17.7	2.53	1.5	40	12	1.15E-03
CR1.5-L50	3-175451	17.7	2.53	1.5	50	120	1.15E-02
CR1.5-L60	3-175452	17.7	2.53	1.5	60	382	3.67E-02
CR1.5-L70	3-175453	17.7	2.53	1.5	70	911	8.76E-02
CR1.5-L80	3-175454	17.7	2.53	1.5	80	1.46E+03	1.40E-01
CR1.5-L90	3-175455	17.7	2.53	1.5	90	2.09E+03	2.01E-01
CR1.5-L100	3-175456	17.7	2.53	1.5	100	3.36E+03	3.23E-01
CR1.5-L110	3-175457	17.7	2.53	1.5	105	4.13E+03	3.97E-01
CR1.5-L120	3-175458	17.7	2.53	1.5	110	5.33E+03	5.13E-01
CR1.5-L130	3-175459	17.7	2.53	1.5	115	5.29E+03	5.09E-01
CR1.5-L140	3-175460	17.7	2.53	1.5	120	6.60E+03	6.35E-01

Appendix C-2: Cesium Column Elution for 1.5 BV/h Loading Test with Aged AN-107 Simulant

Elution Flow rate = 0.93 BV/h; BV is based on loading resin bed height

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Cs]_{eff}$ (ug/L)	Cs profile [C/Co]
CR1.5-E1	3-175470	19.5	1.75	0.94	1	7.04E+02	6.77E-02
CR1.5-E2	3-175471	nm	1.73	0.93	2	7.48E+05	7.19E+01
CR1.5-E3	3-175472	nm	1.73	0.93	3	2.28E+05	2.19E+01
CR1.5-E4	3-175473	nm	1.73	0.93	4	4.03E+03	3.88E-01
CR1.5-E5	3-175474	15.3	1.73	0.93	5	3.26E+03	3.13E-01
CR1.5-E7	3-175475	15.3	1.73	0.93	6	322	3.10E-02
CR1.5-E13	3-175478	nm	1.73	0.93	10	247	2.38E-02
CR1.5-E15	3-175480	nm	1.73	0.93	14	109	1.05E-02

Appendix C-3: Cesium Column Loading at 3 BV/h; Aged AN-107 Simulant and Resin batch # 991022smc-IV29

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Cs]_{eff}$ (ug/L)	Cs profile [C/Co]
CR3-L5	3-176007	17.9	5.07	3.0	5	10	9.26E-04
CR3-L10	3-176008	17.8	5.07	3.0	10	10	9.26E-04
CR3-L20	3-176009	17.8	5.07	3.0	20	77	7.13E-03
CR3-L30	3-176010	17.8	5.07	3.0	30	nm	nm
CR3-L40	3-176011	17.8	5.07	3.0	40	nm	nm
CR3-L50	3-176012	17.8	5.07	3.0	50	570	5.28E-02
CR3-L60	3-176013	17.8	5.07	3.0	60	43	3.98E-03
CR3-L70	3-176014	17.8	5.07	3.0	70	929	8.60E-02
CR3-L80	3-176015	17.8	5.07	3.0	80	1460	1.35E-01
CR3-L90	3-176016	17.8	5.07	3.0	90	1830	1.69E-01
CR3-L100	3-176017	17.8	5.07	3.0	100	1890	1.75E-01
CR3-L110	3-176150	17.8	5.07	3.0	110	2090	1.94E-01
CR3-L120	3-176151	17.8	5.07	3.0	120	3090	2.86E-01
CR3-L130	3-176152	17.8	5.07	3.0	130	3300	3.06E-01

Appendix C-4: Cesium Column Elution for 3 BV/h Loading Test with Aged AN-107 Simulant

Elution Flow rate = 1.1 BV/h; BV is based on loading resin bed height

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV* processed	$[Cs]_{eff}$ (ug/L)	Cs profile [C/Co]
CR3-E1	3-176157	15.8	1.64	1.1	1.1	1760	1.63E-01
CR3-E2	3-176158	12.8	1.64	1.1	2.2	1.29E+06	1.19E+02
CR3-E3	3-176159	12.8	1.64	1.1	3.3	5570	5.16E-01
CR3-E4	3-176160	12.7	1.64	1.1	4.4	5080	4.70E-01
CR3-E5	3-176161	12.7	1.64	1.1	5.4	5360	4.96E-01
CR3-E7	3-176162	12.7	1.64	1.1	6.5	212	1.96E-02
CR3-E9	3-176163	12.7	1.64	1.1	8.7	nm	nm
CR3-E13	3-176164	12.6	1.64	1.1	10.9	162	1.50E-02
CR3-E15	3-176165	12.6	1.64	1.1	13.1	200	1.85E-02
CR3-E17	3-176166	12.5	1.64	1.1	15.2	41	3.80E-03
CR3-E19	3-176167	12.5	1.64	1.1	17.4	nm	nm
CR3-E21	3-176168	12.5	1.64	1.1	19.6	21	1.94E-03

Appendix C-5: Cesium Column Loading at 18 BV/h; Aged AN-107 Simulant and Resin batch # 991022smc-IV29

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Cs]_{eff}$ (ug/L)	Cs profile [C/Co]
CR18-L5	3-176383	20.2	29.03	15.1	5	224	2.07E-02
CR18-L10	3-176384	20.2	29.03	15.1	10	1320	1.22E-01
CR18-L20	3-176385	16.3	29.03	18.7	20	2800	2.59E-01
CR18-L30	3-176386	16.3	29.03	18.7	30	3940	3.65E-01
CR18-L40	3-176387	16.3	29.03	18.7	40	4670	4.32E-01
CR18-L50	3-176388	16.3	29.03	18.7	50	5450	5.05E-01
CR18-L60	3-176389	16.3	29.03	18.7	60	5980	5.54E-01
CR18-L70	3-176390	16.3	29.03	18.7	70	6380	5.91E-01
CR18-L80	3-176391	16.3	29.03	18.7	80	6660	6.17E-01
CR18-L90	3-176392	16.3	29.03	18.7	90	7000	6.48E-01
CR18-L100	3-176393	16.3	29.03	18.7	100	7100	6.57E-01
CR18-L110	3-176394	16.3	29.03	18.7	110	7370	6.82E-01
CR18-L120	3-176395	16.3	29.03	18.7	120	7580	7.02E-01
CR18-L130	3-176396	16.3	29.03	18.7	130	7520	6.96E-01
CR18-L140	3-176397	16.3	29.03	18.7	140	8120	7.52E-01
CR18-L150	3-176398	16.3	29.03	18.7	150	8110	7.51E-01

Appendix C-6: Cesium Column Elution for 18 BV/h Loading Test with Aged AN-107 Simulant

Elution Flow rate = 1 BV/h; BV is based on loading resin bed height

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Cs]_{eff}$ (ug/L)	Cs profile [C/Co]
CR18-E1	3-176405	17.3	1.64	0.99	0.99	216	2.00E-02
CR18-E2	3-176406	14.8	1.64	0.99	1.99	3.36E+05	3.11E+01
CR18-E3	3-176407	13.7	1.64	0.99	2.98	1.28E+05	1.19E+01
CR18-E4	3-176408	13.2	1.64	0.99	3.97	1.22E+03	1.13E-01
CR18-E5	3-176409	13	1.64	0.99	4.97	409	3.79E-02
CR18-E6	3-176410	13	1.64	0.99	5.96	109	1.01E-02
CR18-E7	3-176411	13	1.64	0.99	6.95	nm	nm
CR18-E8	3-176412	13	1.64	0.99	7.95	nm	nm
CR18-E10	3-176413	13	1.64	0.99	9.93	33	3.06E-03
CR18-E12	3-176414	12.5	1.64	0.99	11.92	24	2.22E-03
CR18-E14	3-176415	12.5	1.64	0.99	13.91	92	8.52E-03
CR18-E16	3-176416	12.5	1.64	0.99	15.89	16	1.48E-03
CR18-E18	3-176417	12.5	1.64	0.99	17.88	14	1.30E-03

Appendix C-7: Cesium Loading at 3 BV/h (repeat); Aged AN-107 Simulant and Resin batch # 991022smc-IV29

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Cs]_{eff}$ (ug/L)	Cs Profile [C/Co]
CR3R-L5	3-176793	18.2	5.2	3.0	5	20	1.85E-03
CR3R-L10	3-176794	18	5.2	3.0	10	20	1.85E-03
CR3R-L20	3-176795	17.3	5.2	3.1	20	20	1.85E-03
CR3R-L30	3-176796	17.3	5.2	3.1	30	163	1.51E-02
CR3R-L40	3-176797	17.3	5.2	3.1	40	172	1.59E-02
CR3R-L50	3-176798	17.3	5.2	3.1	50	734	6.80E-02
CR3R-L60	3-176799	17.3	5.2	3.1	60	1520	1.41E-01
CR3R-L70	3-1767800	17.3	5.2	3.1	70	2290	2.12E-01
CR3R-L80	3-1767801	17.3	5.2	3.1	80	3770	3.49E-01
CR3R-L90	3-1767802	17.3	5.2	3.1	90	4420	4.09E-01
CR3R-L100	3-1767803	17.3	5.2	3.1	100	5030	4.66E-01
CR3R-L110	3-1767804	17.3	5.2	3.1	110	5550	5.14E-01
CR3R-L120	3-1767805	17.3	5.2	3.1	120	6150	5.69E-01
CR3R-L130	3-1767806	17.3	5.2	3.1	130	6920	6.41E-01
CR3R-L140	3-1767807	17.3	5.2	3.1	140	7170	6.64E-01

Appendix C-8: Cesium Elution for 3 BV/h (repeat) Test with Aged AN-107 Simulant and Resin batch # 991022smc-IV29

Elution Flow rate = 1.1 BV/h; BV is based on loading resin bed height

Sample ID	ADS #	resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Cs]_{eff}$ (ug/L)	Cs profile [C/Co]
CR3R-E1	3-176902	17.1	1.74	1.1	1.1	463	4.29E-02
CR3R-E2	3-176903	13.4	1.74	1.1	2.1	665	6.16E-02
CR3R-E3	3-176904	13	1.74	1.1	3.2	2.44E+05	2.26E+01
CR3R-E4	3-176905	12.8	1.74	1.1	4.3	2.01E+03	1.86E-01
CR3R-E5	3-176906	12.8	1.74	1.1	5.3	708	6.56E-02
CR3R-E6	3-176907	12.7	1.74	1.1	6.4	814	7.54E-02
CR3R-E7	3-176908	12.7	1.74	1.1	7.5	556	5.15E-02
CR3R-E8	3-176909	12.6	1.74	1.1	8.5	nm	nm
CR3R-E9	3-176910	12.6	1.74	1.1	9.6	183	1.69E-02
CR3R-E10	3-176911	12.6	1.74	1.1	11.7	65.7	6.08E-03
CR3R-E12	3-176912	12.6	1.74	1.1	13.9	138	1.28E-02
CR3R-E14	3-176913	12.6	1.74	1.1	16.0	51.3	4.75E-03
CR3R-E16	3-176914	12.6	1.74	1.1	18.1	25.3	2.34E-03
CR3R-E18	3-176915	12.6	1.74	1.1	20.3	29.3	2.71E-03
CR3R-E20	3-176916	12.6	1.74	1.1	22.4	22.6	2.09E-03

Appendix-D

Iron Column Loading and Elution Data

Appendix D-1: Iron Column Loading at 1.5 BV/h; Aged AN-107 Simulant and Resin batch # 991022smc-IV29

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Fe]_{eff}$ (mg/L)	Fe profile [C/Co]
CR1.5-L5	3-175446	17.7	2.53	1.5	5	4.77	0.183
CR1.5-L10	3-175447	17.7	2.53	1.5	10	4.44	0.170
CR1.5-20	3-175448	17.7	2.53	1.5	20	5.27	0.202
CR1.5-L30	3-175449	17.7	2.53	1.5	30	4.85	0.186
CR1.5-L40	3-175450	17.7	2.53	1.5	40	8.59	0.329
CR1.5-L50	3-175451	17.7	2.53	1.5	50	11.5	0.440
CR1.5-L60	3-175452	17.7	2.53	1.5	60	14.1	0.540
CR1.5-L70	3-175453	17.7	2.53	1.5	70	17.4	0.668
CR1.5-L80	3-175454	17.7	2.53	1.5	80	17.9	0.686
CR1.5-L90	3-175455	17.7	2.53	1.5	90	19.2	0.736
CR1.5-L100	3-175456	17.7	2.53	1.5	100	22.4	0.858
CR1.5-L110	3-175457	17.7	2.53	1.5	105	23.1	0.885
CR1.5-L120	3-175458	17.7	2.53	1.5	110	23.1	0.885
CR1.5-L130	3-175459	17.7	2.53	1.5	115	23.0	0.881
CR1.5-L140	3-175460	17.7	2.53	1.5	120	23.9	0.916

Appendix D-2: Iron Column Elution for 1.5 BV/h Loading Test with Aged AN-107 Simulant

Elution Flow rate = 0.93 BV/h; BV is based on loading resin bed height

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Fe]_{eff}$ (mg/L)	Fe profile [C/Co]
CR1.5-E1	3-175470	19.5	1.75	0.94	1	4.27	0.164
CR1.5-E2	3-175471	nm	1.73	0.93	2	546	20.9
CR1.5-E3	3-175472	nm	1.73	0.93	3	205	7.85
CR1.5-E4	3-175473	nm	1.73	0.93	4	13.9	0.533
CR1.5-E5	3-175474	15.3	1.73	0.93	5	9.85	0.377
CR1.5-E7	3-175475	15.3	1.73	0.93	6	2.60	0.099
CR1.5-E13	3-175478	nm	1.73	0.93	10	5.78	0.220
CR1.5-E15	3-175480	nm	1.73	0.93	14	2.40	0.090

Appendix D-3: Iron Column Loading at 3 BV/h; Aged AN-107 Simulant and Resin batch # 991022smc-IV29

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Fe]_{eff}$ (ug/L)	Fe profile [C/Co]
CR3-L5	3-176007	17.9	5.07	3.0	5	4.94	0.189
CR3-L10	3-176008	17.8	5.07	3.0	10	5.23	0.200
CR3-L20	3-176009	17.8	5.07	3.0	20	5.29	0.203
CR3-L30	3-176010	17.8	5.07	3.0	30	9.36	0.359
CR3-L40	3-176011	17.8	5.07	3.0	40	12.1	0.464
CR3-L50	3-176012	17.8	5.07	3.0	50	13.7	0.527
CR3-L60	3-176013	17.8	5.07	3.0	60	nm	nm
CR3-L70	3-176014	17.8	5.07	3.0	70	17.0	0.651
CR3-L80	3-176015	17.8	5.07	3.0	80	18.5	0.709
CR3-L90	3-176016	17.8	5.07	3.0	90	15.7	0.601
CR3-L100	3-176017	17.8	5.07	3.0	100	16.9	0.648
CR3-L110	3-176150	17.8	5.07	3.0	110	18.8	0.720
CR3-L120	3-176151	17.8	5.07	3.0	120	19.2	0.736
CR3-L130	3-176152	17.8	5.07	3.0	130	21.0	0.805

Appendix D-4: Iron Column Elution for 3 BV/h Loading Test with Aged AN-107 Simulant

Elution Flow rate = 1.1 BV/h; BV is based on loading resin bed height

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV* processed	$[Fe]_{eff}$ (mg/L)	Fe profile [C/Co]
CR3-E1	3-176157	15.8	1.64	1.1	1.1	9.43	0.3625
CR3-E2	3-176158	12.8	1.64	1.1	2.2	211	8.1226
CR3-E3	3-176159	12.8	1.64	1.1	3.3	16.8	0.6475
CR3-E4	3-176160	12.7	1.64	1.1	4.4	16.0	0.6169
CR3-E5	3-176161	12.7	1.64	1.1	5.4	14.6	0.5632
CR3-E7	3-176162	12.7	1.64	1.1	6.5	3.67	0.1410
CR3-E9	3-176163	12.7	1.64	1.1	8.7	4.29	0.1651
CR3-E13	3-176164	12.6	1.64	1.1	10.9	3.11	0.1195
CR3-E17	3-176166	12.5	1.64	1.1	15.2	1.35	0.0521
CR3-E19	3-176167	12.5	1.64	1.1	21	0.79	0.0304

Appendix D-5: Iron Column Loading at 18 BV/h; Aged AN-107 Simulant and Resin batch # 991022smc-IV29

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Fe]_{eff}$ (mg/L)	Fe profile [C/Co]
CR18-L5	3-176383	20.2	29.03	15.1	5	9.07	0.348
CR18-L10	3-176384	20.2	29.03	15.1	10	14.2	0.545
CR18-L20	3-176385	16.3	29.03	18.7	20	21.1	nm
CR18-L30	3-176386	16.3	29.03	18.7	30	18.9	0.725
CR18-L40	3-176387	16.3	29.03	18.7	40	20.5	0.784
CR18-L50	3-176388	16.3	29.03	18.7	50	20.4	0.783
CR18-L60	3-176389	16.3	29.03	18.7	60	21.9	0.837
CR18-L70	3-176390	16.3	29.03	18.7	70	21.6	0.828
CR18-L80	3-176391	16.3	29.03	18.7	80	21.9	0.840
CR18-L90	3-176392	16.3	29.03	18.7	90	22.3	0.854
CR18-L100	3-176393	16.3	29.03	18.7	100	22.5	0.862
CR18-L110	3-176394	16.3	29.03	18.7	110	22.6	0.867
CR18-L120	3-176395	16.3	29.03	18.7	120	22.8	0.874
CR18-L130	3-176396	16.3	29.03	18.7	130	22.8	0.875
CR18-L140	3-176397	16.3	29.03	18.7	140	22.5	0.862
CR18-L150	3-176398	16.3	29.03	18.7	150	23.2	0.888

Appendix D-6: Iron Column Elution for 18 BV/h Loading Test with Aged AN-107 Simulant

Elution Flow rate = 1 BV/h; BV is based on loading resin bed height

Sample ID	ADS #	Resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Fe]_{eff}$ (mg/L)	Fe profile [C/Co]
CR18-E1	3-176405	17.3	1.64	0.99	0.99	< 0.3	< 1.15E-02
CR18-E2	3-176406	14.8	1.64	0.99	1.99	< 0.3	< 1.15E-02
CR18-E3	3-176407	13.7	1.64	0.99	2.98	< 0.3	< 1.15E-02
CR18-E4	3-176408	13.2	1.64	0.99	3.97	< 0.3	< 1.15E-02
CR18-E5	3-176409	13	1.64	0.99	4.97	< 0.3	< 1.15E-02
CR18-E6	3-176410	13	1.64	0.99	5.96	< 0.3	< 1.15E-02
CR18-E7	3-176411	13	1.64	0.99	6.95	< 0.3	< 1.15E-02
CR18-E8	3-176412	13	1.64	0.99	7.95	< 0.3	< 1.15E-02
CR18-E10	3-176413	13	1.64	0.99	9.93	< 0.3	< 1.15E-02
CR18-E12	3-176414	12.5	1.64	0.99	11.92	< 0.3	< 1.15E-02
CR18-E14	3-176415	12.5	1.64	0.99	13.91	< 0.3	< 1.15E-02
CR18-E16	3-176416	12.5	1.64	0.99	15.89	< 0.3	< 1.15E-02
CR18-E18	3-176417	12.5	1.64	0.99	17.88	< 0.3	< 1.15E-02

Appendix D-7: Iron Loading at 3 BV/h (repeat); Aged AN-107 Simulant and Resin batch # 991022smc-IV29

Sample ID	ADS #	resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Fe]_{eff}$ (mg/L)	Fe profile [C/Co]
CR3R-E1	3-176902	17.1	1.74	1.1	1.1	0.463	4.29E-02
CR3R-E2	3-176903	13.4	1.74	1.1	2.1	1.95	6.16E-02
CR3R-E3	3-176904	13	1.74	1.1	3.2	237	2.26E+01
CR3R-E4	3-176905	12.8	1.74	1.1	4.3	27.4	1.86E-01
CR3R-E5	3-176906	12.8	1.74	1.1	5.3	4.27	6.56E-02
CR3R-E6	3-176907	12.7	1.74	1.1	6.4	3.42	7.54E-02
CR3R-E7	3-176908	12.7	1.74	1.1	7.5	2.53	5.15E-02
CR3R-E9	3-176910	12.6	1.74	1.1	9.6	1.55	1.69E-02
CR3R-E10	3-176911	12.6	1.74	1.1	11.7	1.22	6.08E-2
CR3R-E12	3-176912	12.6	1.74	1.1	13.9	1.18	1.28E-03
CR3R-E14	3-176913	12.6	1.74	1.1	16.0	0.87	4.75E-3
CR3R-E16	3-176914	12.6	1.74	1.1	18.1	0.77	2.34E-3
CR3R-E18	3-176915	12.6	1.74	1.1	20.3	0.72	2.71E-3
CR3R-E20	3-176916	12.6	1.74	1.1	22.4	0.20	2.09E-3

Appendix C-8: Iron Column Elution for 3 BV/h (repeat) Test with Aged AN-107 Simulant and Resin batch # 991022smc-IV29

Elution Flow rate = 1.1 BV/h; BV is based on loading resin bed height

Sample ID	ADS #	resin bed height (cm)	Flow rate (mL/min)	Flow rate (BV/h)	# BV processed	$[Fe]_{eff}$ (mg/L)	Fe profile [C/Co]
CR3R-E1	3-176902	17.1	1.74	1.1	1.1	0.463	4.29E-02
CR3R-E2	3-176903	13.4	1.74	1.1	2.1	1.95	6.16E-02
CR3R-E3	3-176904	13	1.74	1.1	3.2	237	2.26E+01
CR3R-E4	3-176905	12.8	1.74	1.1	4.3	27.4	1.86E-01
CR3R-E5	3-176906	12.8	1.74	1.1	5.3	4.27	6.56E-02
CR3R-E6	3-176907	12.7	1.74	1.1	6.4	3.42	7.54E-02
CR3R-E7	3-176908	12.7	1.74	1.1	7.5	2.53	5.15E-02
CR3R-E9	3-176910	12.6	1.74	1.1	9.6	1.55	1.69E-02
CR3R-E10	3-176911	12.6	1.74	1.1	11.7	1.22	6.08E-2
CR3R-E12	3-176912	12.6	1.74	1.1	13.9	1.18	1.28E-03
CR3R-E14	3-176913	12.6	1.74	1.1	16.0	0.87	4.75E-3
CR3R-E16	3-176914	12.6	1.74	1.1	18.1	0.77	2.34E-3
CR3R-E18	3-176915	12.6	1.74	1.1	20.3	0.72	2.71E-3
CR3R-E20	3-176916	12.6	1.74	1.1	22.4	0.20	2.09E-3