

**MULTIPLE ION EXCHANGE COLUMN RUNS FOR
CESIUM AND TECHNETIUM REMOVAL FROM
AW-101 WASTE SAMPLE (U)**

JULY 2003

SAVANNAH RIVER TECHNOLOGY CENTER

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Test Plan
WSRC-TR-2001-00545, Rev. 1
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24590-WTP-TEF-RT-02-077

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LIST OF ACRONYMS

AW-101	Hanford Site Tank 241-AW-101
ADS	Analytical Development Section
BV	Bed volume
C _e	Equilibrium concentration of a species
C _o	Initial concentration of a species
C/C _o	Metal concentration in the column effluent divided by the metal concentration in feed
DF	Decontamination factor
DI	De-ionized water
F-Factor	Mass of oven-dried resin divided by the mass of nitrogen-dried resin
GEA	Gamma energy analysis
HLC	High level cell
HLW	High level waste
IC	Ion chromatography
ICP-AES	Inductively coupled plasma - atomic emission spectroscopy
ICP-MS	Inductively coupled plasma - mass spectroscopy
ILC	Intermediate level cell
K _d	Equilibrium sorption distribution coefficient
LSC	Liquid scintillation counter
MRQ	Minimum reportable quantity
na	not applicable
NAA	Neutron activation analysis
nm	not measured
PNNL	Pacific Northwest National Laboratory
PSD	Particle size distribution
RCRA	Resource Conservation Recovery Act
RPP-WTP	River Protection Project – Waste Treatment Plant
RSD	Relative standard deviation
SRTC	Savannah River Technology Center
TAV	Total apparatus volume
TCLP	Toxicity Characteristic Leaching Procedure
TIC	Total inorganic carbon
TOC	Total organic carbon
TTA	Thenoyltrifluoroacetone

ABSTRACT

The River Protection Project -Waste Treatment Plant (RPP-WTP) will be performing cesium (^{137}Cs) removal from Hanford tank waste supernatants using SuperLig[®] 644 resin. This work also covers technetium (^{99}Tc) removal with SuperLig[®] 639, though this is no longer in the flowsheet. These elutable resins will be used multiple times to process large volumes of radioactive waste samples and will both be subjected to chemical and radiation degradation during use at the waste treatment plant (WTP). The RPP-WTP process design assumes that resin batches can be used a minimum of 10 cycles before the resin must be replaced due to degradation. The effects of radiation and chemical degradation on SuperLig[®] 644 and 639 resins were separately studied in the past under static conditions, i.e., in contact with air, water, and simulated waste solutions. To determine the chemical degradation effects under dynamic or column conditions, Battelle, Pacific Northwest National Laboratory (PNNL), and IBC Advanced Technologies conducted multiple load/elute/regenerate cycles with simulated Hanford waste samples. Savannah River Technology Center (SRTC) was contracted to demonstrate the performance of SuperLig[®] 644 and 639 resins to treat repetitively radioactive waste solutions.

Six cycles of loading, elution, and regeneration were performed to remove ^{137}Cs from a Hanford waste sample retrieved from Tank 241-AW-101. Dual ion exchange columns of 0.57-inch (1.45-cm) in diameter were installed in the Intermediate Level Cell (ILC #2) in SRTC. The columns, designated as primary (lead) and polishing (lag) were each packed with approximately $5.3 \times 10^{-3} \text{ ft}^3$ (15 mL) of SuperLig[®] 644 resin. The cycles each consisted of processing AW-101 feed sample diluted to 5 M Na^+ , displacing residual feed from the column, eluting adsorbed ions, and conditioning the column to process the next feed solution. To ensure the lead columns experience the maximum degradation due to chemical and radiation exposure, the lead and lag columns were not reversed during the cyclic tests. Two additional ion exchange columns of 0.57-inch (1.45-cm) in diameter were installed in a radiochemical hood in SRTC. The columns were each packed with $4.24 \times 10^{-4} \text{ ft}^3$ (12 mL) of SuperLig[®] 639 resin. Five load/elute/regenerate cycles were carried out to remove ^{99}Tc from cesium-depleted effluent solutions.

The multiple load/elute/regenerate cycles demonstrated that ^{137}Cs and ^{99}Tc can be effectively removed from a 241-AW-k1k01 sample using SuperLig[®] 644 and 639 resins. A total 15 L of AW-101 waste sample at 5 M Na^+ was processed through the SuperLig[®] 644 ion exchange columns. The volume of AW-101 feed processed ranged from 168 to 225 BV at < 50% breakthrough of ^{137}Cs . The average ^{137}Cs decontamination factor (DF) achieved for the six cycles was $> 1 \times 10^4$. The percent ^{137}Cs removal was $> 99.99\%$ for each of the six cycles. Elution of SuperLig[®] 644 resin with 0.5 M HNO_3 was generally effective, except for cycle #6, where strong tailing at the base was observed. The cumulative radiation exposure for the resin in the primary column (lead column) was 1.99×10^7 rad. Less than 24% reduction of resin loading capacity was observed after completion of the six load/elute/regeneration cycles. Thus, the overall performance of the dual ion exchange column was unchanged. All major chemical constituents in the feed reported to the pretreated product solutions and the RCRA characteristically hazardous elements were below TCLP limits.

Approximately 250 BV of AW-101 solution was processed at < 10 % breakthrough of ⁹⁹Tc. The percent of ⁹⁹Tc (pertechnetate) removal was > 99.94% for each of the five cycles. Approximately 99% of the ⁹⁹Tc was eluted from resin in < 15 BV using de-ionized water at 65 °C. The DF obtained for ⁹⁹Tc was on average ~1.7 x 10³ during the five cycles. Radiation dose was not expected to reduce SuperLig[®] 639 resin capacity and, therefore, was not an issue in this test.

1.0 SUMMARY OF TESTING

1.1 OBJECTIVES

The objectives of the multiple loading/elution tests were to:

- Demonstrate that SuperLig[®] 644 and 639 resins can be used repetitively to treat radioactive waste solutions
- Quantify reduction in exchange capacity for each resin as a function of the number of loading/elution cycles
- Produce and characterize cesium and technetium eluate solutions for use in eluate evaporation tests (separate test specification)
- Pretreat the AW-101 sample to reduce the concentrations of Cs¹³⁷ and Tc⁹⁹ to meet LAW vitrification criteria
- Analyze the spent ion exchange resins to determine residual radionuclide and metals content, and to perform a modified (due to sample size) Toxicity Characteristic Leaching Procedure to determine the spent resin waste disposal pathways

1.2 CONDUCT OF TESTING

Multiple column load/elute/regenerate cycles were performed to remove ¹³⁷Cs and ⁹⁹Tc from the Hanford Tank 241-AW-101 waste sample using SuperLig[®] 644 and 639 resins, respectively. Cesium removal tests were performed in the Intermediate Level Cell (ILC #2) at the Savannah River Technology Center to provide shielding from radiation emitted by the high concentrations of ¹³⁷Cs in the feed. The tests were conducted as follows:

Actual Hanford waste solutions from Tank 241-AW-101 were passed downward through two ion exchange columns made of borosilicate glass tubing of 0.57-inch (1.45-cm) in diameter. The columns, each of which contained 15 mL (5.156 g) of N₂-dried SuperLig[®] 644 resin, were used to remove ¹³⁷Cs from the waste sample. The AW-101 waste sample was previously diluted to 5 M Na⁺. Two additional columns of the same size, each of which contained 12 mL (7.366 g) of N₂-dried SuperLig[®] 639 resin, were used to remove ⁹⁹Tc from the waste sample. The columns were arranged in series during loading and were referred to as the “lead” and “lag” columns. Prior to column loading, the columns were regenerated separately with 0.25 M NaOH. Column loaded with SuperLig[®] 644 to remove ¹³⁷Cs utilized flow rate of 0.48-0.69 BV/h, which were lower than the RPP design flow rate of 3 BV/h. The reason for the deviation from the design flow rate was to increase the dose to the resin during the loading step. Columns used to remove ⁹⁹Tc were loaded at WTP design flow rate of 3 BV/h. Elution of the cesium columns utilized 0.5 M HNO₃ at 1 BV/h and 25 °C. Technetium elution was performed using de-ionized water at 1 BV/h and 65 °C. The details of the column testing procedure are presented in section 3 (Experimental section).

The tests were performed according to the “Task Technical and Quality Assurance Plan for Cesium and Technetium Ion Exchange Using Tank 241-AW-101 Sample (U)”¹². The Task Plan was generated from the “Task Specification for Cesium and Technetium Ion Exchange Using Tank 241-AW-101 Sample”¹³. Test exceptions were documented in 24590-WTP-TEF-RT-02-077.

1.3 RESULTS AND PERFORMANCE AGAINST OBJECTIVES

The objectives of the multiple column load/elute/regenerate tests were to evaluate the combined chemical and radiation effects on Cs and Tc removal from actual Hanford waste sample from Tank 241-AW-101. The longevity of SuperLig[®] 644 and 639 resins to treat radioactive waste solutions was demonstrated in six load/elute/regenerate cycles for cesium and five cycles for technetium. The results showed that SuperLig[®] 644 and 639 resins can be used repeatedly to remove ¹³⁷Cs and ⁹⁹Tc from radioactive waste samples. After six cycles, the cumulative dose to the SuperLig[®] 644 resin was 1.99×10^7 rad and the measured cesium capacity loss for the lead column was approximately 31%. Since the dose to resin was significantly below the 10^8 rad threshold at which radiation damage to the resin becomes significant, the loss of resin capacity was due to chemical degradation⁸.

The SuperLig[®] 639 resin performance was very good. The average loading volume during the five load/elute/regenerate cycles was about 250 BV. Since cesium was removed a priori by SuperLig[®] 644 columns, the dose to resin was not an issue for technetium columns. Hence, no attempt was made to calculate the cumulative dose to the SuperLig[®] 639 resin. Technetium removal from all but three tanks at the Hanford Site meets Class A specifications. Further, the RPP-WTP has recently determined that technetium removal from the remaining three tanks is not required.

Elution of cesium from SuperLig[®] 644 was as expected for cycles 1-5. Approximately 99% of the cesium was eluted in less than 12 BV, at flow rates that varied from 0.5 (cycle #1) to 1 BV/h (cycles #2 to #6). Elution of the resin during cycle #6 tailed strongly at the base. The elution tail extended from about 13 to 24 BV before reaching a target C/Co of 0.01. Technetium was eluted very effectively from SuperLig[®] 639 using de-ionized water at 65 °C.

Analyses of the feed and product solutions show that the treated effluent from the lag column had overall cesium and technetium decontamination factors (DFs) of $> 1 \times 10^4$ and 1.7×10^3 , respectively. The percent removal of ¹³⁷Cs from the AW-101 sample was better than $> 99.99\%$ for all six cycles; the percent removal of ⁹⁹Tc (pertechnetate) exceeded 99.94% for the five cycles. The effluent composite product analysis showed that all major constituents in the feed were accounted in the effluent product solutions. Large dilutions prevented detection of most analytes in cesium and technetium eluate product solutions. The analysis of SuperLig[®] 644 and 639 spent resins from the lead columns showed all RCRA characteristically hazardous elements were below theoretical TCLP limits. A detailed analysis of the results will be provided in Section 4 (Results and Discussions) of the report.

1.4 QUALITY REQUIREMENTS

SRTC conducted this work in accordance with the quality assurance (QA) plan approved by the RPP-WTP QA organization. SRTC has provided to WTP matrices contained in the task and technical QA Plan, demonstrating compliance of the SRTC QA program with the requirements specified by WTP. (Note: since the goal of spent resin analysis was not longer for environmental permitting, the requirement of the QAPjP (PL-24590-QA00001) was not applicable. The work was conducted to the requirements of NQA-1 1989, Part 1, Basic and Supplementary Requirements and NQA-2a 1990, Subpart 2.7, as indicated by the QA Plan Checklist in Section VIII of reference 12. The work was also implemented in accordance with the WSRC Quality Assurance Program, which has been approved by WTP. The measuring and test equipment used in the testing is in compliance with the SRS QA Program. The data collected and reported was verified by an independent technical reviewer.

1.5 ISSUES

None

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2.0 INTRODUCTION

The River Protection Project Waste Treatment Plant (RPP-WTP) has identified a process to vitrify Hanford tank waste into low activity and high level waste glass wastefoms. The process includes sludge washing, filtration, precipitation, and ion exchange unit operations. Each of these operations removes certain radionuclides from the bulk of the waste and produces a relatively small volume of high level waste (HLW) sludge. This sludge is vitrified with glass forming compounds as high activity level glass. The remaining Low Activity Waste (LAW) after pretreatment contains the bulk of the waste volume and is vitrified as a low activity glass.

Removal of ^{137}Cs and ^{99}Tc is required to produce low activity waste from Hanford tank waste supernates using two ion exchange resins, SuperLig[®] 644 and 639 from IBC Advanced Technologies, American Fork, Utah. Extensive experimental investigations were conducted at Savannah River Technology Center (SRTC) and Battelle, Pacific Northwest National Laboratory (PNNL) with actual waste samples from Tanks 241-AW-101, 241-AN-103, 241-AN-102, 241-AZ-102, 241-AN-107, 241-AP-101, and a mixture of 241-AN-102 and a leachate from C-104 sludge.¹⁻⁷ The experiments focused on the decontamination factors produced by the resins for ^{137}Cs and ^{99}Tc removal from each of the waste tanks. The radiation stability of SuperLig[®] 644 was studied under static conditions (i.e., batch irradiation tests with resins in contact with air, water, and simulant waste solution)^{5, 8, 9}. The effects of chemical degradation were studied by IBC Advanced Technologies and Battelle, PNNL with simulated Hanford waste samples^{10, 11}. These studies were to quantify the decrease in resin performance due to combined effects of radiation and chemical degradation and to provide information on the RCRA metals and radionuclide contents of the spent resins.

The objective of this work was to perform multiple ion exchange column tests using Hanford tank waste supernatants from Tank 241-AW-101. The multiple load/elute/regenerate tests will quantify the decrease in ion exchange capacity and the loss of SuperLig[®] 644 and 639 resin performance as a function of received dose. The multiple column tests were also aimed at producing pretreated product solutions for use in the LAW glass vitrification and assessing the disposal pathways for the spent resins. The experiments were performed according to the "Task Technical and Quality Assurance Plan for Cesium and Technetium Ion Exchange Using Tank 241-AW-101 Sample (U)".¹² The Task Plan was generated from the "Task Specification for Cesium and Technetium Ion Exchange Using Tank 241-AW-101 Sample".¹³ This report will present the results from the multiple cycle tests and will discuss the resin performance as a function of the cycles.

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3.0 EXPERIMENTAL

3.1 FEED PREPARATION

A total of thirty 500-mL glass jars of waste samples from Tank 241-AW-101 were received at SRTC in January and March 2001. The 500-mL grab samples were obtained from riser 22 of the 241-AW-101 waste tank in July, 2000. The as-received 241-AW-101 samples were mixed together. They were then diluted with deionized water to provide supernate with a 5M Na⁺ concentration. The dilution was performed in the High Level Cells (HLC) at SRTC. After dilution the bulk solution was sampled and analyzed. The homogenization, dilution, and characterization of diluted bulk solution was reported by Hay.¹⁴

The bulk solution was filtered through a 0.1-micron sintered metal Mott crossflow filter to remove entrained solids.¹⁵ A total 15 L of the AW-101 filtrate at 5M Na⁺ was transferred from the HLC to the Intermediate Level Cell (ILC) in 4-L polyethylene bottles. After the transfer to the ILC, the solutions in individual transfer bottles were not further homogenized. However, randomly selected bottles were analyzed by gamma energy counting and ICP-AES to determine the concentration of ¹³⁷Cs and metals, respectively. The total cesium was determined by ICP-MS. It was found to be 3.8 times the amount of ¹³⁷Cs present in waste sample. The total cesium includes ¹³³Cs, ¹³⁵Cs, ¹³⁶Cs, and ¹³⁷Cs. The solutions in the individual transfer bottles were used for multiple ion exchange column loading/elution testing.

A simulant representing the AW-101 waste sample was prepared from the best available recipe.¹⁶ Approximately 1.5 L of the simulant at ~ 5M sodium concentration was prepared. After preparation the simulant was allowed to stand for 24 hours, then filtered through a 0.45- μ m filter. Duplicate samples of the filtrate were analyzed to determine the concentrations of Cs, Re, metals, anions, hydroxide, and total organic carbon. The compositions of the diluted AW-101 actual waste and simulant solutions are shown in Table 3-1.

3.2 RESIN PROPERTIES

SuperLig[®] 644 was used to remove ¹³⁷Cs from the AW-101 waste sample while SuperLig[®] 639 resin was used for ⁹⁹Tc removal. The resins were developed and supplied by IBC Advanced Technologies, American Fort, Utah. The SuperLig[®] 644 (batch # I-D5-03-06-02-35-60, also called the “one-gallon batch”) was received wet in the hydrogen form. A small mass of the resin was dried under nitrogen at room temperature and then stored in a tight-capped bottle prior to use in batch contact and column load/elute/regenerate testing. The SuperLig[®] 639 (batch # I-R2-03-27-02-20-45) was received wet in de-ionized water. A small mass of the resin was dried under nitrogen at room temperature for use in batch and column load/elute/regeneration testing.

Table 3-1. Composition of AW-101 Feed Samples

Analyte	AW-101, ILC	AW-101, HLC [¶]	Simulant
⁹⁹ Tc, µg/L	4.02E+03	nm	na
⁹⁹ Tc*, µCi/mL	6.62E-02	7.31E-02	na
¹³⁷ Cs, µCi/mL	1.75E+02	1.76E+02	na
¹³³ Cs, µg/L	4.16E+03	4.74E+03	nm
¹³⁵ Cs, µg/L	1.46E+03	1.46E+03	nm
¹³⁶ Cs, µg/L	9.22E+01		nm
¹³⁷ Cs, µg/L	2.05E+03	2.08E+03	na
Total Cs, µg/L	7.76E+03	nm	8.59E+03
Total Cs, M	5.84E-05	nm	6.46E-05
Total carbon, µg/L	2.21E+03		2.75E+03
TIC, mg/L	8.52E+02	9.18E+02	1.05E+03
TOC, mg/L	1.36E+03	9.92E+02	1.70E+03
Free OH-, M	1.81E+00	1.94E+00	1.78E+00
²³⁸ U/Pu, ug/L	1.56E+03	nm	nm
²³⁸ U/Pu, M	6.57E-03	nm	nm
specific gravity	1.25E+00	1.25E+00	1.25E+00
IC (anions), M			
Cl ⁻	6.94E-02	7.67E-02	6.71E-02
F ⁻	9.48E-02	1.42E-02	3.79E-03
HCOO ⁻	2.43E-02	2.32E-02	2.22E-03
NO ₃ ⁻	1.25E+00	1.56E+00	6.84E-01
NO ₂ ⁻	9.97E-01	1.13E+00	7.98E-01
(C2O4) ₂ ⁻	2.58E-03	3.28E-03	1.12E-03
PO ₄ ⁻	4.70E-03	nm	2.06E-03
SO ₄ ⁻	1.77E-03	1.51E-03	1.64E-03
ICP-AES, M			
Al	4.74E-01	6.04E-01	5.02E-01
B	1.68E-04	1.68E-03	3.89E-05
Ba	2.58E-06	2.98E-05	1.34E-04
Ca	1.97E-05	1.56E-04	6.06E-04
Cd	3.07E-07	1.51E-05	2.49E-07
Cr	9.17E-05	9.67E-04	2.56E-05
Cu	9.08E-06	nm	1.57E-06
Fe	5.64E-06	3.84E-05	9.80E-05
K	4.68E-01	5.98E-01	4.27E-01
Na	5.09E+00	4.96E+00	4.87E+00
Na/K	1.09E+01	8.28E+00	1.14E+01
Na/Al	1.08E+01	8.20E+00	9.70E+00
Na/Cs	8.81E+04	nm	7.54E+04
K/Cs	8.11E+03		6.61E+03

[¶] (see ref. 14)

nm = not measured; na = not applicable

The physical properties measured for the resins were bulk density, particle (skeletal) density, F-factor, and particle size distribution. The bulk density was determined by weighing a small mass of nitrogen-dried resin into a graduated cylinder filled with de-ionized water and measuring the resin volume after tamping the cylinder walls to obtain uniform packing. The skeletal density was determined using a pycnometer. The F-Factor (ratio of oven-dried mass to nitrogen-dried mass of the resin) was determined by weighing approximately 2.205×10^{-3} lb (1.0 g) of resin and drying in a vacuum oven at 45 ± 5 °C until a constant mass was obtained. The metals content (Na⁺ and K⁺) in the “as received” resins was determined by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) analysis of the digested resins. The particle size distributions (PSD) were determined by dry sieve analysis on nitrogen-dried resin. The wet particle size distribution of the resin was determined using a Lazentec instrument. Some physical properties of the SuperLig[®] 644 and 639 resins are presented in Table 3-2.

Table 3-2. Properties of SuperLig[®] 644 and 639 Resins

Property	SuperLig[®] 644	SuperLig[®] 639
Batch ID	I-D5-03-06-02	I-R-30-27-02
F-Factor	0.64	0.98
Bulk density (nitrogen-dried basis)	0.24 g/mL	0.41 g/mL
Skeletal density	1.56 g/mL	nm
Particle size	35-60 mesh	20-45 mesh
Mean particle size	425 micron	475 micron
Metals – Na, K (mg/g)	0.64, 0.03	nm

nm = not measured

3.3 EQUIPMENT

The equipment for batch contact testing for cesium and rhenium (surrogate for Tc) included an incubator shaker, filtration unit, a vacuum oven for F-Factor determination, an analytical balance, a high precision thermometer, and 20-mL high density polyethylene bottles. New Brunswick Scientific Co., Edison New Jersey, supplied the incubator shaker (model C24), Nalgene Nunc International, Rochester, New York, supplied Nalgene[®] filter units, and the analytical balance (model AG285) was obtained from Mettler Toledo, Ohio. The analytical balance was accurate to ± 0.001 g. A high precision (0.01 °C) thermometer traceable to National Institute of Standards and Testing (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. In the cell, a smaller Maxi Mix III orbital shaker was used instead of an incubator shaker to perform batch contact testing with the actual AW-101 waste solutions. The shaking speed of the orbital shaker was sufficient to swirl the solution and resin without excessive agitation, which might damage the resin.

The experimental apparatus for the ion exchange column tests were dual glass columns, FMI pumps, auto-sampling units, and a constant temperature water-bath circulator. The apparatus was housed in the intermediate level cell in SRTC. The columns were made of borosilicate glass tube with adjustable plungers on the tops. The inside diameter of the columns was 0.57-inch (1.45-cm) and the total length was 6 inches (15 cm). When connected in series, the primary column was referred to as the "lead," while the secondary column was referred to as the "lag." The outside of the column walls was coated with a layer of clear polyvinyl chloride to reduce hazards associated with potentially pressurizing the columns. A ruler affixed to the column walls allowed visual observation of the resin bed height and liquid level changes during column runs. The adjustable plungers at the top of the columns were used to eliminate freeboard (headspace) liquid and to minimize the volumes of secondary waste generated. The columns were equipped with SRTC-patented 200-mesh screens to hold the resin in place. A closed-loop constant-temperature water-bath circulator pumped water through the jacket around the columns to provide precise bed temperature control. All tubing connections were made of polypropylene lines, which had Teflon[®] quick-connect fittings attached to each end. Solutions were passed downward through the columns.

Liquid delivery into the columns was accomplished using FMI metering pumps (model RP-1, Fluid Metering, Inc. Oyster Bay, NY). The pump heads had shaft sizes of 1/18", 1/4", and 3/8" to produce desired wide range of desired flow rates. The pumps were run at the desired flow rates by specifying the rotational speed of the motor (RPM), which was driven by direct current (D.C). The pump controllers/readout were located in a service console outside the cell. Volumetric flow rates were determined from the mass of lag column effluent composite fractions, the density, and the time to collect the effluent composite fractions.

3.4 SAMPLING AND ANALYSIS

Sampling the ion exchange columns was accomplished using custom-designed auto-sampling apparatus. The apparatus consisted of assembly pieces that can be directly installed in the hot cell. The main piece was an electrically actuated six-position rotary valve with 1/16" flangeless tubing. The valve was mounted on an aluminum plate, 3" tall x 3" wide. At the bottom of the valve, six holes were drilled on the back of a second support plate (6" tall x 6" wide) and six stainless steel tubes (1/16" ID) were connected through ball head fittings. Polypropylene tubing (1/16" ID) was used to connect the rotary valve to the stainless steel tubing, which directed samples into sample vials. The carousel slipped into a section-groove (5/8" deep x 3" long) in the middle of a solid polyethylene block (4 1/2" long x 3" wide x 2 1/2" high) for support. The carousel and the solid block were then raised by a small jiffy-jack to align the vials with stainless steel tubing, which delivered the sample into the sample vials in a way that minimized evaporation during sampling was minimized. The rotary valve was controlled from a service console located outside of the cell and involved no use of a cell manipulator. Instructions were provided to allow the rotary valve to be programmed for unattended sampling.

The basic sampling mechanism was to divert small aliquots (~ 6 mL) of the column effluent into one of five sampling valve positions for collection in vials. A valve opened every 14 hours and 15 minutes to collect samples in an 8-mL glass vial for 45 minutes. Dilution of each sample by residual liquid in the valve tubing during a sampling event was less than 10%. However, this created unexpected data spikes in the loading data for several cycles, for which the rinse and purge of the liquid out of the valve tubing after elution was incomplete.

Samples of the effluent were collected from the lead column in 10 BV increments. The lag column was sampled every 20 BV. The samples were submitted to the Analytical Development Section (ADS) and analyzed per approved procedures. The analyses performed included inductively coupled plasma – atomic emission spectroscopy (ICP-AES) - metals and ^{99}Tc , ion chromatography (IC) – anions, gamma energy analysis (GEA) – ^{137}Cs , inductively coupled plasma-mass spectroscopy (ICP-MS) – actinides, ^{99}Tc and Cs, total organic carbon (TOC), and free hydroxide (OH^-).

The ^{99}Tc concentration was determined by chemical separation and beta counting method. A 1 milliliter aliquot of the AW-101 sample was spiked with $^{99\text{m}}\text{Tc}$ tracer and diluted with nitric acid to adjust the concentration to 0.2 M HNO_3 . The 0.2 M HNO_3 solutions were added to pre-conditioned Eichrom TEVA columns. The columns were rinsed successively with dilute nitric and 1 M NaOH . The ^{99}Tc in the sample was eluted from the columns using two successive additions (5 mL) of 9 N HNO_3 . The eluate was neutralized with NaOH and poured through Eichrom TEVA Discs, which were pre-conditioned with 0.1 N nitric, prior to assay. The Eichrom TEVA Discs were added to a liquid scintillation cocktail, analyzed by gamma spectrometry (to quantify Tc-99m recoveries) and then after a suitable decay period, liquid scintillation (LS) spectrometry was applied to quantify the ^{99}Tc (pure beta emitter) in the sample. The gamma measurements were conducted using a NaI well counter in conjunction with a Canberra Industries Genie2K gamma spectroscopy platform. Liquid scintillation analyses were conducted using a Packard Industries 2750AB Liquid Scintillation Analyzer. The details of this separation and beta counting method were reported by Sigg.¹⁷

3.5 PROCEDURE

3.5.1 Batch Contact Tests

Batch contacts were performed using the AW-101 actual waste and simulant solutions, and SuperLig[®] 644 and 639 resins. The actual waste solution (AW-101) contained 175 $\mu\text{Ci/mL}$ ^{137}Cs and 0.064 $\mu\text{Ci/mL}$ ^{99}Tc (pertechnetate form). The bulk simulant (at 5 M Na^+) contained 8.59×10^3 $\mu\text{g/L}$ of Cs (total) and 4.73×10^3 $\mu\text{g/L}$ of rhenium. The measurements were carried out in duplicate at a liquid volume to resin mass ratio (phase ratio) of 10 and 100. Typically, 3.53×10^{-4} ft^3 (10 mL) of the solution was added to 2.205×10^{-4} lb (0.1 g) or 2.205×10^{-3} lb (1.0 g) of nitrogen-dried resin in high-density polyethylene bottles.

The volume of solution was transferred by pipette, but the mass and density of the solutions were used to determine the actual volume. The phase ratio of 10 was used to ensure that higher than detection values are obtained for competing ions. All contacts with resin were made for a period of 48 hours. Agitation was provided by an incubator shaker set at 275 rpm for AW-101 simulant, and a Maxi Mix orbital shaker, adjusted between 400 and 600 rpm, was used for actual AW-101 waste solution. The temperature in the cell was not controlled, but was recorded as 25 ± 1 °C during the period of contact. Duplicate control samples (i.e., solution without resin) were prepared and treated in the same manner as the contact samples. After the contact period of 48 hours, the solutions were separated from the ion exchange resins by filtration through a 0.45-micron Nalgene[®] filter unit.

Small aliquots of the filtrate were analyzed by GEA to determine the ¹³⁷Cs concentrations. Inductively coupled plasma-mass spectroscopy (ICP-MS) was used to determine the concentrations of cesium (total) and rhenium (surrogate for technetium). Chemical separation and beta counting method was used to determine the ⁹⁹Tc (pertechnetate) concentration in filtered solutions. Aliquots of the control samples were diluted with 1:10 volume ratio of de-ionized water in order to reduce the dose rate and transfer samples out of the cell.

3.5.2 Simulant Column Tests

Single-column load/elute/regenerate tests were performed for cesium and rhenium (surrogate for technetium) removal from AW-101 simulant prepared per Eibling recipe¹⁶. The tests were aimed to confirm the ion exchange columns were properly functioning before processing AW-101 actual waste solution. Dual ion exchange columns (lead and lag) were connected in series during the loading phase. The columns were prepared as follows: A known mass of nitrogen-dried SuperLig[®] 644 resin (batch # I-D5-03-06-02-35-60) was weighed in a HDPE bottle. The resin was soaked in de-ionized water and then added through a funnel into the columns. An as-measured mass of 5.1562 g of the resin was added each into the lead column; the lag column contained 5.5313 g. To ensure uniform packing of resin, the column walls were tapped gently with a rubber stopper while the resin particles were gravity settling in the columns. After the resin was added, the columns were each pre-conditioned with 12 BV of 0.25 M NaOH. The pre-conditioning solution was pumped as down flow separately into the lead and lag columns at 3 BV/h. The resin was allowed to stand in the pre-conditioning solution overnight. The volume of the swollen resin bed in the lead column was ~ 14.8 mL. The lag column had initial swollen bed volume of ~ 16.5 mL.

Rhenium (surrogate for technetium) columns were prepared by adding 7.3659 and 7.3651 grams of SuperLig[®] 639 resin (batch # I-R2-03-27-02-20-45) into two HDPE bottles. The resin in each bottle was soaked in 0.25 M NaOH for one hour and then added into the columns designated as “lead” and “lag”. The resin bed was constrained with quartz wool and 3-mm glass beads. Twelve BV's of 0.25 M NaOH was pumped separately as down flow into each column at 3 BV/h. The columns were stored in the 0.25 M NaOH solution overnight. The SuperLig[®] 639 resin beds exhibited no swelling during overnight storage.

After preconditioning, the lead and lag columns were connected in series. The feed was pumped as down flow with a single pump in the upstream position. Loading the columns was considered to start the moment the simulant contacted the liquid on top of the resin bed. The cesium and rhenium columns were loaded at 0.67 and 3 BV/h, respectively. The effluent was collected in polyethylene bottles from the lag columns. The first 3 BV of effluent were discarded as a waste because of the feed dilution with residual NaOH in the columns. The first effluent sample from the cesium column (lead) was collected manually after 5 BV of feed had passed through the column. Subsequent samples of effluent from the lead column were collected via the auto-sampler every 10 BVs. Individual samples of the effluent from the lag column were collected manually every 20 BVs. Samples of the effluent from the rhenium columns were collected at intervals of 10 and 20 BVs for the lead and lag, respectively. The heights of the resin beds and the liquid levels in the columns were recorded several times during the day.

After loading, the columns were washed with 4 BV of 0.1 M NaOH solution and rinsed with 4 BV of de-ionized water. The solutions were pumped as downflow through the lead into the lag column at 3 BV/h. The effluent was collected from the bottom of the lag column and discarded as waste. The 0.1 M NaOH solution was used to displace the feed and remove sodium aluminate from the columns prior to water washing. This was done to avoid aluminum precipitation on the resin beds. To avoid exothermic reaction with nitric acid during the elution, the 0.1 M NaOH solution was displaced from the columns with deionized water rinse. The lead and lag columns were disconnected after completing the water rinse step. The columns were eluted separately.

Cesium elution was accomplished using 0.5 M HNO₃ solution. Rhenium was eluted with de-ionized water at 65 °C. The lead and lag columns were eluted separately at ~1.0 BV/hr and only the lead columns were sampled. Elution was considered to begin the moment the eluent contacted the liquid solution above the resin beds. The eluate passing from the bottom of each column was collected in polyethylene bottles. The eluate samples from the lead cesium ion exchange column were collected via the auto-samplers every 1 BV or one hour for the first 5 hours. Sampling frequency was changed to every 2 BV or two hours for the next 10 hours. The eluate samples from the rhenium columns were collected in 1 BV increments using an automatic fraction collector. Rhenium elution was continued for up to 26 BV. After elution, the columns were each washed separately with 4 BV of deionized water at 1 BV/h. The columns were stored in de-ionized water for several weeks prior to initiating the multiple cycle column tests. Samples of the eluate were analyzed by ICP-MS for cesium and rhenium concentrations. Composite samples of the cesium and rhenium eluate were also prepared and analyzed by ICP-MS.

3.5.3 Cesium Column Multi-Cycle Tests –Hot Cell

Multiple column runs for cesium removal from the AW-101 waste sample were conducted in a shielded cell (Intermediate Level Cell or ILC #2) in SRTC. The equipment for the cesium ion exchange was transferred from the chemical hood, where the simulant test was performed, to the hot cell. The ion exchange columns, pumps, auto-samplers were remotely installed inside the cell using remotely controlled manipulator arms. A photograph of the equipment in operation inside the hood is shown in Figure 3-1. A summary of the test conditions for the cesium and technetium ion exchange systems is shown in Table 3-3

Table 3-3. A Summary of the Test Conditions

AW-101 Column Tests	SuperLig® 644	SuperLig® 639
Column size, cm	1.45	1.45
Dual column set-up	Lead & lag	Lead & lag
Bed volume, mL	15	12
Mass of resin/column, g	5.1562 (H- form)*	7.3659
Resin batch #	I-D5-03-06-02-35-60	I-R-03-27-02-20-45
Preconditioning solution	0.25 <u>M</u> NaOH	0.25 <u>M</u> NaOH
Displacement solution	0.1 <u>M</u> NaOH	0.1 <u>M</u> NaOH
Flow rate, BV/h		
Loading	0.48-0.69	3.0
Displacement	3.0	3.0
Elution	1.0	1.0
Temperature		
Loading	25 °C	25 °C
Elution	25 °C	65 °C
Eluant	0.5 <u>M</u> HNO ₃	De-ionized water
Sampling frequency, BV		
Lead column	10	10
Lag column	20	20
[¹³⁷ Cs]o, µCi/mL	175	NA
[⁹⁹ Tc]o, µCi/mL	NA	0.0662

* air-dry

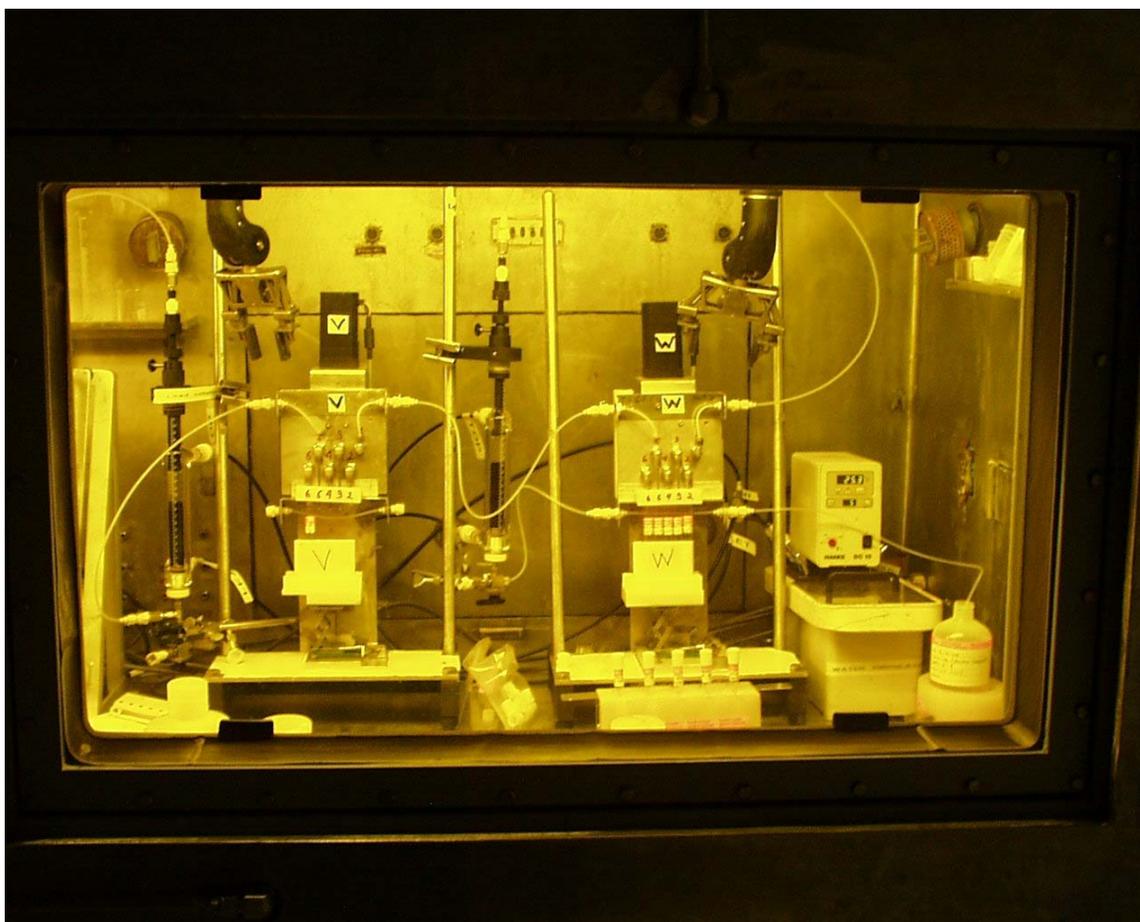


Figure 3-1. Photograph of Test Equipment in Operation Inside the Hot Cell

The lead and lag columns were each regenerated using 12 BV of 0.25 M NaOH. The 0.25 M NaOH solution was pumped as down flow into each column at a flow rate of 3 BV/h and the effluent was collected in polyethylene bottles. The heights of resin beds and the liquid levels in the columns were measured during regeneration step. After regeneration, the lead and lag columns were connected in series. The pump delivering feed to the lead column was connected to a feed bottle containing diluted AW-101 sample. The pump was set to the target flow rate of 0.67 BV/h, but the flow rates drifted slightly downward during the column runs. The low flow rate was chosen to maximize radiation exposure of resin bed in the lead column. The custom auto-sampler was programmed for the desired sample volume, frequency of collection, and number of samples. The pump was then turned on. Samples of the effluent from the lead and lag columns were collected every 10 and 20 BV, respectively.

The column loading was considered to start when the feed contacted the liquid on top of the resin bed in the lead column. The heights of resin bed and the liquid level were measured for each column at this time. The initial 3 BV's of the effluent from the lag column, which contained 0.25 M NaOH solution, were discarded into a waste residue bottle. Flow rate through the columns was initially verified by timing the collection of a small sample volume (6 mL) of the effluent from the bottom of the lag column. The volume and the time of its collection provided the check on the flow rate. Later, flow rates were determined by weighing composite effluent solutions from the lag column of about 20 BV every 30 h. The loading of the columns was continued until approximately 200 BV of the AW-101 waste sample was processed. The composite effluent fractions collected from the lag column were weighed and the volume of each fraction was determined based on its mass and density. A sub-sample was taken from each composite fraction and analyzed for ^{137}Cs .

After loading, a feed displacement (0.1 M NaOH) and de-ionized water rinse were performed using 4 BVs of each solution at a flow rate of 3 BV/h. Once the columns were washed and rinsed, they were disconnected and then eluted separately with 0.5 M HNO_3 . Elution was carried out as downward flow at ~ 1 BV/h. Samples of the eluate were collected via the auto-samplers every 1 BV for the first 5 BVs and every 2 BVs until a total of 15 BVs of the eluant was processed. Samples of the eluate and composite fraction from the lead column were analyzed only for ^{137}Cs . The elution volume was determined using the original volume of the sodium hydroxide form resin beds during the loading phase, as a basis. When elution was complete, each resin bed was rinsed with 4 BVs of de-ionized water at a flow rate of 1 BV/h. The lead and lag columns were regenerated separately in a downward flow with 12 BVs of 0.25 M NaOH at 3 BV/h. The procedure described above was repeated for each cycle.

3.5.4 Technetium Column Runs

The load/elute/regenerate experiments for ^{99}Tc (TcO_4^- form) was carried out inside a radiochemical hood. A photograph of the apparatus is shown in Figure 3-2. The load tests started after sufficient effluent were collected from the cesium column runs. The lead and lag columns were each regenerated using 12 BV of 0.25 M NaOH. The columns were regenerated separately at 3 BV/h. After regeneration, the columns were connected in series and the solution was pumped as down flow at 3 BV/h. After loading, the feed displacement step with 0.1 M NaOH. Samples of the feed solutions were collected at 0.5 BV increments from the bottom of the lead column. The elution of the lead and lag columns was performed separately. The eluant (deionized water) bottle and the column jacket were preheated to 65 °C. The eluent was pumped as down flow at 1 BV/h. Eluate samples were collected every 0.5 BV for the first 4 BVs and the every 2 BVs thereafter, until a total of 26 BVs of eluent was processed. After elution, the columns were regenerated with 12 BV of 0.25 M NaOH to prepare for the next cycle.



Figure 3-2. Photograph of Test Equipment in Operation Inside the Radiochemical Hood

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4.0 RESULTS AND DISCUSSION

4.1 BATCH CONTACT TESTS

Batch contact tests were aimed at measuring the equilibrium distribution coefficients (K_{ds}) for cesium and technetium. The K_{ds} were calculated according to the following equation:

Equation 1

$$K_d = \left[\left(\frac{C_o}{C_e} \right) - 1 \right] \left[\frac{V}{M * F} \right]$$

where

C_o and C_e = the analyte concentration in the waste solution before and after contacting with resin

V = the volume of solution used

M = the mass of resin (nitrogen-dry in H-form)

F = the F-factor defined as the ratio of the nitrogen-dried resin mass to that of the oven-dried mass.

Typically, the distribution coefficients are measured at equilibrium so the data represents one point on the equilibrium isotherm. The K_d is used as an indicator of the affinity of an ion towards the resin in the presence of a complex matrix of interfering ions.

In this work, the K_d measurements were performed in duplicate at liquid to solid phase ratio of 100 and 10, at contact times of 48 h. The cesium K_d s for both AW-101 simulant and actual AW-101 waste solutions are presented in Table 4-1. The average K_d of 1540 mL/g is in good agreement with the value of 1317 mL/g reported by Fiskum et al.¹⁸ using SuperLig[®] 644 resin (batch # BZ) and AW-101 simulant. The ¹³⁷Cs K_d value of 1368 mL/g for AW-101 actual waste sample compares reasonably well (i.e. within 30%) with the K_d value reported by Hassan and McCabe for unidentified batch of SuperLig[®] 644, using a liquid to solid ratio of 100 for a contact time of 24 h.¹⁹

The ⁹⁹Tc K_d s are presented in Table 4-2. The values of 802 and 238 mg/L were the average of duplicate measurements for ⁹⁹Tc (pertechnetate) at phase ratios of 100 and 10 mL/g, respectively. The reason for the decline of the K_d obtained at the phase ratio of 10 mL/g is not known. However, the density of SuperLig[®] 639 was about the same as the AW-101 actual waste solution. Therefore, floating of the resin during the batch contact testing could have resulted in relatively poor contact of the resin and solution. The K_d of 802 mL/g obtained in this study is 47% less than the K_d previously reported for AW-101 actual waste solution by Hassan and McCabe.¹⁹

Table 4-1. K_d s for Cesium in AW-101 Actual Waste and Simulant Solutions

AW-101 Actual Waste	phase ratio, mL/g	$[^{137}\text{Cs}]_0^*$ ($\mu\text{Ci/mL}$)	$[^{137}\text{Cs}]_e$ ($\mu\text{Ci/mL}$)	K_d (mL/g)	avg. K_d (mL/g)	% RSD
NH44-AW101-Kd-1	99	175	20.2	1268	na	na
NH44-AW101-Kd-1D	98	175	17.6	1468	1368	10.4
NH44-AW101-Kd-2	9.7	175	1.1	2672	na	na
NH44-AW101-Kd-2D	9.5	175	1.0	2810	2741	3.6
AW-101 Simulant	phase ratio, mL/g	$[\text{Cs}]_0^*$ ($\mu\text{Ci/mL}$)	$[\text{Cs}]_e$ ($\mu\text{Ci/mL}$)	K_d (mL/g)	avg. K_d (mL/g)	% RSD
NH44-AW101Sim-Kd-1	98	9515*	896	1572	na	na
NH44-AW101Sim-Kd-1D	98	9515*	932	1508	1540	2.9

* $[\text{Cs}]_0$ measured in simulant control samples of $9.52 \times 10^3 \mu\text{g/L}$ is 9.7% higher than $[\text{Cs}]_0$ of $8.59 \times 10^3 \mu\text{g/L}$ in the bulk stimulant (see Table 3-1).

na = not applicable

Table 4-2. K_d s for Technetium in AW-101 Actual Waste Sample

AW-101 Actual Waste Sample ID	phase ratio, mL/g	$[^{99}\text{Tc}]_0$ ($\mu\text{Ci/mL}$)	$[^{99}\text{Tc}]_e$ ($\mu\text{Ci/mL}$)	K_d (mL/g)	avg. K_d (mL/g)	% RSD
NH39-AW101-Kd-1	96	4725	492	839	na	na
NH39-AW101-Kd-1D	90	4725	508	766	802	6.4
NH39-AW101-Kd-2	9.5	4725	190	231	na	na
NH39-AW101-Kd-2D	9.5	4725	181	245	238	4.1

na = not applicable

4.2 SIMULANT COLUMN TESTS

Figure 4-1 displays the results for the AW-101 simulant lead column test. The cesium concentration profile (C/C_0) was plotted in a log scale against the number of BV of simulant processed. In this run, we processed only 110 BV of AW-101 simulant and a cesium breakthrough was not observed. Elution of the lead and lag columns was carried out separately at 25 ± 1 °C and at a flow rate of ~ 1 BV/h. The columns were eluted with down flow of 15 BV of 0.5 M HNO_3 . The C/C_0 elution peak was observed after 3 BV (Figure 4-1); the C/C_0 value of 0.01 was reached at 7 BV. The results from this shake-down simulant test demonstrated the ion exchange columns were properly functioning to be used for multiple load/elute/regenerate cycles with the radioactive waste sample.

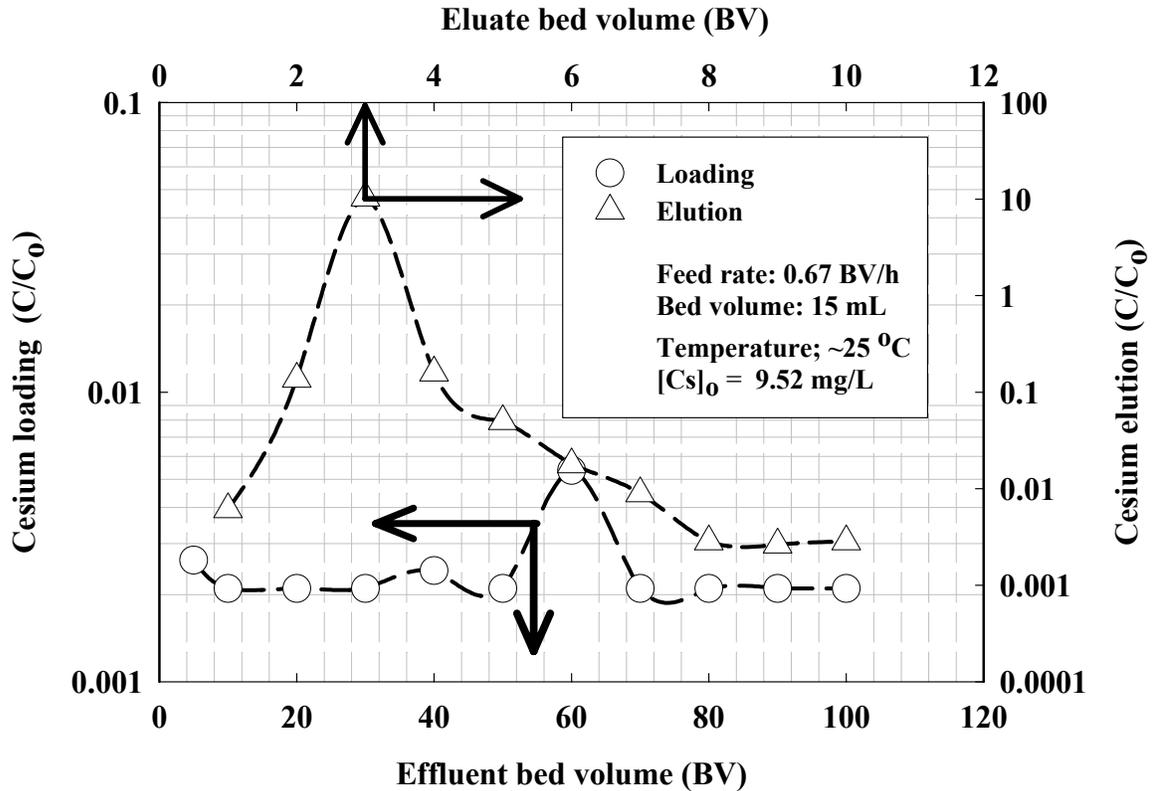


Figure 4-1. Cs Breakthrough and Elution Curves - Simulant

Figure 4-2 displays the lead column loading and elution data for Re (surrogate for Tc) with AW-101 simulant. The C/Co for rhenium was plotted on log scale against the number of BV processed. The C/Co was constant (0.012) up to 112 BV of simulant processed, and then it increased linearly on the log scale as the loading progressed. The C/Co of 0.1 was observed at 192 BV. Rhenium was eluted from the lead and lag columns separately with deionized water at 65 °C and at a flow rate of ~1 BV/h. The rhenium elution was fast, exhibiting a C/Co peak after at 2.5 BV. The C/Co of 0.01 was reached at 12 BV. Since the SuperLig® 639 resin floated earlier in the AW-101 simulant run, the resin beds were restrained with quartz wool and glass beads, thus preventing potential channeling problems. Based on the results from this simulant shake-down test, the ion exchange columns were regarded as being well packed and properly functioning for use with radioactive waste sample.

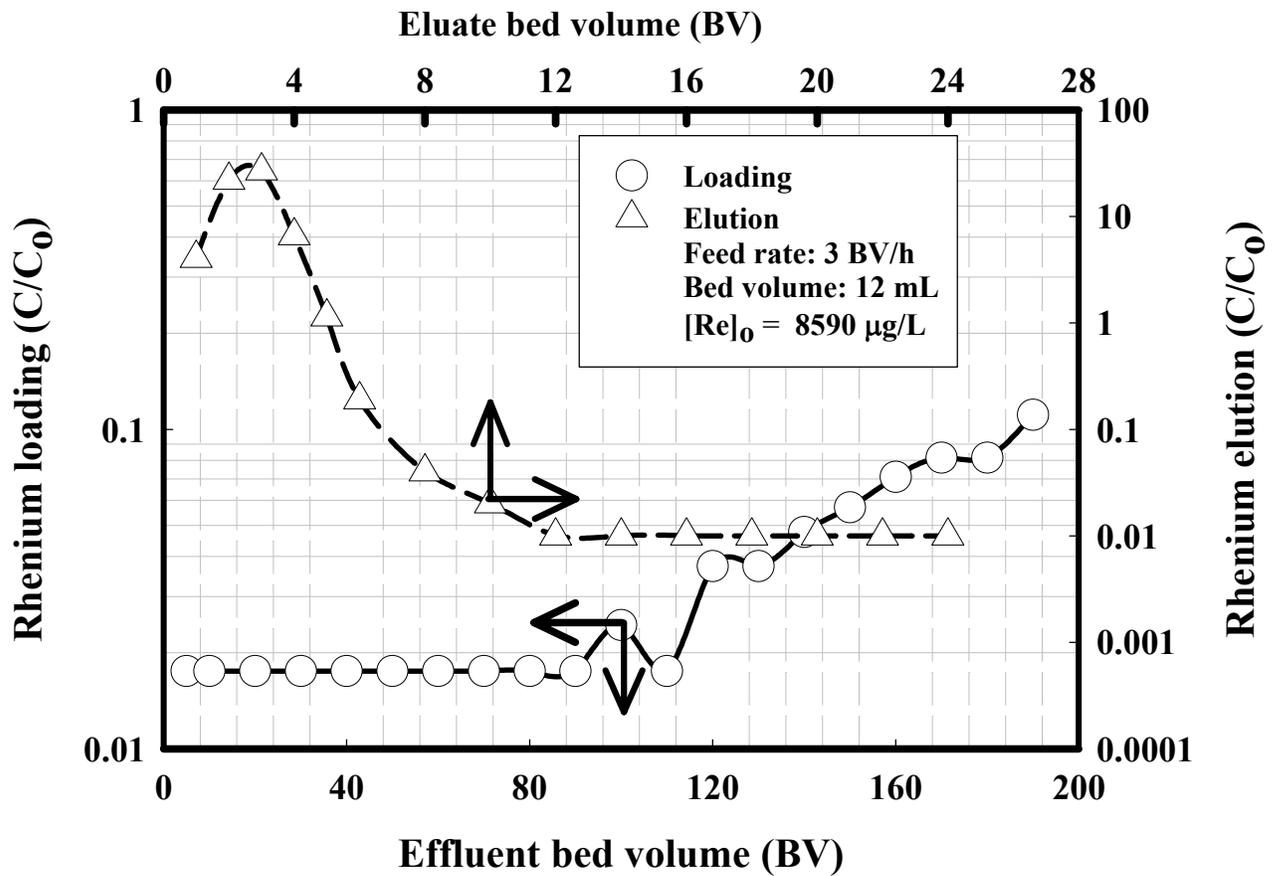


Figure 4-2. Re Breakthrough and Elution Curves - Simulant

4.3 CESIUM LOADING CYCLES

The multiple load/elute/regenerate cycles were carried out in a hot cell using a dual ion exchange column system. Six load cycles were performed to remove ^{137}Cs from AW-101 waste sample. The AW-101 sample at 5 M Na^+ was loaded onto the columns at a flow rate of 0.49-0.69 BV/h. The columns were then washed with 0.1 M NaOH , and rinsed with deionized water. The columns were eluted separately with 0.5 M HNO_3 at $\sim 1 \text{ BV/h}$ and regenerated with 0.25 M NaOH at 3 BV/h . The ^{137}Cs concentration in the feed (AW-101 filtrate) was $175 \text{ }\mu\text{Ci/mL}$.

The ^{137}Cs lead column breakthrough curves for six loading cycles are shown in Figure 4-3; the average flow rates for each cycle appear in the figure. The C/Co for ^{137}Cs was plotted as a function of the number of BV processed per cycle. The BV was defined as the volume of the resin bed during the loading. The shape of the breakthrough curves were generally found as expected. The average BV processed at the break point ($<1\%$ breakthrough), 10% , and 50% breakthroughs are reported in Table 4-3. These values were obtained from the breakthrough curves in Figure 4-3. The BVs for cycles #1, #3, and #5 at 50% breakthrough were extrapolated. The general trend suggests the performance of the resin gradually declined as the loading progressed from cycle #1 to #6. Cycle #4 is not consistent with the other cycles at 10% and 50% breakthrough levels, where the volume of feed processed is lower than cycles #5 and #6. The cause for the lower than expected performance for cycle #4 at $C/\text{Co} = 0.1$ and 0.5 is not known.

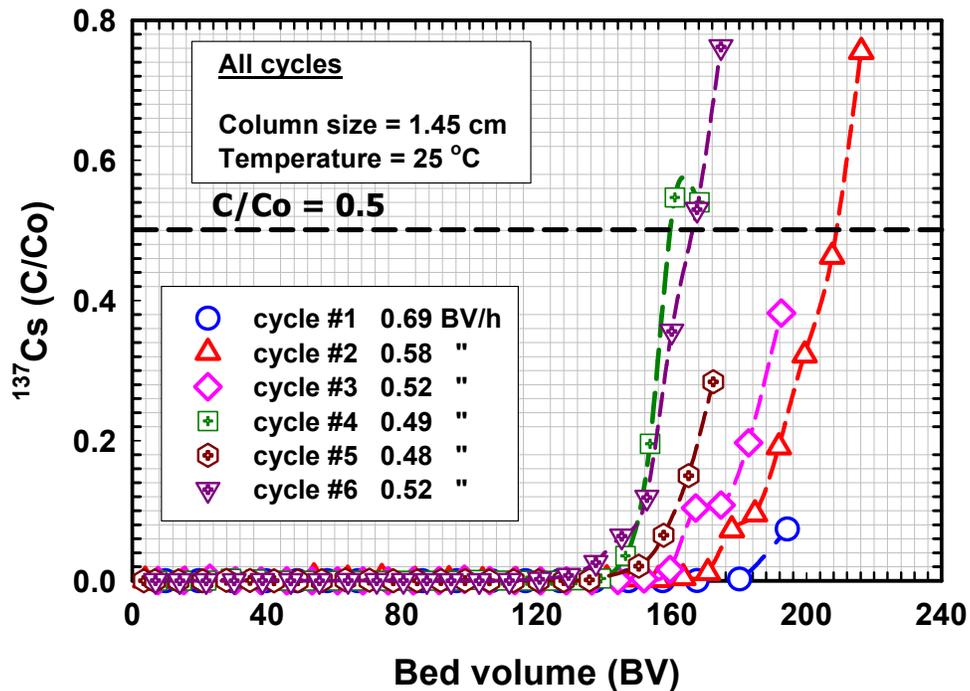


Figure 4-3. ^{137}Cs Breakthrough Curves – All Cycles

Table 4-3. Summary of ^{137}Cs loading Performance (BV)

Cycle #	Break point (< 1%)	C/Co = 0.1	C/Co = 0.5
1	167.5	197.5	222.4
2	170.7	183.0	208.6
3	159.5	168.9	195.8
4	135.1	146.1	155.6
5	135.6	161.1	180.1
6	120.8	147.7	166.9

Figure 4-4 shows the results for ^{137}Cs loading in cycle #1. The ^{137}Cs concentration per mole of Na^+ was plotted on a log scale as a function of BVs processed through the lead and lag columns. The log scale was chosen to show clearly the several orders of magnitude decrease in the ^{137}Cs concentration and to highlight the loading performance of each cycle in terms of Ci per mole of Na^+ as specified in the contract. In the interest of those who prefer C/Co breakthrough curves, the data are presented in Appendix C. The diamond symbols pertain to individual grab samples collected from the bottom of the lag column; the hexagonal symbols pertain to effluent product solutions or composites of 20 BVs collected also from the lag column.

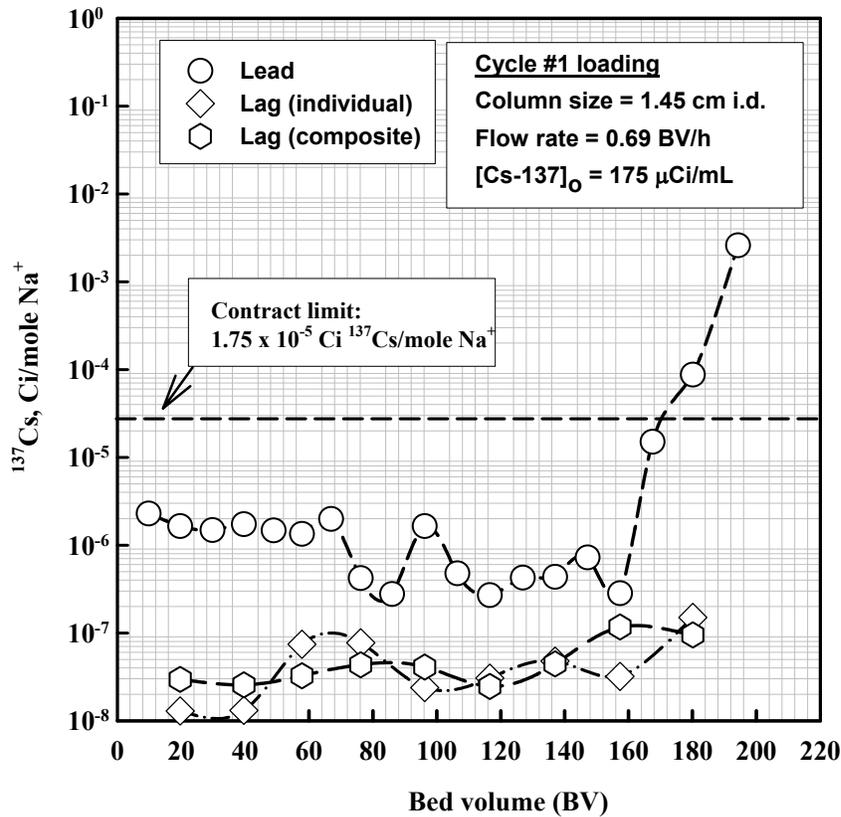


Figure 4-4. ^{137}Cs Breakthrough Curves - Cycle #1

In Figure 4-4, the ^{137}Cs concentration corresponding to the contract limit of 1.75×10^{-5} Ci/mole Na^+ is shown as a horizontal dashed line. The Na^+ concentration in selected effluent samples from the lead column was measured during the run and the average concentration was 4.98 M Na^+ . This value was used to calculate the concentration exhibited on the Y-axis of Figure 4-4. The Na^+ concentration in the effluent composite product for cycle #1 was used to calculate the lag column Y-axis data. The average concentration of K^+ in effluent samples from the lead and lag columns was 0.49 and 0.44 M , respectively.

The data show that the concentration of ^{137}Cs per mole of Na^+ in the lead effluent samples was below 10^{-5} until 157 BV of feed was processed. The concentration then increased sharply and crossed the contract limit (1.75×10^{-5} Ci/mole Na^+) at 172 BV. The ^{137}Cs concentration in the lag column effluent was several orders of magnitude lower than the contract limit. The lag column data displayed in Figure 4-4 include individual samples collected from the bottom of the lag column and effluent composite collected in 20-BV fractions. Approximately 2915 mL of the AW-101 waste sample at $\sim 5 \text{ M Na}^+$ was processed through the lead column and 2798 mL of effluent composite product was collected from the lag column. The average concentration of ^{137}Cs in the effluent composite product was $3.0 \times 10^{-4} \text{ } \mu\text{Ci/mL}$ or 6.0×10^{-8} Ci/mole Na^+ which is significantly below the contract limit of $8.07 \times 10^{-2} \text{ } \mu\text{Ci/mL}$ or 1.75×10^{-5} Ci/mole Na^+ for AW-101 sample at 5 M Na^+ . The overall performance for cycle #1 was excellent, exhibiting a DF of 5.8×10^5 . The DF was calculated from the initial concentration of ^{137}Cs in the feed and the concentration in the effluent composite product. It should be noted that the flow rate employed in this test (0.69 BV/h) was significantly below the nominal design flow rate of 3 BV/h . Therefore, the column loading results and the overall performance indicated for the test do not fully mimic the WTP plant conditions.

Figure 4-5 shows the ^{137}Cs loading data in cycle # 2. The initial loading performance of the lead column was very poor. The ^{137}Cs concentration in effluent samples collected up to 160 BV was at or above the contract limit. The reason for the initial poor performance was due to the fact that the lead column was re-packed after cycle #1 was completed. When the lead column regeneration for cycle #2 started, the liquid head above the resin bed suddenly dropped to less than 2 cm above the resin. In order to restore the liquid head, several BV of 0.25 M NaOH was pumped as up flow through the column. The column re-packing could possibly have resulted in channeling during the early stages of loading. The ^{137}Cs concentration increased linearly after 160 BV as shown by the log curve on the Y-axis (Figure 4-5). The Na^+ concentration used for Y-axis calculation was 5.06 M ; it was determined from ICP-AES measurements of eight effluent samples from the lead column. The average concentration of K^+ was 0.52 M . The loading performance of the lag column was excellent, exhibiting a ^{137}Cs concentration $< 10^{-6}$ Ci/mole of Na^+ at 190 BV. The concentration of K^+ in the effluent composite product was 0.42 M .

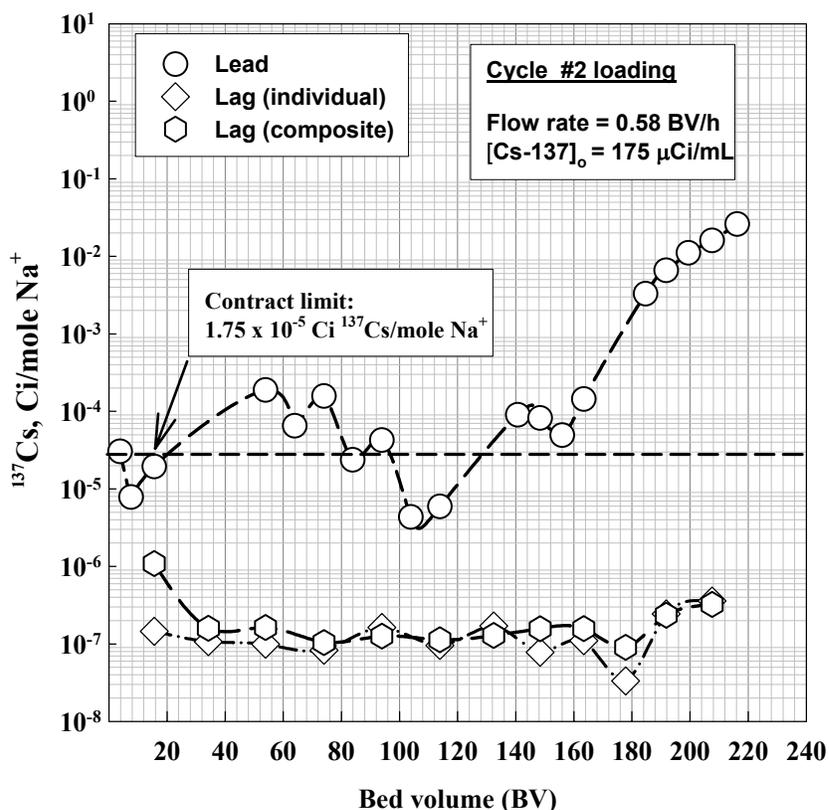


Figure 4-5. ¹³⁷Cs Breakthrough Curves – Cycle # 2

Figure 4-6 shows the loading data for ¹³⁷Cs in cycle #3. The concentration of ¹³⁷Cs in lead column effluent samples crossed the contract limit of 1.75×10^{-5} Ci/mole Na⁺ after processing 142 BV. The concentration then increased linearly on the log scale, which indicates the onset of breakthrough. The concentration of Na⁺ used in the Y-axis calculation was 4.5 M; it was determined from measurement of six effluent samples (lead column) by atomic absorption (AA). The performance of the lag column was excellent, exhibiting ¹³⁷Cs concentration significantly below 10^{-5} Ci/mole Na⁺ in effluent samples. The Na⁺ concentration in the effluent composite product of cycle #3 (5.22 M) was used to calculate the Y-axis lag column data. The ¹³⁷Cs concentration of the last sample from the lag column (see last data point) was sharply lower than expected. It is suspected that the sample was diluted by 0.1 M NaOH feed displacement solution when the sample was collected. Although the overall performance of column was outstanding in cycle #3, it should be recognized that the flow rate produced these results does not mimic the WTP design flow rate. The reason for the deviation from the WTP plant design flow rate was to increase the dose to resin, which could only be achieved by processing the feed solution at very low flow rate.

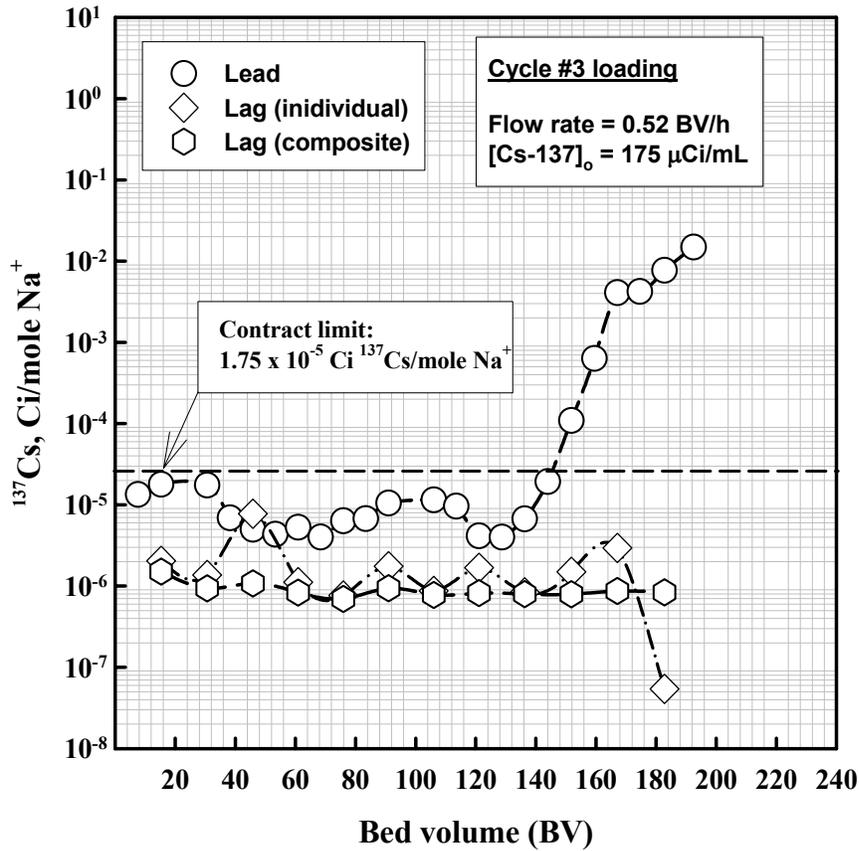


Figure 4-6. ¹³⁷Cs Breakthrough Curves – Cycle # 3

The ¹³⁷Cs loading data for cycle #4 are shown in Figure 4-7. The initial performance of the lead column was very good; exhibiting a cesium concentration below 10⁻⁵ Ci/mole Na⁺ until 120 BV of the AW-101 sample was processed. The concentration increased linearly on the log scale and crossed the contract limit of 1.75 x 10⁻⁵ Ci ¹³⁷Cs/mole Na⁺ at 128 BV. The decline in ¹³⁷Cs concentration after 160 BV was not expected and the cause is not known. The Na⁺ concentration (4.3 M) used in Y-axis calculation was determined from the measurement of four individual lead column effluent samples by ICP-AES. The average concentration of K⁺ in these samples was 0.50M.

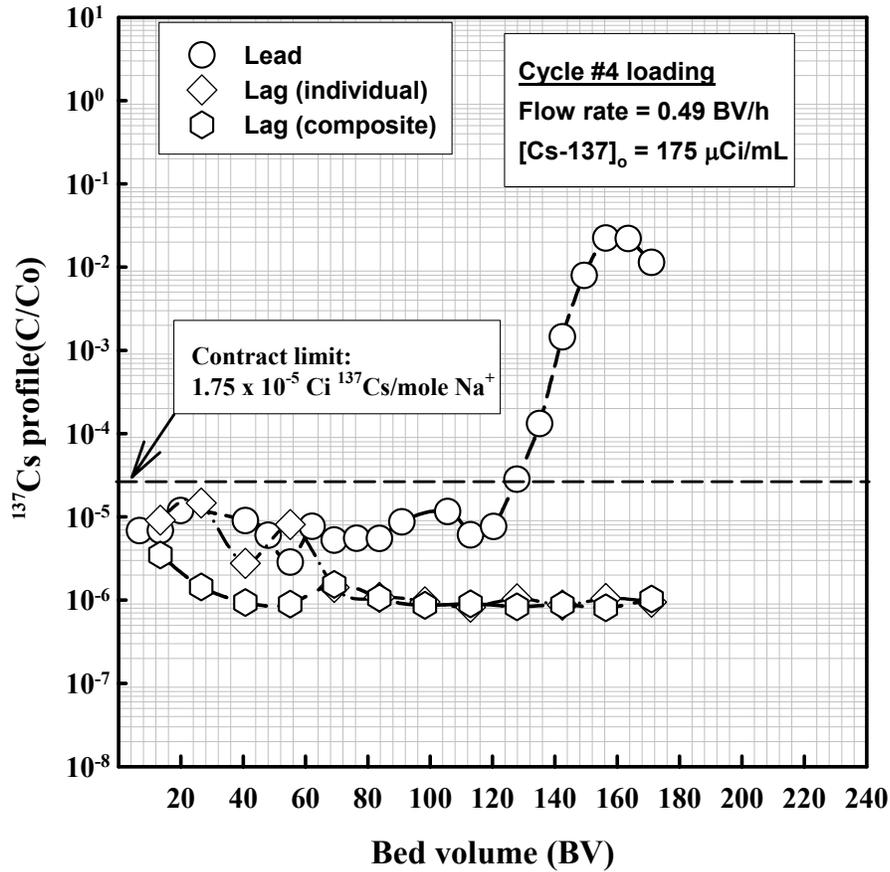


Figure 4-7. ^{137}Cs Breakthrough Curves – Cycle # 4

Although the initial performance of the lag column (up to 70 BV) was poor compared to previous 3 cycles, the ^{137}Cs concentration in effluent samples was below the contract limit. The reason for the initial poor performance of the lag column could be incomplete resin conditioning or cesium bleed from the resin. The ^{137}Cs concentration was at $\sim 10^{-6} Ci \text{ } ^{137}Cs/mole Na$ after processing 70 BV. The ^{137}Cs concentration in the effluent composite samples from the lag column was $5.4 \times 10^{-3} \mu Ci/mL$. The overall DF for ^{137}Cs (3.3×10^4) was calculated from feed and effluent composite product concentrations.

Figure 4-8 displays the results of ^{137}Cs loading data for cycle # 5. The scatter of the lead column data was significant until 120 BV of sample was processed. The scatter was caused by inadequate flushing of the auto-sampler lines at the end of elution step in cycle # 4. The ^{137}Cs peak samples were collected in sampling lines #4, #5 and #6 and later flushed with DI water. However, the flush samples were not analyzed to determine residual cesium concentration. When cycle #5 loading started, the lead column effluent samples collected from sampling lines #4 #5, and #6 were contaminated with residual Cs from the elution. As a result, the cesium concentration of several effluent samples exceeded the contract limit. In Figure 4-8, the ^{137}Cs concentration increased linearly on the log scale after processing 120 BV and it crossed the contract limit at 128 BV. A concentration of 4.78 M for Na^+ was used in the Y-axis calculation. The concentration of K^+ in the effluent samples was 0.51 M . The lag column performance was good, exhibiting cesium concentration below the contract limit during the entire column loading. The average ^{137}Cs concentration in the composite lag column samples was $4.01 \times 10^{-3} \mu\text{Ci/mL}$, which calculates an overall DF of 4.4×10^4 for cycle #5.

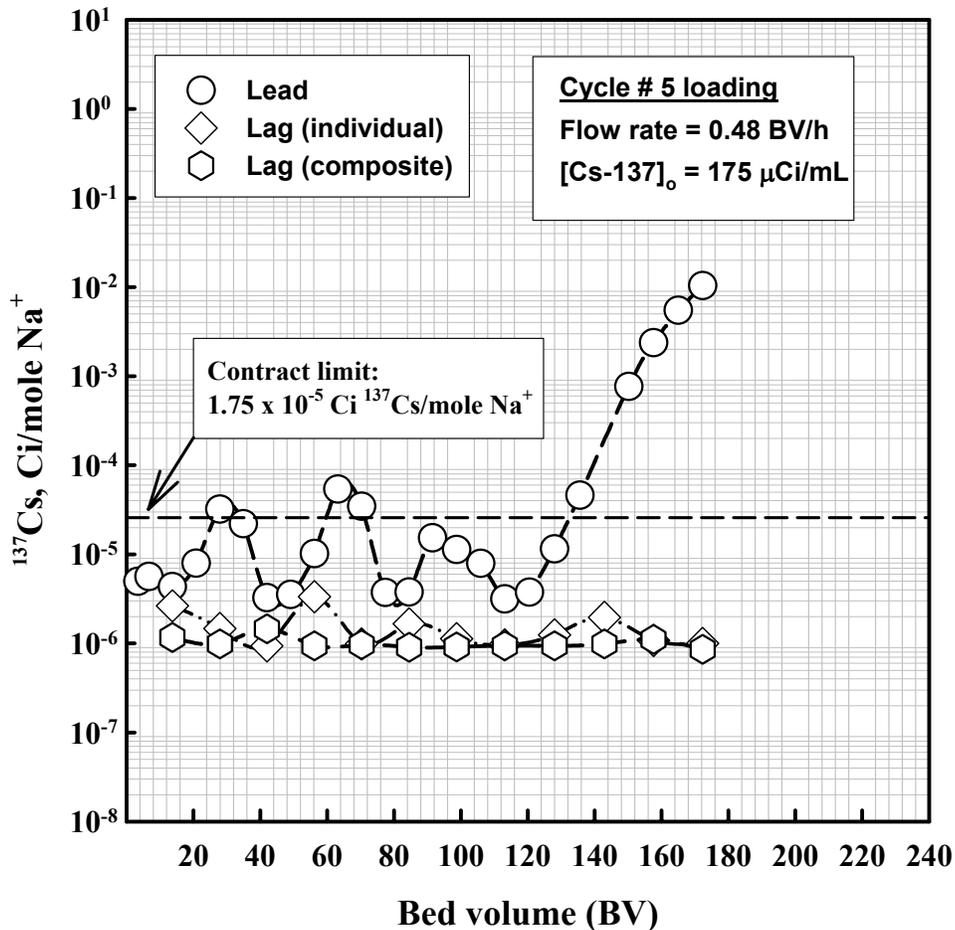


Figure 4-8. ^{137}Cs Breakthrough Curves – Cycle # 5

Figure 4-9 shows the loading data in cycle # 6. The loading performance of lead column deteriorated significantly as compared to cycle #1. The ^{137}Cs concentration per mole Na^+ was constant (horizontally flat) near the contract limit until 100 BV was processed. The concentration crossed the contract limit permanently at 112 BV. The start breakthrough corresponds to beginning of linear increase of cesium concentration on log scale. The concentration of Na^+ used to calculate the Y-axis data was determined from ICP-AES measurement of five lead column effluent samples. The average value of 3.7 M was lower than expected; the average concentration of K^+ in the lead column effluent samples was 0.43 M. The cause for the low concentration of Na^+ in the effluent samples is not identified. The performance of the lag column was very good. The ^{137}Cs concentration in lag column composite fractions was below the contract limit of 1.75×10^{-5} Ci/mole Na^+ during the entire loading period. The average ^{137}Cs concentration in lag column effluent composite fractions was 4×10^{-3} $\mu\text{Ci/mL}$, which corresponds to overall DF of 4.4×10^4 .

Table 4-4 shows a summary of column loading capacity, dose to resin for each cycle, and the total dose to resin during six loading cycles. The column loading capacity was calculated from the breakthrough curve at the breakpoint (i.e., onset of Cs breakthrough), at 10 and 50% breakthrough. The dose to the ion exchange resin bed was calculated using the commercial code MicroShield (v. 5.03) software.²⁰ The beta decay provides the majority of the radiation dose and because beta particles have a very short range they deposit all their energy in a small volume around the point at which the decay takes place. The gamma rays on the other hand have a long range, which will normally escape due to small size of the column. The dose to resin was determined from the radioactivity (Ci of ^{137}Cs) loaded in each cycle, the flow rate, and the time to load the column. Details of the dose to resin calculations are given in Appendix F.

Table 4-5 shows a summary of the swelling and shrinking history of lead column during loading, feed displacement (0.1 M NaOH), elution (0.5 M HNO_3), and regeneration (0.25 M NaOH). When the SuperLig[®] 644 resin was first slurred into the columns with DI water, the volume of the resin bed in the lead column was 8.3 mL (i.e. 5-cm resin bed height in 1.45-cm diameter glass column). The lag column contained 7.25 mL of resin in DI water. After passing 12 BV of 0.25 M NaOH through each resin bed and allowing it to soak overnight, the volumes of fully swollen bed in the lead was 14.8 mL. The volume of resin bed during loading, elution, and regeneration were calculated from recorded height of the resin bed during six loading cycles. The average BV volume during loading, feed displacement, elution, and regeneration for all six cycles was ~ 14.8, 15.8, 11.7, and 15 ml, respectively.

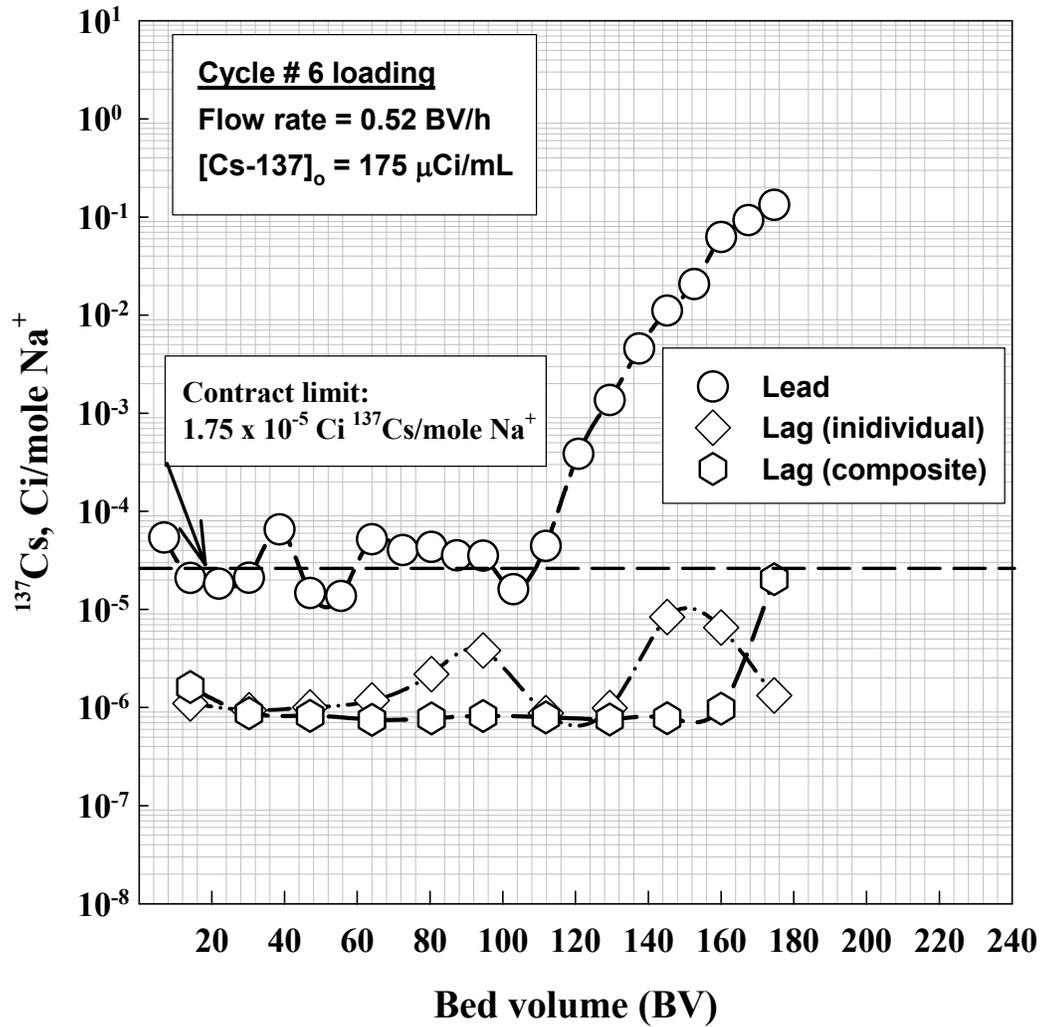


Figure 4-9. ¹³⁷Cs Breakthrough Curves for - Cycle #6

Table 4-4. Summary of ¹³⁷Cs Column Dose and Loading Capacity

Cycle #	Dose/cycle (Rad)	Total dose (Rad)	Break point (mmole/g)	C/Co = 0.1 (mmole/g)	C/Co =0.5 (mmole/g)
1	2.60E+06	2.60E+06	1.26E-02	1.41E-02	*
2	4.24E+06	6.84E+06	1.16E-02	1.31E-02	1.42E-02
3	3.57E+06	1.04E+07	1.08E-02	1.18E-02	1.34E-02
4	3.24E+06	1.36E+07	9.69E-03	1.04E-02	1.08E-02
5	2.98E+06	1.66E+07	9.76E-03	1.15E-02	1.24E-02
6	3.30E+06	1.99E+07	8.70E-03	1.07E-02	1.14E-02

* = not estimated

Thus, the percent volume change of the resin bed in the lead column between elution and regeneration was ~ 22%. During column loading and elution, the resin bed swells and shrinks. Swelling is often observed when the resin converts between sodium and hydrogen forms. Generally, some swelling of the resin is desirable for the ion exchange process to take place. A swollen resin allows faster mass transfer by reducing intra-particle resistance. Resin swelling and shrinking, however, can become undesirable from operations point of view since excessive swelling could potentially cause hydraulic problems and channeling. The swelling and shrinking behavior of this resin batch was essentially invariant with superficial velocity under the present experimental conditions.

Table 4-5. Resin Bed Swelling and Shrinking History for Lead Column

Cycle #	Flow rate (BV/h)	5 M Na ⁺ AW-101	Volume of resin bed (mL)		
			0.1 M NaOH	0.5 M HNO ₃	0.25 M NaOH
1	0.69	14.9	15.0	11.7	14.9
2	0.59	14.7	15.7	11.2	14.4
3	0.52	14.7	15.7	12.2	15.2
4	0.49	14.9	16.2	11.9	16.0
5	0.49	14.9	16.0	11.4	14.4
6	0.52	14.5	16.2	11.9	nm

nm = not measured

4.4 CESIUM ELUTION CYCLES

Following each loading cycle, the lead and lag columns were eluted separately. Elution was generally performed immediately after feed displacement with 0.1 M NaOH and DI water rinse steps were completed. The ¹³⁷Cs was eluted from the ion exchange columns using 0.5 M HNO₃ solutions at a flow rate of approximately 1 BV/h. At all times, elution was carried out downward using a separate pump from that employed during the column loading. While the lead and lag columns were both eluted, data on elution profile were collected only on the lead column.

Figure 4-10 displays the C/Co for ¹³⁷Cs in lead column eluate samples for cycle #1. The C/Co was plotted on a logarithmic scale against the eluate BV that passed through the column. The elution was performed at a flow rate of 0.63 BV/h based on average resin bed volume of 10.9 mL from the start to the end of elution. The target flow rate for elution runs was 1 BV/h. The ¹³⁷Cs peak was exhibited in less than 2 BV with C/Co value of 46. The C/Co gradually declined after the peak, reaching a target C/Co of 0.01 after 8 BVs. The ¹³⁷Cs concentration in the composite eluate solution was 1.73 x 10³ μCi/mL. The composite eluate volume collected during elution was 141.5 mL. This was diluted by a minimum 2 BV of deionized water in the column headspace. Thus, the total ¹³⁷Cs recovered in the eluate was 2.4 x 10⁵ μCi (i.e. 1730*141.5). The total ¹³⁷Cs loaded on the resin in the lead column was approximately 5 x 10⁵ μCi, which suggests that a significant amount of the Cs was not accounted in the eluate.

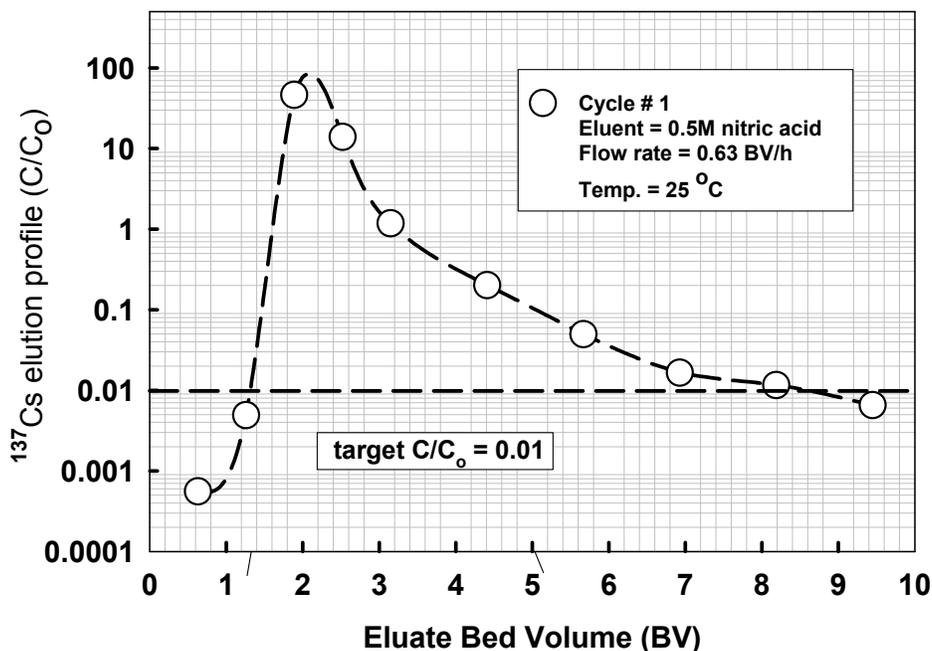


Figure 4-10. ¹³⁷Cs Elution Curve- Cycle #1

Figure 4-11 shows the concentrations of Na⁺ and K⁺ in the eluate as function of the eluate BV. The K⁺ and Na⁺ exhibited maximum concentration at about 1.5 BV, which coincided with the ¹³⁷Cs C/Co peak elution. Generally, hydronium ions (H⁺) are removed from the 0.5 M HNO₃ solution passing through the resin bed and exchanged with equivalent number of moles with of Cs, K⁺, and Na⁺ ions on the resin. Since most RPP-WTP studies have not measured K⁺ and Na⁺ ions in the eluate samples, elution peaks for these ions were not identified and their significance has yet to be understood. In this cycle, we note that both K⁺ and Na⁺ ions exhibited elution peak at 2 BV, which corresponds to that of Cs⁺. In addition, Na⁺ exhibited a second hump at 5 BV. The significance of this hump is not clear.

Figure 4-12 shows the C/Co for ¹³⁷Cs plotted on logarithmic scale as a function of eluate BV (for cycle 2) to show the large range of C/Co values. The flow rate during the elution was 1.05 BV/h (based on average elution volume). The peak C/Co for ¹³⁷Cs was observed at about 3 BV, but the value was just 31 times the feed concentration. The C/Co of 0.01 was reached after 12 BV of the eluent passed through the column. The ¹³⁷Cs concentration in the composite eluate solution was 2.19 x 10³ μCi/mL. The composite eluate volume collected during elution was about 220 mL. Thus, the total ¹³⁷Cs recovered in the eluate solution was 4.8 x 10⁵ μCi.

The ¹³⁷Cs in post-elution rinse and regeneration data are also shown in Figure 4-12. The C/Co increased during the first 2 BV to a value of 0.49 and then steeply declined to ~ 0.003 of its value in the feed sample. The trend of the ¹³⁷Cs profile during regeneration was similar to that of the post-elution DI water rinse. The reason for the C/Co increase in the post elution rinse water is not known, but similar observations has been previously reported.⁽²¹⁾

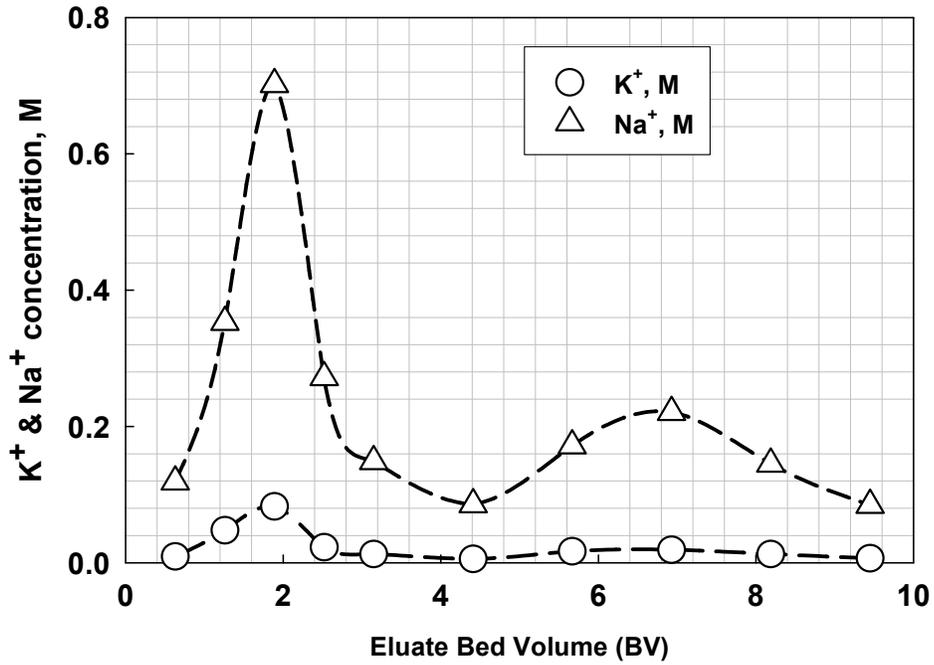


Figure 4-11. Na^+ and K^+ in Eluate samples - Cycle #1

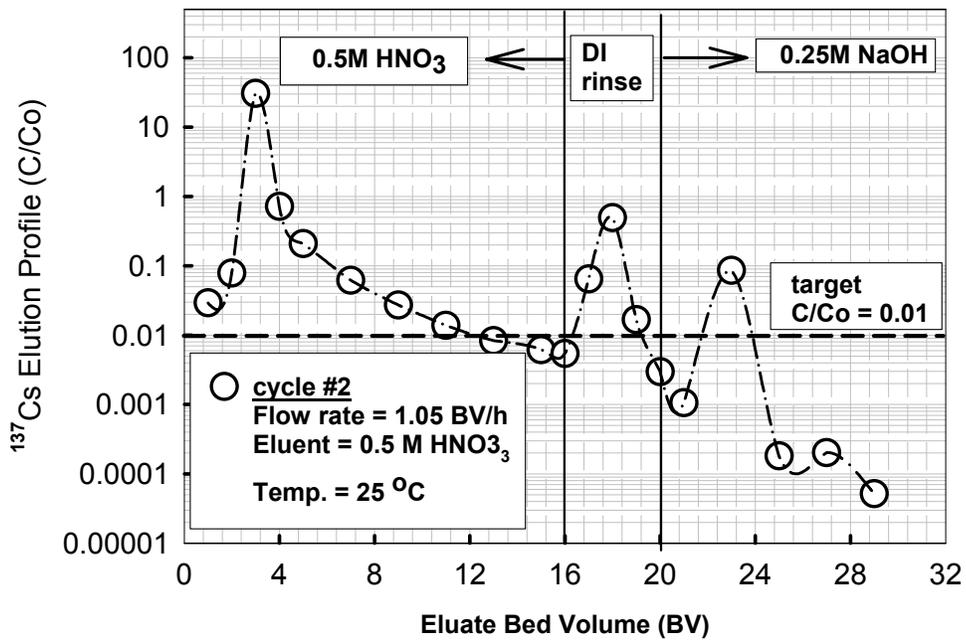


Figure 4-12. ^{137}Cs Elution Curve - Cycle #2

Figure 4-13 displays the ^{137}Cs elution for cycle #3. Elution flow rate was ~ 1.01 BV/h, based on average elution bed volume of 11.7 mL. The C/Co peak for ^{137}Cs was exhibited at 4 BV with a value was 56 times its feed concentration. The C/Co reached 0.01 after 9 BV of eluent passed through the column. The ^{137}Cs concentration in the composite eluate solution was approximately $2.1 \times 10^3 \mu\text{Ci/mL}$ and the eluate composite volume collected during the elution was 186 mL. The Na^+ concentration in the eluate samples was measured and the average value of 1.87 M was higher than would be expected during elution.

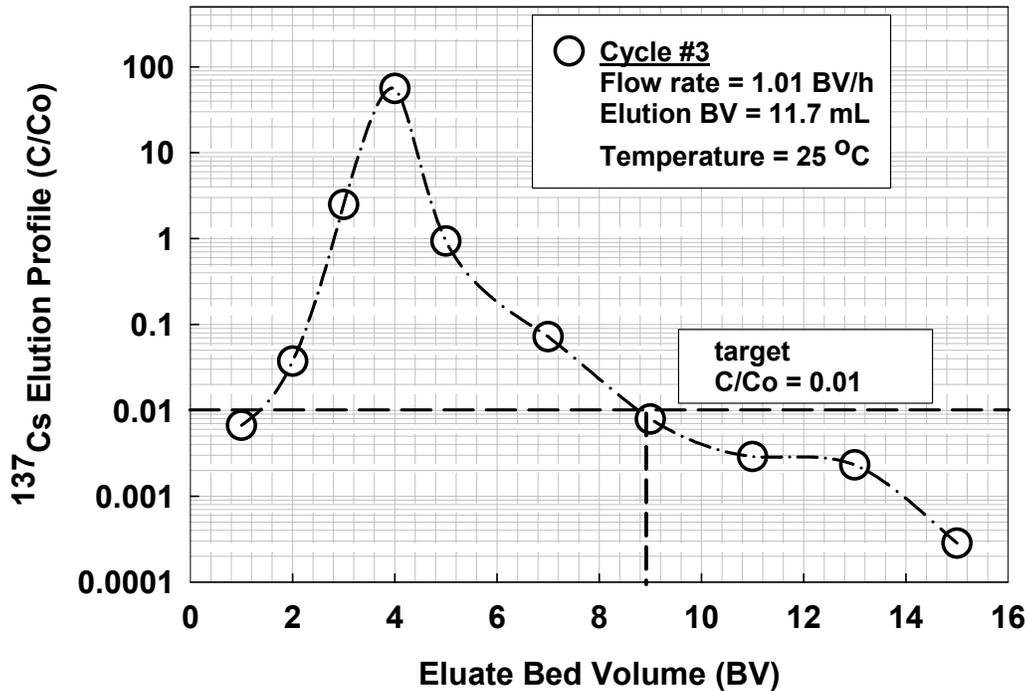


Figure 4-13. ^{137}Cs Elution Curve - Cycle #3

Figure 4-14 shows the C/Co values for ^{137}Cs elution during cycle # 4. The average bed volume from the start to the end of elution was 11.7 mL. The flow rate, based on the elution volume, was 0.99 BV/h. The C/Co peak for ^{137}Cs was exhibited at 4 BV and the value was 103 times its feed concentration. The C/Co reached 0.01 at 11 BV, and then gradually increased to a final value of 0.1. It is not clear why the C/Co increased after 11 BV and remained level at 15 BV. Also, the post-elution rinse and regeneration samples were not collected.

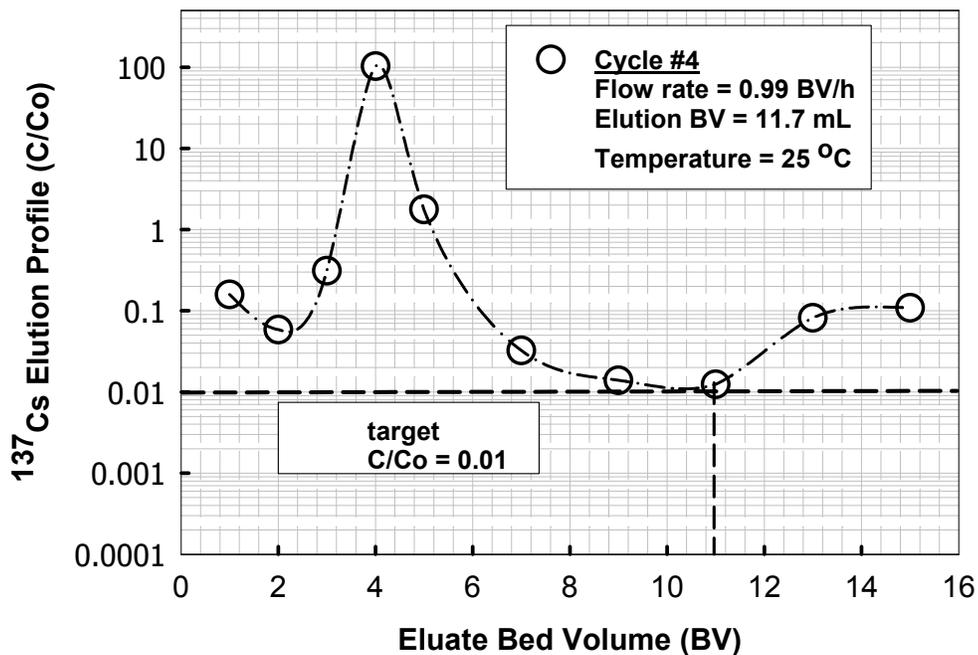


Figure 4-14. ¹³⁷Cs Elution Curve - Cycle #4

The ¹³⁷Cs elution for cycle #5 is shown in Figure 4-15. The elution flow rate was 0.95 BV/h, based on average elution volume. The C/Co peak was exhibited at about 4 BV with a value of 100. The C/Co reached a value of 0.01 at 11 BV, then increased momentarily to 0.1 before dropping back to 0.002 at 15 BV. The ¹³⁷Cs concentration in the composite eluate solution was $1.59 \times 10^3 \mu\text{Ci/mL}$. The volume of composite eluate collected during the elution was 211 mL. The C/Co for ¹³⁷Cs in the post-elution rinse increased after passing the first BV of DI water into the column, and then edged up again after 4 BV of solution passed through the column. The C/Co for ¹³⁷Cs in the regeneration solution (0.25 M NaOH) declined steadily during the first 5 BVs, and then slightly increased in the last 3 BV. The C/Co rise and fall of the ¹³⁷Cs concentration in the post-elution rinse and regeneration solutions were observed in several elution cycles where the data were collected.

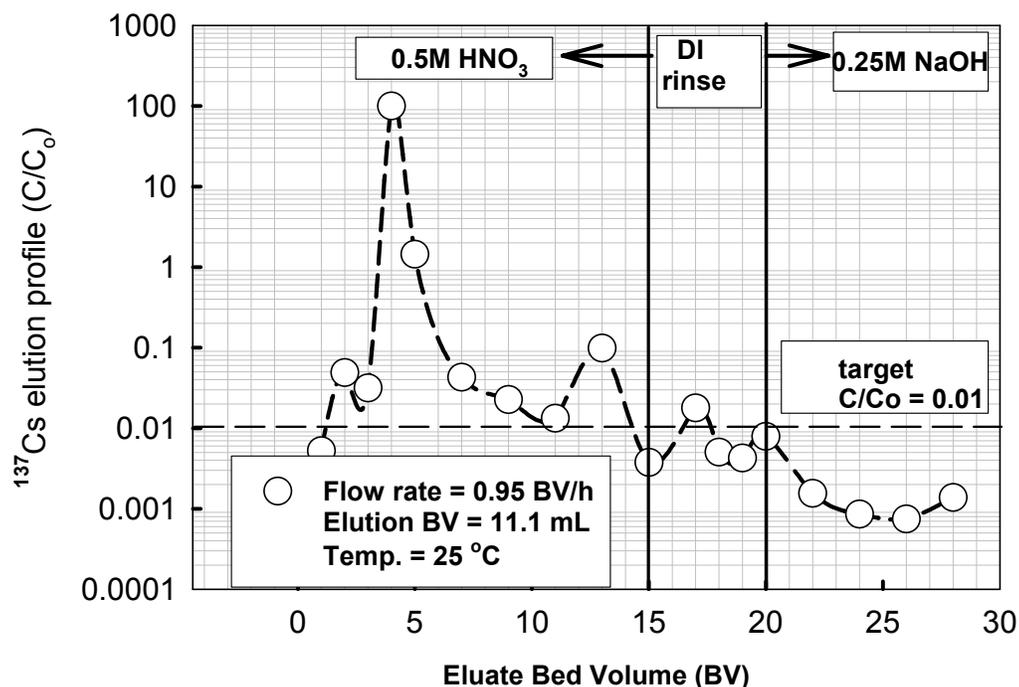


Figure 4-15. ¹³⁷Cs Elution Curve - Cycle #5

Figure 4-16 displays the C/Co for ¹³⁷Cs elution in cycle #6. The elution was extended to 28 BV to ensure all elutable Cs was removed from the resin. The C/Co peak with a value of 126 was observed at 4 BV. The C/Co reached a value of 0.02 at 10 BV, and then a long tail that lasted up to 24 BV was exhibited. The C/Co of 0.01 was reached after 24 BV of eluent passed through the column. The ¹³⁷Cs concentration in the composite eluate solution was $8.9 \times 10^2 \mu\text{Ci/mL}$, and the volume of the composite solution was 339 mL. The seemingly low ¹³⁷Cs concentration in the composite eluate solution is due to large volume of acid dilution.

Figure 4-17 shows the pH and the concentration of Na⁺ in eluate samples in cycle # 6. The pH of the eluate samples remained at ~ 2.5, except in the sample collected at 11 BV. The concentration of Na⁺ decreased initially from ~0.8 M at 1 BV to 0.22 M at 13 BV. The Na⁺ concentration (1.2 M) and the pH (7.3) observed at 11 BV were not expected. The C/Co of cesium in the post-elution DI rinse increased from less than 0.002 to value of 0.03. The reason for the increase in the C/Co of cesium in the post-elution DI water rinse is not known.

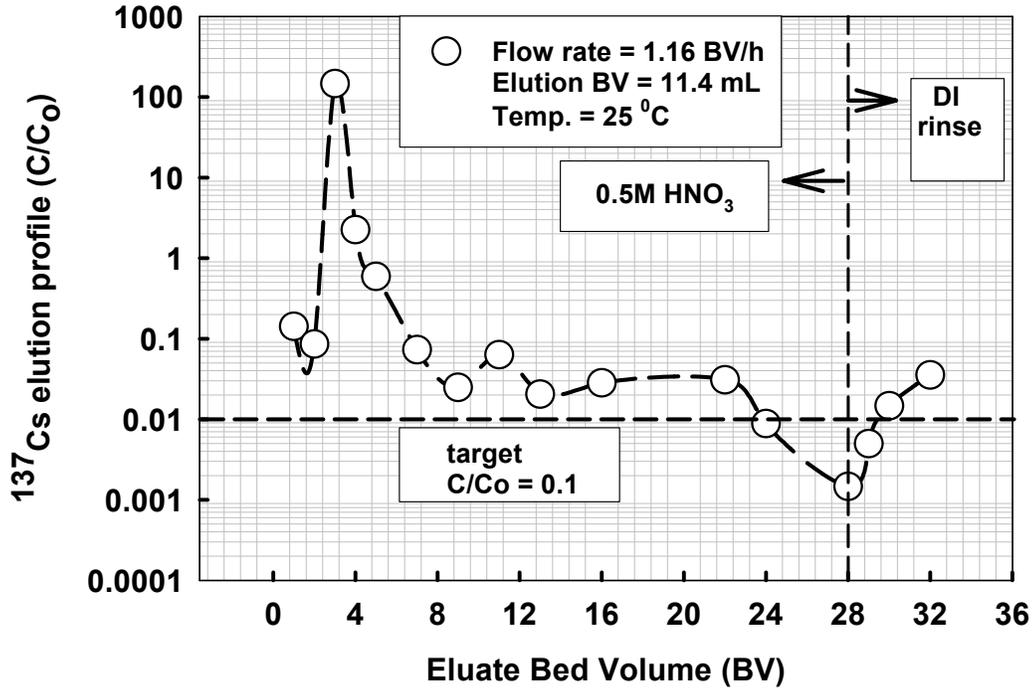


Figure 4-16. ^{137}Cs Elution Curve - Cycle #6

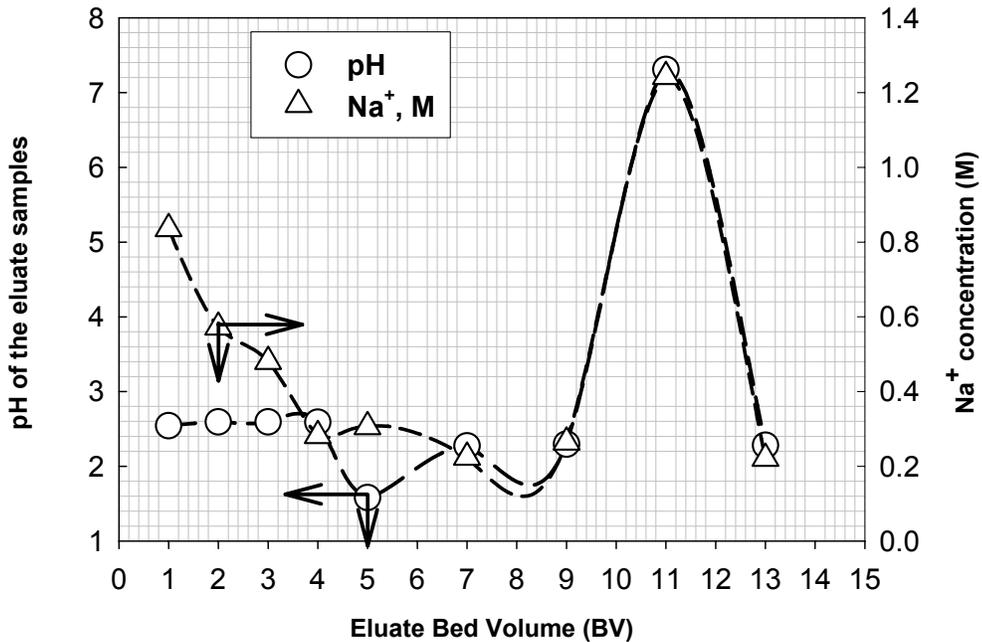


Figure 4-17. pH and Na^+ in Eluate Sample - Cycle #6

4.5 TECHNETIUM LOADING CYCLES

Five loading/elution/regeneration cycles were performed to remove ^{99}Tc from AW-101 waste sample. The effluent from cesium ion exchange column testing was used for the technetium ion exchange column testing. Two ion exchange columns (lead and lag) were previously loaded with rhenium from AW-101 simulant until $\sim 10\%$ breakthrough occurred, and then eluted with de-ionized water at $65\text{ }^\circ\text{C}$. The columns were stored in DI water for several weeks prior to their transfer into radiochemical hood. After the equipment transfer, the columns were regenerated separately with 0.25 M NaOH , and then connected in series for technetium loading. The columns were loaded in the downward direction at a rate of 3 BV/h .

The ^{99}Tc breakthrough curves for the five lead column loading cycles are shown in Figure 4-18. The C/Co (^{99}Tc activity of effluent samples/activity of ^{99}Tc in feed) was plotted as a function of the number of BV. The concentration of ^{99}Tc in the feed (AW-101 waste sample) was $6.62 \times 10^{-2}\ \mu\text{Ci/mL}$. Since ^{99}Tc is not adsorbed on SuperLig[®] 644 resin, the effluent from the cesium ion exchange columns was assumed to have the same concentration as the diluted AW-101 waste filtrate at 5 M Na^+ . Thus, no additional characterization was performed on the effluent composite solutions from cesium ion exchange columns.

Table 4-6 shows a summary of the ^{99}Tc loading performance for five cycles. The values presented in the table are BV processed during each loading cycle at C/Co of 0.1 with 95% confidence interval. It should be noted that the average loading was better than 250 BV at the 10% breakthrough. There is no significant difference in the loading performance of cycles #1-5, even though cycle # 1 appears to be slightly better than the other cycles. In other words, the performance of the resin did not deteriorate up to the fifth cycle. Based on these results, it can be inferred that this batch of SuperLig[®] 639 resin (batch # I-R2-03-27-02-20-45) performed better than all previous batches

Table 4-6. Statistical Summary of ^{99}Tc Lead Column Performance at $C/\text{Co} = 0.1$

Cycle #	Mean value (BV)	Lower Limit (BV)	Upper Limit (BV)
1	262	251	282
2	250	240	267
3	258	252	265
4	251	249	252
5	251	248	253

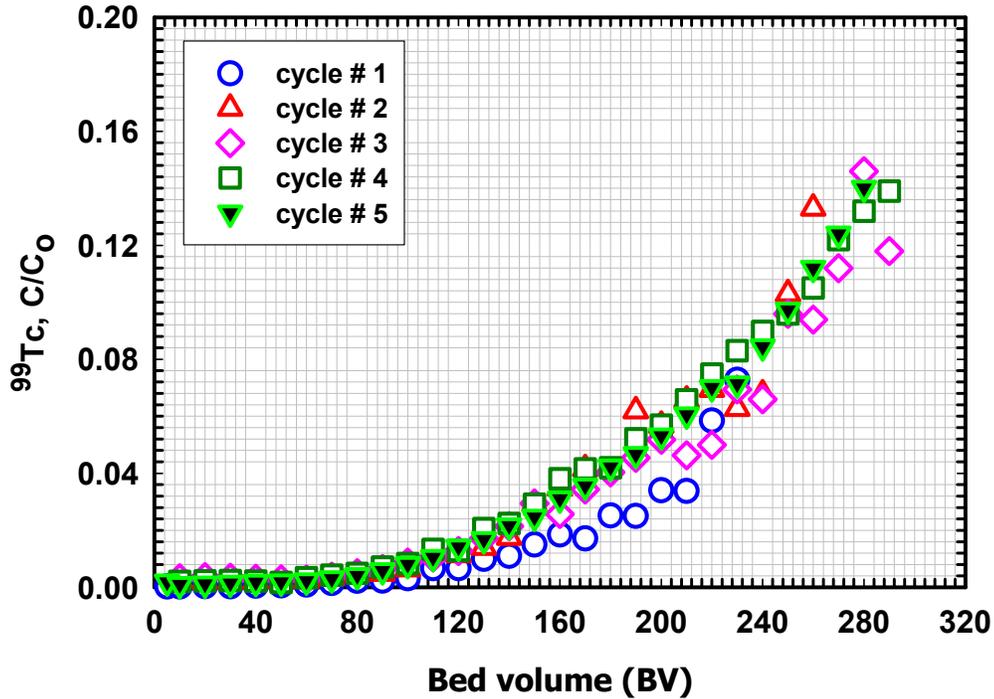


Figure 4-18. ⁹⁹Tc Breakthrough Curves – All Cycles

Figure 4-19 displays the ⁹⁹Tc loading data in cycle #1. The ⁹⁹Tc concentration in curie per mole of Na⁺ was plotted on a log scale as a function of the volume (BV) of waste sample processed. The concentration in the effluent samples from the lead column was nearly a straight line on the log scale, as expected. The performance of the dual ion exchange columns was excellent. The ⁹⁹Tc concentration was below the contract limit after processing 230 BVs. The lag column data show no immediate breakthrough after processing nearly 230 BV. The volume of effluent composite product collected from the lag column was 2964 mL; the ⁹⁹Tc concentration in the product was $\sim 3.66 \times 10^{-5} \mu\text{Ci/mL}$. Based on initial ⁹⁹Tc concentration of $6.62 \times 10^{-2} \mu\text{Ci/mL}$, the DF achieved for cycle # 1 was ~ 1810 . The percent removal of ⁹⁹Tc from the AW-101 sample was $\sim 99.94\%$.

Figure 4-20 shows the loading data for ⁹⁹Tc in cycle #2. The loading performance of lead and lag columns was very good. The ⁹⁹Tc concentration in the effluent samples was below the contract limit of $5.83 \times 10^{-5} \text{ Ci/mole Na}^+$ even after processing 280 BV of sample. The lead and lag column effluent had Tc concentration below $1 \times 10^{-7} \text{ Ci/mole of Na}^+$ until 100 BV of sample was processed. The concentration in lead column effluent was a straight-line on the log scale after 100 BV of solution was processed. The Tc concentration in the lag effluent remained constant below 10^{-7} throughout the run. The volume of effluent composite product generated from cycle #2 was 3570 mL; the ⁹⁹Tc concentration in the product was $5.95 \times 10^{-5} \mu\text{Ci/mL}$. The percent removal of ⁹⁹Tc (pertechnetate) in cycle #2 was 99.91%; with a DF of 1100.

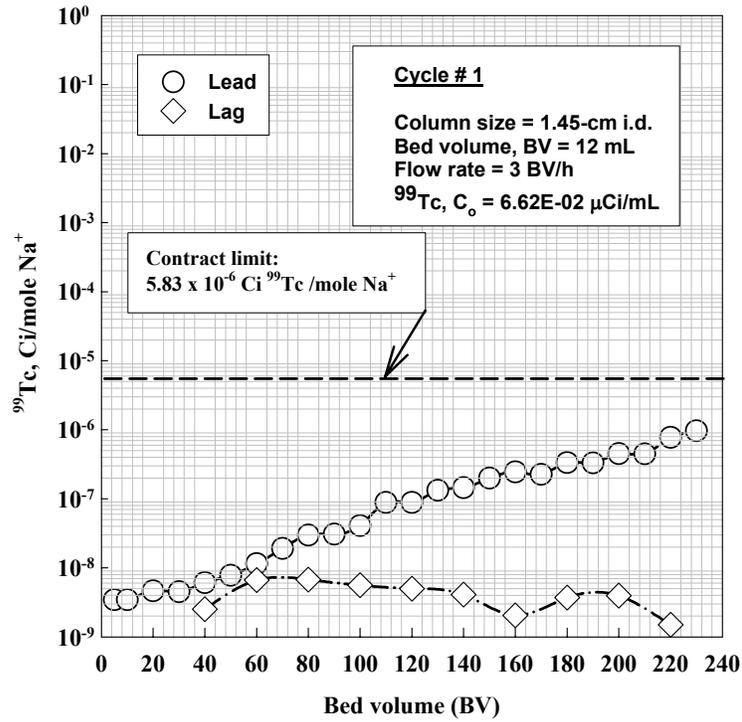


Figure 4-19. ^{99}Tc Breakthrough Curves - Cycle #1

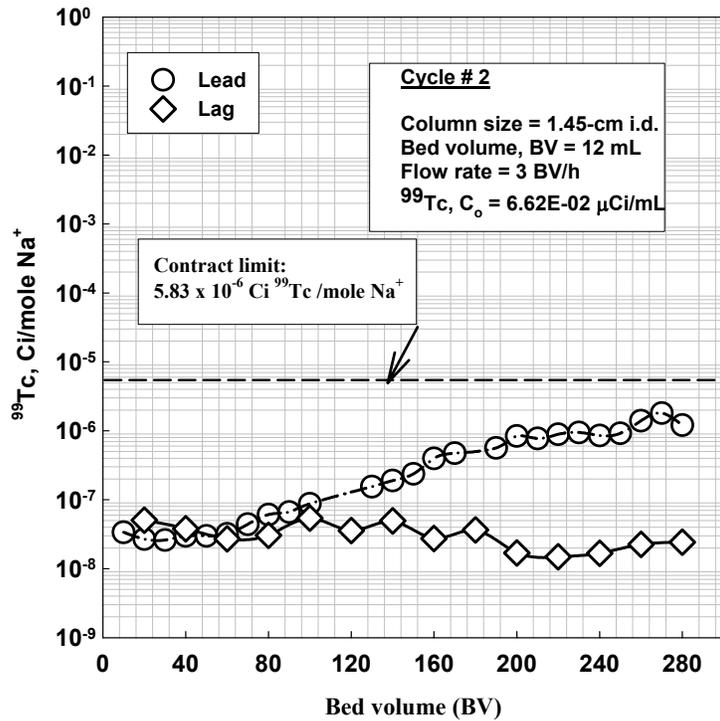


Figure 4-20. ^{99}Tc Breakthrough Curves - Cycle #2

The loading data for ^{99}Tc in cycle #3 are displayed in Figure 4-21. The performance of dual ion exchange columns was again very good in cycle #3. The first sample from the lead column at 5 BV exhibited unexpected spike in Tc concentration; the concentration then remained constant below 4×10^{-7} Ci/mole Na^+ until 60 BV of sample was processed. After 60 BV, the concentration was nearly a straight line on the log scale. The lag column performance was excellent, although some scatter of the data was observed. The Tc concentration in the lag effluent samples was constant at $\sim 1 \times 10^{-8}$ Ci/mole of Na^+ throughout the run. The volume of effluent composite product generated in cycle #3 was 3600 mL; the ^{99}Tc concentration in the product was 4.2×10^{-5} $\mu\text{Ci/mL}$. The percent removal for the ^{99}Tc from the AW-101 was $> 99.94\%$ and the DF achieved was ~ 1570 .

Figure 4-22 shows the loading data for ^{99}Tc in cycle #4. The performance of the dual column system was similar to cycle #3. The ^{99}Tc concentration for lead column was constant at 5×10^{-8} Ci/mole Na^+ until the initial 50 BV of feed was processed. The concentration then exhibited a straight-line on log scale until 170 BV, where the slope shifted but the line remained straight. The concentration in the effluent from the lag column was at 1×10^{-8} Ci/mole Na^+ , which is significantly below contract limit (5.83×10^{-5} Ci/mole Na^+). The amount of effluent composite product collected in cycle #4 was 3650 mL. The ^{99}Tc concentration in the product was 3.7×10^{-5} $\mu\text{Ci/mL}$; the corresponding DF was 1770 and the percent removal of ^{99}Tc (pertechnetate) was 99.94%.

The loading data for ^{99}Tc in cycle #5 is displayed in Figure 4-23. The ^{99}Tc concentration per mole of Na^+ was plotted in log curve as a function of BV processed. The horizontal dashed line shows the contract limit (5.83×10^{-5} Ci ^{99}Tc /mole of Na^+). The results show excellent performance for both lead and lag columns; the ^{99}Tc concentration of effluent samples from both lead and lag columns was below contract limit throughout the run. The concentration of the lead column was nearly straight-line on the log scale, as expected. After processing 160 BV, the slope of the straight-line shifted slightly to the right. The volume of composite product generated during cycle #5 was 3630 mL. The ^{99}Tc concentration in the product solution was 2.94×10^{-5} $\mu\text{Ci/mL}$; the corresponding DF and the percent ^{99}Tc removal were ~ 2250 and 99.9%, respectively.

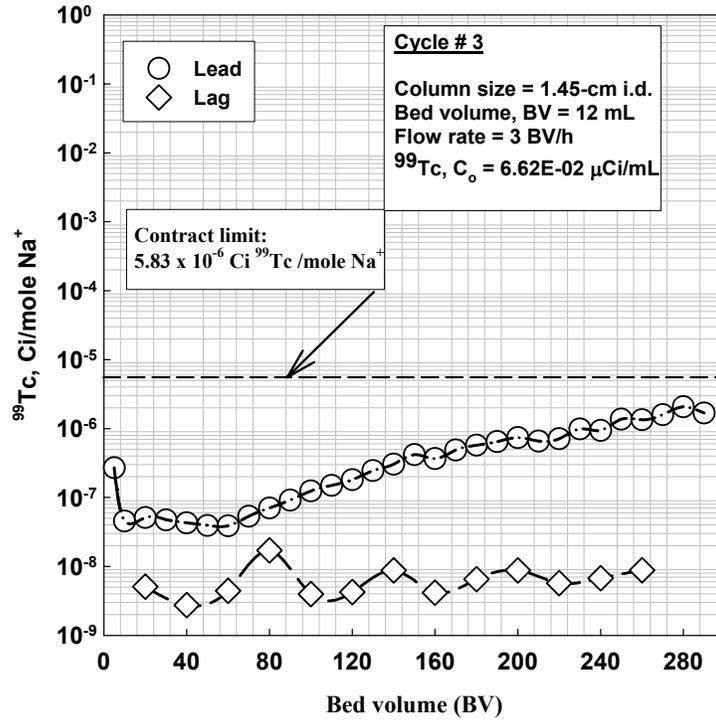


Figure 4-21. ^{99}Tc Breakthrough Curves - Cycle #3

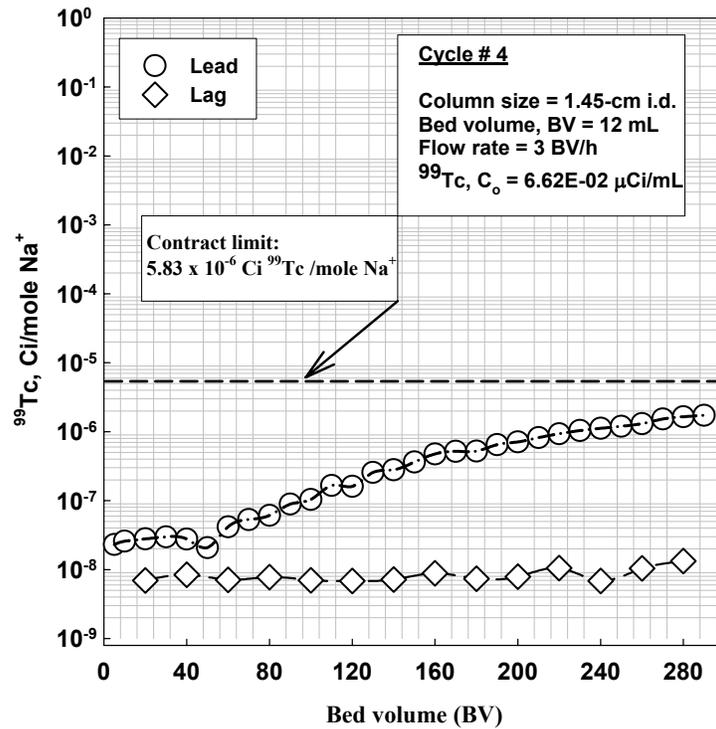


Figure 4-22. ^{99}Tc Breakthrough Curves - Cycle #4

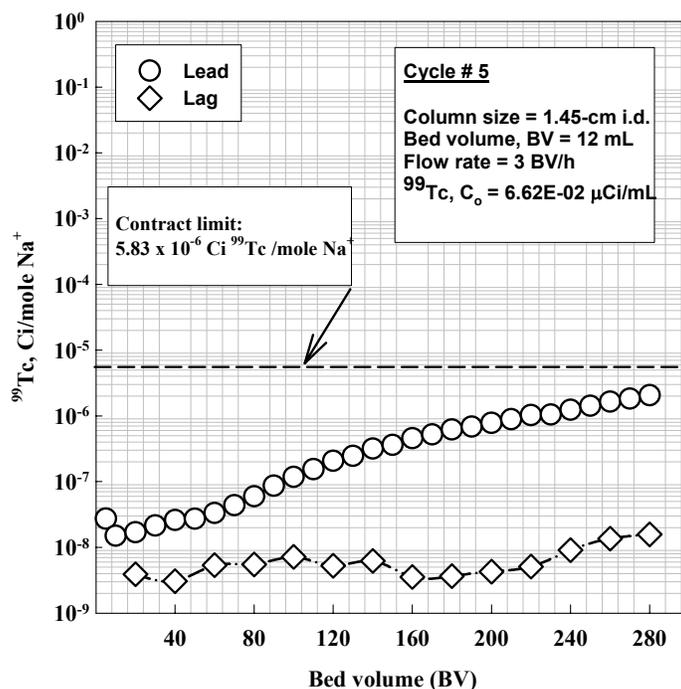


Figure 4-23. ⁹⁹Tc Breakthrough Curves - Cycle #5

4.6 TECHNETIUM DISPLACEMENT AND ELUTION

After the completion of each loading cycle the lead and lag columns were disconnected, and then eluted separately with de-ionized water at a flow rate of 1 BV/h and at 65 °C. Prior to elution, feed displacement was performed with 4 BV of 0.1 M NaOH at a flow rate of 3 BV/h. Feed displacement and eluate samples were collected only from the lead column in 0.5 BV increments for the first 4 BV. After 4 BV, eluate samples were collected in 2 BV increments. The concentrations of ⁹⁹Tc, K⁺, and Na⁺ in the feed displacement and eluate samples were determined by ICP-AES. The concentration of ⁹⁹Tc in selected samples was also determined by chemical separation, followed by beta counting. The NO₃⁻ concentration in selected samples was determined by ion chromatography (IC).

Figure 4-24 shows the lead column elution data for ⁹⁹Tc in cycle # 1. The C/Co was plotted on log scale as a function of eluate BV. The open circle and triangle symbols show the pertechnetate species and total ⁹⁹Tc, respectively. The total ⁹⁹Tc was measured by inductively coupled plasma – atomic emission spectroscopy (ICP-AES) and the pertechnetate fraction was determined by chemical separation, followed by beta counting. The ICP-AES and beta scintillation counting methods provided near identical results, thus suggesting that the ⁹⁹Tc eluted was pertechnetate.

It should be noted that after approximately 10 BV, the ICP-AES measurement reached its detection limit. Elution of ^{99}Tc from the lead column at 65 °C was fast. The C/Co peak was observed at 2.5 BV with a value of 94. The target C/Co of 0.01 was reached after only 12 BV of eluent passed through the column. The target (C/Co = 0.01) was arbitrarily chosen by WTP to suggest an end of elution for the tests. The lag column was eluted at 65 °C, but no data were collected.

The concentrations of ^{99}Tc , K^+ , Na^+ , and NO_3^- in the feed displacement and eluate samples for the lead column are shown in Figure 4-25. The K^+ and Na^+ concentration decreased sharply from at the beginning of the feed displacement step. The K^+ curve exhibited a broad peak between 3 and 4 BV, and then the K^+ concentration continued to decline. At 10 BV, the ICP-AES instrument detection limit was approached, where the measured values would not meet their required MRQ. The Na^+ concentration exhibited no distinct peak, but the concentration sharply decreased during feed displacement and at the beginning of elution.

The elution data for ^{99}Tc in cycle #2 are shown in Figure 4-26. The elution curve was nearly identical to cycles #1. The plot of C/Co on log scale vs. eluate BV shows similar characteristics as cycle # 1. The C/Co peak was observed at 2.5 BV with a value of 92. The C/Co target of 0.01 (dashed line) was reached after passing 16 BV of eluent through the column. The ICP-AES and chemical separation/beta counting methods provided near identical results until the volume of eluate processed was 12 BV. The ICP-AES measurements after 12 BV were close to detection limit and therefore, the results were not as reliable.

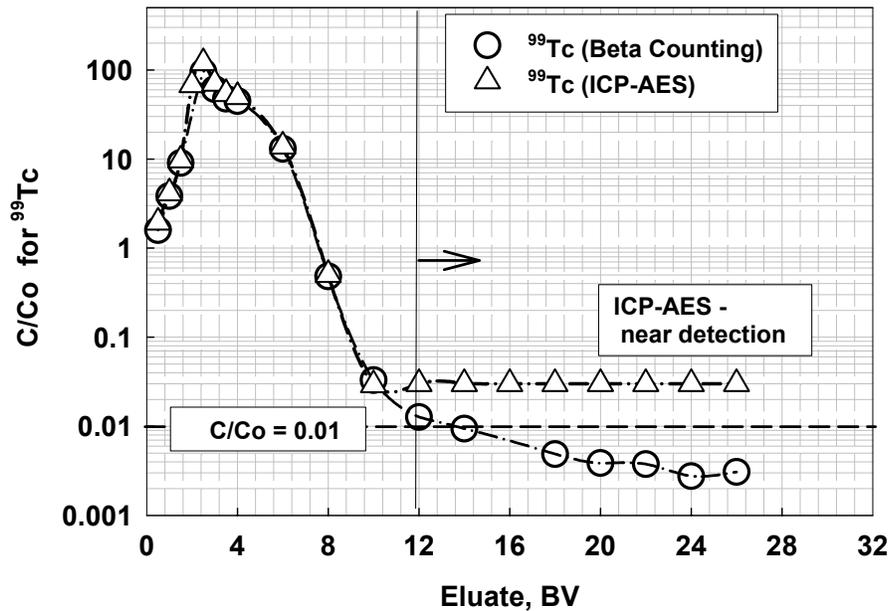


Figure 4-24. ^{99}Tc Elution Curves - Cycle #1

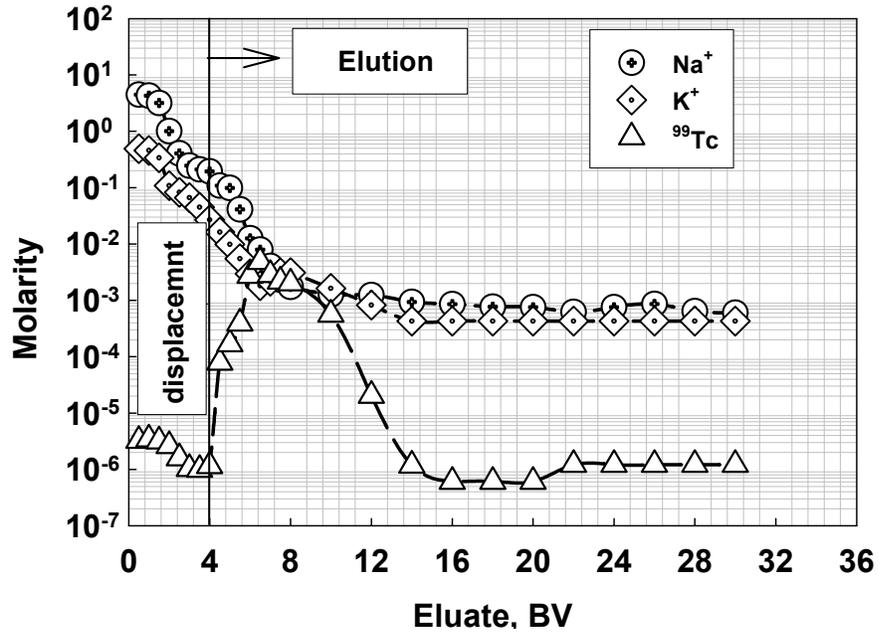


Figure 4-25. Feed Displacement and Elution - Cycle #1

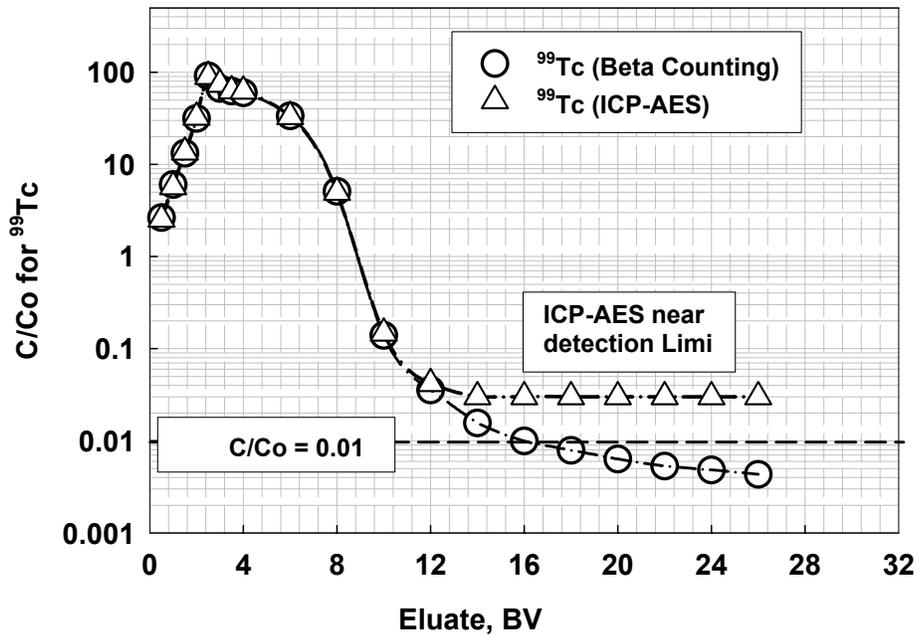


Figure 4-26. ⁹⁹Tc Elution Curve - Cycle # 2

Concentrations of K^+ , and Na^+ and NO_3^- in the feed displacement and eluate samples are shown in Figure 4-27. The K^+ and Na^+ concentrations both decreased sharply after 2 to 3 BV of the eluent passed through the column. A broad elution peak was exhibited for K^+ at 4 BV and a small hump was observed for Na^+ at 8 BV. It is not clear if the Na^+ hump was an experimental artifact or a real elution peak.

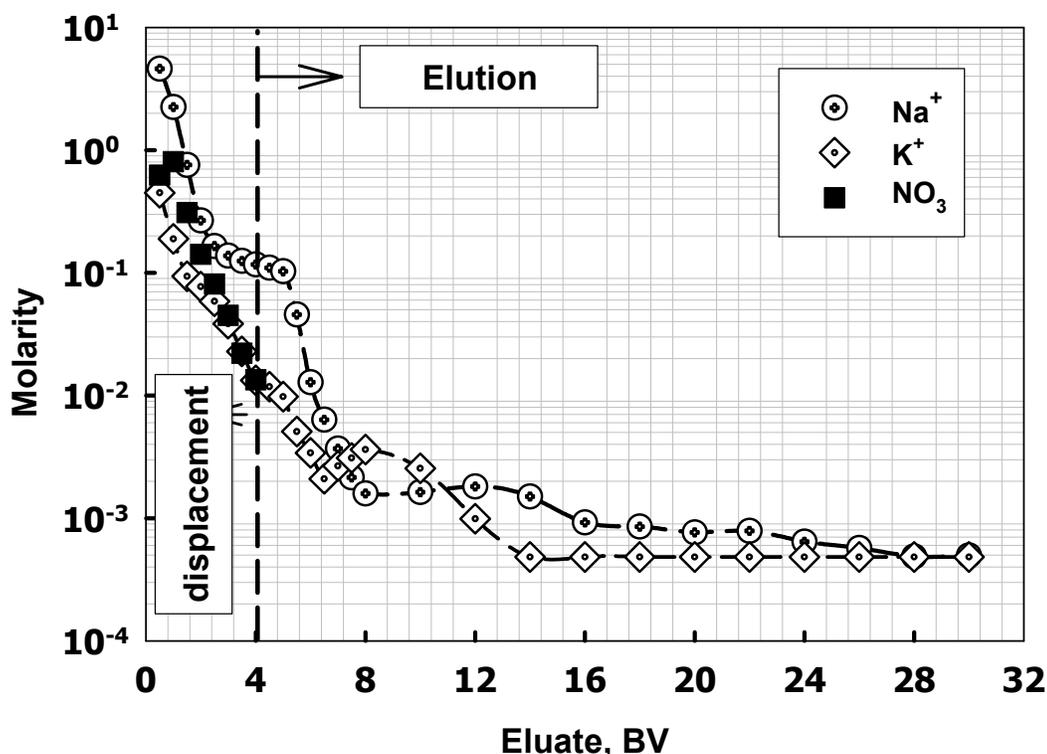


Figure 4-27. Feed Displacement and Elution - Cycle # 2

The data for ⁹⁹Tc elution in cycle #3 are presented in Figure 4-28. The elution performance was again comparable to the preceding cycles #1 and #2. The C/Co peak was exhibited at 3.5 - 4 BV with a value of 91. The C/Co of 0.01 was observed at 16 BV. The ICP-AES and beta counting methods provided comparable results, although after 6 BV the measured values by the beta counting method were slightly higher than the ICP-AES results. It should be mentioned that the ICP-AES method measures total ⁹⁹Tc while the beta scintillation and counting method provides ⁹⁹Tc pertechnetate fraction. Since the SuperLig[®] 639 adsorbs only pertechnetate fraction, the results by the two methods should be nearly the same.

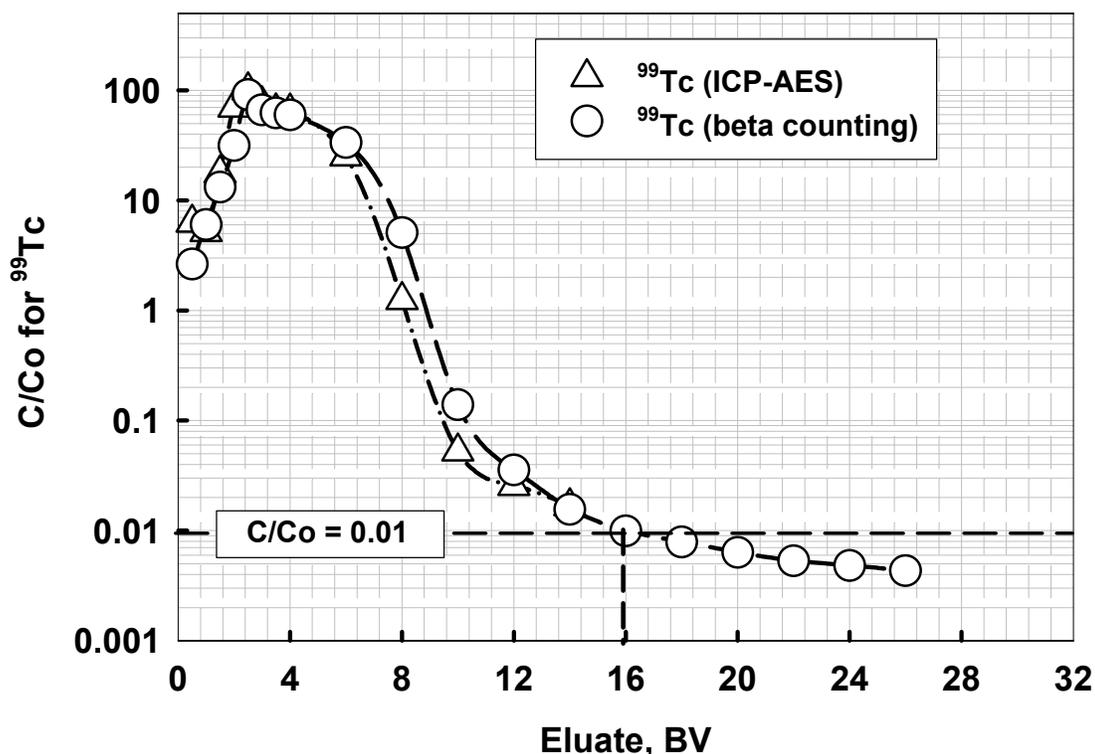


Figure 4-28. ^{99}Tc Elution Curve - Cycle # 3

Figure 4-29 shows the ^{99}Tc , K^+ , Na^+ , and NO_3^- concentrations in the feed displacement and eluate samples in cycle #3. The data show a sharp decrease of K^+ , Na^+ , and NO_3^- concentrations at 2 BV of feed displacement. The Na^+ concentration reached 0.1 M at 2 BV and then remained constant for the next 2 BV of displacement. As the elution started, the Na^+ concentration decreased sharply again and the K^+ and NO_3^- concentrations continued their downward trend. The K^+ , Na^+ , and NO_3^- leveled off after 4 BV of eluent passed through the column. At this point, the K^+ exhibited a broad hump next to the ^{99}Tc peaks at about 6 BV. Also, a broad Na^+ peak appeared at 8 BV. While the K^+ and Na^+ are not sufficiently resolved, their presence suggests that ^{99}Tc was present on the resin as potassium pertechnetate and sodium pertechnetate.

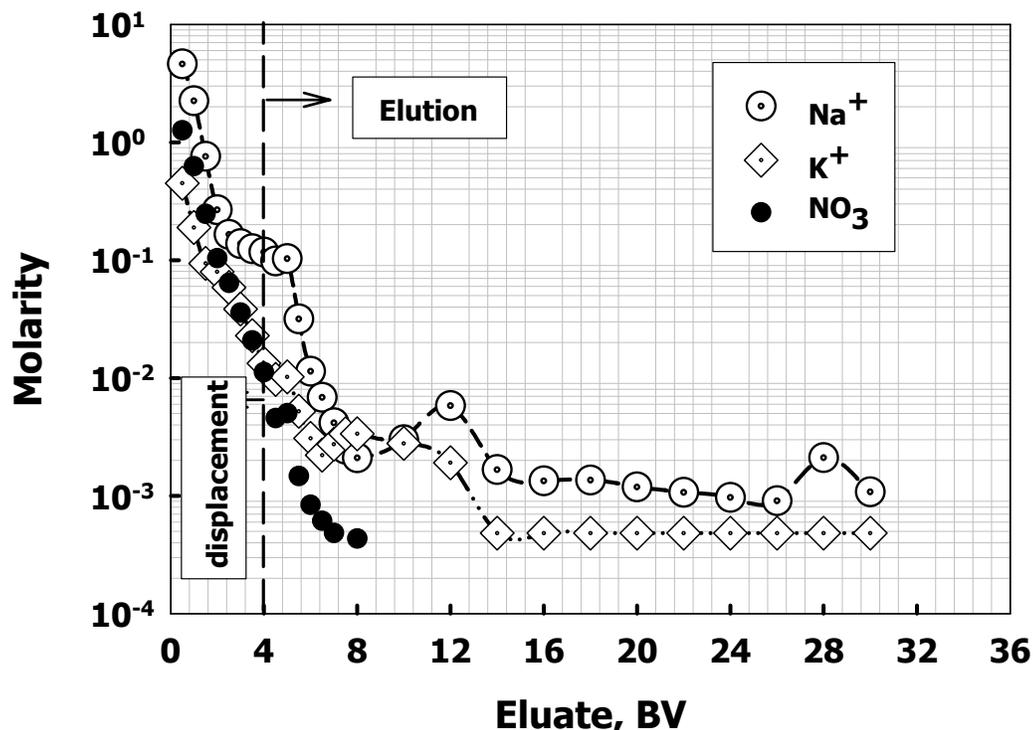


Figure 4-29. Feed Displacement and Elution - Cycle # 3

Figure 4-30 shows the ⁹⁹Tc elution data in cycle #4. Elution was performed on the lead and lag columns using de-ionized water at a flow rate of 1 BV/h and at 65 °C. However, data were collected on the lead column only. Since ICP-AES and chemical separation/beta counting methods provided identical results in cycle #1 and cycle #2, we used ICP-AES to measure ⁹⁹Tc in the first 12 BV of eluate samples; beta counting was used to measure the ⁹⁹Tc concentration in the remaining samples. The ⁹⁹Tc elution was fast at 65 °C. The C/Co peak was exhibited at ~ 2.5 BV with a peak value of 128. The peak C/Co value was ~ 37% higher than the corresponding peak C/Co values of cycles #1, # 2, and # 3. The C/Co of 0.01 (target) was observed after 14 BV; the C/Co gradually declined thereafter until the elution was terminated at 26 BV.

Figure 4-31 displays the concentration of ⁹⁹Tc, K⁺, Na⁺, and NO₃⁻ in the feed displacement and eluate samples in cycle #4. The general trend of K⁺, Na⁺, and NO₃⁻ concentrations in the displacement and elution steps was similar to that observed in cycle # 3. The Na⁺ concentration decreased sharply after 2 BV of feed displacement and leveled off at 0.1 M. The K⁺ and NO₃⁻ concentrations continued to decline throughout the feed displacement. The concentrations of K⁺, Na⁺, and NO₃⁻ dropped by about 98% of their feed concentration after 4 BV of feed displacement. During the elution, the Na⁺ concentration resumed its sharp decline and it leveled off at about the same time the ⁹⁹Tc peak was observed. The broad hump for K⁺ was observed next to the ⁹⁹Tc peak, although it was less pronounced this time.

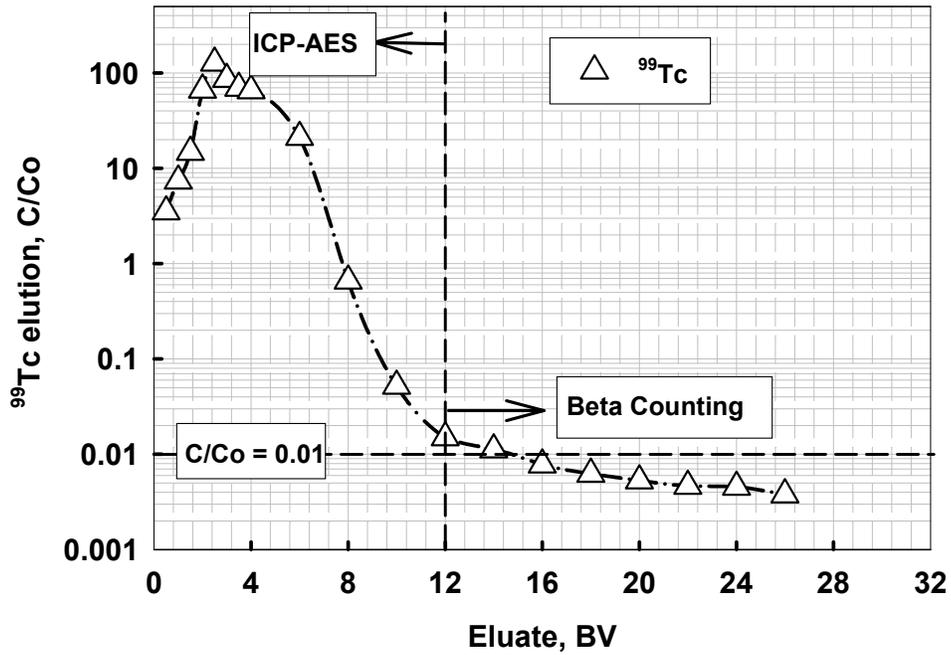


Figure 4-30. ⁹⁹Tc Elution Curve - Cycle # 4

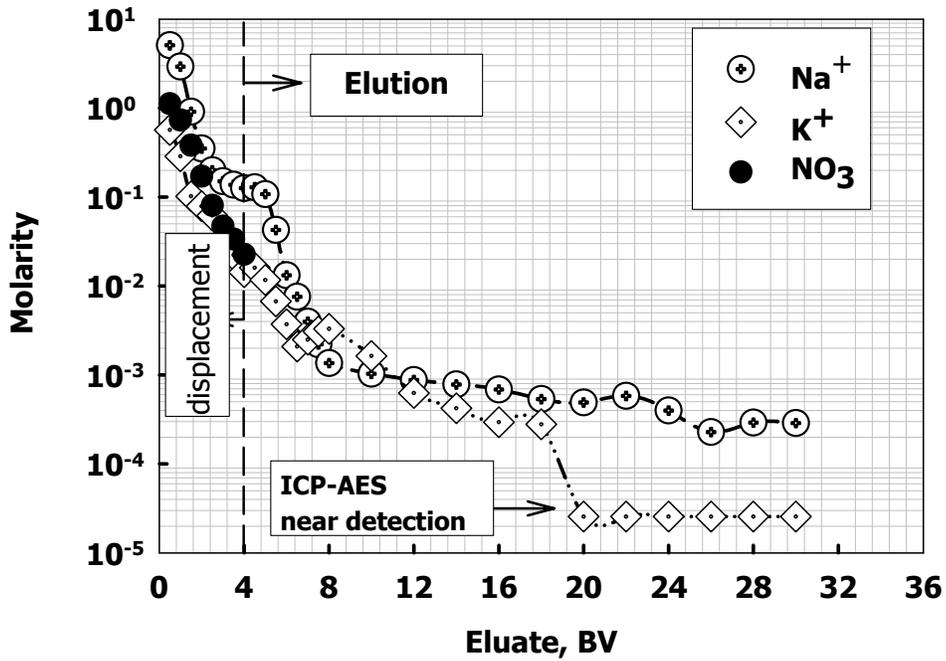


Figure 4-31. Feed Displacement and Elution - Cycle # 4

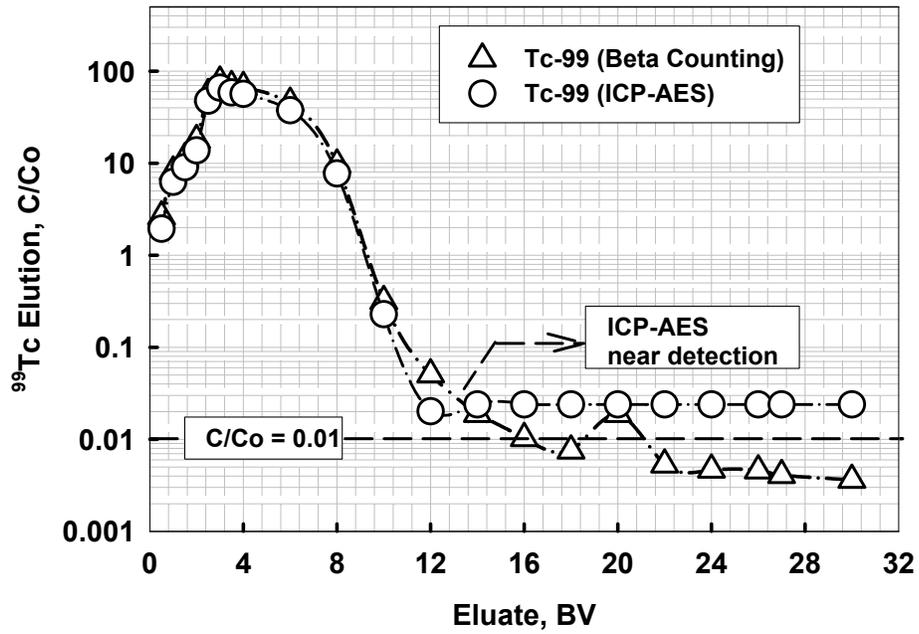


Figure 4-32. ^{99}Tc Elution Curves - Cycle # 5

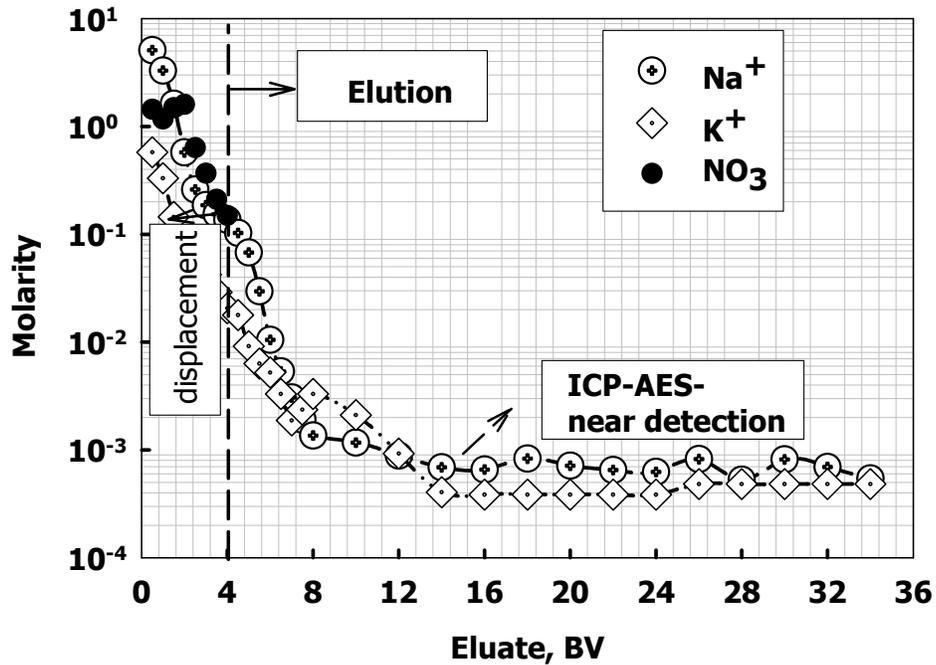


Figure 4-33. Feed Displacement and Elution - Cycle # 5

4.7 EFFLUENT COMPOSITE PRODUCTS

The effluent composite fractions from each technetium loading cycle were combined and thoroughly mixed in a 4-L carboy and then designated as “effluent composite product.” Homogeneous sub-samples from each product were analyzed in duplicate to determine the concentration of radionuclide, metals and anions. The results are shown in Table 4-7. The average concentrations of ^{137}Cs and ^{99}Tc in all five composite products were less than WTP required cesium limit of 8.7×10^{-2} and 2.9×10^{-2} $\mu\text{Ci/mL}$ for AW-101 waste sample, respectively. Thus, the performance of the cesium and technetium ion exchange dual systems has met the LAW vitrification criteria under the current experimental conditions. The percent removal of ^{137}Cs from the AW-101 waste sample for the six cycles was better than 99.99%. The percent removal was calculated from the average concentrations of ^{137}Cs in feed (Appendix A-1) and in the effluent composite products (Table 4-7). The percent removal of ^{99}Tc (pertechnetate) from the AW-101 waste sample was better than 99.94%. The contract requirement for overall Tc removal from envelopes A, B, and C was 80%.²³ Thus, a minimum 95% removal of ^{99}Tc was required of envelopes A and B waste and only 30% removal was needed in envelope C.

The overall DFs for ^{137}Cs and ^{99}Tc dual ion exchange columns are shown in Table 4.8. The DFs were calculated from the concentrations of ^{137}Cs and ^{99}Tc in effluent composite products (Table 4-7) and in the feed (Appendix A-1). The best DF for ^{137}Cs (5.0×10^5) was achieved in cycle #1, as expected. The average DF from other five cycles was $\sim 4.8 \times 10^4$. The average DF obtained for ^{99}Tc cycles was 1.7×10^3 , which significantly exceeded required DF (~ 30) for AW-101 waste sample. The good performance exhibited by SuperLig[®] 639 columns could be due to improved resin manufacturing process.

The DF for major constituents of interest in the feed is shown in Table 4-8. The DF obtained for Al^+ , Na^+ , and K^+ was about 1. The low DF for K^+ , in particular, indicates the SuperLig[®] 644 resin was highly selective for cesium over K^+ . With the exception of F^- , the DF for the anions was approximately 1.

4.8 CESIUM ELUATE PRODUCTS

The cesium eluate composite products were analyzed at the completion of the elution step for each cycle. The chemical and radionuclide content are given in Tables 4.9. In Table 4.9, the average concentration of ^{137}Cs in the eluate products was $\sim 2 \times 10^3$ $\mu\text{Ci/mL}$. The concentration of ^{137}Cs (8.89×10^2 $\mu\text{Ci/mL}$) in cycle #6 was lower because of the large dilutions made in order to transfer sub-samples from the hot cell. The ^{137}Cs was dominant radionuclide in the cesium eluate product solutions. The ^{137}Cs was above required MRQ level, but other radionuclides ^{60}Co , ^{154}Eu , and ^{155}Eu were not measured. The CST-treated samples of the composite eluate show that only Cl^- and NO_3^- were above detection (See Table 4.9; data in brackets).

Table 4-7. Composition of Effluent Composite Product

Radionuclides	Cycle #1	Cycle #2	Cycle #3	Cycle #4	Cycle #5
¹³⁷ C, μCi/mL	3.48E-04	3.72E-03	2.87E-03	4.50E-03	4.01E-03
⁹⁹ Tc, μCi/mL	3.66E-05	5.95E-05	4.20E-05	3.73E-05	2.94E-05
⁹⁹ Tc, μg/L (ICP-MS)	1.73E+02	1.73E+02	1.99E+02	1.34E+02	1.25E+02
Total carbon, mg/L	2.30E+03	2.26E+03	2.34E+03	1.62E+04	1.52E+04
TIC	1.01E+03	9.18E+02	1.08E+03	1.51E+04	1.41E+04
TOC	1.29E+03	1.34E+03	1.26E+03	1.11E+03	1.05E+03
Total base, M	2.79E+00	2.83E+00	2.79E+00	2.88E+00	2.83E+00
Free OH, M	2.05E+00	2.01E+00	1.84E+00	2.10E+00	2.09E+00
wt. % dissolved solids	3.15E+01	3.22E+01	3.24E+01	nm	nm
specific gravity	1.23E+00	1.23E+00	1.23E+00	1.23E+00	1.23E+00
IC (anions), M					
Cl-	6.22E-02	6.35E-02	6.18E-02	6.60E-02	6.46E-02
F-	9.64E-03	6.92E-03	6.87E-03	nm	4.90E-03
HCOO-	1.31E-02	6.74E-03	7.09E-03	1.15E-02	1.15E-02
NO3-	1.35E+00	1.28E+00	1.22E+00	1.32E+00	1.25E+00
NO2-	8.97E-01	9.12E-01	8.95E-01	9.27E-01	9.25E-01
(C2O4)2-	2.11E-03	1.93E-03	1.84E-03	1.92E-03	2.14E-03
PO4-	2.42E-03	1.96E-03	2.04E-03	2.38E-03	2.73E-03
SO4-	1.65E-03	1.39E-03	1.30E-03	1.17E-03	1.43E-03

nm = not measured

Table 4-7. Composition of Effluent Composite Product - continued

Analytes	Cycle #1	Cycle #2	Cycle #3	Cycle #4	Cycle #5
by ICP-AES	µg/mL	µg/mL	µg/mL	µg/mL	µg/mL
Ag	3.57E-01	3.79E-01	4.12E-01	2.98E-01	3.33E-01
Al	1.37E+04	1.40E+04	1.40E+04	1.15E+04	1.17E+04
B	1.85E+01	1.91E+01	1.89E+01	1.68E+01	1.72E+01
Ba	5.38E-01	5.82E-01	5.80E-01	nm	nm
Ca	5.95E+00	6.22E+00	6.23E+00	5.00E+00	5.30E+00
Cd	9.82E-01	1.07E+00	1.03E+00	7.84E-01	8.20E-01
Ce	4.17E+00	4.42E+00	4.76E+00	3.88E+00	4.21E+00
Cr	3.73E+01	4.32E+01	4.16E+01	3.54E+01	3.68E+01
Cu	3.78E+00	2.50E+00	2.65E+00	1.59E+00	1.20E+00
Fe	1.45E+00	1.77E+00	1.80E+00	1.58E+00	1.86E+00
K	2.13E+04	2.19E+04	2.18E+04	1.75E+04	1.77E+04
La	7.75E-01	7.92E-01	8.54E-01	5.84E-01	6.10E-01
Mo	4.27E+01	4.36E+01	4.39E+01	3.47E+01	3.54E+01
Na	1.16E+05	1.21E+05	1.20E+05	1.01E+05	1.04E+05
Ni	2.46E+00	2.53E+00	2.35E+00	2.19E+00	2.16E+00
P	1.46E+02	1.49E+02	1.49E+02	1.30E+02	1.36E+02
Pb	1.50E+01	1.62E+01	1.56E+01	1.30E+01	1.38E+01
Sb	3.94E+01	4.07E+01	4.09E+01	3.09E+01	3.22E+01
Si	9.15E+01	8.96E+01	8.99E+01	6.73E+01	6.86E+01
Sn	7.70E+01	7.91E+01	7.89E+01	6.02E+01	6.16E+01
Sr	2.00E+00	2.07E+00	2.08E+00	1.59E+00	1.81E+00
Zn	4.58E+00	4.69E+00	4.85E+00	3.98E+00	4.08E+00
Zr	4.44E+00	6.06E+00	5.44E+00	4.95E+00	5.24E+00

nm = not measured

Table 4-8. Measured DF for Analytes

Radionuclides	Cycle #1	Cycle #2	Cycle #3	Cycle #4	Cycle #5
¹³⁷ Cs	5.03E+05	4.71E+04	6.10E+04	3.89E+04	4.27E+04
⁹⁹ Tc	1.81E+03	1.11E+03	1.57E+03	1.77E+03	2.25E+03
Metals					
Al	0.94	0.91	0.91	1.12	1.09
K	1.10	1.07	1.08	1.34	1.32
Na	1.01	0.97	0.98	1.16	1.13
Anions					
Cl ⁻	1.12	1.09	1.12	1.05	1.07
F ⁻	1.47	2.05	2.07	Nm	2.90
NO ₃	1.16	1.22	1.28	1.18	1.25
NO ₂	1.02	1.00	1.02	0.98	0.99
TOC	nm	nm	nm	0.81	0.77

nm = not measured

Table 4-9. Composition of Cesium Eluate Composite Products

Radionuclides	Cycle -1	Cycle -2	Cycle -3	Cycle -4	Cycle -5	Cycle -6	MRQ
¹³⁷ Cs, μCi/mL	1.74E+03	2.19E+03	2.06E+03	2.34E+03	1.59E+03	8.89E+02	9.00E+00
⁹⁹ Tc, μCi/mL	1.64E-03	2.93E-03	4.07E-03	1.02E-02	1.69E-03	2.27E-03	1.50E-03
⁹⁹ Tc, μg/L (ICP-MS)	2.29E+02	2.75E+02	2.37E+02	3.00E+02	2.10E+02	nm	--
²³⁸ U, μg/L (ICP-MS)	6.65E+01	7.65E+01	8.10E+01	1.63E+02	6.55E+01	nm	--
Total carbon, mg/L	1.54E+03	1.24E+03	3.78E+03	1.19E+03	7.88E+02	nm	--
TIC, μg/mL	<2.61E+02	<2.71E+02	<3.78E+03	<2.49E+02	<2.58E+02	nm	1.50E+02
TOC, μg/L	1.54E+03	1.24E+03	3.78E+03	1.19E+03	7.88E+02	nm	1.50E+03
IC (anions), M	Cycle -1	Cycle -2	Cycle -3	Cycle -4	Cycle -5	Cycle -6	MRQ
Cl ⁻	<1.47E-02, (1.68E-02)	<1.53E-02, (1.79E-02)	<1.51E-02, (1.85E-02)	<1.47E-02, (1.71E-02)	<1.45E-02, (1.70E-02)	<1.56E-02, (1.72E-02)	8.46E-03
F ⁻	<2.75E-02	<2.85E-02	<2.82E-02	<2.75E-02	<2.71E-02	<2.91E-02	7.89E-03
HCOO ⁻	<5.51E-02	>6.02E-02	<5.96E-02	<5.53E-02	<5.72E-02	<6.13E-02	--
NO ₃ ⁻	4.48E-01, (8.74E-01)	4.29E-01, (8.87E-01)	7.92E-01, (8.85E-01)	6.31E-01, (8.90E-01)	4.61E-01, (8.74E-01)	2.89E-01, (8.82E-01)	4.69E-02
NO ₂ ⁻	<5.68E-02	<5.89E-02	<1.02E-01	<5.41E-02	<5.60E-02	<6.00E-02	6.52E-02
(C ₂ O ₄) ₂ ⁻	<2.97E-02	<3.08E-02	<3.05E-02	<2.83E-02	<2.93E-02	<3.12E-02	--
PO ₄ ⁻	<2.75E-02	<2.86E-02	<2.82E-02	<2.62E-02	<2.71E-02	<2.91E-02	2.63E-02
SO ₄ ⁻	<1.36E-02	<1.41E-02	<1.40E-02	<1.30E-02	<1.34E-02	<1.43E-02	2.40E-02

Dashes (--) indicate no MRQ was specified.

Table 4-9. Composition of Cesium Eluate Composite Products - continued

Analytes by	Cycle -1	Cycle -2	Cycle -3	Cycle -4	Cycle -5	Cycle -6	MRQ
ICP-AES	µg/mL	µg/mL	µg/mL	µg/mL	µg/mL	µg/mL	µg/mL
Ag	<4.18E+01	<4.34E+01	<4.29E+01	<3.97E+01	<4.12E+01	<4.35E+01	--
Al	<2.98E+02	<3.09E+02	<3.06E+02	<2.84E+02	<2.94E+02	<3.11E+02	7.50E+01
B	6.76E+02	6.78E+02	5.54E+02	6.44E+02	6.97E+02	8.60E+02	--
Ba	9.95E+01	1.03E+02	1.02E+02	9.50E+01	9.80E+01	1.04E+02	2.30E+00
Ca	<1.20E+02	<1.15E+02	<1.23E+02	<1.15E+02	<1.19E+02	<1.26E+02	1.50E+02
Cd	2.19E+01	2.27E+01	2.25E+01	2.09E+01	2.16E+01	2.29E+01	7.50E+00
Ce	3.03E+02	3.59E+02	3.11E+02	2.68E+02	2.82E+02	1.47E+02	--
Cr	3.13E+01	3.25E+01	3.22E+01	2.99E+01	3.09E+01	3.27E+01	1.50E+01
Cu	1.46E+02	1.55E+02	1.47E+02	1.39E+02	1.43E+02	8.97E+01	--
Fe	1.88E+01	1.95E+01	1.93E+01	1.80E+01	1.85E+01	1.96E+01	1.50E+02
Gd	<1.22E+02	<1.27E+02	<1.25E+02	<1.17E+02	<1.21E+02	<1.28E+02	--
K	<4.91E+03	<5.09E+03	<5.38E+03	<4.68E+03	<4.84E+03	<5.12E+03	7.50E+01
La	4.89E+01	5.91E+01	5.25E+01	4.16E+01	4.60E+01	3.92E+01	3.50E+01
Li	2.25E+02	2.33E+02	2.31E+02	2.14E+02	2.22E+02	2.34E+02	--
Mg	<2.77E+01	<2.87E+01	<2.84E+01	<2.64E+01	<2.73E+01	<2.89E+01	3.00E+02
Mn	<4.20E+00	<4.30E+00	<4.30E+00	<4.00E+00	<4.10E+00	<4.35E+00	--
Mo	<2.77E+02	<2.87E+02	<2.84E+02	<2.64E+02	<2.73E+02	<2.89E+02	--
Na	1.59E+03	1.95E+03	1.62E+03	1.95E+03	1.54E+03	1.92E+03	7.50E+01
Ni	7.05E+01	7.31E+01	7.23E+01	6.72E+01	6.95E+01	7.35E+01	3.00E+01
P	<3.60E+02	<3.74E+02	<3.70E+02	<3.44E+02	<3.56E+02	<3.76E+02	6.00E+02
Pb	<1.67E+02	<1.73E+02	<1.71E+02	<1.59E+02	<1.65E+02	<1.74E+02	3.00E+02
Sb	<1.97E+03	<2.05E+03	<2.02E+03	<1.88E+03	<1.95E+03	<2.06E+03	--
Si	<8.72E+01	<9.05E+01	<8.94E+01	<8.32E+01	<8.60E+01	<9.09E+01	--
Sn	3.32E+02	4.47E+02	3.55E+02	3.89E+02	3.52E+02	2.45E+02	--
Sr	3.97E+01	4.12E+01	4.07E+01	3.79E+01	3.91E+01	4.14E+01	--
Tc	<3.13E+01	<3.25E+01	<3.22E+01	<2.99E+01	<3.09E+01	<3.27E+01	--
Ti	<4.02E+01	<4.17E+01	<4.13E+01	<3.83E+01	<3.97E+01	<4.19E+01	--
U	<1.18E+03	<1.23E+03	<1.22E+03	<1.13E+03	<1.17E+03	<1.24E+03	6.00E+02
Zn	<1.67E+01	<1.73E+01	<1.72E+01	<1.60E+01	<1.65E+01	<1.75E+01	--
Zr	<1.19E+02	<1.24E+02	<1.22E+02	<1.14E+02	<1.18E+02	<1.22E+02	--

Dashes (--) indicate no MRQ was specified.

4.9 TECHNETIUM ELUATE PRODUCTS

The technetium eluate composite products were analyzed to determine the composition of the chemical species and radionuclides and the results are shown in Table 4-10. The major radionuclide in the eluate products was ⁹⁹Tc with concentration with concentration in the range 3.6×10^{-1} to 4.9×10^{-1} $\mu\text{Ci/mL}$. The concentrations of the metals (cations) were as expected. Sodium and potassium were dominant in the eluate products and their MRQs were met. The concentrations of the majority of the metals were below their MRQs. The dominant anions were NO_3^- and NO_2^- . The MRQs for the anions were not met.

Table 4-10. Composition of Technetium Eluate Composite Products

Analyte	Cycle -1	Cycle -2	Cycle -3	Cycle -4	Cycle -5	MRQ
¹³⁷ Cs, mCi/mL	8.31E-05	2.78E-04	6.65E-03	2.41E-04	1.63E-02	9.00E+00
⁹⁹ Tc, mCi/mL	2.46E-01	3.84E-01	3.64E-01	3.90E-01	4.89E-01	1.50E-03
⁹⁹ Tc, mg/L (ICP-MS)	1.47E+03	2.11E+04	2.05E+04	2.21E+04	nm	--
²³⁸ U, mg/L (ICP-MS)	3.6	8.8	23.4	29.1	nm	--
IC (anions), M						
Cl-	<5.64E-05	3.33E-03	1.69E-04	5.36E-04	nm	8.46E-03
F-	<1.05E-04	2.63E-04	<1.05E-04	<1.05E-04	nm	7.89E-03
HCOO-	<2.22E-04	1.08E-03	<2.22E-04	<2.22E-04	nm	--
NO3-	3.39E-04	8.73E-02	4.33E-03	3.18E-03	nm	4.69E-02
NO2-	1.85E-04	4.42E-02	3.20E-03	2.38E-03	nm	6.52E-02
(C2O4)2-	<1.14E-04	1.02E-04	<1.14E-04	<1.14E-04	nm	--
PO4-	<1.05E-04	8.95E-05	<1.05E-04	<1.05E-04	nm	2.63E-02
SO4-	<5.21E-04	6.25E-05	<5.21E-04	<5.21E-04	nm	2.40E-02

nm = not measured

Dashes (--) indicate no MRQ was specified.

Table 4-10. Composition of Technetium Eluate Composite Products - continued

Analyte	Cycle -1	Cycle -2	Cycle -3	Cycle -4	Cycle -5	MRQ
ICP-ES	µg/mL	µg/mL	µg/mL	µg/mL	µg/mL	µg/mL
Ag	<0.160	<0.160	<0.160	<0.160	<0.160	--
Al	2.0	614	45.4	30.9	34	7.50E+01
B	6.88	3.31	4.51	5.37	2.03	--
Ba	<0.380	<0.380	<0.380	<0.428	<0.380	2.30E+00
Be	<0.020	0.069	0.035	<0.030	0.055	1.50E+02
Ca	<0.460	<0.460	<0.460	<0.518	<0.460	7.50E+00
Cd	<0.084	<0.084	<0.084	<0.095	<0.084	--
Ce	1.0	1.61	1.25	0.964	<0.540	1.50E+01
Cr	<0.120	1.84	<0.120	<0.135	<0.120	--
Cu	0.25	0.298	0.24	0.263	0.319	1.50E+02
Fe	0.43	0.459	0.208	0.187	<0.072	--
K	32.05	1220	96.6	82	100.4	7.50E+01
La	<0.144	0.221	0.168	<0.162	<0.144	3.50E+01
Li	<0.860	<0.860	<0.860	<0.970	<0.860	--
Mg	<0.106	<0.106	<0.106	<0.120	<0.106	3.00E+02
Mn	<0.016	<0.016	<0.016	<0.018	<0.016	--
Mo	<1.06	2.29	<1.06	<1.20	<1.06	--
Na	89	5770	461	364	416	7.50E+01
Ni	<0.270	<0.270	<0.270	<0.304	<0.270	3.00E+01
P	5.6	13.6	6.41	6.31	<1.38	6.00E+02
Pb	<0.638	<0.638	<0.638	<0.718	<0.638	3.00E+02
S	<2.74	11.2	<2.74	<3.09	<2.74	--
Sb	<7.56	<7.56	<7.56	<8.51	<7.56	--
Si	10.89	17.8	7.71	6.07	4.6	--
Sn	<0.900	4.01	<0.900	<1.02	<0.900	--
Sr	<0.152	<0.152	<0.152	<0.171	<0.152	--
Ti	<0.154	<0.154	<0.154	<0.174	<1.54	--
U	<4.54	<4.54	<4.54	<4.61	<4.54	6.00E+02
Zn	<0.064	0.206	<0.064	<0.072	<0.064	--
Zr	<0.456	<0.456	<0.456	<0.463	<0.456	--

Dashes (--) indicate no MRQ was specified.

4.10 SPENT RESIN ANALYSIS

The spent resins from the cesium and technetium ion exchange lead columns were analyzed to determine the concentrations of radionuclide and toxic metals that may be left on the resin after multiple load/elute/regenerate cycles. The amount of SuperLig[®] 644 resin initially added to the cesium lead column was 5.1562 g of H- form resin. After six cycles, the lead column was eluted with 24 BV of 0.5 M HNO₃, and then rinsed with excess amount of DI water. The resin was slurred from the column with DI water into a Nalgene filter unit, where a house vacuum (20-inch water) was used to remove standing water. The resin was allowed to dry for two weeks to a constant mass of 3.11 g.

Following the processing of the AW-101 sample, the technetium lead column was eluted with 28 BV of DI water at 65 °C. The amount of SuperLig[®] 639 resin initially added to the technetium lead column was 7.3659 g (12 mL on a wet-basis). Since this material does not exhibit an appreciable change in volume when in contact with the various processing solutions, the volume of resin was unchanged. After elution, the SuperLig[®] 639 resin was slurried into a Nalgene filter unit under house vacuum (20-inch water) and the standing water was removed. The resin was allowed to dry in the hood for two weeks. The dry spent resin was stored in glass vial and submitted to SRTC Analytical Development Section (ADS) for analysis.

The analyses performed on each sample of the spent resins included Toxicity Characterization Leaching Procedure (TCLP), microwave dissolution of spent resin samples, ICP-AES analysis (metals), GEA analysis (radionuclide), and chemical separation and beta counting (⁹⁹Tc, ⁹⁰Sr). The concentrations of arsenic, selenium and mercury were measured by Atomic Absorption Spectrometry.

The Toxicity Characteristic Leaching Procedure (TCLP) was performed in SRTC to analyze the spent resins for hazardous constituents. The TCLP is a standard procedure accepted by Environmental Protection Agency to determine if the solid form of waste is hazardous. The EPA standard method (SW-376) requires a minimum 50-gram sample to perform the procedure.²³ Due to small size of the resin samples available, SRTC employed a modified TCLP test. A small portion (1.0 gram) of each spent resin sample was weighed in 25-mL plastic vials containing 20 mL of TCLP Extraction Fluid 1, then the vials were capped. TCLP Extraction Fluid 1 was prepared by adding 5.7 mL glacial acetic acid to 500 mL deionized water, followed by adding 64.3 mL of 1.0 M NaOH, and diluting the solution to a volume of exactly 1 L. The vials were placed in an extractor vessel and rotated end-over-end at 30 ± 2 rpm for 18 hours. The solution was then filtered through a 0.7 micron porosity fiberglass filter and the filtrate transferred to sample bottles for analysis.

Small portions (1.0 gram) of each sample of SuperLig[®] 644 and 639 resins were subjected to microwave dissolution, and an aliquot of each dissolved sample was analyzed by ICP-AES. Gamma analysis was performed on an aliquot of each dissolved samples to determine ¹³⁷Cs, ⁶⁰Co, ¹⁵⁴Eu, and ¹⁵⁵Eu using a high purity germanium detector. The ⁹⁹Tc concentration was determined by chemical separation, followed by beta counting, using small aliquots of the dissolution samples. Total alpha and beta concentrations were measured by rad screen.

Aliquots of the dissolved samples were wet-ashed with a sodium persulfate/silver nitrate oxidation in conjunction with concentrated sulfuric acid. The carbon dioxide emitted was absorbed with Packard Instruments Carbosorb E. The Carbosorb E was then slurred into Ultima Gold AB, and analyzed by liquid scintillation analysis for C-14. A laboratory control blank solution, spiked with a C-14 standard, was run in duplicate, in parallel with the samples to determine C-14 recoveries, the average of which were applied to the sample C-14 Liquid Scintillation Counting (LSC) results to quantify the C-14 concentrations in the samples. A blank solution was also run through the process to ensure no cross contamination existed at the laboratory level.

An aliquot of each dissolved sample was spiked with stable iodide and was subjected to a silver iodide precipitation method to separate any iodide in the matrix from other radionuclides. A blank DI water sample was analyzed along with the batch. The precipitates were analyzed for I-129 activity with a low energy HPGe gamma spectroscopy detector. After the gamma analyses, the precipitates were analyzed by neutron activation analysis (NAA) to determine the levels of stable iodide carrier in the precipitates. The recoveries of the iodide carrier were used to correct the gamma spectroscopy results for the I-129 recoveries.

Strontium-90 separation and analysis was performed using another pair of aliquots from the dissolved samples. The separation was performed using an Eichrom Sr-Spec based extraction procedure. Once the extraction was completed for the aliquots, the resultant Sr-90 containing extracts were mixed with liquid scintillation cocktail and counted in the ADS Radiochemistry Counting Facility. The samples were counted on a Packard Instruments liquid scintillation counter.

Plutonium separation and analysis were performed using an aliquot from each dissolved samples. An aliquot of each sample was initially spiked with a Pu-239 tracer. A second aliquot of sample was analyzed along with the spiked sample. All of the plutonium in the samples was reduced once using hydroxylamine. An anion complexing reagent (aluminum nitrate) was then added, and the solutions were oxidized with 4 M sodium nitrite. The plutonium was then extracted from the matrix using a thenoyltrifluoroacetone (TTA) solution. The TTA layer was mounted on a counting dish, the mount was then analyzed by alpha spectroscopy.

The results of the radionuclide concentrations of SuperLig[®] 644 and 639 spent resins and the WTP specified minimum reportable quantities (MRQ) are given in Table 4-11. Specifically listed are the isotope, the analysis method and isotopic activity. The results given in the table show that ⁶⁰Co, ¹³⁷Cs, and ⁹⁹Tc were dominant among the radionuclides accumulated on the spent SuperLig[®] 644 resins. The ¹³⁷Cs accumulated on the spent resin was 20 μCi/g by GEA measurement; the beta activity measured 23.5 μCi/g. These values compare very well with the results (20 μCi/g) previously reported by Kurath.²¹ As expected, ⁹⁹Tc was dominant on the spent SuperLig[®] 639 spent resin with a value of 3.6 x 10⁻¹ μCi/g. The ¹³⁷Cs and total beta activity found on SuperLig[®] 639 spent resin were very small, suggesting the dose to the resin was not significant. The concentration of plutonium isotopes on spent resin (SuperLig[®] 644) was set by total alpha (1.36 x 10⁻¹ μCi/g). The analytes measured above the minimum reportable quantities (MRQs) for cesium spent resin (SuperLig[®] 644) were ⁶⁰Co, ¹³⁷Cs, ⁹⁹Tc, ²³⁸Pu, and ²⁴¹Pu. The only analyte above MRQ for technetium spent resin (SuperLig[®] 639) was ⁹⁹Tc.

Table 4-11. Radionuclide Accumulation in Spent Resins

Analyte	Method	SL-644 μCi/g resin*	SL-639 μCi/g resin*	MRQ μCi/g resin*
⁶⁰ Co	GEA	8.24E-01	< 1.91E-02	1.2E-01
¹³⁷ Cs	GEA	2.00E+01	< 3.10E-02	1.0E-02
¹⁵⁴ Eu	GEA	nm	nm	3.0E-01
¹⁵⁵ Eu	GEA	nm	nm	6.0E+00
Pu ²³⁸	Pu TTA	3.40E-02	7.79E-04	1.0E-02
Pu ^{239/240}	Pu TTA	6.67E-03	2.03E-03	3.0E-02
Pu ²⁴¹	Pu-241 LSC	3.39E-02	nm	3.0E-02
⁹⁰ Sr	Beta LSC	nm	nm	1.50E-04
⁹⁹ Tc	Beta LSC	1.41E-01	3.65E-01	6.0E-04
¹⁴ C	Beta LSC	< 2.60E-04	nm	nm
¹²⁹ I	GEA	< 1.00E-05	nm	nm
Total alpha	Rad screen	1.36E-01	3.14E-03	nm
Total beta	Rad screen	2.35E+01	4.86E-01	nm

*H- form (After extended elution and rinse with DI water, the resin was dried in air for two weeks.)

The results of the TCLP analyses of SuperLig[®] 644 and 639 spent resins are shown in Table 4-12. The table contains the Resource Conservation and Recovery Act (RCRA) limits for hazardous constituents. The results show that the RCRA metals for each spent resin were below the hazardous limit. Since SRTC is not a certified laboratory, the TCLP results are to augment the process knowledge for RPP-WTP in an effort to determine disposal alternatives for spent resins generated during the operation of the WTP plant.

Table 4-12. TCLP Results for Spent Resins

Analyte	SL644	SL639	Limits	Units
As	<0.025	<0.025	5	mg/L
Ba	0.383	0.468	100	mg/L
Cd	<0.042	<0.042	1	mg/L
Cr	<0.060	<0.060	5	mg/L
Pb	<0.319	<0.319	5	mg/L
Hg	<0.110	<0.110	0.2	mg/L
Se	<0.025	<0.025	1	mg/L
Ag	<0.080	<0.080	5	mg/L

The results for spent resin (solids) analysis by ICP-AES, along with specified MRQ are shown in Table 4-13. The data provided in the table are based on mass of analyte accumulated on dry resin samples. The metals above their MRQ that were found on SuperLig[®] 644 and 639 resin samples were Al, Cr, Na, K, and Ni. The presence of K, Na, and Cr on SuperLig[®] 644 and 639 samples was expected since the resins are known to have some affinity for these metals. Other metals found on the resin samples above their detection limits were Ag, Ca, Ce, Cu, Fe, Mg, Si, Sr, and Zn. The presence of Si (silicon) is likely from leaching of glassware used in sample handling and preparation.

Table 4-13. ICP-AES Results of Spent Resin Dissolution Samples

Analyte ICP-AES	SL644 mg/g	SL639 mg/g	MRQ* mg/g
Ag	2.4E+01	<6.75	--
Al	1.8E+02	1.3E+02	7.5E+01
B	<22.5	<23.6	--
Ba	<15.2	<16.0	2.3E+01
Ca	6.0E+01	4.5E+01	1.5E+02
Cd	<3.37	<3.54	7.5E+00
Ce	4.6E+01	4.0E+01	--
Cr	5.7E+02	3.9E+01	1.5E+01
Cu	8.7E+01	1.7E+02	--
Fe	1.1E+02	1.5E+02	1.5E+02
Gd	<18.8	<19.7	--
K	7.5E+02	7.9E+02	7.5E+01
La	<5.78	<6.07	3.5E+01
Li	<34.5	<36.3	--
Mg	6.1E+01	1.9E+02	3.0E+02
Mn	<0.642	<0.675	--
Mo	<42.5	<44.7	--
Na	2.8E+03	1.2E+02	7.5E+01
Ni	3.2E+01	5.7E+01	3.0E+01
P	<55.4	<58.2	6.0E+02
Pb	<25.6	<26.9	3.0E+02
Sb	<303	<319	--
Si	1.6E+02	1.7E+02	--
Sn	<36.1	<37.9	--
Sr	7.1E+00	<6.41	--
Ti	<6.18	6.5E+00	--
U	<182	<191	6.0E+02
Zn	8.2E+00	2.1E+01	--
Zr	8.8E+02	<19.2	--

* Dashes (--) indicate no MRQ was specified

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5.0 CONCLUSION

Six loading/elution/regeneration cycles for cesium and five loading/elution/regeneration cycles for technetium were performed to remove ^{137}Cs and ^{99}Tc (pertechnetate) from Tank 241-AW-101 waste sample with SuperLig[®] 644 and 639 resins, respectively. Dual ion exchange columns of 1.45-cm inside diameter were used. The columns were connected in series during loading, feed displacement, and water rinse; then were separately eluted and regenerated. The following conclusions were drawn from the tests:

1. Six cycles of loading, elution, and regeneration were performed to demonstrate ^{137}Cs could be effectively removed from a 241-AW-101 tank sample using SuperLig[®] 644 in a small dual ion exchange column system installed in a hot cell.
 - Total volume of AW-101 waste sample processed through the cesium ion exchange columns was 15 L or an average 180 BVs per cycle.
 - Percent ^{137}Cs removal was > 99.99% for all six cycles.
 - Cesium decontamination factor (DF) was on average 3.8×10^4 .
 - The cumulative dose (1.99×10^7 rad) exposed to the lead column resin was significantly below the target 1.0×10^8 rad to have considerable impact on resin performance. At this low radiation exposure, chemical degradation may have caused most of the observed loss in resin capacity.
 - A 24% reduction of resin loading capacity was observed between cycle # 1 and cycle #6 based on the difference of column loading at 10% breakthrough. Based on the chemical degradation model by Battelle (WTP-RPT-046), a 14% reduction in loading capacity was observed between cycles 5 and 10. This suggests that the radiation effect in the AW-101 testing contributed up to 40% of the capacity reduction. The capacity reduction was due to the synergistic effect of exposed dose to resin and chemical degradation.
 - Elution of SuperLig[®] 644 with 0.5 M HNO_3 was generally effective, except for cycle #6, where strong tailing at the base was observed.
2. Five cycles of loading, elution, and regeneration were performed to demonstrate ^{99}Tc could be effectively removed from a 241-AW-101 tank sample using SuperLig[®] 639 resin in a small dual ion exchange system.
 - SuperLig[®] 639 resin showed good loading performance with an average of 250 BVs per cycle at 10 % breakthrough.
 - Percent ^{99}Tc (pertechnetate) removal was > 99.94% for all five cycles.
 - The ^{99}Tc DF was on average ~1700 during the five cycles. This DF was 30 times higher than previous DF observed for AW-101 testing with SuperLig[®] 639.
 - Feed displacement and elution data suggest that ^{99}Tc is removed by SuperLig[®] 639 resin in the form of sodium and potassium pertechnetate and the presence of potassium in the Hanford solutions could possible enhance ^{99}Tc removal.
 - Technetium elution with de-ionized water at 65 °C was effective. Less than 1% of the ^{99}Tc remained on SuperLig[®] 639 resin after 14 BV.
 - Radiation exposure of SuperLig[®] 639 resin is not an issue with the RPP-WTP process.

3. Generated 12 L of effluent composite product for LAW vitrification.
 - The average ^{137}Cs concentration of $3 \times 10^{-3} \mu\text{Ci/mL}$ in 12 L of product solution was below the maximum allowable concentration ($8.7 \times 10^{-2} \mu\text{Ci/mL}$) for LAW vitrification. The ^{99}Tc concentration was $< 3 \times 10^{-5} \mu\text{Ci/mL}$ to meet the concentration limit of $2.9 \times 10^{-3} \mu\text{Ci/mL}$ for LAW vitrification.
 - All major constituents in the feed were accounted for in the effluent product solutions.
 - Large dilutions prevented detection of most analytes in the cesium eluate product solutions.
 - No major technical issues were identified.
4. All RCRA hazardous elements were below TCLP limits.

6.0 REFERENCES

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APPENDIX A
AW-101 FEED CONCENTRATIONS

Table A-1. ^{137}Cs [C]_o in AW-101 Sample at 5 M Na^+

LIMS #	[^{137}Cs], $\mu\text{Ci/mL}$
3-178765	1.86E+02
3-178766	1.83E+02
3-180091	1.64E+02
3-180092	1.70E+02
3-183211	1.63E+02
3-183212	1.63E+02
3-185766	1.76E+02
3-185767	1.75E+02
3-186524	1.72E+02
3-186525	1.83E+02
3-186681	1.71E+02
3-186682	1.74E+02
3-187416	1.72E+02
3-187417	1.99E+02
Average	1.75E+02
RSD	5.49E-02

Table A-2. ^{99}Tc [C]_o in AW-101 wastes Sample (filtrate at 5 M Na^+)

PERTECHNETATE			
LIMS #	[Tc-99], dpm/mL	[Tc-99], $\mu\text{Ci/mL}$	[Tc-99], mg/L
3-186357	1.45E+05	6.53E-02	3840
3-186358	1.40E+05	6.31E-02	3720
3-186780	1.56E+05	7.03E-02	4140
3-186781	1.47E+05	6.62E-02	3890
Average	1.47E+05	6.62E-02	3.90E+03
RSD	4.55E-02	4.55E-02	4.53E-02

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APPENDIX B - BATCH CONTACT DATA

APPENDIX B-1: CESIUM BATCH DATA

Envelope A (Tank 241-AW-101 actual & stimulant)

Resin: SuperLig[®] 644

Batch #: 1-D5-03-06-02-35-60

Table B-1-1. K_d Values for ^{137}Cs from AW-101 Actual Waste Sample

^{137}Cs -Kd values K^+ (M) 0.43 Hanford: Envelope A (AW-101)										Concentration Used in Kd Tests			
Sample ID	LIMS #	Solution Mass (g)	Resin Mass (g)	Solution Vol. (mL)	Phase Ratio	F-factor	Cs-137* ($\mu\text{Ci/mL}$)	Cs-137* (M)	Dilution Factor	Cs-137* ($\mu\text{Ci/mL}$)	Cs-137* (M)	K_d (mL/g)	Avg. K_d (mL/g)
NH44-AW101-Kd-1	3-180087	12.629	0.1002	9.92	99	0.60	1.72	1.45E-07	11.7	20.2	1.70E-06	1201	na
NH44-AW101-Kd-1D	3-180088	12.559	0.1002	9.87	98	0.60	1.61	1.36E-07	10.9	17.6	1.48E-06	1392	1297
NH44-AW101-Kd-2	3-180089	12.4	1.0024	9.74	9.7	0.60	9.54E-02	8.05E-09	11.1	1.1	8.90E-08	2546	na
NH44-AW101-Kd-2D	3-180090	12.094	1.0023	9.50	9.5	0.60	8.89E-02	7.50E-09	11.0	1.0	8.26E-08	2678	2612
AW101-LCS-02513-1	3-180091	12.295	na	9.66	na	na	15.01	1.27E-06	10.9	163.7	1.38E-05	na	na
AW101-LCS-02513-1D	3-180092	12.188	na	9.57	na	na	15.52	1.31E-06	11.0	170.0	1.43E-05	na	na

* dilution corrected

na – not applicable

Table B-1-2. K_d Values for ^{137}Cs from AW-101 Simulant

^{137}Cs -Kd values K^+ (M) 0.43 Hanford: Envelope A (AW-101)										
Sample ID	LIMS #	Solution Mass (g)	Resin Mass (g)	Solution Vol. (mL)	Phase Ratio	F-factor	Cs (total) ($\mu\text{g/L}$)	Blank Avg. ($\mu\text{g/L}$)	K_d (mL/g)	Avg. K_d (mL/g)
NH44-AW101Sim-Kd-1	3-180691	12.5587	0.1006	9.87	98	0.60	896	na	1572	na
NH44-AW101Sim-Kd-1D	3-180692	12.5476	0.1003	9.86	98	0.60	932	na	1508	1540
AW101-LCS-02605-1	3-180693	12.6377	na	9.93	na	na	9450	na	na	na
AW101-LCS-02605-1D	3-180694	12.5103	na	9.83	na	na	9580	9515	na	na

na = not applicable

APPENDIX B-2: CESIUM BATCH DATA

Envelope A (Tank 241-AW-101 actual)

Resin: SuperLig® 639

Batch #: 1-R2-03-27-02-20-45

Table B-2-1: K_d values for ⁹⁹Tc from AW-101 Actual Waste Sample

Tc (99) K _d values Actual: Envelope A (AW-101)			NO ₃ ⁻ 1.4 M								
Sample ID	LIMS #	Solution Mass (g)	Resin Mass (g)	Solution Vol. (mL)	Phase Ratio	F-factor	Tc99 (µg/L)	Dilution Factor	Tc-99 dl Corrected	K _d ¹ (mL/g) ¹	Avg. K _d ¹ (mL/g)
AW101-Kd39-1-filtrate-1	3-180695	12.161	0.1	9.55	96	0.98	43	11.4	492	839	na
AW101-Kd39-1-filtrate-2	3-180696	11.74	0.102	9.22	90	0.98	44	11.5	508	766	802
AW101-Kd39-2-filtrate-1	3-180697	12.121	1.000	9.52	10	0.98	16	11.9	190	231	na
AW101-Kd39-2-filtrate-2	3-180698	12.157	1.000	9.55	10	0.98	16	11.3	181	245	238
NH39-CTR-02607-1	3-178765	nm	na	na	na	na	308	15.9	4900	na	na
NH39-CTR-02607-1D	3-178766	nm	na	na	na	na	290	15.7	4550	na	na

nm = not measured

na = not applicable

APPENDIX C - CESIUM LOADING AND ELUTION DATA**APPENDIX C1-1: LOADING CYCLE #1****Lead Column****Resin: SuperLig[®] 644****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm; L/D = 6.2****Flow rate = 0.69 BV/h (0.17 mL/min); BV = 15 mL****Temperature = 25 ± 1 °C**

LIMS #	BV	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co	[K ⁺], M	[Na ⁺], M
3-183188	9.8	1.14E-02	6.51E-05	0.47	5.52
3-183189	19.7	8.24E-03	4.71E-05	nm	nm
3-183190	29.8	7.37E-03	4.21E-05	nm	nm
3-183191	39.6	8.60E-03	4.91E-05	nm	nm
3-183192	48.9	7.34E-03	4.19E-05	0.48	5.83
3-183193	57.8	6.69E-03	3.82E-05	nm	nm
3-183194	66.9	9.87E-03	5.64E-05	nm	nm
3-183195	76.2	2.09E-03	1.19E-05	nm	nm
3-183196	86.0	1.38E-03	7.88E-06	nm	nm
3-183197	96.2	8.22E-03	4.70E-05	0.47	4.18
3-183198	106.4	2.37E-03	1.35E-05	nm	nm
3-183199	116.6	1.34E-03	7.65E-06	nm	nm
3-183200	126.9	2.12E-03	1.21E-05	nm	nm
3-183201	137.0	2.16E-03	1.23E-05	nm	nm
3-183202	147.2	3.59E-03	2.05E-05	0.51	4.74
3-183532	157.3	1.41E-03	8.05E-06	nm	nm
3-183533	167.5	7.48E-02	4.27E-04	nm	nm
3-183534	180.1	4.35E-01	2.48E-03	0.52	4.74
3-183535	194.3	1.29E+01	7.37E-02	0.54	4.87

[¹³⁷Cs]₀ = 175 μCi/mL

nm = not measured

APPENDIX C1-2: LOADING CYCLE #1**Lag Column****Resin: SuperLig[®] 644****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Flow rate = 0.69 BV/h (0.17 mL/min); BV = 15 mL****Individual Samples – Lag Column**

LIMS #	# BV Effluent	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co	[K ⁺], M*
3-183203	19.7	6.45E-05	3.68E-07	0.450128
3-183204	39.6	6.55E-05	3.74E-07	0.460358
3-183205	57.8	3.71E-04	2.12E-06	0.465473
3-183206	76.2	3.86E-04	2.20E-06	0.491049
3-183207	96.2	1.19E-04	6.80E-07	0.480818
3-183208	116.6	1.53E-04	8.74E-07	0.411765
3-183209	137.0	2.39E-04	1.37E-06	0.409207
3-183210	157.3	1.60E-04	9.14E-07	0.332481
3-183543	180.1	7.52E-04	4.30E-06	nm

Composite Fractions – Lag Column

LIMS #	Effluent fraction #	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co
3-183215	bottle # 1 - ~20 BV	1.48E-04	8.45E-07
3-183216	bottle # 2 - ~20 BV	1.28E-04	7.31E-07
3-183217	bottle # 3 - ~20 BV	1.63E-04	9.31E-07
3-183218	bottle # 4 - ~20 BV	2.17E-04	1.24E-06
3-183219	bottle # 5 - ~20 BV	2.05E-04	1.17E-06
3-183220	bottle # 6 - ~20 BV	1.23E-04	7.03E-07
3-183221	bottle # 7 - ~20 BV	2.22E-04	1.27E-06
3-183222	bottle # 8 - ~20 BV	5.85E-04	3.34E-06
3-183547	bottle # 9 - ~20 BV	4.74E-04	2.70E-06
3-183548	bottle # 10 - ~10 BV	1.24E-03	7.08E-06

* by atomic absorption (AA)

nm = not measured

APPENDIX C1-3: ELUTION CYCLE #1**Lead Column****Eluant = 0.5M HNO₃****Flow rate = 0.63 BV/h (0.11 mL/min); BV – 10.9 mL****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Elution samples; BV -elution based**

LIMS #	BV	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co	[K ⁺], M	[Na ⁺], M
3-183693	0.63	9.73E-02	5.56E-04	9.21E-03	1.19E-01
3-183694	1.26	8.60E-01	4.91E-03	4.77E-02	3.53E-01
3-183695	1.89	8.08E+03	4.62E+01	8.26E-02	7.02E-01
3-183696	2.52	2.43E+03	1.39E+01	2.27E-02	2.72E-01
3-183697	3.15	2.07E+02	1.18E+00	1.27E-02	1.49E-01
3-183698	4.41	3.54E+01	2.02E-01	5.53E-03	8.56E-02
3-183699	5.67	8.68E+00	4.96E-02	1.68E-02	1.72E-01
3-183700	6.93	2.90E+00	1.66E-02	1.91E-02	2.21E-01
3-183701	8.19	2.04E+00	1.16E-02	1.28E-02	1.45E-01
3-183702	9.45	1.14E+00	6.53E-03	6.59E-03	8.46E-02

Dilution Factors

Eluate Sample ID	LIMS #	Water, mL	Sample, mL	Dilution Factor	[¹³⁷ Cs], μCi/mL	[K ⁺], mg/L	[Na ⁺], mg/L
NH-W101-CR1-LEE-1	3-183693	24.5532	0.098825832	249	3.90E-04	1.44	11
NH-W101-CR1-LEE-2	3-183694	24.8675	0.100782779	248	3.47E-03	7.51	32.8
NH-W101-CR1-LEE-3	3-183695	24.877	0.096868885	258	3.14E+01	12.5	62.6
NH-W101-CR1-LEE-4	3-183696	24.9181	0.096868885	258	9.41E+00	3.43	24.2
NH-W101-CR1-LEE-5	3-183697	24.8395	0.098825832	252	8.22E-01	1.96	13.6
NH-W101-CR1-LEE-7	3-183698	5.0021	0.096868885	53	6.72E-01	4.1	37.4
NH-W101-CR1-LEE-9	3-183699	4.983	0.100782779	50	1.72E-01	13	78.6
NH-W101-CR1-LEE-11	3-183700	4.9803	0.098825832	51	5.64E-02	14.5	99
NH-W101-CR1-LEE-13	3-183701	4.9894	0.076320939	66	3.07E-02	7.52	50.2
NH-W101-CR1-LEE-15	3-183702	4.9816	0.090998043	56	2.05E-02	4.61	34.9

APPENDIX C2-1: LOADING CYCLE #2

Lead Column

Resin: SuperLig[®] 644

Resin batch # I-D5-03-06-02-35-60

Column size = 1.45 cm; L/D = 6.2

Flow rate = 0.58 BV/h (0.15 mL/min); BV = 15 mL

LIMS #	BV	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co	[K ⁺], M	[Na ⁺], M
3-184237	3.8	1.54E-01	8.82E-04	nm	nm
3-184238	7.6	3.97E-02	2.27E-04	0.51	5.61
3-184239	15.6	9.80E-02	5.60E-04	nm	nm
3-184243	53.9	9.57E-01	5.47E-03	nm	nm
3-184244	63.9	3.29E-01	1.88E-03	nm	nm
3-184245	74.0	7.98E-01	4.56E-03	nm	nm
3-184246	83.9	1.20E-01	6.85E-04	nm	nm
3-184247	93.9	2.16E-01	1.24E-03	0.48	5.39
3-184248	103.9	2.20E-02	1.26E-04	nm	nm
3-184249	113.9	3.00E-02	1.72E-04	nm	nm
3-184252	140.7	4.56E-01	2.61E-03	0.56	4.74
3-184253	148.4	4.15E-01	2.37E-03	nm	nm
3-184254	156.0	2.49E-01	1.42E-03	nm	nm
3-184255	163.4	7.31E-01	4.18E-03	nm	nm
3-184256	170.7	2.02E+00	1.16E-02	nm	nm
3-184257	177.8	1.27E+01	7.25E-02	0.52	4.61
3-184258	184.7	1.67E+01	9.54E-02	nm	nm
3-184259	191.8	3.34E+01	1.91E-01	nm	nm
3-184260	199.4	5.64E+01	3.22E-01	nm	nm
3-184261	207.6	8.10E+01	4.63E-01	nm	nm
3-184262	216.2	1.32E+02	7.55E-01	nm	4.46

nm – not measured

APPENDIX C2-2: LOADING CYCLE #2**Lag Column****Resin: SuperLig[®] 644****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Flow rate = 0.58 BV/h (0.15 mL/min); BV = 15 mL****Individual Samples – Lag Column**

LIMS #	# BV Effluent	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co	[K ⁺], M*
3-184263	15.6	7.65E-04	4.37E-06	0.41
3-184264	34.2	5.60E-04	3.20E-06	nm
3-184265	53.9	5.19E-04	2.97E-06	nm
3-184266	74.0	4.35E-04	2.49E-06	nm
3-184267	93.9	8.54E-04	4.88E-06	0.43
3-184268	113.9	5.00E-04	2.86E-06	nm
3-184269	132.4	8.95E-04	5.11E-06	nm
3-184270	148.4	4.09E-04	2.34E-06	nm
3-184271	163.4	5.78E-04	3.30E-06	nm
3-184272	177.8	1.75E-04	9.98E-07	0.43
3-184273	191.8	1.28E-03	7.31E-06	nm
3-184274	207.6	1.88E-03	1.07E-05	nm

nm = not measured

Composite Fractions – Lag Column

LIMS #	Effluent fraction #	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co
3-184275	bottle # 1 - ~20 BV	5.70E-03	3.26E-05
3-184276	bottle # 2 - ~20 BV	8.35E-04	4.77E-06
3-184277	bottle # 3 - ~20 BV	8.55E-04	4.89E-06
3-184278	bottle # 4 - ~20 BV	5.47E-04	3.12E-06
3-184279	bottle # 5 - ~20 BV	6.62E-04	3.78E-06
3-184280	bottle # 6 - ~20 BV	5.91E-04	3.38E-06
3-184281	bottle # 7 - ~20 BV	6.77E-04	3.87E-06
3-184282	bottle # 8 - ~20 BV	8.25E-04	4.71E-06
3-184283	bottle # 9 - ~20 BV	8.26E-04	4.72E-06
3-184284	bottle # 10 - ~20 BV	4.74E-04	2.71E-06
3-184285	bottle # 11 - ~20 BV	1.23E-03	7.03E-06
3-184286	bottle # 12 - ~20 BV	1.69E-03	9.66E-06

* = by atomic absorption (AA)

APPENDIX C2-3: ELUTION CYCLE #2**Lead Column****Eluant = 0.5M HNO₃****Flow rate = 1 BV/h (0.18 mL/min); BV = 10.8 mL****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Elution samples; BV -elution based**

LIMS #	BV	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co
3-184879	1	5.11E+00	0.029175708
3-184880	2	1.37E+01	0.078487971
3-184881	3	5.35E+03	30.59252898
3-184882	4	1.26E+02	0.717379229
3-184883	5	3.66E+01	0.208926912
3-184884	7	1.08E+01	0.06172
3-184885	9	4.77E+00	0.027248571
3-184886	11	2.42E+00	0.013811415
3-184887	13	1.46E+00	0.00832758
3-184888	15	1.08E+00	0.006165411
3-184879	1	5.11E+00	0.029175708
3-184880	2	1.37E+01	0.078487971
3-184881	3	5.35E+03	30.59252898

Dilution Factors – Eluate Cycle #2

Eluate Sample ID	LIMS #	Water, mL	Sample, mL	Dilution Factor	[¹³⁷ Cs], μCi/mL
NH-AW101-CR2-LEE-1	3-184879	24.7315	0.119373777	208	2.45E-02
NH-AW101-CR2-LEE-2	3-184880	24.8013	0.091976517	271	5.08E-02
NH-AW101-CR2-LEE-3	3-184881	24.8161	0.099804305	250	2.14E+01
NH-AW101-CR2-LEE-4	3-184882	24.6724	0.100782779	246	5.11E-01
NH-AW101-CR2-LEE-5	3-184883	24.8062	0.095890411	260	1.41E-01
NH-AW101-CR2-LEE-7	3-184884	no dilution	no dilution	no dilution	1.08E+01
NH-AW101-CR2-LEE-9	3-184885	no dilution	no dilution	no dilution	4.77E+00
NH-AW101-CR2-LEE-11	3-184886	4.9538	0.093933464	54	4.50E-02
NH-AW101-CR2-LEE-13	3-184887	4.9778	0.091976517	55	2.64E-02
NH-AW101-CR2-LEE-15	3-184888	4.952	0.097847358	52	2.09E-02

APPENDIX C3-1: LOADING CYCLE #3

Lead Column

Resin: SuperLig[®] 644

Resin batch # I-D5-03-06-02-35-60

Column size = 1.45 cm; L/D = 6.1

Flow rate = 0.52 BV/h (0.13 mL/min); BV = 15 mL

LIMS #	BV	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co	[K ⁺], M	[Na ⁺], M
3-185717	7.6	5.97E-02	3.41E-04	0.50	4.88
3-185718	15.3	7.98E-02	4.56E-04	nm	nm
3-185720	30.6	7.84E-02	4.48E-04	nm	nm
3-185721	38.2	3.09E-02	1.77E-04	0.38	4.01
3-185722	45.8	2.24E-02	1.28E-04	nm	nm
3-185723	53.3	1.95E-02	1.11E-04	nm	nm
3-185724	60.9	2.37E-02	1.35E-04	nm	nm
3-185725	68.4	1.80E-02	1.03E-04	nm	nm
3-185726	75.9	2.84E-02	1.62E-04	0.37	3.92
3-185727	83.4	3.02E-02	1.73E-04	nm	nm
3-185728	91.0	4.68E-02	2.68E-04	nm	nm
3-185730	106.0	5.15E-02	2.94E-04	nm	nm
3-185731	113.5	4.31E-02	2.46E-04	0.45	4.65
3-185732	121.1	1.86E-02	1.06E-04	nm	nm
3-185733	128.7	1.79E-02	1.02E-04	nm	nm
3-185734	136.3	2.99E-02	1.71E-04	nm	nm
3-185735	144.0	8.61E-02	4.92E-04	nm	nm
3-185736	151.8	4.85E-01	2.77E-03	0.42	4.70
3-185737	159.5	2.82E+00	1.61E-02	nm	nm
3-185738	167.1	1.83E+01	1.04E-01	nm	nm
3-185739	174.6	1.89E+01	1.08E-01	nm	nm
3-185740	182.8	3.44E+01	1.97E-01	nm	nm
3-185741	192.5	6.68E+01	3.82E-01	0.44	4.65

nm – not measured

APPENDIX C3-2: LOADING CYCLE #3**Lag Column****Resin: SuperLig[®] 644****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Flow rate = 0.52 BV/h (0.13 mL/min); BV = 15 mL****Individual Samples – Lag Column**

LIMS #	# BV Effluent	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co
3-185742	15.3	1.06E-02	6.08E-05
3-185743	30.6	7.14E-03	4.08E-05
3-185744	45.8	nm	na
3-185745	60.9	5.87E-03	3.35E-05
3-185746	75.9	4.00E-03	2.29E-05
3-185747	91	9.13E-03	5.22E-05
3-185748	106	4.55E-03	2.60E-05
3-185749	121.1	8.79E-03	5.02E-05
3-185750	136.3	4.37E-03	2.50E-05
3-185751	151.8	7.85E-03	4.49E-05
3-185752	167.1	1.54E-02	8.78E-05
3-185753	182.8	2.84E-04	1.62E-06

Composite Fractions – Lag Column

LIMS #	Effluent fraction #	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co
3-185754	bottle # 1 - ~20 BV	7.88E-03	4.50E-05
3-185755	bottle # 2 - ~20 BV	4.89E-03	2.79E-05
3-185756	bottle # 3 - ~20 BV	5.62E-03	3.21E-05
3-185757	bottle # 4 - ~20 BV	4.34E-03	2.48E-05
3-185758	bottle # 5 - ~20 BV	3.63E-03	2.07E-05
3-185759	bottle # 6 - ~20 BV	4.91E-03	2.81E-05
3-185760	bottle # 7 - ~20 BV	4.06E-03	2.32E-05
3-185761	bottle # 8 - ~20 BV	4.28E-03	2.44E-05
3-185762	bottle # 9 - ~20 BV	4.15E-03	2.37E-05
3-185763	bottle # 10 - ~20 BV	4.15E-03	2.37E-05
3-185764	bottle # 11 - ~20 BV	4.54E-03	2.60E-05
3-185765	bottle # 12 - ~20 BV	4.38E-03	2.50E-05

nm = not measured

na = not applicable

APPENDIX C3-3: ELUTION CYCLE #3**Lead Column****Eluant = 0.5M HNO₃****Flow rate = 1 BV/h (0.20 mL/min); BV = 11.7 mL****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Elution samples; BV -elution based**

LIMS #	BV	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co	[Na ⁺], M
3-186278	1	1.17E+00	6.67E-03	2.00
3-186279	2	6.51E+00	3.72E-02	1.57
3-186280	3	4.36E+02	2.49E+00	1.81
3-186281	4	9.78E+03	5.59E+01	1.53
3-186282	5	1.63E+02	9.33E-01	0.85
3-186283	7	1.26E+01	7.19E-02	1.81
3-186284	9	1.38E+00	7.90E-03	2.30
3-186285	11	5.06E-01	2.89E-03	2.40
3-186286	13	4.04E-01	2.31E-03	2.34
3-186287	15	4.94E-02	2.83E-04	2.07

Dilution Factors – Eluate Cycle #3

Eluate Sample ID	LIMS #	Water, mL	Sample, mL	Dilution Factor	[¹³⁷ Cs], μCi/mL	[Na ⁺], mg/L
NH-AW101-CR3-LEE1	3-186278	24.6913	0.108610568	228	5.11E-03	2.01E+02
NH-AW101-CR3-LEE2	3-186279	24.7063	0.102739726	241	2.70E-02	1.49E+02
NH-AW101-CR3-LEE3	3-186280	24.695	0.102739726	241	1.81E+00	1.72E+02
NH-AW101-CR3-LEE4	3-186281	24.7232	0.104696673	237	4.12E+01	1.48E+02
NH-AW101-CR3-LEE5	3-186282	24.6261	0.104696673	236	6.91E-01	8.28E+01
NH-AW101-CR3-LEE7	3-186283	5.0032	0.101761252	50	2.51E-01	8.31E+02
NH-AW101-CR3-LEE9	3-186284	4.9909	0.112524462	45	3.05E-02	1.16E+03
NH-AW101-CR3-LEE11	3-186285	5.035	0.112524462	46	1.11E-02	1.20E+03
NH-AW101-CR3-LEE13	3-186286	4.9977	0.107632094	47	8.52E-03	1.14E+03
NH-AW101-CR3-LEE15	3-186287	5.0072	0.108610568	47	1.05E-03	1.01E+03

APPENDIX C4-1: LOADING CYCLE #4

Lead Column

Resin: SuperLig[®] 644

Resin batch # I-D5-03-06-02-35-60

Column size = 1.45 cm; L/D = 6.2

Flow rate = 0.49 BV/h (0.12 mL/min); BV = 15 mL

LIMS #	BV	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co	[K ⁺], M	[Na ⁺], M
3-186683	6.7	2.94E-02	1.68E-04	0.46	4.11
3-186684	13.4	2.95E-02	1.68E-04	nm	nm
3-186685	19.9	5.10E-02	2.91E-04	nm	nm
3-186688	40.7	3.87E-02	2.21E-04	nm	nm
3-186689	48.0	2.58E-02	1.48E-04	nm	nm
3-186690	55.1	1.23E-02	7.03E-05	nm	nm
3-186691	62.1	3.31E-02	1.89E-04	nm	nm
3-186692	69.2	2.26E-02	1.29E-04	0.45	4.06
3-186693	76.4	2.38E-02	1.36E-04	nm	nm
3-186694	83.7	2.37E-02	1.35E-04	nm	nm
3-186695	90.9	3.75E-02	2.14E-04	nm	nm
3-186696	98.3	2.02E-01	1.15E-03	nm	nm
3-186697	105.6	5.01E-02	2.86E-04	0.52	4.39
3-186698	112.9	2.61E-02	1.49E-04	nm	nm
3-186699	120.3	3.30E-02	1.89E-04	nm	nm
3-186700	127.8	1.22E-01	6.96E-04	nm	nm
3-186701	135.1	5.69E-01	3.25E-03	nm	nm
3-186702	142.4	6.22E+00	3.55E-02	0.52	4.57
3-186703	149.4	3.42E+01	1.96E-01	nm	nm
3-186704	156.3	9.57E+01	5.47E-01	nm	nm
3-186705	163.5	9.45E+01	5.40E-01	nm	nm
3-186706	171.0	4.91E+01	2.81E-01	nm	nm

nm – not measured

APPENDIX C4-2: LOADING CYCLE #4**Lag Column****Resin: SuperLig[®] 644****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Flow rate = 0.49 BV/h (0.12 mL/min); BV = 15 mL****Individual Samples – Lag Column**

LIMS #	# BV Effluent	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co
3-186710	13.4	3.99E-02	2.28E-04
3-186711	26.5	6.42E-02	3.67E-04
3-186712	40.7	1.21E-02	6.89E-05
3-186713	55.1	3.53E-02	2.02E-04
3-186714	69.2	6.19E-03	3.54E-05
3-186715	83.7	4.70E-03	2.69E-05
3-186716	98.3	4.16E-03	2.38E-05
3-186717	112.9	3.60E-03	2.06E-05
3-186718	127.8	4.53E-03	2.59E-05
3-186719	142.4	3.82E-03	2.19E-05
3-186720	156.3	4.59E-03	2.62E-05
3-186721	171.0	4.14E-03	2.36E-05

Composite Fractions – Lag Column

LIMS #	Effluent fraction #	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co
3-186951	bottle # 1 - ~20 BV	1.52E-02	8.71E-05
3-186952	bottle # 2 - ~20 BV	6.28E-03	3.59E-05
3-186953	bottle # 3 - ~20 BV	4.10E-03	2.34E-05
3-186954	bottle # 4 - ~20 BV	3.91E-03	2.23E-05
3-186955	bottle # 5 - ~20 BV	6.76E-03	3.86E-05
3-186956	bottle # 6 - ~20 BV	4.62E-03	2.64E-05
3-186957	bottle # 7 - ~20 BV	3.79E-03	2.17E-05
3-186958	bottle # 8 - ~20 BV	3.95E-03	2.25E-05
3-186959	bottle # 9 - ~20 BV	3.63E-03	2.08E-05
3-186960	bottle # 10 - ~20 BV	3.85E-03	2.20E-05
3-186961	bottle # 11 - ~20 BV	3.55E-03	2.03E-05
3-186962	bottle # 12 - ~20 BV	4.49E-03	2.57E-05

APPENDIX C4-3: ELUTION CYCLE #4**Lead Column****Eluant = 0.5M HNO₃****Flow rate = ~1 BV/h (~0.2 mL/min); BV = 11.7 mL****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Elution samples; BV -elution based**

LIMS #	BV	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co	[Na ⁺], M
3-187406	1	2.79E+01	1.59E-01	3-187406
3-187407	2	1.03E+01	5.88E-02	3-187407
3-187408	3	5.44E+01	3.11E-01	3-187408
3-187409	4	1.79E+04	1.03E+02	3-187409
3-187410	5	3.09E+02	1.77E+00	3-187410
3-187411	7	5.67E+00	3.24E-02	3-187411
3-187412	9	2.44E+00	1.39E-02	3-187412
3-187413	11	2.17E+00	1.24E-02	3-187413
3-187414	13	1.43E+01	8.18E-02	3-187414
3-187415	15	1.91E+01	1.09E-01	3-187415

Dilution Factors – Eluate Cycle #4

Eluate Sample ID	LIMS #	Water, mL	Sample, mL	Dilution Factor	[¹³⁷ Cs], μCi/mL
NH-AW101-CR4-LEE-1	3-187406	25.2609	0.105675147	240.0429611	1.16E-01
NH-AW101-CR4-LEE-2	3-187407	25.1093	0.095890411	262.8541286	3.91E-02
NH-AW101-CR4-LEE-3	3-187408	25.0628	0.093933464	267.8143917	2.03E-01
NH-AW101-CR4-LEE-4	3-187409	25.1264	0.096868885	260.3856646	6.89E+01
NH-AW101-CR4-LEE-5	3-187410	25.138	0.090019569	280.2503913	1.10E+00
NH-AW101-CR4-LEE-7	3-187411	4.9791	0.099804305	50.88862941	1.11E-01
NH-AW101-CR4-LEE-9	3-187412	4.9626	0.094911937	53.28636289	4.57E-02
NH-AW101-CR4-LEE-11	3-187413	4.92	0.094911937	52.83752577	4.10E-02
NH-AW101-CR4-LEE-13	3-187414	4.9789	0.089041096	56.91687692	2.52E-01
NH-AW101-CR4-LEE-15	3-187415	4.9268	0.102739726	48.95418667	3.89E-01

APPENDIX C5-1: LOADING CYCLE #5

Lead Column

Resin: SuperLig[®] 644

Resin batch # I-D5-03-06-02-35-60

Column size = 1.45 cm, L/D = 6.2

Flow rate = 0.48 BV/h (0.12 mL/min); BV = 15 mL

LIMS #	BV	[¹³⁷ Cs], $\mu\text{Ci/mL}$	[¹³⁷ Cs], C/Co	[K ⁺], M	[Na ⁺], M
3-187438	3.4	2.38E-02	1.36E-04	0.21	2.86
3-187439	6.7	2.70E-02	1.54E-04	nm	nm
3-187440	13.7	2.08E-02	1.19E-04	nm	nm
3-187441	20.8	3.80E-02	2.17E-04	nm	nm
3-187442	27.9	1.54E-01	8.81E-04	nm	nm
3-187443	34.9	1.06E-01	6.04E-04	0.48	4.52
3-187444	42.0	1.57E-02	8.95E-05	nm	nm
3-187445	49.1	1.69E-02	9.66E-05	nm	nm
3-187446	56.2	4.89E-02	2.79E-04	nm	nm
3-187447	63.2	2.58E-01	1.47E-03	nm	nm
3-187448	70.3	1.66E-01	9.47E-04	0.47	4.48
3-187449	77.4	1.78E-02	1.02E-04	nm	nm
3-187450	84.5	1.80E-02	1.03E-04	nm	nm
3-187451	91.5	7.32E-02	4.19E-04	nm	nm
3-187452	98.7	5.41E-02	3.09E-04	nm	nm
3-187454	105.9	3.79E-02	2.17E-04	0.57	5.35
3-187455	113.1	1.51E-02	8.63E-05	nm	nm
3-187456	120.5	1.80E-02	1.03E-04	nm	nm
3-187457	128.0	5.48E-02	3.13E-04	nm	nm
3-187458	135.6	2.21E-01	1.26E-03	nm	nm
3-187460	150.2	3.66E+00	2.09E-02	nm	nm
3-187461	157.6	1.14E+01	6.50E-02	nm	nm
3-187462	165.0	2.62E+01	1.50E-01	nm	nm
3-187463	172.3	4.97E+01	2.84E-01	nm	nm

nm = not measured

APPENDIX C5-2: LOADING CYCLE #5**Lag Column****Resin: SuperLig[®] 644****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Flow rate = 0.48 BV/h (0.12 mL/min); BV = 15 mL****Individual Samples – Lag Column**

LIMS #	# BV Effluent	[¹³⁷ Cs], µCi/mL	[¹³⁷ Cs], C/Co
3-187469	13.7	1.19E-02	6.80E-05
3-187470	27.9	6.61E-03	3.78E-05
3-187471	42	4.22E-03	2.41E-05
3-187472	56.2	1.51E-02	8.62E-05
3-187473	70.3	4.45E-03	2.54E-05
3-187474	84.5	7.48E-03	4.27E-05
3-187475	98.7	5.08E-03	2.90E-05
3-187476	113.1	4.34E-03	2.48E-05
3-187477	128	5.62E-03	3.21E-05
3-187478	142.9	8.80E-03	5.03E-05
3-187479	157.3	4.87E-03	2.78E-05
3-187480	172.3	4.51E-03	2.58E-05

Composite Fractions – Lag Column

LIMS #	Effluent fraction #	[¹³⁷ Cs], µCi/mL	[¹³⁷ Cs], C/Co
3-187483	bottle # 1 - ~20 BV	5.25E-03	2.99714E-05
3-187484	bottle # 2 - ~20 BV	4.46E-03	2.548E-05
3-187485	bottle # 3 - ~20 BV	6.59E-03	3.76354E-05
3-187486	bottle # 4 - ~20 BV	4.23E-03	2.41823E-05
3-187487	bottle # 5 - ~20 BV	4.35E-03	2.486E-05
3-187488	bottle # 6 - ~20 BV	4.08E-03	2.33257E-05
3-187489	bottle # 7 - ~20 BV	4.11E-03	2.34726E-05
3-187490	bottle # 8 - ~20 BV	4.24E-03	2.42514E-05
3-187491	bottle # 9 - ~20 BV	4.24E-03	2.42109E-05
3-187492	bottle # 10 - ~20 BV	4.45E-03	2.54097E-05
3-187493	bottle # 11 - ~20 BV	4.97E-03	2.84263E-05
3-187494	bottle # 12 - ~20 BV	3.86E-03	2.20743E-05

APPENDIX C5-3: ELUTION CYCLE #5**Lead Column****Eluant = 0.5M HNO₃****Flow rate = ~1 BV/h (~0.19 mL/min); BV = 1 mL****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Elution samples; BV -elution based**

LIMS #	BV	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co	[K ⁺], M	[Na ⁺], M	pH
3-187497	1	9.17E-01	5.24E-03	< 0.118	5.23E-01	2.61
3-187498	2	8.56E+00	4.89E-02	nm	nm	2.60
3-187499	3	5.53E+00	3.16E-02	< 0.121	5.93E-01	2.60
3-187500	4	1.76E+04	1.00E+02	nm	nm	2.59
3-187501	5	2.52E+02	1.44E+00	nm	nm	1.58
3-187502	7	7.51E+00	4.29E-02	< 0.025	2.62E-01	2.28
3-187503	9	3.95E+00	2.26E-02	nm	nm	2.26
3-187504	11	2.33E+00	1.33E-02	< 0.025	2.74E-01	2.28
3-187505	13	1.72E+01	9.86E-02	nm	nm	9.30
3-187506	15	6.56E-01	3.75E-03	nm	nm	9.31

Dilution Factors

Eluate Sample ID	LIMS #	Water, mL	Sample, mL	Dilution Factor	[¹³⁷ Cs], μCi/mL	[K ⁺], mg/L	[Na ⁺], mg/L
NH-AW-CR5-LEE-1	3-187497	25.2033	0.102739726	246.31212	3.72E-03	< 18.8	48.8
NH-AW-CR5-LEE-2	3-187498	25.0533	0.100782779	249.5871126	3.43E-02	nm	nm
NH-AW-CR5-LEE-3	3-187499	25.0327	0.099804305	251.8178373	2.20E-02	< 18.8	54.2
NH-AW-CR5-LEE-4	3-187500	25.052	0.097847358	257.03144	6.84E+01	nm	nm
NH-AW-CR5-LEE-5	3-187501	25.0363	0.095890411	262.0928429	9.60E-01	nm	nm
NH-AW-CR5-LEE-7	3-187502	5.0299	0.097847358	52.405578	1.43E-01	< 18.8	115
NH-AW-CR5-LEE-9	3-187503	5.0245	0.093933464	54.48998958	7.24E-02	nm	nm
NH-AW-CR5-LEE-11	3-187504	5.0355	0.097847358	52.46281	4.44E-02	< 18.8	120
NH-AW-CR5-LEE-13	3-187505	5.0333	0.102739726	49.99078667	3.45E-01	nm	nm
NH-AW-CR5-LEE-15	3-187506	5.033	0.1037182	49.52571698	1.32E-02	nm	nm

APPENDIX C6-1: LOADING CYCLE #6

Lead Column

Resin: SuperLig[®] 644

Resin batch # I-D5-03-06-02-35-60

Column size = 1.45 cm, L/D = 6.1

Flow rate = 0.52 BV/h (0.13 mL/min); BV = 15 mL

LIMS #	BV	[137Cs], $\mu\text{Ci/mL}$	[137Cs], C/Co	[K ⁺], M	[Na ⁺], M
300188355	6.9	5.39E-02	3.08E-04	0.40	3.58
300188356	14.1	2.09E-02	1.20E-04	nm	nm
300188357	21.9	1.83E-02	1.05E-04	nm	nm
300188358	30.2	2.10E-02	1.20E-04	nm	nm
300188359	38.6	6.53E-02	3.73E-04	0.40	3.57
300188360	47.0	1.47E-02	8.38E-05	nm	nm
300188361	55.5	1.37E-02	7.82E-05	nm	nm
300188362	64.0	5.19E-02	2.96E-04	nm	nm
300188363	72.5	4.02E-02	2.30E-04	nm	nm
300188364	80.4	4.33E-02	2.48E-04	0.39	3.46
300188365	87.4	3.55E-02	2.03E-04	nm	nm
300188366	94.6	3.52E-02	2.01E-04	nm	nm
300188367	102.9	1.60E-02	9.13E-05	nm	nm
300188368	111.8	4.42E-02	2.53E-04	nm	nm
300188369	120.8	3.85E-01	2.20E-03	0.48	3.98
300188370	129.4	1.36E+00	7.76E-03	nm	nm
300188371	137.5	4.55E+00	2.60E-02	nm	nm
300188372	145.2	1.11E+01	6.37E-02	nm	nm
300188373	152.6	2.07E+01	1.19E-01	nm	nm
300188374	160.0	6.24E+01	3.56E-01	0.47	3.97
300188375	167.5	9.28E+01	5.30E-01	nm	nm
300188376	174.6	1.33E+02	7.62E-01	nm	nm

nm = not measured

APPENDIX C6-2: LOADING CYCLE #6**Lag Column****Resin: SuperLig[®] 644****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Flow rate = 0.52 BV/h (0.12 mL/min); BV = 15 mL****Individual Samples – Lag Column**

LIMS #	# BV Effluent	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co
3-188384	14.1	4.95E-03	2.83E-05
3-188385	30.2	4.21E-03	2.41E-05
3-188386	47.0	4.52E-03	2.58E-05
3-188387	64.0	5.30E-03	3.03E-05
3-188388	80.4	9.85E-03	5.63E-05
3-188389	94.6	1.72E-02	9.84E-05
3-188390	111.8	3.94E-03	2.25E-05
3-188391	129.4	4.46E-03	2.55E-05
3-188392	145.2	3.77E-02	2.15E-04
3-188393	160.0	2.94E-02	1.68E-04
3-188394	174.6	6.00E-03	3.43E-05
3-188395	186.1	6.15E-03	3.51E-05
3-188396	197.0	6.40E-03	3.66E-05

Composite Fractions – Lag Column

LIMS #	Effluent fraction #	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co
3-188398	bottle # 1 - ~20 BV	7.27E-03	4.16E-05
3-188399	bottle # 2 - ~20 BV	3.93E-03	2.24E-05
3-188400	bottle # 3 - ~20 BV	3.71E-03	2.12E-05
3-188401	bottle # 4 - ~20 BV	3.37E-03	1.93E-05
3-188402	bottle # 5 - ~20 BV	3.49E-03	1.99E-05
3-188403	bottle # 6 - ~20 BV	3.70E-03	2.11E-05
3-188404	bottle # 7 - ~20 BV	3.57E-03	2.04E-05
3-188405	bottle # 8 - ~20 BV	3.40E-03	1.94E-05
3-188406	bottle # 9 - ~20 BV	3.51E-03	2.00E-05
3-188407	bottle # 10 - ~20 BV	4.38E-03	2.50E-05
3-188408	bottle # 11 - ~20 BV	3.54E-03	2.03E-05
3-188409	bottle # 12 - ~20 BV	4.22E-03	2.41E-05

APPENDIX C6-3: ELUTION CYCLE #6**Lead Column****Eluant = 0.5M HNO₃****Flow rate = ~1 BV/h (~0.19 mL/min); BV = 11.4 mL****Resin batch # I-D5-03-06-02-35-60****Column size = 1.45 cm****Elution samples; BV -elution based**

LIMS #	BV	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], C/Co	[K ⁺], M	[Na ⁺], M	pH
3-188413	1	2.48E+01	1.42E-01	< 0.1375	0.84	2.54
3-188414	2	1.50E+01	8.59E-02	< 0.1226	0.57	2.59
3-188415	3	2.55E+04	1.46E+02	< 0.1226	0.48	2.59
3-188416	4	3.94E+02	2.25E+00	< 0.1241	0.28	2.59
3-188417	5	1.04E+02	5.92E-01	< 0.1265	0.31	1.58
3-188418	7	1.27E+01	7.28E-02	0.0298478	0.22	2.27
3-188419	9	4.34E+00	2.48E-02	0.0347861	0.26	2.29
3-188420	11	1.11E+01	6.32E-02	0.1118847	1.24	7.31
3-188421	13	3.60E+00	2.05E-02	0.027201	0.22	2.28
3-188958	16	4.95E+00	2.83E-02	nm	nm	nm

Dilution Factors

Eluate Sample ID	LIMS #	Water, mL	Sample, mL	Dilution Factor	[¹³⁷ Cs], μCi/mL	[¹³⁷ Cs], μCi/mL	[K ⁺], mg/L	[Na ⁺], mg/L
NH-AW101-CR6- LEE-1	3-188413	25.1047	0.088062622	286	8.66E-02	2.48E+01	< 18.8	< 5376.8
NH-AW101-CR6- LEE-2	3-188414	24.8541	0.097847358	255	5.90E-02	1.50E+01	< 18.8	< 4794
NH-AW101-CR6- LEE-3	3-188415	24.8826	0.097847358	255	9.99E+01	2.55E+04	< 18.8	< 4794
NH-AW101-CR6- LEE-4	3-188416	24.8596	0.096868885	258	1.53E+00	3.94E+02	< 18.8	< 4850.4
NH-AW101-CR6- LEE-5	3-188417	24.8266	0.094911937	263	3.95E-01	1.04E+02	< 18.8	< 4944.4
NH-AW101-CR6- LEE-7	3-188418	5.0141	0.095890411	53	2.39E-01	1.27E+01	21.9	1167.0488
NH-AW101-CR6- LEE-9	3-188419	4.9654	0.099804305	51	8.55E-02	4.34E+00	26.8	1360.1365
NH-AW101-CR6- LEE-11	3-188420	4.983	0.1037182	49	2.26E-01	1.11E+01	89.2	4374.6928
NH-AW101-CR6- LEE-13	3-188421	4.9783	0.096868885	52	6.86E-02	3.60E+00	20.3	1063.5606
NH-AW101-CR6- LEE-15	3-188422	4.9913	nm	nm	4.75E+00	nm	nm	nm

nm = not measured

APPENDIX D - TECHNETIUM LOADING AND ELUTION DATA

APPENDIX D1-1: LOADING CYCLE #1

Lead Column

Resin: SuperLig[®] 639

Resin Batch # I-R2-03-27-02-20-45

Column size = 1.45 cm

Flow rate = 3 BV/h (0.6 mL/min); BV = 12 mL

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], μCi/mL	[Tc-99], μg/L	[Tc-99],C/Co	[NO ₃ ⁻], M
3-186327	5	3.82E+01	1.74E-05	1.01E+00	2.60E-04	nm
3-186328	10	3.83E+01	1.74E-05	1.02E+00	2.61E-04	1.35
3-186329	20	5.15E+01	2.34E-05	1.36E+00	3.50E-04	nm
3-186330	30	5.01E+01	2.28E-05	1.33E+00	3.41E-04	nm
3-186331	40	6.76E+01	3.07E-05	1.79E+00	4.60E-04	1.44
3-186332	50	8.64E+01	3.93E-05	2.29E+00	5.88E-04	nm
3-186333	60	1.27E+02	5.77E-05	3.35E+00	8.64E-04	nm
3-186334	70	2.12E+02	9.64E-05	5.62E+00	1.44E-03	nm
3-186335	80	3.31E+02	1.50E-04	8.76E+00	2.25E-03	0.71
3-186336	90	3.41E+02	1.55E-04	9.04E+00	2.32E-03	nm
3-186337	100	4.55E+02	2.07E-04	1.21E+01	3.10E-03	nm
3-186532	110	9.82E+02	4.46E-04	2.60E+01	6.68E-03	nm
3-186338	120	9.79E+02	4.45E-04	2.59E+01	6.66E-03	nm
3-186339	130	1.47E+03	6.68E-04	3.89E+01	1.00E-02	1.04
3-186340	140	1.61E+03	7.32E-04	4.26E+01	1.10E-02	nm
3-186341	150	2.21E+03	1.00E-03	5.86E+01	1.50E-02	nm
3-186342	160	2.72E+03	1.24E-03	7.21E+01	1.85E-02	1.21
3-186343	170	2.51E+03	1.14E-03	6.65E+01	1.71E-02	nm
3-186344	180	3.71E+03	1.69E-03	9.82E+01	2.52E-02	nm
3-186345	190	3.67E+03	1.67E-03	9.71E+01	2.50E-02	nm
3-186346	200	5.00E+03	2.27E-03	1.32E+02	3.40E-02	1.12
3-186347	210	4.97E+03	2.26E-03	1.32E+02	3.38E-02	nm
3-186348	220	8.60E+03	3.91E-03	2.28E+02	5.85E-02	nm
3-186349	230	1.07E+04	4.86E-03	2.82E+02	7.28E-02	nm

APPENDIX D

WSRC-TR-2003-00098, REVISION 0
SRT-RPP-2003-00026, REVISION 0

APPENDIX D1-2: LOADING CYCLE #1

Lead Column

Resin: SuperLig[®] 639

Resin batch # I-R2-03-27-02-20-45

Column size = 1.45 cm

Flow rate = 3 BV/h (0.6 mL/min); BV = 12 mL

Individual Samples – Lag Column

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], µg/L	C/Co
3-186360	40	2.81E+01	7.45E-01	1.91E-04
3-186361	60	7.40E+01	1.96E+00	5.03E-04
3-186362	80	7.51E+01	1.99E+00	5.11E-04
3-186363	100	6.23E+01	1.65E+00	4.24E-04
3-186364	120	5.55E+01	1.47E+00	3.78E-04
3-186365	140	4.55E+01	1.21E+00	3.10E-04
3-186366	160	2.27E+01	6.02E-01	1.54E-04
3-186367	180	4.13E+01	1.09E+00	2.81E-04
3-186368	200	4.39E+01	1.16E+00	2.99E-04
3-186369	220	1.66E+01	4.39E-01	1.13E-04

Composite Fractions – Lag Column

LIMS #	Effluent fraction #	[Tc-99], * dpm/mL	[Tc-99], µg/L	C/Co	[Tc-99], ** mg/L	[K ⁺], M
3-186374	bottle # 1 - ~20 BV	3.30E+01	8.73E-01	2.24E-04	< 120	4.05E-01
3-186375	bottle # 2 - ~20 BV	3.76E+01	9.96E-01	2.56E-04	< 150	4.79E-01
3-186376	bottle # 3 - ~20 BV	6.12E+01	1.62E+00	4.16E-04	NA	NA
3-186377	bottle # 4 - ~20 BV	1.25E+01	3.32E-01	8.50E-05	< 120	4.69E-01
3-186378	bottle # 5 - ~20 BV	1.07E+01	2.83E-01	7.28E-05	< 122.5	4.62E-01
3-186379	bottle # 6 - ~20 BV	5.91E+01	1.56E+00	4.02E-04	< 600	5.03E-01
3-186380	bottle # 7 - ~20 BV	2.90E+04	7.69E+02	1.97E-01	< 1200	3.13E-02
3-187431	bottle # 8 - ~20 BV	8.88E+01	2.35E+00	6.04E-04	NA	NA
3-187432	bottle # 9 - ~20 BV	8.41E+01	2.23E+00	5.72E-04	NA	NA

* by separation/counting

** by ICP-AES

APPENDIX D1-3: WASHING CYCLE #1**Lag Column****Resin: SuperLig[®] 639****Resin batch # I-R2-03-27-02-20-45****Column size = 1.45 cm****Flow rate = 3 BV/h (0.6 mL/min); BV = 12 mL****AW-101 Wash with 0.1 NaOH (Feed Displacement)**

Sample	LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], * µg/L	[Tc-99], C/Co	[Tc-99], ** µg/L	[Tc-99], M	[K+], M	[Na+], M
wash-1	3-186533	0.50	1.15E+04	3.05E+02	7.82E-02	3.22E+02	3.25E-06	4.92E-01	4.48E+00
wash-2	3-186534	1.00	6.62E+03	1.75E+02	4.50E-02	3.40E+02	3.43E-06	4.59E-01	4.29E+00
wash-3	3-186535	1.50	7.66E+03	2.03E+02	5.21E-02	3.13E+02	3.16E-06	3.38E-01	3.17E+00
wash-4	3-186536	2.00	8.84E+03	2.34E+02	6.01E-02	2.59E+02	2.62E-06	1.09E-01	1.01E+00
wash-5	3-186537	2.50	5.00E+03	1.33E+02	3.40E-02	1.57E+02	1.59E-06	8.28E-02	4.06E-01
wash-6	3-186538	3.00	2.55E+03	6.75E+01	1.73E-02	1.02E+02	1.03E-06	6.67E-02	2.46E-01
wash-7	3-186539	3.50	2.63E+03	6.97E+01	1.79E-02	9.80E+01	9.90E-07	4.49E-02	2.11E-01
wash-8	3-186540	4.00	2.58E+04	6.84E+02	1.76E-01	1.15E+02	1.16E-06	2.69E-02	1.94E-01

* by separation/counting

** by ICP-AES

APPENDIX D1-4: ELUTION CYCLE #1

Lead Column

Eluant – DI Water

Temperature – 65 °C

Flow rate = ~1 BV/h (0.2 mL/min); BV = 12 mL

Resin batch # I-R2-03-27-02-20-45

Column size = 1.45 cm

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], * µg/L	[Tc-99], C/Co	[Tc-99], µg/L	[Tc-99], ** C/Co	[Tc-99], M	[K+], M	[Na+], M
3-186542	0.5	2.33E+05	6.18E+03	1.59E+00	7.81E+03	1.95E+00	7.88E-05	1.63E-02	1.09E-01
3-186543	1	5.65E+05	1.50E+04	3.84E+00	1.67E+04	4.16E+00	1.68E-04	9.90E-03	9.87E-02
3-186544	1.5	1.33E+06	3.52E+04	9.05E+00	3.89E+04	9.71E+00	3.92E-04	5.49E-03	4.12E-02
3-186545	2	NA	NA	#VALUE!	2.72E+05	6.80E+01	2.75E-03	2.97E-03	1.26E-02
3-186546	2.5	1.39E+07	3.69E+05	9.46E+01	4.79E+05	1.20E+02	4.84E-03	1.82E-03	7.96E-03
3-186547	3	8.96E+06	2.38E+05	6.10E+01	2.83E+05	7.06E+01	2.85E-03	2.19E-03	4.07E-03
3-186548	3.5	7.00E+06	1.85E+05	4.76E+01	2.17E+05	5.41E+01	2.19E-03	3.08E-03	2.32E-03
3-186549	4	6.56E+06	1.74E+05	4.46E+01	2.00E+05	5.00E+01	2.02E-03	3.10E-03	1.73E-03
3-186550	6	1.91E+06	5.05E+04	1.30E+01	5.58E+04	1.39E+01	5.64E-04	1.63E-03	1.27E-03
3-186551	8	7.09E+04	1.88E+03	4.82E-01	2.02E+03	5.03E-01	2.04E-05	8.23E-04	1.24E-03
3-186552	10	4.85E+03	1.28E+02	3.30E-02	1.17E+02	2.92E-02	1.18E-06	< 4.82E-04	9.39E-04
3-186553	12	1.86E+03	4.94E+01	1.27E-02	< 1.2E+02	< 3.00E-02	<6.06E-07	< 4.82E-04	8.57E-04
3-186554	14	1.38E+03	3.65E+01	9.39E-03	< 1.2E+02	< 3.00E-02	<6.06E-07	< 4.82E-04	7.70E-04
3-186555	16	nm	nm	nm	< 1.2E+02	< 3.00E-02	<6.06E-07	< 4.82E-04	7.57E-04
3-186556	18	7.18E+02	1.90E+01	4.88E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	6.22E-04
3-186526	20	5.68E+02	1.50E+01	3.86E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	7.57E-04
3-186527	22	5.53E+02	1.47E+01	3.76E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	8.61E-04
3-186528	24	4.06E+02	1.08E+01	2.76E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	6.43E-04
3-186529	26	4.52E+02	1.20E+01	3.07E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	6.00E-04

* by separation/counting

** by ICP-AES

APPENDIX D2-1: LOADING CYCLE #2

Lead Column

Column size = 1.45 cm

Resin: SuperLig[®] 639

Flow rate = 3 BV/h (0.6 mL/min)

Resin Batch # I-R2-03-27-02-20-45

BV = 12 mL

LIMS #	# BV effluent	By Counting		By ICP-AES				
		[Tc-99], dpm/mL	[Tc-99], μCi/mL	[Tc-99], μg/L	[Tc-99], C/Co	[Tc-99], M	[K+], M	[Na+], M
3-186815	10	3.65E+02	1.66E-04	9.68E+00	2.48E-03	< 1.20E-06	3.49E-01	3.50E+00
3-186816	20	2.90E+02	1.32E-04	7.67E+00	1.97E-03	< 1.20E-06	4.79E-01	4.96E+00
3-186817	30	2.81E+02	1.28E-04	7.45E+00	1.91E-03	NA	NA	NA
3-186818	40	3.23E+02	1.47E-04	8.57E+00	2.20E-03	NA	NA	NA
3-186819	50	3.24E+02	1.47E-04	8.58E+00	2.20E-03	NA	NA	NA
3-186820	60	3.46E+02	1.57E-04	9.17E+00	2.35E-03	< 1.20E-06	4.85E-01	4.87E+00
3-186821	70	4.77E+02	2.17E-04	1.26E+01	3.24E-03	NA	NA	NA
3-186822	80	6.59E+02	3.00E-04	1.75E+01	4.48E-03	NA	NA	NA
3-186823	90	7.15E+02	3.25E-04	1.90E+01	4.86E-03	NA	NA	NA
3-186824	100	9.47E+02	4.30E-04	2.51E+01	6.44E-03	< 1.20E-06	4.74E-01	4.91E+00
3-186825	110	2.64E+04	1.20E-02	3.88E+01	1.80E-01	NA	NA	NA
3-186826	120	1.68E+03	7.64E-04	4.44E+01	1.14E-02	NA	NA	NA
3-186827	130	2.06E+03	9.36E-04	5.46E+01	1.40E-02	NA	NA	NA
3-186828	140	2.57E+03	1.17E-03	6.81E+01	1.75E-02	NA	NA	NA
3-186829	150	4.30E+03	1.95E-03	1.14E+02	2.93E-02	2.20E-06	4.79E-01	4.91E+00
3-186830	160	5.12E+03	2.33E-03	1.36E+02	3.48E-02	NA	NA	NA
3-186831	170	6.11E+03	2.78E-03	1.62E+02	4.16E-02	NA	NA	NA
3-186832	180	7.28E+07	3.31E+01	1.85E+02	4.95E+02	2.50E-06	4.64E-01	4.96E+00
3-186833	190	9.10E+03	4.14E-03	2.41E+02	6.19E-02	NA	NA	NA
3-186834	200	8.35E+03	3.80E-03	2.21E+02	5.68E-02	NA	NA	NA
3-186835	210	9.64E+03	4.38E-03	2.55E+02	6.56E-02	2.20E-06	4.64E-01	4.87E+00
3-186836	220	1.02E+04	4.64E-03	2.70E+02	6.94E-02	NA	NA	NA
3-186837	230	9.22E+03	4.19E-03	2.44E+02	6.27E-02	NA	NA	NA
3-186838	240	9.96E+03	4.53E-03	2.64E+02	6.78E-02	NA	NA	NA
3-186839	250	1.52E+04	6.91E-03	4.02E+02	1.03E-01	3.30E-06	4.62E-01	4.96E+00
3-186840	260	1.96E+04	8.91E-03	5.20E+02	1.33E-01	NA	NA	NA
3-186841	270	1.31E+04	5.95E-03	3.46E+02	8.91E-02	NA	NA	NA
3-186842	280	1.02E+04	4.64E-03	2.69E+02	6.94E-02	NA	NA	NA

APPENDIX D2-2: LOADING CYCLE #2

Lag Column

Resin: SuperLig[®] 639

Resin Batch # I-R2-03-27-02-20-45

Column size = 1.45 cm

Flow rate = 3 BV/h (0.6 mL/min)

BV = 12 mL

Individual Samples – Lag Column

LIMS #	# BV effluent	[Tc-99], dpm/mL	Tc-99, µg/L	C/Co
3-186845	20	5.46E+02	< 14.5	3.71E-03
3-186846	40	4.11E+02	< 10.9	2.80E-03
3-186847	60	2.94E+02	< 7.78	2.00E-03
3-186848	80	3.30E+02	< 8.74	2.24E-03
3-186849	100	5.86E+02	< 15.5	3.99E-03
3-186850	120	3.86E+02	< 10.2	2.63E-03
3-186851	140	5.33E+02	< 14.1	3.63E-03
3-186852	160	2.96E+02	< 7.84	2.01E-03
3-186853	180	3.94E+02	< 10.5	2.68E-03
3-186854	200	1.83E+02	< 4.85	1.24E-03
3-186855	220	1.61E+02	< 4.28	1.10E-03
3-186856	240	1.81E+02	< 4.8	1.23E-03
3-186857	260	2.43E+02	< 6.43	1.65E-03
3-186858	280	2.63E+02	< 6.96	1.79E-03

Composite Fraction

LIMS #	Effluent Fraction	[Tc-99], dpm/mL	Tc-99, µg/L	C/Co
3-186860	bottle # 1 - ~20 BV	2.48E+02	< 6.56	1.69E-03
3-186861	bottle # 2 - ~20 BV	2.62E+02	< 6.95	1.78E-03
3-186862	bottle # 3 - ~20 BV	4.20E+02	< 11.1	2.86E-03
3-186863	bottle # 4 - ~20 BV	2.43E+02	< 6.43	1.65E-03
3-186864	bottle # 5 - ~20 BV	2.11E+02	< 5.58	1.44E-03
3-186865	bottle # 6 - ~20 BV	1.64E+02	< 4.35	1.12E-03
3-186866	bottle # 7 - ~20 BV	2.12E+02	< 5.61	1.44E-03
3-186867	bottle # 8 - ~20 BV	8.88E+01		6.04E-04

APPENDIX D2-3: WASHING CYCLE #2

Lag Column

Column size = 1.45 cm

Resin: SuperLig[®] 639

Flow rate = 3 BV/h (0.6 mL/min)

Resin Batch # 1-R2-03-27-02-20-45

BV = 12 mL

Feed Displacement – 0.1 NaOH

Sample	LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], µg/L	[Tc-99], C/Co	[Tc-99], µg/L	[Tc-99], M	[K ⁺], M	[Na ⁺], M	[NO ₃ ⁻], M
wash-1	3-186922	0.50	1.91E+04	5.05E+02	1.30E-01	3.86E+02	3.89E-06	4.49E-01	4.61E+00	6.26E-01
wash-2	3-186923	1.00	1.74E+04	4.62E+02	1.18E-01	4.00E+02	4.04E-06	1.89E-01	2.24E+00	8.06E-01
wash-3	3-186924	1.50	1.52E+04	4.03E+02	1.03E-01	2.32E+02	2.34E-06	9.38E-02	7.57E-01	3.10E-01
wash-4	3-186925	2.00	7.27E+03	1.93E+02	4.95E-02	1.12E+02	1.13E-06	7.72E-02	2.67E-01	1.41E-01
wash-5	3-186926	2.50	6.03E+03	1.60E+02	4.10E-02	8.80E+01	8.89E-07	5.85E-02	1.65E-01	8.11E-02
wash-6	3-186927	3.00	6.57E+03	1.74E+02	4.47E-02	< 1.2E+03	< 1.21E+06	3.85E-02	1.38E-01	4.50E-02
wash-7	3-186928	3.50	9.01E+03	2.39E+02	6.13E-02	1.53E+02	1.55E-06	2.29E-02	1.25E-01	2.21E-02
wash-8	3-186929	4.00	1.34E+04	3.54E+02	9.12E-02	2.75E+02	2.77E-06	1.33E-02	1.17E-01	1.34E-02

APPENDIX D2-4: ELUTION CYCLE #2

Lead Column

Column size = 1.45 cm

Eluant = DI Water

Flow rate = ~1 BV/h (0.2 mL/min); BV = 12 mL

Resin Batch # I-R2-03-27-02-20-45

Temperature = 65 °C

Elution Samples

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], µg/L	[Tc-99], C/Co	[Tc-99], µg/L	[Tc-99], C/Co	[Tc-99], M	[K+], M	[Na+], M
3-186930	0.5	3.88E+05	1.03E+04	2.64E+00	1.02E+04	2.54E+00	1.03E-04	1.18E-02	1.10E-01
3-186931	1	8.87E+05	2.35E+04	6.03E+00	2.29E+04	5.72E+00	2.31E-04	9.79E-03	1.03E-01
3-186932	1.5	1.94E+06	5.01E+07	1.32E+01	5.46E+04	1.36E+01	5.51E-04	5.08E-03	4.57E-02
3-186933	2	4.63E+06	1.23E+05	3.15E+01	1.30E+05	3.24E+01	1.31E-03	3.41E-03	1.28E-02
3-186934	2.5	1.34E+07	3.54E+05	9.12E+01	3.60E+05	8.99E+01	3.64E-03	2.09E-03	6.35E-03
3-186935	3	9.77E+06	2.59E+05	6.65E+01	2.97E+05	7.41E+01	2.99E-03	2.67E-03	3.68E-03
3-186936	3.5	9.15E+06	2.42E+05	6.22E+01	2.52E+05	6.28E+01	2.54E-03	3.10E-03	2.15E-03
3-186937	4	8.78E+06	2.33E+05	5.97E+01	2.50E+05	6.23E+01	2.52E-03	3.62E-03	1.59E-03
3-186938	6	4.93E+06	1.31E+05	3.35E+01	1.33E+05	3.31E+01	1.34E-03	2.55E-03	1.63E-03
3-186939	8	7.50E+05	1.99E+04	5.10E+00	2.00E+04	4.98E+00	2.02E-04	9.87E-04	1.81E-03
3-186940	10	2.04E+04	5.41E+02	1.39E-01	5.89E+02	1.47E-01	5.95E-06	< 4.82E-04	1.50E-03
3-186941	12	5.23E+03	1.39E+02	3.56E-02	< 1.67E+02	< 4.17E-02	< 1.69E-06	< 4.82E-04	9.22E-04
3-186942	14	2.30E+03	6.10E+01	1.56E-02	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	8.52E-04
3-186943	16	1.46E+03	3.88E+01	9.93E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	7.65E-04
3-186944	18	1.16E+03	3.07E+01	7.89E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	7.87E-04
3-186945	20	9.31E+02	2.47E+01	6.33E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	6.43E-04
3-186946	22	7.82E+02	2.07E+01	5.32E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	5.70E-04
3-186947	24	7.08E+02	1.88E+01	4.82E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	4.87E-04
3-186948	26	6.35E+02	1.68E+01	4.32E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	4.96E-04

APPENDIX D3-1: LOADING CYCLE #3

Lead Column

Column size = 1.45 cm

Resin: SuperLig[®] 639

Flow rate = 3 BV/h (0.6 mL/min)

Resin Batch # I-R2-03-27-02-20-45

BV – 12 mL

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], μCi/mL	[Tc-99], ug/L	[Tc-99],C/Co	[K+], M	[Na+], M	[NO3-], M
3-187298	5	2.79E+03	1.26E-03	7.38E+01	1.90E-02	3.36E-01	3.40E+00	9.39E-01
3-187299	10	4.70E+02	2.12E-04	1.24E+01	3.20E-03	nm	na	na
3-187300	20	5.28E+02	2.38E-04	1.40E+01	3.59E-03	nm	na	nm
3-187301	30	4.90E+02	2.21E-04	1.30E+01	3.33E-03	nm	na	na
3-187302	40	4.42E+02	1.99E-04	1.17E+01	3.01E-03	nm	na	na
3-187303	50	4.06E+02	1.83E-04	1.07E+01	2.76E-03	4.74E-01	4.65E+00	1.17E+00
3-187304	60	4.01E+02	1.81E-04	1.06E+01	2.73E-03	nm	na	na
3-187305	70	5.51E+02	2.48E-04	1.46E+01	3.75E-03	nm	na	na
3-187306	80	7.27E+02	3.27E-04	1.93E+01	4.95E-03	nm	na	na
3-187307	90	9.45E+02	4.26E-04	2.50E+01	6.43E-03	nm	na	na
3-187308	100	1.28E+03	5.77E-04	3.38E+01	8.71E-03	4.74E-01	4.61E+00	1.30E+00
3-187309	110	1.55E+03	6.98E-04	4.10E+01	1.05E-02	nm	na	na
3-187310	120	1.87E+03	8.42E-04	4.94E+01	1.27E-02	nm	na	na
3-187311	130	2.53E+03	1.14E-03	6.71E+01	1.72E-02	nm	na	na
3-187312	140	3.14E+03	1.41E-03	8.31E+01	2.14E-02	v	na	na
3-187313	150	4.32E+03	1.95E-03	1.14E+02	2.94E-02	4.69E-01	4.65E+00	1.18E+00
3-187314	160	3.78E+03	1.70E-03	1.00E+02	2.57E-02	na	na	na
3-187315	170	5.04E+03	2.27E-03	1.34E+02	3.43E-02	na	na	na
3-187316	180	5.92E+03	2.67E-03	1.57E+02	4.03E-02	na	na	na
3-187317	190	6.67E+03	3.00E-03	1.77E+02	4.54E-02	na	na	na
3-187318	200	7.62E+03	3.43E-03	2.02E+02	5.18E-02	na	na	1.11E+00
3-187319	210	6.80E+03	3.06E-03	1.80E+02	4.63E-02	na	na	na
3-187320	220	7.35E+03	3.31E-03	1.95E+02	5.00E-02	na	na	na
3-187321	230	1.02E+04	4.59E-03	2.69E+02	6.94E-02	na	na	na
3-187322	240	9.70E+03	4.37E-03	2.57E+02	6.60E-02	na	na	na
3-187323	250	1.41E+04	6.35E-03	3.75E+02	9.59E-02	4.74E-01	4.70E+00	1.36E+00
3-187324	260	1.38E+04	6.22E-03	3.64E+02	9.39E-02	na	na	na
3-187325	270	1.64E+04	7.39E-03	4.35E+02	1.12E-01	na	na	na
3-187326	280	2.14E+04	9.64E-03	5.66E+02	1.46E-01	na	na	na
3-187327	290	1.74E+04	7.84E-03	4.61E+02	1.18E-01	na	na	na

APPENDIX D3-2: LOADING CYCLE #3

Lag Column

Resin: SuperLig[®] 639

Resin Batch # I-R2-03-27-02-20-45

Column size = 1.45 cm

Flow rate = 3 BV/h (0.6 mL/min)

BV = 12 mL

Composite Fractions – Lag Column

LIMS #	Effluent fraction #	[Tc-99], dpm/mL	[Tc-99], µg/L	C/Co
3-187366	bottle # 1 - ~20 BV	5.99E+01	1.59E+00	4.07E-04
3-187367	bottle # 2 - ~20 BV	6.49E+01	1.72E+00	4.41E-04
3-187368	bottle # 3 - ~20 BV	6.02E+01	1.60E+00	4.10E-04
3-187369	bottle # 4 - ~20 BV	7.49E+01	1.99E+00	5.10E-04
3-187370	bottle # 5 - ~20 BV	5.79E+01	1.53E+00	3.94E-04
3-187371	bottle # 6 - ~20 BV	2.64E+02	6.99E+00	1.80E-03
3-187372	bottle # 7 - ~20 BV	1.45E+02	3.84E+00	9.86E-04
3-187436	bottle # 8 - ~20 BV	1.77E+02	4.69E+00	1.20E-03

Individual Samples – Lag Column

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], µg/L	C/Co
3-187351	20	5.26E+01	1.39E+00	3.58E-04
3-187352	40	2.84E+01	7.53E-01	1.93E-04
3-187353	60	4.59E+01	1.22E+00	3.12E-04
3-187354	80	1.77E+02	4.70E+00	1.20E-03
3-187355	100	4.10E+01	1.09E+00	2.79E-04
3-187356	120	4.38E+01	1.16E+00	2.98E-04
3-187357	140	9.04E+01	2.40E+00	6.15E-04
3-187358	160	4.31E+01	1.14E+00	2.93E-04
3-187359	180	6.74E+01	1.79E+00	4.59E-04
3-187360	200	9.04E+01	2.40E+00	6.15E-04
3-187361	220	5.91E+01	1.57E+00	0.000402
3-187362	240	6.97E+01	1.85E+00	0.0004741
3-187363	260	9.07E+01	2.40E+00	0.000617

APPENDIX D3-3: LOADING CYCLE #3

Lag Column

Column size = 1.45 cm

Resin: SuperLig[®] 639

Flow rate = 3 BV/h (0.6 mL/min)

Resin Batch # I-R2-03-27-02-20-45

BV = 12 mL

Feed Displacement – 0.1 NaOH

Sample	LIMS #	BV	[Tc-99], dpm/mL	[Tc-99],C/Co	[K ⁺], M	[Na ⁺], M	[NO ₃ ⁻], M
wash-1	3-187343	0.50	1.91E+04	1.30E-01	4.49E-01	4.61E+00	1.26E+00
wash-2	3-187344	1.00	1.74E+04	1.18E-01	1.89E-01	2.24E+00	6.26E-01
wash-3	3-187345	1.40	1.52E+04	1.03E-01	9.38E-02	7.57E-01	2.47E-01
wash-4	3-187346	2.00	7.27E+03	4.95E-02	7.95E-02	2.67E-01	1.04E-01
wash-5	3-187347	2.50	6.03E+03	4.10E-02	5.85E-02	1.65E-01	6.40E-02
wash-6	3-187348	3.00	6.57E+03	4.47E-02	3.85E-02	1.38E-01	3.58E-02
wash-7	3-187349	3.50	9.01E+03	6.13E-02	2.29E-02	1.25E-01	2.08E-02
wash-8	3-187350	4.00	1.34E+03	9.12E-03	1.33E-02	1.17E-01	1.12E-02

APPENDIX D3-4: LOADING CYCLE #3

Lead Column

Column size = 1.45 cm

Eluant = DI Water

Flow rate = ~1 BV/h (~0.2 mL/min) BV = 12 mL

Resin Batch # I-R2-03-27-02-20-45

Temperature = 65 °C

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], µg/L	[Tc-99], C/Co	[Tc-99], µg/L	[Tc-99], C/Co	[Tc-99], M	[K ⁺], M	[Na ⁺], M	[NO ₃], M
300187374	0.5	nm	nm	nm	2.51E+04	6.27E+00	2.54E-04	9.72E-03	9.83E-02	4.56E-03
300187375	1	nm	nm	nm	2.07E+04	5.17E+00	2.09E-04	1.02E-02	1.03E-01	5.02E-03
300187376	1.5	nm	nm	nm	7.05E+04	1.76E+01	7.12E-04	5.23E-03	3.17E-02	1.47E-03
300187377	2	nm	nm	nm	2.79E+05	6.96E+01	2.81E-03	3.08E-03	1.14E-02	8.39E-04
300187378	2.5	nm	nm	nm	4.01E+05	1.00E+02	4.05E-03	2.21E-03	6.83E-03	6.13E-04
300187379	3	nm	nm	nm	3.00E+05	7.50E+01	3.03E-03	2.74E-03	4.16E-03	4.84E-04
300187437	3.5	nm	nm	nm	2.58E+05	6.45E+01	0.00260606	3.36E-03	2.48E-03	nm
300187380	4	nm	nm	nm	2.57E+05	6.41E+01	2.59E-03	3.36E-03	2.10E-03	4.35E-04
300187381	6	nm	nm	nm	1.01E+05	2.51E+01	1.02E-03	2.79E-03	2.99E-03	nm
300187382	8	nm	nm	nm	4.99E+03	1.25E+00	5.04E-05	1.91E-03	5.83E-03	nm
300187383	10	8.03E+03	nm	5.46E-02	2.10E+02	5.25E-02	2.12E-06	< 4.82E-04	1.67E-03	nm
300187384	12	nm	nm	v	1.02E+02	2.55E-02	1.03E-06	< 4.82E-04	1.34E-03	nm
300187385	14	nm	nm	nm	6.70E+01	1.67E-02	6.7677E-07	< 4.82E-04	1.36E-03	nm
300187386	16	nm	v	nm	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	1.19E-03	nm
300187387	18	nm	nm	nm	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	1.07E-03	nm
300187388	20	9.58E+02	nm	6.52E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	9.70E-04	nm
300187389	22	8.15E+02	nm	5.54E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	9.09E-04	nm
300187390	24	nm	nm	nm	< 1.2E+02	< 3.00E-02	< 1.21E-06	5.62E-04	2.11E-03	nm
300187391	26	5.56E+02	nm	3.78E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	1.08E-03	nm

APPENDIX D

WSRC-TR-2003-00098, REVISION 0
SRT-RPP-2003-00026, REVISION 0

APPENDIX D4-1: LOADING CYCLE #4

Lead Column

Column size = 1.45 cm

Resin: SuperLig® 639

Flow rate = 3 BV/h (0.6 mL/min)

Resin Batch # I-R2-03-27-02-20-45

BV = 12 mL

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], µCi/mL	[Tc-99], µg/L	[Tc-99],C/Co	[Tc-99], M	[K+], M	[Na+], M
3-188442	5	2.72E+02	1.23E-04		1.85E-03	nm	nm	nm
3-187912	10	3.04E+02	1.37E-04	8.06E+00	2.07E-03	< 6.00E-07	0.45	5.13
3-187913	20	3.29E+02	1.48E-04	8.73E+00	2.24E-03	nm	nm	nm
3-187914	30	3.51E+02	1.58E-04	9.29E+00	2.39E-03	nm	nm	nm
3-187915	40	3.26E+02	1.47E-04	8.64E+00	2.22E-03	nm	nm	nm
3-187916	50	2.45E+02	1.10E-04	6.50E+00	1.67E-03	< 6.00E-07	0.47	5.30
3-187917	60	4.92E+02	2.22E-04	1.30E+01	3.35E-03	nm	nm	nm
3-187918	70	6.27E+02	2.82E-04	1.66E+01	4.27E-03	nm	nm	nm
3-187919	80	7.19E+02	3.24E-04	1.90E+01	4.89E-03	nm	nm	nm
3-187920	90	1.05E+03	4.73E-04	2.78E+01	7.14E-03	nm	nm	nm
3-187921	100	1.22E+03	5.50E-04	3.23E+01	8.30E-03	< 6.00E-07	0.48	5.43
3-187922	110	1.96E+03	8.83E-04	5.19E+01	1.33E-02	nm	nm	NA
3-187923	120	1.89E+03	8.51E-04	5.01E+01	1.29E-02	nm	nm	NA
3-187924	130	3.03E+03	1.36E-03	8.02E+01	2.06E-02	nm	nm	NA
3-187925	140	3.30E+03	1.49E-03	8.76E+01	2.24E-02	nm	nm	NA
3-187926	150	4.29E+03	1.93E-03	1.14E+02	2.92E-02	8.18182E-07	0.48	5.35
3-187927	160	5.60E+03	2.52E-03	1.48E+02	3.81E-02	8.0303E-07	0.47	5.35
3-187928	170	6.12E+03	2.76E-03	1.62E+02	4.16E-02	nm	nm	nm
3-187929	180	6.16E+03	2.77E-03	1.63E+02	4.19E-02	nm	nm	nm
3-187930	190	7.66E+03	3.45E-03	2.03E+02	5.21E-02	nm	nm	nm
3-187931	200	8.36E+03	3.77E-03	2.22E+02	5.69E-02	nm	nm	nm
3-187932	210	9.67E+03	4.36E-03	2.56E+02	6.58E-02	2.13131E-06	0.47	5.39
3-187933	220	1.10E+04	4.95E-03	2.93E+02	7.48E-02	nm	nm	nm
3-187934	230	1.22E+04	5.50E-03	3.23E+02	8.30E-02	nm	nm	nm
3-187935	240	1.32E+04	5.95E-03	3.50E+02	8.98E-02	nm	nm	nm
3-187936	250	1.41E+04	6.35E-03	3.73E+02	9.59E-02	nm	nm	nm
3-187937	260	1.54E+04	6.94E-03	4.09E+02	1.05E-01	3.02525E-06	0.57	5.17
3-187938	270	1.80E+04	8.11E-03	4.76E+02	1.22E-01	nm	nm	nm
3-187939	280	1.94E+04	8.74E-03	5.15E+02	1.32E-01	nm	nm	nm
3-187940	290	2.04E+04	9.19E-03	5.42E+02	1.39E-01	nm	nm	nm

APPENDIX D4-2: LOADING CYCLE #4

Lag Column

Resin: SuperLig® 639

Resin Batch # I-R2-03-27-02-20-45

Column size = 1.45 cm

Flow rate = 3 BV/h (0.6 mL/min)

BV = 12 mL

Composite Fractions – Lag Column

LIMS #	Effluent fraction #	[Tc-99], dpm/mL	[Tc-99], µg/L	C/Co
3-187965	bottle # 1 - ~20 BV	6.23E+01	1.65E+00	4.24E-04
3-187966	bottle # 2 - ~20 BV	8.97E+01	2.38E+00	6.10E-04
3-187967	bottle # 3 - ~20 BV	8.74E+01	2.32E+00	5.95E-04
3-187968	bottle # 4 - ~20 BV	6.03E+01	1.60E+00	4.10E-04
3-187969	bottle # 5 - ~20 BV	8.57E+01	2.27E+00	5.83E-04
3-187970	bottle # 6 - ~20 BV	6.44E+01	1.71E+00	4.38E-04
3-187971	bottle # 7 - ~20 BV	8.75E+01	2.32E+00	5.95E-04
3-187972	bottle # 8 - ~20 BV	1.38E+02	3.64E+00	9.39E-04
3-187973	bottle # 9 - ~20 BV	nm	nm	nm
3-187974	bottle # 10 - ~20 BV	nm	nm	nm
3-187975	bottle # 11 - ~20 BV	nm	nm	nm
3-187976	bottle # 12 - ~20 BV	nm	nm	nm

Individual Samples – Lag Column

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], µg/L	C/Co
3-187950	20	8.22E+01	2.18E+00	5.59E-04
3-187951	40	9.95E+01	2.64E+00	6.77E-04
3-187952	60	8.37E+01	2.22E+00	5.69E-04
3-187953	80	9.18E+01	2.43E+00	6.24E-04
3-187954	100	8.26E+01	2.19E+00	5.62E-04
3-187955	120	8.03E+01	2.13E+00	5.46E-04
3-187956	140	8.46E+01	2.24E+00	5.76E-04
3-187957	160	1.04E+02	2.75E+00	7.07E-04
3-187958	180	8.70E+01	2.31E+00	5.92E-04
3-187959	200	9.29E+01	2.46E+00	6.32E-04
3-187960	220	1.24E+02	3.28E+00	8.44E-04
3-187961	240	8.07E+01	2.14E+00	5.49E-04
3-187962	260	1.23E+02	3.25E+00	8.37E-04
3-187963	280	1.57E+02	4.16E+00	1.07E-03

nm = not measured

APPENDIX D4-3: LOADING CYCLE #4

Lag Column

Column size = 1.45 cm

Resin: SuperLig[®] 639

Flow rate = 3 BV/h (0.6 mL/min)

Resin Batch # I-R2-03-27-02-20-45

BV = 12 mL

Feed Displacement – 0.1 NaOH

Sample	LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], M	[K ⁺], M	[Na ⁺], M	[NO ₃ ⁻], M
wash-1	3-186942	0.5	4.44E+02	4.48E-06	5.69E-01	5.09E+00	1.12E+00
wash-2	3-186943	1	5.37E+02	5.42E-06	2.87E-01	2.92E+00	7.34E-01
wash-3	3-186944	1.5	3.90E+02	3.94E-06	1.02E-01	9.09E-01	3.82E-01
wash-4	3-186945	2	nm	nm	7.90E-02	3.51E-01	1.71E-01
wash-5	3-186946	2.5	nm	nm	6.21E-02	2.00E-01	8.05E-02
wash-6	3-186947	3	nm	nm	3.33E-02	1.50E-01	4.71E-02
wash-7	3-186948	3.5	nm	nm	2.23E-02	1.37E-01	3.37E-02
wash-8	3-186949	4	nm	nm	1.43E-02	1.26E-01	2.27E-02

APPENDIX D4-4: LOADING CYCLE #4

Lead Column

Column size = 1.45 cm

Eluant = DI Water

Flow rate = ~1 BV/h (~0.2 mL/min); BV = 12 mL

Resin Batch # I-R2-03-27-02-20-45

Temperature = 65 °C

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], µg/L	[Tc-99], C/Co	[Tc-99], µg/L	[Tc-99], C/Co	[Tc-99], M	[K ⁺], M	[Na ⁺], M	[NO ₃ ⁻], M
3-187977	0.5	nm	nm	na	1.41E+04	3.51E+00	1.42E-04	1.60E-02	1.29E-01	3-187977
3-187978	1	nm	nm	na	2.97E+04	7.41E+00	2.99E-04	1.17E-02	1.08E-01	3-187978
3-187979	1.5	nm	nm	na	5.92E+04	1.48E+01	5.98E-04	6.72E-03	4.26E-02	3-187979
3-187980	2	nm	nm	na	2.67E+05	6.67E+01	2.70E-03	3.72E-03	1.32E-02	3-187980
3-187981	2.5	nm	nm	na	5.14E+05	1.28E+02	5.19E-03	2.09E-03	7.57E-03	3-187981
3-187982	3	nm	nm	na	3.46E+05	8.63E+01	3.49E-03	2.50E-03	3.97E-03	3-187982
3-187983	3.5	nm	nm	na	2.79E+05	6.97E+01	2.82E-03	3.08E-03	2.21E-03	3-187983
3-187984	4	nm	nm	na	2.62E+05	6.55E+01	2.65E-03	3.31E-03	1.36E-03	3-187984
3-187985	6	nm	nm	na	8.50E+04	2.12E+01	8.58E-04	1.64E-03	1.03E-03	3-187985
3-187986	8	nm	nm	na	2.64E+03	6.60E-01	2.67E-05	6.28E-04	8.78E-04	3-187986
3-187987	10	nm	nm	na	2.09E+02	5.22E-02	2.11E-06	4.23E-04	7.83E-04	3-187987
3-187988	12	nm	nm	na	< 6.0E+01	< 1.50E-02	<6.00E-07	2.95E-04	6.87E-04	3-187988
3-187989	14	1.65E+03	4.38E+01	1.12E-02	< 6.0E+01	< 1.50E-02	<6.00E-07	2.79E-04	5.35E-04	3-187989
3-187990	16	1.14E+03	3.02E+01	7.76E-03	< 6.0E+01	< 1.50E-02	<6.00E-07	< 2.56E-05	4.91E-04	3-187990
3-187991	18	9.14E+02	2.42E+01	6.22E-03	< 6.0E+01	< 1.50E-02	<6.00E-07	< 2.56E-05	5.83E-04	3-187991
3-187992	20	7.78E+02	2.06E+01	5.29E-03	< 6.0E+01	< 1.50E-02	<6.00E-07	< 2.56E-05	3.99E-04	3-187992
3-187993	22	6.83E+02	1.81E+01	4.65E-03	< 6.0E+01	< 1.50E-02	<6.00E-07	< 2.56E-05	2.28E-04	3-187993
3-187994	24	6.68E+02	1.77E+01	4.54E-03	< 6.0E+01	< 1.50E-02	<6.00E-07	< 2.56E-05	2.92E-04	3-187994
3-187995	26	5.56E+02	1.47E+01	3.78E-03	< 6.0E+01	< 1.50E-02	<6.00E-07	< 2.56E-05	2.88E-04	3-187995

nm = not measured

na = not applicable

APPENDIX D5-1: LOADING CYCLE #5

Lead Column

Column size = 1.45 cm

Resin: SuperLig[®] 639

Flow rate = 3 BV/h (0.6 mL/min)

Resin Batch # I-R2-03-27-02-20-45

BV = 12 mL

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], μCi/mL	[Tc-99], μg/L	[Tc-99],C/Co	[Tc-99], M	[K+], M	[Na+], M
3-188867	5	2.74E+02	1.23E-04	7.27E+00	1.86E-03	< 1.00E-06	0.33	4.01
3-188868	10	1.50E+02	6.76E-05	3.97E+00	1.02E-03	nm	0.60	4.78
3-188869	20	1.70E+02	7.66E-05	4.51E+00	1.16E-03	nm	nm	nm
3-188870	30	2.15E+02	9.68E-05	5.71E+00	1.46E-03	nm	nm	nm
3-188871	40	2.60E+02	1.17E-04	6.89E+00	1.77E-03	nm	nm	nm
3-188872	50	2.73E+02	1.23E-04	7.23E+00	1.86E-03	< 1.00E-06	0.46	4.01
3-188873	60	3.34E+02	1.50E-04	8.84E+00	2.27E-03	nm	nm	nm
3-188874	70	4.39E+02	1.98E-04	1.16E+01	2.99E-03	nm	nm	nm
3-188875	80	5.97E+02	2.69E-04	1.58E+01	4.06E-03	nm	nm	nm
3-188876	90	8.64E+02	3.89E-04	2.29E+01	5.88E-03	nm	nm	nm
3-188877	100	1.18E+03	5.32E-04	3.13E+01	8.03E-03	< 1.00E-06	0.46	2.97
3-188878	110	1.55E+03	6.98E-04	4.11E+01	1.05E-02	nm	nm	nm
3-188879	120	2.07E+03	9.32E-04	5.48E+01	1.41E-02	nm	nm	nm
3-188880	130	2.46E+03	1.11E-03	6.51E+01	1.67E-02	nm	nm	nm
3-188881	140	3.18E+03	1.43E-03	8.43E+01	2.16E-02	nm	nm	nm
3-188882	150	3.62E+03	1.63E-03	9.59E+01	2.46E-02	< 1.00E-06	0.50	4.10
3-188883	160	4.56E+03	2.05E-03	1.21E+02	3.10E-02	nm	nm	nm
3-188884	170	5.22E+03	2.35E-03	1.38E+02	3.55E-02	nm	nm	nm
3-188885	180	6.20E+03	2.79E-03	1.64E+02	4.22E-02	nm	nm	nm
3-188886	190	6.85E+03	3.09E-03	1.81E+02	4.66E-02	nm	nm	nm
3-188887	200	7.80E+03	3.51E-03	2.07E+02	5.31E-02	< 1.00E-06	0.48	3.97
3-188888	210	8.90E+03	4.01E-03	2.36E+02	6.05E-02	nm	nm	nm
3-188889	220	1.03E+04	4.64E-03	2.72E+02	7.01E-02	nm	nm	nm
3-188890	230	1.05E+04	4.73E-03	2.78E+02	7.14E-02	nm	nm	nm
3-188891	240	1.24E+04	5.59E-03	3.28E+02	8.44E-02	nm	nm	nm
3-188892	250	1.43E+04	6.44E-03	3.78E+02	9.73E-02	2.38E-06	0.53	4.43
3-188893	260	1.64E+04	7.39E-03	4.36E+02	1.12E-01	nm	nm	nm
3-188894	270	1.83E+04	8.24E-03	4.86E+02	1.24E-01	nm	nm	nm
3-188895	280	2.06E+04	9.28E-03	5.47E+02	1.40E-01	nm	nm	nm

APPENDIX D5-2: LOADING CYCLE #5

Lag Column

Resin: SuperLig[®] 639

Resin Batch # I-R2-03-27-02-20-45

Column size = 1.45 cm

Flow rate = 3 BV/h (0.6 mL/min)

BV = 12 mL

Composite Fractions – Lag Column

LIMS #	Effluent fraction #	[Tc-99], dpm/mL	[Tc-99], ug/L
3-188912	bottle # 1 - ~20 BV	4.26E+01	1.13E+00
3-188913	bottle # 2 - ~20 BV	8.96E+01	2.38E+00
3-188914	bottle # 3 - ~20 BV	8.66E+01	2.29E+00
3-188915	bottle # 4 - ~20 BV	8.14E+01	2.16E+00
3-188916	bottle # 5 - ~20 BV	1.05E+02	2.78E+00
3-188917	bottle # 6 - ~20 BV	4.20E+01	1.11E+00
3-188918	bottle # 7 - ~20 BV	9.34E+01	2.48E+00
3-188919	bottle # 8 - ~20 BV	1.23E+02	3.26E+00
3-188920	bottle # 9 - ~20 BV	nm	nm
3-188921	bottle # 10 - ~20 BV	nm	nm
3-188922	bottle # 11 - ~20 BV	nm	nm

Individual Samples – Lag Column

LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], µg/L	C/Co
3-188897	20	3.90E+01	1.03E+00	2.65E-04
3-188898	40	3.07E+01	8.12E-01	2.09E-04
3-188899	60	5.36E+01	1.42E+00	3.65E-04
3-188900	80	5.50E+01	1.46E+00	3.74E-04
3-188901	100	7.16E+01	1.90E+00	4.87E-04
3-188902	120	5.25E+01	1.39E+00	3.57E-04
3-188903	140	6.22E+01	1.65E+00	4.23E-04
3-188904	160	3.54E+01	9.39E-01	2.41E-04
3-188905	180	3.65E+01	9.68E-01	2.48E-04
3-188906	200	4.28E+01	1.14E+00	2.91E-04
3-188907	220	5.09E+01	1.35E+00	3.46E-04
3-188908	240	9.08E+01	2.41E+00	6.18E-04
3-188909	260	1.36E+02	3.59E+00	9.25E-04
3-188910	280	1.58E+02	4.19E+00	1.07E-03

APPENDIX D5-3: LOADING CYCLE #5

Lag Column

Resin: SuperLig® 639

Resin Batch # I-R2-03-27-02-20-45

Column size = 1.45 cm

Flow rate = 3 BV/h (0.6 mL/min)

BV = 12 mL

Feed Displacement – 0.1 NaOH

Sample	LIMS #	BV	[Tc-99], dpm/mL	[Tc-99], C/Co	[Tc-99], µg/L	[Tc-99], M	[K+], M	[Na+], M	[NO3-], M
wash-1	3-188923	0.5	2.10E+04	1.43E-01	4.23E+02	4.27E-06	5.77E-01	5.09E+00	1.44E+00
wash-2	3-188924	1	2.41E+04	1.64E-01	2.12E+02	2.14E-06	3.31E-01	3.29E+00	1.17E+00
wash-3	3-188925	1.5	1.91E+04	1.30E-01	3.98E+02	4.02E-06	1.45E-01	1.62E+00	1.49E+00
wash-4	3-188926	2	1.39E+04	9.46E-02	2.21E+02	2.23E-06	8.36E-02	5.74E-01	1.60E+00
wash-5	3-188927	2.5	1.10E+04	7.48E-02	< 4.80E+02	< 4.85E-06	5.77E-02	2.60E-01	6.35E-01
wash-6	3-188928	3	9.08E+03	6.18E-02	< 1.92E+02	< 1.94E-06	4.21E-02	1.86E-01	3.67E-01
wash-7	3-188929	3.5	1.02E+04	6.94E-02	< 2.40E+02	< 2.42E-06	2.90E-02	1.53E-01	2.11E-01
wash-8	3-188930	4	2.60E+04	1.77E-01	< 3.33E+02	< 3.36E-06	2.06E-02	1.36E-01	1.49E-01

APPENDIX D5-4: LOADING CYCLE #5

Lead Column

Column size = 1.45 cm

Eluant = DI Water

Flow rate = ~1 BV/h (~0.2 mL/min); BV = 12 mL

Resin Batch # I-R2-03-27-02-20-45

Temperature = 65 °C

LIMS #	BV Eluate	[Tc-99], dpm/mL	[Tc-99], µg/L	[Tc-99], C/Co	[Tc-99], µg/L	[Tc-99], C/Co	[Tc-99], M	[K ⁺], M	[Na ⁺], M
3-188931	0.5	3.86E+05	1.02E+04	2.63E+00	7.77E+03	1.94E+00	7.85E-05	1.78E-02	1.03E-01
3-188932	1	1.19E+06	3.16E+04	8.10E+00	2.51E+04	6.27E+00	2.54E-04	9.18E-03	6.78E-02
3-188933	1.5	1.66E+06	4.41E+04	1.13E+01	3.61E+04	9.02E+00	3.65E-04	6.31E-03	2.96E-02
3-188934	2	2.63E+06	6.97E+04	1.79E+01	5.51E+04	1.38E+01	5.56E-04	5.23E-03	1.05E-02
3-188935	2.5	8.29E+06	2.20E+05	5.64E+01	1.91E+05	4.77E+01	1.93E-03	3.31E-03	5.35E-03
3-188936	3	1.13E+07	2.99E+05	7.69E+01	2.65E+05	6.61E+01	2.67E-03	1.88E-03	3.07E-03
3-188937	3.5	1.01E+07	2.67E+05	6.87E+01	2.35E+05	5.87E+01	2.37E-03	2.36E-03	1.91E-03
3-188938	4	9.87E+06	2.61E+05	6.71E+01	2.27E+05	5.67E+01	2.29E-03	3.31E-03	1.36E-03
3-188939	6	6.66E+06	1.77E+05	4.53E+01	1.50E+05	3.75E+01	1.52E-03	2.11E-03	1.17E-03
3-188940	8	1.42E+06	3.75E+04	9.66E+00	3.10E+04	7.75E+00	3.13E-04	9.26E-04	8.83E-04
3-188941	10	4.68E+04	1.24E+03	3.18E-01	9.12E+02	2.28E-01	9.21E-06	4.05E-04	6.91E-04
3-188942	12	7.46E+03	1.98E+02	5.07E-02	8.10E+01	2.02E-02	8.18E-07	< 3.85E-04	6.57E-04
3-188943	14	2.78E+03	7.37E+01	1.89E-02	< 9.6E+01	< 2.40E-02	<9.70E-07	< 3.85E-04	8.30E-04
3-188944	16	1.52E+03	4.02E+01	1.03E-02	< 9.6E+01	< 2.40E-02	<9.70E-07	< 3.85E-04	7.13E-04
3-188945	18	1.11E+03	2.94E+01	7.55E-03	< 9.6E+01	< 2.40E-02	<9.70E-07	< 3.85E-04	6.52E-04
3-188946	20	2.78E+03	7.36E+01	1.89E-02	< 9.6E+01	< 2.40E-02	<9.70E-07	< 3.85E-04	6.26E-04
3-188947	22	7.82E+02	2.07E+01	5.32E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	8.22E-04
3-188948	24	6.88E+02	1.82E+01	4.68E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	5.30E-04
3-188949	26	6.75E+02	1.79E+01	4.59E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	8.17E-04
3-188950	27	6.00E+02	1.59E+01	4.08E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	6.96E-04
3-188952	30	5.34E+02	1.41E+01	3.63E-03	< 1.2E+02	< 3.00E-02	< 1.21E-06	< 4.82E-04	5.43E-04

APPENDIX E - COMPOSITE PRODUCTS DATA

APPENDIX E1 – EFFLUENT COMPOSITE PRODUCTS

Analyte	cycle -1	cycle -1D	cycle -2	cycle -2D	cycle -3	cycle -3D	cycle -4	cycle -4D	cycle -5	cycle -5D
LIMS #	3-188182	3-188183	3-188184	3-188185	3-188186	3-188187	3-190142	3-190143	3-190138	3-190139
C-137, $\mu\text{Ci/mL}$	3.73E-04	3.23E-04	3.70E-03	3.73E-03	2.83E-03	2.91E-03	4.49E-03	4.52E-03	6.11E-01	6.07E-01
Tc-99, $\mu\text{Ci/mL}$	4.82E-05	2.49E-05	5.59E-05	6.31E-05	3.73E-05	4.68E-05	3.31E-05	4.16E-05	3.78E-05	2.10E-05
Tc-99, $\mu\text{g/L}$ (ICP-MS)	205	242	170	193	201	196	132	137	124	127
U-238, $\mu\text{g/L}$ (ICP-MS)	24.9	< DTL	< DTL	55.6	5.96	< DTL	nm	nm	nm	nm
Total carbon, mg/L	3120	2280	2860	2600	2230	2640	11600	20700	7560	23800
TIC, mg/L	1070	840	1130	1070		983	9610	20500	5430	22800
TOC, mg/L	2050	1440	1730	1530	22230	1657	1990	200	2130	1000
Total base, M	2.79	2.78	2.84	2.82	2.79	2.78	2.93	2.83	2.85	2.81
Free OH ⁻ , M	2.07	2.03	2.03	1.99	1.81	1.86	2.1	2.1	2.1	2.07
wt. % dissolved solids	31.557	31.4187	32.3644	32.1323	32.3107	32.3923	nm	nm	nm	nm
specific gravity	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23
IC (anions), M	3-188188	3-188189	3-188190	3-188191	3-188192	3-188193	3-190144	3-190145	3-190140	3-190141
Cl ⁻	6.15E-02	6.29E-02	6.09E-02	6.60E-02	5.87E-02	6.49E-02	6.60E-02	6.60E-02	6.46E-02	6.46E-02
F ⁻	9.69E-03	9.58E-03	6.64E-03	7.21E-03	6.16E-03	7.58E-03	1.05E-03	1.05E-03	4.90E-03	1.05E-03
HCOO ⁻	7.36E-03	1.88E-02	6.11E-03	7.38E-03	6.04E-03	8.13E-03	1.15E-02	1.14E-02	1.14E-02	1.17E-02
NO ₃ ⁻	1.37E+00	1.32E+00	1.16E+00	1.40E+00	1.09E+00	1.35E+00	1.32E+00	1.31E+00	1.18E+00	1.31E+00
NO ₂ ⁻	8.85E-01	9.09E-01	8.72E-01	9.52E-01	8.52E-01	9.37E-01	9.26E-01	9.28E-01	9.22E-01	9.28E-01
H(COO) ₂ ⁻	2.04E-03	2.12E-03	1.89E-03	1.93E-03	1.73E-03	1.91E-03	1.93E-03	1.87E-03	2.30E-03	1.92E-03
PO ₄ ⁻	2.34E-03	2.50E-03	2.12E-03	1.81E-03	2.19E-03	1.90E-03	2.27E-03	2.48E-03	2.62E-03	2.84E-03
SO ₄ ⁻	1.63E-03	1.68E-03	1.39E-03	1.34E-03	1.68E-03	1.26E-03	1.21E-03	1.13E-03	1.41E-03	1.45E-03

APPENDIX E1 – EFFLUENT COMPOSITE PRODUCTS - continued

Analyte	cycle -1	cycle -1D	cycle -2	cycle -2D	cycle -3	cycle -3D	cycle -4	cycle -4D	cycle -5	cycle -5D
ICP-ES, mg/L										
Ag	0.357	0.356	0.389	0.369	0.412	0.411	0.314	0.282	0.279	0.387
Al	13600	13700	13900	14100	14000	14000	11700	11200	12000	11400
B	18.5	18.5	18.9	19.2	18.8	19.0	17.9	15.6	16.8	17.6
Ba	0.542	0.533	0.588	0.576	0.588	0.572	<0.380	<0.380	<0.380	<0.380
Ca	5.95	5.95	6.22	6.21	6.20	6.25	5.06	4.93	5.56	5.03
Cd	0.987	0.976	1.05	1.08	1.03	1.03	0.833	0.735	0.839	0.801
Ce	4.16	4.18	4.48	4.35	4.78	4.73	3.98	3.78	3.68	4.73
Cr	37.1	37.4	43.4	42.9	41.5	41.7	36.6	34.2	37.3	36.2
Cu	3.74	3.82	2.46	2.54	2.62	2.67	1.67	1.51	1.21	1.19
Fe	1.45	1.44	1.77	1.77	1.79	1.80	1.64	1.52	1.91	1.81
Gd	<0.468	<0.468	0.468	<0.468	0.510	0.510	<0.468	<0.468	<0.468	0.517
K	21200	21400	22000	21800	21700	21800	17800	17100	18400	16900
La	0.777	0.772	0.814	0.770	0.866	0.841	0.590	0.577	0.553	0.666
Li	<0.860	<0.860	<0.860	<0.860	<0.860	1.10	0.887	<0.860	<0.860	1.06
Mg	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106
Mn	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016
Mo	43.1	42.2	43.7	43.5	44.4	43.3	35.5	33.8	35.3	35.4
Na	116000	116000	119000	122000	120000	120000	103000	98700	106000	101000
Ni	2.52	2.40	2.53	2.53	2.24	2.46	2.32	2.06	2.22	2.09
P	145	146	150	148	149	149	134	126	138	133
Pb	15.1	14.9	16.4	15.9	15.1	16.0	13.6	12.4	14.3	13.3
Sb	39.3	39.5	40.7	40.6	41.3	40.4	31.7	30.0	32.8	31.5
Si	91.5	91.5	91.7	87.5	89.6	90.2	70.0	64.6	69.5	67.7
Sn	76.0	77.9	80.0	78.1	78.7	79.0	62.1	58.3	62.3	60.8
Sr	2.00	1.99	2.05	2.08	2.05	2.10	1.64	1.54	1.84	1.77
Tc	<0.060	<0.060	<0.060	<0.060	<0.060	<0.060	<0.060	<0.060	<0.060	<0.060
Tc	<0.180	<0.180	<0.180	<0.180	<0.180	<0.180	<0.180	<0.180	<0.180	<0.180
Ti	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154
U	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54
Zn	4.60	4.56	4.69	4.69	4.75	4.95	4.16	3.79	4.12	4.03
Zr	4.41	4.46	6.06	6.05	5.45	5.43	5.07	4.83	5.38	5.10

APPENDIX E2 – CESIUM ELUATE - COMPOSITE PRODUCTS

Analyte	cycle -1	cycle -1D	cycle -2	cycle -2D	cycle -3	cycle -3D	cycle -4	cycle -4D	cycle -5	cycle -5D	cycle -6	cycle -6D
C-137, μCi/mL	1.89E+03	1.69E+03	2.28E+03	2.22E+03	2.12E+03	2.11E+03	1.72E+03	3.08E+03	1.64E+03	1.64E+03	9.90E+02	8.36E+02
Tc-99, μCi/mL	1.68E-03	???	1.83E-03	4.19E-03	4.18E-03	2.11E-03	1.96E-03	1.04E-02	1.48E-03	1.98E-03	2.26E-03	2.40E-03
Tc-99, μg/L (ICP-MS)	2.38E+02	2.20E+02	2.96E+02	2.54E+02	2.61E+02	2.12E+02	2.16E+02	3.83E+02	2.09E+02	2.11E+02	nm	nm
U-238, μg/L (ICP-MS)	70	63	82	71	86	76	172	154	68	63	nm	nm
Total carbon, mg/L	2.09E+03	1.07E+03	1.09E+03	1.46E+03	1.27E+03	6.51E+03	1.32E+03	1.13E+03	9.04E+02	7.15E+02	nm	nm
TIC, mg/L	<DTL	<DTL	<DTL	<DTL	<DTL	3.87E+03	<DTL	<DTL	<DTL	<DTL	nm	nm
TOC, mg/L	2.09E+03	1.07E+03	1.09E+03	1.46E+03	1.27E+03	2.64E+03	1.32E+03	1.13E+03	9.04E+02	7.15E+02	nm	nm
IC (anions), M											nm	nm
Cl-	1.55E-02	1.47E-02	1.46E-02	1.68E-02	1.55E-02	1.55E-02	1.52E-02	1.37E-02	1.46E-02	1.52E-02	1.51E-02	1.65E-02
F-	2.90E-02	2.75E-02	2.73E-02	3.13E-02	2.89E-02	2.90E-02	2.83E-02	2.55E-02	2.73E-02	2.84E-02	2.82E-02	3.07E-02
HCOO-	6.11E-02	5.80E-02	5.76E-02	6.61E-02	6.10E-02	6.12E-02	5.98E-02	5.38E-02	5.75E-02	6.00E-02	5.94E-02	6.48E-02
NO3-	2.94E+04	2.77E+04	2.82E+04	2.65E+04	4.37E+04	5.73E+04	3.34E+04	4.70E+04	2.87E+04	3.00E+04	nm	nm
NO2-	5.98E-02	5.68E-02	5.63E-02	6.46E-02	5.97E-02	5.99E-02	5.85E-02	5.27E-02	5.63E-02	5.87E-02	5.81E-02	6.34E-02
H(COO)2-	3.09E-02	2.93E-02	2.91E-02	3.34E-02	3.08E-02	3.09E-02	3.02E-02	2.72E-02	2.91E-02	3.03E-02	3.00E-02	3.28E-02
PO4-	2.90E-02	2.75E-02	2.73E-02	3.13E-02	2.89E-02	2.90E-02	2.83E-02	2.55E-02	2.73E-02	2.84E-02	2.81E-02	3.07E-02
SO4-	1.43E-02	1.36E-02	1.35E-02	1.55E-02	1.43E-02	1.43E-02	1.40E-02	1.26E-02	1.35E-02	1.41E-02	1.39E-02	1.52E-02
Dilution factors	275	261	259	297	275	275	269	242	259	270	267	292

APPENDIX E2 – CESIUM ELUATE - COMPOSITE PRODUCTS - continued

Analyte	cycle -1	cycle -1D	cycle -2	cycle -2D	cycle -3	cycle -3D	cycle -4	cycle -4D	cycle -5	cycle -5D	cycle -6	cycle -6D
ICP-ES, mg/L											nm	nm
Ag	<0.160	<0.160	<0.160	<0.160	<0.160	<0.160	<0.160	<0.160	<0.160	<0.160	nm	nm
Al	<1.14	<1.14	<1.14	<1.14	<1.14	<1.14	<1.14	<1.14	<1.14	<1.14	nm	nm
B	7.18E+02	6.71E+02	6.35E+02	7.58E+02	8.10E+02	3.28E+02	6.40E+02	6.83E+02	7.46E+02	6.86E+02	nm	nm
Ba	<0.380	<0.380	<0.380	<0.380	<0.380	<0.380	<0.380	<0.380	<0.380	<0.380	nm	nm
Ca	<0.460	<0.460	<0.460	<0.460	<0.460	<0.460	<0.460	<0.460	<0.460	<0.460	nm	nm
Cd	<0.084	<0.084	<0.084	<0.084	<0.084	<0.084	<0.084	<0.084	<0.084	<0.084	nm	nm
Ce	3.22E+02	3.00E+02	3.39E+02	3.98E+02	2.91E+02	3.47E+02	3.07E+02	2.45E+02	2.80E+02	3.00E+02	nm	nm
Cr	<0.120	<0.120	<0.120	<0.120	<0.120	<0.120	<0.120	<0.120	<0.120	<0.120	nm	nm
Cu	1.55E+02	1.46E+02	1.48E+02	1.71E+02	1.45E+02	1.56E+02	1.49E+02	1.38E+02	1.44E+02	1.49E+02	nm	nm
Fe	<0.072	<0.072	<0.072	<0.072	<0.072	<0.072	<0.072	<0.072	<0.072	<0.072	nm	nm
Gd	<0.468	<0.468	<0.468	<0.468	<0.468	<0.468	<0.468	<0.468	<0.468	<0.468	nm	nm
K	<18.8	<18.8	<18.8	<18.8	<18.8	21.4	<18.8	<18.8	<18.8	<18.8	nm	nm
La	4.45E+01	5.59E+01	5.93E+01	6.21E+01	5.08E+01	5.70E+01	4.39E+01	4.17E+01	4.17E+01	5.29E+01	nm	nm
Li	<0.860	<0.860	<0.860	<0.860	<0.860	<0.860	<0.860	<0.860	<0.860	<0.860	nm	nm
Mg	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106	nm	nm
Mn	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	nm	nm
Mo	<1.06	<1.06	<1.06	<1.06	<1.06	<1.06	<1.06	<1.06	<1.06	<1.06	nm	nm
Na	1.68E+03	1.58E+03	1.92E+03	2.07E+03	1.44E+04	3.61E+04	1.58E+03	2.42E+03	1.65E+03	1.51E+03	nm	nm
Ni	<0.270	<0.270	<0.270	<0.270	<0.270	<0.270	<0.270	<0.270	<0.270	<0.270	nm	nm
P	<1.38	<1.38	<1.38	<1.38	<1.38	<1.38	<1.38	<1.38	<1.38	<1.38	nm	nm
Pb	<0.638	<0.638	<0.638	<0.638	<0.638	<0.638	<0.638	<0.638	<0.638	<0.638	nm	nm
Sb	<7.56	<7.56	<7.56	<7.56	<7.56	<7.56	<7.56	<7.56	<7.56	<7.56	nm	nm
Si	<0.334	<0.334	<0.334	<0.334	<0.334	<0.334	<0.334	<0.334	<0.334	<0.334	nm	nm
Sn	3.16E+02	3.66E+02	3.78E+02	5.41E+02	3.46E+02	3.83E+02	4.65E+02	3.34E+02	3.73E+02	3.51E+02	nm	nm
Sr	<0.152	<0.152	<0.152	<0.152	<0.152	<0.152	<0.152	<0.152	<0.152	<0.152	nm	nm
Tc	<0.060	<0.060	<0.060	<0.060	<0.060	<0.060	<0.060	<0.060	<0.060	<0.060	nm	nm
Tc	<0.180	<0.180	<0.180	<0.180	<0.180	<0.180	<0.180	<0.180	<0.180	<0.180	nm	nm
Ti	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154	nm	nm
U	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54	nm	nm
Zn	<0.064	<0.064	<0.064	<0.064	<0.064	<0.064	<0.064	<0.064	<0.064	<0.064	nm	nm
Zr	<0.456	<0.456	<0.456	<0.456	<0.456	<0.456	<0.456	<0.456	<0.456	<0.456	nm	nm

APPENDIX E3 – TECHNICIUM ELUATE - COMPOSITE PRODUCTS

Analyte	cycle -1	cycle -1D	cycle -2	cycle -2D	cycle -3	cycle -3D	cycle -4	cycle -4D	cycle -5	cycle -5D
¹³⁷ Cs, μ Ci/mL	7.93E-05	8.68E-05	2.89E-04	2.66E-04	1.06E-02	2.70E-03	2.51E-04	2.30E-04	1.64E-02	1.61E-02
⁹⁹ Tc, μ Ci/mL	2.48E-01	2.44E-01	3.81E-01	3.87E-01	3.66E-01	3.62E-01	3.93E-01	3.87E-01	4.95E-01	4.82E-01
⁹⁹ Tc, μ g/mL	1.45E+04	1.48E+04	2.08E+04	2.13E+04	2.03E+04	2.06E+04	2.12E+04	2.29E+04	nm	nm
²³⁸ U, μ g/mL	4.5	2.7	7.4	10.2	9.5	37.3	16.2	41.9	nm	nm
IC (anions), M										
Cl-	<5.64E-05	<5.64E-05	3.33E-03	3.33E-03	1.69E-04	1.69E-04	1.13E-04	9.59E-04	nm	nm
F-	<1.05E-04	<1.05E-04	2.63E-04	2.63E-04	<1.05E-04	<1.05E-04	<1.05E-04	<1.05E-04	nm	nm
HCOO-	<2.22E-04	<2.22E-04	1.07E-03	1.09E-03	<2.22E-04	<2.22E-04	<2.22E-04	<2.22E-04	nm	nm
NO3-	3.39E-04	3.39E-04	8.81E-02	8.65E-02	4.34E-03	4.32E-03	3.16E-03	3.19E-03	nm	nm
NO2-	1.74E-04	1.96E-04	4.46E-02	4.37E-02	3.22E-03	3.17E-03	2.37E-03	2.39E-03	nm	nm
(C2O4)2-	<1.14E-04	<1.14E-04	1.02E-04	1.02E-04	<1.14E-04	<1.14E-04	<1.14E-04	<1.14E-04	nm	nm
PO4-	<1.05E-04	<1.05E-04	9.48E-05	8.42E-05	<1.05E-04	<1.05E-04	<1.05E-04	<1.05E-04	nm	nm
SO4-	<5.21E-04	<5.21E-04	6.25E-05	6.25E-05	<5.21E-04	<5.21E-04	<5.21E-04	<5.21E-04	nm	nm

nm = not measured

APPENDIX E3 – TECHNICIUM ELUATE - COMPOSITE PRODUCTS - continued

Analyte	cycle -1	cycle -1D	cycle -2	cycle -2D	cycle -3	cycle -3D	cycle -4	cycle -4D	cycle -5	cycle -5D
ICP-ES, mg/L										
Ag	<0.160	<0.160	0.164	<0.160	<0.160	<0.160	<0.160	<0.200	<0.160	<0.160
Al	2.20	1.78	612	616	45.2	45.6	31.1	30.6	34.0	33.9
B	6.37	7.39	3.25	4.36	4.60	4.41	5.37	6.36	1.87	2.19
Ba	<0.380	<0.380	<0.380	<0.380	<0.380	<0.380	<0.380	<0.475	<0.380	<0.380
Be	<0.020	<0.020	0.062	0.072	0.047	0.023	<0.020	0.040	0.055	0.049
Ca	<0.460	<0.460	<0.460	<0.460	<0.460	<0.460	<0.460	<0.575	<0.460	<0.460
Cd	<0.084	<0.084	<0.084	<0.084	<0.084	<0.084	<0.084	<0.105	<0.084	<0.084
Ce	1.06	0.930	1.62	1.59	1.36	1.13	0.888	1.04	<0.540	<0.540
Cr	<0.120	<0.120	1.85	1.83	<0.120	<0.120	<0.120	<0.150	<0.120	<0.120
Cu	0.257	0.245	0.299	0.296	0.242	0.237	0.233	0.293	0.318	0.320
Fe	0.457	0.401	0.526	0.391	0.237	0.178	0.209	0.164	<0.072	<0.072
K	38.7	25.4	1220	1220	98.0	95.1	86.0	77.9	105	98.7
La	<0.144	<0.144	0.221	0.220	0.185	0.150	<0.144	<0.180	<0.144	<0.144
Li	<0.860	<0.860	<0.860	<0.860	<0.860	<0.860	<0.860	<1.08	<0.860	<0.860
Mg	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106	<0.106	<0.133	<0.106	<0.106
Mn	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.020	<0.016	<0.016
Mo	<1.06	<1.06	2.27	2.31	<1.06	<1.06	<1.06	<1.33	<1.06	<1.06
Na	88.2	89.8	5800	5740	459	462	362	366	416	416
Ni	<0.270	<0.270	<0.270	<0.270	<0.270	<0.270	<0.270	<0.338	<0.270	<0.270
P	5.60	5.59	14.2	12.9	6.61	6.20	6.62	5.99	<1.38	<1.38
Pb	<0.638	<0.638	0.724	<0.638	<0.638	<0.638	<0.638	<0.798	<0.638	<0.638
S	<2.74	<2.74	11.2	11.3	<2.74	<2.74	<2.74	<3.43	<2.74	<2.74
Sb	<7.56	<7.56	<7.56	<7.56	<7.56	<7.56	<7.56	<9.45	<7.56	<7.56
Si	9.67	12.1	16.5	19.0	7.13	8.28	4.84	7.29	4.60	4.93
Sn	<0.900	<0.900	4.06	3.95	<0.900	1.11	<0.900	<1.13	<0.900	<0.900
Sr	<0.152	<0.152	<0.152	<0.152	<0.152	<0.152	<0.152	<0.190	<0.152	<0.152
Ti	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154	<0.154	<0.193	<0.154	<0.154
U	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54	<4.54	<5.68	<4.54	<4.54
Zn	<0.064	<0.064	0.204	0.207	<0.064	<0.064	<0.064	<0.080	<0.064	<0.064
Zr	<0.456	<0.456	<0.456	<0.456	<0.456	<0.456	<0.456	<0.570	<0.456	<0.456

nm = not measured

APPENDIX F - DOSE CALCULATIONS FOR CS-137 LOADINGS OF ION EXCHANGE COLUMNS



WESTINGHOUSE SAVANNAH RIVER COMPANY
INTEROFFICE MEMORANDUM

June 9, 2003

SRT-ADS-2003-0325

TO: Neguib Hassan, 773-A

FROM: Frank Moore, 773A (5-5622)

A handwritten signature in black ink, appearing to be "F. Moore", is written over the "FROM:" line.

DOSE CALCULATIONS FOR CS-137 LOADINGS OF ION EXCHANGE COLUMNS

Ref: (1) SRT-ADS-2002-0207, F.S. Moore to Neguib Hassan, Dose Rate Calculations for Cesium Ion Exchange Column, April 25, 2002

(2) SRT-ADS-2003-0131, F.S. Moore to Neguib Hassan, Dose Rate Calculations for Cs-137 Loadings of Ion Exchange Columns, March 18, 2003

At your request, I have calculated the beta and gamma ray doses to the ion exchange medium during loadings with Cs-137. The following assumptions are used in the analysis:

- (1) Cs-137 concentration is 175 microCuries/ml.
- (2) The loading rate in column volumes/hr is given in column 5 of table 1.
- (3) All of the Cs-137 is retained on the medium.
- (4) The Cs-137 is uniformly distributed throughout the medium.

The ion exchange column is 1.45 cm in diameter, and has a volume of 15 ml. This analysis is identical to that reported in reference 2 for revised column volumes loaded and flow rates. Only one case, loading of the entire column volume, is considered here. As discussed in reference 1, beta decay provides the majority of the radiation dose. This is because the beta particles have a very short range and deposit all their energy in a small volume around the point at which the decay takes place.

Table 1 gives, for each run, the number of column volumes run through the column, the Ci of Cs-137 loaded in each run, the flow rate in column volumes/hr, and the time to load the column. From Appendix 1 of the referenced memo, the integrated dose received by the ion exchange medium is:

$$D_{\text{ose}} = (Dr_{\text{max}}/2T) * t^2,$$

Where T is the total time to load the column, and t is the time after loading started at which the information is desired, and Dr_{mas} is the dose rate to the medium when loading has been

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June 9, 2003
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completed. This may be obtained from table two of the referenced memo as follows: $Dr_{max} = (Dr_{table\ 2}) * (Ci\ loaded) / 4.8$; where 4.8 is the number of Ci loaded in the referenced memo. For example: for the first case: $Dr_{max} = (1.89e4) * (.50) / 4.8$. The time t used for the dose to the column is the time at which loading is completed.

Table 2 gives the results of these calculations. The fifth column, "Dose to resin" gives the resulting dose if each of the 6 runs uses a separate column. If the same resin is used for more than one run, the Cs-137 being eluted from the resin between runs, the total dose to the resin will be additive. This value is given in the sixth column "Total Dose to resin" assuming one column is used for all 6 runs. The doses are given in Roentgens (R).

Table 1

Cs-137 loaded to column during run					15 ml column
run no	Cs-137 uCi/ml	col vol loaded	Ci loaded per run	flow rate cv/hr	Time to load hours
1	175	190	0.50	0.69	275.36
2	175	225	0.59	0.59	381.36
3	175	193	0.51	0.52	371.15
4	175	179	0.47	0.49	365.31
5	175	172	0.45	0.49	351.02
6	175	186	0.49	0.52	357.69

Table 2

run number	Ci added	max dose rate R/hr	run time hours	Dose to Resin in run R	Total Dose to Resin R
1	0.5	1.89E+04	275.36	2.60E+06	2.60E+06
2	0.59	2.22E+04	381.36	4.24E+06	6.84E+06
3	0.51	1.92E+04	371.15	3.57E+06	1.04E+07
4	0.47	1.77E+04	365.31	3.24E+06	1.36E+07
5	0.45	1.70E+04	351.02	2.98E+06	1.66E+07
6	0.49	1.85E+04	357.69	3.30E+06	1.99E+07

c: Saleem Salaymeh 773-41A