The Removal of Technetium-99 from the Effluent Treatment Facility Basin 44 Waste Using Purolite A-530E, Reillex HPQ, and Sybron IONAC SR-7 Ion Exchange Resins

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U.S. Department of Energy Contract DE-AC27-99RL14047

EDT/ECN:	UC:
Cost Center: 7S110	Charge Code: 502074
B&R Code:	Total Pages: 30

Key Words: effluent, treatment, facility, Purolite, Reillex, Sybron

Abstract:
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Release Approval 10/29/04
Date

DATE:
STA: 4
HANFORD RELEASE
ID 2
OCT 29 2004
Release Stamp

Approved For Public Release

RPP-RPT-23199
Revision 0

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October 2004

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Prepared for the U.S. Department of Energy
Office of River Protection

Contract No. DE-AC27-99RL14047

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1. INTRODUCTION

This report documents the laboratory testing and analyses as directed under the test plan, RPP-20407 (Reference 1), and documented in laboratory notebook HNF-274 2. The overall goal of this task was to evaluate and compare candidate anion exchange resins for their capacity to remove ^{99}Tc from Basin 44 Reverse Osmosis (RO) reject stream. The candidate resins evaluated were Purolite[1] A-530E, Reillex[2] HPQ, and Sybron[3] IONAC SR-7. The specific objectives of this task were as follows:

a. Determine the column distribution ratio of the sorbents using the Effluent Treatment Facility (ETF) Basin 44 RO reject stream. Each column system was operated with continuous ^{99}Tc loading, such that breakthrough is measurable and is increasing at a constant rate, through bed saturation if possible.

b. Analytically determine the sorbents' capacity to reduce concentration of ^{99}Tc in the ETF Basin 44 RO reject stream matrix.

It should be noted that the samples delivered to 222-S Laboratory were not taken directly from the RO reject stream, but rather from the secondary waste receiving tank (SWRT). The RO reject stream is one of several secondary streams that this tank receives. As a result, the sample was several orders of magnitude lower in the pertechnetate ion (TcO_4^-) concentration than was expected. Therefore, the samples were spiked with a solution of TcO_4^- to yield a concentration of 3.0 to 3.3 µCi/L.

1.1 BACKGROUND

Technetium-99 is present in LERF Basin 44 liquid feed coming to ETF in the pertechnetate ion (TcO_4^-) form. Technetium-99 is a β-emitting radionuclide (E_{max} = 0.29 MeV) with a half-life of 2.13E05 years and a specific activity of 1.7E-02 Ci/g (References 2 and 3).

From Basin 43 (groundwater), the concentration of technetium in the liquid feed to the ETF is approximately 2000 pCi/L. Concentrations in Basin 44 feeds are roughly 400 times greater at 0.76 µCi/L and the estimated concentration in the future effluent stream from the Waste Treatment and Immobilization Plant (WTP) is 2 µCi/L which is 1000 times greater than Basin 43 feed.

The ETF main treatment train includes filtration, two RO units to remove dissolved solids, and two mixed-bed ion exchange (IX) columns (in series) as a polishing step. The concentrated reject stream from the first RO system, filter backwash, and regeneration solutions from the IX columns are routed to the secondary waste treatment train for pH adjustment, evaporation, and drying to a solid powder waste form.

[1] Purolite is a trademark of The Purolite Company, Bala Cynwyd, Pennsylvania.
[2] Reillex is a trademark of Reilly Industries, Inc., Indianapolis, Indiana.
[3] Sybron is a trademark of Bayer Corporation, Birmingham, New Jersey.

Technetium-99 and other anions are largely rejected in the RO process and are routed to the secondary waste treatment train. Any ^{99}Tc present in the feedwater that permeates the RO membrane is captured by the mixed bed IX column. The RO reject stream becomes feed to the evaporator and is the likely point in the process to implement a TcO_4^- removal step.

Implementation of IX for ^{99}Tc removal is predicated on the fact that the ETF may process liquid feed streams containing elevated ^{99}Tc concentrations that would require stabilization (grouting) of the resulting solid waste powder prior to disposal. If ^{99}Tc could be effectively captured and bound to an anion exchange resin, then a minimization of solid waste volume requiring stabilization would result. This in turn would reduce disposal costs and reduce hazards to workers who are required to stabilize the powdered waste drums.

1.2 RESIN CANDIDATES

The ion exchange media to be evaluated for the removal of pertechnetate include Purolite A-530E, Reillex HPQ, and Sybron IONAC SR-7.

The Purolite and Sybron resins are strong base anion exchangers. The Purolite and the Sybron are composed of a polystyrene copolymer cross-linked with divinylbenzene, which are preferred matrices for ion exchange resins due to their significant loading capacity and stability. Both are macroporous resins, meaning the cross-linkage is at 12% or higher. This degree of cross-linking creates a higher resistance to oxidation and organic fouling. The Purolite A-530E is the commercial production of the Oak Ridge National Laboratory's biquat resin (Reference 4).

The Reillex is a macroporous polyvinylpyridine resin, originally developed by Los Alamos to separate plutonium using a nitrate counter ion (Reference 5).

1.3 IONIC EQUILIBRA

All mobile components of an ion-exchange system can distribute themselves across a two-phase system; however, a true ion-exchange system can be defined as one in which the net transfer of ions from the outside phase to the inside phase results in an equivalent transfer.

When the products of an ion exchange reaction are fully ionized, the reaction normally does not go to completion either to the right or left (for ions of identical charge). Rather, equilibrium is reached in which both ions present in the reaction are found in both phases. An exchange between two ions of identical charge can be represented as

$$A + \boldsymbol{B} \leftrightarrow \boldsymbol{A} + B \qquad (1)$$

(Note the resin-bound ion will be represented as bold italicized.) Ion A from the outside (liquid) phase is displacing ion ***B*** from the resin (solid phase). If the concentrations of the reactants and

the products are expressed as moles per liter C_i, then the concentration mass-action expression for this reaction is

$$K_{AB} = [C_A\, C_B] / [C_A\, C_B] \quad (2)$$

This is not an accurate thermodynamic argument of the system because ion activity terms have been omitted. This omission is because ion activity terms cannot be independently determined for the inside phase and for the outside phase since they are reasonably close to unity for the dilute solutions found in many ion-exchange processes. The selectivity coefficient K_{AB} is not constant for a given exchange. It will vary with the ionic form of resin and with minor variations in polymeric structure from one lot of resin to another. Nonetheless, the mass-action expression is a valuable tool in understanding ion-exchange behavior and in the initial screening of proposed ion-exchange processes.

The K_{AB} term is the molar-selectivity coefficient as indicated in Helfferich (Reference 6). The first letter in the subscript indicates the ion entering the resin phase, and the second letter indicates the ion leaving the resin phase. For all exchanges between ions of identical valence, the mass-action expression is given by equation (2). To apply this relationship, K_{AB} is considered constant for a given pair of ions exchanging on a given resin over a wide range of solution conditions.

The consequences of mass-action behavior become clearer if the relationship is shown as a function of equivalent fractions for both phases. For example, if the total ionic concentration (normality) of the solution phase is C, eq/L, the equivalent fraction, x_i of an ion of valence z_i present at concentration C_i, is given by

$$x_i = [z_i\, C_i] / C \quad (3)$$

Concentrations in the resin phase are expressed in the same units as volume exchange capacity, equivalents per liter of bulk volume. If the total exchange capacity of the resin is R, the equivalent fraction y_i, of valence z_i, present in the resin phase at a concentration of C_i, is given by

$$y_i = [z_i\, C_i] / R \quad (4)$$

Substituting the values from equation (3) and (4) into equation (2), the expression becomes

$$K_{AB} = [y_A\, x_B] / [y_B\, x_A] \quad (5)$$

Now, since only two counter ions are present in each phase

$$y_A + y_B = 1 \quad (6)$$

and

$$x_A + x_B = 1 \quad (7)$$

equation (5) becomes

$$y_A / (1 - y_A) = K_{AB} [x_A / 1 - x_A] \quad (8)$$

Equation (8) indicates the fraction of the resin capacity occupied by a given ion at equilibrium and is dependent on the fraction of the total ions in solution, which are represented by the ion and a selectivity coefficient. The total-concentration terms C and R do not appear in equation (8). This indicates the distribution of ions between phases will not be directly dependent on total resin or solution concentrations. Secondary effects on relative ionic ratios may occur due to changing ionic activities (Reference 7).

2. MATERIALS AND METHODS

2.1 MATERIALS

Approximately 454 g of each commercial resin was procured from the respective resin manufacturer. The supplied resins were in the chloride form and ready to use without preparation.

All ion exchange hardware was purchased from Kontes,[4] including the ion exchange columns (1 x 15 cm), flow controllers, column tubing, and valves. The Masterflex[5] pumps and tubing were purchased from Cole-Palmer.

The influent waste sample to the ion exchange resin was received from the ETF. The ETF retrieved the sample during a Liquid Effluent Retention Basin (LERF) 44 campaign. For testing purposes, the sample was requested from the RO reject stream; however, the sample material that was provided to 222-S Laboratory came from the SWRT and therefore was diluted with other secondary waste streams within the ETF. The dilution required the use of a pertechnetate spike, procured from the Pacific Northwest National Laboratory. The spike allowed the pertechnetate concentration in the sample to be increased from approximately 3.4E-03 µCi/L to approximately 3.3 µCi/L.

2.2 METHODS

2.2.1 Chemical and Radiological Analyses

a. Chemical analyses for metals were conducted using inductively coupled plasma with a Thermal Jerral Ash model 61E. Analyses for anions were conducted on a Dionex[6] model AS14A, using SW-846 methods (Reference 8).

[4] Kontes is a registered trademark of Kontes Glass Company Corporation, Vineland, New Jersey.
[5] Masterflex is a registered trademark of Cole-Palmer Instrument Company Corporation, Chicago, Illinois.
[6] Dionex is a registered trademark of Dionex Corporation, Sunnyvale, California.

a. Radiological analyses for ^{99}Tc were carried out using a Thermo Electron[7] inductively coupled plasma mass spectrometer, which is a more sensitive method than scintillation counting. The inductively coupled plasma mass spectrometer has a detection limit of 3E-06 μg/mL. The gamma energy scan was carried out using a Canberra[8] Genie.

2.2.2 Column Preparation

a. Each resin was rinsed using an upflow configuration to remove any fines present that might plug the column. The hydrated resin was then slurried into respective individual columns. The resin was then classified within each column by achieving 100% bed expansion and then allowing the resin bed to settle. Vendor-recommended flow rates (Table 1) and flow rates for a 3-mL bed volume (BV) is shown in Table 1.

Table 1. Vendor Recommended Flow Rates.

Resin	Recommended Flow	Lab Scale Flow @ 3 mL Bed Volume
Purolite A-530E	25 BV/hour	1.25 mL/minute
Sybron IONAC SR-7	20 BV/ hour	1 mL/minute
Reillex HPQ	0.37 mL/minute · cm^{-3}	1.11 mL/minute

The test resin columns were operated in a down flow configuration. Each column had a dedicated Masterflex[9] peristaltic pump due to the difference in recommended flow rates. Prior to testing, a pump curve was obtained for each pump (Figure 1). These pumps were carefully numbered and later assigned to a resin column with that same number.

b. A 24-hour distribution coefficient (Kd) was obtained from a carboy composite sample for each resin. Additionally, ETF requested that a Pacific Northwest National Laboratory experimental formulation of self-assembling monomolecular layers (SAMMs) be evaluated along with each of the candidate resins. Dry weights were determined for each resin. The distribution coefficients were reported on a dry weight basis.

c. The pumps, tubing, and columns containing each resin were leak tested in the 222-Standards Laboratory then transported to Hood 1, room 1-G-A in the contamination area of the 222-S Laboratory. Figure 2 is a schematic of the test column configuration. The flow rates were confirmed before each effluent sample was taken.

[7] Thermal Elemental is a registered trademark of Thermo Electron Corporation, Waltham, Massachusetts.
[8] Canberra is a registered trademark of Societe des Participations du Commissariat A l'Energie Atomique, Paris, France.
[9] Masterflex is a registered trademark of the Cole-Palmer Instrument Company, Chicago, Illinois.

Figure 1. Pump Curves for Masterflex Peristaltic Pumps.

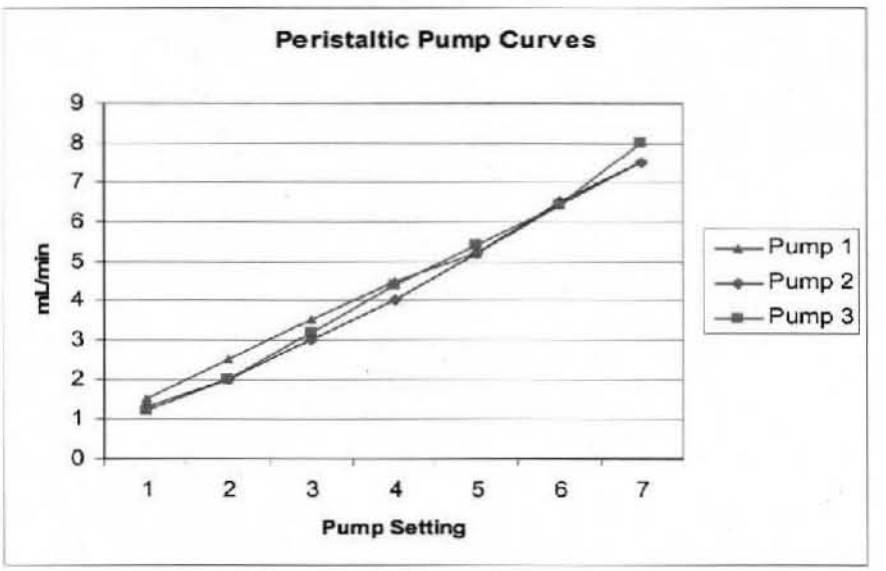
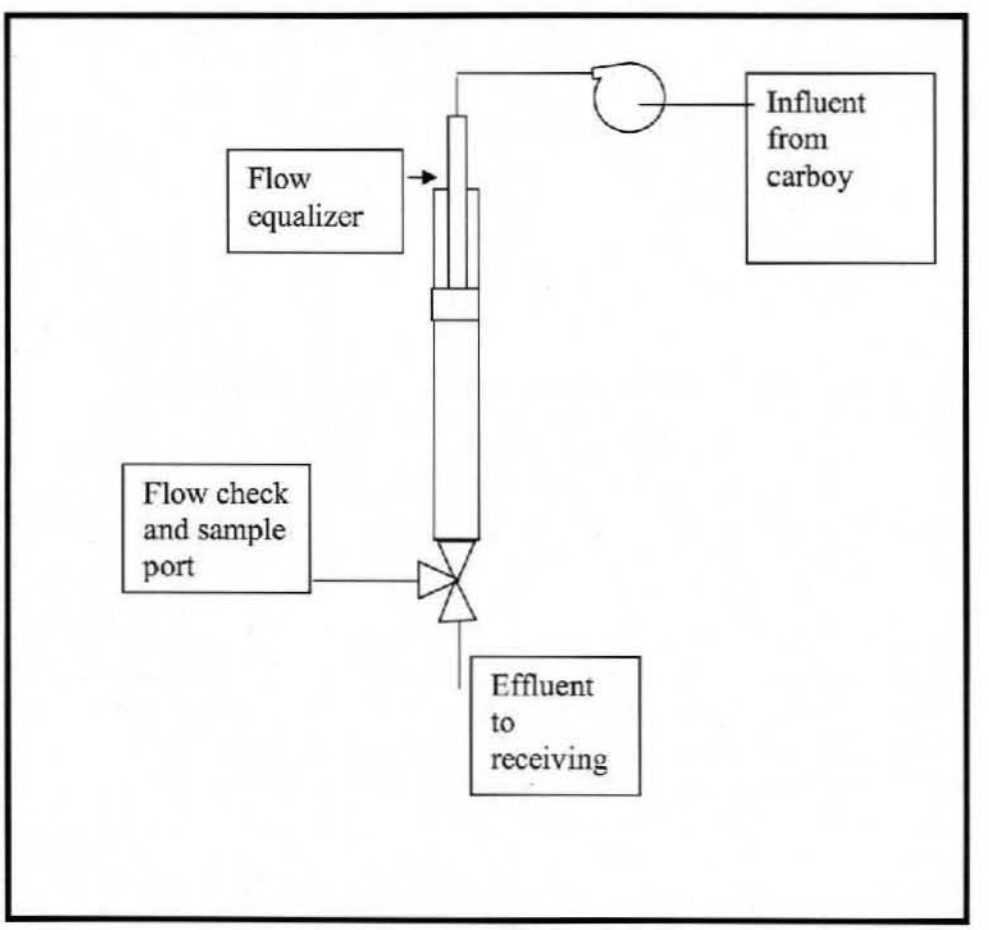


Figure 2. Ion Exchange Column.



3. RESULTS AND DISCUSSION

3.1 RESULTS

The as-received carboys were composited at 222-S Laboratory after thoroughly mixing. A 100-mL aliquot was retrieved from the composite sample to use for determining the Kd for each resin. Additionally, 25 mL of this composite sample was submitted for ion chromatography (IC), inductively coupled plasma spectroscopy (ICP), and inductively coupled plasma-mass spectroscopy (ICP-MS) analysis (Appendix A).

The distribution coefficient provides information regarding the loading and selectivity of the resin for the ions of interest. The Kd is mathematically defined (Reference 6):

$$Kd = [\text{Concentration in solid phase}] / [\text{Concentration in liquid phase}] \quad (9)$$

The distribution coefficients for each of the resins, including the SAMMs material are shown in Table 2. Appendix B contains chemical composition data before and after resin introduction. Appendix C contains chemical composition data before and after SAMMs introduction.

Table 2. Distribution Coefficients (Kds).

Sorbent	Distribution Coefficient (mL/g)
Purolite A-530E	49,879
Sybron IONAC SR-7	216,603
Reillex HPQ[a]	42,483
PNNL SAMMs	863

[a] The Reillex was taken out of the study due to column plugging and ALARA concerns in Hood 1, room 1-G-A; subsequently the Kd and some column work are the only values reported.

Based on the analyses performed at the end of the 24-hour Kd run, it was observed that the resins also sorbed the competing anions nitrate and uranium. Therefore, selectivity coefficients were determined for the technetium, nitrate, and uranium. Sulfate was not among the competing anions in this matrix. The mathematical form of the selectivity coefficient is defined as Reference 9:

$$K_A^B = [C_B]_r [C_A]_s / [C_A]_r [C_B]_s \quad (10)$$

here

$[C_B]_r$ = molar concentration of ion B in the resin
$[C_A]_s$ = molar concentration of ion A in the bulk solution
$[C_A]_r$ = molar concentration of ion A in the resin
$[C_B]_s$ = molar concentration of ion B in the bulk solution

Uranium in aqueous solutions around neutral pH levels exists in the carbonate form, such as liebigite, sodium uranyl carbonate, and rutherfordine. Speciation of uranium was beyond the scope of this task and was not carried out. The selectivity coefficient was calculated based solely on uranium concentration. Table 3 provides the calculated selectivity coefficients.

Table 3. Selectivity Coefficients.

Sorbent	Selectivity Coefficient		
	Technetium	Nitrate	Uranium
Purolite A-530E	360	3	>1[a]
Sybron IONAC SR-7	1169	2	1

[a] Reported below detection limit.

Once the resin columns were placed in Hood 1, forward flow began and sampling for technetium in the effluent stream was performed. Sampling was performed at approximately 24-hour intervals. During the course of the run, the Reillex HPQ resin began experiencing plugging after only a few effluent samples had been taken. The plugging was determined to be due to the physical properties of the resin. The plugging caused overflow through the column's flow controller, and since this was a radioactive material, the column was taken out of operation for as low as reasonably achievable (ALARA) and other safety reasons.

After 19 days (10,730 BV) the Purolite column was terminated due to the effluent line plugging from algae growth. Because of time constraints, the study was terminated when the Sybron column attained 24 days of run time (13,738 BV).

During the course of the study, it was noticed that all resins achieved a brown coloration much different from the white color of the as-received resin. An example is shown in Figure 3. At the end of the run, both the Purolite and the Sybron resins were completely discolored to a deep brown.

On examination with an RO-3B instrument, the Purolite and Sybron columns developed readings of 11 mrem/hour. Technetium-99 is a very weak beta emitter (0.29 MeV beta maximum) so the glass column would be a sufficient barrier to isotopic energy. A candidate radioisotope was likely ^{90}Y (2.2 MeV beta, maximum). After the Purolite column was left to stand for 1 week, the radiation reading had dropped to ~1 mrem/hour. Because of the energy recorded by instrumentation, the rather fast decay (^{90}Y has a 64-hour half-life), ^{90}Y was identified as the likely radioisotope. Meanwhile, the functioning Sybron column continued to maintain a reading of 11 mrem/hour. At the end of the column runs, resin samples were submitted for a gamma energy analysis (GEA) to identify the presence of gamma-emitting isotopes.

Figure 4 shows the breakthrough response of each resin for technetium removal. The graph is normalized to the X-axis (Appendix D gives the data associated with Figure 4).

Figures 5 and 6 provide the results of the GEA scan. It is important to note the Bremsstrahlung effect at the lower energy levels. The Bremsstrahlung emanates from the deep beta interacting with materials of construction in the sample container and emitting photons. The ^{137}Cs peak is at

662 KeV and the K-40 peak is at 1460.5 KeV. The ^{137}Cs is not of sufficient quantity for concern, and is in fact lower than the background K-40, which is naturally occurring. However, the hard beta evidenced by the Bremsstrahlung is of concern for in-plant shielding. MicroShield is a computer program used to determine dose rate and shielding requirements that uses the input of gamma energies only. Since the energies derived from the GEA scans were below any usable levels, a Microshield calculation could not be performed.

Figure 3. Photo of the Ion Exchange Resin Beginning to Darken.

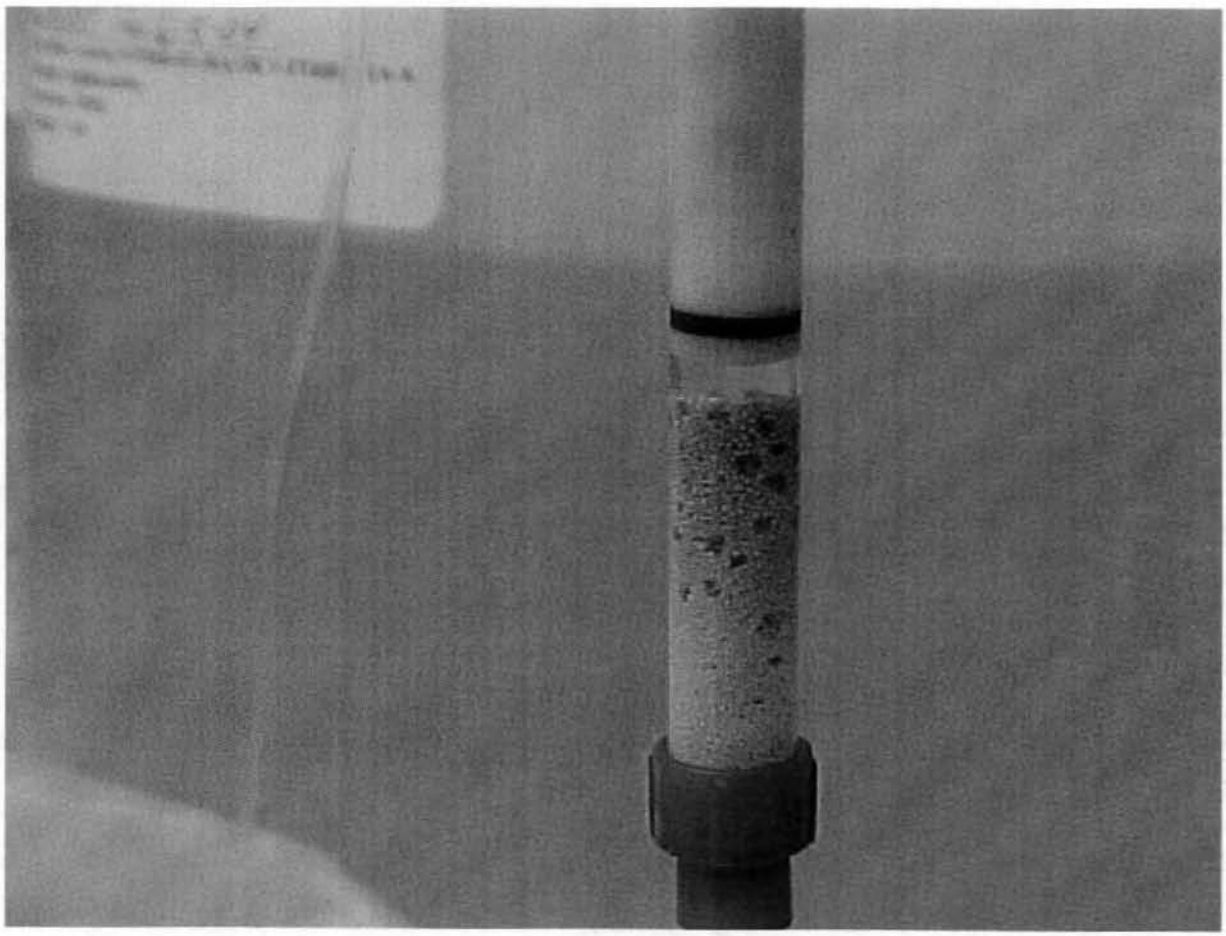
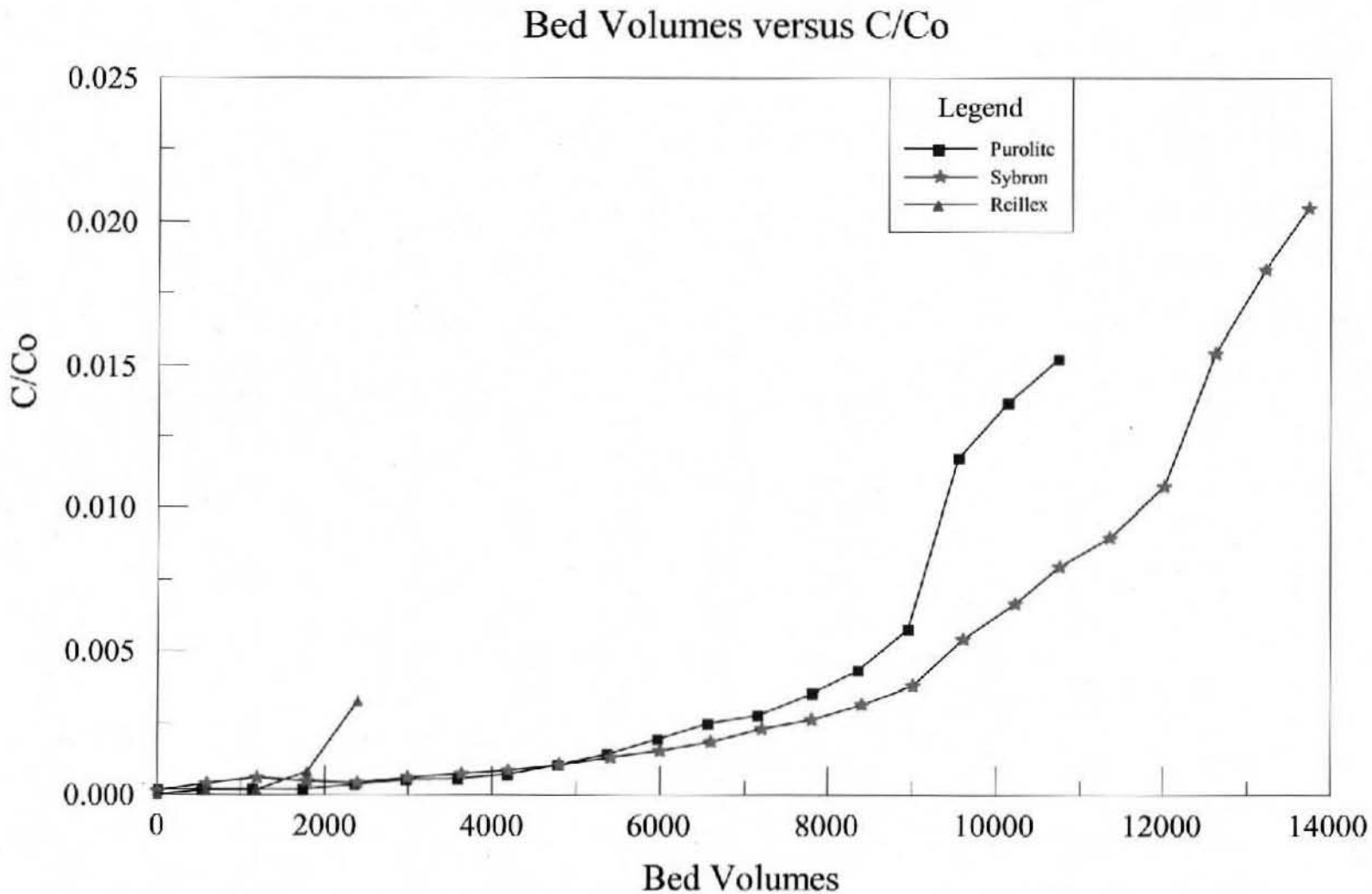


Figure 4. Response of Purolite A-530E, Sybron IONAC SR-7, and Reillex HPQ to Technetium-99 in Effluent Treatment Facility Basin 44 Matrix.



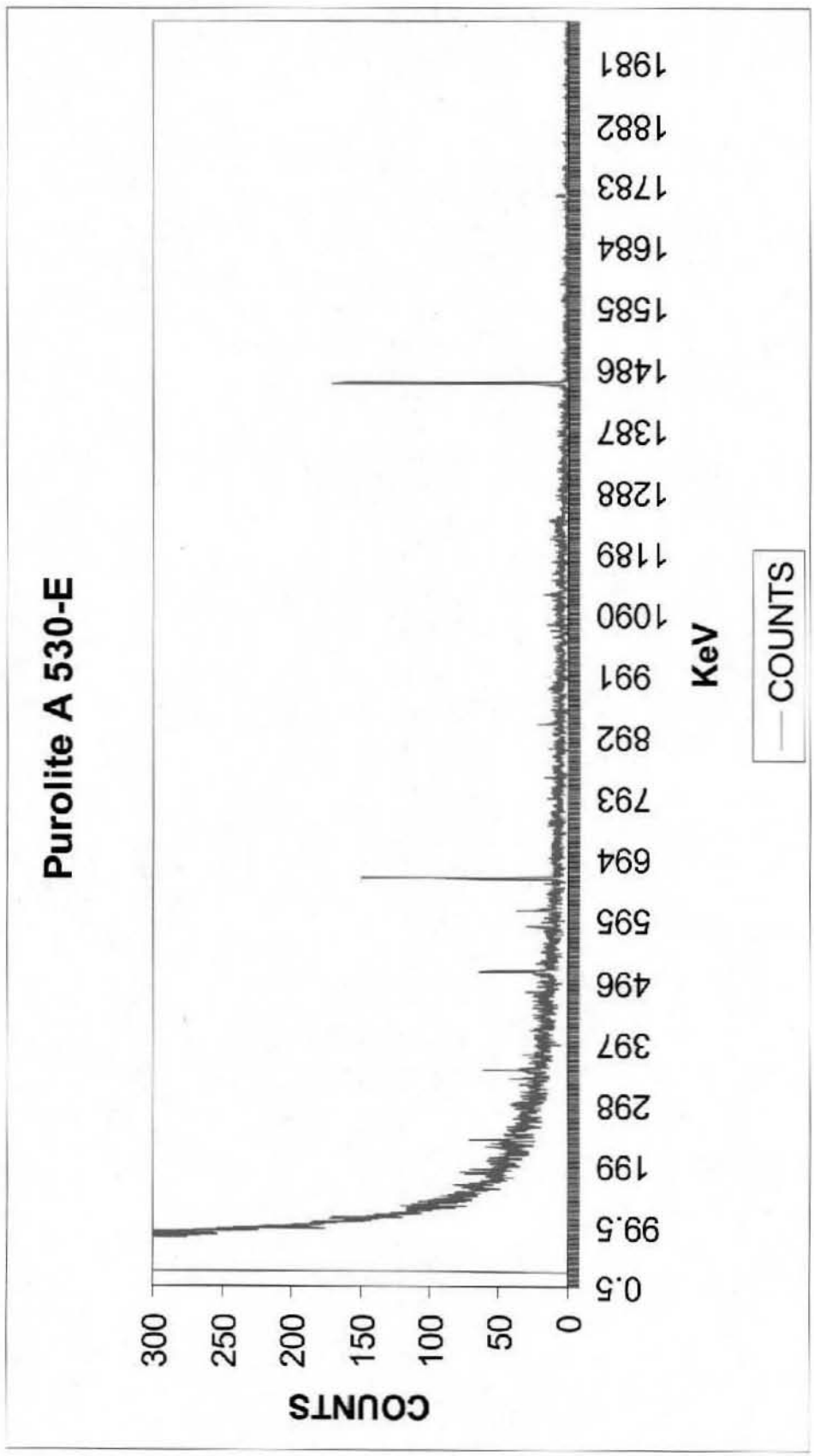


Figure 5. Gamma Energy Analysis of Purolite A-530E; Notice the Bremsstrahlung at Lower Energy Levels.

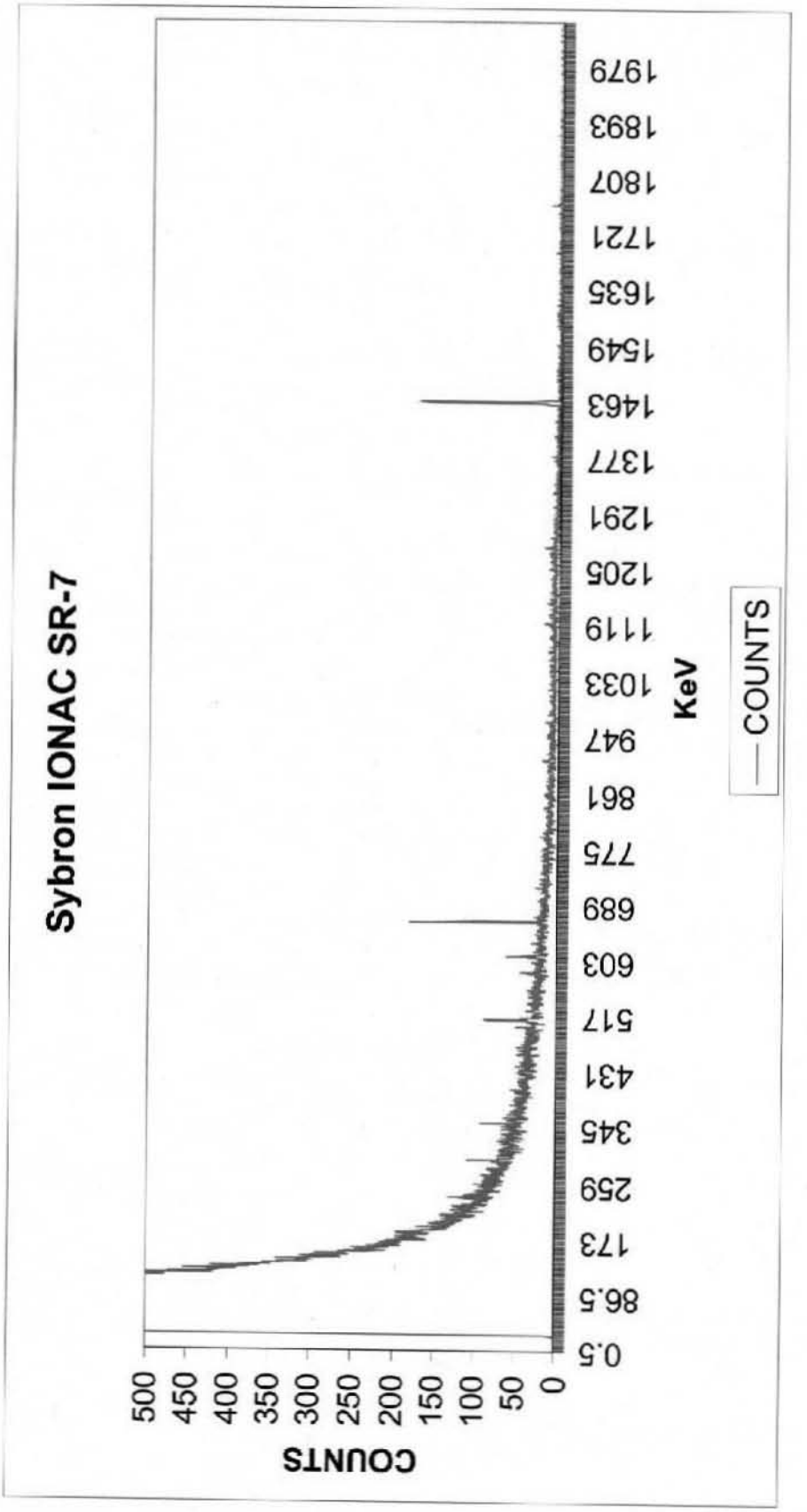


Figure 6. Gamma Energy Analysis of Sybron IONAC SR-7; Notice the Bremsstrahlung at Lower Energy Levels.

3.2 DISCUSSION

3.2.1 Resin Selection

Based on the resins and waste matrix tested, the Sybron IONAC SR-7 is likely the best candidate. Although the Purolite A-530E did exhibit a very high Kd for this waste matrix, the Sybron IONAC SR-7 Kd was much higher (approximately 4X). This may possibly be attributed to activation coefficients within the resin, as described in Section 1.3.

With respect to the radiological properties of the test matrix, it was observed that the resin turned brown, which indicated that radioactivity was present in more than a transient manner, most likely within the resin itself. Although outside the scope of this study, it appears that ^{90}Y became captured within the resin, either by physisorption or chemisorption. Bremsstrahlung effects resulting from a hard beta emitter should be considered when selecting the materials of construction for the IX column. To prevent this effect, a resin column consisting of thick high-density polyethylene, thick fiberglass, a water jacket, etc., should provide sufficient shielding.

3.2.2 Conceptual Design Options

The resin volume/column size required for the process can be estimated using the following laboratory data, vendor information, and simple assumptions:

a. The ^{99}Tc concentration is approximately 3 μCi/L.
b. The Sybron Kd value of 216,603 mL/gram resin will be applied.
c. Based on vendor information, the flow rate through the column will be 20 BV/hour.
d. The volume of resin per 1E06 gallons waste processed through column.
e. Process flow of 20 gpm (1200 gph) = 60 gal/BV.
f. Resin density of Sybron 1.02 g/cc
g. The ion exchange column will be taken off-line at a C/Co = 0.02.

From the laboratory data, 41.215 L of waste was processed through a 3-mL (BV) column, resulting in a C/Co of 0.02. Scaling proportionally, the column BV of 9.78 ft^3 (277 L) would be required to treat a process waste volume of 1 million gallons, (3,785,000 L). Therefore, it is recommended that a lead and lag column containing 10 ft^3 each of resin be used. For the WTP waste matrix it is recommended that a Kd and column breakthrough curve be determined to confirm correct column volume.

According to cost information provided by the Klenzoid Equipment Company to the ETF personnel, the Sybron resin was quoted at \$195.00/ft^3.

A potential process control recommendation is that the ETF determine a Kd on a batch-by-batch basis and then sample the effluent for technetium (ICP-MS analyses) at set time intervals based on the Kd value, technetium influent concentration, and mass of resin in the column. Unless an

on-line or at-line method with adequate sensitivity is available, this would be the most efficient process control methodology.

The use of a high-integrity container (HIC) such as the NUHIC[10]-55 from RWE NUKEM (or other Hanford approved HIC) is recommended to be designed to accommodate resin dewatering and disposal. The volume capacity of the NUHIC-55 is 14.8 ft^3, which will easily accommodate the recommended 10 ft^3 of resin. The U.S. Department of Energy has approved these containers for disposal of depleted resin at the Hanford Site. The HIC units are fabricated using a high-density, cross-linked polyethylene matrix. This matrix offers strength, durability, radiation resistance, and chemical resistance for storage or disposal life in excess of 300 years.

[10] NUHIC is a registered trademark of NUKEM GMBH Corporation Germany 6, Rodenbacher Chaussee 6 Hanau Germany D-6450

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APPENDIX A

Chemical Analyses

Chemical Analyses

Analyte	Unit	Result
pH Direct	pH	7.39
^{99}Tc by ICP-MS Acid Addition	µg/mL	0.205
Silver-ICP-Acid Dilution	µg/mL	<0.0250
Aluminum-ICP-Acid Dilution	µg/mL	<0.400
Arsenic-ICP-Acid Dilution	µg/mL	<0.200
Boron-ICP-Acid Dilution	µg/mL	8.25
Barium-ICP-Acid Dilution	µg/mL	0.144
Beryllium-ICP-Acid Dilution	µg/mL	<0.0200
Bismuth-ICP-Acid Dilution.	µg/mL	<0.300
Calcium-ICP-Acid Dilution	µg/mL	349
Cadmium-ICP-Acid Dilution	µg/mL	<0.0200
Cerium-ICP-Acid Dilution	µg/mL	<0.125
Cobalt-ICP-Acid Dilution	µg/mL	<0.0300
Chromium-ICP-Acid Dilution	µg/mL	0.0206
Copper-ICP-Acid Dilution	µg/mL	0.0296
Europium ICP-Acid Dilution	µg/mL	<0.0750
Iron-ICP-Acid Dilution	µg/mL	0.0147
Potassium-ICP-Acid Dilution	µg/mL	260
Lanthanum-ICP-Acid Dilution	µg/mL	<0.0175
Lithium-ICP-Acid Dilution	µg/mL	0.394
Magnesium-ICP-Acid Dilution	µg/mL	74.4
Manganese-ICP-Acid Dilution	µg/mL	<0.0250
Molybdenum-ICP-Acid Dilution	µg/mL	<0.0400
Sodium-ICP-Acid Dilution	µg/mL	505
Neodymium-ICP-Acid Dilution	µg/mL	<0.0500
Nickel-ICP-Acid Dilution	µg/mL	<0.100
Niobium -ICP-Acid Digest	µg/mL	<0.125
Phosphorus-ICP-Acid Dilution	µg/mL	0.545
Lead-ICP-Acid Dilution	µg/mL	<0.150
Palladium -ICP-Acid Dilution	µg/mL	<0.400
Praseodymium-ICP Acid Dilution	µg/mL	<0.100
Rubidium-ICP-Acid Dilution	µg/mL	<10.0
Rhodium -ICP-Acid Dilution	µg/mL	<0.500
Ruthenium ICP-Acid Dilution	µg/mL	<0.250
Sulfur-ICP-Acid Dilution	µg/mL	503
Antimony-ICP-Acid Dilution	µg/mL	<0.125
Selenium-ICP-Acid Dilution	µg/mL	<0.200
Silicon-ICP-Acid Dilution	µg/mL	33.9
Samarium-ICP-Acid Dilution	µg/mL	<0.0750
Tin -ICP-Acid Dilution	µg/mL	<0.100
Strontium-ICP-Acid Dilution	µg/mL	1.42

Analyte	Unit	Result
Tantalum -ICP-Acid Dilution	µg/mL	<0.100
Tellurium-ICP-Acid Dilution	µg/mL	<0.250
Thorium -ICP-Acid Dilution	µg/mL	<0.125
Titanium-ICP-Acid Dilution	µg/mL	<0.0100
Thallium-ICP-Acid Dilution	µg/mL	<0.500
Uranium-ICP-Acid Dilution	µg/mL	0.802
Vanadium-ICP-Acid Dilution	µg/mL	<0.0250
Tungsten -ICP-Acid Dilution	µg/mL	<0.250
Yttrium -ICP-Acid Dilution	µg/mL	<5.00E-03
Zinc-ICP-Acid Dilution	µg/mL	0.0606
Zirconium-ICP-Acid Dilution	µg/mL	<0.0250
Fluoride IC SW-846	µg/mL	<1.21
Chloride SW-846	µg/mL	549
Nitrite IC SW-846	µg/mL	<10.9
Bromide by IC SW-846	µg/mL	<12.6
Nitrate by IC SW-846	µg/mL	216
Phosphate by IC SW-846	µg/mL	<12.1
Sulfate by IC SW-846	µg/mL	1.46E+03
Oxalate by IC SW-846	µg/mL	<10.6

APPENDIX B

Distribution Coefficient Data

Distribution Coefficient Data

Carboy Composite Analyses Before Resin			Reillex Result	Sybron Result	Purolite Result
Analyte	Unit	Result			
pH Direct	pH	7.39	7.61	ND	ND
^{99}Tc by ICP/MS Acid Addition	µg/mL	0.205	4.85E-04	1.19E-04	6.73E-04
Silver-ICP-Acid Dilution	µg/mL	<0.0250	<0.0250	<0.0250	0.0264
Aluminium-ICP-Acid Dilution	µg/mL	<0.400	<0.400	<0.400	<0.400
Arsenic-ICP-Acid Dilution	µg/mL	<0.200	<0.200	<0.200	0.215
Boron-ICP-Acid Dilution	µg/mL	8.25	7.97	7.98	7.81
Barium-ICP-Acid Dilution	µg/mL	0.144	0.146	0.226	0.195
Beryllium-ICP-Acid Dilution	µg/mL	<0.0200	<0.0200	<0.0200	<0.0200
Bismuth-ICP-Acid Dilution	µg/mL	<0.300	<0.300	<0.300	<0.300
Calcium-ICP-Acid Dilution	µg/mL	349	348	349	349
Cadmium-ICP-Acid Dilution	µg/mL	<0.0200	<0.0200	<0.0200	<0.0200
Cerium-ICP-Acid Dilution	µg/mL	<0.125	<0.125	<0.125	<0.125
Cobalt-ICP-Acid Dilution	µg/mL	<0.0300	<0.0300	<0.0300	<0.0300
Chromium-ICP-Acid Dilution	µg/mL	0.0206	<0.0125	<0.0125	<0.0125
Copper-ICP-Acid Dilution	µg/mL	0.0296	0.0238	0.026	0.0187
Europium ICP-Acid Dilution	µg/mL	<0.0750	<0.0750	<0.0750	<0.0750
Iron-ICP-Acid Dilution	µg/mL	0.0147	<0.0125	<0.0125	0.0154
Potassium-ICP-Acid Dilution	µg/mL	260	261	260	260
Lanthanum-ICP-Acid Dilution	µg/mL	<0.0175	<0.0175	<0.0175	<0.0175
Lithium-ICP-Acid Dilution	µg/mL	0.394	0.401	0.396	0.393
Magnesium-ICP-Acid Dilution	µg/mL	74.4	75.1	75.2	75.1
Manganese-ICP-Acid Dilution	µg/mL	<0.0250	<0.0250	<0.0250	<0.0250
Molybdenum-ICP-Acid Dilution	µg/mL	<0.0400	<0.0400	<0.0400	<0.0400
Sodium-ICP-Acid Dilution	µg/mL	505	507	510	508
Neodymium-ICP-Acid Dilution	µg/mL	<0.0500	<0.0500	<0.0500	<0.0500
Nickel-ICP-Acid Dilution	µg/mL	<0.100	<0.100	<0.100	<0.100
Niobium -ICP-Acid Digest	µg/mL	<0.125	<0.125	<0.125	<0.125
Phosphorus-ICP-Acid Dilution	µg/mL	0.545	0.609	0.548	0.546
Lead-ICP-Acid Dilution	µg/mL	<0.150	<0.150	<0.150	<0.150
Palladium -ICP-Acid Dilution	µg/mL	<0.400	<0.400	<0.400	<0.400
Praseodymium-ICP Acid Dilution	µg/mL	<0.100	<0.100	<0.100	<0.100
Rubidium-ICP-Acid Dilution	µg/mL	<10.0	<10.0	<10.0	<10.0
Rhodium -ICP-Acid Dilution	µg/mL	<0.500	<0.500	<0.500	<0.500
Ruthenium ICP-Acid Dilution	µg/mL	<0.250	<0.250	<0.250	<0.250
Sulfur-ICP-Acid Dilution	µg/mL	503	381	528	450
Antimony-ICP-Acid Dilution	µg/mL	<0.125	<0.125	<0.125	<0.125
Selenium-ICP-Acid Dilution	µg/mL	<0.200	<0.200	<0.200	<0.200
Silicon-ICP-Acid Dilution	µg/mL	33.9	33.7	32.8	32.5
Samarium-ICP-Acid Dilution	µg/mL	<0.0750	<0.0750	<0.0750	<0.0750
Tin -ICP-Acid Dilution	µg/mL	<0.100	<0.100	<0.100	<0.100
Strontium-ICP-Acid Dilution	µg/mL	1.42	1.42	1.44	1.42
Tantalum -ICP-Acid Dilution	µg/mL	<0.100	<0.100	<0.100	<0.100
Tellurium-ICP-Acid Dilution	µg/mL	<0.250	<0.250	<0.250	0.262
Thorium -ICP-Acid Dilution	µg/mL	<0.125	<0.125	<0.125	<0.125

Carboy Composite Analyses Before Resin			Reillex Result	Sybron Result	Purolite Result
Analyte	Unit	Result			
Titanium-ICP-Acid Dilution	µg/mL	<0.0100	<0.0100	<0.0100	<0.0100
Thallium-ICP-Acid Dilution	µg/mL	<0.500	<0.500	<0.500	<0.500
Uranium-ICP-Acid Dilution	µg/mL	0.802	<0.275	0.649	<0.275
Vanadium-ICP-Acid Dilution	µg/mL	<0.0250	<0.0250	<0.0250	<0.0250
Tungsten -ICP-Acid Dilution	µg/mL	<0.250	<0.250	<0.250	<0.250
Yttrium -ICP-Acid Dilution	µg/mL	<5.00E-03	<5.00E-03	<5.00e-03	<5.00e-03
Zinc-ICP-Acid Dilution	µg/mL	0.0606	0.0332	<0.0250	0.0541
Zirconium-ICP-Acid Dilution	µg/mL	<0.0250	<0.0250	<0.0250	<0.0250
Fluoride IC SW-846	µg/mL	<1.21	<1.21	<1.21	<1.21
Chloride SW-846	µg/mL	549	925	581	783
Nitrite IC SW-846	µg/mL	<10.9	<10.9	<10.9	<10.9
Bromide by IC SW-846	µg/mL	<12.6	<12.6	<12.6	<12.6
Nitrate by IC SW-846	µg/mL	216	66.4	51.6	62.4
Phosphate by IC SW-846	µg/mL	<12.1	<12.1	<12.1	<12.1
Sulfate by IC SW-846	µg/mL	1.46E+03	1.08E+03	1.53E+03	1.28E+03
Oxalate by IC SW-846	µg/mL	<10.6	<10.6	<10.6	<10.6

APPENDIX C

Self-Assembling Monomolecular Distribution Coefficient Data

Self-Assembling Monomolecular Distribution Coefficient Data

Analyses Before SAMMs Introduction			After SAMMs Result
Analyte	Unit	Result	
pH Direct	pH	7.59	7.52
^{99}Tc by ICP-MS Acid Addition	µg/mL	0.196	0.0203
Silver-ICP-Acid Dilution	µg/mL	<0.0250	<0.0250
Aluminium-ICP-Acid Dilution	µg/mL	<0.400	<0.400
Arsenic-ICP-Acid Dilution	µg/mL	<0.200	<0.200
Boron-ICP-Acid Dilution	µg/mL	8.03	7.34
Barium-ICP-Acid Dilution	µg/mL	0.147	0.153
Beryllium-ICP-Acid Dilution	µg/mL	<0.0200	<0.0200
Bismuth-ICP-Acid Dilution	µg/mL	<0.300	<0.300
Calcium-ICP-Acid Dilution	µg/mL	347	342
Cadmium-ICP-Acid Dilution	µg/mL	<0.0200	<0.0200
Cerium-ICP-Acid Dilution	µg/mL	<0.125	<0.125
Cobalt-ICP-Acid Dilution	µg/mL	<0.0300	<0.0300
Chromium-ICP-Acid Dilution	µg/mL	0.0126	<0.0125
Copper-ICP-Acid Dilution	µg/mL	0.0275	1.88
Europium ICP-Acid Dilution	µg/mL	<0.0750	<0.0750
Iron-ICP-Acid Dilution	µg/mL	0.0241	<0.0125
Potassium-ICP-Acid Dilution	µg/mL	263	260
Lanthanum-ICP-Acid Dilution	µg/mL	<0.0175	<0.0175
Lithium-ICP-Acid Dilution	µg/mL	0.403	0.405
Magnesium-ICP-Acid Dilution	µg/mL	75.2	73.5
Manganese-ICP-Acid Dilution	µg/mL	<0.0250	<0.0250
Molybdenum-ICP-Acid Dilution	µg/mL	<0.0400	<0.0400
Sodium-ICP-Acid Dilution	µg/mL	509	505
Neodymium-ICP-Acid Dilution	µg/mL	<0.0500	<0.0500
Nickel-ICP-Acid Dilution	µg/mL	<0.100	<0.100
Niobium -ICP-Acid Digest	µg/mL	<0.125	<0.125
Phosphorus-ICP-Acid Dilution	µg/mL	0.78	0.469
Lead-ICP-Acid Dilution	µg/mL	<0.150	<0.150
Palladium -ICP-Acid Dilution	µg/mL	<0.400	<0.400
Praseodymium-ICP Acid Dilution	µg/mL	<0.100	<0.100
Rubidium-ICP-Acid Dilution	µg/mL	<10.0	<10.0
Rhodium -ICP-Acid Dilution	µg/mL	<0.500	<0.500
Ruthenium ICP-Acid Dilution	µg/mL	<0.250	<0.250
Sulfur-ICP-Acid Dilution	µg/mL	508	360
Antimony-ICP-Acid Dilution	µg/mL	<0.125	<0.125
Selenium-ICP-Acid Dilution	µg/mL	<0.200	<0.200
Silicon-ICP-Acid Dilution	µg/mL	33.2	35.4
Samarium-ICP-Acid Dilution	µg/mL	<0.0750	<0.0750
Tin -ICP-Acid Dilution	µg/mL	<0.100	<0.100
Strontium-ICP-Acid Dilution	µg/mL	1.42	1.44
Tantalum -ICP-Acid Dilution	µg/mL	<0.100	<0.100
Tellurium-ICP-Acid Dilution	µg/mL	<0.250	<0.250

Analyses Before SAMMs Introduction			After SAMMs Result
Analyte	Unit	Result	
Thorium -ICP-Acid Dilution	µg/mL	<0.125	<0.125
Titanium-ICP-Acid Dilution	µg/mL	<0.0100	<0.0100
Thallium-ICP-Acid Dilution	µg/mL	<0.500	<0.500
Uranium-ICP-Acid Dilution	µg/mL	0.963	0.403
Vanadium-ICP-Acid Dilution	µg/mL	<0.0250	<0.0250
Tungsten -ICP-Acid Dilution	µg/mL	<0.250	<0.250
Yttrium -ICP-Acid Dilution	µg/mL	<5.00e-03	<5.00e-03
Zinc-ICP-Acid Dilution	µg/mL	0.0563	<0.0250
Zirconium-ICP-Acid Dilution	µg/mL	<0.0250	<0.0250
Fluoride IC SW-846	µg/mL	<1.21	<1.21
Chloride SW-846	µg/mL	560	899
Nitrite IC SW-846	µg/mL	<10.9	<10.9
Bromide by IC SW-846	µg/mL	<12.6	<12.6
Nitrate by IC SW-846	µg/mL	215	165
Phosphate by IC SW-846	µg/mL	<12.1	<12.1
Sulfate by IC SW-846	µg/mL	1.45E+03	1.02E+03
Oxalate by IC SW-846	µg/mL	<10.6	<10.6

APPENDIX D

Resin Response to Challenge

Resin Response to Challenge

Bed Volume	C/Co
Purolite A-530E	
7	1.68E-04
544	2.10E-04
1,144	2.07E-04
1,744	2.12E-04
2,357	3.84E-04
2,965	5.61E-04
3,581	5.82E-04
4,180	7.36E-04
4,779	1.06E-03
5,365	1.45E-03
5,964	1.96E-03
6,557	2.52E-03
7,156	2.81E-03
7,802	3.55E-03
8,349	4.33E-03
8,949	5.79E-03
9,546	1.18E-02
10,134	1.37E-02
10,730	0.015212
Sybron IONAC SR-7	
4	1.57E-04
593	4.05E-04
1,193	6.11E-04
1,795	5.01E-04
2,390	4.26E-04
2,985	6.10E-04
3,638	7.48E-04
4,192	8.57E-04
4,801	1.06E-03
5,403	1.34E-03
5,998	1.57E-03
6,600	1.88E-03
7,210	2.33E-03
7,806	2.67E-03
8,406	3.18E-03
9,006	3.82E-03
9,610	5.44E-03
10,224	6.67E-03
10,748	7.98E-03
11,354	8.99E-03
12,003	1.08E-02
12,610	1.54E-02
13,211	1.83E-02
13,738	2.05E-02
Reillex HPQ	
0	0.000000
588	0.000160
1,187	0.000182
1,790	0.000807
2,392	0.003300