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Demonstration of Strontium Removal from Hanford N-Area Well Water

C. D. Carlson
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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

As part of the Efficient Separations and Processing Crosscutting Program, the Pacific Northwest National Laboratory^(a) conducted this study to demonstrate the efficiency of several ion-exchange materials in removing strontium-90 from actual groundwater from the Hanford N-Springs Pump and Treat Demonstration Facility. The objective of this experiment was to determine the strontium-loading distribution coefficients (Kds) for some titanate ion-exchange materials, modified minerals, and organic ion-exchange resins

The equilibrium uptake data presented in this report are useful for identifying potential materials that are capable of removing strontium from N-Area groundwaters. The data show the relative selectivities of the ion-exchange materials under similar operating conditions, and show that additional flow studies are needed to predict materials capacities and to develop complete ion-exchange process flow sheets.

The materials investigated in this study include commercially available ion exchangers such as IONSIV IE-911 (manufactured by UOP) and SuperLig[®] 644^(b) (IBC Advanced Technologies, Inc.), and materials produced on an experimental basis by Allied Signal (nonatitanates), Selion Inc. (titanates), and Pennsylvania State University (modified mica). In all, the performance of seven different ion-exchange materials was evaluated using actual N-Area groundwater. The evaluation consisted of the determining strontium batch distribution coefficients, loading, and decontamination factors. Tests were performed at two different solution-to-exchanger mass ratios (i.e., phase ratios) of 2000 and 4000 using actual N-Area groundwater samples from three different wells. Actual N-Area groundwater used in the present study was obtained from three monitoring wells in FY 1998. These samples were taken from wells with strontium-90 concentrations ranging from 0.25 to 3.9 pCi/L.

The Pennsylvania State University modified mica and the IONSIV IE-911 exhibited the best performance by removing over 95% of the strontium at both phase ratios. The results of the remaining titanate materials were all within an order of magnitude of the IONSIV IE-911 and the Pennsylvania State University modified mica. Therefore, a cost-benefit comparison is necessary to determine which material would be the best for strontium removal from groundwater.

(a) Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle under Contract DE-AC06-76RLO 1830.

(b) SuperLig 644 is a registered trademark of IBC Advanced Technologies, Inc. in Provo, Utah.

Acknowledgments

Pacific Northwest National Laboratory (PNNL) collaborates with universities, national laboratories, and industry to develop and test new materials for the pretreatment of nuclear process wastes and groundwaters at Hanford. This work has been performed under the direction of the U. S. Department of Energy's Office of Science and Technology. The experimental work described in this report would not have been possible without the encouragement and resources provided by the Efficient Separations and Processing Crosscutting Program. A special recognition is due to Mr. Lane A. Bray, formerly the Principal Investigator for the Develop and Test Sorbers task at PNNL. In addition, the authors would like to acknowledge the contributions of G. N. Brown and W. F. Bonner of PNNL, and Renee Nielson of CHI Analytical Field Services, to this effort.

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1.0 Introduction

Under the Efficient Separations and Processing Crosscutting Program, the Pacific Northwest National Laboratory (PNNL)^(a) conducts experimental ion-exchange studies to evaluate newly emerging materials (Bray, Carson, and Elovich 1990; Bray, Carson, and Elovich 1993; Brown et al. 1995a; Brown et al. 1996a) and technologies for removing cesium, strontium, cobalt, technetium, and transuranic elements from simulated and actual wastes at Hanford. Previous work (Bray et al. 1984; Brown et al. 1995b; Brown, Bray, and Elovich 1995) focused on applications to treat high-level alkaline tank wastes, but many of the technologies can also be applied in process and groundwater remediation (Brown et al. 1996b; Herbst et al. 1995). Ultimately, each process must be evaluated in terms of life-cycle costs, removal efficiency, process chemical consumption and recycle, stability of materials exposed to chemicals and radiation, compatibility with other process streams, secondary waste generation, process and maintenance costs, and final material disposal.

1.1 Background

Hanford's 100-N Area N-Springs well water (from wells 199-N-75, 199-N-103A, and 199-N-106A) is known to be contaminated with traces of radioactive strontium-90 and tritium. Other radionuclides and organic and inorganic species have been detected, but generally exist at levels below federal drinking water standards (Dirkes 1990; Hartman and Lindsey 1993). Strontium-90 levels vary between 1000 and 2000 pCi/L, depending upon the water table level. Tritium concentrations are normally about 60,000 pCi/L. In addition, the groundwater contains high concentrations of nonradioactive strontium (0.23 ppm), calcium (45 ppm), and magnesium (9 ppm), the presence of which frustrates efforts to remediate the strontium-90 using ion-exchange technologies. The major anionic component of the groundwater is carbonate.

The N-Springs Pump and Treat Demonstration Facility currently processes groundwater from the 100-N Area wells at 50 gallons per minute (gpm) using conventional ion-exchange technology. The present system consists of four columns, each capable of holding 65 ft³ of a natural zeolite, clinoptilolite. Normally, three columns are connected in series. The fourth column is held offline for disposal and installation of the spent exchanger. The system is typically operated continuously at 50 gpm for 2 weeks, and then the lead column is removed from service. The column previously held in reserve is then placed in service at the end or trailing position, and solution processing is continued. Strontium is removed by the ion exchanger to levels below federal drinking water standards of 0.040 pCi/L. However, the process generates a large amount of solid radioactive waste. Bechtel Hanford, Inc. operators and engineers are searching for methods to improve the process and reduce the amount of secondary waste.

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1.2 Task Objectives

The purpose of this task was to assess the performance of several ion exchangers, including a newly identified mica, for removing trace quantities of strontium from actual Hanford N-Springs groundwater. The experimental objective was to determine the relative effectiveness of various ion-exchange materials, including a newly developed modified mica material (PSU modified mica) from the laboratory of Dr. Sridhar Komarneni at Pennsylvania State University (Komarneni, Pidugu, and Amonette 1998), to remove strontium.

2.0 Experimental Approach

The removal of strontium from actual N-Area groundwater was determined using the water from three different wells in two separate tests. The first test was with performed using a liquid-to-solid ratio of 2000, while the second test was performed on a selected number of ion exchangers using a liquid-to-solid ratio of 4000. The water used was collected on 7/9/98 between 08:18 and 08:53 from wells 199-N-75, 199-N-103A, and 199-N-106A. The raw data are presented in Appendix A.

2.1 Test Parameters

The analyses of the groundwater samples are shown in Table 2.1. The samples were analyzed by inductively coupled plasma/mass spectrometry (ICP/MS) and for strontium-90 activity. The results are ng/mL (ppb) and pCi/mL. Prior to contacting the solutions with the solids, each of the solutions was spiked with strontium-85 so that the contacts could be tracked by gamma counting.

Table 2.1. ICP/MS and Strontium-90 Analysis of N-Area Groundwater Samples

Analyte	199-N-75 (ng/mL)	199-N-103A (ng/mL)	199-N-106A (ng/mL)
Li	<2	<2	3
Be	<0.5	<0.5	<0.5
Na	5250	5800	6350
Mg	6250	8780	6800
K	2030	2000	1960
Ca	37,300	46,400	39,400
Cr	1.6	3.43	2.76
Mn	<0.5	<0.5	<0.5
Rb	1.58	1.40	1.28
Sr	198	234	183
Cs	<0.5	0.7	<0.5
Ba	30.0	38.9	23.2
⁹⁰ Sr ^(a)	0.556 ^(b)	0.293 ^(b)	3.91 ^(b)
⁹⁰ Sr/Sr ratio	2.03x10 ⁻⁸	9.07x10 ⁻⁹	1.55x10 ⁻⁷
(a) The federal drinking water standard is 0.040 pCi/mL.			
(b) These values are in units of pCi/mL.			

As stated earlier, the two tests were run using different liquid-to-solid ratios. The reason for using the two different ratios was because the materials were so efficient at removing strontium, the final (i.e., equilibrium) strontium concentrations were very low. To increase the final concentrations, a higher solution ratio test was performed. Because of the limited amount of sample, only those ion-exchange

materials that showed a high-removal capacity were tested using the higher liquid-to-solid ratio. The PSU modified mica was not available when the low liquid-to-solid ratio test was performed, so it was only tested at the high liquid-to-solid ratio.

Table 2.2 shows the ion-exchange materials that were used for testing. For the 2000 liquid-to-solid ratio test, duplicate 0.0500-gram samples of each ion exchanger were added to a 125-mL high-density polyethylene bottle for each of the groundwater samples (see Table 2.1). One hundred milliliters of the strontium-85 spiked groundwater were then added to each bottle, and the bottles were placed in a shaker table for 72 hours. The samples were then filtered through a 0.20- μ m filter and counted by gamma counting.

Table 2.2. Ion Exchanger Properties

Ion-Exchange Material	Sample Identification	Liquid/Solid Ratio	Manufacturer	Batch No.	$\rho^{(a)}$	F-Factor^(b)
IONSIV IE-911	A	2000	UOP	99096810002	0.85	0.9112
R-F Resin	B	2000	Boulder Scientific	18-210	0.3044	0.8190
Sodium Nonatitanate	C	2000	Allied Signal	8212-152	0.84	0.9393
Sr-Treat	D	2000	Selion, Inc.	H18	0.71	0.8966
SuperLig® 644	E	2000	IBC Inc.	10-SM-171	0.22	0.9330
TIE-96	F	2000	UOP	97579100001 2-A	0.77	0.8822
IONSIV IE-911	G	4000	UOP	99096810002	0.85	0.9112
Sr-Treat	I	4000	Selion, Inc.	H18	0.71	0.8966
PSU Modified Mica	J	4000	Pennsylvania State University	SK-1	(b)	0.9424
(a) The bed density for this ion-exchange material was not measured because this was an insufficient sample for measurement.						
(b) The F-factor is the mass of dry ion exchanger divided by the mass of wet ion exchanger.						

For the 4000 liquid-to-solid ratio test, duplicate 0.0500-gram samples of each ion exchanger were added to a 250-mL high-density polyethylene bottle for each of the groundwater samples (see Table 2.1). Two hundred milliliters of the spike groundwater were then added to each bottle, and the bottles were placed in a shaker table for 72 hours. The samples were then filtered through a 0.20- μ m filter and counted by gamma counting.

2.2 Ion Exchange Distribution and Decontamination Factor

The batch K_d ($K_d = [\text{Sr}]_{\text{solid}} / [\text{Sr}]_{\text{liquid}}$) is an equilibrium measure of the overall ability of the solid phase ion-exchange material to remove an ion from solution under the particular experimental conditions that exist during the contact. In most batch K_d tests, a known quantity of ion-exchange material is placed in contact with a known volume of solution containing the ions of interest (in this case, strontium). The material is allowed to contact the solution for a sufficient time to achieve equilibrium at a constant temperature, after which the solid ion-exchange material and liquid supernate are separated and analyzed. The equation for determining the K_d can be simplified by determining the concentration of the analyte before and after contact, and calculating the quantity of analyte on the ion exchanger by the difference (Equation 2.1)

$$K_d = \frac{(C_i - C_f)}{C_f} \times \frac{V}{M * F} \quad (2.1)$$

where C_i = initial amount or activity of the ion of interest in the feed solution prior to contact
 C_f = amount or activity after contact
 V = solution volume
 M = exchanger mass
 F = mass of dry ion exchanger divided by the mass of wet ion exchanger (F-factor).

K_d (mL/g) represents the theoretical volume of solution that can be processed per mass of exchanger under equilibrium conditions.

Lambda, the theoretical number of bed volumes of solution that can be processed per volume of exchanger, is obtained by multiplying K_d by the exchanger bed density, ρ_b (g/mL), as shown in Equation 2.2. Lambda is termed the column distribution ratio and is useful for estimating the 0.5 C/C_0 point (50% breakthrough) in column-loading experiments.

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

The final method of comparison for ion-exchange materials is the decontamination factor (DF, as shown in Equation 2.3). The DF is the initial activity in solution of the species of interest divided by the final activity in solution of the species of interest.

$$DF = C_i / C_f \quad (2.3)$$

3.0 Experimental Results

In this study, only radioactive strontium, rather than total strontium, was measured both before and after contact. This does not effect the K_d or the DF results, but it will affect the calculation of loading of the ion exchangers. Since the actual loading of strontium onto these materials is of interest, the loading of all the strontium was calculated for each experiment. Tables 3.1, 3.2, and 3.3 show the K_d , DF, and loading results for the various ion-exchange materials for the groundwater samples (having different strontium-90 content).

Table 3.1. Strontium Removal Data from Groundwater Sample 199-N-103A (Low Strontium-90 Concentration)

Ion-Exchange Material	Sample Identification	Liquid/Solid Ratio	K_d (mL/g)	Total Sr Loading (mmol/g)	^{90}Sr Loading (mmol/g)	DF
IONSIV IE-911	A	2000	7.48E+04	5.09E-03	4.49E-11	3.58E+01
R-F Resin	B	2000	1.52E+03	2.05E-03	1.81E-11	1.63E+00
Sodium Nonatitanate	C	2000	7.72E+03	3.61E-03	3.19E-11	5.35E+00
Sr-Treat	D	2000	1.57E+04	4.55E-03	4.01E-11	8.27E+00
SuperLig® 644 ^(a)	E	2000	9.27E+01	2.22E-04	1.96E-12	1.04E+00
TIE-96	F	2000	9.11E+03	2.32E-03	2.05E-11	9.23E+00
IONSIV IE-911	G	4000	1.24E+04	7.70E-03	6.80E-11	3.90E+00
Sr-Treat	I	4000	7.40E+03	6.58E-03	5.81E-11	2.26E+00
PSU Modified Mica	J	4000	5.07E+04	9.62E-03	8.50E-11	1.33E+01
(a) SuperLig 644 is a registered trademark of IBC Advanced Technologies, Inc., in Provo, Utah.						

**Table 3.2. Strontium Removal Data from Groundwater Sample 199-N-75
(Intermediate Strontium-90 Concentration)**

Ion-Exchange Material	Sample Identification	Liquid/Solid Ratio	K_d (mL/g)	Total Sr Loading (mmol/g)	⁹⁰Sr Loading (mmol/g)	DF
IONSIV IE-911	A	2000	9.97E+04	4.12E-03	8.15E-11	4.99E+01
R-F Resin	B	2000	2.91E+03	2.45E-03	4.85E-11	2.19E+00
Sodium Nonatitanate	C	2000	1.72E+04	3.34E-03	6.61E-11	1.10E+01
Sr-Treat	D	2000	2.84E+04	4.18E-03	8.26E-11	1.38E+01
SuperLig® 644	E	2000	1.03E+02	2.08E-04	4.11E-12	1.04E+00
TIE-96	F	2000	1.41E+04	2.05E-03	4.05E-11	1.37E+01
IONSIV IE-911	G	4000	2.14E+04	7.29E-03	1.44E-10	6.11E+00
Sr-Treat	I	4000	1.42E+04	6.39E-03	1.26E-10	4.52E+00
PSU Modified Mica	J	4000	7.41E+04	8.61E-03	1.70E-10	1.83E+01

Table 3.3. Strontium Removal Data from Groundwater Sample 199-N-106A (High Strontium-90 Concentration)

Ion-Exchange Material	Sample Identification	Liquid/Solid Ratio	K_d (mL/g)	Total Sr Loading (mmol/g)	⁹⁰Sr Loading (mmol/g)	DF
IONSIV IE-911	A	2000	9.01E+04	4.01E-03	6.05E-10	4.28E+01
R-F Resin	B	2000	2.60E+03	2.11E-03	3.20E-10	2.08E+00
Sodium Nonatitanate	C	2000	1.40E+04	3.06E-03	4.62E-10	8.96E+00
Sr-Treat	D	2000	2.21E+04	3.92E-03	5.92E-10	1.06E+01
SuperLig® 644	E	2000	8.95E+01	1.23E-04	1.85E-11	1.04E+00
TIE-96	F	2000	1.23E+04	1.95E-03	2.95E-10	1.16E+01
IONSIV IE-911	G	4000	1.62E+04	6.56E-03	9.91E-10	4.68E+00
Sr-Treat	I	4000	1.13E+04	5.83E-03	8.80E-10	3.63E+00
PSU Modified Mica	J	4000	7.32E+04	7.62E-03	1.15E-09	1.89E+01

4.0 Discussion

The strontium batch K_d s for this testing are shown in Figures 4.1, 4.2, and 4.3. Since the final (i.e., equilibrium) strontium concentration for each of these tests is well below the values for the groundwater, these results are mainly useful in determining the relative effectiveness of each of the ion exchangers.

Figure 4.1 shows the results for the 199-N-103A well water. This sample had the lowest strontium-90 concentration but the highest total strontium concentration. For the test with the lower liquid-to-solid ratio (the first six columns), the crystalline silico-titanate (IONSIV IE-911) had the best strontium removal, but the PSU modified mica material was not available for that test. The last three columns represent the higher liquid-to-solid ratio test. In this test, the PSU modified mica gave the best removal.

For the low liquid-to-solid test, the IONSIV IE-911 removed approximately 97% of the strontium from the groundwater. In the higher liquid-to-solid test, the IONSIV IE-911 removed about 75% of the strontium while the PSU modified mica removed 93% of the strontium. Figures 4.2 (results from 199-N-75 well water) and 4.3 (results from 199-N-106A well water) show the same trends in the relative efficiency of strontium removal.

Figure 4.1 Strontium K_d s for N-Area Groundwater from Well 199-N-103A

Figure 4.2. Strontium K_d s for N-Area Groundwater from Well 199-N-75

Figure 4.3. Strontium K_d s for N-Area Groundwater from Well 199-N-106A

5.0 Conclusions

This report evaluates the strontium removal efficiency for seven different ion-exchange materials including inorganic titanate materials (IONSIV IE-911, sodium nonatitanate, and Sr-Treat); modified minerals (TIE-96 and PSU modified mica); and regenerable organic resins (R-F Resin and SuperLig® 644). All of the materials tested here are commercially available except for the PSU modified mica provided by Dr. Komarneni at Pennsylvania State University. Because of the low concentrations of strontium in the groundwater samples and the extent of removal of strontium, these results should only be used to relate the relative efficiency of these materials for the removal of strontium from N-Area groundwater.

For the removal of strontium, the PSU modified mica showed the best strontium removal. The crystalline silico-titanate (IONSIV IE-911) was the second best in strontium removal. The PSU modified mica had approximately five times the efficiency of removing strontium from this groundwater as the IONSIV IE-911. The remaining materials had one third or less of the removal efficiency of IONSIV IE-911. The titanate materials (including the TIE-96) all have similar removal capacities while the organic resins are one to two orders of magnitude less efficient than the inorganic materials.

While the PSU modified mica is the best at removing strontium, the physical form of the material is different. All of the commercially available materials are in a form that can be used in an ion-exchange column. The PSU modified mica is an experimental material in powdered form. The powdered form gives the material a higher surface area, and it does not have a binder to take up part of the volume. Although the binder would reduce the effective capacity of the PSU modified mica by as much as 40% to 60%, it would still have a higher strontium removal capacity. Another advantage of the PSU modified mica is that it is made from a cheap, readily available mineral. The high removal capacity of the PSU modified mica would make it a candidate for additional studies for the removal of strontium from groundwater. The economics of making this material into an engineered form suitable for use in ion-exchange columns should be determined so that its cost may be compared to the other ion-exchange materials.

When considering all of the materials, the ability to regenerate the organic resins must be taken into consideration. In high-level waste applications, the stability of the materials can be an important factor, but the radiation field in the removal of strontium from N-Area groundwater is relatively low, and ion-exchange material stability will not be a factor. Because of the relatively low radiation field, the regenerable resins are good candidates. If the number of cycles that these resins can be used is relatively high, then the overall cost of using them may be low enough to make them a reasonable alternative. Before an informed judgement can be made of the relative cost of the regenerable resins compared to the one-pass inorganic materials, additional tests must be performed to determine the lifetime of the resins.

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Appendix A

100-N Area Groundwater Batch Testing Data

Appendix A

100-N Area Groundwater Batch Testing Data

The raw data for the groundwater batch testing of 100-N-Area groundwater samples are included in Tables A.1 and A.2. Table A.1 contains the data from the 2000 liquid-to-solid ratio test, and Table A.2 contains the data from the 4000 liquid-to-solid ratio test.

Table A.1. Data From Groundwater Batch Test, 2000 Liquid-to-Solid Ratio

Sample	IX Resin	Activity	Mass of Solution	Volume of Solution	Mass of Exchanger	F-factor	K _d	Lamda	DF	Sr C _i	Sr C _f	% Removed	Loading	⁹⁰ Sr Loading	Final Sr Conc.
N-75-A1	IE-911	7286	93.3	93.55259	0.05255	0.91122	99236.67	84351.17	51.79399	198	3.822837	98.06927	0.003945	7.8E-11	4.36E-11
N-75-A2	IE-911	7874	99.7	99.96992	0.05136	0.91122	100239	85203.12	47.92621	198	4.131351	97.91346	0.004307	8.51E-11	4.72E-11
N-103A-A1	IE-911	5231	99.5	99.76938	0.05093	0.91122	72415.48	61553.15	34.68457	234	6.746515	97.11687	0.005081	4.49E-11	7.7E-11
N-103A-A2	IE-911	4918	99.8	100.0702	0.05106	0.91122	77196.69	65617.19	36.89203	234	6.342834	97.28939	0.005092	4.5E-11	7.24E-11
N-106A-A1	IE-911	4028	98.8	99.06748	0.0507	0.91122	95536.84	81206.31	45.55238	183	4.062744	97.77992	0.00399	6.02E-10	4.64E-11
N-106A-A2	IE-911	4586	99.9	100.1705	0.05062	0.91122	84716.53	72009.05	40.00981	183	4.625557	97.47237	0.004029	6.08E-10	5.28E-11
N-75-B1	RF-BSC-210	168174	100.3	100.5715	0.05163	0.81905	2958.416	900.5417	2.243932	198	88.23797	55.43537	0.00244	4.82E-11	1.01E-09
N-75-B2	RF-BSC-210	175948	99.2	99.46857	0.04867	0.81905	2856.53	869.5278	2.144787	198	92.31686	53.37533	0.002465	4.87E-11	1.05E-09
N-103A-B1	RF-BSC-210	109676	99.6	99.86965	0.05	0.81905	1595.577	485.6938	1.654282	234	141.4511	39.5508	0.00211	1.86E-11	1.61E-09
N-103A-B2	RF-BSC-210	113352	101.3	101.5743	0.05117	0.81905	1455.685	443.1104	1.600633	234	146.1921	37.52473	0.001989	1.76E-11	1.67E-09
N-106A-B1	RF-BSC-210	90369	100	100.2707	0.04963	0.81905	2541.7	773.6935	2.030398	183	91.14849	50.19208	0.002118	3.2E-10	1.04E-09
N-106A-B2	RF-BSC-210	86301	100.2	100.4713	0.05195	0.81905	2659.04	809.4118	2.126105	183	87.0454	52.43421	0.002118	3.2E-10	9.93E-10
N-75-C1	AS NaTi	32601	100.3	100.5715	0.06239	0.93933	18148.49	15244.73	11.57544	198	17.10518	91.36102	0.003328	6.58E-11	1.95E-10
N-75-C2	AS NaTi	36530	98.8	99.06748	0.06023	0.93933	16338.13	13724.03	10.33044	198	19.16666	90.31987	0.003357	6.63E-11	2.19E-10
N-103A-C1	AS NaTi	36074	100.8	101.0729	0.05924	0.93933	7319.056	6148.007	5.029523	234	46.52529	80.1174	0.003651	3.22E-11	5.31E-10
N-103A-C2	AS NaTi	31899	99.6	99.86965	0.06142	0.93933	8114.732	6816.375	5.687796	234	41.14072	82.4185	0.003579	3.16E-11	4.7E-10
N-106A-C1	AS NaTi	18557	99	99.26802	0.06141	0.93933	15294.62	12847.48	9.887643	183	18.71707	89.77209	0.003031	4.57E-10	2.14E-10
N-106A-C2	AS NaTi	22834	99	99.26802	0.05867	0.93933	12672.92	10645.25	8.035605	183	23.03096	87.41478	0.003089	4.66E-10	2.63E-10

Table A.1. (contd)

Sample	IX Resin	Activity	Mass of Solution	Volume of Solution	Mass of Exchanger	F-factor	K _d	Lamda	DF	Sr C _i	Sr C _f	% Removed	Loading	⁹⁰ Sr Loading	Final Sr Conc.
N-75-D1	Sr Treat	28099	99.8	100.0702	0.04976	0.89664	27879.13	19794.18	13.43005	198	14.74306	92.55401	0.004206	8.31E-11	1.68E-10
N-75-D2	Sr Treat	26790	100.1	100.371	0.0507	0.89664	28893.35	20514.28	14.08626	198	14.05625	92.90089	0.004156	8.21E-11	1.6E-10
N-103A-D1	Sr Treat	21022	98.9	99.16775	0.05201	0.89664	16226.73	11520.98	8.63072	234	27.11245	88.41348	0.004502	3.98E-11	3.09E-10
N-103A-D2	Sr Treat	22956	99.3	99.56884	0.05059	0.89664	15153.61	10759.06	7.903598	234	29.60677	87.34753	0.004391	4.05E-11	3.38E-10
N-106A-D1	Sr Treat	16000	100.5	100.7721	0.04919	0.89664	23916.7	16980.86	11.46781	183	16.13801	91.18141	0.003901	5.89E-10	1.84E-10
N-106A-D2	Sr Treat	19024	100.1	100.371	0.04762	0.89664	20321.78	14428.47	9.644922	183	19.18809	89.5147	0.003941	5.95E-10	2.19E-10
N-75-E1	Superlig 644	362446	99.6	99.86965	0.04927	0.93295	89.46715	19.68277	1.041179	198	190.1691	3.954994	0.000181	3.58E-12	2.17E-09
N-75-E2	Superlig 644	358249	100.2	100.4713	0.04895	0.93295	117.43	25.83461	1.053376	198	187.967	5.067162	0.000235	4.64E-12	2.15E-09
N-103A-E1	Superlig 644	174719	100.9	101.1732	0.04849	0.93295	85.96573	18.91246	1.038439	234	225.3383	3.701601	0.000206	1.82E-12	2.57E-09
N-103A-E2	Superlig 644	173535	99.8	100.0702	0.04915	0.93295	99.34885	21.85675	1.045524	234	223.8112	4.354176	0.000237	2.09E-12	2.55E-09
N-106A-E1	Superlig 644	176408	99.1	99.36829	0.05206	0.93295	82.07601	18.05672	1.040117	183	177.9296	2.770689	0.00011	1.67E-11	2.03E-09
N-106A-E2	Superlig 644	175628	100.4	100.6718	0.04981	0.93295	96.91611	21.32154	1.044737	183	177.1429	3.200595	0.000135	2.04E-11	2.02E-09
N-75-F1	TIE-96	27356	98.6	98.86694	0.10173	0.88218	14095.45	10814.03	13.79482	198	14.35322	92.7509	0.002037	4.03E-11	1.64E-10
N-75-F2	TIE-96	27756	99.5	99.76938	0.10144	0.88218	14043.13	10773.89	13.59602	198	14.56309	92.6449	0.002059	4.07E-11	1.66E-10
N-103A-F1	TIE-96	19747	99	99.26802	0.10012	0.88218	9202.546	7060.193	9.187978	234	25.46806	89.11621	0.00236	2.08E-11	2.91E-10
N-103A-F2	TIE-96	19563	99.1	99.36829	0.10335	0.88218	9018.129	6918.708	9.274396	234	25.23075	89.21763	0.002291	2.02E-11	2.88E-10
N-106A-F1	TIE-96	16138	100	100.2707	0.09667	0.88218	12192.52	9354.101	11.36975	183	16.2772	91.10535	0.001974	2.98E-10	1.86E-10
N-106A-F2	TIE-96	15497	100.1	100.371	0.09921	0.88218	12431.58	9537.506	11.84003	183	15.63067	91.45865	0.001933	2.92E-10	1.78E-10
N-75-X ^(a)		377371													
N-103A-X ^(a)		181435													
N-106A-X ^(a)		183485													

(a) Well water samples (strontium-85 spiked) not contacted with ion-exchange materials.

Table A.2. Data From Groundwater Batch Test, 4000 Liquid-to-Solid Ratio

Sample	IX Resin	Activity	Mass of Solution	Volume of Solution	Mass of Exchanger	F-factor	K _d	Lamda	DF	Sr C _i	Sr C _f	% Removed	Loading	⁹⁰ Sr Loading	Final Sr Conc.
N-75-G1	IE-911	19659	196.3	196.8314	0.056	0.91122	23884.78	20302.06	7.1921	198	27.53021	86.09586	0.006838	1.35E-10	3.14E-10
N-75-G2	IE-911	28085	197.9	198.4358	0.0464	0.91122	18934.4	16094.24	5.034342	198	39.32987	80.13643	0.007745	1.53E-10	4.49E-10
N-103A-G1	IE-911	38581	196.4	196.9317	0.0493	0.91122	11715.65	9958.305	3.67252	234	63.71646	72.77074	0.007763	6.85E-11	7.27E-10
N-103A-G2	IE-911	34283	198.5	199.0374	0.0527	0.91122	12985.32	11037.52	4.132938	234	56.61832	75.80414	0.007646	6.75E-11	6.46E-10
N-106A-G1	IE-911	34872	197	197.5333	0.054	0.91122	13830.32	11755.78	4.445157	183	41.1684	77.5036	0.005921	8.94E-10	4.7E-10
N-106A-G2	IE-911	31528	193.6	194.1241	0.0448	0.91122	18624.76	15831.05	4.91663	183	37.22062	79.66086	0.007209	1.09E-09	4.25E-10
N-75-I1	Sr Treat	31083	192.8	193.322	0.0545	0.89664	14039.28	9967.887	4.548773	198	43.52823	78.01605	0.006254	1.24E-10	4.97E-10
N-75-I2	Sr Treat	31545	193.4	193.9236	0.0521	0.89664	14455.15	10263.16	4.482152	198	44.1752	77.68929	0.006535	1.29E-10	5.04E-10
N-103A-I1	Sr Treat	53403	200.3	200.8423	0.0506	0.89664	7318.383	5196.052	2.653212	234	88.19498	62.30984	0.006605	5.83E-11	1.01E-09
N-103A-I2	Sr Treat	51866	196.5	197.032	0.0509	0.89664	7476.667	5308.434	2.731838	234	85.65662	63.39461	0.006554	5.79E-11	9.78E-10
N-106A-I1	Sr Treat	41717	194.1	194.6255	0.0502	0.89664	11742.85	8337.426	3.715787	183	49.24932	73.0878	0.005918	8.93E-10	5.62E-10
N-106A-I2	Sr Treat	43689	197.4	197.9344	0.0517	0.89664	10879.87	7724.704	3.548067	183	51.57738	71.81564	0.005742	8.67E-10	5.89E-10
N-75-J1	SK-1 (PSU)	7888	198.8	199.3382	0.0481	0.94245	74422.87		17.92463	198	11.04625	94.42109	0.008843	1.75E-10	1.26E-10
N-75-J2	SK-1 (PSU)	7540	201.5	202.0455	0.0516	0.94245	73754.18		18.75192	198	10.55892	94.66721	0.008376	1.66E-10	1.21E-10
N-103A-J1	SK-1 (PSU)	10756	201.6	202.1458	0.0523	0.94245	49923.46		13.17307	234	17.76352	92.40875	0.009539	8.42E-11	2.03E-10
N-103A-J2	SK-1 (PSU)	10620	199.8	200.3409	0.051	0.94245	51442.05		13.34176	234	17.53891	92.50474	0.009705	8.57E-11	2E-10
N-106A-J1	SK-1 (PSU)	7954	198.5	199.0374	0.0512	0.94245	76261.97		19.4885	183	9.390155	94.86877	0.007703	1.16E-09	1.07E-10
N-106A-J2	SK-1 (PSU)	8448	193.9	194.4249	0.051	0.94245	70177.1		18.3489	183	9.97335	94.55008	0.007528	1.14E-09	1.14E-10
N-75-X1 ^(a)		141389.5													
N-103A-X1 ^(a)		141689.5													
N-106A-X1 ^(a)		155011.5													

(a) Well water samples (strontium-85 spiked) not contacted with ion-exchange materials.

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