

## **Ion Exchange Removal of Strontium from Simulated and Actual N-Springs Well Water at the Hanford 100-N Area**

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**MASTER**

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## Summary

Pacific Northwest National Laboratory (PNNL),<sup>(a)</sup> in conjunction with 3M; AlliedSignal, Inc.; Bechtel Hanford Inc. (BHI); and CH2M Hill, conducted this study as part of the Efficient Separations and Processing Crosscutting Program. The study's purpose was to assess the performance of the 3M Process Absorber Development Unit (PADU) and the sodium nonatitanate (NaTi) material produced by AlliedSignal for removing strontium from simulated and actual ground water from the Hanford N-Springs Pump and Treat Demonstration Facility. The objective of these experiments was to determine the strontium-loading breakthrough profiles of actual and simulated ground waters by ion exchange using a proprietary 3M engineered material (termed NaTi/WWL) in either disk or cartridge forms. Specific experimental objectives included 1) demonstrating the PADU as a viable cartridge test unit; 2) generating complete strontium, calcium, and magnesium breakthrough curves for the cartridge and disk tests; 3) demonstrating strontium decontamination to meet drinking-water standards; and 4) verifying simulant performance.

Experiments were completed using actual and simulated N-Springs ground water and either 18-cm cartridges (100-g NaTi/WWL, 0.163-L bed volume (BV) each) or 2.5-cm disks (0.59-g NaTi/WWL, 0.98-mL BV) of NaTi/WWL web. Simulants were developed based on available analytical data. The laboratory disk studies were completed using the following process steps: 1) web preparation in caustic, 2) loading at neutral pH, 3) elution with 0.5M HNO<sub>3</sub>, 4) water wash, 5) caustic regeneration, and 6) water rinse. Laboratory and field cartridge studies were undertaken in the loading mode (steps 1 and 2) only. The following results were obtained in this study:

- BHI personnel successfully operated the 3M PADU at the N-Springs Pump and Treat Facility. Although minor system difficulties were encountered, the effectiveness of the NaTi/WWL membrane in removing strontium from Hanford ground water was demonstrated.
- Laboratory testing of small-scale disks and process-scale cartridges using simulated and actual ground water effectively predicted the field performance of the PADU. Approximately 1000 BV of solution could be processed before reaching a Sr C/C<sub>0</sub> of 0.5, where C<sub>0</sub> is equal to 1.49E-6M Sr. The data suggest that accurate scale-up of process performance data from laboratory disk tests to full-scale cartridge systems is likely. Complete loading breakthrough curves were generated for barium, calcium, magnesium, and strontium.
- The disk loading (mmol Sr per gram or milliliter of resin) of the NaTi/WWL was calculated to be 2.61E-03 mmol/g (1.57E-03 mmol/mL) for the actual N-Springs water. Elution was accomplished with 0.5M HNO<sub>3</sub> at 7.5 BV/min and required 80 BV to reach 0.1 Sr C/C<sub>0</sub>.

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- During the field demonstration, the PADU cartridge loading (mmol/g) was determined to be  $2.84\text{E-}04$ ,  $8.68\text{E-}01$ ,  $7.58\text{E-}02$ , and  $2.85\text{E-}03$  for barium, calcium, magnesium, and strontium, respectively. In addition,  $1.78\text{E+}00$  mmol Na/g was released during loading, effectively confirming the mass balance.
- The strontium breakthrough curves described in this report were nearly identical irrespective of solution (simulated and actual ground water), geometry of the ion exchange material (disks or cartridges), or material volume (single or multiple cartridges), and indicate an ability to mimic strontium ion exchange with the intelligent formulation of nonradioactive simulant solutions.

## Acknowledgments

Pacific Northwest National Laboratory (PNNL) is collaborating with universities, national laboratories, and industry to develop and test new materials for the pretreatment of nuclear process wastes and ground waters 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 (ESP) 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 to this effort of D. R. Baker, D. L. Bowers, A. I. Davis, J. A. Kion, T. E. Moody, B. Mukherjee, and N. A. Puckett of Bechtel Hanford Incorporated (BHI); D. J. Vaught (CH2M Hill); B. M. Mauss and D. E. Olson of the U.S. Department of Energy Richland Operations; W. F. Bonner and W. L. Kuhn (PNNL); D. Boggs, K. Carlson, T. Fredrickson, D. Seely, I. Shaw-Epperson, N. Stern, and E. Wisted at 3M (St. Paul, MN); and S. F. Yates (AlliedSignal). This work was performed jointly by researchers at 3M, BHI, and PNNL.



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# 1.0 Introduction

Experimental ion exchange studies are being conducted by the Pacific Northwest National Laboratory (PNNL)<sup>(a)</sup> under the Efficient Separations and Processing (ESP) Crosscutting Program to evaluate newly emerging materials (Bray et al. 1990; Bray et al. 1993; Brown et al. 1995a; Brown et al. 1996) and technologies for removing cesium, strontium, cobalt, technetium, and transuranic elements (TRUs) from simulated and actual wastes at Hanford. Previous work (Bray et al. 1984; Brown et al. 1995b; Brown et al. 1995c) focused on applications to treat high-level alkaline tank wastes, but many of the technologies can also be applied in process and ground-water remediation (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.

This report assesses the performance of the 3M-designed Process Absorber Development Unit (PADU) and the AlliedSignal-produced sodium nonatitanate (NaTi) material in removing trace quantities of strontium from simulated and actual Hanford N-Springs ground water. The experimental objective was to determine the strontium-loading breakthrough profile of a proprietary 3M-engineered material (termed NaTi/WWL) in either disk or cartridge forms.

## 1.1 Background

Hanford's 100-N Area N-Springs well water (from wells 199-N-106A, 199-N-14, and 199-N-75) is known to be contaminated with traces of radioactive strontium-90 and tritium-3. 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 ground water contains high concentrations of nonradioactive strontium (0.13 ppm), calcium (30 ppm), and magnesium (5 ppm), the presence of which frustrates efforts to remediate the strontium-90 using ion exchange technologies. The major anionic component of the ground water is carbonate.

The N-Springs Pump and Treat Demonstration Facility is currently processing ground water from the 100-N Area wells at 189.3 L/min (50 gallons per minute [gpm]) using conventional ion exchange technology. The present system consists of four columns, each capable of holding 65 ft<sup>3</sup> of a natural zeolite, clinoptilolite. Normally, three columns are connected in series, with the fourth held off-line for disposal and installation of the spent exchanger. The system is typically operated continuously at 189.3 L/min (50 gpm) for 2 weeks and then the lead column is removed from service. The column

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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 40 pCi/L. However, the process generates a large amount of solid radioactive waste. Bechtel Hanford Inc. (BHI) operators and engineers are searching for methods to improve the process and reduce the amount of secondary waste.

## **1.2 Task Objectives**

The overall objectives of this task are to 1) develop and evaluate newly conceived materials for recovering radionuclides from process wastes, 2) determine loading and elution efficiency of the materials, 3) determine the materials' physical life cycle (including stability when exposed to radiation and chemicals), and 4) determine if basic ion exchange data can be applied to a broad range of chemical compositions. The goal of this subtask was to determine the loading of barium, calcium, magnesium, and strontium on 3M WWL webs that contain NaTi in actual and simulated Hanford N-Springs ground water.

## 2.0 Experimental Approach

The removal of strontium from actual and simulated ground water using an engineered form of sodium nonatitanate (NaTi, AlliedSignal, Des Plaines, IL) was investigated in three separate tests. In the first test, a small-scale laboratory disk loading experiment was completed at PNNL using actual N-Springs water containing approximately 1100 pCi/L strontium-90. The water was collected from well 199-N-106A on 11/1/95, 11:10AM. In the second test, a single cartridge loading experiment was completed at 3M (St. Paul, MN) using a simulated ground-water composition designed to mimic the N-Springs ground water. The final test was completed at the N-Springs Pump and Treat Demonstration Facility on January 25, 1996, using the PADU, a skid-mounted cartridge-based system designed by 3M and operated by BHI personnel.

### 2.1 Test Parameters

Table 2.1 compares the experimental parameters used in each of the three tests, and Table 2.2 compares the actual and simulated ground-water chemical compositions. Inductively coupled plasma (ICP) analysis of the nonradioactive strontium was used as an analytical method for the 3M simulant and N-Springs PADU cartridge tests. In addition, to confirm the ICP results for strontium, strontium-90 beta analysis was completed on selected samples obtained from the N-Springs PADU demonstration. For the PNNL disk test, radioactive strontium-85 tracer was added to the water and was measured by gamma energy analysis (GEA). All material calculations were based on the mass of the entire NaTi/WWL web and did not account for the percentage of active particle in the web.

In general, the purpose of the laboratory tests was to estimate the strontium loading characteristics of the adsorbent material before conducting the actual N-Springs PADU demonstration. Therefore, an accurate comparison of the solution flow rate was not critical. However, the difference in flow rates between the three tests must be emphasized. The PNNL disk test was completed at 6.35 bed volumes per minute (BV/min), whereas the flow rates for the cartridge tests were much higher. The PADU was run at 28.1 BV/min, while the 3M cartridge test was run at constant pressure (10 psig) and the flow rate varied from 17.7 to 14.0 BV/min. The effect of flow rate on ion exchange breakthrough curves is well known (Kurath et al. 1994) and may affect the results presented in this report.

### 2.2 Ion Exchange Distribution

Although batch distribution coefficients ( $K_d$ 's) were not determined for the experiments described in this report, the information in this section is useful for understanding the relationship of the current disk and cartridge loading experiments to previous batch  $K_d$  results. The column size is estimated by carefully analyzing these data.

The batch  $K_d$  ( $K_d = [Cs]_{\text{solid}} \div [Cs]_{\text{liquid}}$ ) 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

**Table 2.1.** Comparison of Experimental Test Conditions for the PNNL Laboratory Disk Test, the 3M Laboratory Cartridge Test, and the N-Springs PADU Demonstration

Parameter	PNNL Laboratory Disk Test	3M Laboratory Cartridge Test	Actual Test N-Springs
Analytical Method	GEA Sr-85	ICP	ICP and Sr-90
Sorbent Material	NaTi	NaTi	NaTi
Sorbent Mass (g)	0.593	100	300
Sorbent BV (mL, L)	0.982 mL	0.163 L	0.488 L
Sorbent Area (cm <sup>2</sup> )	4.91	680	2040
Number of Pleats	0	13	39
Pleat Height (cm)	0	1.59	1.59
Pleat Length (cm)	0	16.5	16.5
Sorbent Fraction	0.72	0.72	0.72
Sorbent Particle (μm)	12.4	12.4	12.4
Sorbent Thickness (cm)	0.2	0.24	0.24
Solution Flow Rate (mL/min)	6.24	2870	13,700
Solution Flow Rate (BV/min)	6.35	17.7	28.1
Solution Flow Rate (cm/min)	1.27	4.21	6.7
Sorbent Lot #	92095-2	NA <sup>(a)</sup>	NA
Flow Rate (L/min)	0.00624	2.3-2.9	13.7
Flow (mL min <sup>-1</sup> g <sup>-1</sup> )	10.5	28.7	45.7
(a) Sample information not available.			

**Table 2.2.** Analytical Results for the Composition of 3M Simulant and Actual N-Springs Water

Species	Species Concentration (M)		
	PNNL Lab Test <sup>(a)</sup>	3M Simulant	N-Springs Test <sup>(b)</sup>
Ba	1.15E-07	0.00E+00	(1.12±0.03)E-07 n=18
Ca	7.39E-04	7.24E-04	(7.28±0.07)E-04 n=19
K	5.29E-05	5.12E-05	(5.35±NA)E-05 n=1
Mg	2.20E-04	2.06E-04	(2.16±0.02)E-04 n=19
Na	1.64E-04	1.74E-04	(2.61±0.13)E-04 n=19
P	3.45E-06	0.00E+00	(3.39±0.18)E-06 n=5
S	2.30E-04	2.29E-04	NA <sup>(c)</sup>
Si	3.33E-04	0.00E+00	(3.21±0.05)E-04 n=19
Sr	1.49E-06	1.71E-06	(1.49±0.02)E-06 n=19
Sr-90	1.10 pCi/mL	0.00E+00	(1.35±0.10) pCi/mL n=3
Ca/Sr Ratio	4.98E+02	4.23E+02	(4.88±0.08)E+02 n=19

(a) Sample collected from the N-Springs well 199-N-106A by AG Rizzo on 11/1/95 at 11:10 a.m.  
 (b) Sample collected from the N-Spring Pump and Treat Demonstration Facility by DL Bowers on 11/25/96 at 10:30 a.m.  
 (c) Not analyzed.

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 difference (Equation 1).

$$K_d = \frac{(C_i - C_f)}{C_f} \times \frac{V}{M * F} \quad (1)$$

where  $C_i$  = the initial amount or activity of the ion of interest in the feed solution prior to contact  
 $C_f$  = the amount or activity after contact  
 $V$  = the solution volume  
 $M$  = the exchanger mass  
 $F$  = the 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,  $\rho_b$  (g/mL), as shown in Equation 2. Lambda is termed the column distribution ratio and is useful for estimating the 0.5  $C/C_0$  point in column loading experiments. Historically, several methods and materials, NaTi included, have been employed to remove radioactive strontium from waste matrices (Brown et al. 1994).

$$\lambda = K_d \times \rho_b \quad (2)$$

### 2.3 Preliminary Disk Tests

The ion exchange material used in the preliminary PNNL laboratory tests consisted of a fine powdered sodium nonatitanate (NaTi) (AlliedSignal, Des Plaines, IL) entrapped in a proprietary web matrix developed by 3M (St. Paul, MN). The material (3M Lot #92095-2) was cut into a 2.5-cm-dia. disk (0.2 cm thick) with a leather punch and placed into a Millipore in-line disk filter holder, as shown in Figure 2.1. The ion exchange web was used in the form received from the manufacturer and was not chemically pretreated. The feed solution (N-Springs water from well 199-N-106A) was passed upwards through the web at 6.24 mL/min (6.35 BV/min) and ambient temperature (25°C). The system pressure was measured upstream of the web and the effluent downstream was discharged to either a sample or waste container at atmospheric pressure. After loading, the strontium was removed from the material by eluting with 0.5M  $HNO_3$  at 6.08 mL/min (6.19 BV/min) and ambient temperature (25°C). Following elution and in preparation for a second loading cycle, the web was flushed with distilled water, 50-mL 2M NaOH, and a second distilled water rinse until the effluent reached pH 8. The system was then left overnight and the second load/elute cycle was initiated the following morning. All data described in this

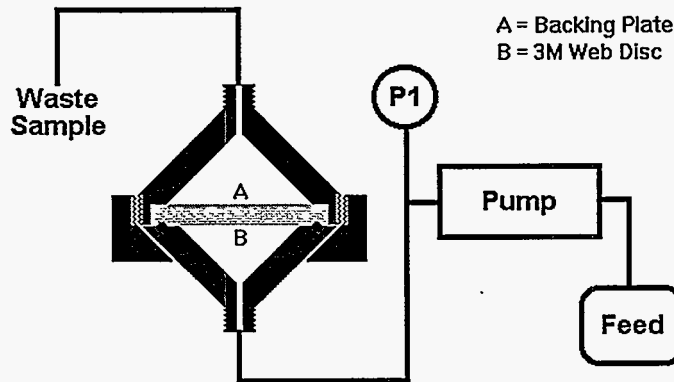


Figure 2.1. Schematic Diagram of the Laboratory Disk Filtration Apparatus



report are from the second cycle. Elution and/or repeated cycling of the disk was not necessary for the current systems evaluation and for determining loading predictions at the Hanford N-Springs, but was completed for future reference in case elution is necessary for additional applications of this technology.

## 2.4 Preliminary Cartridge Tests

The preliminary cartridge test was done to evaluate the strontium loading required to produce a full breakthrough curve for an 18-cm-long NaTi cartridge before using the PADU skid unit to process N-Springs water. 3M personnel tested a single NaTi cartridge for the Sr loading characteristics before the entire lot of cartridges was delivered for the N-Springs PADU field demonstration. The NaTi material was converted to the sodium form by pretreating the intact cartridge with a solution containing 0.1M NaOH and 5M NaNO<sub>3</sub>, followed by rinsing with deionized water. The 18-cm cartridge (Figure 2.2) was installed in a commercial filtration housing, and a simulated ground water designed to mimic the actual N-Springs water was passed through the system at constant pressure and at a flow rate that varied from 2.88 to 2.27 L/min. Table 2.2 provides the exact composition of the ground-water simulant. The solution flowed inward (radially) through the web material and out the top of the cartridge in the axial direction, as shown in Figure 2.2. The flow rate varied between 17.7 and 14.0 BV/min.

Throughout the test, a constant pressure drop of approximately 10 to 12 psig was maintained across the cartridge material. Temperature control during cartridge loading was not attempted but ambient was 25°C. Table 2.1 lists additional experimental conditions. Elution and/or repeated cycling of the cartridge during the field demonstration was not planned and therefore was not necessary for evaluating the overall system.

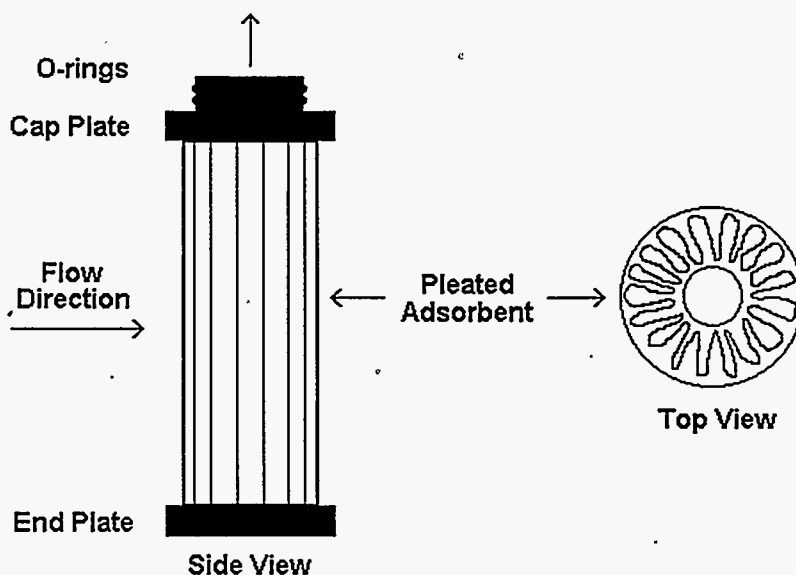


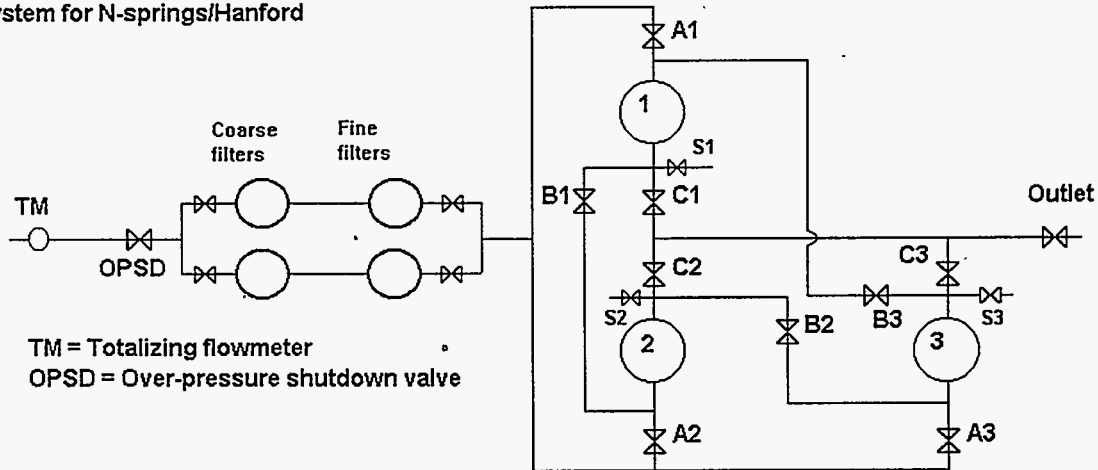
Figure 2.2. Schematic Diagram of the 3M Cartridge

## 2.5 N-Springs PADU Test

The PADU is a skid-mounted, cartridge-based system designed to demonstrate the removal of various radionuclides from contaminated ground water or other low-level process streams. The self-contained system is approximately 4 x 5 x 4 feet and consists of three vessels, each of which contain multiple cartridges in parallel. Figure 2.3 shows a schematic diagram of the PADU system, with a photograph of the unit in operation at the N-Springs Pump and Treat Demonstration Facility shown in Figure 2.4.

Section 2.4 described the cartridges included in the PADU. The cartridge size and number can vary, but for this demonstration, three 18-cm cartridges per vessel were used. Two-stage pre-filtration capability (in the current experiment, 2- $\mu$ m (3M) and 0.1- $\mu$ m (Pall) commercial filters), pressure indicators, electronic valves, and all associated piping are included with the system. In addition, the unit is electronically controlled and can shut down automatically if over-pressure conditions occur.

Test system for N-springs/Hanford



TM = Totalizing flowmeter  
OPSD = Over-pressure shutdown valve

Valve sequencing for 3-cartridge absorber  
O denotes valve open, C denotes valve closed.

A, B, & C valves are electrically actuated  
S valves are manual and are for sampling

Sequence ID	Valve ID								
	A1	B1	C1	A2	B2	C2	A3	B3	C3
1, 1 to 2, 3 idle	O	O	C	C	C	O	C	C	C
2, 2 to 3, 1 idle	C	C	C	O	O	C	C	C	O
3, 3 to 1, 2 idle	C	C	O	C	C	C	O	O	C

CARTSYS7.BMP

Figure 2.3. Schematic Diagram of the 3M PADU



Figure 2.4. 3M PADU Used at Hanford N-Springs

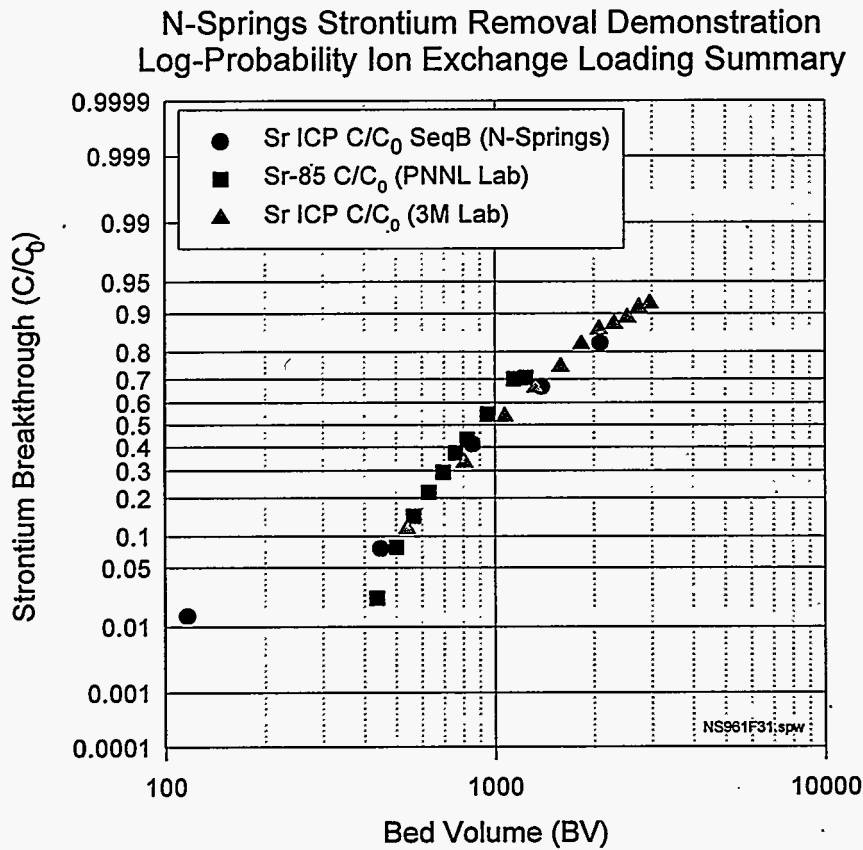
During normal operations, solution flows through two vessels in series, with the third vessel held off-line in reserve. The system automatically switches the sequence of vessels based on a pre-programmed cycle time. In the first sequence, the first or leading vessel (#1) is completely loaded with the radionuclide of interest, while the second or trailing vessel (#2) polishes the remaining radionuclide from the system effluent. In the second sequence, flow is electronically switched so vessel #2 becomes the leading vessel and vessel #3 is placed in service as the trailing or polishing vessel. At this point, vessel #1 is taken off-line and the loaded cartridges are manually removed for disposal. It is important to note that the system is designed as a demonstration unit for low-activity solutions and requires contact maintenance (e.g., cartridge removal by hand). The use of this system for highly radioactive solutions was not intended and is not recommended.

The PADU system was operated at ambient temperature and used a side stream from the N-Springs Pump and Treat Demonstration Facility. Because the demonstration took place in January and involved water from the 199-N-106A well, the water temperature was substantially lower than it was in the previously described laboratory tests (see Sections 2.3 and 2.4). The system flow rate was approximately 13.6 L/min or 28.1 BV/min, much faster than the flow rate used in the previous laboratory tests (see Table 2.1). The effect of temperature and flow rate on ion exchange breakthrough curves has been investigated previously (Kurath et al. 1994) and may affect the results presented in this report. In general, earlier breakthrough is observed at higher flow rates.

### 3.0 Results and Discussion

#### 3.1 Strontium Loading Comparison

Figure 3.1 shows results for the removal of strontium from simulated and actual N-Springs water. The normalized strontium concentration ( $Sr\ C/C_0$ ) is plotted against the BVs of solution passed through the NaTi web. For visual clarity, the data are plotted in the log-probability format. The typical sigmoidal or S-shaped loading breakthrough curve will appear linear when displayed in this manner (Buckingham 1967). The data are displayed in this format to facilitate comparison between the small-scale disk tests, the larger-scale cartridge tests, and the variety of analytical methods used to measure strontium concentration. For reference, Table 2.2 displays the initial concentration (approximately  $1.5E-06M$  Sr) of strontium in the various feed solutions.



**Figure 3.1.** Comparison of Strontium Breakthrough Curves for NaTi/WWL Disks and Cartridges in Simulated and Actual Ground Water from Hanford N-Springs

As shown in Figure 3.1, the 0.5  $C/C_0$  breakthrough point corresponds to approximately 900, 1000, and 1000 BV of solution passed through the NaTi web for the PNNL disk test, the 3M cartridge simulant test, and the PADU N-Springs demonstration, respectively. As described in Section 2.2, the 0.5  $C/C_0$  point can be used as an estimate of the theoretical volume of solution that can be processed to fully load an ion exchanger. The assumption is valid if the wave shape of the loading curve is symmetric about the 0.5  $C/C_0$  point. At this point, one can assume that the quantity of radionuclide that has exited the column (e.g., broken through) is equivalent to the quantity that can still be loaded if the experiment were continued to 1.0  $C/C_0$ . Alternatively, one can integrate the amount of strontium exiting the disk or cartridge from the analytical data and back calculate the strontium loading.

From the data in Figure 3.1, it appears that an accurate estimate of the PADU operations was obtained using either a small-scale disk, single cartridge, or a ground-water simulant with the appropriate chemical composition. It is interesting to note that the results were not affected by the higher strontium concentration of the 3M simulant (1.71E-06 M) as compared to the actual N-Springs water (1.49E-06M). It is likely that the calcium concentration, which is nearly 500 times higher than the strontium concentration, is controlling the volume of solution that can be processed.

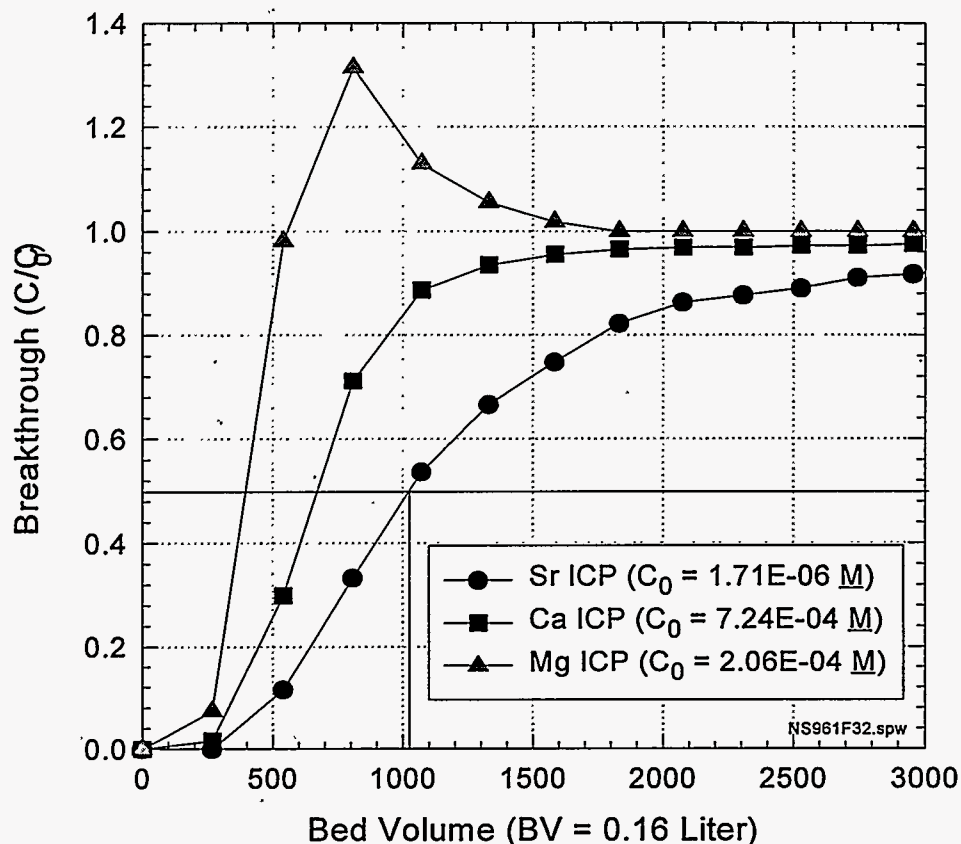
### 3.2 Interferant Loading

Figure 3.2 shows the 3M cartridge results for the removal of calcium, magnesium, and strontium from the simulated N-Springs solution. Magnesium is initially loaded on the NaTi material for the first 500 BV, but is displaced later in the loading sequence. The magnesium concentration exceeds the input value between 500 and 1500 BV, indicating that the magnesium is being eluted from the cartridge by another more strongly bound ion (e.g., calcium and/or strontium). Calcium, however, is not displaced and is loaded on the NaTi in a manner similar to strontium. This same alkaline earth breakthrough behavior was noted previously (Herbst et al. 1995) for the NaTi material loaded with ground water from the Test Area North (TAN) at the Idaho National Engineering Laboratory (INEL). Since the concentration of calcium is approximately 500 times greater than that of strontium, the NaTi becomes saturated with calcium. Therefore, the majority of the material's capacity is filled with calcium. Strontium breakthrough is eventually observed even though the material exhibits a high selectivity for strontium over calcium. It is interesting to note that the cartridge effluent strontium concentration does not completely return to the influent or feed value over the course of the experiment, suggesting that either strontium continues to load onto the NaTi material and additional solution could be processed given additional time, or the influent sample analysis ( $C_0$ ) may be in error.

### 3.3 PADU Demonstration

Figures 3.3 and 3.4 show the results for the PADU demonstration. The PADU was evaluated through three load sequences, each containing two vessels in series and one cartridge change-out. Unfortunately, an ongoing operational failure prevented the system from loading two vessels in series. One or more of the cartridges in vessel #2 detached during system pressurization before the experiment began. Because of this problem, the cartridges never properly loaded and they allowed unprocessed

## N-Springs Strontium Removal Demonstration Ca, Mg, Sr Ion Exchange Loading Summary

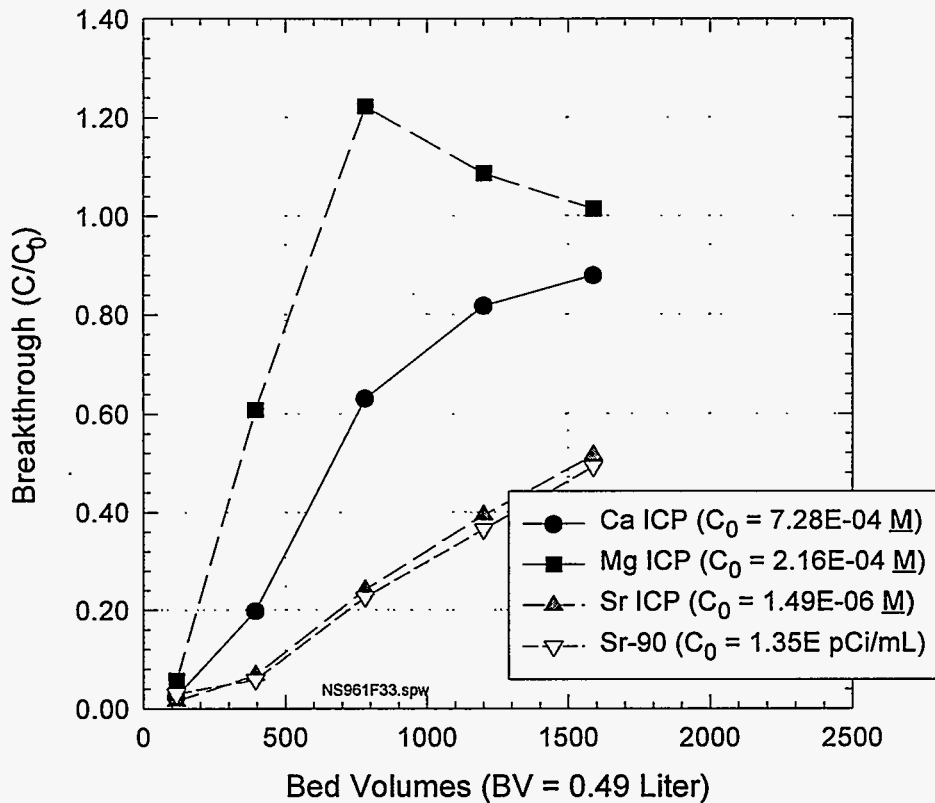


**Figure 3.2.** Calcium, Magnesium, and Strontium Breakthrough Curves for a Laboratory-Scale NaTi/WWL Cartridge in Simulated Ground Water from Hanford N-Springs

water to pass through the vessel throughout the entire test. When the unit electronically switched to the second sequence, this vessel became the lead vessel. At this point, solution passed untreated to the trailing vessel, forcing a premature loading of those cartridges. In effect, at no point during the experiment were there two fully functional vessels in series.

The PADU system was designed to hold 25-cm cartridges, not the 18-cm cartridges. Because of the time constraints placed on the demonstration, 3M could not produce the larger cartridges on such short notice. In addition, a spacer capable of holding the smaller cartridges in place was thought to be unnecessary and potentially difficult to work with under radiological conditions. For these reasons, the system was delivered without the necessary spacers. During the preliminary system pressurization and functional testing, a large back pressure developed that evidently dislodged the cartridges from their position within the second vessel. The pressure drop across each vessel indicated a problem might exist, but the specific problem and its source could not be confirmed until the test had been completed.

N-Springs Strontium Removal Demonstration  
Ca, Mg, Sr Ion Exchange Loading Summary  
3M PADU Samples NSS3-C0 to NSS3-C4



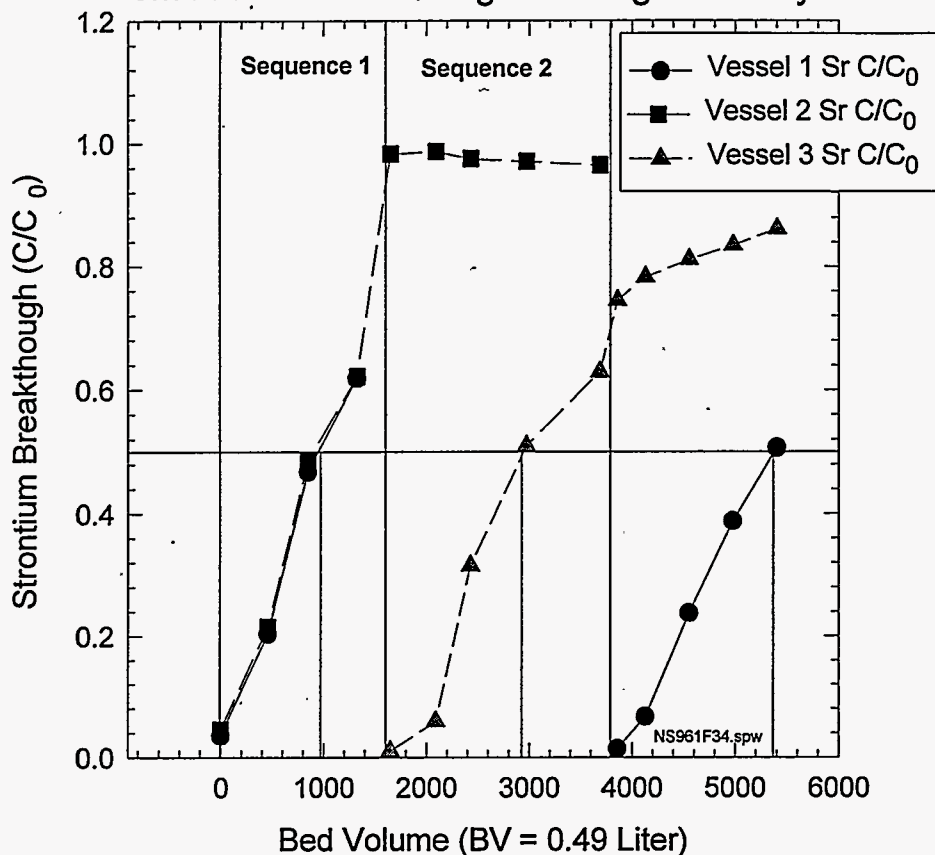
**Figure 3.3.** Calcium, Magnesium, and Strontium Breakthrough Curves for a NaTi/WWL Cartridge in Actual Ground Water During the Third Sequence of Hanford N-Springs PADU Demonstration

The results displayed in Figure 3.3 depict the loading of calcium, magnesium, and strontium on the three parallel cartridges contained in the trailing vessel (#1) during the third PADU sequence. Strontium removal data were collected using strontium ICP and strontium-90 beta counting. Note that the two strontium analyses are nearly identical, with the strontium-90 beta counting results only slightly below those of the strontium ICP. One possible reason for this difference could be a less than 100% collection efficiency during the strontium-90 analytical separation method. Note that the strontium breakthrough results displayed in Figure 3.3 are slightly better (i.e., shifted to higher volume) than those shown in Figure 3.1 because of a slightly reduced strontium concentration (1.0 vs. 1.3 pCi/mL) reaching the trailing vessel.

The effect of the dislodged cartridge is evident in Figure 3.4. During the first sequence, the effluent from both vessel #1 and #2 show identical breakthrough, suggesting that the second vessel is ineffective. During the second sequence, vessel #2 passes untreated water (constant  $C/C_0 = 1$ ) to the third vessel,



## N-Springs Strontium Removal Demonstration 3M PADU Ion Exchange Loading Summary



**Figure 3.4.** Strontium Breakthrough Curves During PADU Sequencing at Hanford N-Springs

which loads to nearly 0.7 C/C<sub>0</sub>. At this point, the unit switched to the third sequence and the effluent of vessel #3 increased to nearly 0.9 C/C<sub>0</sub>. A slightly delayed breakthrough curve is observed for vessel #1 since that vessel is in the trailing position and is subjected to a slightly reduced strontium concentration.

### 3.4 Ion Exchange Loading Capacity

The total cation loading of the NaTi/WWL web material was evaluated by determining the influent and effluent barium, calcium, magnesium, and strontium concentrations as a function of time and volume over the course of the PADU field demonstration at the Hanford N-Springs. The elemental loadings are displayed in Table 3.1 as a function of NaTi/WWL web mass (mmol/g) and volume (mmol/mL). From these data, it is clear that the majority of the NaTi/WWL web capacity (9.47E-01 mmol/g) is loaded with calcium (8.68E-01 mmol/g) under the conditions of the test. Based on an assumed total capacity of 9.47E-01 mmol/g, only 0.30% of the material's capacity is loaded with strontium. Barium, calcium, and magnesium occupy 0.03%, 91.66%, and 8.01% of the total, respectively.

The capacity and loading data described above assume that the NaTi/WWL material removes only the detected alkaline earth metals (i.e., barium, calcium, magnesium, and strontium) from the N-Springs water. No other metals loading was measured using the ICP analytical data because the data were below the detection limit. However, the sodium ICP data displayed in Table 3.1 provide an additional check on the NaTi/WWL capacity. To preserve the ionic charge balance, for each divalent (e.g., Ca<sup>2+</sup>) cation loaded, two monovalent (in this case, Na<sup>+</sup>) cations must be expelled from the material. During the PADU demonstration, 1.78E+00 mmol Na was released per gram of NaTi/WWL. In comparison, a total of 9.47E-01 mmol (1.89E+00 meq) of divalent cations were loaded. These data provide a secondary check and indicate that the majority of the ion exchange has been taken into account. However, it is important to note that these data are reported on the basis of the entire NaTi/WWL web mass or volume and not the mass or volume of the NaTi material alone.

Using the data from Table 3.1 and the equilibrium concentration of barium, calcium, magnesium, and strontium in the actual N-Springs water (Table 2.2), the ion exchange selectivity coefficient (K<sub>c</sub>) can be calculated from the following equation:

$$K_c = \frac{C_B^{v_A} \times C_{SA}^{v_B}}{C_A^{v_B} \times C_{SB}^{v_A}} \quad (3)$$

where C<sub>A</sub> and C<sub>B</sub> = the equilibrium concentrations of ions A and B in solution  
 C<sub>SA</sub> and C<sub>SB</sub> = the equilibrium concentrations of ions A and B on the ion exchange material  
 V<sub>A</sub> and V<sub>B</sub> = the ion valences of each ion, respectively.

K<sub>c</sub> is a measure of the preference of an ion exchange material for one ionic species (A) over another (B) and accounts for the concentrations of each ion in solution. In the actual N-Springs water, the calculated selectivity of strontium over barium, calcium, and magnesium is 0.569, 2.57, and 29.7, respectively.

**Table 3.1.** Alkaline Metal Loading of the PADU NaTi/WWL Web with Actual N-Springs Water

Species	Elemental Loading of NaTi/WWL Web		
	mmol/g	mmol/mL	Capacity (%)
Ba	2.84E-04	1.75E-04	0.03%
Ca	8.68E-01	5.34E-01	91.66%
Mg	7.58E-02	4.67E-02	8.01%
Sr	2.85E-03	1.75E-03	0.30%
Total (mmol)	9.47E-01	5.83E-01	100.00%
Total (meq)	1.89E+00	1.17E+00	100.00%
Na	-1.78E+00	-1.10E+00	-94.25%
Balance (meq)	1.09E-01	6.70E-02	-11.51%

## 4.0 Conclusions

Strontium removal from simulated and actual N-Springs well water was demonstrated using an AlliedSignal NaTi material engineered into a web adsorbent cartridge (NaTi/WWL) developed by 3M. Laboratory tests were completed using a 2.5-cm disk and an 18-cm cartridge. The laboratory tests effectively predicted the loading breakthrough curve expected for the multiple cartridge/multiple vessel PADU. In every test, approximately 1000 BV of solution was passed through the NaTi material before reaching 0.5  $C/C_0$ . This was the case irrespective of solution (simulated or actual), material geometry (disks or cartridges), or material volume (single or multiple cartridges). The NaTi material was shown to remove calcium, magnesium, and strontium from the N-Springs ground-water matrix. Based on these experiments, the following observations and conclusions are made:

- The 3M PADU was operated successfully by BHI personnel at the N-Springs Pump and Treat Demonstration Facility. Although minor system difficulties were encountered, the effectiveness of the NaTi/WWL membrane for removing strontium from Hanford ground water was demonstrated.
- Laboratory testing of small-scale disks and process-scale cartridges using simulated and actual ground water effectively predicted the field performance of the PADU. Approximately 1000 BVs of solution could be processed before reaching a strontium  $C/C_0$  of 0.5. These data suggest that accurate scaleup of process performance data from laboratory disk tests to full-scale cartridge systems is likely. Complete loading breakthrough curves were generated for barium, calcium, magnesium, and strontium.
- The disk loading (mmol strontium per gram or milliliter of resin) of the NaTi/WWL material was calculated to be 2.61E-03 mmol/g (1.57E-03 mmol/mL) for the actual N-Springs water. Elution was accomplished with 0.5M  $HNO_3$  at 7.5 BV/min and required 80 BV to reach 0.1 strontium  $C/C_0$ .
- During the field demonstration, the PADU cartridge loading (mmol/g) was determined to be 2.84E-04, 8.68E-01, 7.58E-02, and 2.85E-03 for barium, calcium, magnesium, and strontium, respectively. In addition, 1.78E+00 mmol Na/g was released during loading, confirming the mass balance.

Additional testing is needed to evaluate this material over a wider range of solution conditions and to compare its performance to other potential strontium removal candidates.

## 5.0 References

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## **Appendix**

### **Laboratory Data**

Table A.1: ICP-AES Instrument Characteristics and Performance

Element	Wavelength (nm)	Estimated IDL (ppm)	EQL (ppm)	Linear Dynamic Range (ppm)
Ag	328.068	0.00206	0.01	0.003-150
Al	308.215	0.00984	0.05	0.025-500
As	193.696	0.02291	0.10	0.050-250
B	249.678	0.00626	0.05	0.006-150
Ba	455.403	0.00031	0.05	0.001-100
Be	313.042	0.00025	0.005	0.001-150
Bi	223.061	0.02461	0.10	0.030-500
Ca	317.933	0.00717	0.10	0.010-500
Cd	226.502	0.00186	0.01	0.004-200
Ce	413.765	0.03011	0.10	0.050-250
Co	228.616	0.00341	0.02	0.003-150
Cr	267.716	0.00204	0.01	0.005-150
Cu	324.754	0.00159	0.01	0.002-150
Eu	393.948	0.00411	0.05	0.005-100
Fe	259.940	0.00261	0.05	0.005-150
K	766.491	0.32211	0.50	0.400-1000
La	408.672	0.00231	0.05	0.004-150
Li	670.784	0.00063	0.01	0.006-200
Mg	279.079	0.01041	0.10	0.015-500
Mn	257.610	0.00042	0.01	0.001-150
Mo	202.030	0.00552	0.05	0.005-200
Na	588.995	0.00698	0.10	0.010-200
Nd	401.225	0.00469	0.10	0.010-200
Ni	231.604	0.01411	0.02	0.010-200
P	178.287	0.03041	0.20	0.060-250
Pb	220.353	0.02721	0.10	0.025-200
S	182.040	0.01971	0.10	0.080-500
Sb	206.838	0.01811	0.06	0.050-200
Se	196.026	0.03491	0.10	0.050-250
Si	251.611	0.00555	0.05	0.010-500
Sm	443.430	0.00943	0.10	0.020-100
Sr	421.552	0.00031	0.01	0.001-100
Th	283.730	0.00316	0.05	0.030-150
Ti	334.941	0.00112	0.01	0.002-200
Tl	190.864	0.03411	0.20	0.050-500
U	385.958	0.03451	0.50	0.100-300
V	292.402	0.00256	0.05	0.002-200
Zn	213.856	0.00238	0.01	0.004-150
Zr	339.198	0.00202	0.01	0.003-250

Table A.2. Strontium Loading Data for PNNL Disk Test Using Actual N-Springs Water

Time (min)	Sample Number	Vol. (BV)	Vol. (mL)	Strontium (mg/L)	Strontium (cnts)	Strontium (C/C <sub>0</sub> )	Loaded (mmol Sr)
0	96B-Fd	0.0	0.0	1.30E-01	1.40E+04	1.00E+00	1.80E-03
5	96B-01	29.3	28.8	9.27E-06	<1.00E+00	<7.13E-05	2.13E-05
10	96B-02	60.9	59.8	9.27E-06	<1.00E+00	<7.13E-05	6.73E-05
15	96B-03	92.6	91.0	9.27E-06	<1.00E+00	<7.13E-05	1.14E-04
20	96B-04	123.6	121.4	9.27E-06	<1.00E+00	<7.13E-05	1.59E-04
25	96B-05	155.2	152.4	9.27E-06	<1.00E+00	<7.13E-05	2.05E-04
30	96B-06	186.5	183.1	9.27E-06	<1.00E+00	<7.13E-05	2.50E-04
35	96B-07	217.5	213.5	9.27E-06	<1.00E+00	<7.13E-05	2.95E-04
40	96B-08	248.9	244.4	9.27E-06	<1.00E+00	<7.13E-05	3.41E-04
45	96B-09	279.8	274.7	9.27E-06	<1.00E+00	<7.13E-05	3.86E-04
50	96B-10	310.8	305.1	9.27E-06	<1.00E+00	<7.13E-05	4.31E-04
55	96B-11	342.3	336.1	9.27E-06	<1.00E+00	<7.13E-05	4.77E-04
60	96B-12	373.4	366.6	9.27E-06	<1.00E+00	<7.13E-05	5.23E-04
70	96B-13	436.6	428.6	2.98E-03	3.22E+02	2.30E-02	6.13E-04
80	96B-14	500.1	491.0	1.03E-02	1.11E+03	7.92E-02	7.01E-04
90	96B-15	564.7	554.4	1.90E-02	2.05E+03	1.46E-01	7.85E-04
100	96B-16	627.5	616.1	2.84E-02	3.07E+03	2.19E-01	8.60E-04
110	96B-17	694.1	681.5	3.80E-02	4.10E+03	2.93E-01	9.32E-04
120	96B-18	757.8	744.0	4.84E-02	5.22E+03	3.72E-01	9.94E-04
130	96B-19	822.6	807.6	5.62E-02	6.06E+03	4.32E-01	1.05E-03
150	96B-20	950.9	933.5	7.13E-02	7.69E+03	5.48E-01	1.15E-03
180	96B-21	1142.2	1121.3	9.12E-02	9.83E+03	7.01E-01	1.25E-03
195	96B-22	1239.1	1216.5	9.17E-02	9.89E+03	7.06E-01	1.29E-03



**Table A.3. Strontium Elution Data for PNNL Disk Test Using Actual N-Springs Water**

Time (min)	Sample Number	Vol. (BV)	Vol. (mL)	Strontium (mg/L)	Strontium (cnts)	Strontium (C/C <sub>0</sub> )	Eluted (mmol Sr)
1	96B-23	5.0	4.9	9.83E-01	1.06E+05	7.56E+00	2.74E-05
2	96B-24	11.5	11.3	5.22E+00	5.63E+05	4.02E+01	2.55E-04
3	96B-25	18.0	17.6	9.46E+00	1.02E+06	7.27E+01	7.83E-04
4	96B-26	24.9	24.5	3.22E+00	3.47E+05	2.47E+01	1.28E-03
5	96B-27	31.1	30.6	8.84E-01	9.54E+04	6.80E+00	1.42E-03
6	96B-28	35.4	34.8	5.46E-01	5.89E+04	4.20E+00	1.45E-03
7	96B-29	40.7	39.9	3.12E-01	3.36E+04	2.40E+00	1.48E-03
8	96B-30	47.2	46.3	2.13E-01	2.29E+04	1.64E+00	1.50E-03
9	96B-31	52.5	51.6	2.01E-01	2.17E+04	1.55E+00	1.51E-03
10	96B-32	59.2	58.1	1.36E-01	1.46E+04	1.04E+00	1.52E-03
11	96B-33	65.0	63.9	5.91E-02	6.37E+03	4.54E-01	1.53E-03
12	96B-34	72.5	71.1	3.83E-02	4.14E+03	2.95E-01	1.53E-03
14	96B-35	82.0	80.5	2.89E-02	3.11E+03	2.22E-01	1.54E-03
16	96B-36	94.8	93.1	2.05E-02	2.21E+03	1.58E-01	1.54E-03
18	96B-37	109.0	107.0	1.52E-02	1.64E+03	1.17E-01	1.54E-03
20	96B-38	123.8	121.6	1.05E-02	1.14E+03	8.10E-02	1.55E-03

**Table A.4. Strontium Loading Data for PADU Cartridge Field Demonstration at N-Springs**

Time (min)	Sample Number	Vol. (BV)	Vol. (L)	Strontium (mg/L)	Strontium (μg/L)	Strontium (C/C <sub>0</sub> )	Loaded (mmol Sr)
0	C3Sr-Fd	0.0	0.0	1.31E-01	1.31E+02	1.00E+00	1.19E+00
6	C3Sr-01	170.5	83.2	2.00E-03	2.00E+00	1.53E-02	6.10E-02
16	C3Sr-02	449.6	219.2	8.90E-03	8.90E+00	6.82E-02	2.55E-01
31	C3Sr-03	837.2	408.2	3.14E-02	3.14E+01	2.41E-01	4.93E-01
46	C3Sr-04	1255.8	612.4	5.12E-02	5.12E+01	3.92E-01	7.01E-01
61	C3Sr-05	1643.4	801.4	6.69E-02	6.69E+01	5.12E-01	8.56E-01

**Table A.5. Barium Loading Data for PADU Cartridge Field Demonstration at N-Springs**

Time (min)	Sample Number	Vol. (BV)	Vol. (L)	Barium (mg/L)	Barium ( $\mu\text{g/L}$ )	Barium ( $C/C_0$ )	Loaded (mmol Ba)
0	C3Ba-Fd	0.0	0.0	1.54E-02	1.54E+01	1.00E+00	8.99E-02
6	C3Ba-01	170.5	83.2	<1.00E-05	<1.00E-02	0.00E+00	4.66E-03
16	C3Ba-02	449.6	219.2	<1.00E-05	<1.00E-02	0.00E+00	1.99E-02
31	C3Ba-03	837.2	408.2	<1.00E-05	<1.00E-02	0.00E+00	4.11E-02
46	C3Ba-04	1255.8	612.4	<1.00E-05	<1.00E-02	0.00E+00	6.40E-02
61	C3Ba-05	1643.4	801.4	<1.00E-05	<1.00E-02	0.00E+00	8.52E-02

**Table A.6. Calcium Loading Data for PADU Cartridge Field Demonstration at N-Springs**

Time (min)	Sample Number	Vol. (BV)	Vol. (L)	Calcium (mg/L)	Calcium (mg/L)	Calcium ( $C/C_0$ )	Loaded (mmol Ca)
0	C3Ca-Fd	0.0	0.0	2.92E+01	2.92E+01	1.00E+00	5.83E+02
6	C3Ca-01	170.5	83.2	7.29E-01	7.29E-01	2.50E-02	2.95E+01
16	C3Ca-02	449.6	219.2	5.79E+00	5.79E+00	1.99E-01	1.18E+02
31	C3Ca-03	837.2	408.2	1.84E+01	1.84E+01	6.30E-01	1.98E+02
46	C3Ca-04	1255.8	612.4	2.38E+01	2.38E+01	8.16E-01	2.39E+02
61	C3Ca-05	1643.4	801.4	2.56E+01	2.56E+01	8.77E-01	2.60E+02

**Table A.7. Magnesium Loading Data for PADU Cartridge Field Demonstration at N-Springs**

Time (min)	Sample Number	Vol. (BV)	Vol. (L)	Magnesium (mg/L)	Magnesium (mg/L)	Magnesium ( $C/C_0$ )	Loaded (mmol Mg)
0	C3Mg-Fd	0.0	0.0	5.25E+00	5.25E+00	1.00E+00	1.73E+02
6	C3Mg-01	170.5	83.2	2.96E-01	2.96E-01	5.64E-02	8.48E+00
16	C3Mg-02	449.6	219.2	3.19E+00	3.19E+00	6.08E-01	2.81E+01
31	C3Mg-03	837.2	408.2	6.41E+00	6.41E+00	1.22E+00	3.16E+01
46	C3Mg-04	1255.8	612.4	5.70E+00	5.70E+00	1.09E+00	2.48E+01
61	C3Mg-05	1643.4	801.4	5.33E+00	5.33E+00	1.01E+00	2.28E+01

Table A.8. Sodium Loading Data for PADU Cartridge Field Demonstration at N-Springs

Time (min)	Sample Number	Vol. (BV)	Vol. (L)	Sodium (mg/L)	Sodium ( $\mu\text{g/L}$ )	Sodium (C/C <sub>0</sub> )	Loaded (mmol Na)
0	C3Na-Fd	0.0	0.0	5.94E+00	5.94E+03	1.00E+00	2.07E+02
6	C3Na-01	170.5	83.2	5.12E+01	5.12E+04	8.62E+00	-8.18E+01
16	C3Na-02	449.6	219.2	3.58E+01	3.58E+04	6.04E+00	-3.04E+02
31	C3Na-03	837.2	408.2	1.39E+01	1.39E+04	2.34E+00	-4.60E+02
46	C3Na-04	1255.8	612.4	9.49E+00	9.49E+03	1.60E+00	-5.11E+02
61	C3Na-05	1643.4	801.4	8.39E+00	8.39E+03	1.41E+00	-5.35E+02

Table A.9. Strontium Loading Data for 3M Laboratory Cartridge Test Using Simulant

Time (min)	Sample Number	Vol. (BV)	Vol. (L)	Strontium (mg/L)	Strontium ( $\mu\text{g/L}$ )	Strontium (C/C <sub>0</sub> )	Loaded (mmol Sr)
0	3MSr-Fd	0.0	0.0	1.47E-01	1.47E+02	1.00E+00	8.06E-01
15	3MSr-01	268.5	43.6	0.00E+00	0.00E+00	0.00E+00	3.66E-02
30	3MSr-02	540.2	87.8	1.70E-02	1.70E+01	1.16E-01	1.06E-01
45	3MSr-03	808.7	131.4	4.90E-02	4.90E+01	3.33E-01	1.63E-01
60	3MSr-04	1072.7	174.4	7.90E-02	7.90E+01	5.37E-01	2.04E-01
75	3MSr-05	1331.1	216.4	9.80E-02	9.80E+01	6.67E-01	2.32E-01
90	3MSr-06	1584.2	257.5	1.10E-01	1.10E+02	7.48E-01	2.52E-01
105	3MSr-07	1833.0	297.9	1.21E-01	1.21E+02	8.23E-01	2.67E-01
120	3MSr-08	2077.2	337.6	1.27E-01	1.27E+02	8.64E-01	2.77E-01
135	3MSr-09	2309.2	375.3	1.29E-01	1.29E+02	8.78E-01	2.85E-01
150	3MSr-10	2529.1	411.1	1.31E-01	1.31E+02	8.91E-01	2.92E-01
165	3MSr-11	2745.1	446.2	1.34E-01	1.34E+02	9.12E-01	2.98E-01
180	3MSr-12	2957.0	480.6	1.35E-01	1.35E+02	9.18E-01	3.03E-01

**Table A.10. Calcium Loading Data for 3M Laboratory Cartridge Test Using Simulant**

Time (min)	Sample Number	Vol. (BV)	Vol. (L)	Calcium (mg/L)	Calcium ( $\mu\text{g/L}$ )	Calcium ( $C/C_0$ )	Loaded (mmol Ca)
0	3M <sub>Ca</sub> -Fd	0.0	0.0	2.91E+01	2.91E+04	1.00E+00	3.49E+02
15	3M <sub>Ca</sub> -01	268.5	43.6	4.70E-01	4.70E+02	1.62E-02	1.56E+01
30	3M <sub>Ca</sub> -02	540.2	87.8	8.70E+00	8.70E+03	2.99E-01	4.26E+01
45	3M <sub>Ca</sub> -03	808.7	131.4	2.07E+01	2.07E+04	7.11E-01	5.83E+01
60	3M <sub>Ca</sub> -04	1072.7	174.4	2.58E+01	2.58E+04	8.87E-01	6.45E+01
75	3M <sub>Ca</sub> -05	1331.1	216.4	2.72E+01	2.72E+04	9.35E-01	6.73E+01
90	3M <sub>Ca</sub> -06	1584.2	257.5	2.78E+01	2.78E+04	9.55E-01	6.89E+01
105	3M <sub>Ca</sub> -07	1833.0	297.9	2.81E+01	2.81E+04	9.66E-01	7.01E+01
120	3M <sub>Ca</sub> -08	2077.2	337.6	2.82E+01	2.82E+04	9.69E-01	7.10E+01
135	3M <sub>Ca</sub> -09	2309.2	375.3	2.82E+01	2.82E+04	9.69E-01	7.19E+01
150	3M <sub>Ca</sub> -10	2529.1	411.1	2.83E+01	2.83E+04	9.73E-01	7.26E+01
165	3M <sub>Ca</sub> -11	2745.1	446.2	2.83E+01	2.83E+04	9.73E-01	7.33E+01
180	3M <sub>Ca</sub> -12	2957.0	480.6	2.84E+01	2.84E+04	9.76E-01	7.40E+01

**Table A.11. Magnesium Loading Data for 3M Laboratory Cartridge Test Using Simulant**

Time (min)	Sample Number	Vol. (BV)	Vol. (L)	Magnesium (mg/L)	Magnesium ( $\mu\text{g/L}$ )	Magnesium ( $C/C_0$ )	Loaded (mmol Mg)
0	3M <sub>Mg</sub> -Fd	0.0	0.0	5.40E+00	5.40E+03	1.00E+00	1.07E+02
15	3M <sub>Mg</sub> -01	268.5	43.6	4.00E-01	4.00E+02	7.41E-02	4.49E+00
30	3M <sub>Mg</sub> -02	540.2	87.8	5.30E+00	5.30E+03	9.81E-01	9.12E+00
45	3M <sub>Mg</sub> -03	808.7	131.4	7.10E+00	7.10E+03	1.31E+00	7.69E+00
60	3M <sub>Mg</sub> -04	1072.7	174.4	6.10E+00	6.10E+03	1.13E+00	5.57E+00
75	3M <sub>Mg</sub> -05	1331.1	216.4	5.70E+00	5.70E+03	1.06E+00	4.70E+00
90	3M <sub>Mg</sub> -06	1584.2	257.5	5.50E+00	5.50E+03	1.02E+00	4.37E+00
105	3M <sub>Mg</sub> -07	1833.0	297.9	5.40E+00	5.40E+03	1.00E+00	4.28E+00
120	3M <sub>Mg</sub> -08	2077.2	337.6	5.40E+00	5.40E+03	1.00E+00	4.28E+00
135	3M <sub>Mg</sub> -09	2309.2	375.3	5.40E+00	5.40E+03	1.00E+00	4.28E+00
150	3M <sub>Mg</sub> -10	2529.1	411.1	5.40E+00	5.40E+03	1.00E+00	4.28E+00
165	3M <sub>Mg</sub> -11	2745.1	446.2	5.40E+00	5.40E+03	1.00E+00	4.28E+00
180	3M <sub>Mg</sub> -12	2957.0	480.6	5.40E+00	5.40E+03	1.00E+00	4.28E+00

**Table A.12. Sodium Loading Data for 3M Laboratory Cartridge Test Using Simulant**

Time (min)	Sample Number	Vol. (BV)	Vol. (L)	Sodium (mg/L)	Sodium ( $\mu\text{g/L}$ )	Sodium ( $C/C_0$ )	Loaded (mmol Na)
0	3MNa-Fd	0.0	0.0	3.60E+00	3.60E+03	1.00E+00	7.53E+01
15	3MNa-01	268.5	43.6	5.25E+01	5.25E+04	1.46E+01	-4.64E+01
30	3MNa-02	540.2	87.8	2.97E+01	2.97E+04	8.25E+00	-1.18E+02
45	3MNa-03	808.7	131.4	1.19E+01	1.19E+04	3.31E+00	-1.51E+02
60	3MNa-04	1072.7	174.4	7.50E+00	7.50E+03	2.08E+00	-1.62E+02
75	3MNa-05	1331.1	216.4	6.40E+00	6.40E+03	1.78E+00	-1.69E+02
90	3MNa-06	1584.2	257.5	5.90E+00	5.90E+03	1.64E+00	-1.73E+02
105	3MNa-07	1833.0	297.9	5.70E+00	5.70E+03	1.58E+00	-1.77E+02
120	3MNa-08	2077.2	337.6	5.50E+00	5.50E+03	1.53E+00	-1.80E+02
135	3MNa-09	2309.2	375.3	5.20E+00	5.20E+03	1.44E+00	-1.83E+02
150	3MNa-10	2529.1	411.1	5.10E+00	5.10E+03	1.42E+00	-1.86E+02
165	3MNa-11	2745.1	446.2	5.00E+00	5.00E+03	1.39E+00	-1.88E+02
180	3MNa-12	2957.0	480.6	4.90E+00	4.90E+03	1.36E+00	-1.90E+02

**Table A.13. Strontium-90 Loading Data for PADU Cartridge Field Demonstration at N-Springs**

Time (min)	Sample Number	Vol. (BV)	Vol. (L)	Strontium (pCi/mL)	Strontium (pCi/L)	Strontium ( $C/C_0$ )	Loaded (pCi)
0	C3Sr9-Fd	0.0	0.0	1.32E+00	1.32E+03	1.00E+00	1.06E+06
6	C3Sr9-01	170.5	83.2	4.00E-02	4.00E+01	3.03E-02	5.32E+04
16	C3Sr9-02	449.6	219.2	7.80E-02	7.80E+01	5.91E-02	2.25E+05
31	C3Sr9-03	837.2	408.2	2.99E-01	2.99E+02	2.27E-01	4.39E+05
46	C3Sr9-04	1255.8	612.4	4.82E-01	4.82E+02	3.65E-01	6.28E+05
61	C3Sr9-05	1643.4	801.4	6.50E-01	6.50E+02	4.92E-01	7.71E+05

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