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Treatment Tests for Ex Situ Removal of Chromate, Nitrate, and Uranium (VI) from Hanford (100-HR-3) Groundwater Final Report

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7. Abstract

This report describes batch and ion exchange column laboratory scale studies investigating *ex situ* methods to remove chromate (chromium [VI]), nitrate (NO_3^-) and uranium (present as uranium [VI]) from contaminated Hanford site groundwaters. The technologies investigated include: chemical precipitation or coprecipitation to remove chromate and uranium; and anion exchange to remove chromate, uranium and nitrate. The technologies investigated were specified in the 100-HR-3 Groundwater Treatability Test Plan. The method suggested for future study is anion exchange.

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1.0 INTRODUCTION

This report describes batch and anion exchange column laboratory-scale studies investigating *ex situ* methods to remove chromate (chromium [VI]), nitrate (NO_3^-), and uranium (present as uranyl (uranium [VI]) carbonato anionic species) from contaminated Hanford Site groundwaters. The technologies investigated include chemical precipitation or coprecipitation to remove chromate and uranium, and anion exchange to remove chromate, uranium, and nitrate. The technologies investigated were specified in the *100-HR-3 Groundwater Treatability Test Plan* (DOE-RL 1993). The goal of these tests was to determine the best method to remove selected contaminants to below the concentration of the project performance goals (Table 1). The raw data and observations made during these tests can be found in the Westinghouse Hanford Company (WHC) laboratory notebooks (Beck 1992, Herting 1993).

The method recommended for future study is anion exchange with Dowex 21K resin.

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1.1 BACKGROUND

The 100-HR-3 Operable Unit is a groundwater unit near the 100-H Reactor. Due to past reactor operations, the groundwater has become contaminated with uranium, chromate, and nitrate. The uranium is most likely in the form of a uranyl carbonato anion complex $[UO_2(CO_3)_3]^{-2}$ (IT Corp. 1989, Appendix F). Chromium is present in the groundwater as chromate. Nitrate is also present in this groundwater. Analyses of an uncontaminated well (119-H3-2) from the 100-H Area are presented in Appendix A. The concentrations of selected contaminants for the wells selected for testing can be found in the data on breakthrough tests.

Table 1. Performance Goals (DOE-RL 1993).

Contaminant	Performance goal
Total alpha, pCi/L	15[a]
Total beta, pCi/L	40[b]
Chromium (total), µg/L	100[a]
Nitrate (as NO_3), µg/L	45,000[a]
Uranium, µg/L	22[c]

---

[a] Maximum Contaminant Level (40 CFR 141).

[b] Value is 0.04 x Derived Concentration Guide for radionuclides in water (WHC 1988).

[c] Derived from the total alpha performance goal, assuming natural uranium isotopic composition.

The wells tested were selected in the Test Plan (DOE-RL 1993) to provide a wide range of contaminant levels and to be representative of the groundwater found in the 100-HR-3 Operable Unit. Well 199-H3-2C was used as an uncontaminated starting material for spiking. The spiking levels for nitrate and chromate were chosen to represent the upper bound on groundwater contamination in the 100-H Area. The uranium spiking level was chosen to be considerably above the upper bound of likely groundwater contamination, so that the efficacy of treatment could be ascertained. The uranium spike level was planned to be about 800 ppb; however, due to difficulties in spiking, the actual level was less and is reported along with each test.

The selection of analytes, contaminants for removal, and considerable background are topics discussed at length in the Test Plan (DOE-RL 1993) and the Test Procedures (Beck and Delegard 1993). To avoid duplication, those discussions will not be repeated here. The major thrust of this series of tests is to determine which of several treatment options will remove the contaminants of interest from ambient (not pH adjusted) groundwater from the 100-HR-3 Operable Unit.

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The analytical methods used are presented in Table 2.

2.0 PRECIPITATION METHODS

2.1 INTRODUCTION

Two precipitation methods, sulfide precipitation and brushite coprecipitation, were tested for removal of contaminants. The ferrous sulfate/sodium sulfide method was specified in the Test Plan (DOE-RL 1993) as a likely method for chromate reduction and removal. The brushite coprecipitation method was specified by Beck and Delegard (1993) as a likely method of uranium removal. The goal of the precipitation tests was to determine if the uranium and/or chromium could be removed to less than the performance goals specified in the Test Plan (DOE-RL 1993) and Table 1 of this document.

The chemical rationale for the sulfide method was to use sodium sulfide (Na_2S) and ferrous sulfate ($FeSO_4$) to first reduce Cr(VI) to Cr(III) and then to coprecipitate the reduced chromium with the resulting ferric hydroxide ($Fe(OH)_3$) and/or ferric sulfide (Fe_xS_y). The possible reduction and/or precipitation and retention of uranium (VI) by this technique was also tested. Refer to the Test Procedures (Beck and Delegard 1993) for a more complete discussion and references to the literature.

Table 2. Chemical Analyses.

Analyte(s)	Method #	Title	Minimum detection limit
Cations (ICP)	LA-505-241	ICP Emission Spectrometer Method for Trace Element Analysis of water and waste	50 ppb
Total chromium	LA-505-151 LA-505-241	ICP Emission Spectrometer Method for Trace Element Analysis of water and waste	29 ppb
Chromium(VI)	LA-265-101	Spectrophotometric determination of Cr(VI)	19 ppb
Anion (IC)	LA-533-105 LA-533-201	Anion analysis on Dionex Model 4000i	10,000 ppb
Nitrate	LA-533-105 LA-533-201	Anion analysis on Dionex Model 4000i	10,000 ppb
Uranium	LA-925-007	Uranium by laser induced kinetic phosphorescence	1 ppb U
Total organic carbon	LA-344-105	Determination of carbon in solutions by combustion and coulometry	N/A
Total inorganic carbon	LA-622-102	Determination of carbonate/carbon or TIC in solutions by coulometry	N/A
Total alpha and total beta	LA-548-203	Alpha and beta in liquid sample	
pH	LA-212-102	Determination of pH direct measurement	N/A

N/A - The actual detection limit is determined by the amount of sample available and the count.

Simple addition of disodium hydrogen phosphate (Na_2HPO_4) to precipitate brushite ($CaHPO_4$) from the contained calcium ion naturally present in the Hanford Site groundwater was tested for its efficacy in removing U(VI). Scouting experiments showed that additional calcium ion, introduced as calcium chloride ($CaCl_2$) solution to the groundwater, was required to provide sufficient precipitate to carry uranium. The incidental removal of chromate from solution by coprecipitation with brushite was also investigated.

Neither of these methods was expected to provide nitrate removal.

2.2 EXPERIMENTAL

The precipitation tests were conducted by adding the precipitating agents to 30 mL of spiked groundwater solution, then stirring via a magnetic stir bar for 30 minutes, followed by 3 minutes of centrifugation. A setting of "5" on an International Equipment Company clinical centrifuge was used, yielding a "g" force of 320±130 g (at 90% confidence) at the top of the 30 mL of water and 600±250 g at the bottom of the centrifuge cone. The samples were then filtered, using a 0.45-µm cellulose acetate filter. The sodium sulfide/ferrous sulfate treatment was accomplished by adding a dilute stock solution of sodium sulfide to produce 12 mg S^{-2}/L in the final test solution, and then adding ferrous sulfate stock solution to produce 9.9 mg Fe^{+2}/L in the final test solution. The phosphate treatment was accomplished by adding sodium hydrogen phosphate stock solution to produce 5,550 mg HPO_4^{-2}/L in the final solution and calcium chloride stock solution sufficient to produce (in conjunction with natural calcium) 92 mg Ca^{+2}/L. The levels of HPO_4^{-2} and Ca^{+2} were determined in scouting experiments as those levels that gave the best precipitation, as determined by visual observation.

The test was a full factorial experiment, which means that all combinations of the variables of interest (uranium, nitrate, chromium) were explored. Each variable had two levels, which yields eight different solutions (to vary the concentrations of contaminants). Each test was performed in duplicate. Blanks and standards were shipped with each batch of samples. Due to the small amounts of sample, no replicate analyses were done.

2.2.1 Quality Control

All precipitation tests were done in duplicate. Method blanks and standards were sent with each batch of samples. Analytical quality control (performed at PUREX Laboratory) included standards with every batch run for all the analyses. All standards fell within acceptable (±20% relative standard deviation) limits. No contamination was detected in the method blanks. A test of the effect of the filtering process on the concentrations of contaminants was performed. No effect from filtering could be seen (Appendix B). Values of chromium were higher after treatment for some samples (EBPS1501, EBPD1501, EBPS1601, EBPD1601) than the starting concentrations. No apparent explanation for this discrepancy exists.

2.3 RESULTS

Table 3 summarizes the results of the batch tests for the precipitation tests. The data that Table 3 summarizes can be found in Appendix C. The decontamination factor (DF) is the original concentration of the contaminant, as determined by the laboratory, divided by the amount found after treatment.

$$DF = C_o/C_{final}$$

Table 3. Average Decontamination Factors for Precipitation Methods.

Method	Uranium	Nitrate	Total chromium by ICP	Chromium (VI)
Sodium sulfide/ ferrous sulfate	1.3[a]	0.9	9.6	64
Sodium hydrogen phosphate without added calcium chloride	0.9	1.0	1.2	1.2
Sodium hydrogen phosphate with added calcium chloride	32	1.1	0.9	1.6
Filter alone	0.9	1.0	1.3	0.9
Standard, no treatment	1.5	1.0	1.3	1.9

[a] The data do not support more significant figures than shown in this table.

Higher numbers denote more complete removal of the contaminant from the groundwater. The approximate initial concentrations for the high-level spike are 2,000 ppb for total chromium [chromium by inductively coupled plasma-atomic emission spectroscopy (also referred to as Cr-ICP)] and Cr(VI), 600 ppb for uranium, and 200,000 ppb for nitrate. In this report concentrations are given in terms of parts per billion, which is equivalent to micrograms per liter. Because of experimental errors and the fact that the DF is a ratio, the DFs can be skewed. DF values less than about 2 are not significant, because the standard has DF values not equal to 1 (no apparent change in concentration). The change in concentration could be caused by adsorption of the contaminants (which are at very low levels) onto the wall of the sample container.

The sulfide/ferrous sulfate treatment resulted in a very dark colloidal suspension that was not removed upon centrifugation. This colloidal suspension was, however, removed upon filtration. The volume of material on the filter following was smaller than 1 mL but, due to the small amount of solution treated per test and the corresponding small amount of residue, no measurement of the exact mass or volume was performed. The phosphate-calcium chloride treatment resulted in a fluffy white precipitate that was removed by centrifugation but settled very slowly in gravity settling tests. The phosphate-calcium chloride process precipitate was about one-tenth of the original solution volume before centrifuging and one one-hundredth of the original solution volume after centrifuging. All steps in the process, save the addition of the reagents, were shown to have no significant effect on the concentration of the contaminants.

The high DFs shown in Table 3 may, in fact, be lower than the actual DFs. This is because the limit of detection of the chemical analysis methods as often reached. The limit of detection was used as a final concentration value for those tests in which the final concentration is reported as less than the detection limit. The DFs produced by experimental method (centrifugation and filtration) used are likely to be higher than the DFs produced by a gravity settling and decanting technique, as the method used removed all of the suspension by filtering.

Two conclusions can be drawn: (1) the sodium sulfide, ferrous sulfate treatment removes chromium, especially hexavalent chromium, and (2) the phosphate-calcium chloride treatment produces significant DFs with uranium. Both conclusions are those expected from the literature review. The sulfide treatment fails to remove uranium and the phosphate treatment does not produce significant DFs with chromium. Both treatment methods have little effect on the nitrate concentration.

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The authors are unable to distinguish any effect the other contaminants had on uranium removal by the phosphate method. The apparent effect of nitrate on uranium removal by the phosphate-calcium chloride method may be an artifact of high limits of detections due to insufficient sample. Higher DFs are found in solutions with a high original amount of uranium, probably due to the above-mentioned effect of the limit of detection on the DF. No effect of pH on any batch test (precipitation or anion exchange) could be determined because the experimental procedure did not supply the laboratory with enough sample to perform pH measurements.

The sulfide/ferrous sulfate method removes the chromium (both total chromium and hexavalent chromium). It can be shown that a higher nitrate concentration increased the DF of total chromium (Cr-ICP). The uranium concentration has no effect on the chromium DF. The effect of the limit of detection on the DF is the same as for uranium removal. No effect of other contaminants could be determined, since the detection limit became the lower bound for all final concentrations, thereby yielding the same DF for the same original concentration.

Neither method, as performed in these batch tests, produced easily gravity-settled flocculant. The sulfide tests were especially prone to producing a flocculant that could not be centrifuged. The DFs found may be an effect of the filtering process, instead of centrifugation. Filtering may have removed colloidal particles (which were not removed by centrifuging).

Because neither precipitation method removed both chromium and uranium from solution and each method generated significant quantities of sludge or flocculant, further tests were considered to be superfluous. No concentration-versus-time kinetic study was done as proposed in the Test Procedures (Beck and Delegard 1993).

2.4 FERRIC CHLORIDE/COAGULANT AID TESTS

The removal of colloids and colloidal flocs (due to incomplete agglomeration and relatively small nucleation) has been a part of water and wastewater treatment for decades.

The solid-liquid separation involves two stages: coagulation (charge neutralization and microfloc formation) and flocculation (Raman 1981).

Coagulation (which may be accomplished with iron salts $FeSO_4$, $Fe_2(SO_4)_3$, and $FeCl_3$) is merely the negation of influence of the diffuse layer of counter-ions around the negatively charged colloid (Sawyer and McCarty 1978).

The action of a polymer in flocculation is to accelerate the gravitational forces overcoming inertial forces by adsorption and interparticle bridging (Weber 1972).

The polymer selected for this study was CAT-FLOC L (a trademark of the Calgon Corporation), a medium molecular weight low monomer cationic polyelectrolyte. The polymer is used as a coagulant aid in water clarification in conjunction with ferric salts. CAT-FLOC is a chlorine-resistant polymer and effective over a broad pH range.

2.4.1 Experimental

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A solution of ferric chloride was made up to 30 mg/L iron in deionized, 18 megaohm water. A solution of CAT-FLOC L was made up to 5 mg/L (sp gr 1.032 g/mL) in deionized, 18 megaohm water.

Water from the 100-HR-3 Area wells, 199-H4-4 and 199-D5-15, was used as the test matrix. Changes were made to the well numbers. The choice of the wells was explained in *100-HR-3 Groundwater Treatability Test Plan* (DOE-RL 1993). The contaminants of concern were chromate as chrome (VI), nitrate, and uranium [as uranium (VI) due to the contribution to total alpha and total beta]. Table 4 lists the values as reported in the Hanford Environmental Information System Analysis for 100-HR-3 Groundwater, sampled during the 1992 sampling campaign; this table is also contained in DOE-RL (1993) as Table 1-1.

Table 1 listed the performance goals for each of the contaminants. This table is also contained in *100-HR-3 Groundwater Treatability Test Plan* (DOE-RL 1993, Table 1-1).

To obtain a high turbulence during the initial mixing (rapid mix) phase and ensure complete mixing, a Phipps-Bird paddle stirrer was used. According to Hudson (1981), the jar test (using a Phipps-Bird or equivalent paddle mixer) is the most widely used method to evaluate coagulation-flocculation processes.

Turbidity measurements were made with a HACH Model 2100A Turbidimeter and standardized against HACH turbidity standards supplied with the instrument.

Before any pH measurements were made, the instrument was standardized with the appropriate buffers.

Total solids were measured by evaporating a known volume of sample in a tared evaporating dish at 110 °C.

Table 4. Contaminant Levels (DOE-RL 1993).

Contaminant	Well 199-H4-4	Well 199-D5-15
Gross alpha, pCi/L	28.2	1.3
Gross beta, pCi/L	49	11
Chromium (total), ug/L	110	1,740
Nitrate (as NO_3), ug/L	100,000	10,000

The PUREX laboratory analyzed the chromium, gross alpha, gross beta, nitrates, and uranium from the samples with the lowest turbidity after treatment.

Aliquots (400 mL) of water samples from wells 199-H4-4 and 199-D5-15 were placed in 1-L beakers. Due to the paucity of sample volume, 400 mL was used as a test. The solution additions were adjusted accordingly.

The 1-L beaker containing 400 mL of water was placed in the paddle stirrer and the paddle lowered into the water. The speed was adjusted to the maximum rpm available to induce as high a Reynolds number (N_R) as possible.

The ferric chloride was introduced at a concentration of 30 mg Fe(III)/L via a pipette just under the water surface. (The stock solution was prepared to contain 30 mg of Fe(III)/mL. Therefore, 1 mL of stock solution would be added to 1 L of well water. If less well water was used, the appropriate adjustment to the amount of the stock solution was made.) This aspect of the test represents the rapid mix tank in a physicochemical water treatment system. The ferric chloride was allowed to mix for 2 minutes.

After 2 minutes, the paddles were slowed to 20 rpm and the CAT-FLOC L was introduced just under the water surface. To ascertain the treatment regime that allowed the lowest turbidity to be obtained, the CAT-FLOC was varied from 1% to 4% against 30 mg Fe(III)/L. The CAT-FLOC was allowed to contact the ferric chloride induced pin-floc for 2 minutes. This aspect of the test represents the flocculation basin in a physicochemical water treatment system.

After 2 minutes of contact, the paddles were stopped and removed from the water. The floc was allowed to settle, and turbidity, pH, and solids measurements were made.

The test water was also filtered through a 0.2-micron filter to retain all flocculated material. The samples sent to the PUREX laboratory consisted of the well water without treatment, the flocculated material, and the filtrate.

The test and sample preparation data are recorded in laboratory notebook WHC-N-321 1 (Herting 1993).

2.4.2 Quality Control

These tests were not done in duplicate, nor were replicate analyses performed. Analytical standards were run, and all standards were within acceptable limits.

2.4.3 Results

Table 5 contains the results of the physical measurements from the water samples.

The floc generated, settled within 10 to 15 minutes, and exhibited compression settling. By visual observation, the floc appeared to dewater easily when filtered.

The settleability of the floc was determined in a 1-L graduated cylinder under the ferric chloride and CAT-FLOC conditions that gave the best response to the turbidity measurement.

A liter of well water sample was introduced into a liter-graduated cylinder (approximately 14- by 2.25-in. ID) with a magnetic stir bar and placed on a magnetic stirrer. The ferric chloride and CAT-FLOC was introduced into the sample with the appropriate mixing times as described above. After the CAT-FLOC had contacted the pin-floc for 2 minutes, the stirrer was turned off and the floc was allowed to settle. Measurements were taken of the heavy floc line at 1-minute intervals (Table 6). The measurements were stopped at 10 minutes as the resident time in a clarification basin is usually 15 minutes or more. By 10 minutes, the floc would have cleared the outflow weir inlets in the clarification tank.

As stated above, the chemical analysis was conducted at PUREX laboratory. Table 7 gives the results.

3.0 ANION EXCHANGE METHODS

Strong-base anion exchange has been used in a number of applications to remove chromate from corrosion inhibition solutions used in water-cooled heat exchange equipment and to remove nitrate from nitrate-polluted waters. Strong-base anion exchange also has been used successfully in uranium milling operations, as well as to remove U(VI) from contaminated Hanford Site groundwater. Therefore, three strong-base anion exchange resins were tested for their efficiency and capacity in removing the three contaminants (chromate, uranium, and nitrate) from Hanford Site groundwater. The three resins were selected for these applications on the recommendations of the resin manufacturers, Rohm and Haas Company and Dow Chemical Company.

Table 5. Physical Response Parameters.

Well sample	Turbidity before treatment (NTU)	Turbidity after treatment (NTU)	pH before treatment	pH after treatment	Solids generated (g/L)
H4-4	3.2	1.1	7.4	6.5	0.821
D5-15	1.0	1.0	7.1	5.8	0.660

Table 6. Distance of Floc Line from Top of Water.

Time (minutes)	Well D5-15 (in.)	Well H4-4 (in.)
1	0.5	0.5
2	1.25	1.0
3	2.0	2.25
4	3.0	3.25
5	3.75	4.25
6	4.25	5.5
7	5.75	6.75
8	7.0	7.5
9	8.0	8.25
10	9.25	9.75

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Table 7. Chemical Analysis.

Well[a]	Gross alpha (pCi/L)	Gross beta (pCi/L)	Total chromium (ppb)	Uranium (ppb)	Nitrate (ppb)
H4-4 C	<48	<1,900	67	35	61,000
H4-4 F	57	270	30	<0.97	61,000
H4-4 P1	<936	<2,800	510	207	b
D5-15 C	56	75	2,250	4	5,030
D5-15 F	<61	<401	1,340	<0.97	5,060
D5-15 P	<1,500	23,100	55,500	<0.97	b

[a] C = control (untreated sample); F = filtrate; P = floc.

[b] The precipitate was dissolved in nitric acid and rendered unusable for nitrate analysis.

3.1 BATCH TESTS

3.1.1 Experimental

The anion exchange tests were conducted in much the same manner as the precipitation tests previously mentioned, to facilitate comparisons between the precipitation and anion exchange methods. The levels of resin used in all batch tests were approximately 6 g/30 mL and 1.2 g/30 mL of solution. The centrifugation step was deleted, the resin beads did not pack, and a filtration step was sufficient to remove all the beads. The resins were approximately 16-30 mesh in size.

The test was a full factorial experiment, which means that all combinations of the variables of interest (uranium, nitrate, chromium, and resin concentration) were explored. Each variable had two levels, which yield eight different solution compositions and two different levels of resin, for a total of 16 tests per resin. Blanks and standards were shipped with each batch of samples. Because of the small amount of sample per test, no replicate analyses were done.

3.1.2 Quality Control

All anion exchange batch tests were done in duplicate. Method blanks and standards were sent with each batch of samples. Analytical quality control (performed at PUREX Laboratory) included standards with every batch run, for all the analyses. All standards fell within acceptable (±20% relative standard deviation) limits. No contamination was detected in the method blanks.

3.1.3 Results

All of the DFs presented in Table 8 (which summarizes Appendix D) should be considered to be low estimates, as the limit of detection is the limiting factor in the DFs. The effects of the limit of detection on the DF are discussed in the previous section. This effect is pronounced for the uranium DF of Dowex 21K, as the data for a high initial uranium concentration test are not available and TWO other high initial uranium concentration data points have inflated "less-than" values due to insufficient sample. Reruns for the several different analyses often exhausted the small amount of sample available. The data for low initial amounts of contaminants fail to show any differences among the resins and demonstrate that a limit of detection comparable with the initial concentration yields a low DF.

Dowex 21K has a much higher DF for nitrate than the other two resins and comparable chromium DFs. Given the uncertainties in the data (shown as confidence limits), the uranium DF for Dowex 21K is comparable with the other two resins. All the resins show excellent DFs for uranium and chromate.

The data do not support more significant figures than shown in Table 8. The data are reported as the mean ± one standard deviation.

Table 8. Average Decontamination Factors--Anion Exchange Resin Methods High Initial Concentration Decontamination Factors.

	Uranium	Nitrate	Total chromium by ICP	Chromium (VI)
Dowex 21K	90±70 (7)[a]	40±20 (7)	100±46 (6)	90±12 (4)
Amberlite 410	120±46 (15)	12±2 (7)	60±23 (6)	86±3 (4)
Amberlite 402	110±70 (14)	6±1 (4)	40±23 (6)	60±46 (4)

[a] The numbers in parentheses are the decontamination factors for low initial amount of contaminants.

Freundlich analysis (a plot of the logarithm of mass of solute adsorbed versus log effluent concentration) planned in the test procedures (Beck and Delegard 1993) was performed. Regressions showed the data to be inconclusive; therefore, the analysis yielded no useful information. The goal of a Freundlich analysis is to predict the resin loading at 100% breakthrough (the effluent and initial concentrations are equal) and determine the capacity of the resin in terms of throughput column volumes.

The effect of interactions among the contaminants on the final concentration of the contaminants has been explored using the statistical package Statgraphics (a trademark of Statistical Graphics Corporation). To determine the interactions among the contaminants, Equation 1 was used in a stepwise regression procedure.

The final concentration of contaminant, C_{final}, was modeled using an equation in the form of Equation 1.

$$\begin{aligned} C_{final} &= \text{constant} + \beta_1[U] + \beta_2[Cr] + \beta_3[NO_3] + \beta_4[Resin] \\ &+ \beta_{12}[U]*[Cr] + \beta_{13}[U]*[NO_3] + \beta_{14}[U]*[Resin] \\ &+ \beta_{23}[Cr]*[NO_3] + \beta_{24}[Cr]*[Resin] + \beta_{34}[NO_3]*[Resin] \end{aligned} \tag{1}$$

The stepwise regression procedure was used to estimate and test the significance of the regression coefficients β_1, β_2,.... β_{34}. Appendix E gives the regression coefficients for each of the variables in Equation 1.

The concentrations (e.g., [U]) used in Equation 1 are the initial concentration of each of the contaminants. The interaction terms (e.g., [U]*[Cr]) are the product of the initial concentrations of the contaminants. In the example used, this is the concentration of uranium multiplied by the concentration of chromium. This equation does not take into account the Cr(VI) initial concentration as it is essentially identical to the Cr (Cr-ICP) value. The use of two identical values like the original concentrations of Cr and Cr(VI) in the equation would have created computational difficulties.

A positive coefficient denotes a term that increases C_{final} (decreasing DF) with increasing initial concentration of the interferant. A negative coefficient denotes a term that decreases C_{final} (increasing DF) with increasing initial concentration of the interferant.

One notable result of the regression analysis is that the final uranium concentration model is free from any interactions with any of the resins, indicating that it is probably the specie most tightly bound to the resin and therefore least likely to break through and most likely to be eluted last. Nitrate has significant interactions with chromium (with Amberlite 402) and with the product of the nitrate and chromium concentrations, with Amberlite 402 and 410. This indicates that nitrate and chromate may be competing for the same binding sites on Amberlite 402 and 410. Nitrate and chromium do not interact on Dowex 21K. A very small coefficient in the nitrate equation for the product of the concentrations of uranium and chromium also exists for Dowex 21K. Nitrate is interfered with by uranium on Amberlite 402 and 410.

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3.2 EQUILIBRIUM TESTS

3.2.1 Introduction

The Freundlich analyses failed to yield usable information. Therefore, an alternative method was needed to estimate the amount of solution needed to enable the contaminants to reach breakthrough. The removal efficiency ϵ (given as milliliters of solution treated per milliliters of resin) is the amount of solution that the resin has treated, such that the effluent concentration is 50% of the original (feed) concentration, per milliliters of resin (Bray 1989).

$$\epsilon = (Co\text{-}Cf/Cf) * \text{sample volume/resin mass} \\ * \text{resin bed density} \qquad (2)$$

where Co is the original concentration and Cf is the concentration of the contaminant after equilibrium treatment. Sample volume is in units of milliliters, the resin mass in units of grams, and the resin bed density in units of grams per milliliter.

This equation holds true for all reasonable column flow rates (where equilibrium is approximated) (Daniels et al. 1962).

3.2.2 Experimental

The equilibrium tests were conducted similarly to the aforementioned anion exchange batch tests, but included only the solution that had high U (~500 ppb), NO_3^- (~200,000 ppb), and Cr (~2,000 ppb) concentration. The amount of resin used was 0.1 g/30 mL of solution and 0.05 g/30 mL solution, which is far less than that used in the batch contact tests. The solution was stirred overnight and then treated identically to the batch tests.

3.2.3 Quality Control

All tests were done in duplicate. Method blanks and standards were sent with each batch of samples. Analytical quality control (performed at PUREX laboratory) included standards with every batch run, for all the analyses. All standards fell within acceptable (±20% relative standard deviation) limits. No contamination was detected in the method blanks.

3.2.4 Results

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The equilibrium tests showed that an enormous quantity of spiked groundwater would be required to reach breakthrough (a point where the concentration equals 50% of original concentration, i.e., C/Co=0.5) for uranium and chromium. The least amount of groundwater needed to achieve breakthrough for chromium is approximately 15 L of spiked groundwater per milliliter of resin. Because the minimum amount of resin is 4.6 mL, due to constraints on column size, this would require about 70 L of spiked groundwater. This amount of groundwater was not available and, even if it were, it would exceed the physical limits of the fume hood where the tests were conducted. The value given for the volume required for the effluent concentration to reach 50% of the influent concentration is in fact a minimum, as this equilibrium test, like the batch tests, was limited by the limit of detection of the chemical analysis for both chromium and uranium.

The raw data and some calculated values are presented in Appendix F.

4.0 BREAKTHROUGH TESTS

The four main objectives of performing breakthrough tests are as follows.

- Determine whether the resin will adsorb the contaminants sufficiently in a column with a realistic flow rate.
- Determine the effect, if any, flow rate has on the column retention of contaminants. This is done by running the column at both the low and high end of the manufacturer's suggested flow rates.
- Determine the number of column volumes of groundwater the column can retain, without breakthrough, of each of the contaminants.
- Determine, using actual groundwater from the 100-H and 100-D Areas, the behavior of the contaminants on the column.

4.1 EXPERIMENTAL

The breakthrough tests on the spiked groundwater (from well 199-H3-2C and spiked to approximately 800 ppb U, 2,000 ppb Cr, and 200,000 ppb NO_3) were run to approximately 2,000 column volumes, instead of the test procedure plan of running to breakthrough. The change from the test procedures (Beck and Delegard 1993) was due to the fact that the Freundlich analyses were not usable. An alternative method ("equilibrium tests" suggested by Lane Bray) used to determine the breakthrough capacity of the column suggested that the number of required column volumes to achieve uranium or chromium breakthrough would exceed the amount of groundwater available for spiking. Two thousand column volumes is sufficient to demonstrate whether the estimates for breakthrough are realistic and, in any case, there is insufficient sample to run a larger number of column volumes through the column. The "confirmatory" tests on the unspiked samples were run by running all available samples (wells 199-H4-4, 199-D5-15, and biodenitrified 199-H4-4, 199-D5-15 mix) through the column and measuring the effluent for contaminants. The unspiked groundwaters were not expected to show breakthrough for uranium, due to the limited amount of sample (several liters for each), the low concentration of uranium, and the very high DFs of the resin for uranium.

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The column volume for all breakthrough tests was approximately 4.85 mL, which corresponds to 4.18 g of damp, conditioned resin. The term "column volume" as used in this report denotes the volume of the resin bed, including interstitial water, but does not include the headspace in the column above the resin bed. The column volume of 4.85 mL was chosen to give the column a height-to-diameter ratio of 5 cm to 1 cm, while maintaining a diameter wide enough to avoid wall effects (i.e., channeling at the wall). The tests on spiked groundwater were run at two different flow rates: ~16 column volumes per hour (~80 mL/h) and 27 column volumes per hour (~160 mL/h). The approximate value of the flow rate is due to the inaccuracies of the pumps used, as these flow rates were very close to the minimum flow rates of which the pumps were capable. The flow rates were chosen to bracket the manufacturer's recommended flow rate for Dowex 21K resin. The column was loaded downflow for all breakthrough tests.

The "confirmatory" tests on the unspiked samples were run by feeding all available samples through the column at the "low" (16 column volumes per hour) flow rate and measuring the effluent for contaminants. The unspiked groundwaters were not expected to show breakthrough for uranium, due to the limited amount of sample (several liters for each) and the very high DFs of the resin for uranium. Also included in the "confirmatory" category is groundwater from wells 199-H4-4 and 199-D5-15 that had been biodenitrified by using native Hanford microbial populations at Pacific Northwest Laboratory.

To determine actual breakthrough volumes, a very highly spiked solution (199-H3-2C spiked to 6,580 ppb chromium, 5,920 ppb chromate, 2,840 ppb uranium, and 194,200 ppb NO_3^-) test was run. This test was run with approximately 11 L of solution and a flow rate of about 16 column volumes per hour.

The flow rate for the later tests is quite variable because the metering pump used originally quit permanently and the replacement peristaltic pump was set at its lowest setting. No attempt was made to control the effluent pH or the temperature, although the temperature was moderated by building heating and ventilation controls.

To ensure that each actual groundwater (either 199-D5-15 or 199-H4-4) sample was homogeneous throughout the test, the groundwater which was contained in several bottles was mixed in the original (as-recieved) containers.

4.2 QUALITY CONTROL

Method blanks and standards were sent with each batch of samples for the breakthrough tests. Analytical quality control (performed at PUREX laboratory) included standards with every batch run, for all the analyses. All standards fell within acceptable (±20% relative standard deviation) limits. No contamination was detected in the method blanks.

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4.3 RESULTS AND DISCUSSION

The value C/Co is a measure of the efficiency of the column in removing the contaminant (Table 8). The plot of C/Co versus column volume is most useful for the high spiked solution, showing that Dowex 21K removes the high concentration of contaminants down to the level of detection for several hundred column volumes. For the unspiked solutions, the plot of concentration versus column volumes is the most informative; it shows directly the effect of the actual groundwater on the column's ability to remove the contaminants to below the performance goals. The plot of C/Co versus column volumes for unspiked groundwater can be confusing, due to the fact that if the original concentration (Co) is small, the value of C/Co becomes highly scattered because of analytical uncertainties near the limit of detection. The plot C/Co versus column volumes is included for comparison purposes only. A log scale on the y axis (C/Co or concentration) is used to ensure that all data points are seen clearly, as the concentrations of nitrate and the other contaminants often differ by several orders of magnitude.

4.3.1 Low Flow Rate, Spiked Groundwater

The low flow rate, spiked groundwater [199-H3-2C, spiked to Co = 700 ppb uranium, 1,770 ppb chromium(VI), 2,020 ppb total chromium (chromium by ICP), and 192,300 ppb NO_3^-] results are presented in Appendix G.

The data show that even 1,800 column volumes are insufficient to show breakthrough for uranium. The data appear scattered because of the near-detection level concentrations and the log scale on the C/Co (y) axis. Chromium concentrations at 1,800 column volumes are near the performance level and are only about 3% to 4% of the original concentration. The slight increase (from the detection level) in chromium concentration at high column volumes is consistent with a gradual slope to the breakthrough curve.

Nitrate shows 50% breakthrough at approximately 350 column volumes (about 1,700 mL), which corresponds to a resin loading of 1.1 meq/mL of wet conditioned resin. This loading is very close to the theoretical capacity of 1.2 meq/mL for the resin Dowex 21K. The number of column volumes treated at breakthrough is consistent with that value calculated from the equilibrium test data.

The carbonate concentration in this test solution was approximately 115 ppm, assuming that this test solution was identical to a different sample of low spiked groundwater (with the same contaminant spike level).

4.3.2 High Flow Rate Spiked Groundwater

The fast flow test was performed on water from well 199-H3-2C that was spiked to initial concentrations of 820 ppb uranium, 2,100 ppb chromium, 1,990 ppb chromate, and 212,700 ppb NO_3^-.

The flow rate averaged roughly two times that of the slow flow test, while roughly the same concentration of contaminants was spiked into the well water as for the slow flow tests. The pump essentially destroyed itself during the course of the test, ending it prematurely. The flow rate inconsistencies can be seen in Appendix H.

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Chromium showed no breakthrough tendencies during this abbreviated test.

Uranium data show a slightly higher concentration of uranium in the effluent than the slow flow test demonstrated. This may indicate that the kinetics of uranium adsorption are slow. However, the uranium concentration was always below the project performance goal for uranium.

The carbonate concentration in this test solution was approximately 115 ppm [assuming that this test solution was identical to a different sample of low spiked groundwater (with the same contaminant spike level)].

4.3.3 Well 199-H4-4 Unspiked Groundwater

This (199-H4-4) well water had an original (before treatment) concentration of 49 ppb uranium, 65.5 ppb chromate, 79.4 ppb total chromium, and 84,600 ppb NO_3^-.

Neither uranium, chromium, nor chromate showed any signs of breakthrough.

Nitrate broke through (defined as $C = 0.5^* C_o$) at 390 or 445 column volumes, depending on how the breakthrough curve is interpreted. The spike at 390 column volumes could be an analytical outlier or could reflect the actual concentration of nitrate.

The carbonate concentration in this test solution was approximately 169 ppm.

The graphs and data can be found in Appendix H.

4.3.4 Well 199-D5-15 Unspiked Groundwater

The results of the breakthrough tests with unspiked groundwater D5-15 [with an original concentration of 12 ppb uranium, 1,930 ppb chromium(VI), 2,025 ppb total chromium, and 49,700 ppb NO_3^-] are presented below. The data and graphical representations of the data for this test can be found in Appendix J.

The nitrate is initially adsorbed onto the column and reaches breakthrough at about 450 column volumes.

Both uranium and chromium show good retention. Chromium rises above the performance goal (100 ppb) much sooner (about 1,100 column volumes) than expected from the 199-H3-2C spiked groundwater results, indicating some interference from components in the groundwater. However, 4% is a minimal (within experimental error) difference in the chromium concentration. The decontamination levels are essentially identical, as most of the variation in the D5-15 test comes from concentrations barely above the method detection limit (29 ppb total chromium, 19 ppb chromium +6). Uranium values are highly scattered, probably because they (and the initial uranium concentration) are very close to the detection level. The carbonate concentration of this test solution is approximately 100 ppm.

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4.3.5 Biodenitrified Groundwater

Biodenitrified water, a treated mix (approximately 50%/50% from wells H4-4 and D5-15), had a concentration prior to treatment,of 1,000 ppb total chromium, 735 ppb chromate, 10 ppb uranium, and 10,900 ppb NO_3^-. As shown in Appendix K, Figures K-1 and K-2, this sample is unusual in that nitrate breakthrough occurs at 740 column volumes. Note that the breakthrough volume is only about twice the breakthrough volume of the other tests, which typically had an initial concentration of nitrate over 15 times that of the biodenitrified groundwater. Uranium and chromium show no signs of breakthrough, the effluent concentrations being at the detection level throughout the test. The behavior of the contaminants was consistent with the other tests, given the initial contaminant levels. The flow rate for this test was quite variable.

The carbonate concentration of this test solution is approximately 166 ppm. The biodenitrified water also had a slightly above-background reading of total organic carbon, which is consistent with the biodenitrification process.

4.3.6 Very High Spiked Groundwater, Low Flow Rate

The highly spiked groundwater consisted of water from well 199-H3-2C, spiked to 6,580 ppb chromium, 5,920 ppb chromate, 2,840 ppb uranium, and 194,200 ppb NO_3^-. The chromium values are significantly higher than the values reported for chromate. The high concentration of chromium on the anion exchange resin may be leading to a partial reduction in valance state of chromate. The chromate never reaches breakthrough (C/Co = 0.5) but does exceed the performance goals in a relatively small number of column volumes.

The initial concentration of chromium is three times higher than the highest expected in 100 Area wells.

Uranium does exceed the performance goals for several samples scattered throughout the latter half of the test. No discernable breakthrough trend can be observed. The higher flow rate seems to coincide with the higher uranium concentrations in the treated effluent. It should be noted that the flow rate is a 5-h average; therefore, the actual maximum or minimum flow rates could be much higher or lower.

This test demonstrates that Dowex 21K has a very high affinity for uranium. The initial uranium concentration of the test solution was about 10 times higher than that expected for actual groundwater. The concentration of carbonate in the test solution is approximately 115 ppm (assuming that the carbonate concentration is similar to that of the low spiked groundwater). Graphs and tables of the data for this test can be found in Appendix L.

4.3.7 Total Alpha and Total Beta Analyses

Total alpha and total beta analyses were performed on a select few samples, due to the large effort involved in performing these analyses. Total alpha and total beta are the regulatory analyses of concern (DOE-RL 1993). Samples were generated by compositing. The two samples of starting solution were composited together, while the treated effluent samples were generated by compositing the first half of the same breakthrough run together and compositing the second half of the same breakthrough run together.

The total alpha and total beta results can be compared to uranium values in the appendices for the corresponding breakthrough run. Assumptions can be made that all the alpha activity is due to uranium, while the total beta is due to the immediate daughter products of ^{238}U (^{234}Th and ^{234}Pa). The uranium (as determined by fluorescence spectrophotometry) agrees reasonably well with the value of uranium derived from the total alpha content.

The most noteworthy item is that all the treated samples were below the method limits of detection. Because of the very low values of these samples and counting statistics, the limits of detection ranged from 36 pCi/L -27 ppb uranium to 258 pCi/L -188 ppb uranium for total beta and 14 pCi/L- 20 ppb uranium to 227 pCi/L- 330 ppb uranium. The values for the starting solutions are given in Table 9.

The fact that the total beta levels for several starting solution samples do not match the uranium levels may be due to the daughters (^{234}Th and ^{234}Pa) plating out on the sides of the container, or perhaps the assumption of secular equilibrium is invalid.

Table 9. Values for Starting Solutions.

Sample #	Sample description	Total alpha (pCi/L)	Uranium[a] (ppb)	Total beta (pCi/L)	Uranium[b] (ppb)
ERK29B1	H4-4 breakthrough test	<73	<110	424	308
ERK19B1	D5-15 breakthrough test	<90	<65	<145	<105
ERK31F1	High flow rate spiked H3-2C breakthrough test	320	470	380	280
ERK31L1	Low flow rate spiked H3-2C breakthrough test	360	530	430	320
ERK30B1	Biodenitrified (H4-4, D5-15) breakthrough test	<165	<240	<230	<110
ERK41B1	High spiked H3-2C breakthrough tests	1630	2370	1905	1390
CK31Z1	Cycling test	360	530	<308	<224

[a] Assuming all alpha is natural uranium.

[b] Assuming that the total beta is due solely to ^{234}Th and ^{234}Pa in secular equilibrium with uranium.

The total beta for sample ERK29B1 (199-H4-4) is greater than expected, given the less-than level of total alpha (and therefore of uranium). This implies that the total beta value is the result of some beta emitter not associated with the uranium decay chain. This beta emitter could be technetium, which is known to be in 100-HR-3 groundwater (DOE-RL 1993). Regardless of the identity of the beta emitter(s), the ion exchange treatment removes it, as the treated water samples for the H4-4 breakthrough test are below the limit of detection (<90 pCi/L is the highest limit of detection for these samples).

4.3.8 Common Themes in the Breakthrough Results

The nitrate breakthrough was remarkably constant, given the amount of variance in the initial concentrations of the various anions. A correlation matrix was developed that showed no strong correlations (given uncertainties in the data) between the nitrate breakthrough volume and any independent variable. The independent variables included the initial concentrations of chloride, sulfate, nitrate, and carbonate (as total inorganic carbon). Other independent variables included the flow rate; the range of the flow rate; the average temperature; the range of the temperature; the average pH; the range of the pH; and the products of the concentrations of carbonate and sulfate, carbonate and chloride, carbonate and nitrate, and the sum of the concentrations of carbonate, chloride, nitrate, and sulfate. The chloride and sulfate concentration values were taken from the raw data for ion chromatography (the method for nitrate). The chloride and sulfate data do not have standards associated with them because these analyses were not originally requested. The strongest correlation that does exist is the negative (R= -0.73, R^2=0.53) correlation between the initial nitrate concentration and nitrate breakthrough.

An interesting feature of the nitrate breakthrough curve is that the nitrate concentration in the effluent from the column after breakthrough is higher than the original concentration. The spike in the nitrate breakthrough curve, where the nitrate concentration exceeds that of the initial concentration, implies that some mechanism other than simple breakthrough is taking place. An explanation of this phenomenon could be that another anion could be "pushing" the nitrate off the resin, so that the nitrate eluted by the other anion is added to the nitrate passing right through the column, thus producing the hump in the breakthrough curve. Uranyl tricarbonate anion is not a likely candidate for the "nitrate pushing" anion, since the extremely low amount of uranium in the groundwater precludes it from binding all active sites on the resin and thereby affecting the other anions. Chromate's concentration compared to nitrate is so low that chromate probably is not the responsible anion for the nitrate elution. It is interesting that, despite the fact that the nitrate concentration in the test solutions varies by a factor of 20, the nitrate elution varies by only a factor of 2. Carbonate (as bicarbonate at the pH of these groundwaters) is probably the specie responsible for the nitrate elution and the odd shape of the elution curve. Nonetheless, the carbonate hypothesis is not supported by the previously discussed statistical analysis of the data. A possible reason for this is that the carbonate concentration in all the test solutions (spiked and unspiked well water) is very similar, destroying any correlation.

5.0 CYCLING TEST

The primary purpose of the cycling tests is to determine the frequency and amounts of eluant and wash solutions needed. These parameters are determined by examining the elution curve (concentration of eluate versus column volume). The efficiency of washing will also be ascertained. A secondary goal was to determine if the resin can undergo many cycles of use. To accomplish this, the column underwent 10 cycles of loading, elution, and washing.

5.1 EXPERIMENTAL

The general method used was that of the test procedures (Beck and Delegard 1993), except that the sample was loaded downflow and eluted and washed upflow. This change was made to ensure that channeling did not occur in the small resin bed that was used. The test was run for 10 cycles. Elution and washing for the cycling tests was performed after 19 h of loading at approximately 1.2 mL/min (15 bed vol/h), a treated water sample volume of approximately 300 column volumes. Three hundred column volumes was chosen as the duration of the loading cycle, since this is a point prior to nitrate breakthrough. The solution used is approximately the same concentration as used for the slow and fast-spiked 199-H3-2C tests [676 ppb U, 2,225 ppb total chromium, 1,780 ppb chromium (VI), 203,000 ppb $NO3^-$, and 3,000 ppb Cl^-].

The first elution was done at a flow rate that the authors thought was too high, as the eluant stirred the column and had a broad elution front. The experimental apparatus was also thought to be inadequate, because there was about 14 mL of deadspace from the top of the resin bed to the eluate catch bottle. The tubing that exited the column was changed from 1/8-in.-ID to 1/16-in.-ID tubing to eliminate 10 mL of deadspace. The elution flow rate was decreased by a factor of 4 (to 1.25 mL/min) to eliminate the disruptive effect of the higher flow rate and allow time for the contaminants to be removed from the column into the eluate.

An additional step was added to the wash procedure. The pump was stopped about halfway through the wash and the beads were allowed to settle. The pump was then restarted and the beads circulated throughout the column. At the end of washing, some density gradients (indicating concentrated sodium chloride solutions) were noted for each cycle. Washing does not seem to have been complete, and some excess chloride appears to have remained on the column. The final wash fractions were observed to be colorless, or very lightly colored. The wash flow rate for all cycles through 10 was approximately 9 mL/min (upflow).

Cycles 2 through 10 were run with the changed apparatus and flow rate.

The eluate was gathered as one sample (~22 mL) for cycles 2 through 9. The wash was also gathered as one sample (~20 mL) for cycles 2 through 9. This is in contrast to the first and tenth cycles, in which the eluate was split into 10 (~2 mL) samples and the wash was split into 4 (~5 mL) samples. This was done to minimize the number of samples submitted, maximizing analytical turnaround time.

5.2 RESULTS

The results of the cycling tests (see Appendix M for tables and graphs) are broken up by type of sample, i.e., treated effluent or eluate or wash. The reason for this is the widely different concentrations for the different types of samples. It should be remembered, however, that the chronological order of the samples is "effluent," "eluate," and "wash," followed by the next "effluent" sample for the next cycle. The eluate and wash graphs are presented as a line graph, so each point is one analysis (of duplicates). The eluate and wash data points are in the order generated. The XY method of plotting versus column volumes would have bunched up the first and tenth cycle results, so a line graph was used. Because the effluent concentration graph is presented as an XY graph, some closely spaced duplicates may appear to be one point. The effluent data are plotted versus the total number of column volumes of spiked 199-H3-2C run through the column.

5.2.1 Treated Effluent

The contaminant concentrations in the test solution after ion exchange treatment (hereafter referred to as "treated effluent") are below the performance goals, except for uranium for the last eight cycles. The spike seen in the total chromium data at about 600 column volumes is considered to be an analytical outlier, as the chromate data do not show this drastic increase in the concentration. The value of the outlier is one order of magnitude higher than the surrounding values, leading to the conclusion that these points are outliers. Nitrate concentrations are all below the performance goal. A small upward trend in nitrate concentrations may be evident in the last two treated effluent samples, but the data are not clear. Both total chromium and chromate are well below the performance goal, with a possible downward trend near the end of the test.

Uranium was not completely removed from the test solution for cycles 3 through 10. Some samples of treated effluent water contained as much as 100 ppb uranium. This could be caused by either the wash being incomplete or uranium flowing directly into the effluent sample bottle upon the start of sample loading. This hypothesis is supported by the presence of significant quantities of uranium in the last wash samples.

The upflow wash method, which stirred the beads in the column, could have deposited beads incompletely stripped of uranium close to the bottom of the column. Beads at the bottom of the column could have released uranium into the treated effluent, without the benefit of beads below them to readsorb the uranium.

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Alternatively, the column simply was not adsorbing a portion of the incoming uranium from the test solution bottle. A small fraction of the anion exchange sites could be those specific for uranium binding, and this small fraction could be overloaded, leaving sites more weakly binding for uranium. This hypothesis is not supported by the breakthrough tests, because the total amount of uranium adsorbed during the breakthrough tests was much greater than the amount run through during a few cycles of the cycling test. However, this hypothesis is supported by trending and consistency of the concentration, as the washing process would not likely be that consistent.

Another explanation would be the formation of UO_2Cl_2, a highly soluble neutral compound, during washing, by chloride displacement of carbonate from the uranyl triscarbonato anion.

Despite the above performance level concentrations of uranium, it should be noted that the method always removed six-sevenths of the uranium in 676 ppb uranium spiked groundwater. Given the typical uranium concentrations in actual Hanford Site groundwater (<100 ppb), a removal of six-sevenths of the uranium would meet the performance goal for uranium used in this report.

5.2.2 Eluate

The elution of chromium (total and chromate), uranium, and nitrate is accomplished by the introduction of a 4 M sodium chloride solution onto the column bed.

Contaminant concentrations in the eluate are typically several hundred thousand ppb chromium, ten million ppb nitrate, and thirty thousand ppb uranium. The initial breakthrough of the contaminants is followed by the appearance of chloride in the eluate. This behavior of the chloride concentration is expected, as the chloride must displace the contaminants from the resin before the chloride itself dilutes.

The average percent recovered (based on the amount loaded during each cycle and ignoring any residual) for the 10 elutions is 74±49% of the uranium, 99±66% total chromium, 94±37% chromium (VI), and 71±42% nitrate. The uncertainties are given as the 95% confidence limits. The high uncertainties in the percent recoveries are largely due to the low recovery during the first cycle.

5.2.3 Wash

The contaminant concentration in the wash was significantly lower than in the eluate. The contaminant concentration did not reach a level comparable to the original test solution, even during the final wash sample. This indicates that the elution was not complete. The chloride (the eluant) concentration was not reduced to near zero, indicating that the wash was not entirely successful. However, despite the incompleteness of the elution and wash, the contaminant level in the treated effluent is quite low, as previously discussed.

The average percent recovered (based on the amount loaded during each cycle and ignoring any residual) for the 10 washes is 18±32% of the uranium, 16±33% total chromium, 13±29% chromium (VI), and 20±31% nitrate. The uncertainties are given as the 95% confidence limits. The large uncertainties are probably due to the high recovery values for the first cycle, as the contaminants not removed with the eluate "bleed" over into the wash portion of the cycle.

5.2.4 Common Themes

Statistical analysis (a correlation matrix) of the whole cycling test data set revealed strong correlations between the concentrations of the contaminants. No strong correlation between the contaminant concentrations and chloride (the eluant) concentration is seen. The lack of correlation between the eluant and contaminant concentrations could be caused by a number of factors. The treated effluent concentrations of all the species of interest were steady throughout the tests. The chloride concentrations would be expected to lag behind the contaminant concentrations, as chloride would be adsorbed on the resin as it displaced the contaminant.

The average total (eluate and wash) percent recovered (based on the amount loaded during each cycle and ignoring any residual) for the 10 cycles is 92% of the uranium, 116% total chromium, 107% chromium (VI), and 85% nitrate. The uncertainty in these numbers is roughly equivalent to the uncertainty in the corresponding eluate and wash values.

6.0 DISCUSSION AND CONCLUSIONS

This section gives conclusions from the tests and presents suggestions for the groundwater treatment method. The reasons uranium was chosen as the radionuclide to be treated are discussed. Technetium removal (which was not included in the tests) is discussed, with references to the literature.

6.1 URANIUM

Uranium was chosen as the radionuclide(s) to be tested for removal from Hanford Site groundwaters. Although by itself it is not a contaminant of concern (DOE-RL 1993, Section 1.3), uranium is a contributor to both the gross alpha and the gross beta. The uranium contribution to the gross alpha activity is primarily by way of ^{238}U and ^{234}U (about 98% of the activity of natural uranium). Uranium contribution to the gross beta activity is by way of the ^{238}U daughter products, ^{234}Pa and ^{234}Th. The combined activity of these two daughters is twice that of the ^{238}U parent, which means that their beta activity is comparable (in the number of decay events) to the uranium alpha activity. Removing the uranium parent also removes the daughter product activity, after the daughter products already formed have decayed away (a process that takes about a half of a year) (Negin 1990). Therefore, decreasing the uranium concentration in the groundwater will have a significant impact on gross alpha and beta levels and will, in most probability, bring them within performance limits.

6.2 TECHNETIUM

Technetium was not chosen as a radionuclide to be tested for removal. Although it is present in the groundwater, technetium contributes approximately 6% its beta to the gross beta measurement. This is due to the low-energy beta that it produces. The proposed limit from the U.S. Environmental Protection Agency, July 18, 1991, Federal Register (Vol. 56, No. 138, p. 33120) for ^{99}Tc is 3,790 pCi/L (4 mrem/year exposure) for groundwater. However, the suggested anion exchange remediation technique may also work for this radionuclide, since technetium is in the form of pertechnetate (TcO_4^-) in many groundwaters. This idea is supported by the literature (Del Cul et al. 1993, Anders 1960). Both sources describe the adsorption of technetium (as pertechnetate) to strong base anion exchange resins of the quaternary ammonium type as being very tight. Elution of pertechnetate anion from these resins is only accomplished by high concentrations of powerful eluants (such as perchloric acid) (Anders 1960) and/or reductants (Korkish 1989, p. 19). Given these properties of technetium, it may prove possible to elute nitrate, chromium, and uranium from the resin while retaining technetium. The removal of technetium could be an added value to using the anion exchange method. Del Cul et al. (1993) also describe the use of iron fillings to reduce and precipitate technetium, but state that the speed of technetium removal is slow in very dilute- (groundwater) type solutions.

6.3 BATCH TESTS

6.3.1 Precipitation Methods

Neither precipitation method (sodium sulfide/ferrous sulfate, phosphate/calcium chloride) is suitable for the purposes of this project, since neither removes both metals (uranium and chromium). However, the test procedure (Beck and Delegard 1993) states that one of the precipitation methods will undergo confirmatory testing. Other researchers worked on optimizing (Duncan 1993) the use of cation flocculating agents with these precipitating agents and additional precipitating agents as well. Because the work specified by Duncan (1993) is a complementary effort to the work planned in Beck and Delegard (1993), no further work was done in this area by the principal investigator. This change in work scope was agreed to by the customer. The difficulty of removal of the precipitants and prelimary calculations of the cost of sludge disposal resulted in the decision to terminate further tests of the precipitation methods.

From the precipitation bench-scale tests, the following was determined.

- Physical Conditions-- The samples were tested at ambient temperature and pH. The ferrous sulfate/sodium sulfide and the phosphate/calcium chloride tests had little effect on the final pH of the solution. The ferric chloride did change the pH 0.9 units for well H4-4 and 1.3 units for well D5-15. This would be expected since the iron is in the plus three valance state and would attract three hydroxyl units and thus decrease the pH (see Section 2.4 and Appendix C-1).

- What is the Optimum Removal Chemistry--
  For the sodium sulfide and ferrous sulfate tests, the sodium sulfide was introduced to the test solution to obtain a final concentration of 12 mg S^{-2}/L. The ferrous sulfate was introduced to the test solution to obtain a final concentration of 9.9 mg Fe^{+2}/L.

  For the phosphate/calcium chloride tests, the sodium hydrogen phosphate was introduced to the test solution to obtain a final concentration of 5,550 mg HPO_4^{-2}/L. The calcium chloride was added to obtain a final concentration of 92 mg Ca^{+2}/L (to include the amount of calcium present in the solution).

  For the ferric chloride precipitation tests in conjunction with the polymeric flocculent aid, CAT-FLOC L, the ferric chloride was added to the test solution so that the final concentration of iron was 30 mg Fe^{+3}/L and the CAT-FLOC L introduced (see Sections 2.2, 2.3, and 2.4).

- Reaction Rates--The rates are reported in Table 6. As may be determined from the data, a curvelinear response is given. However, the flocculent fell over 9 in. within 10 minutes. The resulting sludge was stable and easily dewaterable.

- Effects of Feed Variability and Presence of Other Contaminants (such as nitrates)--The feed of the chemicals followed standard water treatment practices (Hudson). Nitrates did not show any interference with the coagulation/precipitation tests (see Section 2.3).

- Biodentrification Process Interference--Due to the process of reduction/precipitation adding chemicals to a treatment train, biodenitrification would occur as the last step.

- Performance Levels for Chromium and Radionuclides--Removal did not demonstrate the efficacy that was required or that demonstrated by the ion exchange (see Sections 2.3 and 2.4).

6.3.2 Anion Exchange Resins

As the anion exchange resins were evaluated as a standalone treatment, Dowex 21K was used for confirmatory testing and cycling tests. The lack of interaction of nitrate (except the product of the nitrate and resin concentrations; see Appendix C) was an added attraction to the use of Dowex 21K.

From the anion exchange resin evaluation, the following was determined.

- Pretreatment Requirements--There were no pretreatment requirements identified in the treatability tests. In the field, it is recommended that a prefilter (such as a spiral wound, polypropylene, 5-micron nominal) be used before the ion exchange unit to filter out extraneous material (well casing material, etc.).

- Optimum Resin for Site Contaminants--From the results of the treatability tests, the resin that was found to be most efficacious was the Dowex 21K, a strong base anion exchange resin.

- Effect of Resin Loading on Contaminant Removal--A synopsis of results reported elsewhere (Sections 3.1.3, 4.3.3, and 4.3.4), indicate that
  - No breakthrough was observed in well H4-4 (except for nitrates at 445 CV); the concentrations introduced were nitrate at 84,600 ppb, uranium (VI) at 49 ppb, chromate at 65.5 ppb, and total chromium at 79.4 ppb.
  - For well D5-15, the concentrations introduced were nitrate at 49,700 ppb, uranium (VI) at 12 ppb, chromate at 1,930 ppb, and total chromium at 2,025 ppb. Breakthrough was observed at 450 CV for nitrate and 1,100 CV for chromium. The chromium was introduced at 2,025 ppb and breakthrough occurred at 100 ppb. Therefore, 1,925 ppb was taken up by the ion exchange resin. The test ion exchange column was approximately 1 mL of Dowex 21K resin. The density of the Dowex 21K resin is 43 lb/ft^3 or 689 mg/mL. The capacity of the resin for D5-15 translates into 1925 μg/mL divided by the resin density, which yields 2.79 μg chromium per milligram of resin.

- Effect of Multiple Cycles on Resin Life--No degradation of the resin was noted on the resin life (see Section 6.7).

- Quality of Effluent Produced--During the multiple cycles, the contaminant concentrations are below the performance goals, with the exception of uranium (VI) for the last eight cycles (see Section 5.2.1).

- Composition of Regenerate (Including Rinse) Produced--The ion exchange is eluded by the introduction of 4M sodium chloride onto the column bed. The contaminate concentrations in the eluate are typically several hundred thousand ppb chromium, ten million ppb nitrate, and thirty thousand ppb uranium. The rinse (wash) contained contaminant concentrations that were significantly lower than the values found in the eluate (see Sections 5.2.2 and 5.2.3).

- Volume of Regenerant (Including Rinse) Produced--The resin is eluted with 4 to 5 CVs of 4 M sodium chloride. The rinse (wash) produces one to two column volumes of liquid. It should be noted here that both the eluate and the rinse will contain uranium (VI) and is a mixed waste.

6.4 FERRIC CHLORIDE/COAGULANT AID TESTS

It was beyond the scope of this effort to optimize the parameters of ferric chloride/CAT-FLOC to the contaminants of concern. Rather, it was to demonstrate the efficacy of ferric chloride along with a polymeric flocculant aid in removing uranium (and to thereby reduce gross alpha and gross beta counts) and chromium.

The gross alpha and gross beta counts have shown an increase in the flocculant as opposed to the filtrate. The values were at detection limit; strong conclusions should not be readily arrived at, except that there appeared to be an effect.

The uranium showed mixed results between D5-15 and H4-4. On sample D5-15, the gross beta appears to have been concentrated (filtrate to flocculant), while the uranium does not appear to have been affected. However, on sample H4-4, the uranium appears to have been concentrated in the flocculant.

Overall, the ferric chloride appeared to have the effect of concentrating the uranium (chromium is yet to be determined). The CAT-FLOC enabled the ferric chloride pin-floc to precipitate and clarify the water. The sludge produced by the ferric chloride/CAT-FLOC combination appears to dewater effectively.

The combination of ferric chloride and a flocculant aid (such as the CAT-FLOC) is an efficacious methodology in the treatment and clarification of groundwater with similar matrices.

6.5 EQUILIBRIUM TESTS

These tests showed that the adsorption potential of Dowex 21K for uranium and chromate was far higher than the amount of groundwater available for spiking. The resin adsorbed uranium and chromium far more strongly than it did nitrate. These tests clearly showed that nitrate would be the limiting factor in the use of the resin.

6.6 BREAKTHROUGH TESTS

Dowex 21K shows very high affinity for uranium and chromium and a substantial affinity for nitrate. The nitrate loading on the resin varies from close to the theoretical loading capacity of the resin to much less. Nitrate adsorption seems to be governed by the presence of other (non-chromium or uranium) anions. Regression analysis of the breakthrough volumes versus the initial concentration of nitrate, sulfate, chloride, the pH, and the product of the concentrations of nitrate and sulfate was performed. No significant relationship between the breakthrough volume and the other variables could be determined. The anion most likely to be the cause of the nitrate breakthrough volume is bicarbonate, which is known to be the dominant anion in Hanford Site groundwater. The nitrate loading had no effect on the adsorption of chromium or uranium.

6.7 CYCLING TESTS

The cycling tests demonstrated that chloride partially elutes the contaminants of interest. No degradation of the resin or its performance was noted (except in the case of uranium removal). The amount of eluant solution and wash solution does not seem sufficient to completely strip the resin of contaminants. Performance goals were met for nitrate, total chromium, and chromium (VI). The performance goal for uranium was met for the first two cycles. The failure to meet the performance goal for the last eight cycles may not be that serious, because Hanford Site groundwater typically has less than one-eighth of the concentration of uranium in the test solution. The high number of column volumes (<2,000 for chromium and uranium) treated, which is a measure of cleanup efficiency, should also be noted.

6.8 RECOMMENDATIONS

The results of this series of tests suggest that the most efficacious method for removal of nitrate, chromium [as chromate, chromium (VI)], and uranium is anion exchange with a strong base ion exchange resin.

Loading of the contaminants onto the resin and disposing of the resin may be the most cost-effective means of removing chromate and uranium from the groundwater. This approach would also be the best method for technetium removal due to the difficulties in eluting technetium.

If nitrate removal is desired, loading of the contaminants onto the resin column followed by elution of the contaminants from the resin and reuse of the resin would be the best process.

From the resins tested, Dowex 21K has been demonstrated to be a strong candidate for pilot-scale testing. The Dowex 21K was orginally developed for the acid mine tailings associated with uranium mining. The concentrations encountered were much higher than that encountered in the Hanford groundwater. Therefore, much of the information that was obtained from Dow Chemical Company was directly related to the uranium mine tailings for uranium recovery. Experience with Dowex 21K indicates a stable resin with a long service life for the uranium mining industry.

A field pilot-scale ion exchange unit using Dowex 21K resin is recommended. The suggested unit would entail the following:

Specific issues that should be studied during the pilot-scale operation would include confirmation of the amount of column volumes to attain the performance levels for chromium. Also, a total water analysis should be completed on both the influent and effluent (hydraulic residence time taken into consideration) on either a monthly or biweekly time table.

7.0 REFERENCES

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APPENDIX A

CONCENTRATION VALUES ANALYTICAL BLANK AND SAMPLE 199-H3-2C

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Table A-1. Analytical Blank Values.

Analyte	Concentration (in ppb unless otherwise specified)
Cr6	<56.7
U	<4.73
TIC	48000
TOC	6000
F-	<100
CL-	<100
NO2-	<1000
NO3-	<1000
PO4-	<1000
SO4-	<1000
Al	<51
As	50
Ca	<5
Cr	<15
K	<275
Mg	<3
Na	44
P	<70
S	<39
Si	<34
Sr	<3
V	<11
W	<36

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Table A-2. Concentration Values for 199-H3-2C. (sheet 1 of 2)

Analyte	Concentrations (in ppb unless otherwise specified)
Cr+6	70.2
Cr+6	70.2
pH	8.3
pH	8.25
TIC	35000
TIC	38000
TOC	<5500
TOC	<5500
TOT-ACT	<50000 pCi/L
U	5.59
U	5.59
F-	319
F-	306
CL-	2960
CL-	3058
NO2-	<1000
NO2-	<1000
NO3-	3974
NO3-	4040
PO4-	<1000
PO4-	<1000
SO4-	20933
SO4-	21169
B	10.9
Ba	10.4
Ca	24200
Ca	23800
Cr	27.2
K	4590
K	4650

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Table A-2. Concentration Values for 199-H3-2C. (sheet 2 of 2)

Analyte	Concentrations (in ppb unless otherwise specified)
Mg	8650
Mg	8490
Na	131
Na	12900
P	91.8999
P	86.7999
S	7150
S	7050
Si	27400
Si	26900
Sr	172
Sr	169
V	27.9
V	33.1
W	67.7999
W	66.0999

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APPENDIX B

FILTER METHOD TEST DATA

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Table B-1. Filter Blank Test Data.

Sample #	U	U after test	Total chromium	Total chromium after test	Cr(VI)	Cr(VI) after test	NO3	NO3 after test	pH	pH after test
EFOD1101	786	737	220	90	204	222	190	193	7.38	8.03
EFOS1101	524	714	222	242	204	224	197	190	7.29	8.05

NOTE: All values are given in parts per billion and are not rounded.

APPENDIX C

RAW DATA FROM THE SODIUM SULFIDE-FERROUS SULPHATE PRECIPITATION BATCH TEST AND

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9113722.1696

Table C-1. Raw Data from Sodium Sulfide-Ferrous Sulphate Batch Tests.

SAMPLE #	U	U after test	Total chromium	Total chromium after test	Cr(VI)	Cr(VI) after test	NO3	NO3 after test	pH	pH after test
EBSD2401	52	ND	2000	172	1925	19.4	6257	6068	8.41	8.74
EBSS2401	52	ND	2000	278	1925	19.4	6257	6115	8.39	8.77
EBSD2301	32.8	29.7	1895	44	1865	19.4	192800	188200	8.4	8.69
EBSS2301	32.8	40	1895	116	1865	19.4	192800	182200	8.4	8.32
EBSD2201	504	ND	1920	211	2050	19.4	6519	6305	8.33	8.32
EBSS2201	504	714	1920	246	2050	ND	6519	6317	8.5	8.35
EBSD2101	536	679	1895	176	2050	19.4	195750	193500	8.49	8.38
EBSS2102	536	ND	1895	35	2050	19.36	195750	189200	8.55	8.32
EBSD1801	37.45	43.3	75.99	22	81.6	19.4	70130	6890	8.35	8.44
EBSS1801	37.45	44.1	75.99	31	81.6	19.4	70130	6750	8.06	8.48
EBSD1701	126.2	47.4	79.49	22	82.29	20.7	187600	194100	7.81	8.29
EBSS1701	126.2	43.8	79.49	22	82.29	20.7	187600	195200	7.83	8.27
EBSD1601	613.5	412	80.5	22	79.5	22	6653	13290	8.16	8.63
EBSS1601	613.5	469	80.5	21	79.5	20.7	6653	6550	8.05	8.58
EBSD1501	536	526	73.99	16	83.65	20.7	185750	197700	7.81	8.51
EBSS1501	536	235	73.99	11	83.65	19.4	185750	207300	7.82	8.62

NOTES:
1. All values are given in parts per billion and are not rounded.
2. All "0" values are due to insufficient sample and were not used in calculating DFs.

Table C-2. Raw Data from the Sodium Phosphate Precipitation Batch Test.

Sample #	U	U after test	Total chromium	Total chromium after test	Cr(VI)	Cr(VI) after test	NO3	NO3 after test	pH	pH after test
EBPD2401	52	3.7	2000	1980	1925	1720	6257	5130	8.39	8.28
EBPS2401	52	ND	2000	1980	1925	1740	6257	5070	8.41	8.2
EBPD2301	32.8	21.4	1895	1920	1865	1660	192800	172900	8.4	7.69
EBPS2301	32.8	4.76	1895	1920	1865	988	192800	187000	8.4	7.72
EBPD2201	504	52.9	1920	2250	2050	881	6519	5300	8.33	7.71
EBPS2201	504	<32.3	1920	2120	2050	1680	6519	5440	8.5	7.74
EBPD2101	536	4.81	1895	2050	2050	1620	195750	183000	8.49	7.66
EBPS2101	536	4.17	1895	1990	2050	1600	195750	186800	8.55	7.54
EBPD1801	37.45	20	75.99	83	81.6	55.8	70130	47700	8.06	7.69
EBPS1801	37.45	ND	75.99	78	81.6	35	70130	47600	7.81	7.72
EBPD1701	126.2	ND	79.49	ND	82.29	48	187600	1775000	7.83	7.71
EBPS1701	126.2	ND	79.49	56	82.29	42.8	187600	1831000	8.16	7.74
EBPD1601	613.5	ND	80.5	106	79.5	44.1	6653	5000	8.05	7.66
EBPS1601	613.5	ND	80.5	155	79.5	46.7	6653	5100	7.81	7.54
EBPD1501	536	<21.7	73.99	234	83.65	45.4	185750	1890000	7.82	7.65
EBPS1501	536	3.23	73.99	174	83.65	44.1	185750	1867000	8.06	7.65

NOTES:
1. All values are given in parts per billion and are not rounded.
2. All "ND" (No Data) values are due to insufficient sample and were not used in calculating DFs.

Table C-3. Raw Data from the Phosphate Scoutiing Tests
(Phosphate Treatment Without Added Calcium Chloride).

Sample #	U after test	Total chromium after test	Cr(VI) after test	NO3 after test	pH after test	Treatment level (mg Na2HPO4/L solution treated)
EBT1101[a]	716	189	186	186000	7.4	* Standard No treatment
EBT1102[a]	1100	202	196	189000	7.3	* Standard No treatment
EBPS1101	1080	206	149	186400	7.8	423
EBPD1102[b]	314	206	175	191000	7.8	423
EBPS1102	794	202	178	190000	7.6	84
EBPD1102	1210	198	170	188000	7.6	84
EPBS1103	857	198	169	189000	7.6	17
EPBD1103	722	203	171	188000	7.6	17
EBPS1104	1130	205	169	162000	7.6	3.4
EPBD1104	639	200	169	185000	7.6	3.4

[a] Duplicates of standard solution used; only one solution used for scouting tests.
[b] Mislabeled; should be EBPD1101 (per notebook [Beck 1992]).

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APPENDIX D

RAW DATA FROM ANION RESIN BATCH TESTS

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Table D-1. Raw Data Dowex 21K Anion Exchange Batch Test.

Resin: Dowex 21K	Concentrations (in ppb) of contaminants before and after treatment with Dowex 21K resin								
Sample #	U original	U after test	Total chromium	Total chromium after test	Cr(VI)	Cr(VI) after test	NO3	NO3 after test	Grams resin per 30 mL solution
EBKD1801	37.45[a]	4	75.99	12.7	81.6	19.4	70130	2881	1.2067
EBKS1801	37.45	6.67	75.99	12.7	81.6	19.4	70130	2881	6.0379
EBKD1701	126.2	26.3	79.49	12.7	82.29	19.4	187600	7246	1.2023
EBKS1701	126.2	ND[b]	79.49	12.7	82.29	19.4	187600	3140	6.0043
EBKD1601	613.5	31.3	80.5	12.7	79.5	19.4	6653	2881	1.2144
EBKS1601	613.5	21.7	80.5	12.7	79.5	19.4	6653	2881	6.0387
EBKD1501	536	ND	73.99	12.7	83.65	19.4	185750	7741	1.2104
EBKS1501	536	ND	73.99	20	83.65	19.4	185750	2881	6.0008
EBKD2401	52	4	2000	12.7	1925	19.4	6257	2881	1.217
EBKS2401	52	7.14	2000	32	1925	28.5	6257	2881	6.021
EBKD2301	32.8	3.85	1895	12.7	1865	22	192800	7830	1.2076
EBKS2301	32.8	7.14	1895	30	1865	20.7	192800	3500	6.0495
EBKD2201	504	4	1920	12.7	2050	19.4	6519	2880	1.2142
EBKS2201	504	7.14	1920	31	2050	19.4	6519	2880	6.0143
EBKD2101	536	2.62	1895	18	2050	19.4	195750	7630	1.2084
EBKS2101	536	5.56	1895	40	2050	19.4	195750	3440	6.019

NOTE: "0" values were used to determine the linear regression coefficients.

[a] All values are given in parts per billion and are not rounded.

[b] All "ND" (No Data) values are due to insufficient sample and were not used in calculating DFs.

Table D-2. Raw Data Amberlite 402 Anion Exchange Batch Test.

402 resin		Concentrations (in ppb) of contaminants before and after treatment with Amerlite 402 resin							
Sample #	U	U after test	Total chromium	Total chromium after test	Cr(VI)	Cr(VI) after test	NO3	NO3 after test	grams resin per 30 mL solution
EB2D1801	37.45	20[a]	75.99	12.7	81.6	19.4	70130	2880	1.2012
EB2S1801	37.45	5.26	75.99	12.7	81.6	19.4	70130	ND	6.014
EB2D1701	126.2	3.57	79.49	12.7	82.29	19.4	187600	25780	1.204
EB2S1701	126.2	4.75	79.49	12.7	82.29	19.4	187600	21380	6.0254
EB2D1601	613.5	3.33	80.5	12.7	79.5	9.4	6653	2880	1.2067
EB2S1601	613.5	4.35	80.5	12.7	79.5	19.4	6653	ND	6.0228
EB2D1501	536	3.33	73.99	12.7	83.65	19.4	185750	30660	1.2071
EB2S1501	536	4	73.99	12.7	83.65	19.4	185750	27410	6.0184
EB2D2401	52	ND[b]	2000	23	1925	19.4	6257	ND	1.1999
EB2S2401	52	ND	2000	155	1925	101	6257	ND	6.0592
EB2D2301	32.8	ND	1895	39	1865	22	192800	37140	1.2101
EB2S2301	32.8	20	1895	173	1865	130	192800	30040	6.0055
EB2D2201	504	20	1920	38	2050	19.4	6519	2880	1.2024
EB2S2201	504	ND	1920	155	2050	109	6519	ND	6.0034
EB2D2101	536	22.7	1895	52	2050	23.3	195750	43780	1.2013
EB2S2101	536	3.91	1895	59	2050	122	195750	40050	6.018

NOTE: "ND" values were assumed to be 0 in determining the linear regression coefficients.

[a] All values are given in parts per billion and are not rounded.

[b] All "ND" (No Data) values are due to insufficient sample and were not used in calculating DFs.

Table D-3. Raw Data Amberlite 410 Anion Exchange Batch Test.

Resin Amberlite 410	Concentrations (in ppb) of contaminants before and after treatment with 410 type resin								
Sample #	U	U after test	Total chromium	Total chromium after test	Cr(VI)	Cr(IV) after test	NO3	NO3 after test	Grams resin per 30 mL solution
EB1D1801	37.45[a]	4	75.99	12.7	81.6	19.4	70130	2881	1.2132
EB1S1801	37.45	4	75.99	12.7	81.6	19.4	70130	2881	6.0343
EB1D1701	126.2	3.85	79.49	12.7	82.29	19.4	187600	17600	1.1073
EB1S1701	126.2	4	79.49	12.7	82.29	19.4	187600	13040	6.0371
EB1D1601	613.5	4	80.5	12.7	79.5	19.4	6653	2881	1.2018
EB1S1601	613.5	4	80.5	12.7	79.5	19.4	6653	2881	5.9981
EB1D1501	536	4	73.99	12.7	83.65	19.4	185750	15910	1.2046
EB1S1501	536	5.24	73.99	12.7	83.65	19.4	185750	11350	6.0153
EB1D2401	52	4.76	2000	29	1925	19.4	6257	2881	1.226
EB1S2401	52	4.76	2000	41	1925	19.4	6257	2881	5.966
EB1D2301	32.8	4	1895	25	1865	19.4	192800	24320	1.202
EB1S2301	32.8	4	1895	47	1865	19.4	192800	15910	6.092
EB1D2201	504	4	1920	24	2050	19.4	6519	2881	1.198
EB1S2201	504	20	1920	35	2050	19.4	6519	2881	5.986
EB1D2101	536	3.7	1895	23	2050	19.4	195750	17960	1.2118
EB1S2101	536	3.57	1895	37	2050	19.4	195750	13810	5.988

[a] All values are given in parts per billion and are not rounded.

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APPENDIX E

REGRESSION COEFFICIENT VALUES FOR ANION EXCHANGE METHODS

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Table E-1. Regression Coefficient Values for Anion Exchange Methods.

Dependant variables	R^2 ****	Constant	U	Total chromium	NO3	Resin	U*Cr	U*NO3	U*R	Cr*NO3	Cr*R	NO3*R
Dowex 21K												
Cr(VI)	33%	1.97e+01	-	-	-	-	-2.57e-06	-	-	-	3.35e-04	-
NO3	94%	2.62e+03	-	-	3.10e-02	-	-	-	-	-	-	-4.60e-03
U	***	8.21e+00	-	-	-	-	-	-	-	-	-	-
Total chromium	96%	1.13e+01	-	-1.97e-03	-	-	-	5.77e-08	-	-	2.07e-03	-
Amberlite 402												
Cr(VI)	98%	1.60e+01	-	-1.34e-01	-	-	-	-	-	3.92e-08	1.01e-02	-
NO3	98%	-9.26e+03	1.36e+01	2.54e+00	1.81e-01	-	-	-	-	1.80e-05	-	-5.21e-03
U	***	7.20e+00	-	-	-	-	-	-	-	-	-	-
Total chromium	82%	1.06e+01	-	-	-	-	-	-	-	-	1.08e-02	-
Amberlite 410												
Cr(VI)		N/A	N/A	N/A	N/A	NA	N/A	N/A	N/A	N/A	N/A	N/A
NO3	91%	-1.15e+02	-	1.46e+00	9.7e-02	-	-	-	-	7.83e-06	-	-5.6e-03
U	***	5.12e+01	-	-	-	-	-	-	-	-	-	-
Total chromium	97%	1.19e+01	-	6.6e-03	-	-	-5.67e-06	-	-	-	1.59e-03	-

* A (-) indicates that the term was not used in the final model to predict C_{final}, i.e., these regression coefficients are not significantly different from zero.

** N/A -- Not available, as the dependent variable was a constant (the analytical less than value).

*** R^2 is not applicable, as no regression equation (model) is used.

**** A definition of R^2 is the percent of total variability of the data explained by the regression equation.

APPENDIX F

EQUILIBRIUM EXPERIMENT DATA

Table F-1. Equilibrium Experiment Raw Data.

Sample #	U	NO3	Total chromium	Cr(VI)	Mass of resin (g)
EBKT2111	534	196500	1870	1520	<--Standards
EBKT2110	432	189000	1840	1540	<--Standards
EBKS2111	4.5	119000	62	19.4	0.05
EBKS2110	21.1	69790	30	19.4	0.1071
EBKD2111	3.89	115000	29.8	19.4	0.0557
EBKD2110	5	71600	32	19.4	0.0986
EBKB0911	12.3	5955	29.8	19.4	<--Blanks
EBKB0910	5.79	5030	29.8	19.4	<--Blanks
Measured density of resin 0.86 g/mL					

9413224.1713

Table F-2. Liters of Solution 31 (Spiked 199-H3-2C) Treatable per Milliliter of Resin.

Sample #	U	Nitrate	Total chromium	Cr(VI)
EBKS2111	54.9	0.3	14.9	40.2
EBKS2110	5.3	0.4	14.7	18.8
EBKD2111	57.0	0.3	28.4	36.1
EBKD2110	25.0	0.4	14.9	20.4
Average	35.6	0.4	18.2	28.8

APPENDIX G

RESULTS OF THE LOW FLOW RATE SPIKED GROUNDWATER (WELL 199-H3-2C) BREAKTHROUGH TEST

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9113227.1716

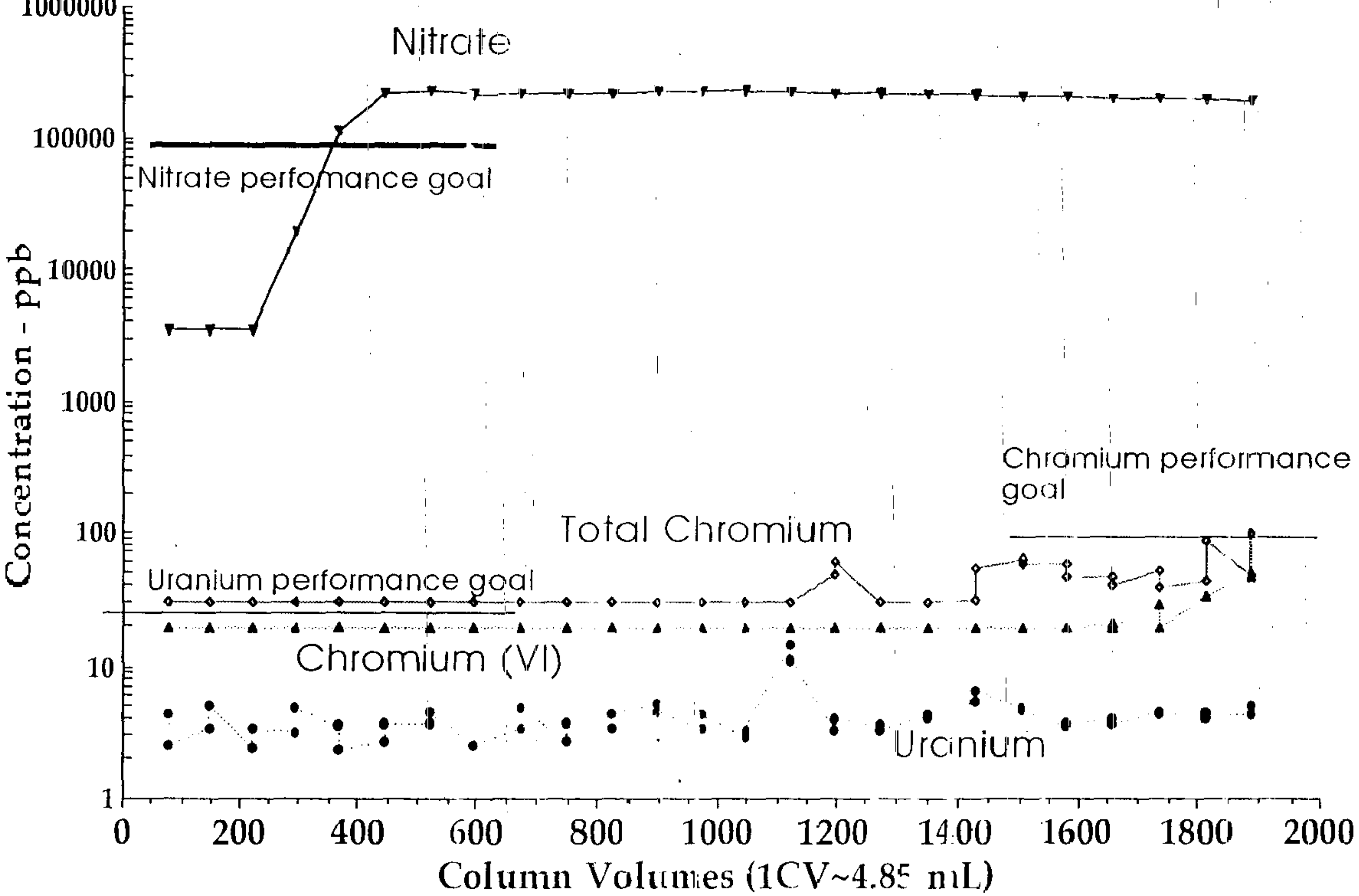

Figure G-1. Spiked H3-2C Slow Flow Concentration Versus Column Volumes.

9413221.1718

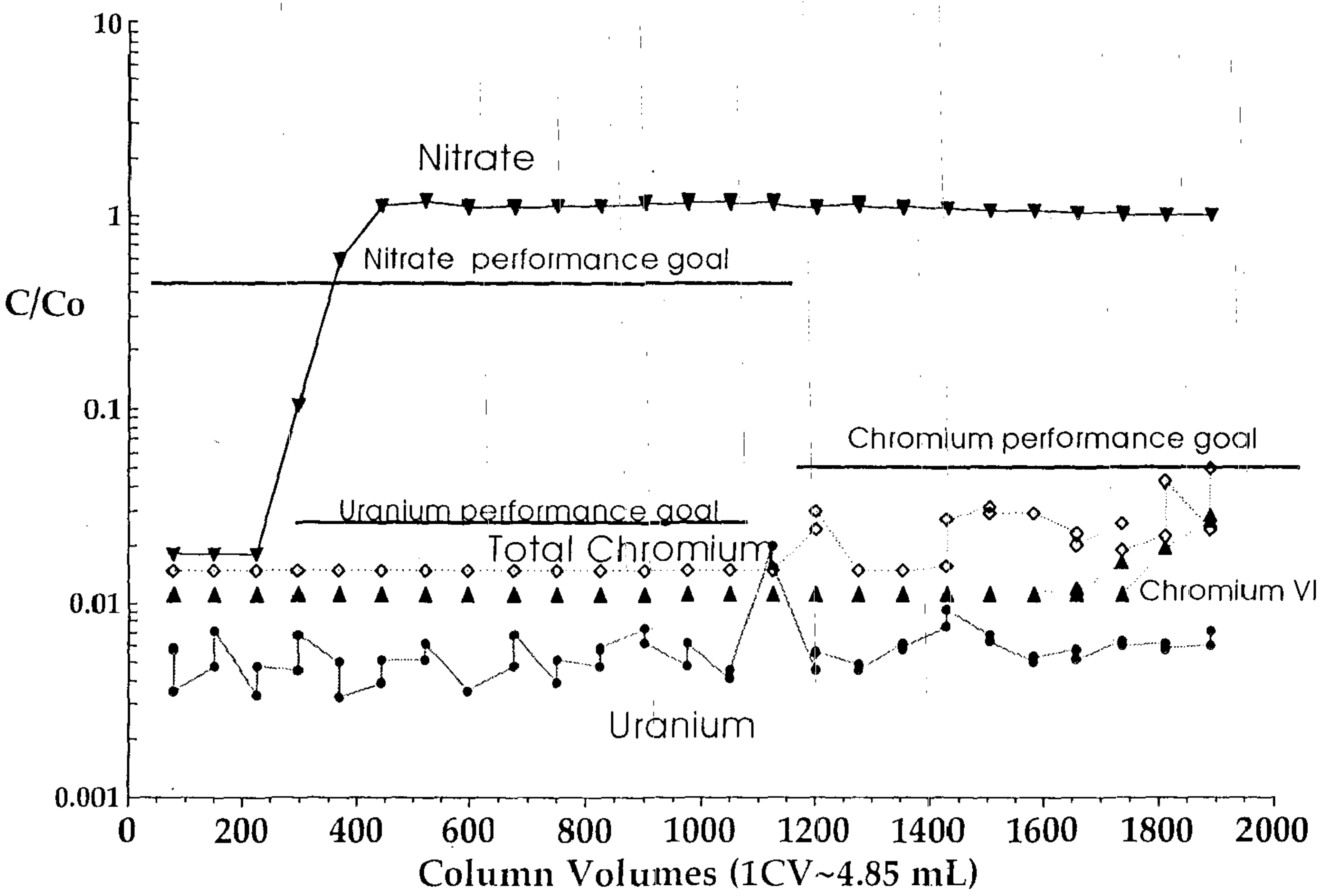

Figure G-2. Spiked H2-3C Slow Flow C/Co Versus Column Volumes.

9413221.1719

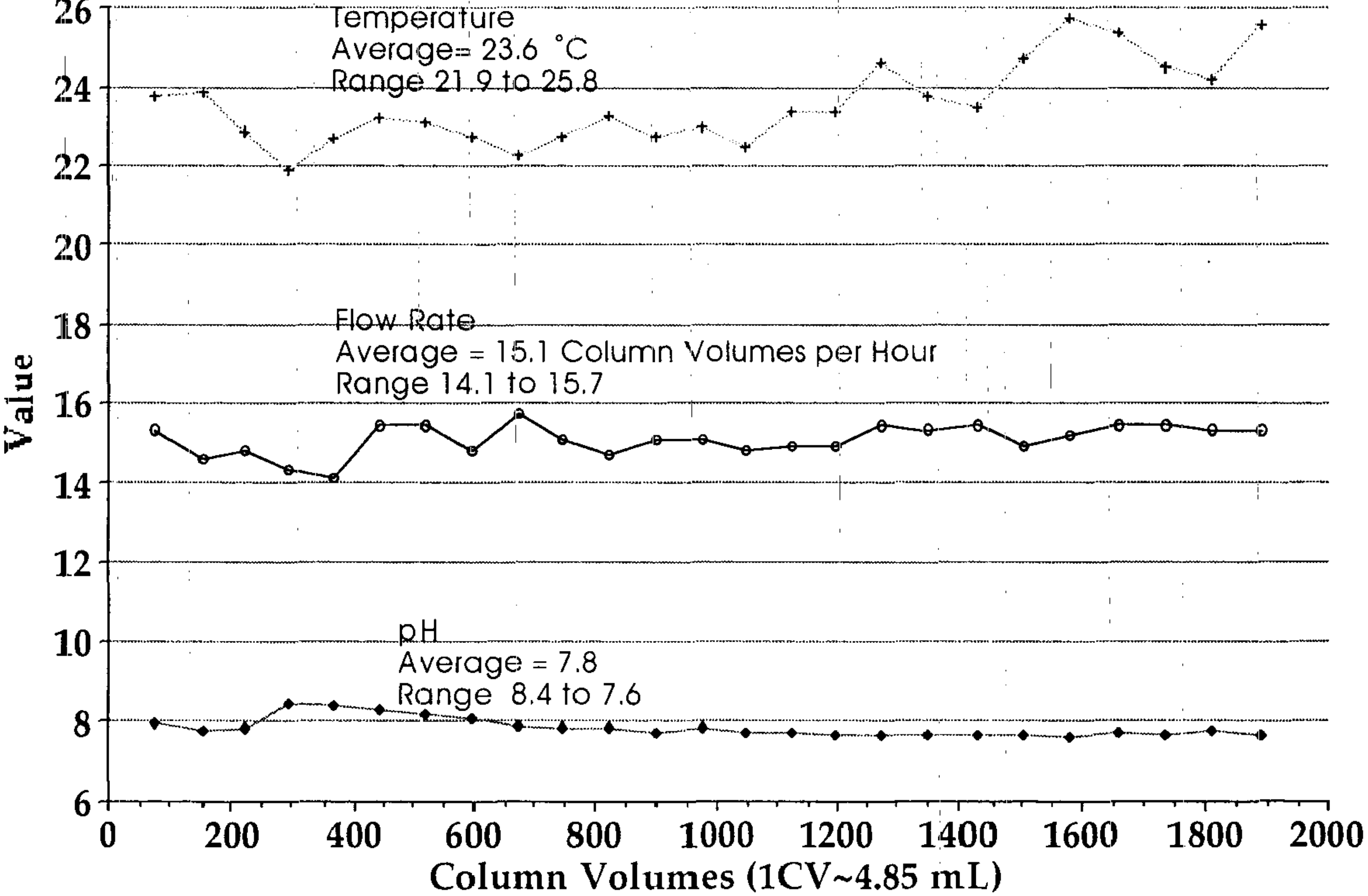

Figure G-3. Spiked H3-2C Slow Flow Temperature, Flow Rate, and pH.

9413221.1721

Table G-1. Raw Data from the Low Flow Rate Spiked Groundwater (Well H3-2C) Breakthrough Test. (sheet 1 of 3)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume ~4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Flow Rate (Column Volumes per Hour)	Temperature (°C) at end of sample collection	pH
P 1554.	ERK31B01		720	1990	1740	199100			8.47
P 1554.	ERK31B01		705	2020	1820	187600			
P 1555.	ERK21T01		620	1930	1670	190500			8.3
P 1555.	ERK21T01		570	1920	1620	198600			
P 1556.	ERK31S01	76.90722	4.2	29.8	19.4	3473	1.24	23.8	7.95
P 1556.	ERK31S01	76.90722	2.5	29.8	19.4	3473	1.24		
P 1557.	ERK31S02	150.1031	3.3	29.8	19.4	3473	1.18	23.9	7.78
P 1557.	ERK31S02	150.1031	5	29.8	19.4	3473	1.18		
P 1558.	ERK31S03	224.3299	2.4	29.8	19.4	3473	1.2	22.9	7.82
P 1558.	ERK31S03	224.3299	3.3	29.8	19.4	3473	1.2		
P 1559.	ERK31S04	296825	3.2	29.8	19.4	19960	1.16	21.9	8.47
P 1559.	ERK31S04	296825	4.8	29.8	19.4	19930	1.16		
P 1560.	ERK31S05	366.5979	3.5	29.8	19.4	112900	1.14	22.7	8.38
P 1560.	ERK31S05	366.5979	2.3	29.8	19.4	112200	1.14		
P 1561.	ERK31S06	443.7113	2.7	29.8	19.4	222200	1.25	23.2	8.3
P 1561.	ERK31S06	443.7113	3.6	29.8	19.4	220800	1.25		
P 1562.	ERK31S07	521309	3.6	29.8	19.4	228400	1.25	23.1	8.19
P 1562.	ERK31S07	521309	4.4	29.8	19.4	228700	1.25		
P 1563.	ERK31S08	595.2577	2.5	29.8	19.4	218200	1.2	22.8	84
P 1563.	ERK31S08	595.2577	2.5	29.8	19.4	212900	1.2		
P 1564.	ERK31S09	673.8144	3.3	29.8	19.4	217200	1.27	22.3	7.88
P 1564.	ERK31S09	673.8144	4.8	29.8	19.4	215900	1.27		
P 1565.	ERK31S10	749.4845	2.7	29.8	19.4	219500	1.22	22.8	7.83
P 1565.	ERK31S10	749.4845	3.6	29.8	19.4	217500	1.22		
P 1566.	ERK31S11	823.5052	3.3	29.8	19.4	221200	1.19	23.3	7.86
P 1566.	ERK31S11	823.5052	4.2	29.8	19.4	218600	1.19		

9413221.1722

Table G-1. Raw Data from the Low Flow Rate Spiked Groundwater (Well H3-2C) Breakthrough Test. (sheet 2 of 3)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume ~4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Flow Rate (Column Volumes per Hour)	Temperature (°C) at end of sample collection	pH
P 1567.	ERK31S12	898.9691	5.2	29.8	19.4	226100	1.22	22.8	7.75
P 1567.	ERK31S12	898.9691	4.4	29.8	19.4	227900	1.22		
P 1568.	ERK31S13	974.433	3.3	29.8	19.4	226500	1.22	23	7.82
P 1568.	ERK31S13	974.433	4.3	29.8	19.4	228900	1.22		
P 1569.	ERK31S14	1048.577	2.9	29.8	19.4	231500	1.2	22.5	7.73
P 1569.	ERK31S14	1048.577	3.2	29.8	19.4	226600	1.2		
P 1570.	ERK31S15	1123.423	14.1	29.8	19.4	228800	1.21	23.4	7.72
P 1570.	ERK31S15	1123.423	10.8	29.8	19.4	227500	1.21		
P 1571.	ERK31S16	1198.268	3.2	48	19.4	216000	1.21	23.4	7.68
P 1571.	ERK31S16	1198.268	3.9	60	19.4	219700	1.21		
P 1572.	ERK31S17	1275.381	3.5	29.8	19.4	227300	1.25	24.6	7.69
P 1572.	ERK31S17	1275.381	3.2	29.8	19.4	221700	1.25		
P 1573.	ERK31S18	1351.876	4.3	29.8	19.4	215400	1.24	23.8	7.66
P 1573.	ERK31S18	1351.876	49	29.8	19.4	217200	1.24		
P 1574.	ERK31S19	1429.196	5.3	31	19.4	215600	1.25	23.5	7.68
P 1574.	ERK31S19	1429.196	6.5	54	19.4	213900	1.25		
P 1575.	ERK31S20	1504.247	4.8	64	19.4	208900	1.21	24.7	7.69
P 1575.	ERK31S20	1504.247	4.5	59	19.4	209000	1.21		
P 1576.	ERK31S21	1580.536	3.5	45	19.4	207600	1.23	25.8	7.63
P 1576.	ERK31S21	1580.536	3.7	42	19.4	206400	1.23		
P 1577.	ERK31S22	1657.649	4	46	20.7	205000	1.25	25.4	7.73
P 1577.	ERK31S22	1657.649	3.6	40	19.4	201400	1.25		
P 1578.	ERK31S23	1734.969	4.4	52	28.5	202500	1.25	24.5	7.69
P 1578.	ERK31S23	1734.969	4.2	38	19.4	200800	1.25		
P 1579.	ERK31S24	1811.876	4.4	59	33.7	199200	1.24	24.2	7.79
P 1579.	ERK31S24	1811.876	49	60	33.7	199100	1.24		

Table G-1. Raw Data from the Low Flow Rate Spiked Groundwater (Well H3-2C) Breakthrough Test. (sheet 3 of 3)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume ~4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Flow Rate (Column Volumes per Hour)	Temperature (°C) at end of sample collection	pH
P 1580.	ERK31S25	1888.557	4.2	68	46.7	196300	1.24	25.6	7.65
P 1580.	ERK31S25	1888.557	5	64	50.6	197200	1.24		
P 1581.	ERK31B02		765	2060	1750	192500			85
P 1581.	ERK31B02		645	2033	1760	189900			

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APPENDIX H

RESULTS OF THE HIGH FLOW RATE SPIKED GROUNDWATER (WELL H3-2C) BREAKTHROUGH TEST

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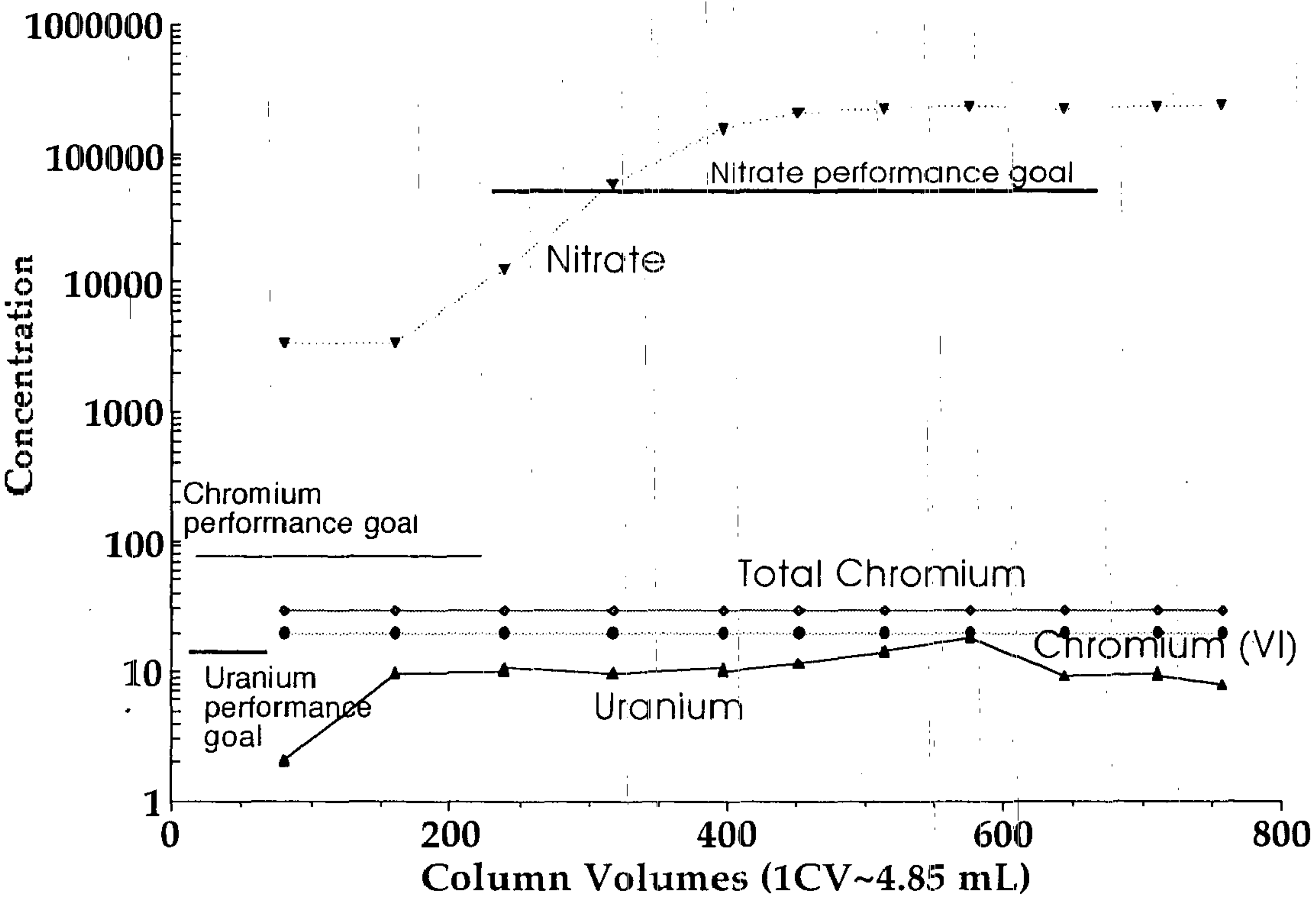

Figure H-1. Fast Flow Spiked H3-2C Concentration Versus Column Volumes.

9413221.1728

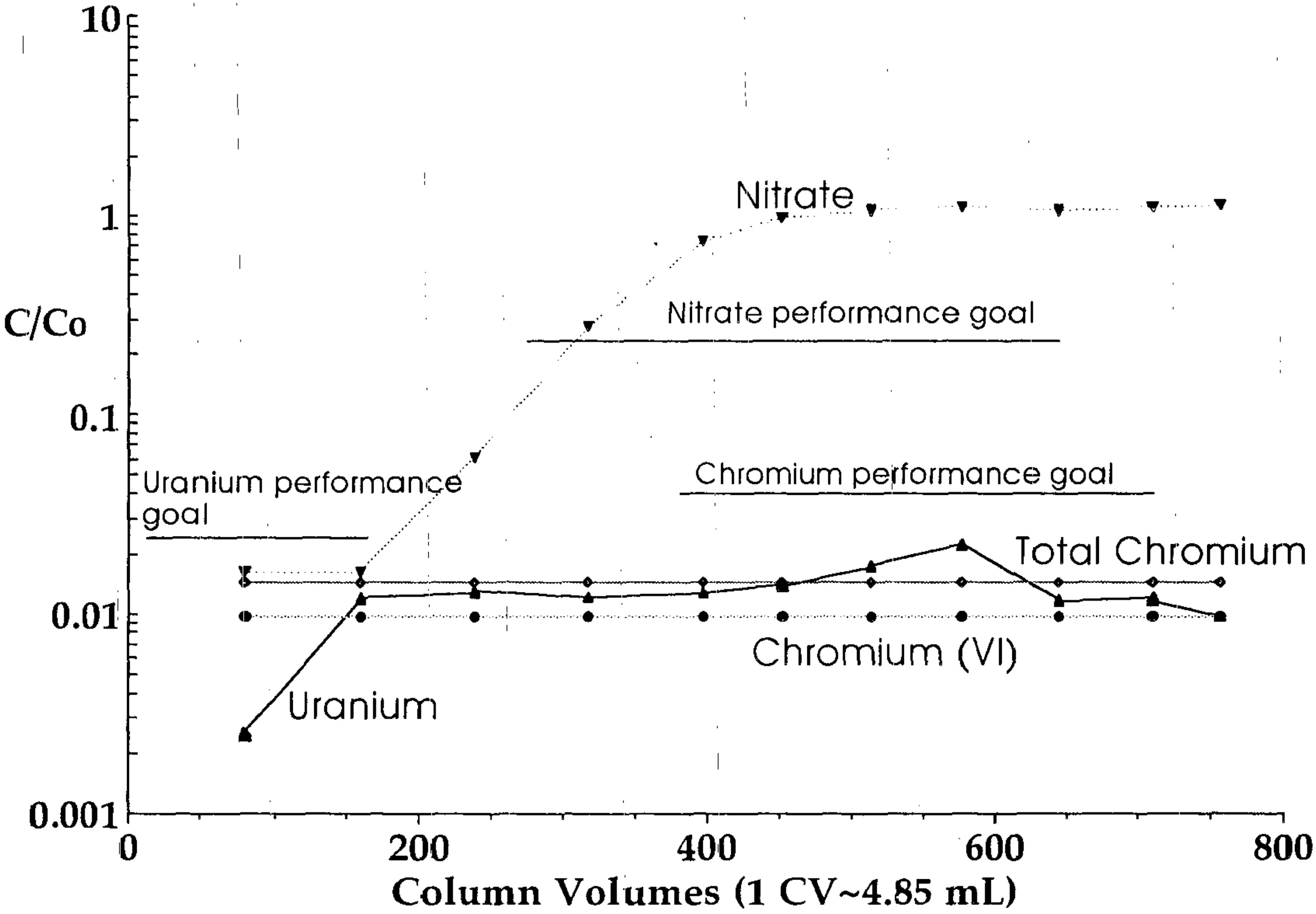

Figure H-2. Fast Flow Test Spiked H3-2C, C/Co Versus Column Volumes.

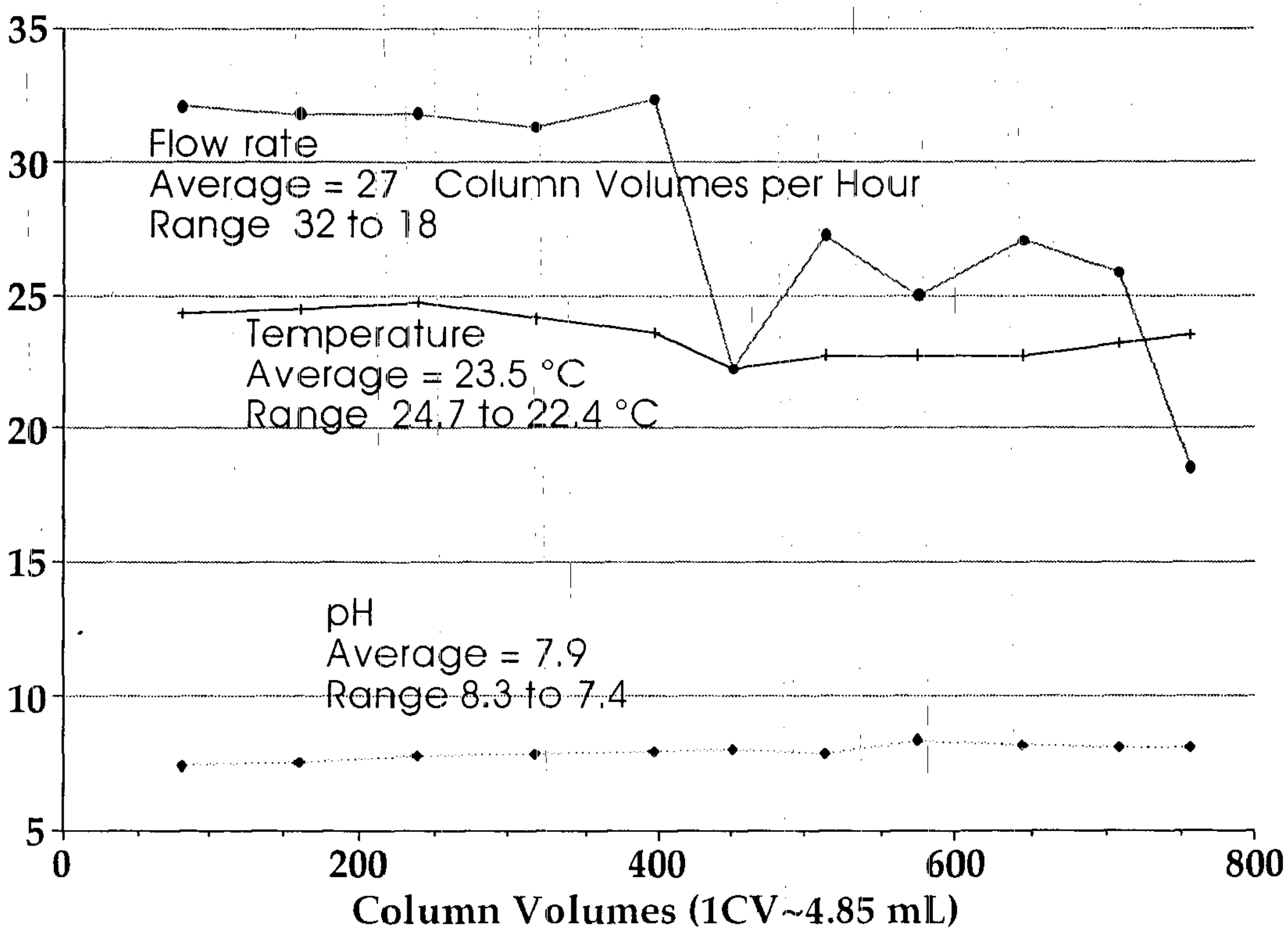

Figure H-3. Fast Flow Test Flow Rate, pH, Temperature Versus Column Volumes.

9113221.1730

9413221.1731

Table H-1. Raw Data from the High Flow Rate Spiked Groundwater (Well H3-2C) Breakthrough Test.

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume = 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Temperature (°C) at end of sample collection	Flow Rate (Column Volumes per Hour)	pH
P 1599.	ERK21T05		970	2050	1900	208160		0	83
P 1599.	ERK21T05		962	2080	1880	207190		0	7.94
P 1600.	ERK31S31	80	2	29.8	19.4	3473	24.3	32	7.4
P 1600.	ERK31S31	80	2.1	29.8	19.4	3473	24.3	32	7.4
P 1601.	ERK31S32	159.6	9.6	29.8	19.4	3473	24.5	31.8	7.5
P 1601.	ERK31S32	159.6	9.7	29.8	19.4	3473	24.5	31.8	7.5
P 1602.	ERK31S33	239.2	10.2	29.8	19.4	12920	24.7	31.8	7.72
P 1602.	ERK31S33	239.2	10.7	29.8	19.4	13040	24.7	31.8	7.72
P 1603.	ERK31S34	317.5	9.8	29.8	19.4	59540	24.1	31.3	7.86
P 1603.	ERK31S34	317.5	9.7	29.8	19.4	59260	24.1	31.3	7.86
P 1604.	ERK31S35	396.5	10.4	29.8	19.4	157370	23.6	32.3	7.97
P 1604.	ERK31S35	396.5	10.3	29.8	19.4	158230	23.6	32.3	7.97
P 1605.	ERK31S36	452.2	11.3	29.8	19.4	211050	22.2	22.3	82
P 1605.	ERK31S36	452.2	11.2	29.8	19.4	211790	22.2	22.3	82
P 1606.	ERK31S37	514	13.8	29.8	19.4	228730	22.8	27.2	7.88
P 1606.	ERK31S37	514	14.3	29.8	19.4	229270	22.8	27.2	7.88
P 1627.	ERK31S38	576.5	18	29.8	19.4	236430	22.8	25	8.33
P 1627.	ERK31S38	576.5	18	29.8	19.4	235980	22.8	25	8.33
P 1608.	ERK31S39	644.3	9.5	29.8	19.4	229340	22.8	27.1	8.15
P 1608.	ERK31S39	644.3	9.2	29.8	19.4	228260	22.8	27.1	8.15
P 1609.	ERK31S40	709.1	9.7	29.8	19.4	235260	23.2	25.9	88
P 1609.	ERK31S40	709.1	9.4	29.8	19.4	237400	23.2	25.9	88
P 1610.	ERK31S41	756.5	7.9	29.8	19.4	242500	23.5	18.6	8.11
P 1610.	ERK31S41	756.5	8	29.8	19.4	244710	23.5	18.6	8.11
P 1625.	ERK31B06	0	771	2160	2070	218380			8.11
P 1625.	ERK31B06	0	728	2160	2060	215890			8.11

9112322.1732

APPENDIX I

RESULTS OF THE UNSPIKED GROUNDWATER (WELL 199-H4-4) BREAKTHROUGH TEST

9113221.1733

9113221 1731

9413221.1735

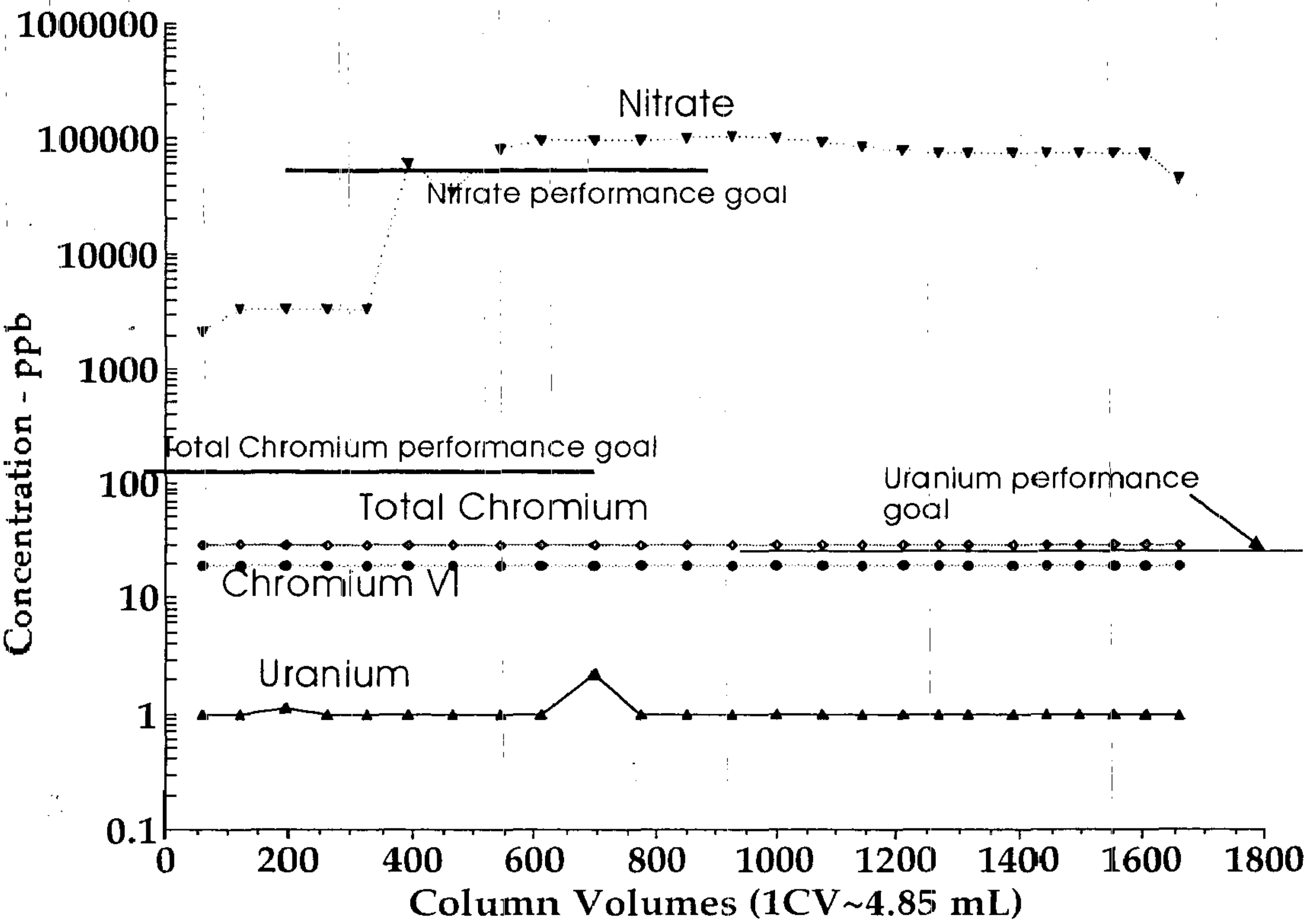

Figure I-1. Well H4-4 Concentration Versus Column Volumes.

9413221.1736

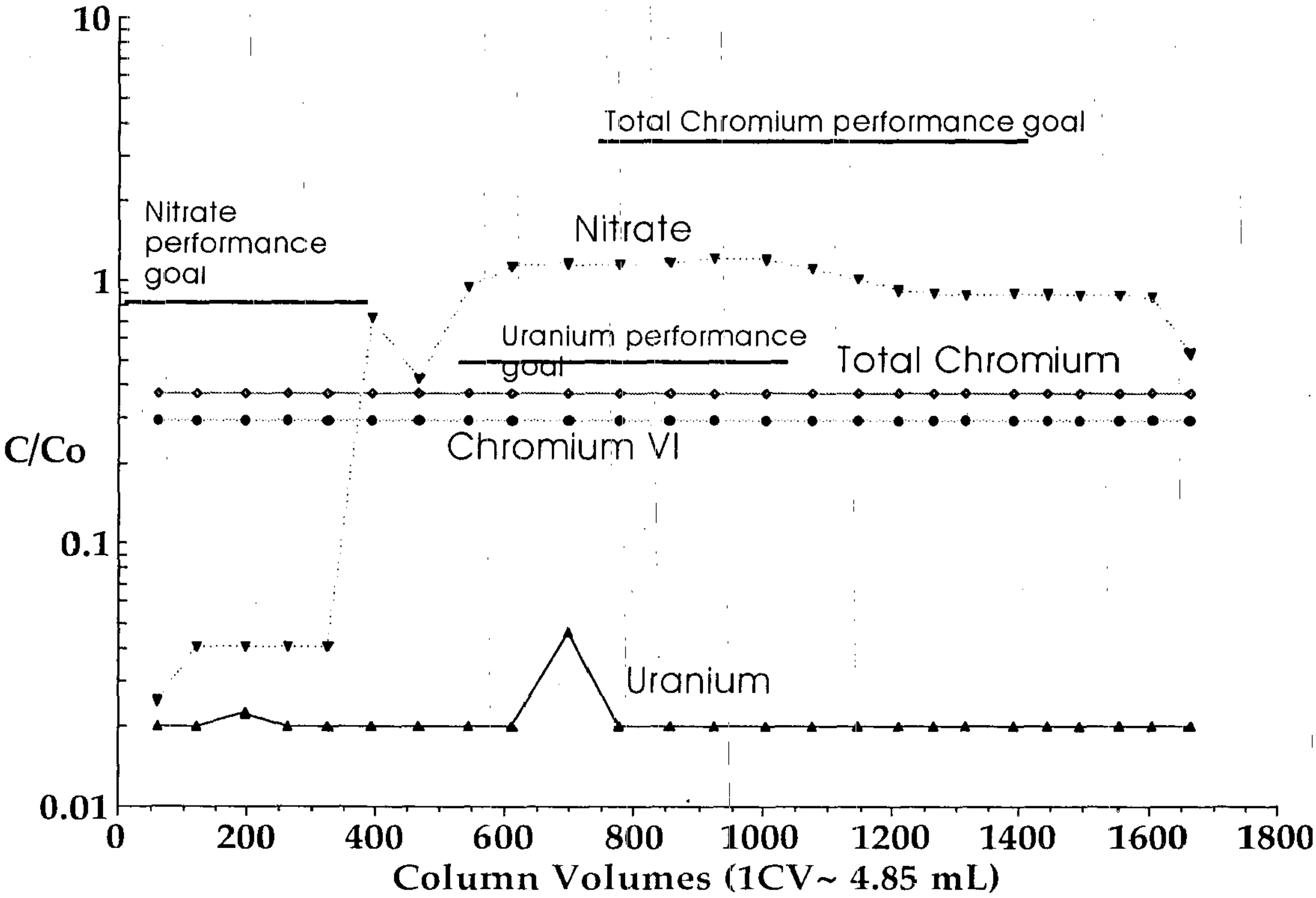

Figure I-2. Well H4-4 C/Co Versus Column Volumes.

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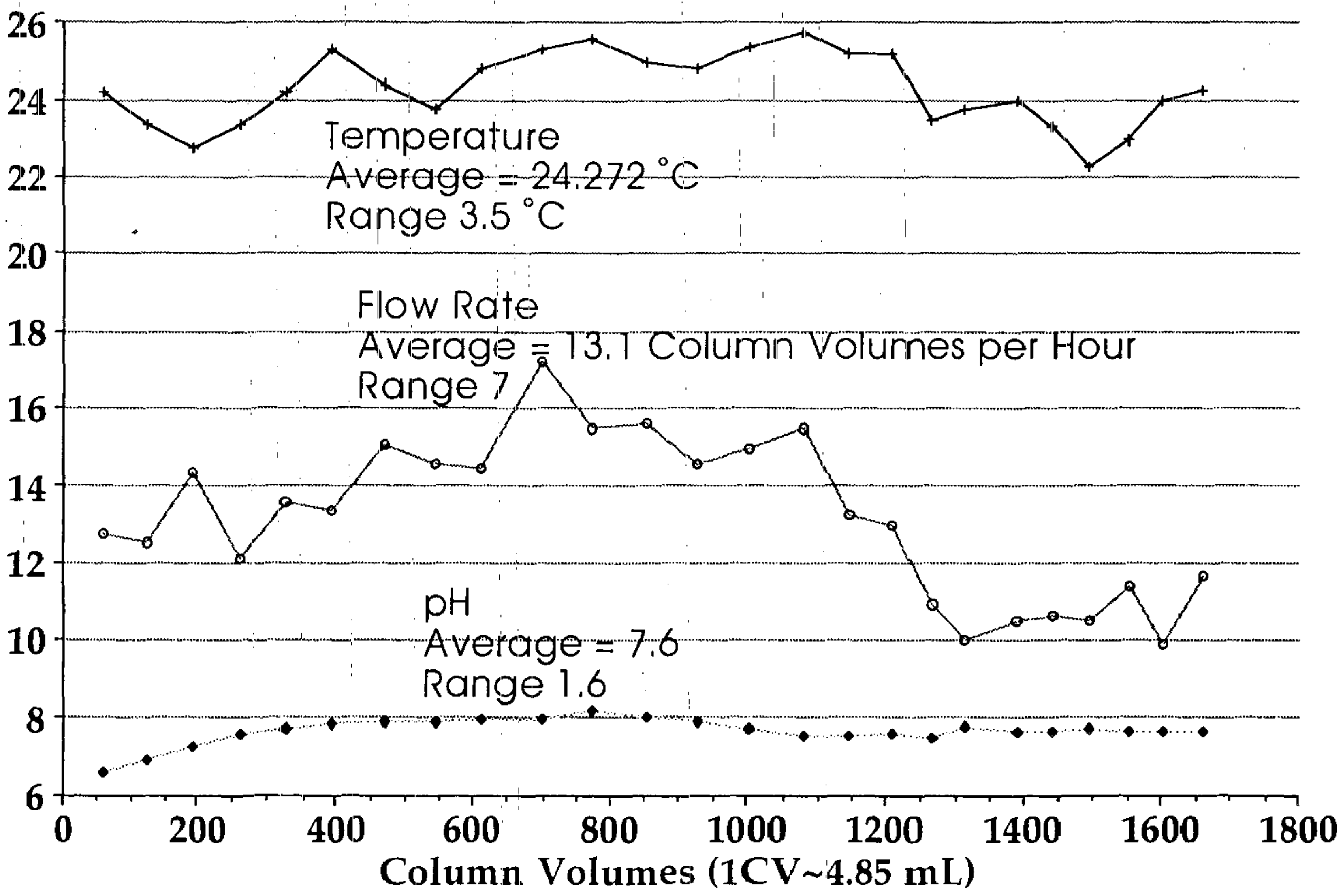

Figure I-3. Well H4-4 Temperature, Flow Rate, and pH.

9112722.1738

9413221.1739

Table I-1. Raw Data from the Unspiked Groundwater (Well H4-4) Breakthrough Test. (sheet 1 of 3)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate	Temperature (°C) at sample collection	Flow Rate (Column Volumes per Hour)	pH
P 1664.	ERK29B01		45	76	70.1	77090			4.5
P 1664.	ERK29B01		44	73	64.9	76900			4.5
P 1665.	ERK21T09		783	2110	2080	186900			7.86
P 1665.	ERK21T09		778	2160	1950	187500			7.86
P 1666.	ERK29S01	60.5	1	29.8	19.4	2138	24.2	12.7	7.94
P 1666.	ERK29S01	60.5	1	29.8	19.4	2158	24.2	12.7	7.94
P 1667.	ERK29S02	123.2	1	29.8	19.4	3473	23.4	12.5	6.57
P 1667.	ERK29S02	123.2	1	29.8	19.4	3473	23.4	12.5	6.57
P 1668.	ERK29S03	195.2	1.1	29.8	19.4	3473	22.8	14.4	6.93
P 1668.	ERK29S03	195.2	1.1	29.8	19.4	3473	22.8	14.4	6.93
P 1669.	ERK29S04	262.9	1	29.8	19.4	3473	23.4	12.1	7.28
P 1669.	ERK29S04	262.9	1	29.8	19.4	3473	23.4	12.1	7.28
P 1670.	ERK29S05	326.4	1	29.8	19.4	3473	24.2	13.6	7.6
P 1670.	ERK29S05	326.4	1	29.8	19.4	3473	24.2	13.6	7.6
P 1671.	ERK29S06	393	1	29.8	19.4	60850	25.3	13.4	7.69
P 1671.	ERK29S06	393	1	29.8	19.4	60950	25.3	13.4	7.69
P 1672.	ERK29S07	468.4	1	29.8	19.4	35740	24.4	15.1	7.82
P 1672.	ERK29S07	468.4	1	29.8	19.4	35650	24.4	15.1	7.82
P 1673.	ERK29S08	544.9	1	29.8	19.4	80720	23.8	14.6	7.86
P 1673.	ERK29S08	544.9	1	29.8	19.4	80400	23.8	14.6	7.86
P 1674.	ERK29S09	611.5	1	29.8	19.4	95260	24.8	14.5	7.9
P 1674.	ERK29S09	611.5	1	29.8	19.4	96160	24.8	14.5	7.9
P 1675.	ERK29S10	697.9	2.3	29.8	19.4	98770	25.3	17.2	7.97
P 1675.	ERK29S10	697.9	2.3	29.8	19.4	97600	25.3	17.2	7.97
P 1676.	ERK29S11	775.6	1	29.8	19.4	98240	25.6	15.5	7.93

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Table I-1. Raw Data from the Unspiked Groundwater (Well H4-4) Breakthrough Test. (sheet 2 of 3)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume ~ 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate	Temperature (°C) at sample collection	Flow Rate (Column Volumes per Hour)	pH
P 1676.	ERK29S11	775.6	1	29.8	19.4	97450	25.6	15.5	7.93
P 1677.	ERK29S12	853.6	1	29.8	19.4	100300	25	15.6	8.18
P 1677.	ERK29S12	853.6	1	29.8	19.4	99670	25	15.6	8.18
P 1678.	ERK29S13	926.5	1	29.8	19.4	103500	24.8	14.6	7.99
P 1678.	ERK29S13	926.5	1	29.8	19.4	103500	24.8	14.6	7.99
P 1679.	ERK29S14	1001.8	1	29.8	19.4	102900	25.4	15	7.88
P 1679.	ERK29S14	1001.8	1	29.8	19.4	107000	25.4	15	7.88
P 1680.	ERK29S15	1079.2	1	29.8	19.4	94910	25.8	15.5	7.69
P 1680.	ERK29S15	1079.2	1	29.8	19.4	94680	25.8	15.5	7.69
P 1681.	ERK29S16	1145.6	1	29.8	19.4	86430	25.2	13.2	7.55
P 1681.	ERK29S16	1145.6	1	29.8	19.4	85800	25.2	13.2	7.55
P 1682.	ERK29S17	1210.7	1	29.8	19.4	78560	25.2	13	7.55
P 1682.	ERK29S17	1210.7	1	29.8	19.4	78010	25.2	13	7.55
P 1683.	ERK29S18	1265.7	1	29.8	19.4	76000	23.5	10.9	7.58
P 1683.	ERK29S18	1265.7	1	29.8	19.4	75720	23.5	10.9	7.58
P 1684.	ERK29S19	1315.8	1	29.8	19.4	75340	23.8	10	7.5
P 1684.	ERK29S19	1315.8	1	29.8	19.4	75290	23.8	10	7.5
P 1685.	ERK29S20	1389.4	1	29.8	19.4	75750	24	10.5	7.79
P 1685.	ERK29S20	1389.4	1	29.8	19.4	76110	24	10.5	7.79
P 1686.	ERK29S21	1442.6	1	29.8	19.4	75300	23.3	10.6	7.65
P 1686.	ERK29S21	1442.6	1	29.8	19.4	75510	23.3	10.6	7.65
P 1687.	ERK29S22	1495.2	1	29.8	19.4	74460	22.3	10.5	7.66
P 1687.	ERK29S22	1495.2	1	29.8	19.4	74190	22.3	10.5	7.66
P 1688.	ERK29S23	1552.3	1	29.8	19.4	75340	23	11.4	7.72
P 1688.	ERK29S23	1552.3	1	29.8	19.4	75280	23	11.4	7.72
P 1689.	ERK29S24	1602.2	1	29.8	19.4	73510	24	9.9	7.63

9413221.1741

Table I-1. Raw Data from the Unspiked Groundwater (Well H4-4) Breakthrough Test. (sheet 3 of 3)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume - 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate	Temperature (°C) at sample collection	Flow Rate (Column Volumes per Hour)	pH
P 1689.	ERK29S24	1602.2	1	29.8	19.4	73940	24	9.9	7.63
P 1690.	ERK29S25	1660.4	1	29.8	19.4	44570	24.3	11.6	7.63
P 1690.	ERK29S25	1660.4	1	29.8	19.4	45020	24.3	11.6	7.63
P 1691.	ERK29B02		54	88	66.2	92400			7.65
P 1691.	ERK29B02		53	81	61	92100			7.65

APPENDIX J

RESULTS OF THE UNSPIKED GROUNDWATER (WELL D5-15) BREAKTHROUGH TEST

9112322.1744

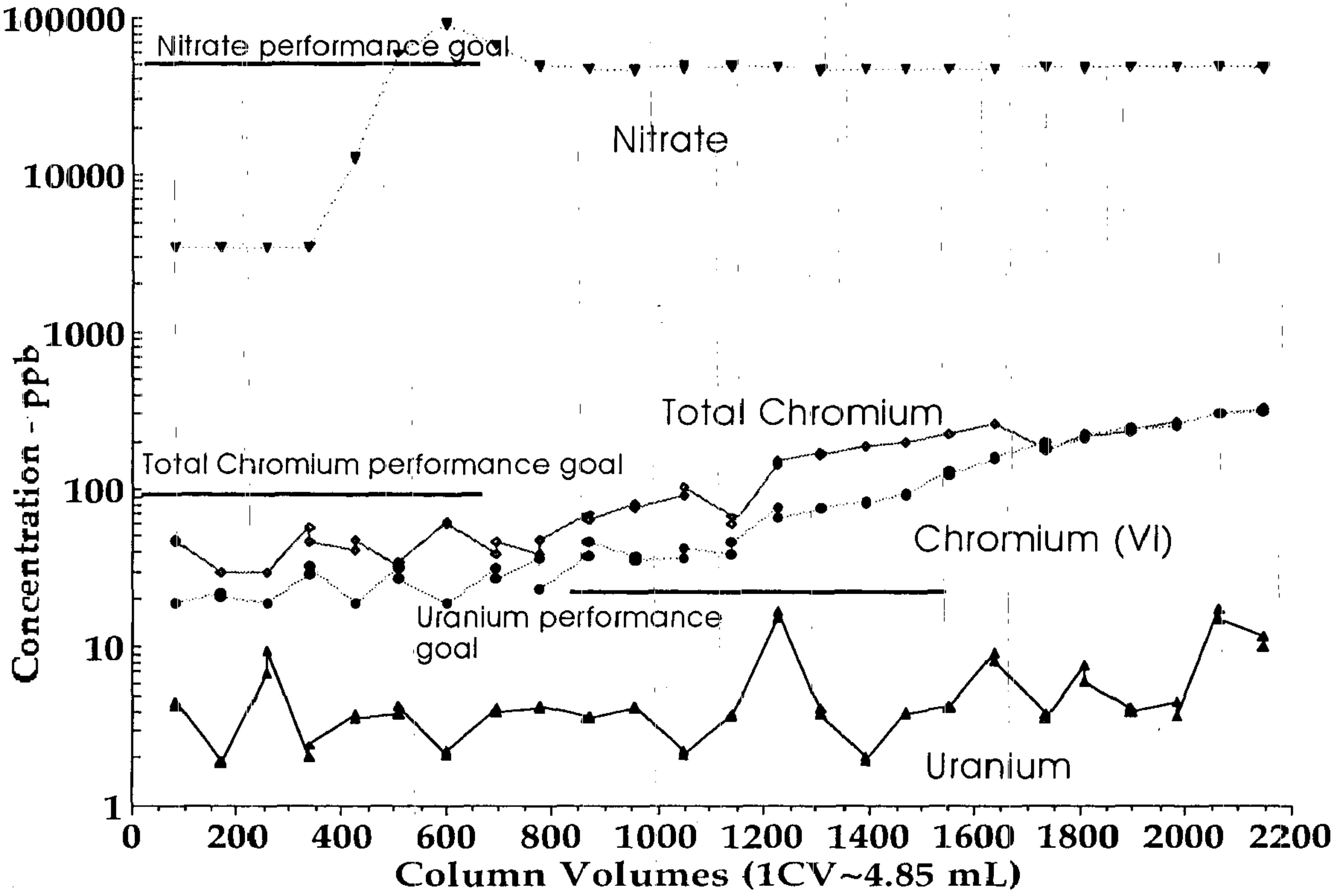

Figure J-1. Well D5-15 Concentration Versus Column Volumes.

9413221.1746

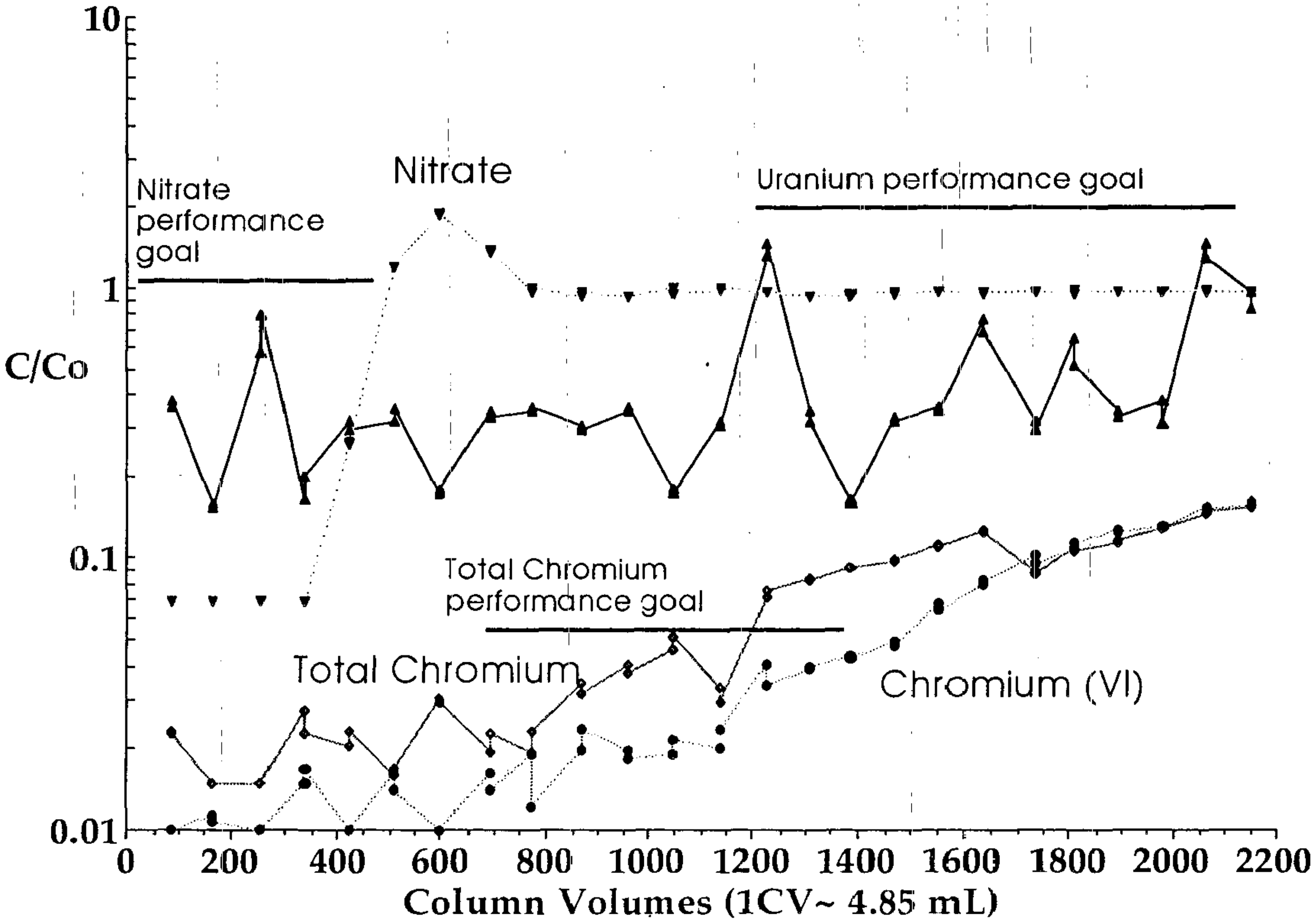

Figure J-2. Well D5-15 C/Co Versus Column Volumes.

9413221.1747

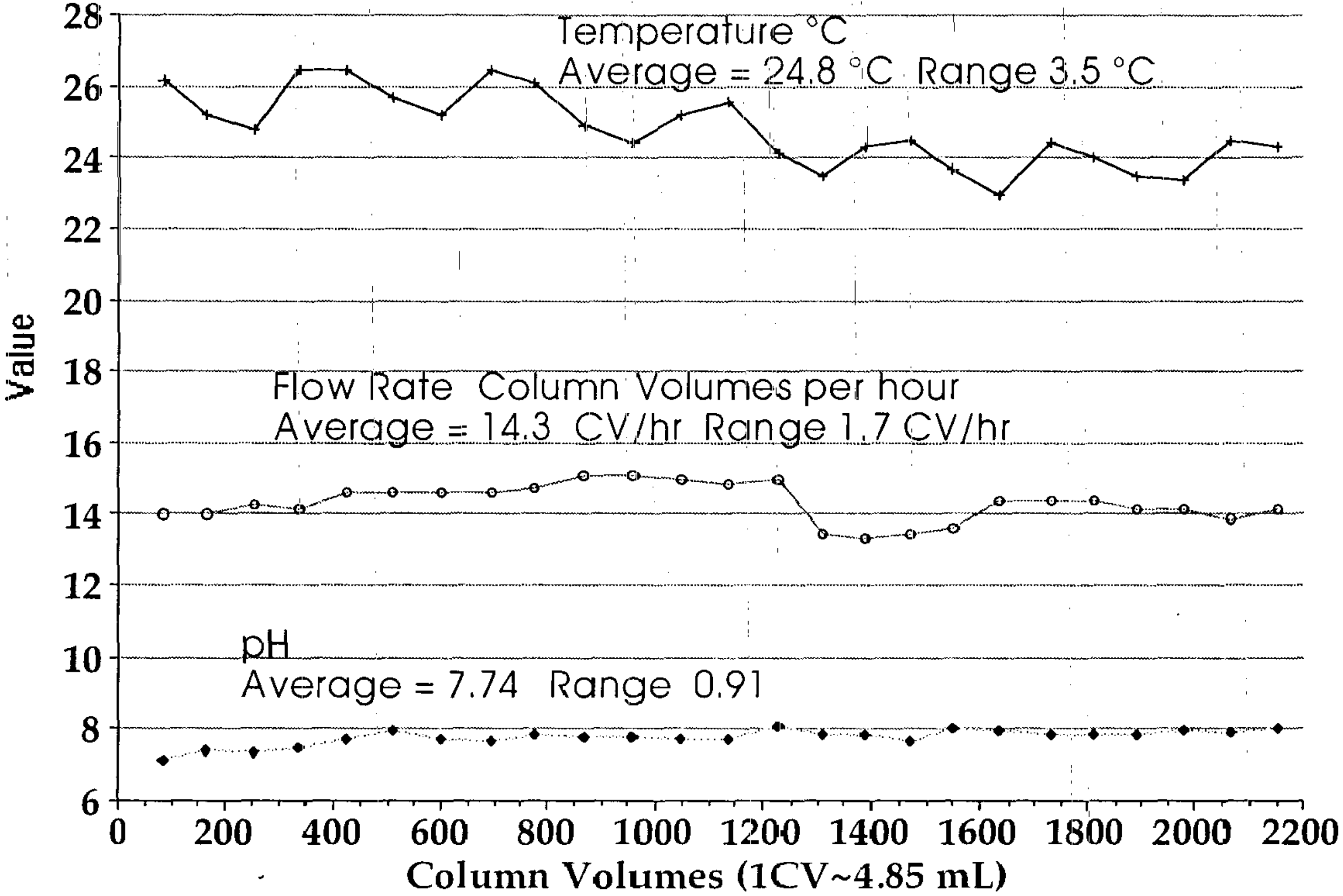

Figure J-3. Well D5-15 Flow Rate, pH, and Temperature.

9413221.1749

Table J-1. Raw Data from the Well 199-D5-15 Breakthrough Test.
(sheet 1 of 3)

Laboratory sample#	Project sample #	Cumulative column volumes (1 Column Volume ~4.85 mL)	Uranium (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Flow Rate (Column Volumes per hour)	Temperature (°C) at end of sample collection	pH
P 1630.	ERK19B01		4.3	2050.0	1990.0	50630			7.8
P 1630.	ERK19B01		6.0	2100.0	2080.0	50630			7.8
P 1631.	ERK21T07		925.0	2140.0	1620.0	184600			8.26
P 1631.	ERK21T07		660.0	2130.0	1550.0	184700			8.26
P 1632.	ERK19S01	84	4.4	47.0	19.4	3473	1.13	26.2	7.17
P 1632.	ERK19S01	84	4.6	46.0	19.4	3473	1.13	26.2	7.17
P 1633.	ERK19S02	168	1.9	29.8	22.0	3473	1.13	25.2	7.39
P 1633.	ERK19S02	168	1.9	29.8	20.7	3473	1.13	25.2	7.39
P 1634.	ERK19S03	255	6.9	29.8	19.4	3473	1.15	24.8	7.35
P 1634.	ERK19S03	255	9.5	29.8	19.4	3473	1.15	24.8	7.35
P 1635.	ERK19S04	338	2.0	56.0	28.5	3473	1.14	26.5	7.48
P 1635.	ERK19S04	338	2.4	46.0	32.4	3473	1.14	26.5	7.48
P 1636.	ERK19S05	425	3.9	41.0	19.4	12960	1.18	26.5	7.72
P 1636.	ERK19S05	425	3.6	47.0	19.4	13200	1.18	26.5	7.72
P 1637.	ERK19S06	510	3.8	32.0	31.1	58840	1.18	25.7	7.92
P 1637.	ERK19S06	510	4.3	34.0	27.2	58600	1.18	25.7	7.92
P 1638.	ERK19S07	601	2.1	62.0	19.4	94000	1.18	25.2	7.67
P 1638.	ERK19S07	601	2.2	60.0	19.4	91310	1.18	25.2	7.67
P 1639.	ERK19S08	694	4.2	39.0	31.1	67850	1.18	26.5	7.62
P 1639.	ERK19S08	694	4.0	46.0	27.2	67410	1.18	26.5	7.62
P 1640.	ERK19S09	777	4.2	39.0	36.3	48000	1.19	26.1	7.81
P 1640.	ERK19S09	777	4.4	47.0	23.3	49090	1.19	26.1	7.81
P 1641.	ERK19S10	868	3.7	70.0	37.6	46410	1.22	24.9	7.75
P 1641.	ERK19S10	868	3.6	64.0	45.4	47290	1.22	24.9	7.75

Table J-1. Raw Data from the Well 199-D5-15 Breakthrough Tests.
(sheet 2 of 3)

Laboratory sample#	Project sample #	Cumulative column volumes (1 Column Volume ~4.85 mL)	Uranium (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Flow Rate (Column Volumes per hour)	Temperature (°C) at end of sample collection	pH
P 1642.	ERK19S11	958	4.2	83.0	37.6	45970	1.22	24.4	7.73
P 1642.	ERK19S11	958	4.4	77.0	35.0	46330	1.22	24.4	7.73
P 1643.	ERK19S12	1048	2.2	93.0	36.3	49240	1.21	25.2	7.71
P 1643.	ERK19S12	1048	2.1	104.0	41.5	47010	1.21	25.2	7.71
P 1644.	ERK19S13	1138	3.9	68.0	38.9	48200	1.2	25.6	7.72
P 1644.	ERK19S13	1138	3.7	60.0	45.4	49620	1.2	25.6	7.72
P 1645.	ERK19S14	1228	15.6	145.0	77.9	47490	1.21	24.1	8.08
P 1645.	ERK19S14	1228	17.2	152.0	66.2	47540	1.21	24.1	8.08
P 1646.	ERK19S15	1309	4.2	171.0	75.3	46230	1.09	23.5	7.82
P 1646.	ERK19S15	1309	3.9	167.0	77.7	45770	1.09	23.5	7.82
P 1647.	ERK19S16	1390	2.0	188.0	84.4	46330	1.08	24.3	7.79
P 1647.	ERK19S16	1390	1.9	188.0	83.1	46610	1.08	24.3	7.79
P 1648.	ERK19S17	1470	4.0	197.0	96.1	47390	1.09	24.5	7.72
P 1648.	ERK19S17	1470	3.9	199.0	92.2	47120	1.09	24.5	7.72
P 1649.	ERK19S18	1552	4.4	225.0	131.0	47370	1.1	23.7	7.64
P 1649.	ERK19S18	1552	4.2	223.0	125.0	47430	1.1	23.7	7.64
P 1650.	ERK19S19	1638	9.1	258.0	155.0	46890	1.16	23	8.02
P 1650.	ERK19S19	1638	8.3	254.0	160.0	47330	1.16	23	8.02
P 1651.	ERK19S20	1733	3.9	180.0	197.0	47570	1.16	24.4	7.93
P 1651.	ERK19S20	1733	3.6	178.0	183.0	47620	1.16	24.4	7.93
P 1652.	ERK19S21	1811	7.8	221.0	208.0	47140	1.16	24	7.82
P 1652.	ERK19S21	1811	6.2	216.0	221.0	48440	1.16	24	7.82
P 1653.	ERK19S22	1896	4.2	234.0	246.0	47630	1.14	23.5	7.81
P 1653.	ERK19S22	1896	4.0	232.0	239.0	47760	1.14	23.5	7.81

9413221.1751

Table J-1. Raw Data from the Well 199-D5-15 Breakthrough Test. (sheet 3 of 3)

Laboratory sample#	Project sample #	Cumulative column volumes (1 Column Volume ~4.85 mL)	Uranium (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Flow Rate (Column Volumes per hour)	Temperature (°C) at end of sample collection	pH
P 1654.	ERK19S23	1981	4.6	262.0	253.0	47600	1.14	23.4	7.79
P 1654.	ERK19S23	1981	3.8	260.0	255.0	47480	1.14	23.4	7.79
P 1655.	ERK19S24	2064	17.5	297.0	298.0	48530	1.12	24.5	7.94
P 1655.	ERK19S24	2064	15.2	300.0	294.0	47740	1.12	24.5	7.94
P 1656.	ERK19S25	2149	11.6	331.0	303.0	48110	1.14	24.3	7.89
P 1656.	ERK19S25	2149	10.0	329.0	304.0	46910	1.14	24.3	7.89
P 1657.	ERK19B02		20.0	1970.0	1830.0	49120			7.97
P 1657.	ERK19B02		19.5	1980.0	1820.0	48460			7.97

9113221.1752

APPENDIX K

RESULTS OF THE BIODENITRIFIED GROUNDWATER (WELLS 199-H4-4 AND 199-D5-15) BREAKTHROUGH TEST

9411322.1753

9113222.1754

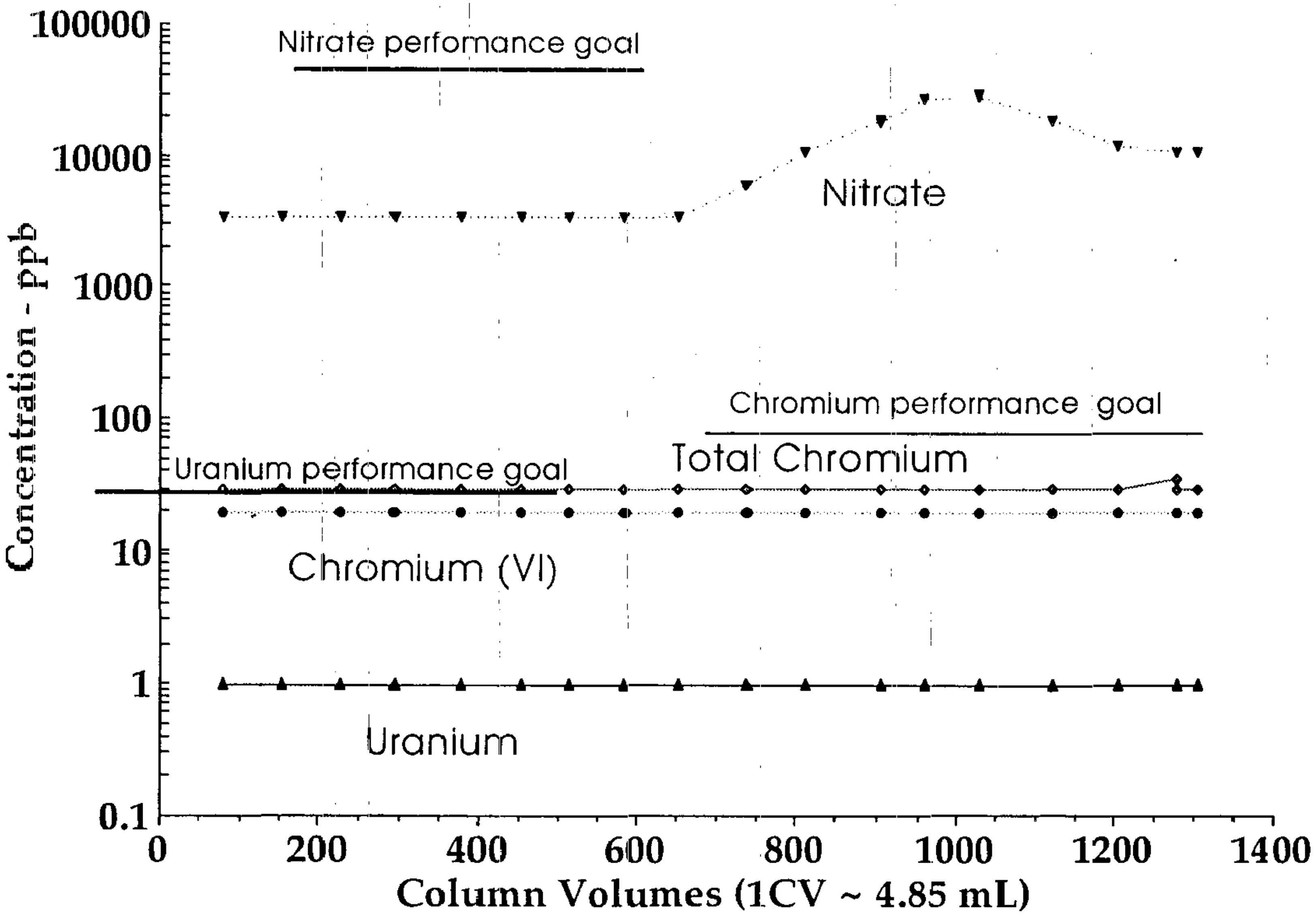

Figure K-1. Biodenitrified - Concentration Versus Column Volumes.

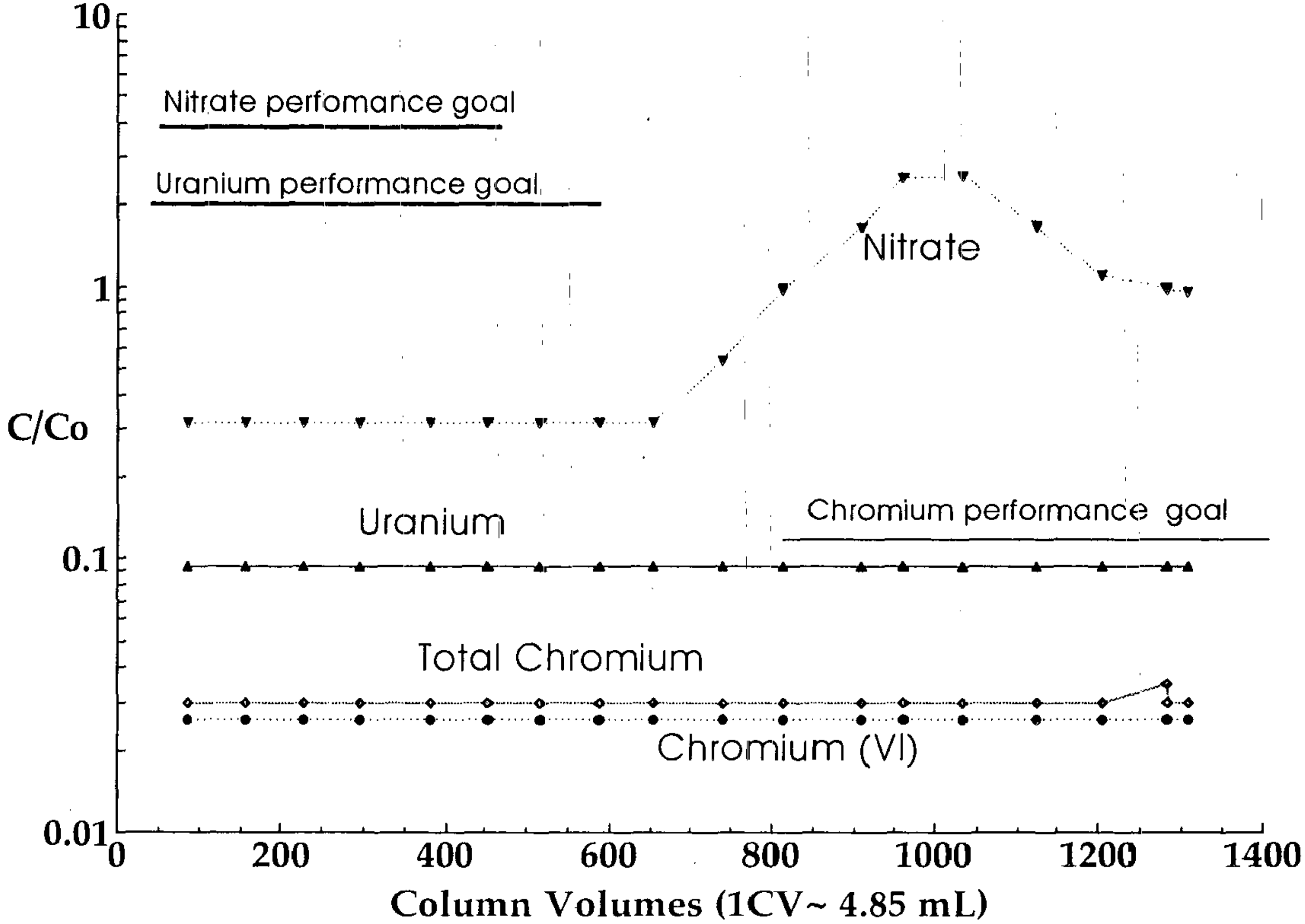

Figure K-2. Biodenitrified - C/Co Versus Column Volumes.

9413221.1757

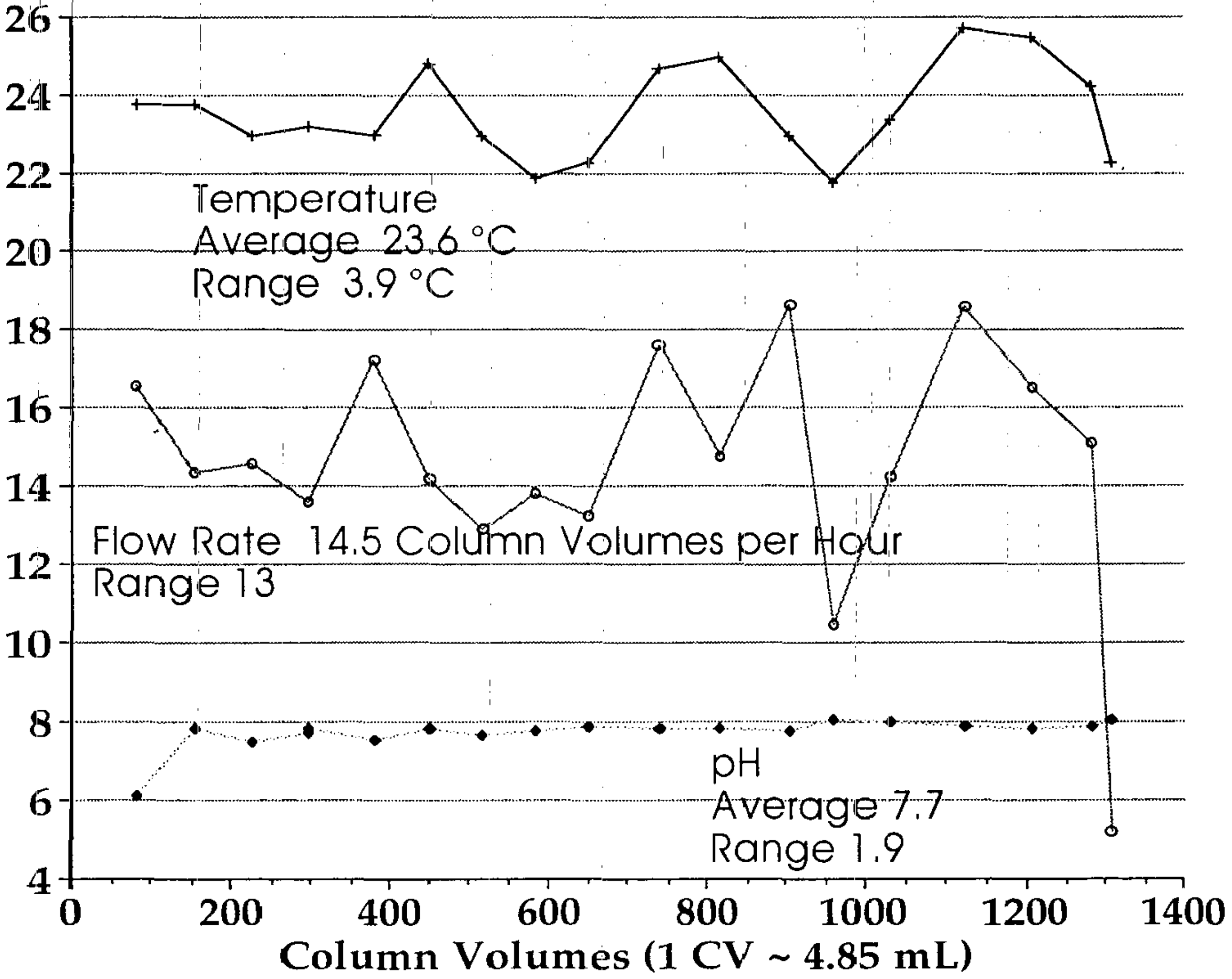

Figure K-3. Biodenitrified - Temperature, Flow Rate, and pH.

9113221758

9413221.1759

Table K-1. Raw Data from the Biodenitrified Groundwater (Wells H4-4 and D5-15) Breakthrough Test. (sheet 1 of 2)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume = 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Temperature (°C) at end of sample collection	Flow Rate (Column Volumes per Hour)	pH
P 1695.	ERK21T11		788	2180	1800	218570			000011
P 1695.	ERK21T11		804	2160	1760	219480			4.33
P 1696.	ERK30B01		10.8	1000	720	11060			7.99
P 1696.	ERK30B01		10.8	1010	694	11020			84
P 1697.	ERK30S01	83.1	1	29.8	19.4	3473	23.8	16.6	6.12
P 1697.	ERK30S01	83.1	1	29.8	19.4	3473	23.8	16.6	6.12
P 1698.	ERK30S02	154.6	1	29.8	19.4	3473	23.8	14.4	7.81
P 1698.	ERK30S02	154.6	1	29.8	19.4	3473	23.8	14.4	7.81
P 1699.	ERK30S03	227.4	1	29.8	19.4	3473	23	14.6	7.49
P 1699.	ERK30S03	227.4	1	29.8	19.4	3473	23	14.6	7.49
P 1700.	ERK30S04	295.5	1	29.8	19.4	3473	23.2	13.6	7.74
P 1700.	ERK30S04	295.5	1	29.8	19.4	3473	23.2	13.6	7.84
P 1701.	ERK30S05	381.4	1	29.8	19.4	3473	23	17.2	7.52
P 1701.	ERK30S05	381.4	1	29.8	19.4	3473	23	17.2	7.52
P 1702.	ERK30S06	452.2	1	29.8	19.4	3473	24.8	14.2	7.84
P 1702.	ERK30S06	452.2	1	29.8	19.4	3473	24.8	14.2	7.84
P 1703.	ERK30S07	516.9	1	29.8	19.4	3473	23	12.9	7.63
P 1703.	ERK30S07	516.9	1	29.8	19.4	3473	23	12.9	7.63
P 1704.	ERK30S08	586.1	1	29.8	19.4	3473	21.9	13.8	7.78
P 1704.	ERK30S08	586.1	1	29.8	19.4	3473	21.9	13.8	7.78
P 1705.	ERK30S09	652.3	1	29.8	19.4	3473	22.3	13.2	7.9
P 1705.	ERK30S09	652.3	1	29.8	19.4	3473	22.3	13.2	7.9
P 1706.	ERK30S10	740.3	1	29.8	19.4	5891	24.7	17.6	7.82
P 1706.	ERK30S10	740.3	1	29.8	19.4	5899	24.7	17.6	7.82
P 1707.	ERK30S11	814	1	29.8	19.4	10812	25	14.7	7.82

9413221.1760

Table K-1. Raw Data from the Biodenitrified Groundwater (Wells H4-4 and D5-15) Breakthrough Test. (sheet 2 of 2)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume - 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Temperature (°C) at end of sample collection	Flow Rate (Column Volumes per Hour)	pH
P 1707.	ERK30S11	814	1	29.8	19.4	10715	25	14.7	7.82
P 1708.	ERK30S12	907.1	1	29.8	19.4	18239	23	18.6	7.8
P 1708.	ERK30S12	907.1	1	29.8	19.4	18000	23	18.6	7.8
P 1709.	ERK30S13	959.3	1	29.8	19.4	27468	21.8	10.4	85
P 1709.	ERK30S13	959.3	1	29.8	19.4	27606	21.8	10.4	85
P 1710.	ERK30S14	1030.5	1	29.8	19.4	27934	23.4	14.2	82
P 1710.	ERK30S14	1030.5	1	29.8	19.4	28137	23.4	14.2	82
P 1711.	ERK30S15	1123.4	1	29.8	19.4	18379	25.7	18.6	7.89
P 1711.	ERK30S15	1123.4	1	29.8	19.4	18232	25.7	18.6	7.89
P 1712.	ERK30S16	1205.9	1	29.8	19.4	12046	25.5	16.5	7.83
P 1712.	ERK30S16	1205.9	1	29.8	19.4	12101	25.5	16.5	7.83
P 1713.	ERK30S17	1281.2	1	35	19.4	10872	24.2	15.1	7.88
P 1713.	ERK30S17	1281.2	1	30	19.4	10689	24.2	15.1	7.88
P 1714.	ERK30S18	1307.3	1	29.8	19.4	10560	22.3	5.2	85
P 1714.	ERK30S18	1307.3	1	29.8	19.4	10560	22.3	5.2	85
P 1722.	ERK30B02		10.1	998	787	10740			85
P 1722.	ERK30B02		10.5	995	814	10830			85

APPENDIX L

RESULTS OF THE LOW FLOW RATE VERY HIGH SPIKED GROUNDWATER (WELL 199-H3-2C) BREAKTHROUGH TEST

9413221.1763

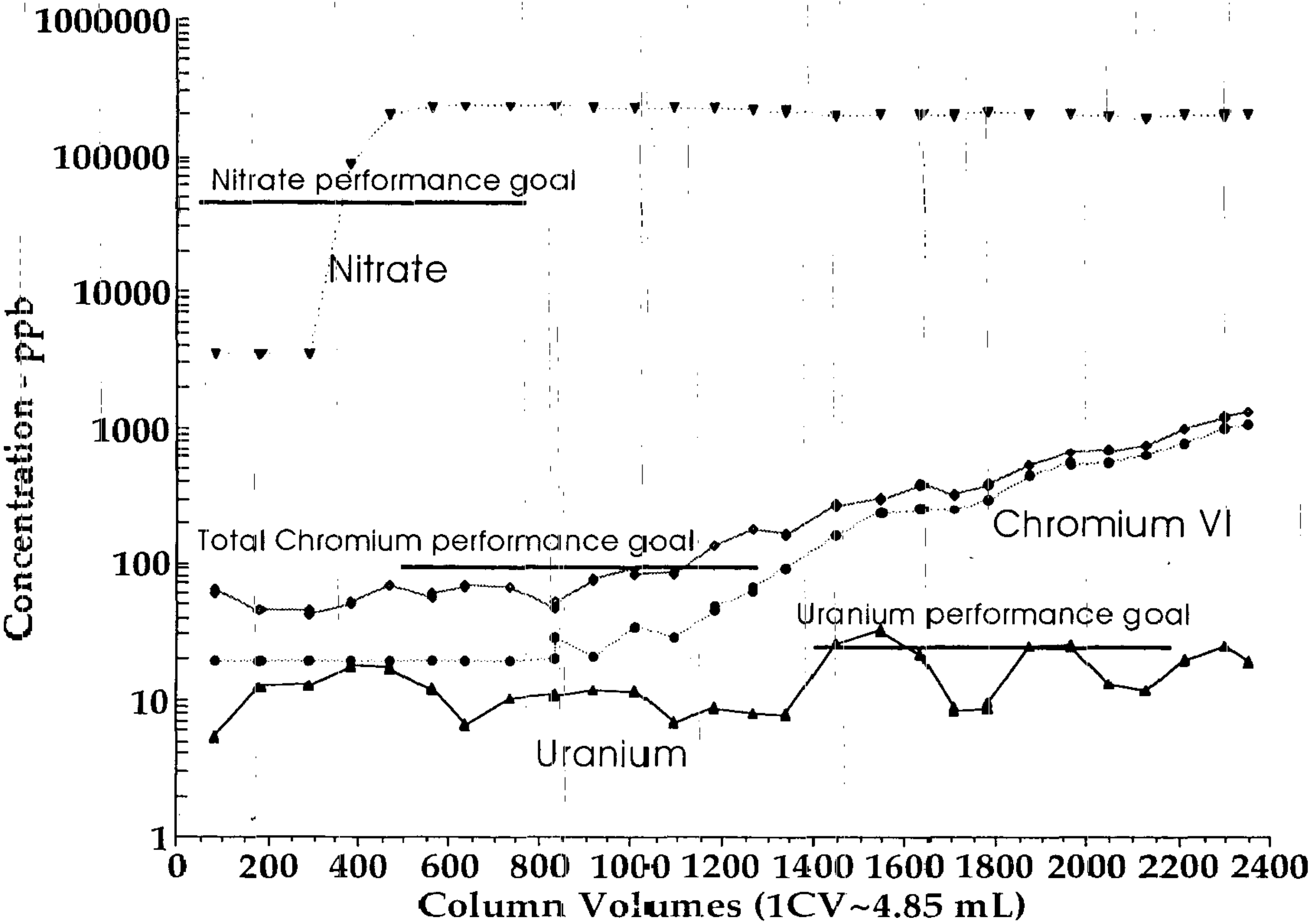

Figure L-1. Very High Spiked H3-2C Concentration Versus Column Volumes.

9413221.1764

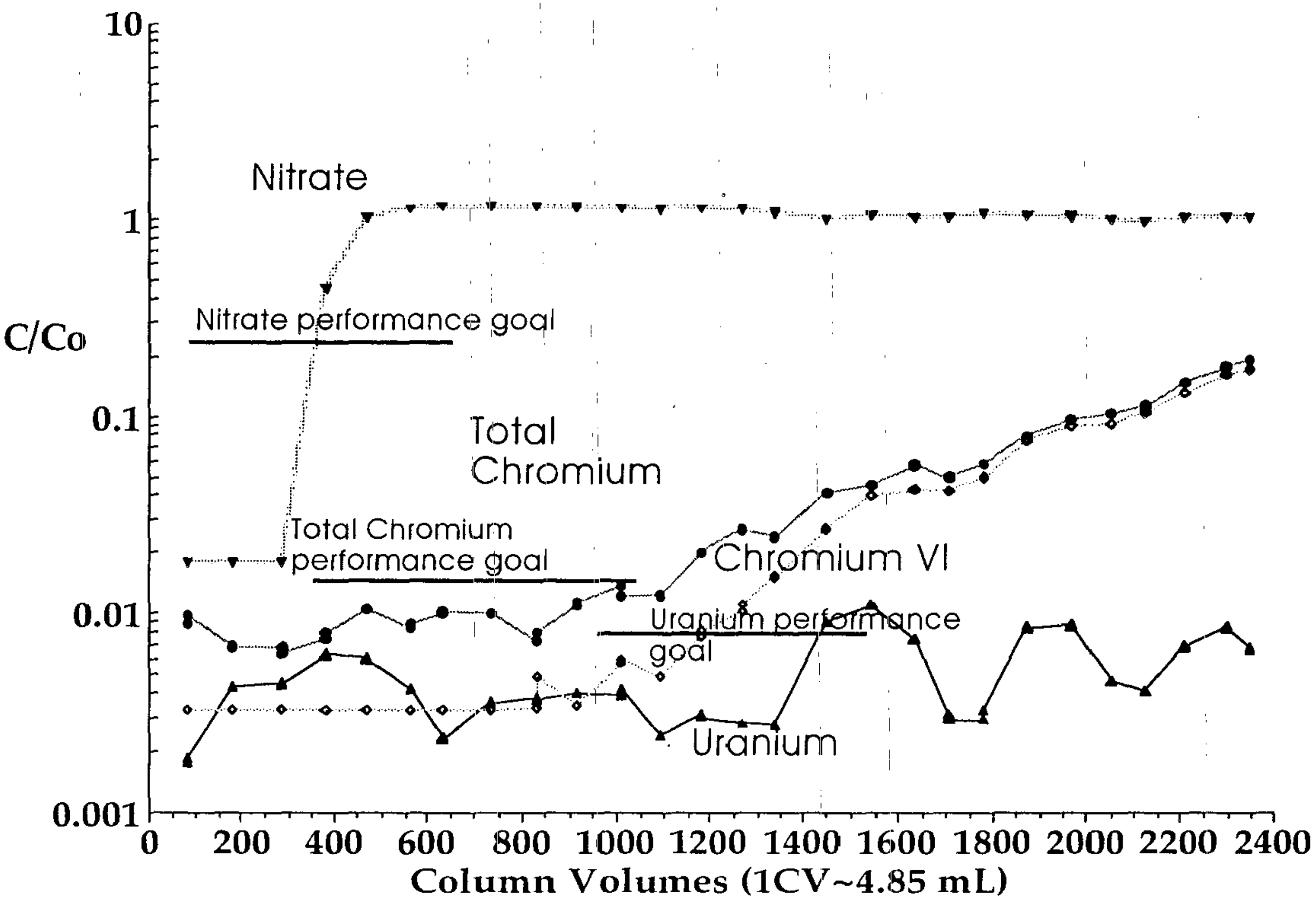

Figure L-2. Very High Spiked H3-2C, C/Co Versus Column Volumes.

9413221.1765

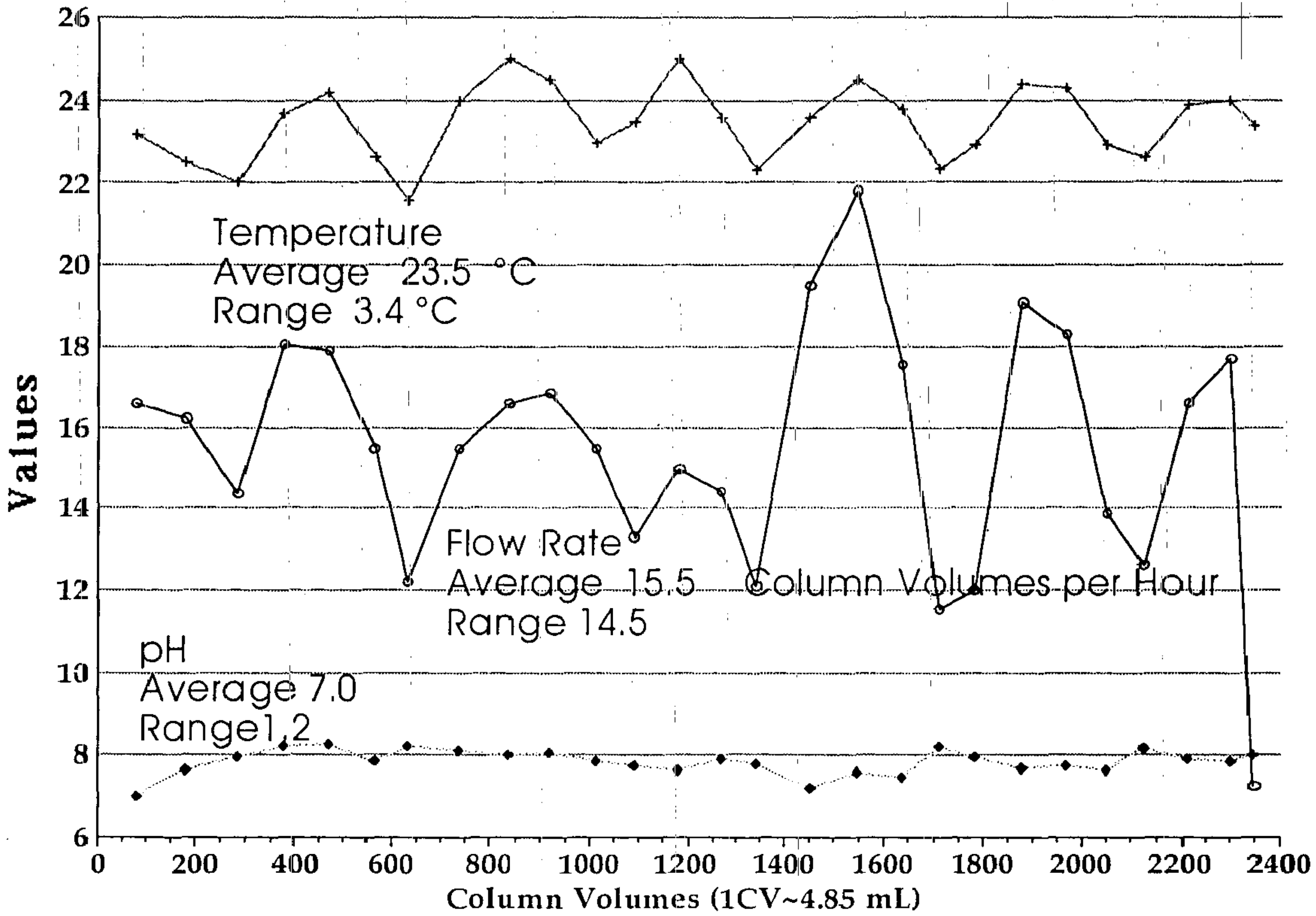

Figure L-3. High Spiked H3-2C Temperature, Flow Rate, and pH Versus Column Volumes.

91123221766

9413221.1767

Table L-1. Raw Data from the Low Flow Rate Very High Spiked Groundwater (Well H3-2C) Breakthrough Test. (sheet 1 of 3)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume ~ 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Flow Rate (Column Volumes per Hour)	Temperature (°C) at end of sample collection	pH
P 1730.	ERK21T04		741	2170	1960	196781			8.16
P 1730.	ERK21T04		744	2200	2000	194006			8.16
P 1731.	ERK41B01		2380	6440	6000	193806			8.19
P 1731.	ERK41B01		2430	6500	5960	193535			8.19
P 1732.	ERK41S01	82.9	5.1	59	19.4	3473	16.6	23.2	.74
P 1732.	ERK41S01	82.9	5.4	66	19.4	3473	16.6	23.2	.74
P 1733.	ERK41S02	179.8	12.1	46	19.4	3473	16.2	22.5	7.63
P 1733.	ERK41S02	179.8	12.3	45	19.4	3473	16.2	22.5	7.63
P 1734.	ERK41S03	288.3	12.7	45	19.4	3473	14.4	22	7.95
P 1734.	ERK41S03	288.3	12.5	42	19.4	3473	14.4	22	7.95
P 1735.	ERK41S04	379.1	17.8	50	19.4	87409	18.1	23.7	8.23
P 1735.	ERK41S04	379.1	18	53	19.4	87219	18.1	23.7	8.23
P 1736.	ERK41S05	468.8	17.3	69	19.4	200471	17.9	24.2	8.24
P 1736.	ERK41S05	468.8	17.1	69	19.4	201108	17.9	24.2	8.24
P 1737.	ERK41S06	561.7	11.8	56	19.4	224250	15.5	22.6	7.87
P 1737.	ERK41S06	561.7	12	59	19.4	225060	15.5	22.6	7.87
P 1738.	ERK41S07	632	6.7	66	19.4	227680	12.2	21.6	8.18
P 1738.	ERK41S07	632	6.6	68	19.4	227620	12.2	21.6	8.18
P 1739.	ERK41S08	734.5	10.3	66	19.4	227570	15.5	24	89
P 1739.	ERK41S08	734.5	10.2	66	19.4	228600	15.5	24	89
P 1740.	ERK41S09	834.3	10.9	48	20	231220	16.6	25	8
P 1740.	ERK41S09	834.3	10.7	53	28.5	229650	16.6	25	8
P 1741.	ERK41S10	918.4	11.5	73	20.7	226312	16.8	24.5	85
P 1741.	ERK41S10	918.4	11.5	76	20.7	226214	16.8	24.5	85
P 1742.	ERK41S11	1011.4	11.1	91	33.7	226140	15.5	23	7.85

9413221.1768

Table L-1. Raw Data from the Low Flow Rate Very High Spiked Groundwater (Well H3-2C) Breakthrough Test. (sheet 2 of 3)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume = 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Flow Rate (Column Volumes per Hour)	Temperature (°C) at end of sample collection	pH
P 1742.	ERK41S11	1011.4	11.8	82	35	223470	15.5	23	7.85
P 1743.	ERK41S12	1091.3	7	83	28.5	220170	13.3	23.5	7.75
P 1743.	ERK41S12	1091.3	6.9	81	28.5	222060	13.3	23.5	7.75
P 1744.	ERK41S13	1181.3	8.9	134	45.4	221280	15	25	7.66
P 1744.	ERK41S13	1181.3	8.6	135	49.3	223010	15	25	7.66
P 1745.	ERK41S14	1267.9	8	180	61	218416	14.4	23.6	7.89
P 1745.	ERK41S14	1267.9	8	177	66.2	216241	14.4	23.6	7.89
P 1746.	ERK41S15	1341.2	7.8	164	92.2	210506	12.1	22.3	7.79
P 1746.	ERK41S15	1341.2	7.9	159	90.9	212082	12.1	22.3	7.79
P 1747.	ERK41S16	1450	25.7	278	160	191980	19.5	23.6	7.21
P 1747.	ERK41S16	1450	25.8	272	162	192360	19.5	23.6	7.21
P 1748.	ERK41S17	1546.3	32.1	305	239	202730	21.8	24.5	7.57
P 1748.	ERK41S17	1546.3	30.9	300	235	201590	21.8	24.5	7.57
P 1749.	ERK41S18	1634.2	21.4	378	255	200520	17.6	23.8	7.5
P 1749.	ERK41S18	1634.2	21.6	385	260	200420	17.6	23.8	7.5
P 1750.	ERK41S19	1707.6	9	323	251	197090	11.5	22.3	8.19
P 1750.	ERK41S19	1707.6	8.4	330	255	198310	11.5	22.3	8.19
P 1751.	ERK41S20	1779.6	8.5	383	300	208316	12	22.9	7.94
P 1751.	ERK41S20	1779.6	9.4	386	296	208747	12	22.9	7.94
P 1752.	ERK41S21	1875.1	24.9	529	448	201840	19.1	24.4	7.69
P 1752.	ERK41S21	1875.1	24.3	536	452	201860	19.1	24.4	7.69
P 1753.	ERK41S22	1966.9	25.6	646	545	197997	18.3	24.3	7.75
P 1753.	ERK41S22	1966.9	24.5	646	541	201389	18.3	24.3	7.75
P 1754.	ERK41S23	2050.4	13.2	693	547	195848	13.9	22.9	7.66
P 1754.	ERK41S23	2050.4	13.1	687	551	196365	13.9	22.9	7.66
P 1755.	ERK41S24	2126.5	11.7	749	632	188500	12.6	22.6	8.15

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Table L-1. Raw Data from the Low Flow Rate Very High Spiked Groundwater (Well H3-2C) Breakthrough Test. (sheet 3 of 3)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume ~ 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Flow Rate (Column Volumes per Hour)	Temperature (°C) at end of sample collection	pH
P 1755.	ERK41S24	2126.5	11.6	744	627	190123	12.6	22.6	8.15
P 1756.	ERK41S25	2209.7	20.1	981	779	198459	16.6	23.9	7.91
P 1756.	ERK41S25	2209.7	19.7	978	784	200919	16.6	23.9	7.91
P 1757.	ERK41S26	2298.2	24.9	1180	976	197562	17.7	24	7.83
P 1757.	ERK41S26	2298.2	24.4	1200	982	200155	17.7	24	7.83
P 1758.	ERK41S27	2347.5	19.5	1290	1050	199296	7.3	23.4	7.99
P 1758.	ERK41S27	2347.5	19.1	1290	1060	198917	7.3	23.4	7.99
P 1762.	ERK41B02		3297	6720	5880	194280			7.62
P 1762.	ERK41B02		3276	6650	5840	195296			7.62
P 1763.	ERK31T05		805	2260	1980	191124			7.63
P 1763.	ERK31T05		801	2250	2000	194087			7.63

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APPENDIX M

CYCLING TEST

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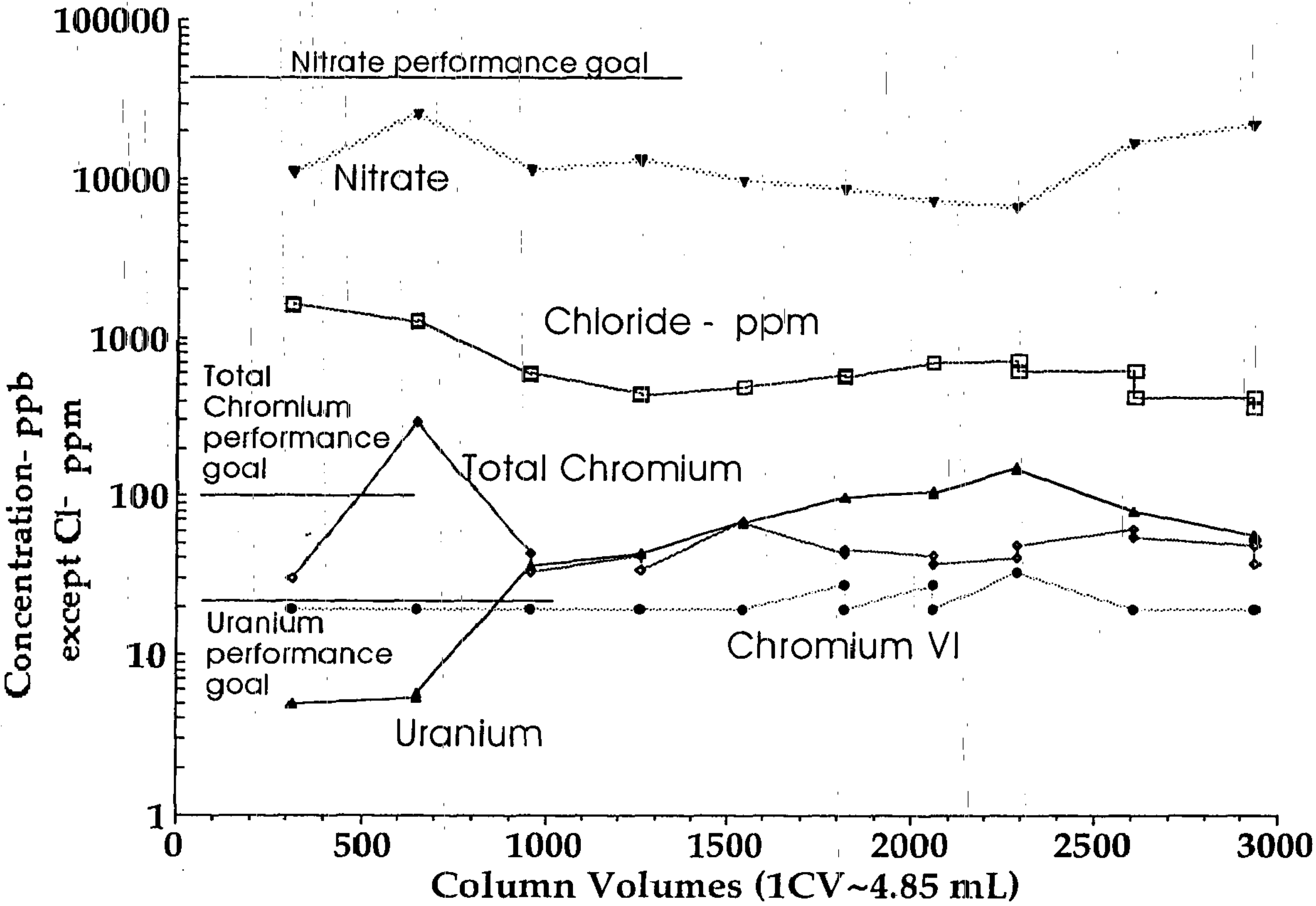

Figure M-1. Cycling Test, Treated Effluent Concentration Versus Column Volumes.

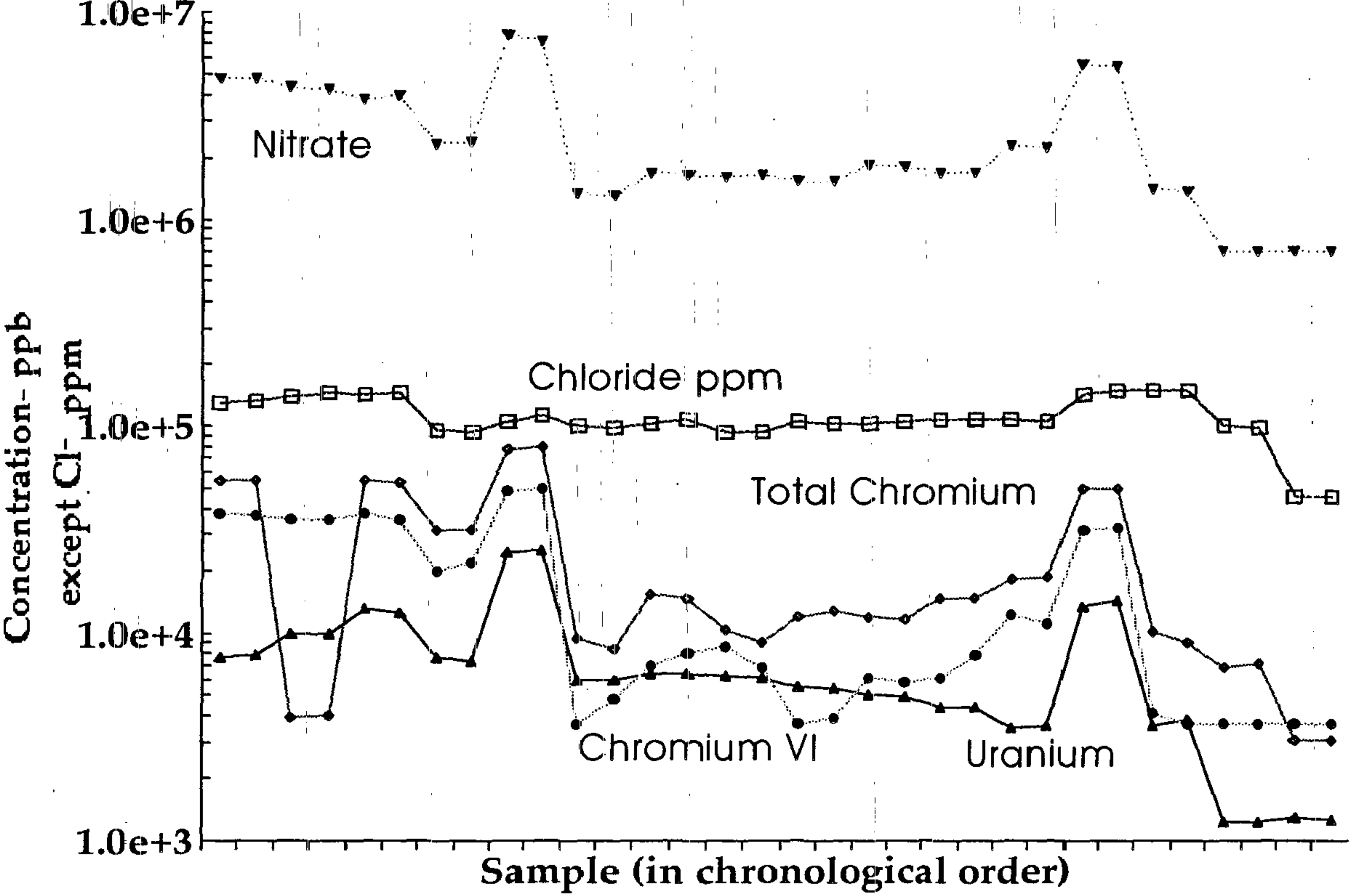

Figure M-2. Cycling Test, Wash Concentrations.

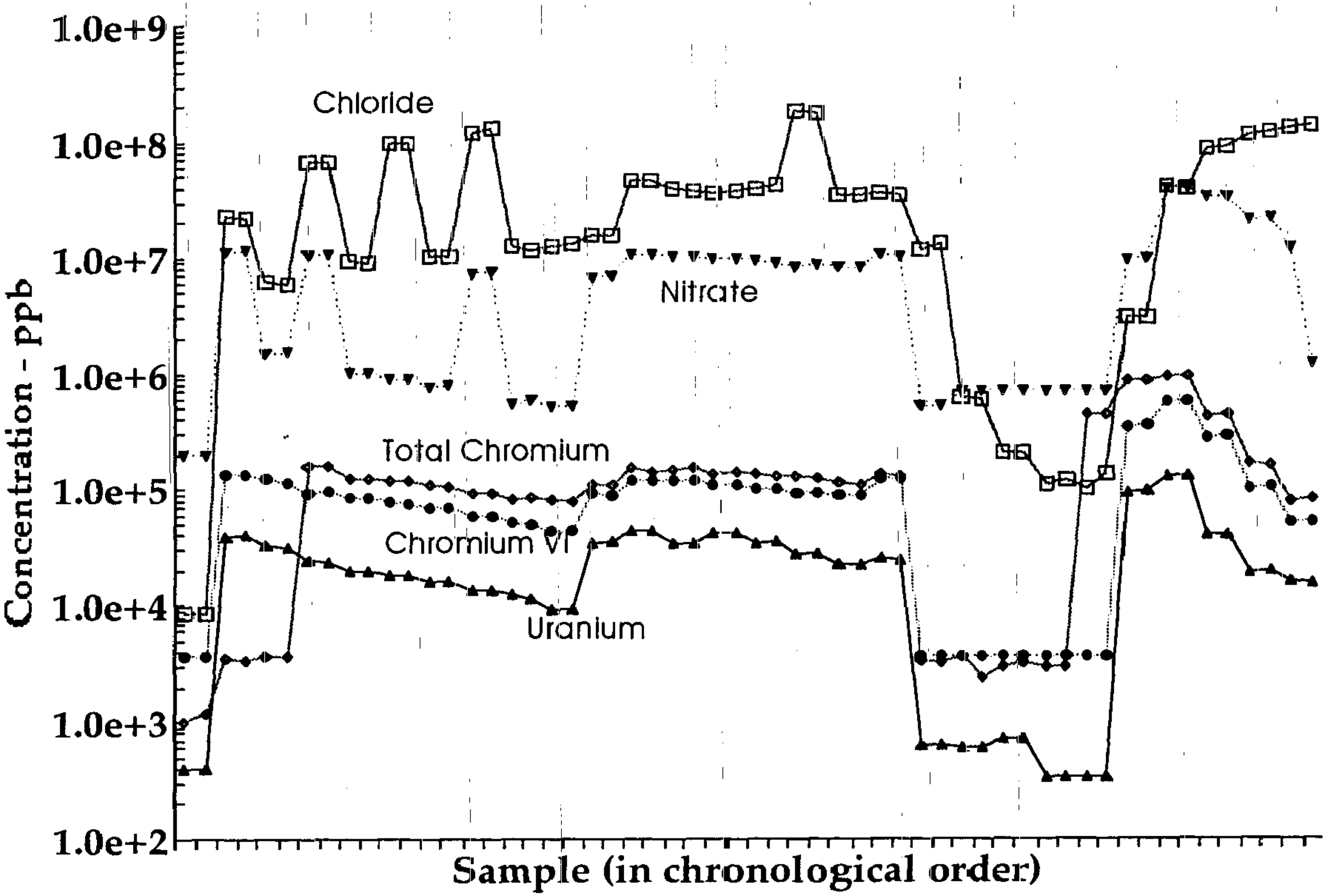

Figure M-3. Cycling Test, Eluate Concentrations.

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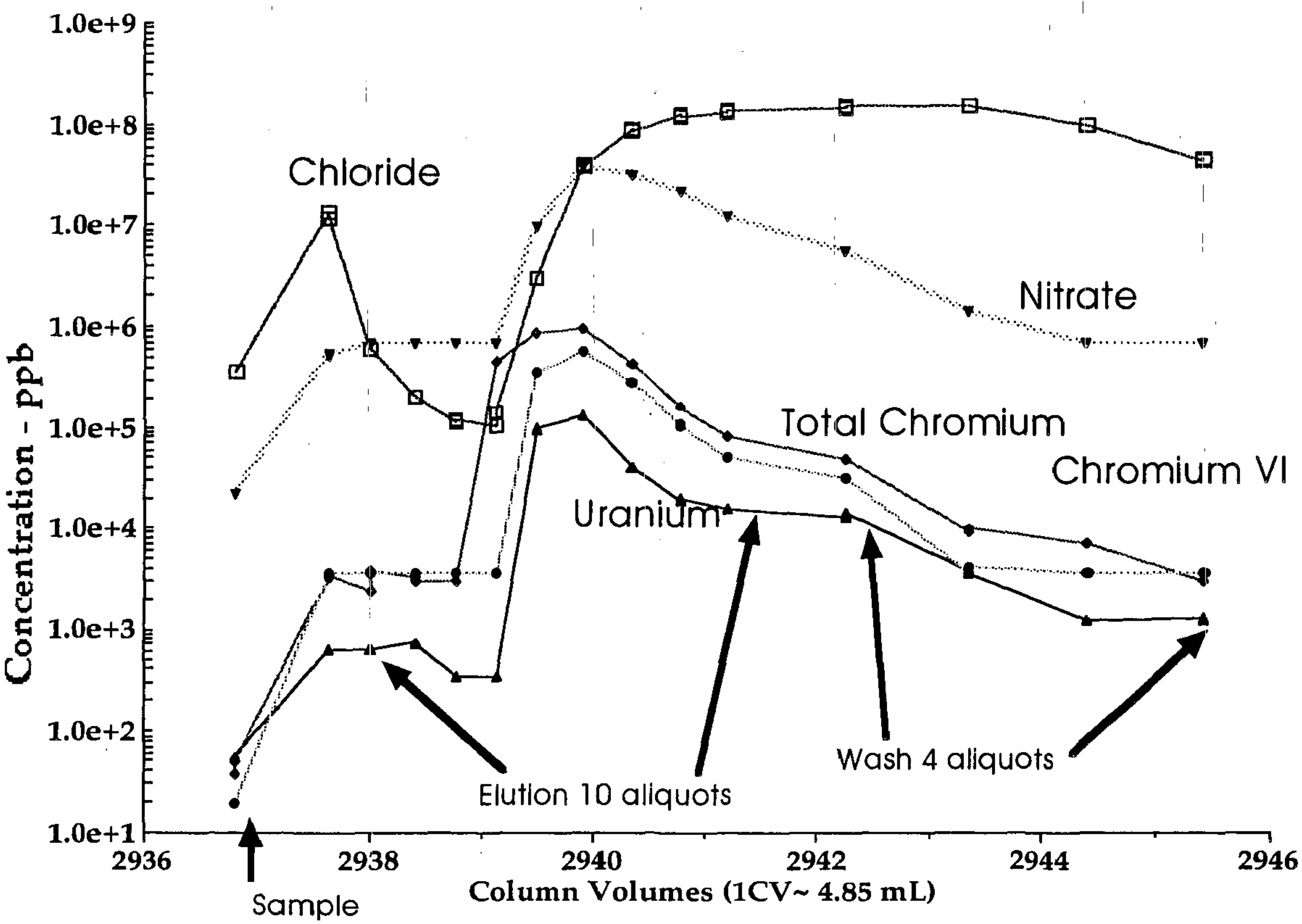

Figure M-4. Cycle 10, Concentration Versus Column Volumes.

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Table M-1. Raw Data from the Cycling Test. (sheet 1 of 5)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume ~ 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Chloride Concentration
P 1779.	CK20BA01		2.7	45	19.4	3443	6.5
P 1779	CK20BA01		2.7	42	19.4	3443	6.9
P 1782.	CK31EA01	311.5	408	1020	3640	198508	8.6
P 1782.	CK31EA01	311.5	400	1170	3640	199514	8.6
P 1783.	CK31EA02	311.9	38700	3480	136000	11414000	22744
P 1783.	CK31EA02	311.9	40800	3450	138000	11481400	21984
P 1784.	CK31EA03	312.4	33000	3760	125000	1483670	6150
P 1784.	CK31EA03	312.4	31900	3650	117000	1542680	6071
P 1785.	CK31EA04	312.8	24030	163000	94500	10562900	68790
P 1785.	CK31EA04	312.8	23900	161000	99600	10658600	68321
P 1791.	CK31EA05	313.2	19500	123000	85200	1007840	9300
P 1791.	CK31EA05	313.2	19400	125000	84500	1012070	9051
P 1786.	CK31EA06	313.5	13400	122000	80600	901663	100934
P 1786.	CK31EA06	313.5	18300	118000	77200	921196	99996
P 1787.	CK31EA07	313.9	15800	109000	69300	779567	10305
P 1787.	CK31EA07	313.9	15900	108000	70300	785582	10259
P 1788.	CK31EA08	314.3	13500	94900	59300	7445010	124606
P 1788.	CK31EA08	314.3	13500	93300	59100	7825000	130877
P 1789.	CK31EA09	314.7	12700	84200	51800	549290	12869
P 1789.	CK31EA09	314.7	11700	84700	50300	606060	11686
P 1790.	CK31EA10	315.2	9170	82600	44900	522227	12540
P 1790.	CK31EA10	315.2	9240	78500	44400	532463	12992
P 1797.	CK31EB01	653.1	34600	111000	92500	6719430	15635
P 1797.	CK31EB01	653.1	35000	109000	91300	6997520	15930
P 1800.	CK31EC01	957.5	43430	153000	119000	10850600	47116
P 1800.	CK31EC01	957.5	43790	142000	119000	10631700	46840

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Table M-1. Raw Data from the Cycling Test. (sheet 2 of 5)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume ~ 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Chloride Concentration
P 1803.	CK31ED01	1260.9	34440	150000	118000	10412700	39132
P 1803.	CK31ED01	1260.9	34280	155000	121000	10134900	38562
P 1806.	CK31EE01	1548.9	41700	137000	112000	9827310	36446
P 1806.	CK31EE01	1548.9	41510	143000	109000	9840590	37182
P 1809.	CK31EF01	1819.8	34060	133000	103000	9425250	39822
P 1809.	CK31EF01	1819.8	35940	137000	101000	9199310	42474
P 1812.	CK31EG01	2062.2	28040	130000	93500	8476550	188334
P 1812.	CK31EG01	2062.2	27730	128000	91800	8718060	180642
P 1815.	CK31EH01	2290.7	22010	114000	89600	8243960	35212
P 1815.	CK31EH01	2290.7	22210	110000	88400	8188840	34231
P 1818.	CK31EI01	2608.3	25190	134000	128000	10735100	36221
P 1818.	CK31EI01	2608.3	24760	129000	127000	10106400	34106
P 1821.	CK31EJ01	2937.6	627.2	3430	3640	532000	11607
P 1821.	CK31EJ01	2937.6	625.8	3230	3640	528000	13186
P 1822.	CK31EJ02	2938	607.7	3740	3640	692040	610
P 1822.	CK31EJ02	2938	607.6	2420	3640	692040	603
P 1823.	CK31EJ03	2938.4	734	3030	3640	692040	206
P 1823.	CK31EJ03	2938.4	729	3230	3640	692040	206
P 1824.	CK31EJ04	2938.8	336	3010	3640	692040	112
P 1824.	CK31EJ04	2938.8	343	3010	3640	692040	120
P 1825.	CK31EJ05	2939.1	337	447000	3640	692040	101
P 1825.	CK31EJ05	2939.1	333	443000	3640	692040	139
P 1826.	CK31EJ06	2939.5	92100	876000	351000	9513730	3069
P 1826.	CK31EJ06	2939.5	95899.9	881000	353000	9759220	3090
P 1827.	CK31EJ07	2939.9	130000	930000	571000	39188200	40667
P 1827.	CK31EJ07	2939.9	130000	941000	573000	39238000	39367

Table M-1. Raw Data from the Cycling Test. (sheet 3 of 5)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume ~ 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Chloride Concentration
P 1828.	CK31EJ08	2940.3	39600	432000	282000	32792000	86325
P 1828.	CK31EJ08	2940.3	40700	437000	285000	32967000	90691
P 1829.	CK31EJ09	2940.8	19200	165000	103000	21475000	118008
P 1829.	CK31EJ09	2940.8	20000	164000	105000	21634000	121821
P 1830.	CK31EJ10	2941.2	16000	80400	51500	12008000	132375
P 1830.	CK31EJ10	2941.2	15700	81300	52000	111913000	136732
P 1781.	CK31SA01	310.7	5	29.8	19.4	11050	1591
P 1781.	CK31SA01	310.7	5	29.8	19.4	10960	1629
P 1796.	CK31SB01	648.4	5.4	298	19.4	25960	1259
P 1796.	CK31SB01	648.4	5.7	298	19.4	25780	1277
P 1799.	CK31SC01	952.7	36	43	19.4	11450	585
P 1799.	CK31SC01	952.7	36	33	19.4	11270	591
P 1802.	CK31SD01	1256.3	43	42	19.4	12990	440
P 1802.	CK31SD01	1256.3	43	34	19.4	13170	434
P 1805.	CK31SE01	1544.3	69	69	19.4	9610	486
P 1805.	CK31SE01	1544.3	67	67	19.4	9690	485
P 1808.	CK31SF01	1815	98	43	27.2	8460	582
P 1808.	CK31SF01	1815	99	45	19.4	8470	571
P 1811.	CK31SG01	2057.9	106	42	27.2	7082	693
P 1811.	CK31SG01	2057.9	105	37	19.4	7094	706
P 1814.	CK31SH01	2286.4	155	40	32.4	6523	620
P 1814.	CK31SH01	2286.4	150	49	32.4	6530	617
P 1817.	CK31SI01	2603.8	79	61	19.4	16870	413
P 1817.	CK31SI01	2603.8	80	550	19.4	17010	417
P 1820.	CK31SJ01	2936.8	56	49	19.4	22070	360
P 1820.	CK31SJ01	2936.8	55	37	19.4	22230	364

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Table M-1. Raw Data from the Cycling Test. (sheet 4 of 5)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume ~ 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Chloride Concentration
P 1780.	CK31TA01		853	2100	1640	203594	3
P 1780.	CK31TA01		846	2150	1750	203468	3.1
P 1835.	CK31TJ01		497	2340	1860	202947	3.1
P 1835.	CK31TJ01		508	2310	1870	202328	2.8
P 1792.	CK31WA01	316.2	7730	54900	38100	4753710	127700
P 1792.	CK31WA01	316.2	7860	54500	37100	4801120	131520
P 1793.	CK31WA02	317.2	9960	3940	35400	4302520	138823
P 1793.	CK31WA02	317.2	9810	4040	34900	4264290	144298
P 1794.	CK31WA03	318.2	12900	54600	38100	3824780	142710
P 1794.	CK31WA03	318.2	12500	53500	35600	3946900	145130
P 1795.	CK31WA04	320.9	7720	31600	20000	2344670	96294
P 1795.	CK31WA04	320.9	7290	31200	21700	2405750	94262
P 1798.	CK31WB01	658.3	24400	78300	49100	7686570	105182
P 1798.	CK31WB01	658.3	24800	79400	50300	7172500	111790
P 1801.	CK31WC01	962.5	5900	9390	3640	1320100	99070
P 1801.	CK31WC01	962.5	6000	8380	4860	1318760	97157
P 1804.	CK31WD01	1265.6	6400	15400	7060	1679920	101794
P 1804.	CK31WD01	1265.6	6400	14700	8030	1650650	106367
P 1807.	CK31WE01	1553.4	6200	10300	8520	1606520	94143
P 1807.	CK31WE01	1553.4	6100	8990	6810	1627910	93045
P 1810.	CK31WF01	1824.1	5600	12020	3640	1548790	104167
P 1810.	CK31WF01	1824.1	5400	12830	3880	1520210	103370
P 1813.	CK31WG01	2066.7	5000	11900	6080	1843750	101952
P 1813.	CK31WG01	2066.7	4900	11600	5840	1823140	103800
P 1816.	CK31WH01	2295.2	4367	14800	6080	1679120	106368
P 1816.	CK31WH01	2295.2	4423	14500	7790	1690510	106071

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Table M-1. Raw Data from the Cycling Test.* (sheet 5 of 5)

Laboratory sample #	Project sample #	Cumulative Column Volumes (1 Column volume ~ 4.85 mL)	Uranium Concentration (ppb)	Total Chromium Concentration (ppb)	Chromium (VI) Concentration (ppb)	Nitrate Concentration (ppb)	Chloride Concentration
P 1819.	CK31WI01	2612.7	3500	18100	12200	2294030	107953
P 1819.	CK31WI01	2612.7	3600	18600	11200	2247260	105157
P 1831.	CK31WJ01	2942.3	13500	49700	31500	5557540	142980
P 1831.	CK31WJ01	2942.3	14300	49700	32000	5482780	149327
P 1832.	CK31WJ02	2943.4	3570	10100	4130	1389790	149374
P 1832.	CK31WJ02	2943.4	3850	9090	3640	1377680	148947
P 1833.	CK31WJ03	2944.4	1220	6870	3640	692040	99109
P 1833.	CK31WJ03	2944.4	1230	7070	3640	692040	97074
P 1834.	CK31WJ04	2945.4	1300	3010	3640	692040	45106
P 1834.	CK31WJ04	2945.4	1270	3010	3640	692040	45940

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