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BENCH SCALE TREATABILITY STUDY AT OPERABLE UNIT 3 (OU 3) WITH TRANSMITTAL
LETTER NTC ORLANDO FL
2/2/2001
TETRA TECH



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February 2, 2001

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Subject: Bench-Scale Treatability Studies – Operable Unit 3
Naval Training Center, Orlando, Florida

Dear Ms. Nwokike:

Enclosed is a report describing the testing and results of the bench-scale treatability studies for OU 3. The studies were performed to (1) test the ability of three candidate materials in removing arsenic from the OU 3 groundwater, and (2) to determine the retardation of arsenic in the saturated soil at OU 3. As reported earlier to the Orlando Partnering Team, activated alumina was proven to be very effective in removing arsenic from the groundwater.

If you need further information or have any questions, please contact me at (865) 220-4730.

Sincerely,

Steven B. McCoy, P.E.
Task Order Manager

SBM:ckf

Enclosure

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BENCH-SCALE TREATABILITY STUDIES - OPERABLE UNIT 3

Site Name: Operable Unit 3: Study Areas 8 and 9
Main Base, Naval Training Center, Orlando, Florida

Test Dates: May – November 2000

Test Lab: PRIMA Environmental, Sacramento, CA

TO Manager: Steve McCoy, P.E.

Participants: Dr. Raju Dantuluri, Lead Engineer
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1. INTRODUCTION

Bench-scale treatability studies were performed on arsenic-contaminated groundwater from Operable Unit 3 (OU 3) at the Naval Training Center (NTC), Orlando, Florida. The purpose of the first study was to evaluate the effectiveness of three sorbent materials in removing arsenic from the groundwater. The ability of the sorbents to simultaneously remove herbicides from the OU 3 groundwater was also evaluated. In the second study, retardation of the arsenic migration relative to the groundwater flow was determined. To perform the testing, Tetra Tech NUS engaged PRIMA Environmental, under the direction of Dr. Cindy Schreier. The results of the studies are summarized in this letter report and copies of the test reports are presented in the appendices.

2. SITE BACKGROUND

OU 3 is comprised of Study Areas (SAs) 8 and 9, located about 600 feet apart on the southeast shore of Lake Baldwin. As part of the base closure for the NTC, environmental investigations and studies were conducted to evaluate the soil and groundwater conditions at OU 3 from past chemical handling, storage, and disposal practices. The investigation of OU 3 found that several pesticide-related chemicals, particularly arsenic, were present in the shallow soil and groundwater. Direct spillage or disposal of pesticides and herbicides on the ground surface at both SAs and via a sump at SA 9 were determined to be the most likely mechanisms for introducing the contaminants to the environment (HLA, 1999). The groundwater contamination is attributed to the leaching of contaminants from the soil. As a result, the contaminated soil was excavated and removed during two Interim Remedial Actions (IRAs) in 1997 and 1999.

Despite the IRAs, the groundwater remains contaminated with arsenic and other chemicals, including the herbicides MCPA and MCPP. Arsenic is the most prevalent contaminant with 13 of 32 wells at OU 3

containing arsenic above the Federal Maximum Contaminant Level (MCL) and the Florida Groundwater Cleanup Target Level (GCTL) of 50 parts per billion (ppb). In the samples collected in October 2000 the arsenic exceedances at OU 3 ranged from 72 to 2700 J ppb (TiNUS, 2000). The U.S. Environmental Protection Agency (EPA) is finalizing a regulation to reduce the public health risks from arsenic in drinking water. The Agency is revising the current drinking water standard for arsenic from 50 ppb to 10 ppb (EPA, 2001), which will increase the magnitude of the exceedances. The EPA is required to issue the final rule by June 22, 2001.

The groundwater from both SAs flows in a northwesterly direction into Lake Baldwin. Measurements of the depth to the groundwater during seven monitoring events during 1999 and 2000 show that the water table ranged between 0.45 and 6.75 feet below ground surface depending upon the well location and the time of year (TiNUS, 2000).

The remedial actions selected for OU 3 consist of (1) groundwater use restrictions, (2) groundwater monitoring, and (3) site reviews (HLA, 2000). However, recent data from the groundwater monitoring program have indicated that more proactive remedial measures may be necessary to meet the groundwater standards. Due to the shallow depth to groundwater, an in situ reactive barrier has been proposed as a process option for cleaning up the groundwater at OU 3. As a result, the bench-scale treatability study was initiated in May 2000 to (1) test candidate sorbents in removing arsenic and other contaminants from the OU 3 groundwater, and (2) determine the retardation of arsenic in the saturated soil at OU 3.

3. TESTING – ARSENIC REMOVAL

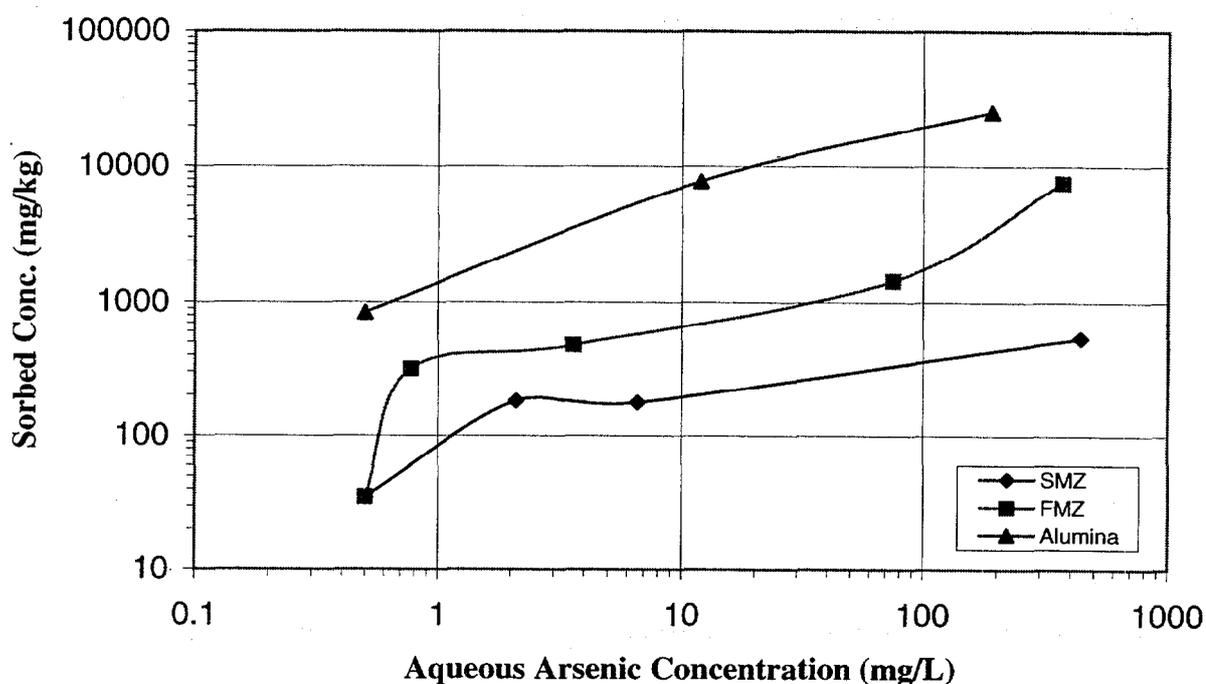
Arsenic in groundwater is typically present as either the oxidized arsenate or the reduced arsenite form. Under normal pH conditions observed in groundwater (i.e., slightly acidic to slightly basic), arsenate will be present as an anion and arsenite will be present as an uncharged complex. In either case, the in situ removal of arsenic from groundwater requires a medium capable of anion exchange and/or neutral species sorption at ambient conditions. A search of the literature suggested three likely candidate media for testing: surfactant-modified zeolite (SMZ), iron-modified zeolite (FMZ), and activated alumina (alumina). The SMZ would potentially remove arsenic by anion exchange. The FMZ and alumina would remove arsenic through a sorption mechanism. The SMZ had the added potential advantage to sorb organic contaminants in the organic portion of the surfactant layer. Alumina is commonly used to remove dissolved arsenic in water treatment facilities where pH adjustment is part of the process. However, alumina has never been used to remove arsenic from groundwater in situ. The FMZ and SMZ are new materials developed to address the increased interest in removing dissolved arsenic from drinking water.

3.1 Batch Tests

Test Description. Equilibrium batch tests were performed on each of the selected media. Details of the batch test procedures are presented in Appendix A. For each test, a standard amount of the solid media was mixed with OU 3 groundwater and stirred for approximately 24 hours. A range of starting dissolved arsenic concentrations was prepared by spiking OU 3 groundwater with varying amounts of a standard sodium arsenite solution. Sodium arsenite (i.e., reduced arsenic) was used because site-specific conditions at OU 3 suggest that a large proportion of the dissolved arsenic is present in this form. After 24 hours, a sample of the liquid was removed and analyzed for dissolved arsenic. The difference between the starting arsenic concentration and that present after equilibration was used to calculate the amount of arsenic sorbed by the media. If the starting arsenic concentration were high enough to saturate the media, the data would be used to calculate the media's sorption capacity. The results of the batch tests were used to identify which of the media would be tested in column tests.

Batch Test Results. Detailed results from the batch tests are presented in Appendix A. The results are summarized in Figure 1 wherein the equilibrium aqueous and sorbed arsenic concentrations are plotted for each of the media. The sorption capacity of the alumina far exceeded that of the modified zeolites. The batch test results indicate that alumina and FMZ clearly perform better than the SMZ, and both activated alumina and FMZ were selected for column testing.

Figure 1. Equilibrium Arsenic Sorption



3.2 Column Tests

Test Description. Two series of column tests (preliminary and final) were performed using activated alumina and FMZ as sorptive media. The details of the tests are presented in Appendix A. Because large quantities of water were required for the flow-through column tests, synthetic groundwater was prepared to simulate the groundwater composition observed at OU 3. The arsenic concentration in the synthetic groundwater was produced by adding sodium arsenite (reduced arsenic) to achieve a concentration similar to the high end of observed concentrations at OU 3. In the final set of column experiments, the synthetic groundwater was also spiked with concentrations of the herbicides MCPA and MCPP, characteristic of OU 3 groundwater.

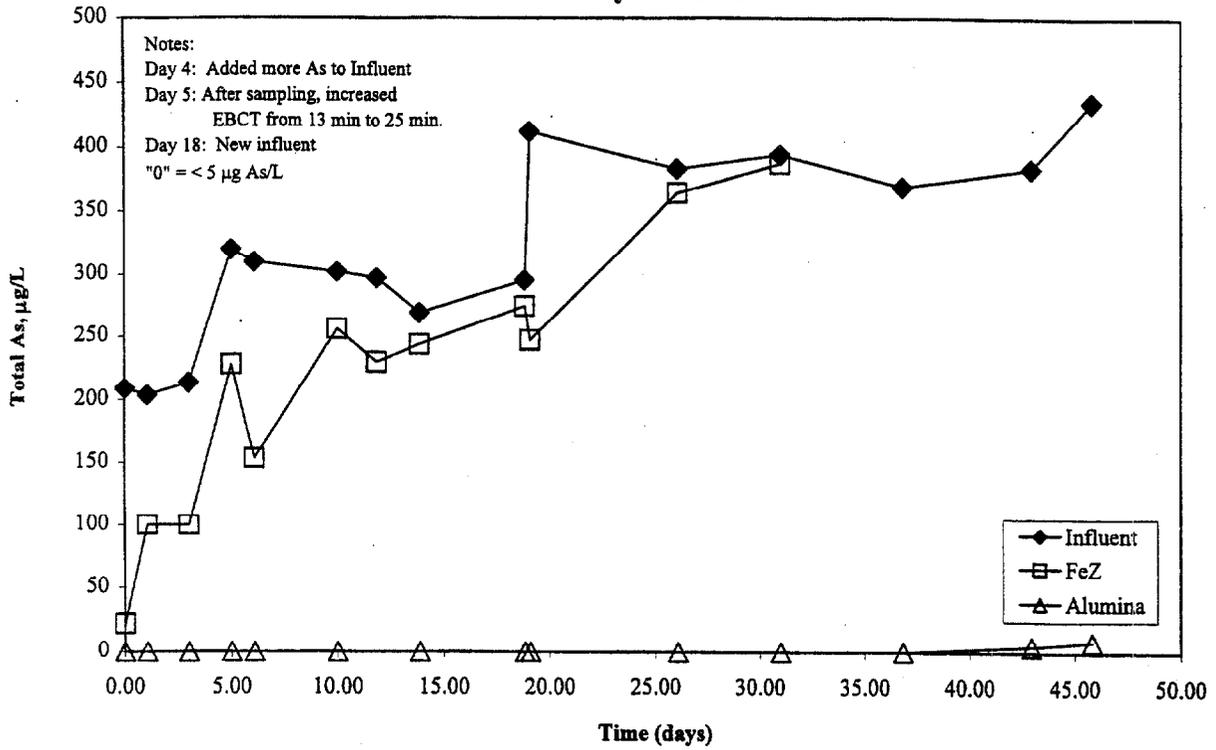
The preliminary set of column tests was run to estimate the time required for breakthrough. Breakthrough was defined as the point where the effluent arsenic concentration exceeded 5 µg/L. The results of the preliminary column tests were used to more closely estimate the breakthrough point in the final column tests and to optimize the timing of sample collection. The results of the column tests will be used to estimate the sorption capacity of the treatment media under actual field conditions.

Column Test Results. The details of the column test results are presented in Appendix A, and the performance of the FMZ and the alumina in the preliminary and final tests is shown in Figures 2 and 3. The results of both preliminary and final column tests were similar and confirmed the results of the batch tests. Activated alumina sorbed significantly more arsenic than FMZ and was able to maintain effluent concentration below the breakthrough concentration.

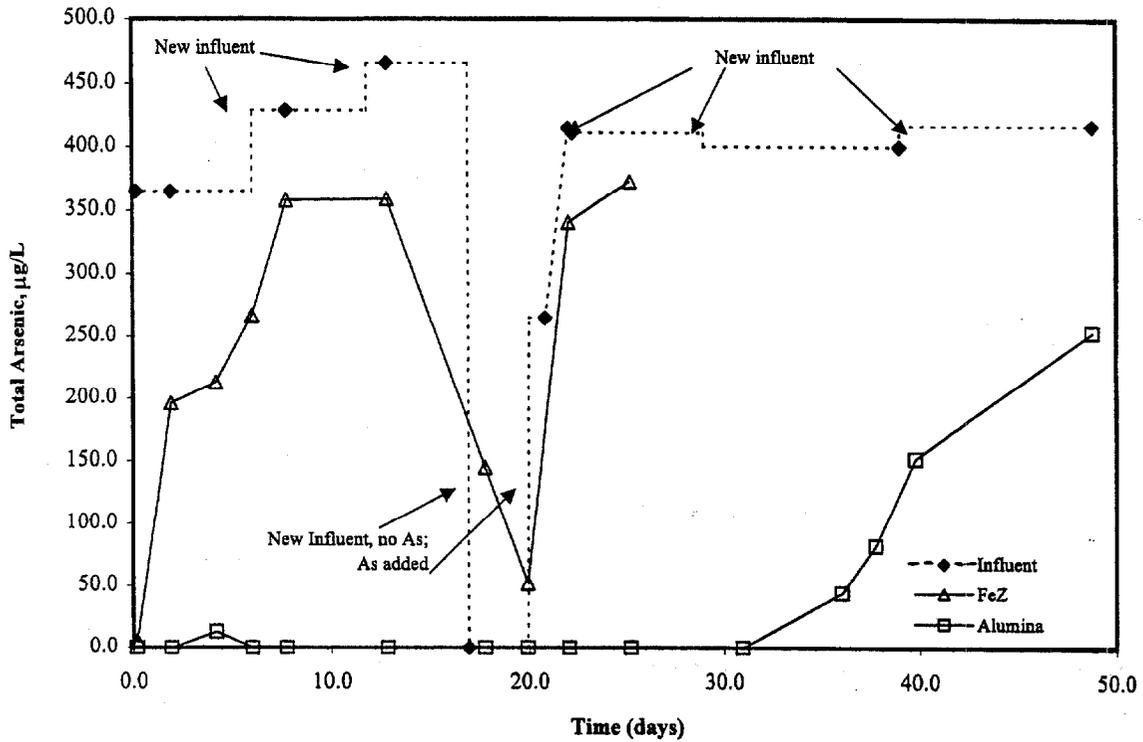
In the preliminary columns the alumina column treated 2,930 bed volumes prior to breakthrough (5 µg/L). Breakthrough occurred after 45 days, at which time the arsenic capacity for the alumina was 1,500 µg arsenic/g sorbent. In contrast, the FMZ column never produced effluent arsenic concentrations less than 5 µg/L.

In the final test columns, under slightly different flow conditions, the effluent from the alumina column did not exceed the breakthrough concentration criteria (5 µg/L) for 36 days. As in the preliminary test, the effluent concentration from the FMZ column was never less than the breakthrough concentration. At the end of the final column test, defined by breakthrough on the alumina column, 3,980 bed volumes had been treated. The alumina sorption capacity was 2,520 µg arsenic/g sorbent, whereas the sorption capacity for the FMZ was <10 µg arsenic/g sorbent when less than 16 bed volumes were treated. Neither sorbent media removed the herbicides from the influent. Effluent water was also analyzed for water quality parameters, including dissolved aluminum. Neither sorbent media adversely affected water quality and there was no evidence of aluminum leaching.

**Figure 2. Total Arsenic Concentrations in Influent and Effluent Streams
Preliminary Columns**



**Figure 3. Total Arsenic Concentrations in Influent and Effluent Streams,
Final Columns**



4.0 TESTING – ARSENIC RETARDATION IN SOIL

Although arsenic in groundwater at OU 3 tends to exist as either an anion or a neutral dissolved species, it does interact with aquifer particle surfaces and, thus, its transport through the aquifer is slower than that of the water. The difference between the transport velocity of a non-reactive tracer (i.e., it flows with the water) and a contaminant like arsenic is a measure of the retardation of the contaminant. Measurement of the retardation factor for a contaminant is useful in accurately predicting the time required for a contaminant to reach a specific point in the environment (e.g., a receptor). A set of tests was run to determine the site-specific retardation factor for arsenic at OU 3.

Test Description. Details of the retardation tests are presented in Appendix B. Soil collected just above the water table near monitoring well OLD-08-11 at OU 3 was used to fill the experimental columns. Synthetic groundwater (similar to that used in the column tests for sorption) and OU 3 groundwater were spiked with a non-reactive tracer (chloride) as well as sodium arsenite for the influent solutions. The synthetic groundwater was used in a preliminary column and the OU 3 groundwater was used in the three final columns. In each test, the test solution was drawn through the soil column and the effluent collected periodically and analyzed for chloride and arsenic [total As, As(V) and As(III)]. The time difference between the appearance in the effluent of chloride and arsenic at 50 percent of the influent concentration was used to calculate the retardation factor for total As, As(V) and As(III).

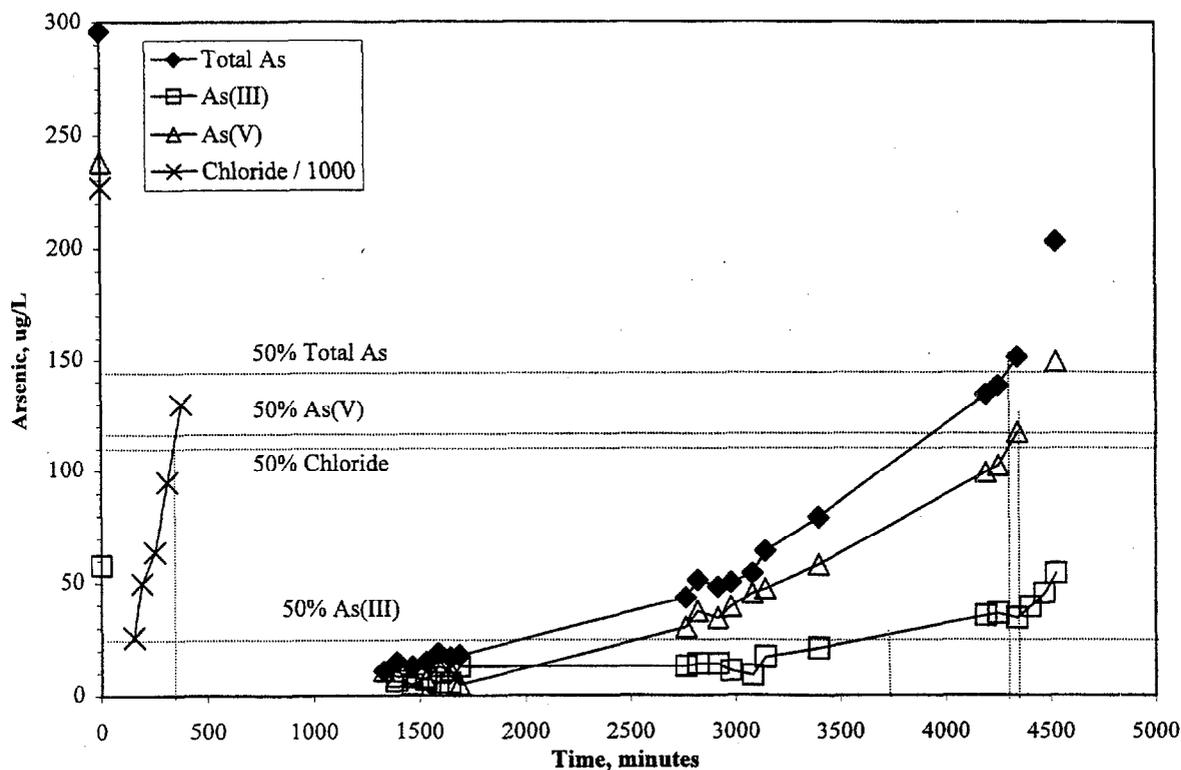
Retardation Test Results. The results of the arsenic retardation study are detailed in Appendix B. The retardation factor for total As and As(V) was approximately 21, while the retardation factor for As(III) was approximately 14. The results suggest that arsenic moves through the aquifer material at OU 3 approximately 14 to 21 times slower than the velocity of the water. Arsenic (III) moves with less interaction, and thus less retardation, than As(V) because in OU 3 groundwater it is present as an uncharged molecule. The results of one of the retardation tests are presented in Figure 4.

5. CONCLUSIONS AND RECOMMENDATIONS

The primary conclusions of the arsenic removal and retardation studies are as follows.

- Of the three media tested, activated alumina was clearly superior in the amount of arsenic removed from the groundwater and in achieving effluent concentrations below the target concentration of 5 µg/L.

**Figure 4. Arsenic Retardation
Site Groundwater, Final Column 2**



Activated alumina is capable of removing a substantial amount of dissolved arsenic at OU 3 without pretreatment of the groundwater.

- The activated alumina was stable with no increase in aluminum concentrations observed in the effluent of the test column.
- The concentrations of other contaminants in the influent groundwater, specifically the herbicides MCPA and MCPP, were unaffected by the alumina.
- The retardation factor for arsenic ranged from 14 to 21 in the saturated soil from OU 3.

The groundwater used in the column tests was prepared to simulate conditions observed at OU 3 (i.e., a mildly reducing environment with a significant proportion of the arsenic present in a reduced form). Several field conditions (e.g., dissolved organic compounds, freshwater flushing) that may affect arsenic sorption and desorption were not simulated in the experiments. Although groundwater transport of arsenic is slow at OU 3 (low gradient and a retardation factor of 14-21), the mildly reducing groundwater environment provides a challenge for any passive remedial option. A field-scale pilot test is recommended to build on the encouraging column test results for activated alumina and the geochemical environment present at OU 3.

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HLA, 2000, *Interim Record of Decision, Operable Unit 3, Naval Training Center, Orlando, Florida*. Unit Identification Code: N65928, Contract No. N62467-89-D-0317/136, September.

TtNUS (Tetra Tech NUS), 2000. *Groundwater Sampling at Operable Unit 3*. Document No. R4710005, November 6.

EPA (U. S. Environmental Protection Agency), 2001, *Fact Sheet: Drinking Water Standard for Arsenic*, EPA 815-F-00-015, January.

APPENDIX A

Report of Findings

Removal of Arsenic from Groundwater at OU 3

PRIMA Environmental

**Final
REPORT OF FINDINGS**

**OU3 Treatability Study: Removal of Arsenic from Groundwater
NTC Orlando, FL**

N7457 – RFP 045 (DW)

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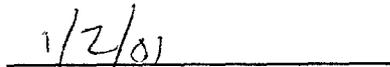
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EXECUTIVE SUMMARY

Three sorbents—surfactant-modified zeolite, iron-modified zeolite, and activated alumina—were evaluated for their ability to remove arsenic from groundwater at Operable Unit 3 at the former Naval Training Center in Orlando, Florida. Of these, only alumina removed arsenic to below the detection limit of 5 µg/L. The arsenic capacity of the alumina measured in the final column test was 2,520 µg As/g alumina. This may be an underestimate because capacity appears to be dependent upon residence time, which would be much greater in the field than in the laboratory. None of the sorbents removed the secondary chemicals of concern, MCPA or MCPP.

Based on the results of this study, PRIMA Environmental recommends that a field pilot test be conducted using alumina as the sorbent for arsenic. The primary goal of the pilot test should be to determine the capacity of the alumina in the presence of native organic matter and at a flowrate representative of field conditions.

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1.0 INTRODUCTION

PRIMA Environmental performed treatability testing to evaluate the ability of three sorbent materials to remove arsenic from groundwater at Operable Unit 3 at the former Naval Training Center in Orlando, Florida. The materials tested were

- Iron-modified zeolite (FeZ)
- Surfactant-modified zeolite (SMZ), and
- Activated alumina (alumina)

The objectives of the study were to

- ♦ Determine whether the sorbents could remove arsenic
- ♦ Estimate the capacity of the sorbents
- ♦ Determine whether the sorbents could also remove secondary contaminants, the herbicides MCPP and MCPA.

Batch and column tests were conducted in order to accomplish these goals.

2.0 MATERIALS AND METHODS

2.1 Materials

2.1.1 Sorbents

Three sorbents were received from TetraTech NUS (TtNUS): Cabsorb ZK406SMZ (a surfactant-modified zeolite), Iron Saturated Zeolite--Chabazite Fe, and DD-2 Activated Alumina (Alcoa Industrial Chemicals). They were designated SMZ, FeZ and Alumina, respectively. Selected physical characteristics of these materials are given in Table 1. The sorbents were stored at room temperature (approximately 25°C).

Table 1. Selected Physical Characteristics of Test Sorbents

	SMZ	FeZ	Alumina
Color	Off-white	Orange/brown	white
Particle shape	Irregular, round	Irregular, round	Irregular, flat
Particle size	8-14 mesh	8 x 20 mesh	14 x 20 mesh
Porosity*	0.5072	0.7460	0.8142
Bulk Density	0.94 g/cm ³	0.57 g/cm ³	0.67 g/cm ³

*Measured by Sierra Testing Laboratories, El Dorado Hills, CA.

2.1.2 Groundwater

Site groundwater (GW) was received from TtNUS and stored at 5°C. Water was brought to room temperature prior to beginning a test. All containers were kept tightly capped in order to minimize diffusion of air/oxygen into the water.

2.2 Methods

2.2.1 Preparation of Synthetic Groundwater

Synthetic groundwater (syn-GW) was prepared in 30 gallon batches by sparging Type II laboratory water with nitrogen gas for approximately 24 hours to remove oxygen. Once dissolved oxygen was reduced to below 2.5 mg/L, sulfuric acid, hydrochloric acid, nitric acid, trisodium phosphate, calcium hydroxide, sodium bicarbonate, magnesium chloride, lime and in some cases, dry ice, were added to obtain water quality parameters similar to site groundwater. Syn-GW was spiked with sodium arsenite to obtain an initial arsenic concentration of 300-500 µg/L. For the final columns, syn-GW was also spiked with approximately 150-800 µg/L each of MCPP and MCPA, two herbicides characteristic of the site groundwater. A floating cover was placed over each batch of syn-GW to prevent formation of headspace and to minimize the diffusion of oxygen into the water.

2.2.2 Batch tests

For each sorbent, four replicates were prepared by adding 100 mL of site groundwater (GW) to 1 g of sorbent. The replicates were spiked with As(III) (sodium arsenite) to give

initial As(III) concentrations of 3.9 mg/L, 8.4 mg/L, 89 mg/L, and 445 mg/L. A replicate without added arsenic was prepared by adding 990 mL GW to 9.9 g sorbent; this replicate was the “as received” test and was not spiked. The headspace in the reaction bottles was purged with nitrogen gas to minimize intrusion of oxygen into the system. The bottles were then capped and placed on a reciprocal shaker. After 23 hours, pH, Eh, and temperature, were measured. A sub-sample was centrifuged and the aqueous phase analyzed for Total As. Total Fe, Sulfate, Nitrate, Chloride, MCPP and MCPA were analyzed in the “as received” replicates. A series of controls containing no sorbent, was also prepared.

Although the concentration of As(III) in site GW does not exceed 1 mg/L, higher As concentrations were used in this study in an effort to estimate the capacity of each sorbent. Such information would aid in comparing the materials and in estimating the breakthrough time for column tests.

2.2.3 Preliminary Column Tests

Based on the results of Section 2.2.2, two sorbents (FeZ and Alumina) were selected for further study. Preliminary column tests were run to determine the minimum contact time needed to achieve the desired degree of arsenic removal and to estimate the time required for breakthrough to occur. Breakthrough was defined as the time required for the effluent concentration of total arsenic to be $> 5 \mu\text{g/L}$. The columns were prepared as shown in Figure 1. Selected column parameters are given in Table 2. Pore volume, bed volume and residence time are defined as follows:

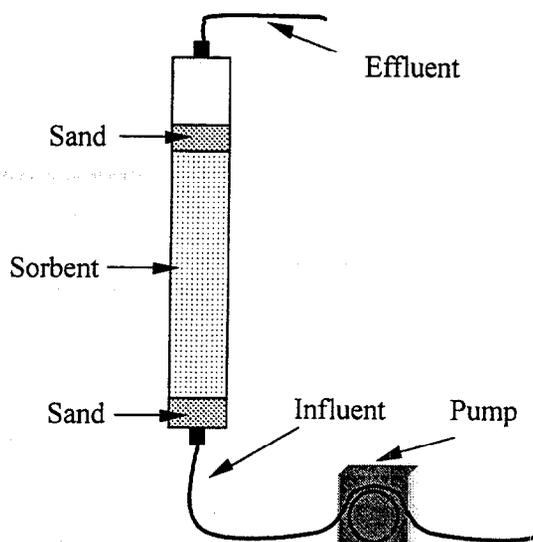


Figure 1. Schematic Diagram of Preliminary and Final Columns.

- *Pore volume*—volume of the void space of the sorbent as packed in the column; determined by measuring the volume of water needed to fill the pore space of a known mass of sorbent.
- *Bed volume*—bulk volume of the sorbent as packed in the column; determined from graduation markings (in mL) on the column.
- *Residence time*—the average time a given volume of water is in contact with the sorbent. Residence time is calculated by dividing the pore volume by the flowrate.

Syn-GW was used as the influent. Two batches of syn-GW (30 gallons each) were needed to complete the test. Both influent and effluent were sampled periodically and analyzed for Total As, As(III) and As(V).

Table 2. Preliminary Column Parameters*

	FeZ	Alumina
Column size	1 in. diam x 2.5 in.	1 in. diam. x 2 in.
Direction of flow	Upgradient	Upgradient
Mass of sorbent	20 g	20 g
Pore volume of sorbent	26 mL	24 mL
Bed volume of sorbent	~ 35 mL	~ 30 mL
Flowrate	2.7 mL/min first 5 days, 1.4 mL/min thereafter	2.4 mL/min first 5 days, 1.2 mL/min thereafter
Residence time	9.6 min (first 5 days) 18 min (after 5 days)	10 min (first 5 days) 20 min (after 5 days)

* See Section 2.2.3 for definitions of pore volume, bed volume and residence time.

2.2.4 Final Column Tests

The final column tests were similar to the preliminary column tests, but used different sized columns and amounts of sorbent (Table 3). In addition, the synthetic GW was spiked with MCPP and MCPA as well as As(III). Samples were collected periodically and analyzed for Total As, pH and Eh. Selected samples were also analyzed for MCPA, MCPP, chloride, nitrate, sulfate, alkalinity, iron and aluminum. Seven batches of syn-GW (at 30 gallons each) were required to complete the test. In most cases, columns were shut down for 8-48 hours between batches.

Table 3. Final Column Parameters*

	FeZ	Alumina
Column size	1.25 in. diam x 3.75 in.	1.25 in. diam. x 3.5 in.
Direction of flow	Upgradient	Upgradient
Mass of sorbent	50 g	50 g
Pore volume of sorbent	65 mL	60 mL
Bed volume of sorbent	~ 88 mL	~ 75 mL
Average Flowrate	4.8 mL/min	6.7 mL/min
Average Residence time	14 min	8.9 min

* See Section 2.2.3 for definitions of pore volume, bed volume and residence time.

2.2.5 Analytical Methods

2.2.5.1 Arsenic

Total arsenic concentration was measured via hydride generation atomic absorption spectrometry (HGAA). As(III) concentration was measured via HGAA, but without the

pre-reduction step. The concentration of As(V) is defined as the difference between the Total As and As(III) concentrations.

2.2.5.2 Alkalinity

Alkalinity was measured by titration by either Alpha Analytical, Sparks NV; CLS Labs, Rancho Cordova, CA; or Sequoia Analytical, Sacramento, CA.

2.2.5.3 Chloride and Nitrate

Chloride and nitrate were measured either with an ion selective electrode (PRIMA Environmental) or by ion chromatography (Alpha Analytical, Sparks NV; CLS Labs, Rancho Cordova, CA; or Sequoia Analytical, Sacramento, CA)

2.2.5.4 Eh

Eh was measured using a platinum electrode and filling solution appropriate for samples with ionic strength < 0.2 mole/L.

2.2.5.5 MCPP and MCPA

MCPP and MCPA were analyzed by Alpha Analytical (Sparks, NV) using EPA Method 8151.

2.2.5.6 pH

pH was measured using a pH electrode. During adjustment of pH of synthetic groundwater, pH was measured by placing the electrode directly in the tank. In all other cases, pH was measured by collecting a sub-sample.

2.2.5.7 Sulfate

Sulfate was measured turbidimetrically using a Hach DR2010 Spectrophotometer and test kit.

2.2.5.8 Iron and Aluminum

Total iron was measured either colorimetrically using Hach DR2010 Spectrophotometer and test kit, or by using EPA 200.7. Aluminum was measured using EPA 200.7.

2.2.6 Data Analysis

2.2.6.1 Calculation of Bed Volumes through Column

The number of bed volumes put through a column was calculated according to

$$\# \text{ Bed Volumes} = (\text{Flowrate} \times \text{Time}) / \text{Bed Volume}$$

“Bed volumes through column” is defined as the number of bed volumes put through over the course of the test. “Bed volumes at breakthrough” is defined as the number bed volumes put through when the concentration of Arsenic in the effluent first exceeds 5 µg/L. See Section 2.2.3 for definition of bed volume.

2.2.6.2 Calculation of Arsenic Capacity

For column tests, arsenic “test capacity” is defined as the amount of arsenic sorbed per mass of sorbent at the completion of the test. “Test capacity” does not indicate whether arsenic was completely removed, nor does it necessarily represent the maximum amount of arsenic that could be adsorbed. The arsenic test capacity was calculated according to:

$$\text{Capacity} = \frac{\sum_0^s \left\{ \left[\text{As}(\text{in}) - \left(\frac{1}{2} \right) (\text{As}(\text{out})_{s-1} + \text{As}(\text{out})_s) \right] \times \text{Flowrate} \times \Delta\text{Time} \right\}}{\text{Mass}} \quad \text{Eqn 1}$$

where

As(in) = concentration of As in influent

As(out)_{s-1} and As(out)_s = concentration of As in effluent at sample number *s* and *s-1*; this is the average effluent concentration between two sampling points

Flowrate = flowrate through the column

ΔTime = difference in time between samples *s* and *s-1*, and

mass = mass of sorbent

“Capacity at breakthrough” is defined as the amount of arsenic that was adsorbed before arsenic was detected at a concentration ≥ 5 µg/L in the effluent. It was estimated using Eqn. 1, with *s* = sample number at which As in effluent first exceeded 5 µg/L.

3.0 RESULTS AND DISCUSSION

3.1 Batch Tests

3.1.1 Arsenic Removal

The results of the batch tests are shown in Table 4. The SMZ sorbent did not remove arsenic from unamended site GW (0.35 mg/L test) or from site GW spiked with 89 or 445 mg/L arsenic. Some removal (21-46%) was achieved when intermediate concentrations of arsenic were used. FeZ removed 89% of the arsenic from unamended site GW, though this still resulted in an aqueous arsenic concentration of 0.039 mg/L. In contrast, alumina completely removed arsenic from unamended site groundwater and removed 57% of the arsenic in the 445 mg/L test, indicating a large capacity for arsenic.

Based on these results, FeZ and alumina were chosen for further testing (Sections 3.2 and 3.3).

3.1.2 Effect of Sorbents on Water Quality

3.1.2.1 Inorganic Parameters

The effect of the different sorbents on several water quality parameters of site GW are listed in Table 4. SMZ decreased the alkalinity from 60 mg/L to 8 mg/L, decreased sulfate from 48 mg/L to 32 mg/L and increased chloride from 11 mg/L to 40 mg/L. It had little effect on nitrate, pH or Eh. FeZ had no effect on alkalinity, chloride or nitrate, but increased the sulfate concentration to 135 mg/L. The pH of the system decreased from 5.82 to 4.44, while Eh increased, suggesting that the sorbent is somewhat oxidizing. Iron was also detected in the aqueous phase, though this may have been due to abrasion (the batch tests were mixed) rather than dissolution. Finally, alumina had little effect on alkalinity, chloride, or nitrate, but decreased sulfate to 13 mg/L. The pH increased to 6.90, and Eh decreased from 83 mV to 0.5 mV, indicating reducing conditions.

Although many differences were seen between the untreated and treated samples, it should be noted that these changes may be transitory in a flow through system such as a column reactor or permeable barrier. For example, changes may be due in part to the initial reaction between sorbent and water. Once a column has been flushed with a few pore volumes of water, the sorbent may have little influence on water quality.

3.1.2.2 Organic Parameters

The only organic parameters specifically tested for were MCPP and MCPA. Neither of these was detected above the 100 µg/L detection limit.

Site GW contains organic matter, however. The amount was not quantified, but was sufficiently high to impart an orange color to the water. Both SMZ and alumina removed the color. This may be important since long-term exposure to organic matter could affect arsenic sorption capacity. (Note that the color was not due to iron(II)—see Table 4.)

Table 4. Batch Test Results

Sorbent	Arsenic					pH	Eh mV	Temp, C	Alkalinity mg/L CaCO3	Total Fe, mg/L	Sulfate mg/L	Chloride mg/L	Nitrate mg/L	MCPFP µg/L	MCPA µg/L
	Initial Aqueous*	Aqueous mg/L	Sorbed mg/kg	Aqueous %	Sorbed %										
SMZ	0.35 ppm	0.38	-3	110	-9	5.74	88	21	8	0	32	40	< 0.1	< 100	< 100
	3.9 ppm	2.1	181	54	46	5.97	92	21							
	8.4 ppm	6.6	176	79	21	6.02	92	21							
	89 ppm	89	35	100	0	7.01	61	21							
	445 ppm	440	535	99	1	8.81	-57	21							
Alumina	0.35 ppm	<0.002	35	0	100	6.90	0.5	21	74	0	13	11	0.1	< 100	< 100
	3.9 ppm	0.028	388	1	99	6.83	9	21							
	8.4 ppm	0.48	788	6	94	6.97	13	21							
	89 ppm	12	7,735	13	87	7.48	-3	21							
	445 ppm	190	25,535	43	57	8.99	-47	21							
FeZ	0.35 ppm	0.039	31	11	89	4.44	152	21	56	1.2	135	9.5	< 0.1	< 100	< 100
	3.9 ppm	0.77	314	20	80	4.49	160	21							
	8.4 ppm	3.6	476	43	57	4.53	169	21							
	89 ppm	75	1,435	84	16	5.21	135	21							
	445 ppm	370	7,535	83	17	7.04	79	21							
Control (no sorbent added)	0.35 ppm	0.4		114		5.82	83	21	60	0	48	11	< 100	< 100	< 100
	3.9 ppm	3.3		84		5.97	92	21							
	8.4 ppm	8		96		5.99	100	21							
	89 ppm	84		94		7.35	55	21							
	445 ppm	390		88		8.97	-63	21							
GW As Received, before batch test		0.35				5.85	97	17.8	62	0	49	10	< 100	< 100	< 100

* Total of Arsenic in GW + added arsenic (III); note that 0.35 ppm is groundwater as received

3.2 Preliminary Column Tests

The results of the preliminary column tests are shown in Figures 2 and 3 and in Tables 5 and 6. The results plotted in Figure 2 show that As was not completely removed by FeZ. Reducing the flowrate by a factor of two did not increase the degree of arsenic removal (Figure 2, Day 5). The lack of removal does not appear to be related to arsenic speciation because both As(III) and As(V) were detected in effluent from the FeZ column (Figure 3).

Table 5. Arsenic Removal, Preliminary Columns*

	FeZ	Alumina
Total Bed Volumes through column	2,060	2,930
Bed Volumes at breakthrough	n.a.**	2,930
Test Capacity, $\mu\text{g As/g sorbent}$	180	1,500
Capacity at Breakthrough, $\mu\text{g As/g sorbent}$	n.a.**	1,500
Breakthrough, days	n.a.**	~ 45

* See Section 2.2 for definitions and methods of calculation.

** not applicable—arsenic never completely removed

In contrast, complete removal of arsenic was achieved with alumina for approximately 43 days (2,770 bed volumes). Breakthrough (effluent concentration $>5 \mu\text{g As/L}$) occurred by 45 days (2,930 bed volumes). Although the effluent concentration was only $8.5 \mu\text{g/L}$, the test was stopped due to time constraints.

Based on these columns, the capacities of the sorbents for arsenic are $180 \mu\text{g As/g}$ for FeZ and $1,500 \mu\text{g As/g}$ for alumina.

3.3 Final Column Tests

3.3.1 Arsenic Removal

The concentrations of Total Arsenic in influent and effluent from the FeZ and alumina columns are depicted in Figure 4 and in Table 7. Arsenic was assumed to be constant in each batch of syn-GW and thus was typically analyzed only once per batch; the dotted lines were added to the influent data in Figure 4 to help visualize this. The capacities and bed volumes put through the columns are given in Table 8.

**Figure 2. Total Arsenic Concentrations in Influent and Effluent Streams
Preliminary Columns**

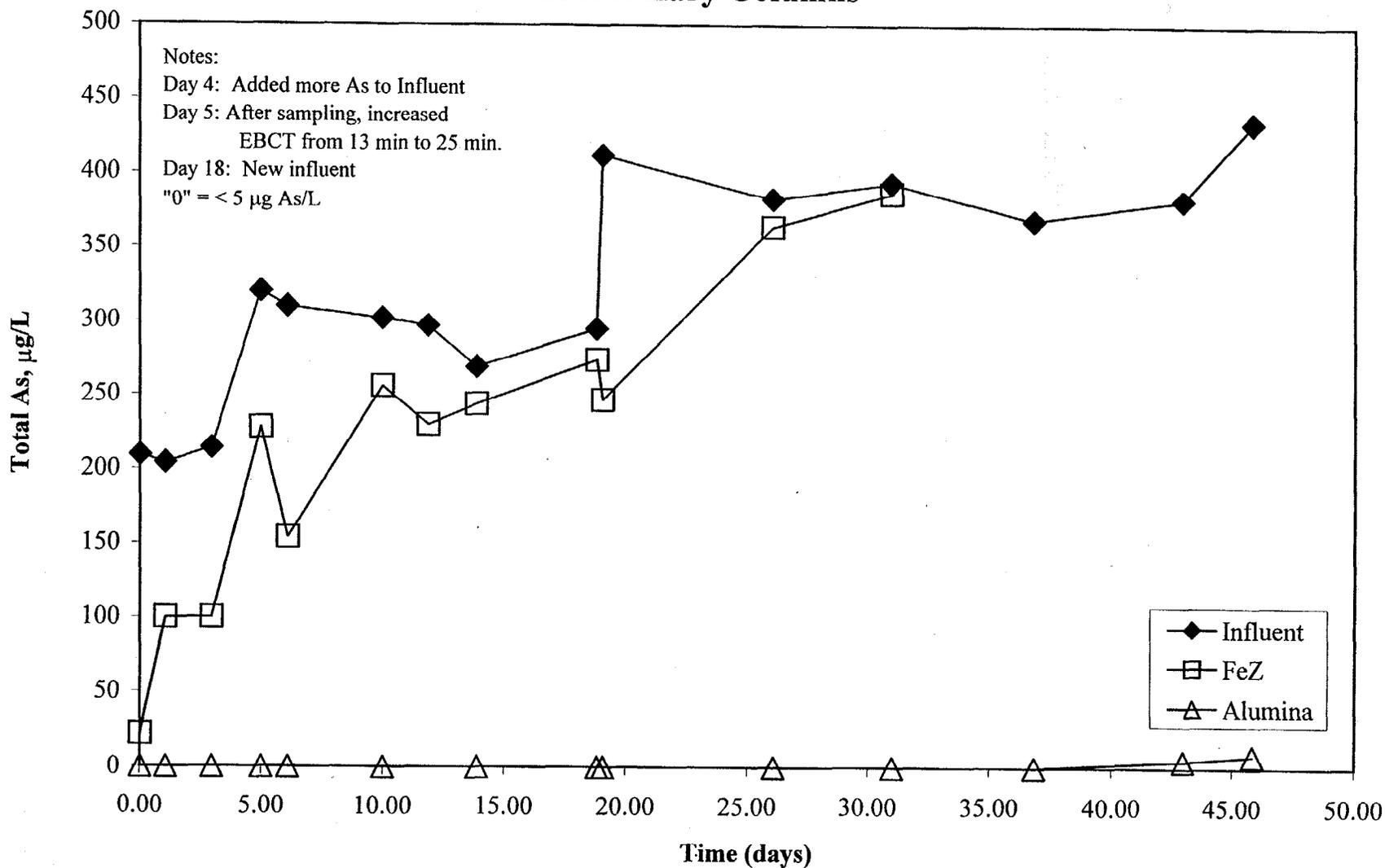


Figure 3. Arsenic Speciation, Preliminary Columns

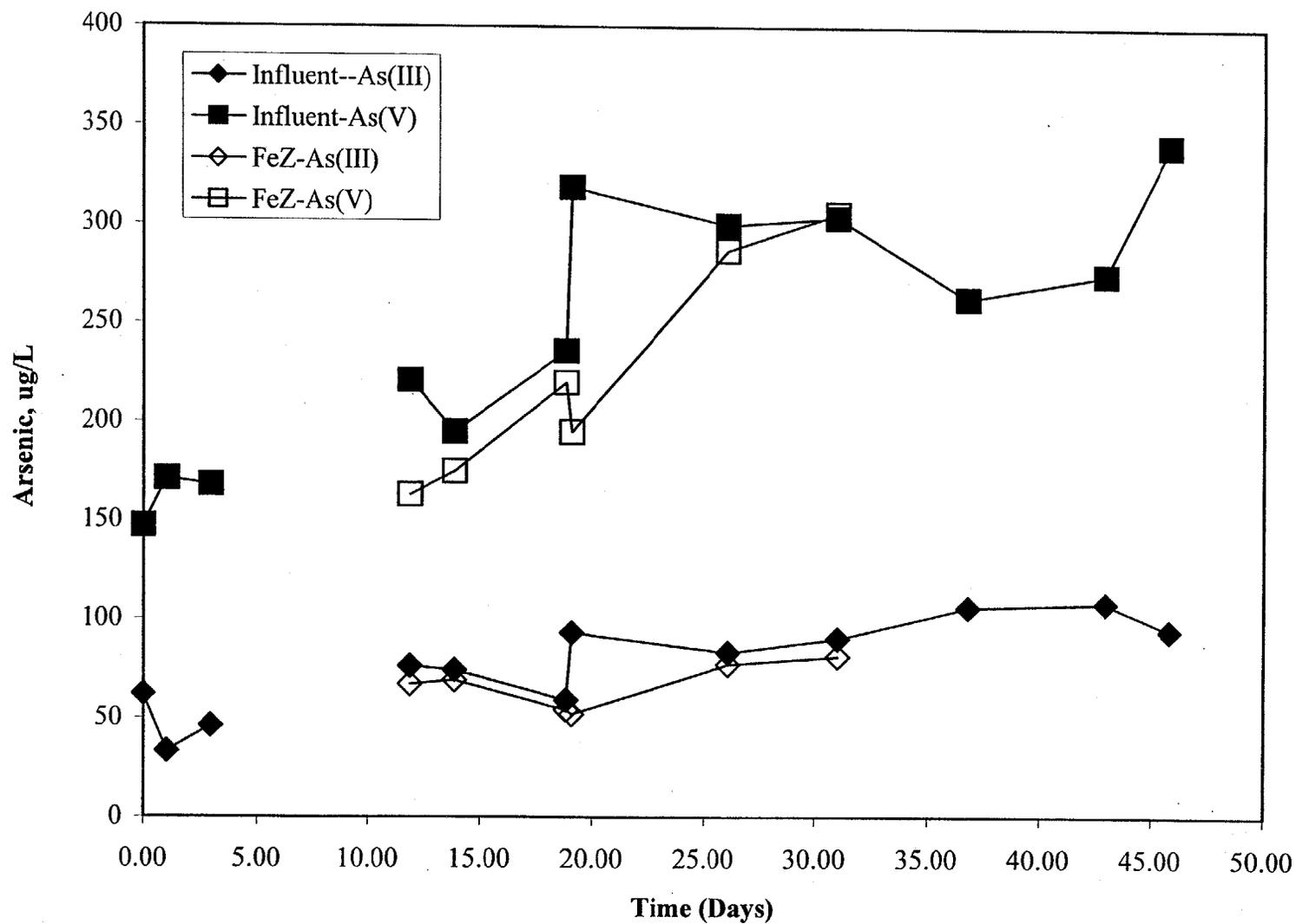


Table 6. Preliminary Column Data

Time Days)	Influent				FeZ			Alumina
	Total As µg/L	As(III) µg/L	As(V) µg/L	% As(III)	Total As µg/L	As(III) µg/L	As(V) µg/L	Total As µg/L
0.01	209	62	147	30	22			< 5
1.06	204	33	171	16	100			< 5
2.99	214	46	168	21	100			< 5
5.00	320				228			< 5
6.08	310				154			< 5
10.00	302				256			< 5
11.88	297	76	221	26	230	67	163	
13.88	269	74	195	28	244	69	175	<5
18.83	295	59	236	20	274	54	220	<5
19.08	412	93	319	23	247	52	195	<5
26.08	383	83	300	22	364	77	287	<5
31.00	394	90	304	23	387	81	306	<5
36.83	369	106	263	29				<5
42.96	383	108	275	28				4.8
45.83	435	94	341	22				8.5

Figure 4. Total Arsenic Concentrations in Influent and Effluent Streams, Final Columns

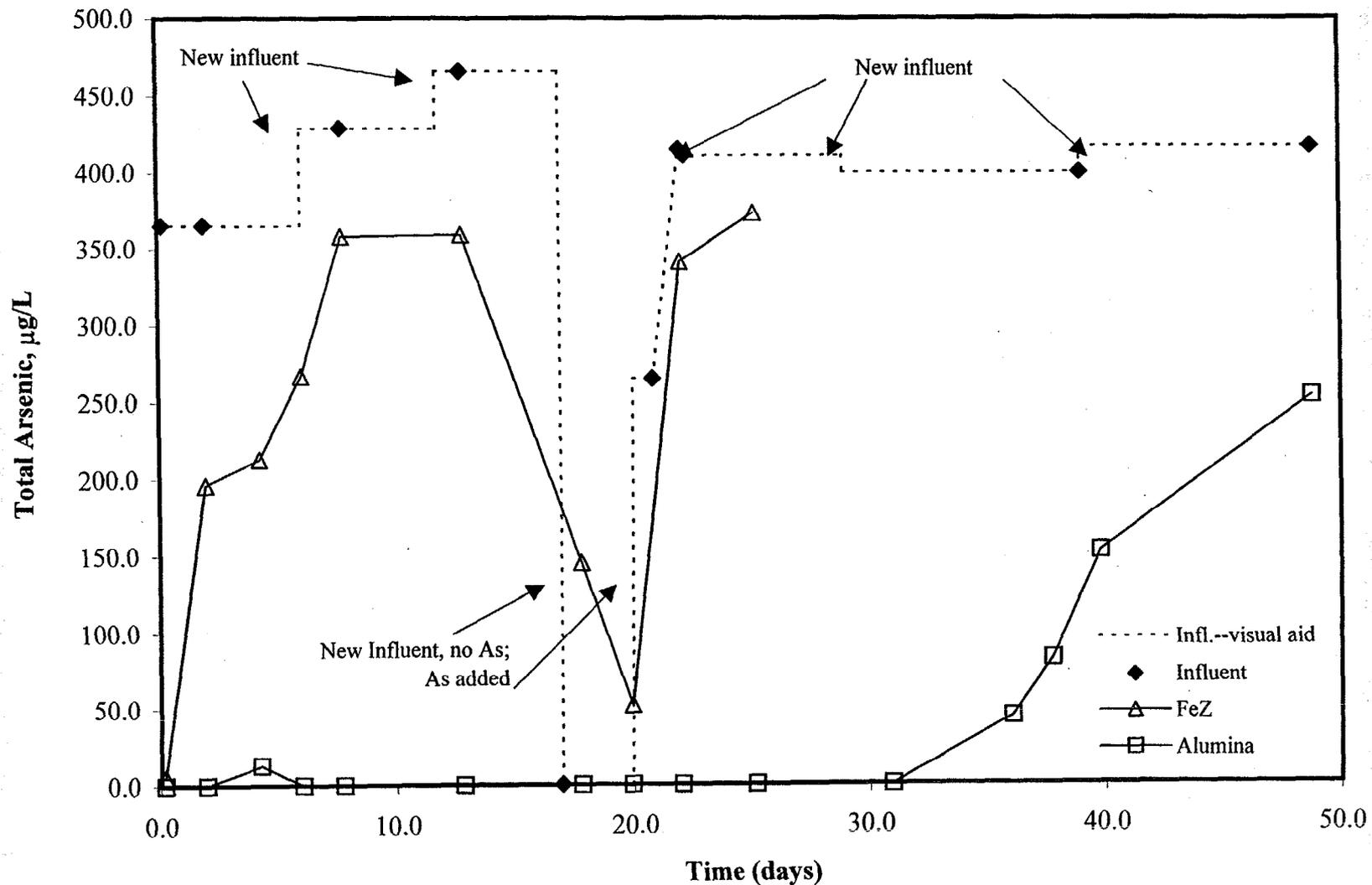


Table 7. Limited Analyte List

Influent Batch #	Day	Total As, µg/L			pH			Eh, mV			Temp. C [#]
		Influent	FeZ	Alumina	Influent	FeZ	Alumina	Influent	FeZ	Alumina	
1	0.2	365	5.9	< 5	6.96	4.43	8.23	84	234	78	25
1	1.9	--	196	--	--	6.71	--	--	68	--	25
1	4.2	--	213	13	--	6.02	6.28	--	159	94	25
1	6	--	267	< 5	--	7.55	6.28	--	134	111	25
2	7.7	429	358	< 5	5.87	6.31	6.21	73	160	134	25
3	12.8	466	359	--	5.51	5.99	--	122	192	--	25
4	17.7	< 5	145	< 5	5.59	5.75	5.72	209	251	247	21
4	19.9	< 5	52	< 5	5.75	5.67	5.64	240	251	244	18
4	20.8	265	--	--	7.21	--	--	176	--	--	21
4	22	415	341	< 5	7.21	7.09**	6.78**	168	164	165	21
5	22.3	411	--	--	5.67	--	--	172	--	--	21
5	25.2	--	373	--	--	6.31**	--	--	158	--	21
6	30.9	--	--	< 5	--	--	6.48	--	--	8	21
6	36	--	--	44	--	--	6.66	--	--	5	21
6	37.7	--	--	82	--	--	6.69	--	--	20	21
6	39	400	--	--	6.55	--	--	63	--	--	21
7	39.8	--	--	152	--	--	6.66	--	--	56	21
7	48.8	417	--	253	--	--	6.54	--	--	53	21

** pH drifted up 0.5-1 pH units before stabilizing at reported value

Room temperature

Table 8. Arsenic Removal, Final Columns*

	FeZ	Alumina
Total Bed Volumes through column	2,020	6,260
Bed volumes at breakthrough	< 16	3,980
Test Capacity, $\mu\text{g As/g sorbent}$	330	3,270
Capacity at Breakthrough, $\mu\text{g As/g sorbent}$	< 10	2,520
Breakthrough ($>5 \mu\text{g/L}$), days	< 0.2	~ 36

* See Section 2.2 for definitions and methods of calculation.

3.3.1.1 Arsenic Removal—FeZ

As with the preliminary columns, FeZ did not completely remove arsenic. Total Arsenic in the first effluent sample was $5.9 \mu\text{g/L}$ (0.2 days). However, the effluent concentration never reached the influent concentration. Speciation data (Tables 9 and 10) indicate that arsenic speciation was not responsible for the lack of removal since both As(III) and As(V) were present in FeZ effluent.

Table 9. Arsenic Speciation for Influent and FeZ Effluent

Infl. Batch #	Day	Influent				FeZ			
		As(III) $\mu\text{g/L}$	As(III) %	As(V) $\mu\text{g/L}$	As(V) %	As(III) $\mu\text{g/L}$	As(III) %	As(V) $\mu\text{g/L}$	As(V) %
1	0.2	290	79	75	21	--	--	--	--
1	1.9	--	--	--	--	45	23	151	77
2	7.7	94	22	335	88	75	21	283	79
3	12.8	317	68	149	32	79	22	280	78
4	17.8	< 5	--	< 5	--	30	21	115	79

Arsenic appears to easily desorb from FeZ. From Day 17 to Day 20, the concentration of arsenic in the influent was $< 5 \mu\text{g/L}$ due to accidental omission of As during preparation of the syn-GW. During this time, arsenic was detected in the FeZ effluent. In contrast, the concentration of arsenic in effluent from the alumina column remained below the detection limit of $5 \mu\text{g/L}$. (See Table 10). This implies that arsenic sorbed to alumina will remain sorbed when flushed with clean site GW.

The test capacity for total arsenic on FeZ was $330 \mu\text{g As / g FeZ}$, though it must be emphasized that effluent As concentrations were approximately equal to influent concentrations throughout most of the test. This loading is approximately twice as great as seen in the preliminary columns. The reason is unclear, but may be related to the down time during preparation of syn-GW. Downtime (during which flow to the columns was turned off and water in the columns was allowed to stand undisturbed) could permit As sorbed on the surface of the particles to migrate into pores, thereby freeing up surface adsorption sites.

Table 10. Expanded Analyte List

Influent Batch #	Day	Influent	FeZ	Alumina	Influent	FeZ	Alumina	Influent	FeZ	Alumina
		Total As, µg/L			As(III), µg/L			As(V), µg/L		
1	0.2	365	--	--	290	--	--	75	--	--
1	1.9	--	196	< 5	--	45	--	--	151	--
2	7.7	429	358	< 5	94	75	--	335	283	--
3	12.8	466	359	< 5	317	79	--	149	280	--
4	17.8	< 5	145	< 5	< 5	30	--	< 5	115	--
6	39	400	--	--	--	--	--	--	--	--
7	48.8	417	--	253	89	--	49	328	--	204
Batch #	Day	pH			Eh, mV			Alkalinity, mg/L		
1	0.2	6.92**	--	--	84	234	78	110	--	--
1	1.9	--	6.71	--	--	68	--	--	83	130
2	7.7	5.87	6.31	6.21	73	160	134	52	49	56
3	12.8	5.51	5.99	6	122	192	169	10.7	16.4	12.9
4	17.8	5.59	5.75	5.72	209	251	247	59.6	57	62.5
6	39	6.55	--	--	63	--	--	26	--	--
7	48.8	--	--	6.54	--	--	53	--	--	14
Batch #	Day	Sulfate, mg/L			Nitrate as NO ₃ , mg/L			Chloride, mg/L		
1	0.2	45	--	--	27	--	--	10	--	--
1	1.9	--	46	36	--	26	27	--	10	10
2	7.7	47	48	45	28	31	29	11	11	11
3	12.8	45	45	41	67.7	70.4	66.9	13.3	12.2	12.8
4	17.8	46	45	50	35.4	36.8	35.6	12	11.4	11.4
6	39	--	--	--	30.8	--	--	12	--	--
7	48.8	54	--	39	--	--	28.6	--	--	11
Batch #	Day	Iron, mg/L			Aluminum, mg/L			MCPP, µg/L		
1	0.2	< 0.1	--	--	--	--	--	< 100	--	--
1	1.9	--	< 0.1	< 0.1	--	--	< 0.05	--	< 100	< 100
2	7.7	0.24	< 0.1	< 0.1	< 0.05	< 0.05	< 0.05	130	< 100	< 100
3	12.8	0.0227	0.0502	< 0.01	0.0635	--	< 0.05	120	< 100	100
4	17.8	0.0576	< 0.01	--	0.063	--	< 0.05	--	--	--
4	20	--	--	--	--	--	--	810	860	760
6	39	--	--	--	< 0.05	--	--	--	--	--
7	48.8	--	--	--	--	--	< 0.05	--	--	--
Batch #	Day	MCPA, µg/L			* Compound present, but quantitation uncertain ** pH drifted up 0.5-1 pH units before stabilizing at reported value					
1	0.2	100	--	--						
1	1.9	--	75*	110						
2	7.7	120	< 100	< 100						
3	12.8	140	120	< 100						
4	17.8	--	--	--						
4	20	560	620	610						
6	39	--	--	--						
7	48.8	--	--	--						

3.3.1.2 Arsenic Removal--Alumina

Alumina was extremely effective at removing arsenic (Figure 5, Tables 7 and 8). Arsenic was not detected above 5 µg/L in the effluent until 36 days. (The only exception is at Day 4.2, when, for reasons that are unclear, arsenic was 13 µg/L.) By 48.8 days, the effluent concentration was still only about 60% of the influent.

At breakthrough ($> 5 \mu\text{g As/L}$), the arsenic capacity for alumina was 2,520 µg As/g sorbent. This is 67% greater than the breakthrough capacity in the preliminary column. Possibly, the down time during preparation of syn-GW permitted As to migrate into pores of the particles, thereby freeing up surface adsorption sites. This hypothesis is supported by the observation that when flow to the column was stopped and water allowed to stand in the column undisturbed for 8 days, arsenic concentration in the effluent dropped from about 253 µg/L before stopping flow to 83 µg/L after resuming flow, even though the influent concentration had not changed (data not shown).

The "test As capacity" is approximately 30% greater than the breakthrough capacity. This indicates that arsenic can be removed even once the effluent concentration was greater than 5 µg/L. Whether this test capacity can be reached under field conditions can only be determined by a field pilot test.

Alumina does not appear to affect the speciation of arsenic, nor is arsenic readily desorbed from alumina by clean water. As seen in Table 9, both As(III) and As(V) are present in effluent from the alumina column. As(III) accounts for 19% of the total As in effluent and 21% of the Total As in influent. When the influent arsenic concentration was $< 5 \text{ mg/L}$, no arsenic was detected in effluent from the alumina column. This is expected since alumina used for arsenic removal in water treatment is typically regenerated by flushing the alumina with 4% sodium hydroxide (Montgomery, J.M. *Water Treatment Principles and Design*, John Wiley & Sons: New York, 1985).

The effect of organic matter, which is present in site GW but not in synthetic GW, was not addressed in this study. Organic matter was not added to synthetic GW because it was not practical to identify the organic matter or to obtain representative material. The effect of organic matter on the arsenic capacity of alumina is unknown, but should be investigated in a field pilot test prior to full-scale implementation of this technology.

3.3.2 Effect of Sorbents on Water Quality

Neither FeZ nor alumina had a noticeable effect on alkalinity, chloride, nitrate, sulfate, MCPA or MCPP (Table 10). Aluminum was not detected in effluent from the alumina column, suggesting that alumina does not readily dissolve or abrade under simulated groundwater conditions. Similarly, iron was not detected in effluent from the FeZ column, except at 12.8 days. The reason is unclear, but indicates that iron is not easily removed from the zeolite.

The pH was not affected by the sorbents except for the first few bed volumes (Tables 7 and 9). In the case of FeZ, the pH of the effluent decreased from 6.96 to 4.43, while the pH of the alumina effluent rose to 8.23. It must be noted that measurement of pH was difficult in many cases because of drift. This was most common in samples with low Eh. In addition, although influent pH was adjusted to between 5.7 and 5.9 before a batch was placed on-line, subsequent pH measurements often yielded different values. The reason may be a combination of factors, including non-equilibrium in the influent when pH was first measured, as well as drift during measurement.

In general, Eh was also not affected by the sorbents (Tables 7 and 9). The only exception is the first few bed volumes of the FeZ column, in which Eh was appeared to be more positive (oxidizing) in the effluent than in the influent.

3.3.3 Observations Regarding Synthetic GW

Syn-GW rather than site GW was used in this study due to the difficulty of shipping and storing the necessary amount of water (~ 300 gallons) at PRIMA Environmental's facility. Although every effort was made to ensure consistency among batches of syn-GW, the influent data in Table 9 clearly show that preparation of a consistent synthetic groundwater was not straightforward. Despite this variability, PRIMA Environmental is confident that the syn-GW prepared was able to provide a reasonable understanding of how FeZ and alumina would behave under field conditions.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Batch and columns tests demonstrated that alumina is an excellent sorbent for both Arsenic(III) and Arsenic(V) in synthetic groundwater. The arsenic capacity in the final column tests was 2,520 $\mu\text{g As/g alumina}$. This may be an underestimate because capacity appears to be dependent upon residence time, which would be much greater in the field than in the laboratory. Neither the surfactant-modified zeolite nor the iron modified zeolite removed arsenic to $< 5 \mu\text{g/L}$. None of the sorbents removed MCPA or MCPP.

Based on the results of this study, PRIMA Environmental recommends that a field pilot test be conducted using alumina as the sorbent for arsenic. The primary goal of the pilot test should be to determine the capacity of the alumina in the presence of organic matter and at a flowrate representative of field conditions. PRIMA Environmental also recommends that the potential for desorption of arsenic from the alumina by clean groundwater be considered—either through a literature review or through additional bench-scale testing—prior to full-scale implementation of this technology.

APPENDIX B

Report of Findings

Arsenic Retardation Study

PRIMA Environmental

**Final
REPORT OF FINDINGS**

**Arsenic Retardation at OU3
NTC Orlando, FL**

N7457 – RFP 045 (DW)

Submitted to

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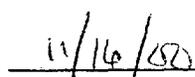
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November 16, 2000

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1.0 INTRODUCTION

Retardation factors of Arsenic(III) and Arsenic (V) by site soil from Operable Unit 3 at the former Naval Training Center in Orlando, Florida were determined by comparing the velocity of a tracer to the velocity of arsenic.

The retardation factor, RF, is defined as

$$RF = V_1/V_2 = 1 + (b/n)K_d \quad \text{Eqn. 1}$$

where

- V_1 = average linear velocity of a non-reactive tracer,
- V_2 = velocity at 50% of the initial concentration of a reactive tracer (arsenic)
- b = bulk density
- n = porosity, and
- K_d = adsorption coefficient = soil concentration / aqueous concentration

Because velocity is given in distance per unit time (e.g. ft/day) and because in a column test, the linear distance traveled by the tracer and arsenic is equal, the retardation factor may be defined as follows

$$RF = T_{As} / T_{tr} \quad \text{Eqn. 2}$$

where

- T_{As} = time required for As concentration in effluent to equal 50% of influent,
- T_{tr} = time required for tracer concentration in effluent to equal 50% of influent.

As(III) and As(V) typically travel at different rates because under most groundwater conditions, As(III) is neutral and As(V) is anionic. Since the retardation factor for Total As will depend upon the ratio of As(III) and As(V) and since this ratio may vary between water used in a laboratory study and *in situ* site groundwater, retardation factors for Total As, As(III) and As(V) were determined in this study.

2.0 MATERIALS AND METHODS

2.1 Materials

Site soil and site groundwater were received from TtNUS and stored at 5°C until needed.

2.2 Determination of Retardation Factors

2.2.1 Preliminary Column (Synthetic Groundwater)

A preliminary column was prepared using 60 g soil sandwiched between 10 g of clean sand. The top of the column was sealed with a stopper and the influent line connected via a hole in the stopper. (See Figure 1.) Effluent was pumped from the bottom of the column. Because the column was sealed, influent water dripped in at the same rate as the effluent was removed. The pump speed was set at about 3 mL/min, but when connected to the soil column, only about 0.3 mL/min could be extracted. Attempts to adjust the extraction rate by increasing the pump speed or tubing size were unsuccessful. Effluent was sampled periodically and analyzed for chloride, Total Arsenic, and/or As(III)/As(V). Selected column parameters are given in Table 1.

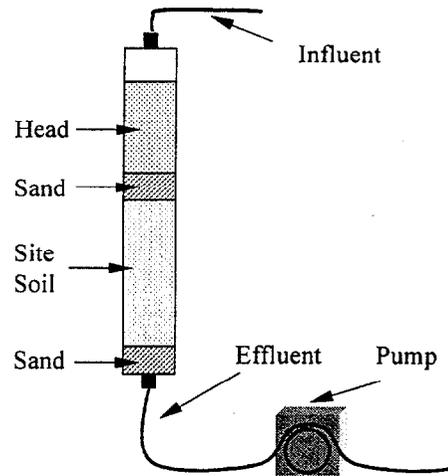


Figure 1. Schematic Column

2.2.2 Final Columns (Site Groundwater)

The final column tests were similar to the preliminary column tests, but used different sized columns and amounts of soil (see Table 1). Three columns were prepared. Deionized water was pumped through overnight to saturate the columns. Immediately before beginning the test, head was removed from the top of the column and the influent changed to site groundwater spiked with approximately 200 mg/L chloride (as the tracer). Samples were collected periodically and analyzed for chloride, Total As, and/or As(III)/As(V).

2.2.3 Data Analysis

The concentrations of chloride, total As, As(III) and As(V) were plotted versus time. The data were interpolated to determine at what time the concentration in the effluent reached 50% of the influent concentration. The retardation factor was calculated using Eqn. 2. The adsorption coefficient was calculated by rearranging Eqn 1 as follows:

$$K_d = (RF-1)/(b/n) \quad \text{Eqn. 3}$$

Table 1. Column Parameters.

	Preliminary (Synthetic GW)	Final (Site GW)
Column size	1 in. diam x 2 in.	1.5 in. diam. x 3 in.
Direction of Flow	downgradient	downgradient
Mass of soil	60 g	150 g
Bulk Density (wet)	2 g/cm ³	1.9 g/cm ³
Porosity	~ 25%	~ 25%
Flowrate	~0.25 mL/min	0.2-0.4 mL/min
Head height	1 in.	4 in.

2.3 Analytical Procedures

2.3.1 Chloride

Chloride was measured using an ion selective electrode.

2.3.2 Total Arsenic, As(III), As(V)

Total As was measured via hydride generation atomic absorption spectrophotometry (HGAA). As(III) was also measured via HGAA, except that the pre-reduction step was skipped. As(V) is defined as the difference between Total As and As(III).

2.3.3 Bulk Density

Bulk density was determined by dividing the mass of site soil in the columns by the volume of the packed soil.

2.3.4 Porosity

Field moist soil was sent to Sierra Testing Laboratories (El Dorado Hills, CA) for analysis. Bulk density information was provided so that porosity could be measured at the appropriate density.

3.0 RESULTS AND DISCUSSION

The results of the four columns are depicted in Figures 2-5 and in Table 2. Tabulated concentration data are located in the Appendix. The values of RF and K_d for the preliminary column using synthetic groundwater are artificially low because the concentration of tracer in the first sample collected (41 mg/L) was greater than the 50% breakthrough concentration (37 mg/L). (The first sample time—60 minutes—was used to calculate RF and K_d .) RF and K_d for As(V) could not be obtained because the final sample was lost.

The average RF for the three columns using site groundwater was 21 ± 9 for Total As, 21 ± 8 for As(V) and 14 ± 3 for As(III). As expected, RF for As(III) was less than RF for As(V). However, RF for Total As and As(V) were essentially the same. This is because As(V) accounted for 77-79% of Total As in both the synthetic and site groundwaters. Previous testing by TTNUS suggested that As(V) accounted for only about 25% of Total As in site groundwater. Unless this discrepancy can be resolved, PRIMA Environmental recommends using RF for As(III) in any As transport models since this would give the most conservative results.

The data for the preliminary column and final column are similar, despite some uncertainty in the preliminary column results. This suggests that the synthetic groundwater used in this study and in the evaluation of adsorbents behaves similarly to site groundwater.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The average retardation factor for As by site soils was 21 ± 9 for Total As, 21 ± 8 for As(V) and 14 ± 3 for As(III). The data were similar using site groundwater and synthetic groundwater, suggesting that the use of synthetic groundwater in studies to evaluate sorbents for As removal at OU3 will provide reliable results.

Because As(III) and As(V) have different RF's and because the ratio of As(III) to As(V) in site groundwater is uncertain, PRIMA Environmental recommends that the RF for As(III) rather than Total As or As(V) be used in any As transport models or arguments since this would produce conservative results.

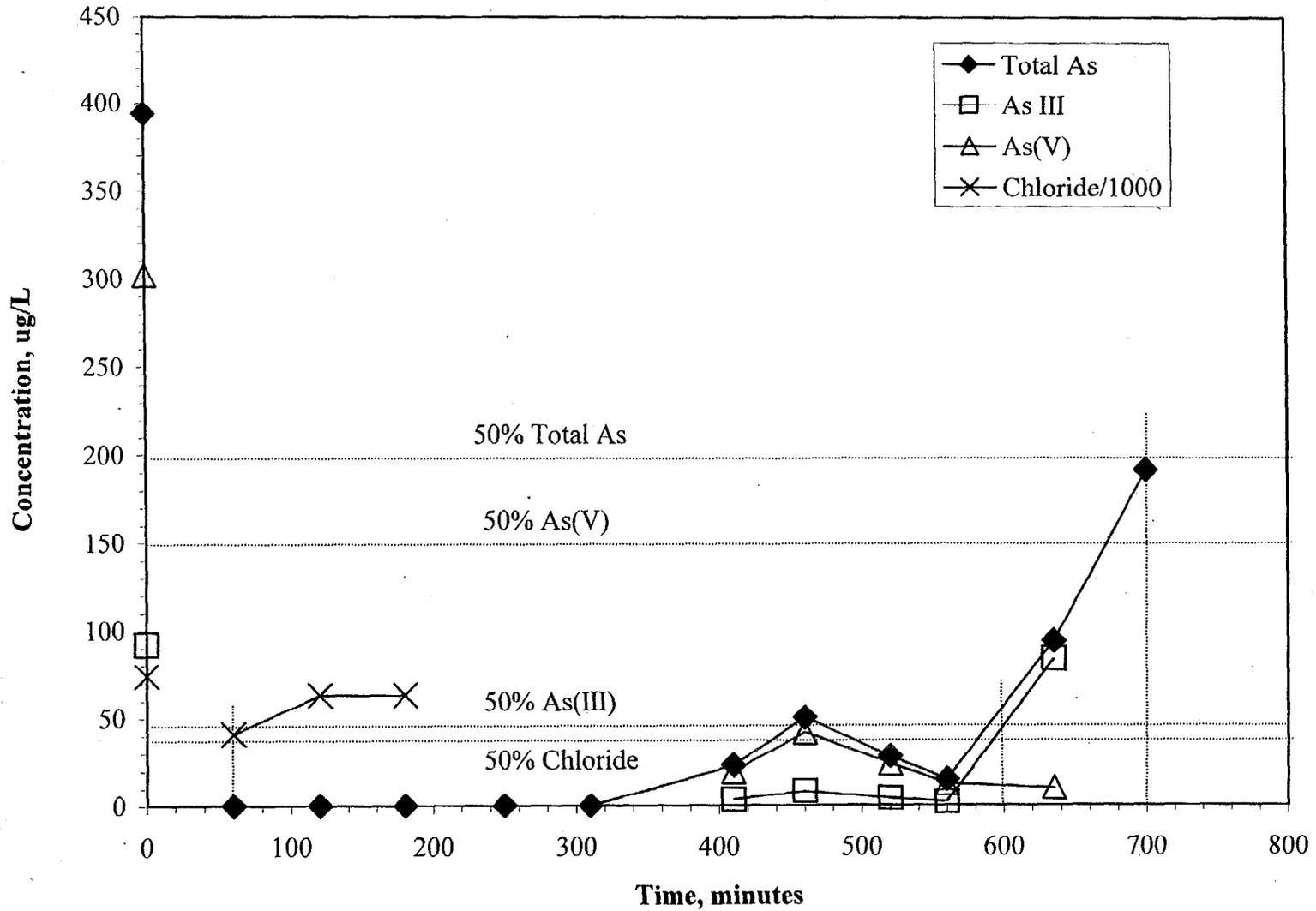
Table 2. Arsenic Retardation Results

Test	Time for 50% Breakthrough*, minutes				Retardation Factor, RF			Adsorption Coefficient, K_d cm ³ /g		
	Tracer, Cl	Total As	As(III)	As(V)	Total As	As(III)	As(V)	Total As	As(III)	As(V)
Prelim (Syn GW)	60	700	600		12	10	--	1.4	1.1	--
Final 1 (Site GW)	120	3,650	1,800	3,650	30	15	30	3.9	1.8	3.9
Final 2 (Site GW)	330	4,300	3,700	4,350	13	11	13	1.6	1.3	1.6
Final 3 (Site GW)	220	4,100	3,750	4,200	19	17	19	2.3	2.1	2.4
Average (Final 1-3)					21 (9)**	14 (3)	21 (8)	3 (1)	1.8 (0.4)	3 (1)

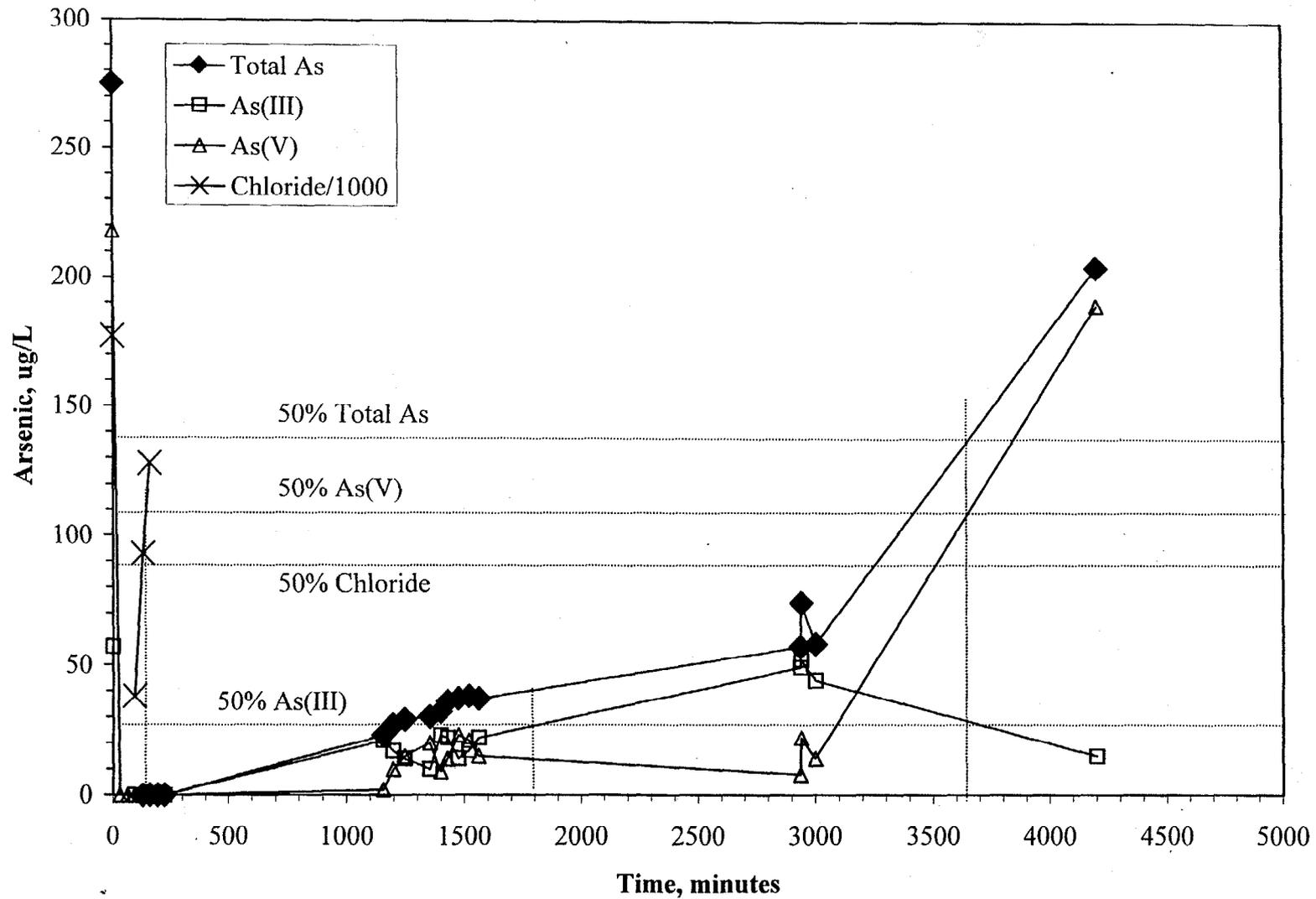
* Values interpolated from data in Figures 2-5

** Numbers in () are standard deviations

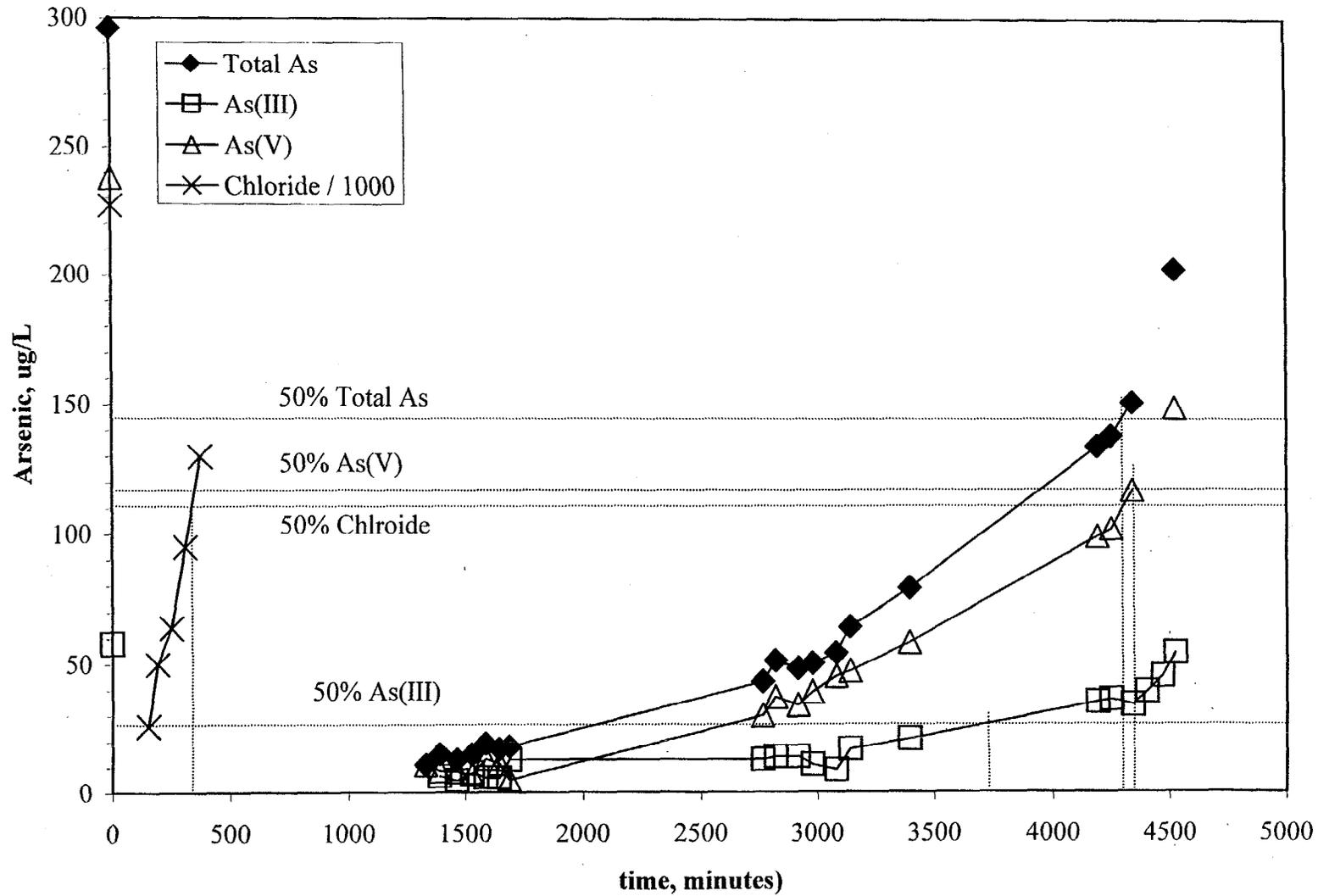
**Figure 2. As Retardation
Synthetic Groundwater Preliminary Column**



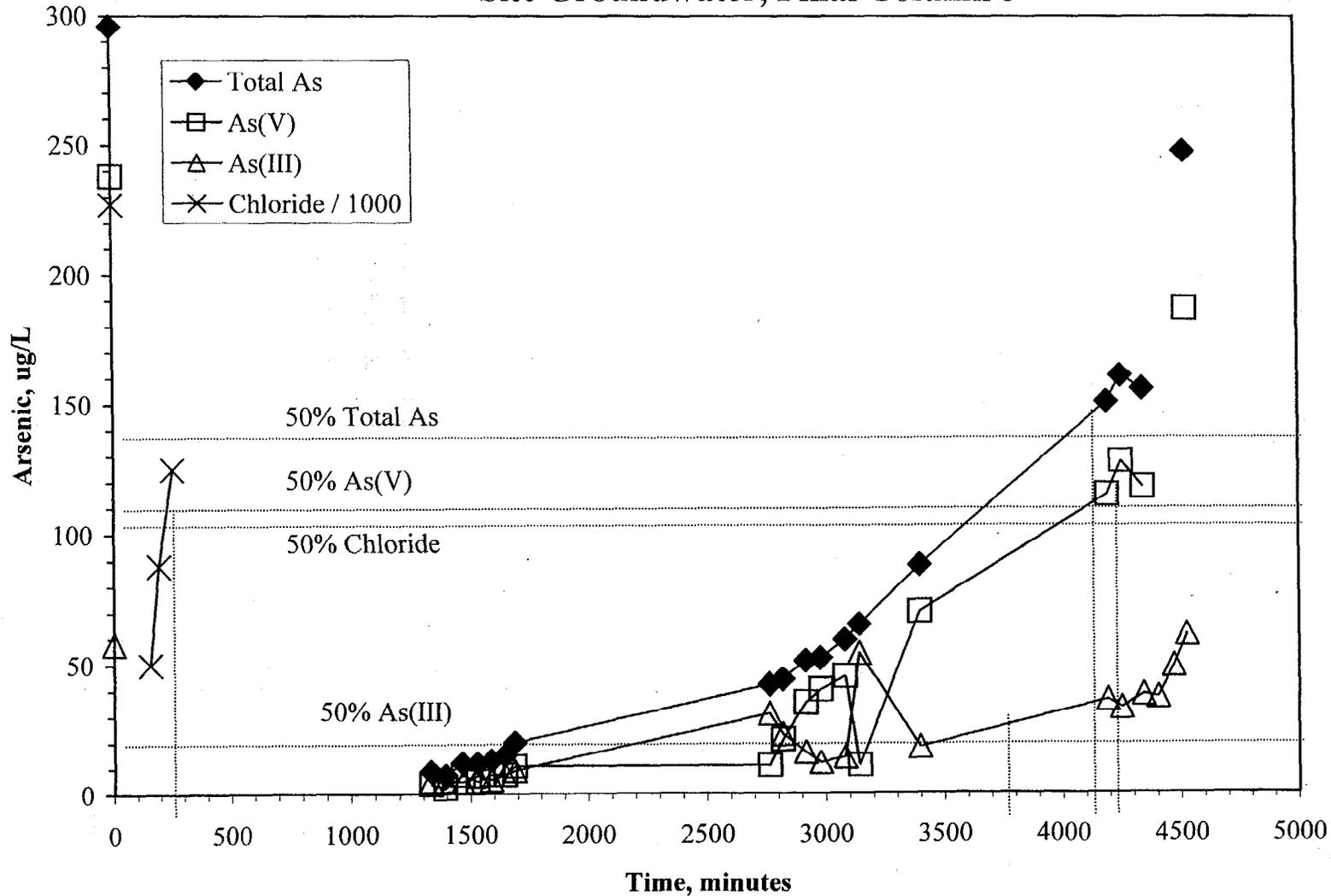
**Figure 3. Arsenic Retardation
Site Groundwater, Final Column 1**



**Figure 4. Arsenic Retardation
Site Groundwater, Final Column 2**



**Figure 5. Arsenic Retardation
Site Groundwater, Final Column 3**



APPENDIX
(Tabulated Data)

Table A1. Preliminary Column, Synthetic Groundwater

Time, min.	Concentration, µg/L			
	Total As	As(III)	As(V)	Chloride
0	394	92	302	74,000
60	< 5	--	--	41,000
120	< 5	--	--	63,000
180	< 5	--	--	63,000
250	< 5	--	--	--
310	< 5	--	--	--
410	23	3.5	19.5	--
460	50	8.3	41.7	--
520	28	4.2	23.8	--
560	15	2.2	12.8	--
635	93	83	10	--
700	191	--	--	--

Table A2. Final Column 1, Site Groundwater

Time, min.	Concentration, µg/L			
	Total As	As(III)	As(V)	Chloride
0	275	57	218	177,000
30			0	
63			0	
93		< 5	< 5	38,000
129	< 5	< 5	< 5	93,000
159	< 5	< 5	< 5	128,000
193	< 5	< 5	< 5	
223	< 5	< 5	< 5	
1,155	23	21	2	
1,196	27	17	10	
1,246	29	14	15	
1,352	30	10	20	
1,398	32	23	9	
1,428	36	22	14	
1,474	37	14	23	
1,519	38	17	21	
1,561	37	22	15	
2,936	57	49	8	
2,940	74	52	22	
3,000	58	44	14	
4,200	205	15	190	

Table A3. Final Column 2, Site Groundwater

Time, min.	Concentration, µg/L			
	Total As	As(III)	As(V)	Chloride
0	296	58	238	227,000
60	--	--	--	--
92	--	--	--	--
122	--	--	--	--
154	--	--	--	26,000
193	--	--	--	50,000
253	--	--	--	64,000
313	--	--	--	95,000
378	--	--	--	130,000
439	--	--	--	--
484	--	--	--	--
1,331	11		11	--
1,391	15	6.5	8.5	--
1,465	13	4.8	8.2	--
1,529	15	7.9	7.1	--
1,587	19	5.8	13.2	--
1,645	17	5.7	11.3	--
1,687	18	13	5	--
2,763	43	13	30	--
2,819	51	14	37	--
2,916	48	14	34	--
2,978	50	11	39	--
3,080	54	8.9	45.1	--
3,141	64	17	47	--
3,396	79	21	58	--
4,191	134	35	99	--
4,250	138	36	102	--
4,341	151	34	117	--
4,402	--	39	--	--
4,469	--	45	--	--
4,524	203	54	149	--

Table A4. Final Column 3, Site Groundwater

Time, min.	Concentration, µg/L			
	Total As	As(III)	As(V)	Chloride
0	296	58	238	227,000
60	--	--	--	--
92	--	--	--	--
122	--	--	--	--
154	--	--	--	50,000
193	--	--	--	88,000
253	--	--	--	125,000
313	--	--	--	--
378	--	--	--	--
439	--	--	--	--
484	--	--	--	--
1,331	8.8	5.1	3.7	--
1,391	7.3	5.2	2.1	--
1,465	12	4.7	7.3	--
1,529	12	7.1	4.9	--
1,587	13	5.5	7.5	--
1,645	15	7.5	7.5	--
1,687	20	9.1	10.9	--
2,763	42	31	11	--
2,819	44	23	21	--
2,916	51	16	35	--
2,978	52	12	40	--
3,080	59	14	45	--
3,141	65	54	11	--
3,396	88	18	70	--
4,191	151	36	115	--
4,250	161	33	128	--
4,341	156	38	118	--
4,402	--	37	--	--
4,469	--	49	--	--
4,524	248	61	187	--

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