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# Arsenic Pilot Plant Operation and Results- Weatherford, Oklahoma

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**Abstract**

Narasimhan Consulting Services, Inc. (NCS), under a contract with the Sandia National Laboratories (SNL), designed and operated pilot scale evaluations of the adsorption and coagulation/filtration treatment technologies aimed at meeting the recently revised arsenic maximum contaminant level (MCL) for drinking water. The standard of 10 μg/L (10 ppb) is effective as of January 2006. The pilot demonstration is a project of the Arsenic Water Technology Partnership program, a partnership between the American Water Works Association Research Foundation (AwwaRF), SNL and WERC (A Consortium for Environmental Education and Technology Development). The pilot evaluation was conducted at Well #30 of the City of Weatherford, OK, which supplies drinking water to a population of more than 10,400. Well water contained arsenic in the range of 16 to 29 ppb during the study. Four commercially available adsorption media were evaluated side by side for a period of three months. Both adsorption and coagulation/filtration effectively reduced arsenic from Well #30. A preliminary economic analysis indicated that adsorption using an iron oxide media was more cost effective than the coagulation/ filtration technology.

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# 1.0 INTRODUCTION

## 1.1 Background

On January 23, 2001, the U.S. Environmental Protection Agency (USEPA) reduced the drinking water maximum contaminant level (MCL) for arsenic from 50 parts per billion (ppb) to 10 ppb. The Federal Arsenic Rule requires all community water systems (CWS) and non-transient non-community water systems (NTNCWS) to comply with the new MCL within five years of promulgation of the Federal Rule (January 23, 2001). Recent rule making efforts allow water systems to apply for three to nine year extensions to the compliance date, based on the influent arsenic concentration and state discretion. This regulation represents one of the first rules under the 1996 Safe Drinking Water Act Amendments that will significantly impact small water supply systems. Given the lack of funding currently available and the high unit costs of smaller arsenic treatment plants, many smaller water supply systems have applied for extensions to construct arsenic treatment systems.

The major issues associated with small water supply systems adopting technologies for control of arsenic include lack of funds and other resources. The cost per customer of centrally treating water can be significant as the customer base is limited. In some cases, "non-treatment" options such as blending with water not contaminated with arsenic, modifying water sources (e.g., changing a well's screen interval), consolidating water sources, replacing water sources with new sources, or becoming consecutive to another water system, are potential methods to meet the new MCL. Where applicable, non-treatment options tend to be more economical and easier to implement and manage than the treatment options described below (NCS, 2004 and 2005). However, for many small water systems non-treatment options may not be feasible, due to a lack of alternative water sources in the vicinity, and treatment for arsenic is necessary.

In 2003, an Arsenic Water Technology Partnership consisting of the Awwa Research Foundation (AwwaRF), Sandia National Laboratories (SNL) and WERC (a Consortium for Environmental Education and Technology Development) was created to evaluate cost effective arsenic removal technologies for small water supply systems. AwwaRF is leading the bench-scale evaluation of innovative arsenic removal technologies, while SNL is leading the pilot scale evaluations to demonstrate application potential of the promising technologies, and WERC will evaluate the economic feasibility of the technologies investigated and conduct technology transfer activities. In March 2005, SNL retained Narasimhan Consulting Services, Inc. (NCS) to identify potential locations for pilot scale evaluation of applicable arsenic removal technologies in the states of Nebraska, Oklahoma, and Utah. In a collaborative effort, the City of Weatherford, OK (Weatherford) was selected for the pilot scale investigations for the adsorption and coagulation/filtration technologies for arsenic control. In July 2006, SNL selected NCS to design and conduct pilot scale investigations at Weatherford.

Weatherford is located 60 miles from Oklahoma City and supplies potable water service to a population of approximately 10,400. It obtains its raw water from approximately 30 wells. Weatherford supplies water to its customers via two entry points to the distribution system (EPDS). This mode of operation allows blending to occur prior to the EPDS to reduce the contaminant concentrations from individual wells. The estimated arsenic level at the two EPDS ranges from 11

to 29 ppb.  Besides arsenic, the groundwater has moderate levels of nitrate (5 mg/L) and pH (7.5).  Well #30, with a historical arsenic concentration of around 40 µg/L, was selected for the pilot.  Other water constituents which adversely impact arsenic removal included silica (24 mg/L), vanadium (36 µg/L), and iron (0.5 mg/L).  The well water is moderately alkaline, has high conductivity and a pH of 7.0.  A summary of water quality observed during the pilot study is included in Chapter 2.

## 1.2   Arsenic Removal Technologies

Arsenic can be present in the dissolved state as either as As(III) in anaerobic/anoxic (reduced) systems or as As(V) in aerobic (oxidized) systems.  In typical drinking water pH ranges of 6 to 9, the predominant arsenite species is neutral in charge ($H_3AsO_3$), while arsenate species are present as $H_2AsO_4^-$ and $HAsO_4^{-2}$.  Although both organic and inorganic forms of arsenic have been detected, organic species (methylated arsenic) are generally not as common in drinking water.  In oxygenated waters, $As^{+5}$ is dominant, existing in anionic forms of either $H_2AsO_4^-$ or $HAsO_4^{-2}$ over the pH range typically encountered in water treatment.  Due to the differences in ionic charge of the arsenate and arsenite in the pH 6-9 range, the neutrally charged arsenite compound ($H_3AsO_3$) is difficult to remove when compared to the divalent ($HAsO_4^{-2}$) and monovalent arsenate anions ($H_2AsO_4^-$).  The negative charges on the arsenate compounds make arsenic easy to remove by adsorptive, co-precipitative, and chemical exchange processes.  Therefore, arsenite is oxidized to arsenate before its removal.

Arsenic removal in drinking water systems is affected by other water quality parameters such as silica, phosphorus, pH, fluoride, sulfate, chloride, vanadium, total dissolved solids (TDS), iron, and manganese.  These parameters affect treatment efficiency by interfering with arsenic removal during the adsorption processes.  Silica levels greater than 20 mg/L and fluoride levels greater than 2 mg/L affect adsorption process using iron-based activated alumina (Fe-AA), and pH values greater than 8.0 and phosphorus levels greater than 0.2 mg/L affect adsorption using granular iron media.  Similarly, sulfate levels greater than 50 mg/L affect ion exchange (IX) treatment processes.

There are a number of technologies available to remove arsenic to meet the 10 ppb MCL. These include IX, alumina and iron media adsorbents (used on a throw away basis), nanofiltration/reverse osmosis, coagulation/filtration, lime softening, and electrodialysis.  In an ideal environment, an arsenic treatment facility (ATF) would be simple to operate, without the use chemicals, and would minimize waste quantities and overall operating costs.  The economics, complexity of operation and/or water quality issues limiting these technologies make them difficult and in some cases nearly impossible for small and rural systems to implement.  Ion exchange has the disadvantage of interference from competing ions (e.g., sulfate) and brine disposal issues.  Reverse osmosis systems have very high capital, operating and maintenance costs, and spent brine disposal issues.  Lime softening systems are complex with significant waste handling issues.  Electrodialysis requires significant process control and a high level of expertise and generates a large volume of reject water.  Coagulation/filtration (C/F) is complex with residuals handling issues.  The adsorption media systems, while effective, require periodic media replacement, which creates a solid waste.  For a small water system, adsorption treatment systems are the easiest to operate and maintain, and therefore provide advantages over other treatment technologies.  New adsorption media, some regenerable, with better adsorption characteristics are becoming commercially available on a regular basis.

## 1.3    Project Objectives

The objectives of the project were to independently evaluate the adsorption and coagulation/filtration technologies for control of arsenic at the selected Weatherford well.  The specific objectives of the project are outlined below:

1.  Evaluate four adsorption media to determine the
    a.  media bed lives, and
    b.  impact of the other water quality constituents on arsenic removal.

2.  Evaluate coagulation/filtration process to determine
    a.  coagulant doses, and
    b.  filter run times.

3.  Conduct preliminary economic analyses of technologies that were pilot tested.

Based on discussions held with the SNL project manager, the selected adsorption media included ADSORBSIA$^{TM}$ GTO$^{TM}$ manufactured by DOW Chemical, npRio by SolmeteX, Kemira CFH0818 by Kemira Water Solutions and E33 by Adedge.  Details of the media properties and pilot column specifications are described in Chapter 2.   For the C/F study, ferric chloride was used as the coagulant and anthracite media was used for filtration.  Details of the C/F pilot unit specifications are described in Chapter 2.

## 2.0   RESEARCH METHODS

### 2.1   Background

For the project, four adsorption media (ADSORBSIA$^{TM}$GTO$^{TM}$, npRio, Kemira CFH0818 and E33) and coagulation/filtration were evaluated for arsenic removal from groundwater at Weatherford, OK.


Detailed experimental protocols including design of adsorption vessels, operational flow rates, sampling, analytical and quality assurance/quality control protocols, roles and responsibilities between research team and participating utility were developed and followed throughout the study. The protocols are described in this chapter.

### 2.2   Description of Pilot Units

The pilot study was conducted at Well #30 which is capable of producing 150 gallons per minute (gpm) of water.  A side stream provided the source water for the pilot units.  Prior to beginning the pilot study,  a technical memorandum describing in detail the design of the pilot units, housing of the pilot units, the site layout, analytical methods and disposal of treated water was prepared and submitted to the Oklahoma Department of Environmental Quality (DEQ) for their review and approval.   The pilot units were assembled after an approval by the OK DEQ for the submitted information.

Figures 2.1, 2.2 and 2.3 display the site layout, equipment layout and a schematic for the pilot units. Electric supply (120 V, 20 amps) was installed by the Weatherford Department of Public Works. As shown in Figure 2.1, water for the pilot units was obtained from a 1½ inch sampling pipe. Weatherford installed a coupling and a valve so that water could be withdrawn for the pilot study. An isolation valve and a backflow preventer (Figure 2.2) was installed to avoid any cross contamination of well water supplied to Weatherford consumers.  A booster pump was also included to increase the pressure to the pilot units.  The pilot units utilized PVC Schedule 40 pipe and fittings for interconnections.   Treated water and spent backwash water from the adsorption and coagulation/filtration pilot units were discharged to sanitary sewer via a manhole located on the east side of the Well #30 fence (Figure 2.2).   To provide an air gap, a 2 inch hose with an isolation valve was utilized for the disposal of water into the sanitary sewer.  The pilot units were installed on a leased, 8' by 15' secured container (www.mobilemini.com), which was located outside the fence. The mobilemini was locked at all times while unattended.
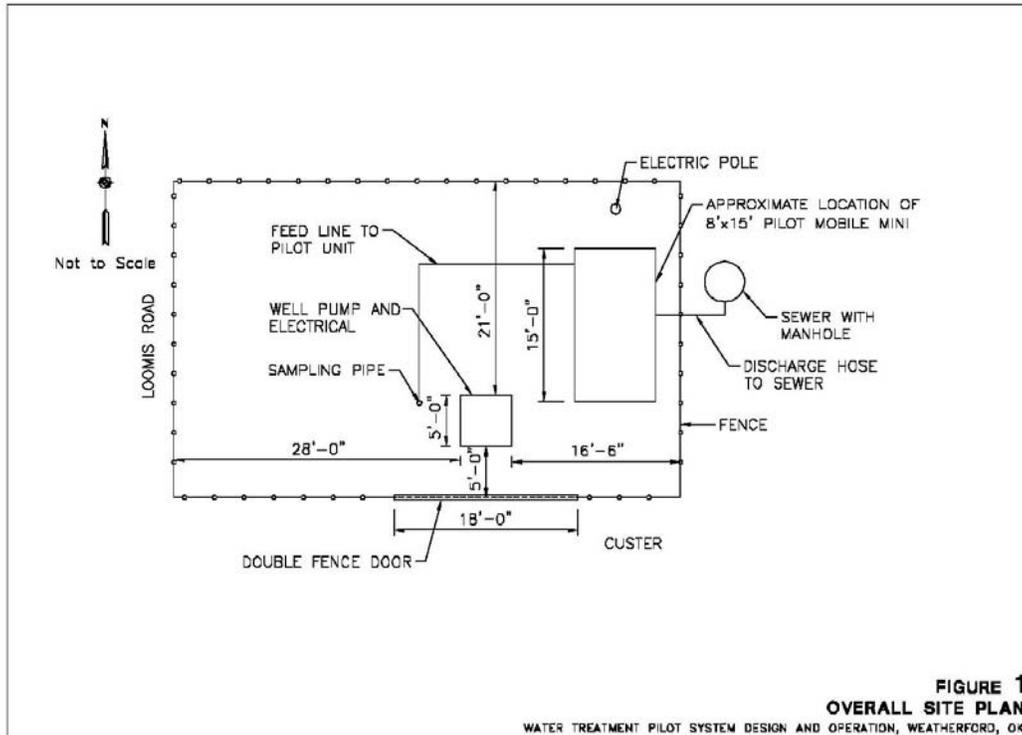
**Figure 2.1: Overall Site Plan**
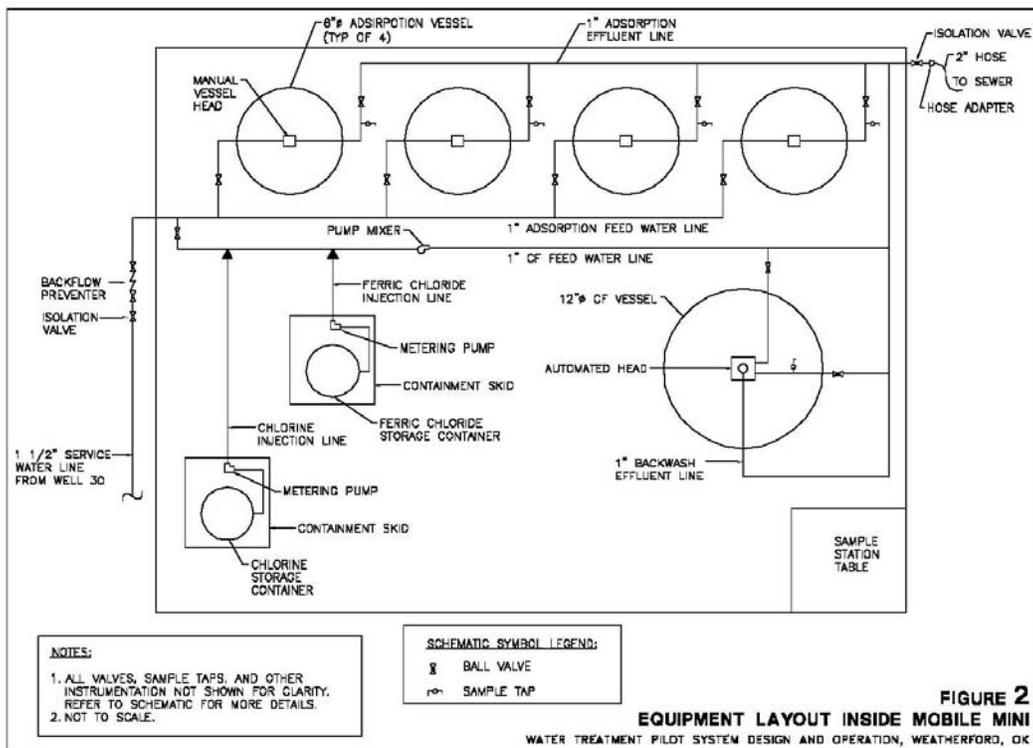


**Figure 2.2: Equipment Layout Inside Mobil-Mini**

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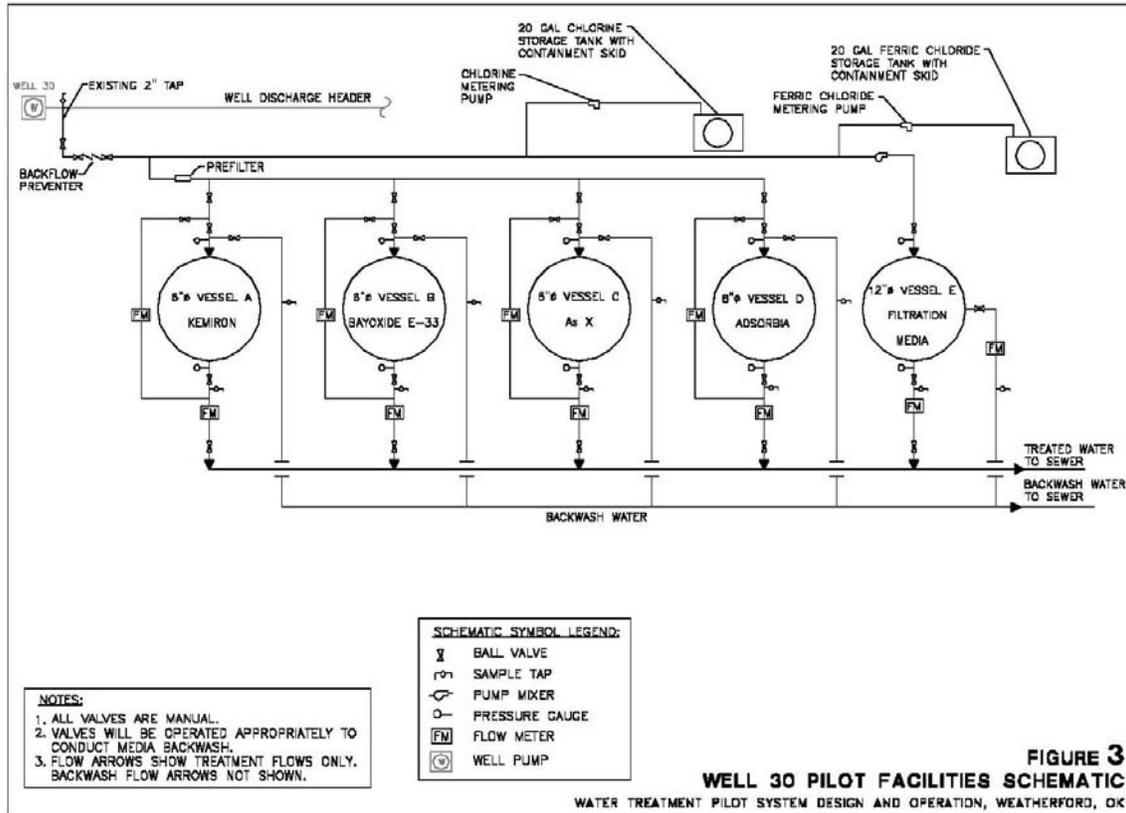
**Figure 2.3 Well #30 Pilot Facilities Schematic**

NCS was responsible for construction, installation and start-up of the pilot units and was responsible for overall management and implementation responsibilities. NCS collected the samples as per the SNL testing schedule and shipped them to either SNL Water Quality Laboratory (WQL) in Albuquerque, NM or USEPA certified Legend Technical Services (LTS) in Phoenix, AZ. After the adsorption pilot integrity testing period, NCS collected samples twice per week. Weatherford staff monitored the pilot units for the remaining days to ensure proper operation, and reported any malfunction of the pilot units to NCS.

## 2.2.1 Adsorption Media

Relevant media properties, as supplied by their manufacturers, are summarized in Table 2.1.

**Table 2.1 Properties of Adsorption Media**

| | ADSORBSIA$^{TM}$GTO$^{TM}$ | npRio | E33 | Kemira CFH0818 |
|---|---|---|---|---|
| **Manufacturer** | DOW | SolmeteX | Adedge | Kemira |
| **Media description** | granular titanium oxide | iron oxide nano-particle resin | granular iron oxide | granular iron oxyhydroxide |
| **Media size, mesh** | 10 x 60 | 16 x 50 | 10 x 35 | 10 x 18 |
| **Surface area, m$^2$/g** | 200 -300 | Not provided | 140 - 150 | 120 |
| **Operating temperature, $^o$C** | NA | 1 - 77 | NA | NA |
| **Maximum Operating pressure, psi** | NA | 120 | NA | NA |
| **Regenerable** | No | Yes | No | No |

NA - Not available

All selected media are certified by the NSF International for use in potable water. ADSORBSIA$^{TM}$GTO$^{TM}$ is a granular titanium oxide media. npRio is a polymeric hybrid media impregnated with iron oxide. E33 is a granular iron oxide media, while Kemira CFH0818 is an iron oxyhydroxide media. Except for the E33 media, the other three media have had a limited full-scale application. However, they have been tested in pilot scale studies and more full-scale treatment facilities are anticipated. One major advantage of using adsorption technology is that any media may be used in the vessel without requiring additional major capital investment.

## 2.2.2 Adsorption Pilot Units

The adsorption pilot units consisted of four, six-inch diameter fiber reinforced plastic (FRP) columns (Figure 2.4). The adsorption media empty bed contact time (EBCT) was 2.5 minutes, which was chosen based on NCS and SNL experiences with other similar pilot studies (Aragon, M., et. al., 2007). Table 2.2 summarizes the design of the adsorption pilot units. A pre-filter (25 μm pore size) was installed on the influent pipe to the adsorption columns to avoid accumulation of any suspended solids within the adsorption media.



**Figure 2.4: Adsorption Columns and Piping**

The adsorption units were operated in downflow mode.  An initial backwash (during the time of installation) was performed for all media, and the spent filter backwash water was disposed to the sanitary sewer.  The backwash rate ranged from 12  gallons per minute per square foot (gpm/ft$^2$) for E33, npRio, ADSORBSIA$^{TM}$GTO$^{TM}$ media to 18 gpm/ft$^2$ for the  Kemira CFH0818 media.  The duration for backwash ranged from 25 minutes for npRio and ADSORBSIA$^{TM}$GTO$^{TM}$ to 35 minutes for Kemira CFH0818 media.  The spent backwash water from ADSORBSIA$^{TM}$GTO$^{TM}$ was turbid and white in color. The spent backwash water from Kemira CFH0818 was turbid and brown in color.  No subsequent backwash was required during the pilot study.  The pilot columns were operated continuously with the exception of a six day period (September 21 to 26, 2006) when the electric motor for the Well #30 pump required replacement.

**Table 2.2 Design of Adsorption Pilot Columns**

| Parameter | Unit | Column 1 | Column 2 | Column 3 | Column 4 |
|---|---|---|---|---|---|
| Media Type | -- | E-33 | npRio | ADSORBSIA$^{TM}$ GTO$^{TM}$ | Kemira CFH0818 |
| Vessel Diameter | inches | 6 | 6 | 6 | 6 |
| EBCT | minutes | 2.5 | 2.5 | 2.5 | 2.5 |
| Loading Rate | gpm/ft$^2$ | 6 | 6 | 6 | 6 |
| Flow Rate | gpm | 1.2 | 1.2 | 1.2 | 1.2 |
| Media Volume Required | gallons | 2.9 | 2.9 | 2.9 | 2.9 |
| | liters | 11.1 | 11.1 | 11.1 | 11.1 |
| Media Depth | ft | 2.0 | 2.0 | 2.0 | 2.0 |
| Gravel Depth | ft | 0.3 | 0.3 | 0.3 | 0.3 |
| Total Depth of Media | ft | 2.3 | 2.3 | 2.3 | 2.3 |
| Vessel Height | ft | 2.9 | 2.9 | 2.9 | 2.9 |
| Freeboard for Backwash | ft | 0.6 | 0.6 | 0.6 | 0.6 |
| % Freeboard | % | 30 | 30 | 30 | 30 |
| Backwash Rate | gpm/ft$^2$ | 12 | 12 | 12 | 15 |
| Backwash Flow | gpm | 2.4 | 2.4 | 2.4 | 2.9 |

## 2.2.3  Chlorination

Prior to starting the pilot study, the majority of arsenic in the Well #30 water was expected to be in the oxidized state (arsenate).  However, source water arsenic data indicated that approximately 2 to 4 µg/L was in the reduced form (arsenite), and therefore chlorination was initiated on October 14th 2006 to oxidize arsenite to arsenate.  The chlorination system consisted of feeding 5% sodium hypochlorite at an approximate dose of 1 mg/L.

## 2.2.4  Coagulation/Filtration (C/F) Pilot Unit

For the coagulation/filtration pilot unit, a one-foot diameter, forty four inch tall translucent fiberglass reinforced plastic (FRP) column was utilized as the pressure filter (Figure 2.5).  Anthracite was used as the filtration media.  Media was slurried and poured into the  column.  The media was backwashed at the beginning of the pilot study to remove any fine particulate matter before it was put into service.  The filter was also backwashed after each pilot run.  Altogether, eight pilot runs were conducted.   Initially, three pilot runs were conducted to evaluate applicability of coagulation/filtration technology for arsenic removal (Phase 1).  The next five pilot runs were conducted to optimize the ferric chloride dose and verify the pilot results (Phase 2).  The design for the pilot filters, including media type and depth, flow rate and loading rate are summarized in Table 2.3.

**Figure 2.5: Coagulation Filter and Chemical Feed Pumps**

**Table 2.3 Design of Coagulation/Filtration Pilot Unit**

| Parameter | Units | Value |
|---|---|---|
| Media Type | -- | Anthracite |
| Flow | gpm | 6.3 |
| Diameter | inches | 12 |
| Cross-sectional Area | $ft^2$ | 0.785 |
| Hydraulic Loading Rate | $gpm/ft^2$ | 8.0 |
| Volume of media | gallons | 15 |
| Media Density | $lbs/ft^3$ | 114 |
| Media Depth | inches | 30 |

Other equipment included the backwash tank, chemical containment skid, chemical feed tanks and metering pumps. Ferric chloride was the coagulant. Backwash of the filter was performed manually at start of each pilot run.

The primary performance indicators for a coagulation/filtration process are arsenic and iron concentrations in the effluent and head loss development across the filter. The following criteria were used for termination of each pilot run:

1. Filter effluent arsenic levels exceeding 10 ppb,
2. Filter effluent iron levels exceeding 0.2 mg/L,
3. Head loss through the filter bed exceeding 8 psi, or
4. Filter run time of approximately 16 hours.

Field test kits were used to monitor arsenic (using Accustrip Kit) and iron (using HACH DR 820) in the influent and treated water samples for onsite pilot run evaluation. Spent filter backwash water (approximately 100 gallons) from each coagulation/filtration pilot run was disposed of to the sanitary sewer.

## 2.3   Sampling Frequencies and Analytical Methods

The influent and effluent samples collected from the adsorption pilot columns and the coagulation/filtration pilot units were analyzed for field and laboratory parameters.  The analytical methods and sampling frequency, as developed by SNL, were followed during the pilot investigations (Siegel, M. et al 2006).  For the adsorption pilot testing, sampling frequency varied for the first two weeks (Integrity Verification Period) from the rest of the testing period (Capacity Verification Period).  Tables 2.4 and 2.5 summarize the field and laboratory sampling frequency and analytical methods for the Integrity Verification Period.  Tables 2.6 and 2.7 summarize the field and laboratory sampling frequency and analytical methods for the Capacity Verification Period.  SNL supplied the Chain of Custody forms for all laboratory analyses which were included with the samples.

**Table 2.4 Integrity Verification Field Parameters**

| Parameter | Sampling Frequency | Sampling Location | Instruments |
|---|---|---|---|
| Conductivity | Daily | Influent and Effluent | Orion conductivity Probe |
| Temperature | Daily | Influent and Effluent | Orion temperature probe |
| pH | Daily | Influent and Effluent | Orion pH meter |
| Arsenic | Daily | Influent and Effluent | Accustrip kit |
| Iron | Daily | Influent and Effluent | HACH DR820 kit |
| Turbidity | Daily | Influent and Effluent | HACH kit |

**Table 2.5 Integrity Verification Laboratory Parameters**

| Parameter | Sampling Frequency | Sampling Location | Analytical Method[1] |
|---|---|---|---|
| Total Arsenic | Daily | Influent and Effluent | EPA 200.8 |
| Iron | Daily | Influent and Effluent | HACH 8008 AA Spectroscopy – WQL |
| Calcium | Daily | Influent and Effluent | AA Spectroscopy - WQL |
| Alkalinity | Daily | Influent and Effluent | HACH 8203 – WQL |
| Magnesium | Daily | Influent and Effluent | AA Spectroscopy - WQL |
| Nitrate | Weekly | Influent and Effluent | EPA 300.0 |
| Manganese | Daily | Influent and Effluent | EPA200.8 |
| Silica | Daily | Influent and Effluent | HACH 8185 – WQL |
| Vanadium | Daily | Influent and Effluent | EPA 200.8 |
| Chloride | Daily | Influent and Effluent | EPA 300.0 |
| Nitrate | Daily | Influent and Effluent | EPA 300.0 |
| Fluoride | Daily | Influent and Effluent | EPA 300.0 |
| Sulfate | Weekly | Influent and Effluent | EPA 300.0 |

[1.] "Methods for the Determination of Metals in Environmental Samples-Supplement I", PA/600/R-94/111, May 1994. Available at NTIS, PB95-125472 and  "Methods for the Determination of Inorganic Substances in Environmental Samples," EPA/600/R-93/100, August 1993. Available at NTIS, PB94-120821.

**Table 2.6 Capacity Verification Field Parameters**

| Parameter | Sampling Frequency | Sampling Location | Instruments |
|---|---|---|---|
| Conductivity | Twice/week | Influent and Effluent | Orion Conductivity Probe |
| Temperature | Twice/week | Influent and Effluent | Orion temperature probe |
| pH | Twice/week | Influent and Effluent | Orion pH meter |
| Free Chlorine | Twice/week | Effluent | HACH Kit |
| Turbidity | Twice/week | Influent and Effluent | HACH Kit |

**Table 2.7 Capacity Verification Laboratory Parameters**

| Parameter | Sampling Frequency | Sampling Location | Analytical Method[1] |
|---|---|---|---|
| Total Arsenic | Weekly | Influent and Effluent | EPA 200.8 |
| Speciated Arsenic | Twice during the study | Influent and Effluent | EPA 200.8 |
| Iron | Weekly | Influent and Effluent | AA Spectroscopy – WQL |
| Alkalinity | Weekly | Influent and Effluent | HACH 8203 – WQL |
| Nitrate | Once per month | Influent and Effluent | EPA 300.0 |
| Calcium | Weekly | Influent and Effluent | AA Spectroscopy – WQL |
| Magnesium | Weekly | Influent and Effluent | AA Spectroscopy – WQL |
| Silica | Weekly | Influent and Effluent | HACH 8185 – WQL |
| Manganese | Weekly | Influent and Effluent | EPA 200.8 |
| Aluminum | Once per month | Influent and Effluent | EPA 200.7, 200.8 |
| Titanium | Weekly | Influent and Effluent | EPA 200.7, 200.8 |
| Vanadium | Weekly | Influent and Effluent | EPA 200.8 |
| Zirconium | Weekly | Influent and Effluent | EPA 200.7, 200.8 |
| Chloride | Weekly | Influent and Effluent | EPA 300.0 |
| Fluoride | Weekly | Influent and Effluent | EPA 300.0 |
| Phosphate | At least once | Influent and Effluent | EPA 300.0 |
| Sulfate | Weekly | Influent and Effluent | EPA 300.0 |

[1] Methods for the Determination of Metals in Environmental Samples-Supplement I", PA/600/R-94/111, May 1994. Available at NTIS, PB95-125472 and "Methods for the Determination of Inorganic Substances in Environmental Samples," EPA/600/R-93/100, August 1993. Available at NTIS, PB94-120821.

Besides the indicated field parameters, flow rate and pressure readings were collected daily during the Integrity Verification Period and twice per week during the Capacity Verification Period. The spent media were analyzed for arsenic, barium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver and zinc using the Toxicity Characteristics Leaching Procedure (TCLP) using the EPA Method 1311. A waste whose TCLP values exceed the specified limits as per the Resource Conservation and Recovery Act is a hazardous waste and must be properly treated and disposed of in a hazardous waste landfill.

The sampling frequencies and analytical procedures followed during the coagulation/filtration pilot testing are summarized in Table 2.8. Field test kits were used to monitor arsenic (using Accustrip Kit Method) and iron (using HACH DR 820) in the influent and effluent samples for onsite pilot run evaluation. For the other field and laboratory parameters, analytical methods included in Tables 2.4 to 2.7 were followed.

**Table 2.8 Coagulation/Filtration Sampling Protocol**

| Sample Location | Field Parameters | Frequency | Laboratory Parameters | Frequency |
|---|---|---|---|---|
| Influent (Raw water) | pH, chlorine, temperature, turbidity, iron, arsenic | Once every 4 hours during the test run | Arsenic, iron, silica | One grab sample per test run |
| Effluent (Treated water) | pH, chlorine, temperature, turbidity, iron, arsenic | First sample was collected 30 minutes after startup, subsequent samples were collected every 2-hour interval | Arsenic, iron, silica | First sample was collected 30 minutes after startup, subsequent samples were collected every 4-hour interval |

Coagulation/filtration Phase 1 test runs were approximately less than eight hours as proper function of the pilot unit was being ensured. During Phase 2, five pilot runs were conducted - four for approximately 16 hours, and one for eight hours (the pilot run was terminated due to inclement weather that froze the coagulant feed pipe). While the influent and effluent pressure gauges were installed, the filter head loss data were not reliable due to continuous malfunction of the effluent pressure gauge. Since the anticipated filter run times of approximately 16 hours were achieved during the pilot testing, head loss through the filter was not a factor in determining filter run length.

## 2.4   Inter Laboratory Quality Control/Assurance

For quality control/quality assurance purposes, samples for arsenic analysis were collected and analyzed by an EPA certified laboratory (Legend Technical Services, Phoenix, AZ). In addition, samples collected for arsenic speciation were also analyzed by the SNL WQL and EPA certified laboratory, and these results (Section 2.5) were also utilized for the quality control/assurance purposes. Tables 2.9 and 2.10 summarize inter laboratory arsenic analysis results, and the percent difference in results ranged from -2.9 to 11.8%. Based on the observed results, it can be concluded that the analytical results from SNL WQL are accurate and precise.

**Table 2.9 Inter Laboratory Arsenic Analysis**

| Sample Date | Location | Arsenic Level, ppb | | Difference[1], % |
|---|---|---|---|---|
| | | SNL | LTS | |
| 11/14/2006 | Influent | 18.3 | 17 | 7.4 |
| | ADSORBSIA$^{TM}$GTO$^{TM}$ Effluent | 9 | 8 | 11.8 |
| | npRIO Effluent | 20.4 | 21 | -2.9 |
| | Kemira CFH0818 Effluent | 9 | 9 | 0.0 |
| | E33 Effluent | 4.9 | 5 | -2.0 |
| 12/6/2006 | Influent | 19.3 | 19 | 1.6 |
| | E33 Effluent | 6.3 | 6 | 4.9 |

[1]. ((SNL-LTS)x100)/((SNL+LTS)/2)

## 2.5   Arsenic Speciation Analysis

Most adsorption media effectively remove arsenate from water.  Arsenite, if present, must be oxidized to arsenate for effective removal.  To determine the arsenite and arsenate levels in the well water, samples were speciated using the aluminosilicate adsorbent method [Meng and Wang (1998), kits supplied by SNL] once (October 21, 2006), and by the aluminosilicate adsorbent method and HAc-EDTA  method [Karori, S. et al (2006), kits supplied by NCS] for a second time (December 6, 2006). The results of the speciation events are summarized in Table 2.10.  Based on the results, the majority of arsenic in ground water was present as arsenate.  The arsenic analysis conducted by the SNL WQL and LTS (Table 2.9 and December 6, 2006 data in Table 2.10) compared very well (within ± 19.2 %) except for one sample for C/F.  It appears that the sample was mislabeled and is included here for completeness.

**Table 2.10 Arsenic Speciation Results**

| Sample | Aluminosilicate Method | | | Aluminosilicate Method | | | HAc - EDTA Method | | | HAc - EDTA Method | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LTS | | | SNL WQL | | | LTS | | | SNL WQL | | |
| | Total Arsenic, ppb | As(III), ppb | As(V), ppb | Total Arsenic, ppb | As(III), ppb | As(V), ppb | Total Arsenic, ppb | As(III), ppb | As(V), ppb | Total Arsenic, ppb | As(III), ppb | As(V), ppb |
| Influent (non chlorinated)[1] | NA | NA | NA | 18.5 | ND | 18.5 | NA | NA | NA | NA | NA | NA |
| ADSORBSIA™GTO™ Effluent[1] | NA | NA | NA | 4.8 | ND | 4.8 | NA | NA | NA | NA | NA | NA |
| npRio Effluent[1] | NA | NA | NA | 13.8 | ND | 13.8 | NA | NA | NA | NA | NA | NA |
| Kemira CFH0818[1] | NA | NA | NA | 5.9 | ND | 5.9 | NA | NA | NA | NA | NA | NA |
| E33 Effluent[1] | NA | NA | NA | 2.1 | ND | 2.1 | NA | NA | NA | NA | NA | NA |
| Influent (non-chlorinated)[2] | 19 | ND | 19 | 19.3 | ND | 19.3 | 19 | ND | 19 | 19.3 | ND | 19.3 |
| Influent (chlorinated)[2] | 19 | ND | 19 | 15.7 | ND | 15.7 | 19 | ND | 19 | 15.7 | NA | NA |
| E33 Effluent[2] | 6 | ND | 6 | 6.3 | ND | 6.3 | 6 | ND | 6 | 6.3 | ND | 6.3 |
| C/F Effluent[2] | 10 | ND | 10 | 23.5 | ND | 23.5 | 10 | ND | 10 | 23.5 | ND | 23.5 |

Notes: Aluminosilicate kits were supplied by SNL; HAc-EDTA kits were supplied by NCS.

NA: not available; ND: not detected.

[1.] Samples analyzed on October 21, 2006.

[2.] Samples analyzed on December 6, 2006.

# 3.0  RESULTS AND DISCUSSIONS

## 3.1  Background

Fixed bed testing of four adsorption media and coagulation/filtration technology were studied at the pilot-scale for arsenic removal at Well #30 of Weatherford, OK.   This chapter provides the results of arsenic removal testing.

## 3.2  Summary of Source Water Quality

The source water quality observed during the pilot study is summarized in Table 3.1.  Arsenic (V) in source water ranged from 15.7 to 29.7 ppb, with an average of 20 ppb.  The observed level is lower than the historical  level (40 ppb) and generally decreased as the study progressed.  This observation may be attributed to continuous well operation and possible dilution effects from area groundwater. The water was neutral to slightly basic, as pH ranged from 6.9 to 7.6 with an average value of 7.3. The pH is suitable for removal of arsenic with adsorption and coagulation/filtration technologies. Sulfate (75 - 119 mg/L), chloride (33 - 43 mg/L), calcium (64 - 73 mg/L), magnesium (12 -15 mg/L) and conductivity (450 -610 μS/cm) levels indicate high total dissolved solids in groundwater. Nitrate levels (18.9 - 25 mg/L as $NO_3$) were moderate in Weatherford groundwater.  The presence of sulfate and nitrate preclude use of ion exchange based technologies for arsenic removal.  Vanadium (0.02 to 0.03 mg/L) in Well #30 water has the potential to impact adsorption of arsenic, as discussed in the following section. Turbidity ranged from 0.35 to 7.72 NTU with an average level of 1.7 NTU. This level is relatively high for a groundwater and may represent oxidized iron (0.3 to 1.2 mg/L). Manganese (< 1 to 4 ppb) was low in Well #30 water.

**Table 3.1 Source Water Quality for Weatherford Well #30**

| Parameter | Range | Average | No. of samples |
|---|---|---|---|
| Total Arsenic, ppb | 15.7 - 29.7 | 20 | 23 |
| Arsenic (V)[1], ppb | 15.7 - 19.7 | 20 | 23 |
| Arsenic (III)[1], ppb | ND | ND | 4 |
| pH, Standard Units | 6.9 - 7.6 | 7.3 | 31 |
| Sulfate, mg/L | 75 -119 | 103 | 14 |
| Chloride, mg/L | 33 – 43 | 37 | 14 |
| Nitrate, mg/L as $NO_3$ | 18.9 - 25.0 | 21.8 | 14 |
| Calcium, mg/L | 64 – 73 | 69 | 13 |
| Magnesium, mg/L | 12 - 15 | 14 | 11 |
| Iron, mg/L | 0.3 - 1.2 | 0.5 | 15 |
| Silica ($SiO_2$), mg/L | 17.9 - 29.2 | 25 | 14 |
| Manganese, µg/L | < 1 - 4 | 1 | 24 |
| Vanadium, ppb | 22 - 31 | 23 | 24 |
| Turbidity, NTU | 0.4 - 7.7 | 1.7 | 31 |
| Temperature, °F | 63 - 74 | 69 | 31 |
| Conductivity, µS/cm | 450 - 610 | 560 | 31 |
| Total Alkalinity (as $CaCO_3$), mg/L | 106 - 114 | 109 | 18 |
| Fluoride, mg/L | 0.2 - 0.3 | 0.2 | 14 |
| Titanium, µg/L | 0.05 - 0.08 | 0.07 | 24 |

[1.] Based on arsenic speciation analysis.

## 3.3   Adsorption Results

Adsorption pilot testing began on September 3rd and finished on December 3rd 2006.  The following sections summarize results for each of the tested adsorption media.  For this study, arsenic breakthrough is defined when a contaminant is detected in the effluent.

## 3.3.1 ADSORBSIA[TM]GTO[TM]

Figure 3.1 displays the arsenic breakthrough profile for ADSORBSIA[TM]GTO[TM] media. The arsenic breakthrough was observed around 14,900 bed volumes (BVs) at 25 days of operation.  At 44,100 BVs (73 days of operation), the effluent arsenic concentration was 10 ppb and remained around 10 ppb up to 47,100 BVs. It should be noted that the ADSORBSIA[TM]GTO[TM] media was not exhausted at the conclusion of the study, however, the useful life for the media for an effluent arsenic level of 10 µg/L was achieved at 44,100 BVs.  At the conclusion of the study (49,600 BVs), the effluent arsenic level was 9.2 ppb and reflected variations in the influent arsenic concentration.

The arsenic removal results compared well with those observed for the City of Rio Rancho pilot study conducted by SNL (Aragon, M., et. al., 2007).  The EBCT at Rio Rancho was 3 minutes compared to 2.5 minutes at Weatherford.  At an average influent arsenic concentration of 19 µg/L, ADSORBSIA[TM]GTO[TM] treated more than 48,000 BVs.  Differences in concentration of other water constituents may explain similar arsenic removal at Rio Rancho and Weatherford even though EBCT at Rio Rancho was higher.
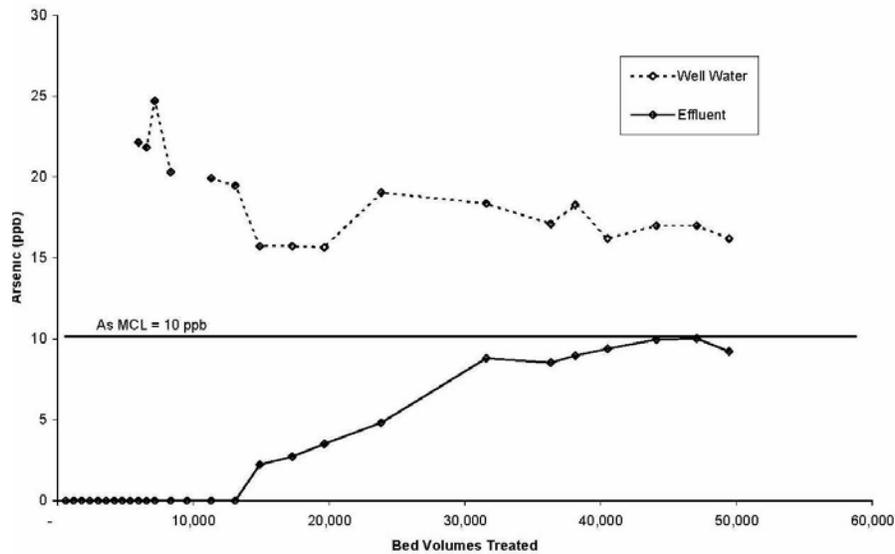
**Figure 3.1 Arsenic Removal by ADSORBSIA™GTO™**

The average silica level at Rio Rancho (30 mg/L) was higher than at Weatherford (24 mg/L). Silica removal by ADSORBSIA$^{TM}$GTO$^{TM}$ is shown in Figure 3.2, and it appears that silica was removed only marginally. Based on the lower silica levels at Weatherford, it appears that silica may not have significantly impacted arsenic adsorption.



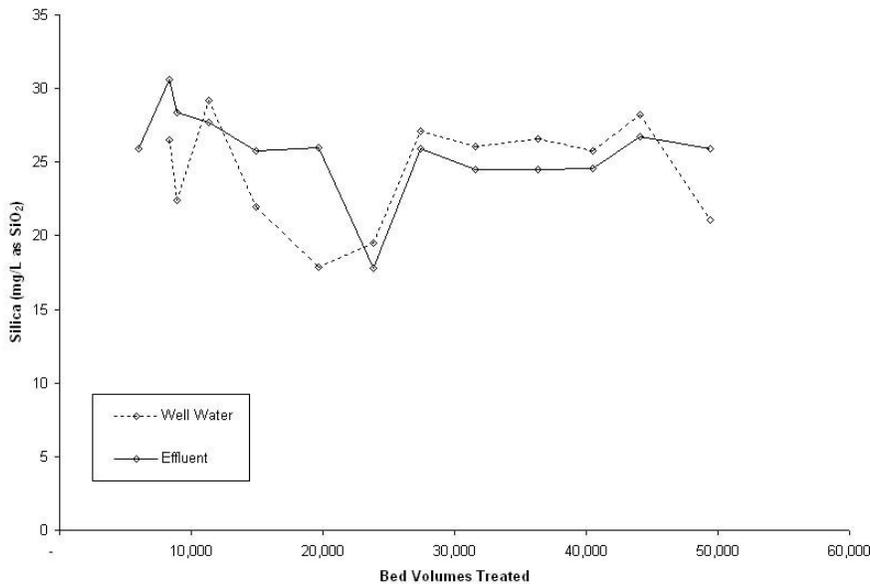**Figure 3.2: Silica Removal by ADSORBSIA™GTO™**

The average vanadium level at Rio Rancho (15 µg/L) was lower than that at Weatherford (23 µg/L). As shown in Figure 3.3, vanadium continues to be removed by ADSORBSIA$^{TM}$GTO$^{TM}$ and may have competed for adsorption sites with arsenic. Further, a higher vanadium concentration at Weatherford may also explain the lower arsenic removal performance than at Rio Rancho.
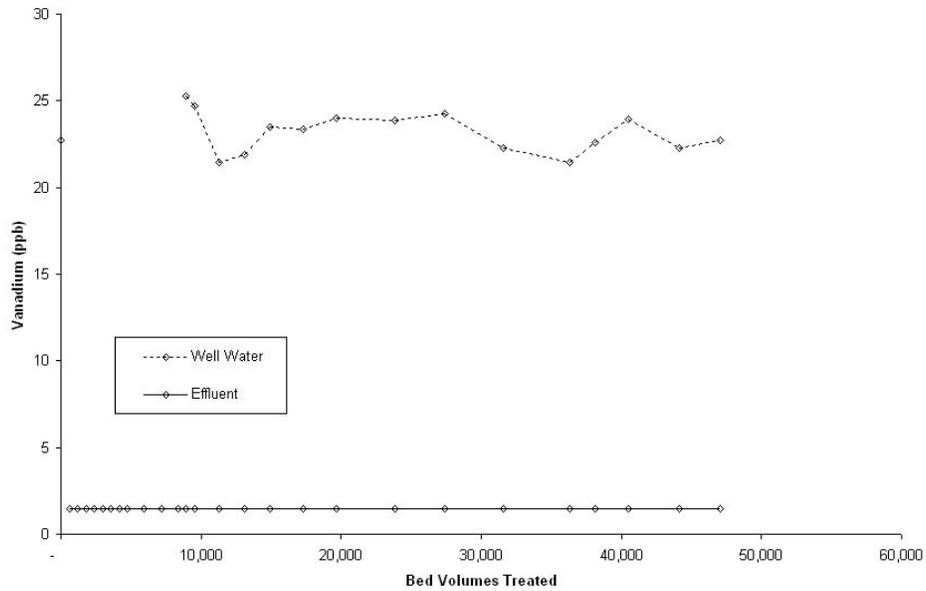
**Figure 3.3: Vanadium Removal by ADSORBSIA™GTO™**

As shown in Figure 3.4, the effluent pH level was slightly lower than the influent pH level up to approximately 7,000 BVs, and this observation may be attributed to leaching of acidic groups from the media. Turbidity in the effluent from the ADSORBSIA$^{TM}$GTO$^{TM}$ column (Figure 3.5) behaved erratically compared to the influent turbidity levels. ADSORBSIA$^{TM}$GTO$^{TM}$ media contains fines which require significant backwashing prior to their complete removal, and higher turbidity levels in the ADSORBSIA$^{TM}$GTO$^{TM}$ may be attributed to continued release of media fines. At Weatherford, ADSORBSIA$^{TM}$GTO$^{TM}$ media was backwashed for approximately twenty five minutes. For the pilot studies conducted by SNL, ADSORBSIA$^{TM}$GTO$^{TM}$ required approximately 30 minutes of backwashing (Aragon, M. et al 2007). At the conclusion of the pilot test, the pressure drop across the ADSORBSIA$^{TM}$GTO$^{TM}$ media was 3.5 psi.



**Figure 3.4: Well Water and Effluent pH Levels through ADSORBSIA™GTO™**

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**Figure 3.5: Well Water and Effluent Turbidity Levels through ADSORBSIA™GTO™**

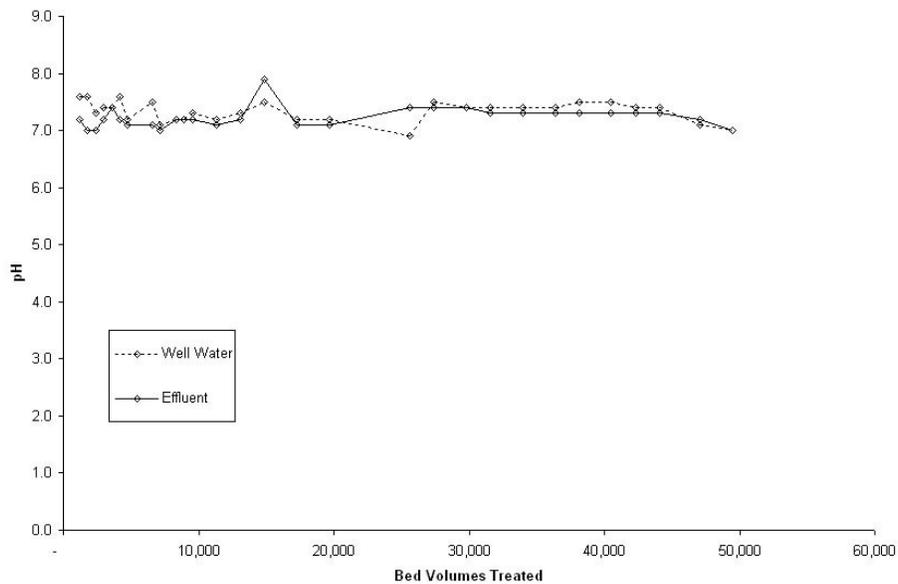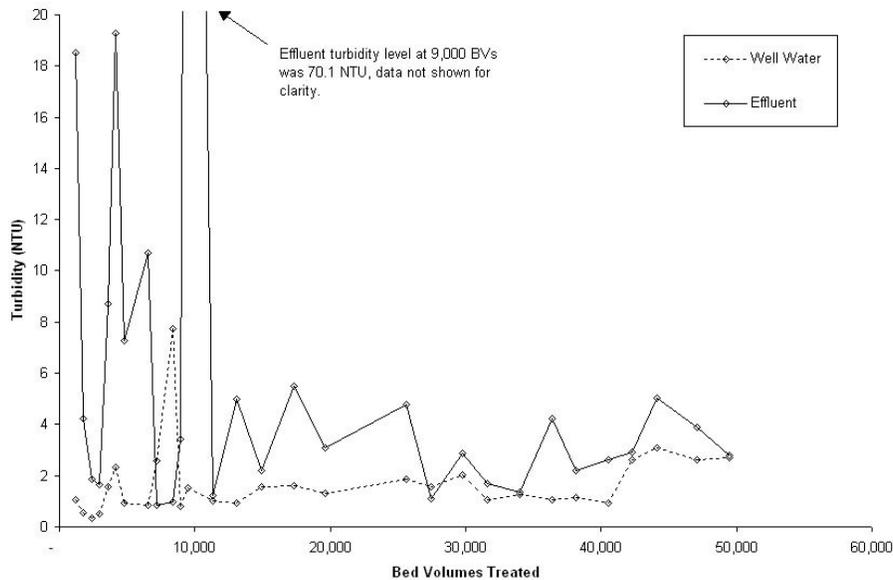Other water constituents such as sulfate and nitrate did not appear to impact arsenic adsorption. Phosphorus can impact arsenic adsorption. During this pilot, phosphorus was analyzed only once; therefore, these results provided limited information.

### 3.3.2 npRio

Figure 3.6 displays the arsenic breakthrough profile for npRio media. The arsenic breakthrough was observed around 14,900 bed volumes (BVs). At 31,600 BVs (52 days of operation), npRio was saturated with arsenic, and effluent arsenic levels higher than influent were observed. The higher effluent arsenic level may be attributed to either lower influent arsenic level and reestablishment of adsorption equilibrium on the media, or due to competitive adsorption with other water constituents. npRio is a new media which is supposed to perform better than a similar media, ArsenX$^{np}$, also manufactured by SolmeteX. ArsenX$^{np}$ was evaluated at the City of Rio Rancho and treated 40,000 (Phase 1) to 44,000 (Phase 2) BVs at an effluent arsenic level of 10 ppb. At Weatherford, npRio treated approximately 20,500 BVs to an effluent arsenic level of 10 ppb. Differences in EBCTs in two studies may partially explain improved performance at Rio Rancho. It also appears that other water constituents, such as vanadium, may have attributed to the npRio's arsenic removal performance at Weatherford.

27
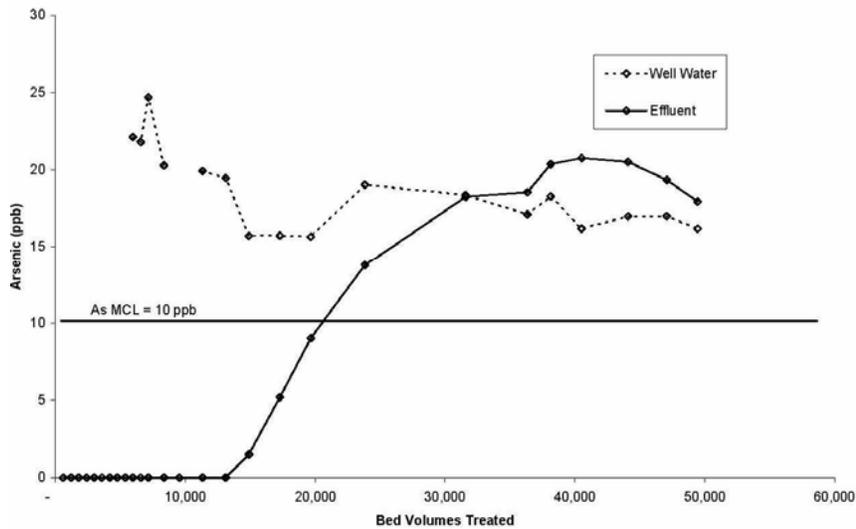
**Figure 3.6 Arsenic Removal by npRio**

Silica removal by npRio is shown in Figure 3.7, and it appears that silica was removed only marginally. Higher effluent silica levels also indicate competitive adsorption onto npRio. Similar to ADSORBSIA$^{TM}$GTO$^{TM}$, npRio removed vanadium completely up to 38,100 BVs (Figure 3.8). At the conclusion of the pilot study, the vanadium level in the effluent from npRio media was 8.3 µg/L (47,100 BVs). Vanadium may also have competed with arsenic for npRio adsorption sites.
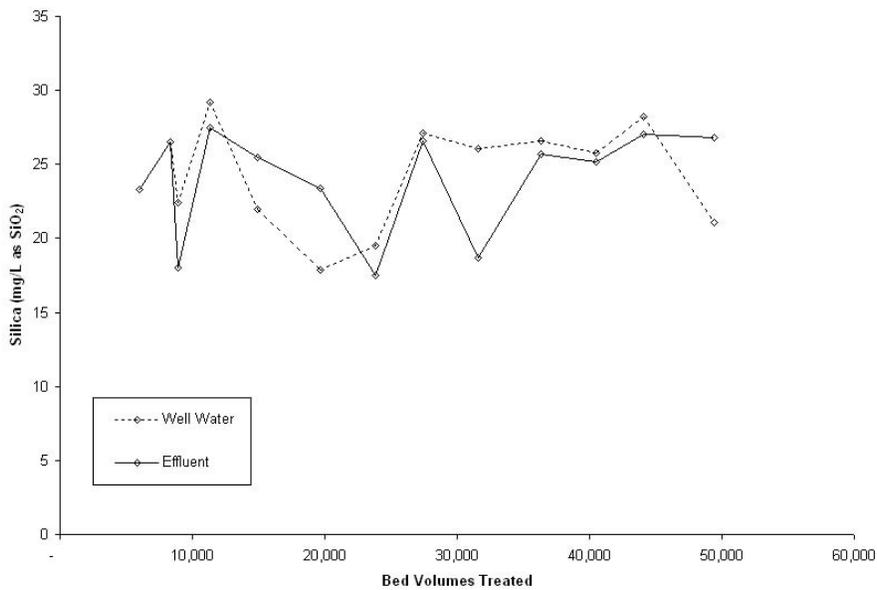


**Figure 3.7: Silica Removal by npRio**
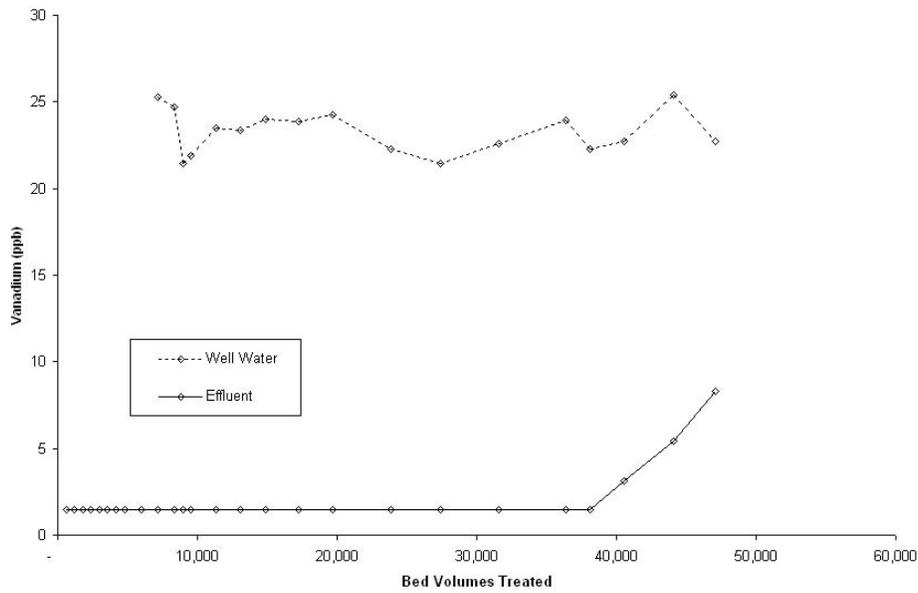
**Figure 3.8: Vanadium Removal by npRio**

As shown in Figure 3.9, the effluent pH level was slightly lower than the influent pH level up to approximately 6,500 BVs, and this observation may be attributed to leaching of acidic groups from the media. Turbidity in the effluent generally followed influent turbidity trends (Figure 3.10). The influent and effluent sulfate levels were similar and therefore sulfate did not impact arsenic removal. The impact of phosphorus on arsenic removal could not be evaluated due to limited data. The final pressure drop across the npRio media was 1.5 psi.
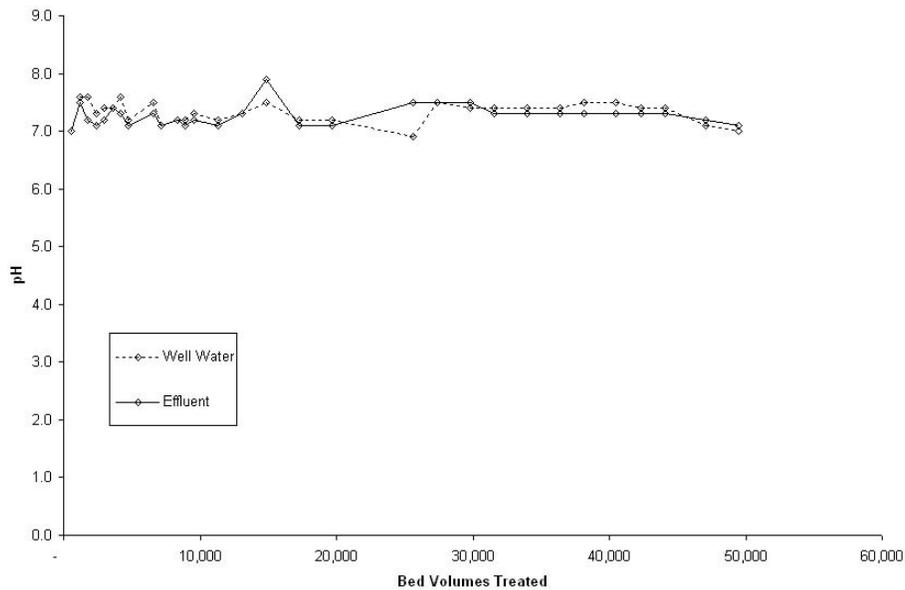


**Figure 3.9: Well Water and Effluent pH Levels through npRio**

29
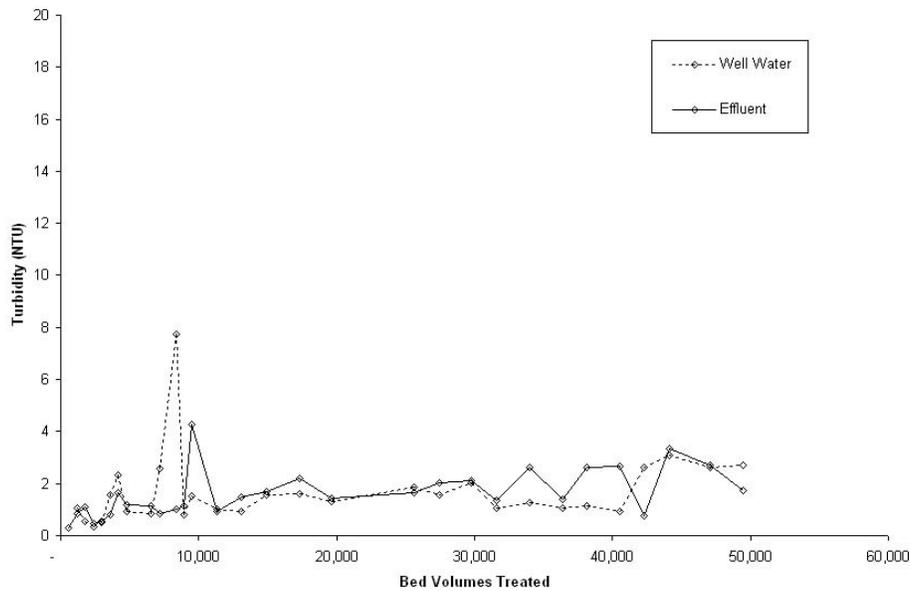
**Figure 3.10: Well Water and Effluent Turbidity Levels through npRio**

### 3.3.3 Kemira CFH0818

Figure 3.11 displays the arsenic breakthrough profile for Kemira CFH0818, and similar to ADSORBSIA$^{TM}$GTO$^{TM}$ and npRio media, the arsenic breakthrough was observed around 14,900 bed volumes (BVs). The effluent arsenic level reached 10 ppb at 31,600 BVs (53 days of operation) but then decreased due to a decrease in the influent arsenic level. The effluent arsenic level was at 10 ppb at 44,100 BVs. Similar to the ADSORBSIA$^{TM}$GTO$^{TM}$ media, Kemira CFH0818 was not exhausted at the conclusion of the study, however, the useful life for the media for an effluent arsenic level of 10 µg/L was achieved at 44,100 BVs. At the conclusion of the study, the effluent arsenic level was 9 ppb at approximately 49,600 BVs. Kemira CFH0818 performed better than npRio, and similar to ADSORBSIA$^{TM}$GTO$^{TM}$ but not as well as E33 media. For a similar adsorbent media (Kemira CFH12) by the same manufacturer, the arsenic breakthrough was estimated at 30,000 to 40,000 BVs at Rio Rancho. The observed performance at Weatherford may be attributed to differences in media properties, EBCTs and water constituents impacting arsenic removal.

30
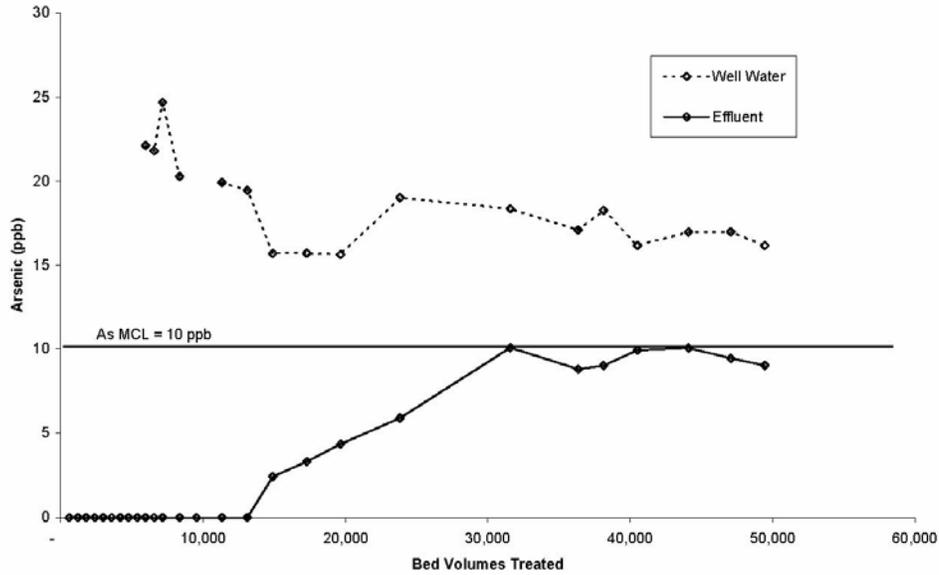
**Figure 3.11 Arsenic Removal by CFH0818**

Similar to ADSORBSIA$^{TM}$GTO$^{TM}$ and npRio, Kemira CFH0818 marginally removed silica (Figure 3.12). Vanadium was removed completely up to 19,700 BVs by Kemira CFH0818 and at 47,100 BVs, the effluent vanadium level was 8.2 ppb (Figure 3.13) and reflected influent variations. Similar to other adsorption media, it appears that vanadium competes for adsorption sites on Kemira CFH0818.
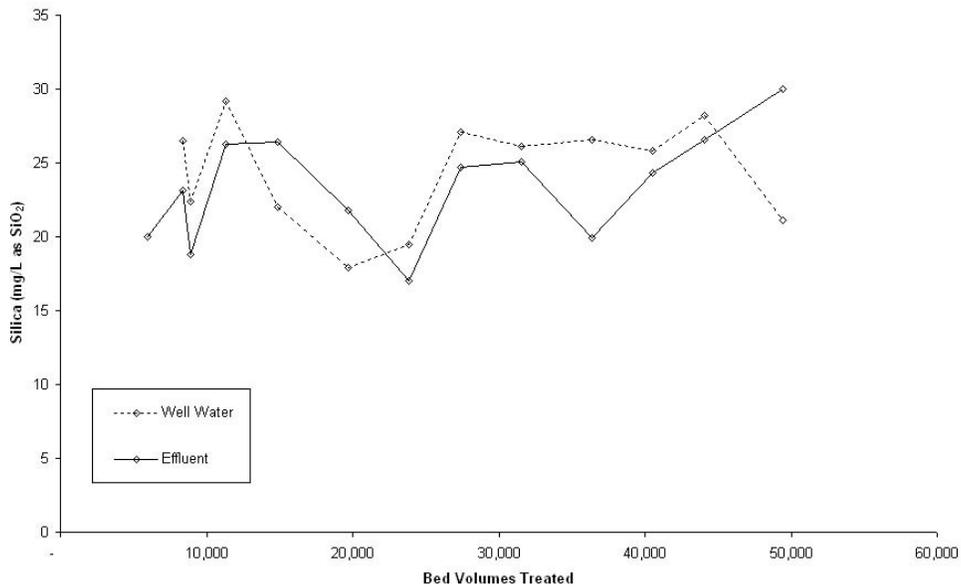


**Figure 3.12: Silica Removal by CFH0818**

31
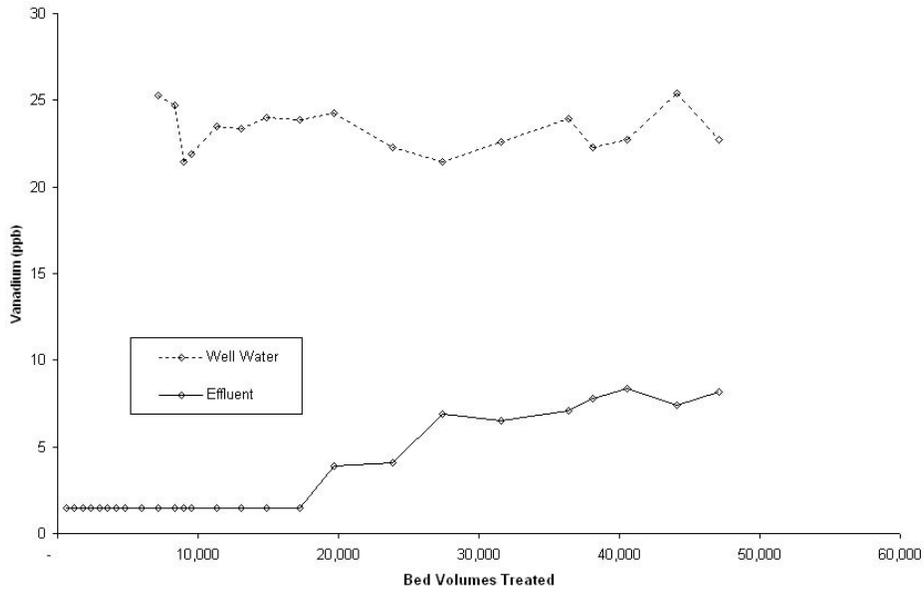
**Figure 3.13: Vanadium Removal by CFH0818**

For Kemira CFH0818 media, effluent pH levels were slightly higher than influent pH for approximately 2,000 BVs, indicating release of basic functional groups (Figure 3.14). After this initial period, effluent pH levels mirrored the influent pH levels. Treatment of turbidity in the effluent generally followed influent turbidity trends. Effluent turbidity levels were higher than the influent turbidity levels (Figure 3.15) and may be attributed to release of media fines similar to the GTO media. The final pressure drop across the KemiraCFH0818 media was 1.0 psi.
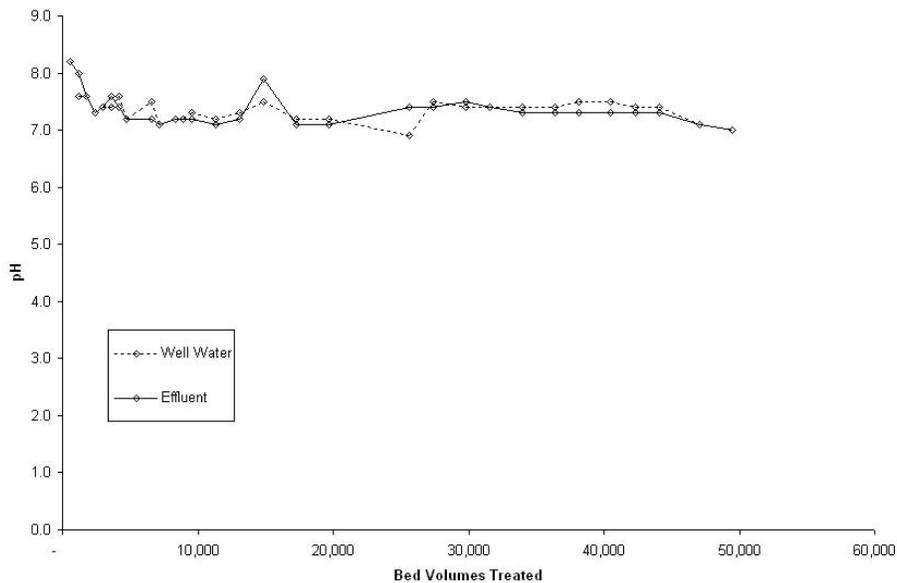

**Figure 3.14: Well Water and Effluent pH Levels through CFH0818**
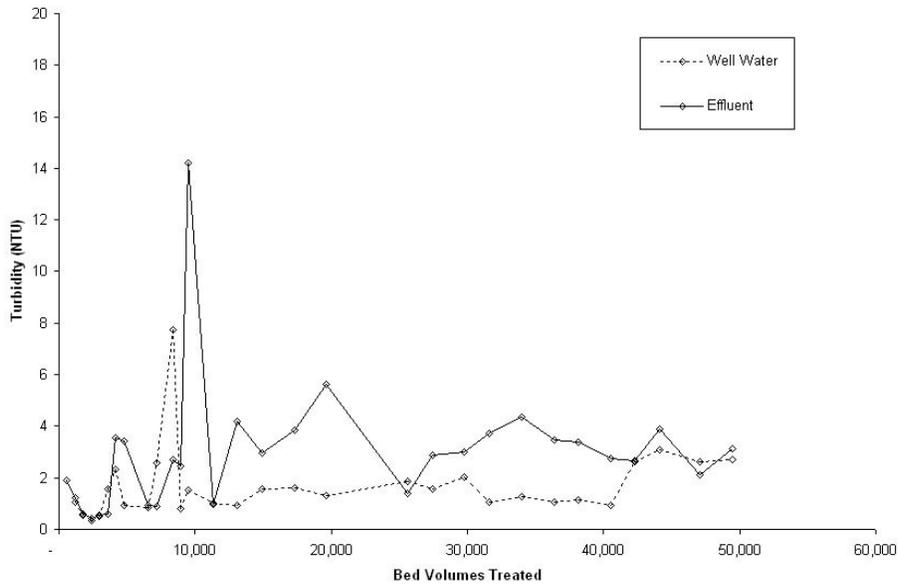
**Figure 3.15: Well Water and Effluent Turbidity Levels through CFH0818**

The influent and effluent sulfate levels were similar and therefore sulfate did not impact arsenic removal. The impact of phosphorus on arsenic removal could not be evaluated due to limited data.

### 3.3.4  E33

Figure 3.16 displays the arsenic breakthrough profile for E33, and arsenic breakthrough was observed around 19,700 bed volumes (BVs). The effluent arsenic level was 6.3 ppb at 53,900 BVs. Therefore, E33 performed the best among the four tested media. To estimate the BVs treated at an effluent arsenic level of 10 ppb, a logarithmic function was fitted to the arsenic breakthrough profile from 17,800 to 51,200 BVs. The fitted correlation (Effluent arsenic level = 5.6ln(BVs)-53.8) described 96 % of the data. Based on the correlation, approximately 95,000 BVs would be treated to an effluent arsenic level of 10 ppb. It should be noted that the actual BVs treated would depend on the future levels of influent arsenic and other competing contaminants and may be different (lower or higher) than the estimated BVs using the correlation. To be conservative, it is assumed that E33 would treat 73,100 (half of the difference between 51,200 and 95,000 BVs). Other studies conducted by SNL (Socorro and Desert Sands, NM) and NCS (City of Phoenix, AZ) have shown better E33 media performance for arsenic removal compared to other adsorption media, including ADSORBSIA$^{TM}$GTO$^{TM}$.

33
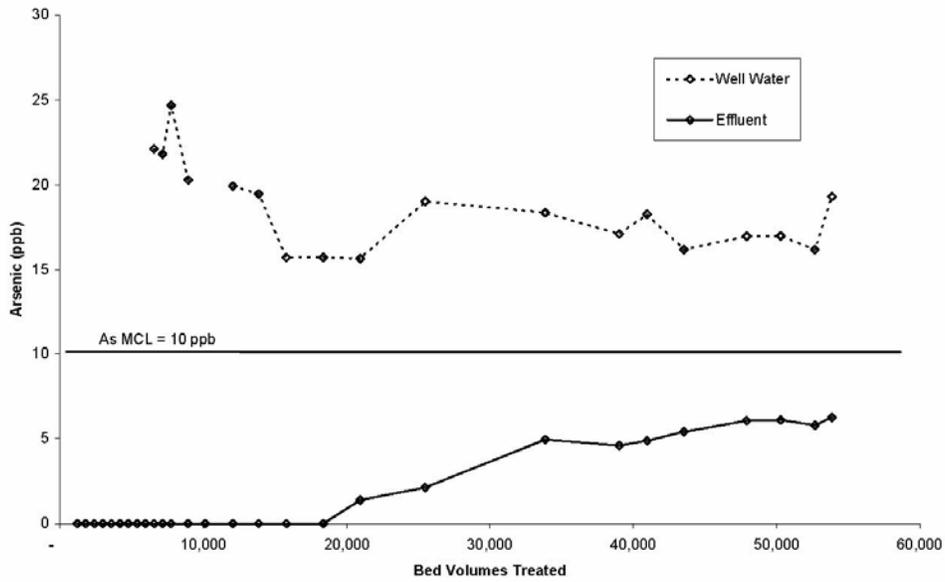
**Figure 3.16 Arsenic Removal by E33**

Because of lack of data during the initial phase of the adsorption test, it is difficult to assess impact of silica on arsenic removal by E33 (Figure 3.17). Silica removal by E33 has been observed at other pilot studies conducted by SNL (Aragon, M., et. al., 2007). The vanadium breakthrough occurred at 29,400 BVs by E33 (Figure 3.18). At the conclusion of the study (52,700 BVs), the effluent vanadium level was 13.9 ppb, the highest compared to other three media. The data indicate that E33 has a lower adsorption capacity for vanadium, and therefore, higher arsenic adsorption capacity.



**Figure 3.17: Silica Removal by E33**

34
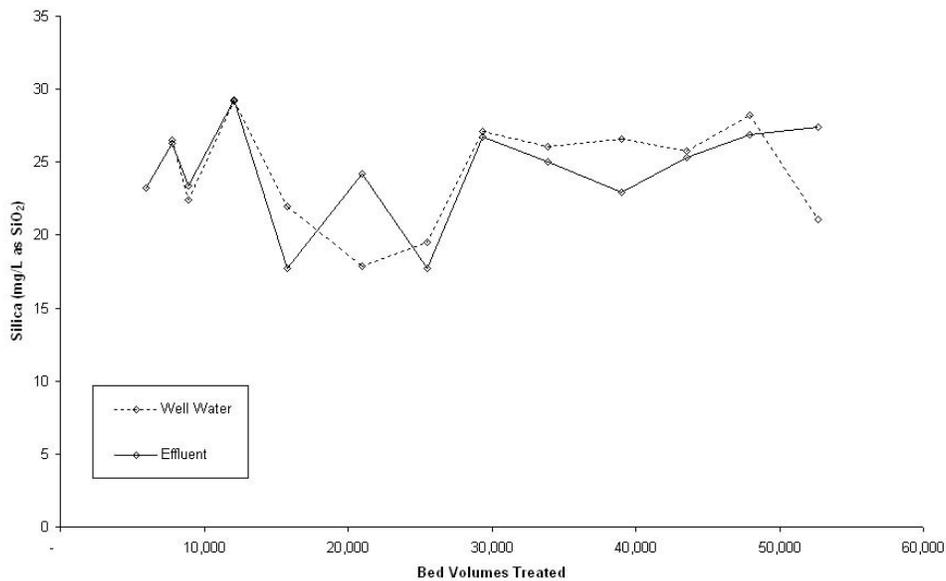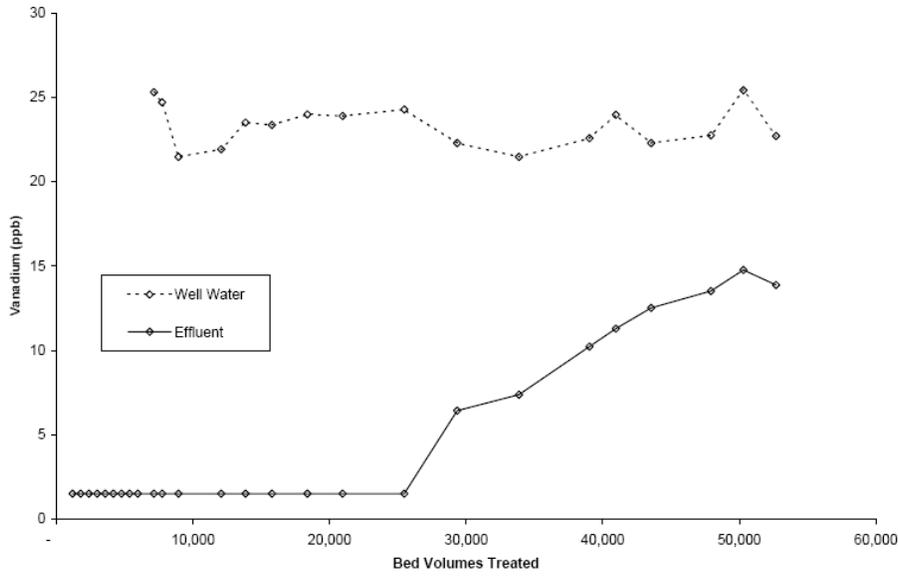
**Figure 3.18: Vanadium Removal by E33**

As shown in Figures 3.19 and 3.20, effluent pH and turbidity levels mirrored the respective influent levels for E33. Similar to other media, the influent and effluent sulfate levels were similar and therefore sulfate did not impact arsenic removal. The impact of phosphorus on arsenic removal could not be evaluated due to limited data. The final pressure drop across the E33 media was 2.5 psi.
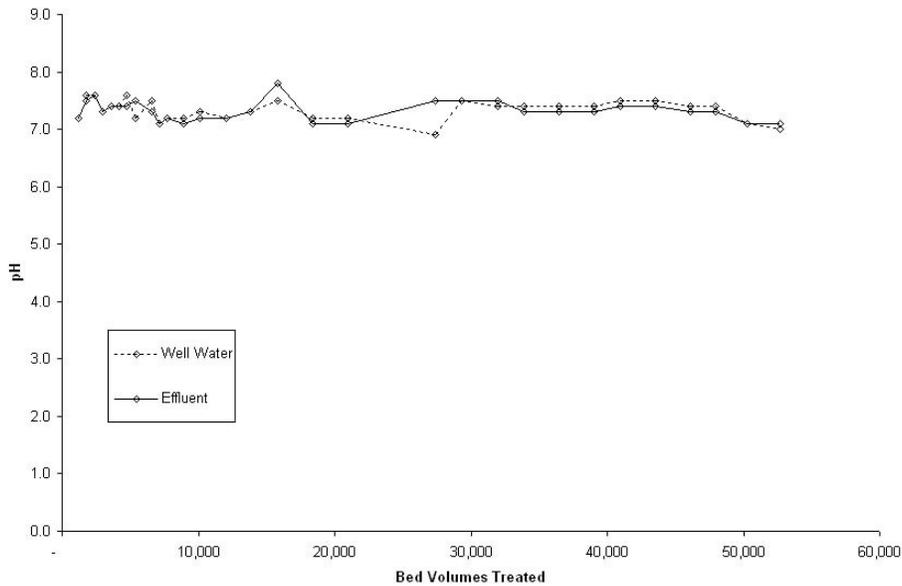


**Figure 3.19: Well Water and Effluent pH Levels through E33**
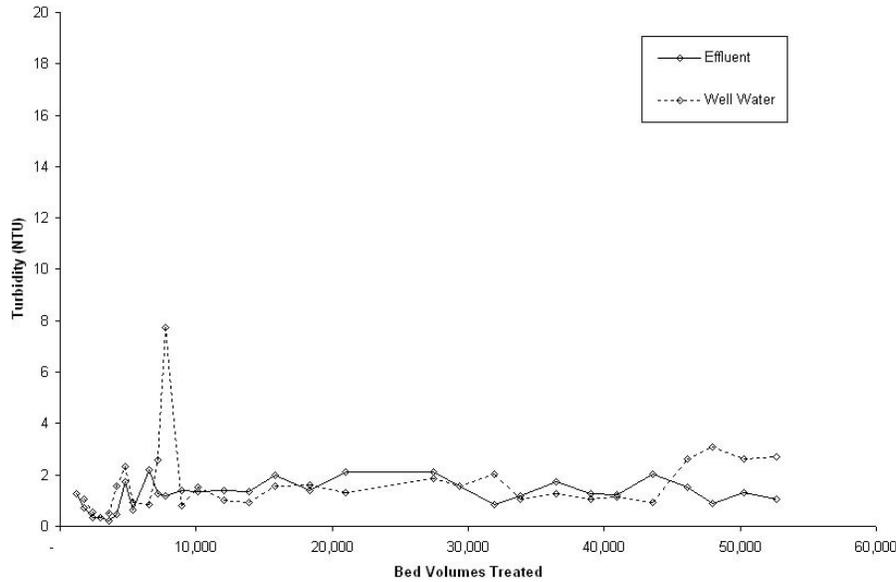
**Figure 3.20: Well Water and Effluent Turbidity Levels through E33**

## 3.4   Comparison of Adsorption Results

Table 3.2 compares the treatment effectiveness of the tested adsorption media.  Based on BVs treated corresponding to an effluent arsenic concentration of 10 ppb, E33 performed the best, followed by ADSORBSIA$^{TM}$GTO$^{TM}$, Kemira CFH0818 and npRio.  Vanadium appears to impact the arsenic adsorbing capacity of all adsorbents tested in this study.  As shown in Table 3.2, Kemira CFH0818 had the earliest breakthrough for vanadium, followed by E33, npRio and then by ADSORBSIA$^{TM}$GTO$^{TM}$.  At the conclusion of the pilot testing, effluent from the E33 column had the highest vanadium level.  The data indicate that E33 had the lowest capacity for vanadium which may explain its higher capacity for arsenic.  Arsenic adsorption capacities for all adsorbents were estimated from the breakthrough profiles.  It should be noted that except for npRio, none of the media were run to complete exhaustion (effluent level equal to influent level of arsenic).  The arsenic adsorption capacity for each media was estimated by integrating the area between the influent and effluent arsenic levels up to the BVs shown in Table 3.2.  The estimated arsenic capacity ranged from 0.26 mg/g for npRio to E33 at 1.4 mg/g.  It should be noted that arsenic in the E33 column effluent did not reach 10 ppb and was estimated using a logarithmic correlation (Section 3.2.4).  It is possible that the estimated breakthrough profile may not accurately represent the actual breakthrough profile.   Therefore, based on a side by side comparison, E33 performed the best, followed by ADSORBSIA$^{TM}$GTO$^{TM}$, Kemira CFH0818 and npRio.  npRio is a regenerable media and several regenerations may result in a cost effective treatment solution versus one time use media, including E33, Kemira CFH0818 and ADSORBSIA$^{TM}$GTO$^{TM}$.

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**Table 3.2 Comparison of Treatment Effectiveness of Adsorption Media**

| Criteria | ADSORBSIA$^{TM}$ GTO$^{TM}$ | npRio | Kemira CFH0818 | E33 |
|---|---|---|---|---|
| BVs to 10 ppb As | 44,100 | 20,500 | 44,100 | 73,100[1] |
| Vanadium breakthrough, BVs | > 47,100 | 40,500 | 19,700 | 29,400 |
| Capacity at 10 ppb As, mg As/g adsorbent[2] | 0.74 | 0.26 | 0.56 | 1.38[1] |

[1] Extrapolated using a logarithmic correlation (Section 3.3.4).
[2] Densities (lb/ft$^3$): ADSORBSIA$^{TM}$GTO$^{TM}$- 47, npRio- 47, Kemira CFH0818 - 72, E33 - 33

## 3.5    Characterization of Spent Adsorption Media

The spent adsorption media were analyzed using TCLP to determine their compliance with RCRA requirements.  The results for the eight RCRA and three additional metals are summarized in Table 3.3.  Most RCRA metals that detected from the TCLP test of the adsorbent media were below detection limits.  Barium was found in leachate from E33, ADSORBSIA$^{TM}$GTO$^{TM}$ and Kemira CFH0818 media, but all values were much lower than the RCRA limit.  Copper was found in leachate from npRio and  ADSORBSIA$^{TM}$GTO$^{TM}$ media. Zinc was found in leachate from npRio, E33 and ADSORBSIA$^{TM}$GTO$^{TM}$ media.  The TCLP results were submitted to the Oklahoma Department of Environmental Quality, and upon receiving the approval, the spent media were disposed of in a sanitary landfill.

**Table 3.3 Results of TCLP Analysis of Adsorption Media**

| Metal | Unit | RCRA Limits | npRio | E33 | ADSORBSIA™ GTO™ | Kemira CFH0818 |
|-------|------|-------------|-------|-----|-----------------|----------------|
| Arsenic | mg/L | 5 | <0.3 | <0.3 | <0.3 | <0.3 |
| Barium | mg/L | 100 | <0.50 | 0.59 | 6.80 | 2.63 |
| Cadmium | mg/L | 1 | <0.005 | <0.005 | <0.005 | <0.005 |
| Chromium | mg/L | 5 | <0.050 | <0.050 | <0.050 | <0.050 |
| Copper | mg/L | n/a | 1.68 | <0.20 | 0.37 | <0.20 |
| Lead | mg/L | 5 | <0.10 | <0.10 | <0.10 | <0.10 |
| Mercury | mg/L | 0.2 | <0.0002 | <0.0002 | <0.0002 | <0.0002 |
| Nickel | mg/L | n/a | <0.400 | <0.400 | <0.400 | <0.400 |
| Selenium | mg/L | 1 | <0.20 | <0.20 | <0.20 | <0.20 |
| Silver | mg/L | 5 | <0.04 | <0.04 | 0.04 | <0.04 |
| Zinc | mg/L | n/a | 1.62 | 1.00 | 10.8 | <0.40 |

n/a: not applicable

## 3.6 Coagulation/Filtration Results

As part of the study, coagulation/filtration technology was tested using a pressure filter containing anthracite. Ferric chloride was used as the coagulant. Table 3.4 summarizes conditions and average arsenic concentrations for the coagulation/filtration pilot runs. The hydraulic loading rate was 8 gpm/ft$^2$ for all runs as it produced the expected filter run times of sixteen hours. The loading rate was selected based on previous experiences with other similar pilot studies conducted for the City of Chandler, AZ (NCS, 2005a), and Carson City, NV (NCS, 2006). Three initial pilot tests (Phase 1) were conducted in September 2006 at a ferric chloride dose of 3 mg/L. Figure 3.21 summarizes the arsenic removal of the Phase 1 pilot tests. For the Pilot test 1, the effluent arsenic concentration was 4.7 ppb after 30 minutes into the run, and increased to 7.3 ppb after 4.5 hours. The average arsenic removal was 73.1 percent (Table 3.4). Pilot tests 2 and 3 were conducted to verify arsenic removal at 3 mg/L ferric chloride dose. Performance of a new filter media improves over time as particles in the filter influent attach irreversibly to the filter media and aid in removal of influent particles. Similarly, it takes some time for the particles in the filter influent to attach to filter media after a filter backwash before an improvement in filter performance is observed. This initial period after a backwash is termed as filter ripening. During the filter ripening period, more particles are released into the effluent than during the normal operations of the filter. As shown on Figure 3.21, the initial period of approximately 2 to 3 hours would be considered as filter ripening. As the influent particles attach to media, the filtration efficiency improves until an increase in effluent particles is observed due to an increase in head loss through the media (Figure 3.22). A filter is backwashed once a specified treatment goal is achieved. Initial arsenic level in the Pilot tests 2 and 3 filtered effluent was 9.1 and 9.5 ppb, respectively, indicating filter ripening period. Though the effluent arsenic level decreased to 6.1 ppb after 1.5 hours in test 2 and 6.2 ppb after 2.5 hours in test 3, the levels are considered high and effluent arsenic levels below 5 ppb are preferred. Therefore, it was decided to increase the ferric chloride dose for Phase 2 Pilot tests.

**Table 3.4 Summary of Coagulation/Filtration Pilot Tests**

| Run No | Date | Ferric Chloride Dose, mg/L | Duration, hr | pH (avg) | Influent Arsenic, ppb (avg) | Effluent Arsenic, ppb (avg) | Arsenic Removal, % |
|---|---|---|---|---|---|---|---|
| 1 | 14-Sep | 3.0 | 4.5 | 7.1 | 22.3 | 6.0 | 73.1 |
| 2 | 15-Sep | 3.0 | 8.0 | 7.1 | 20.7 | 6.4 | 68.8 |
| 3 | 16-Sep | 3.0 | 4.5 | 7.0 | 24.7 | 7.1 | 71.2 |
| 4 | 28-Nov | 3.75 | 16 | 7.1 | 18.7 | 3.7 | 80.4 |
| 5[1] | 29-Nov | 3.75 | 8 | 7.1 | 18.1 | 1.1 | 94.1 |
| 6 | 1-Dec | 4.75 | 16 | 7.1 | 20.9 | 4.7 | 77.3 |
| 7 | 2-Dec | 3.75 | 16 | 7.1 | 19.8 | 2.9 | 85.2 |
| 8 | 3-Dec | 4.75 | 16 | 7.1 | 20.0 | 4.9 | 75.3 |

[1] Run was aborted due to equipment malfunction
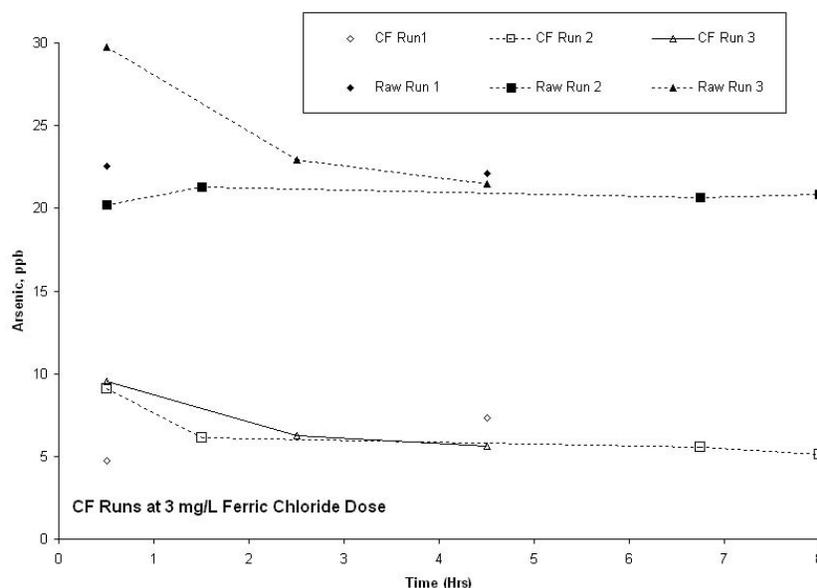


**Figure 3.21: Arsenic Removal during C/F Runs at 3 mg/L Ferric Chloride**

Pilot tests 4 to 8 (Phase 2) were conducted in late November to early December 2006. Increased ferric chloride doses of 3.75 mg/L (Tests 4, 5 and 7) and 4.75 mg/L (Tests 6 and 8) were tested and the arsenic removal effective for Phase 2 Pilot tests is summarized in Table 3.4. After 30 minutes, Pilot test 4 (Figure 3.22) showed slightly higher effluent arsenic level (3.4 ppb) versus test 5 (2.7 ppb) and test 7 (1.2 ppb). The effluent arsenic levels for test 4 were higher than those for test 5 probably because the coagulation/filtration pilot equipment had not operated for more than 2 months.
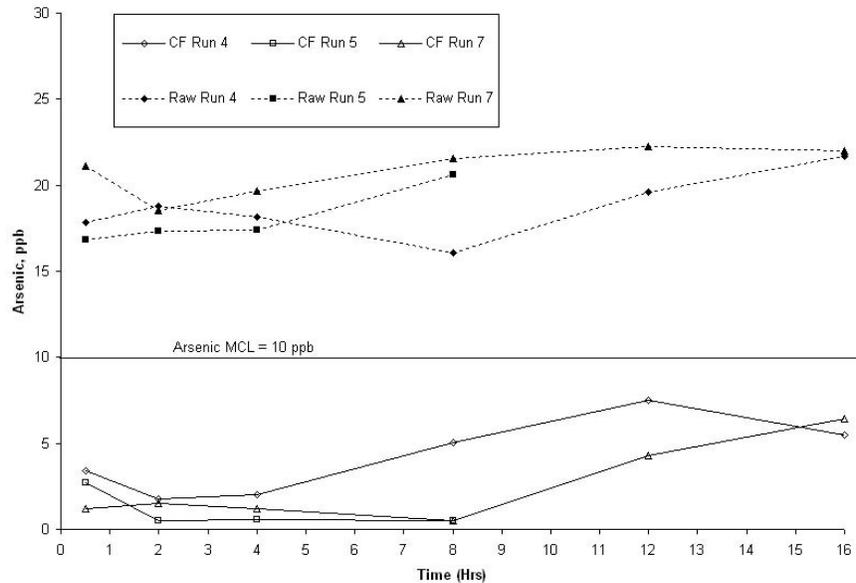
**Figure 3.22: Arsenic Removal during C/F Runs at 3.75 mg/L Ferric Chloride**

The effluent arsenic levels in test 5 were reduced to below the detection limit after two hours, 0.55 ppb after four hours and below the detection limit after 8 hours. It should be noted that the average influent arsenic concentrations were 18.7 and 18.1 ppb for tests 4 and 5, respectively. Based on the effluent arsenic levels from test 5, it can be concluded that a ferric chloride dose of 3.75 mg/L was better than a dose of 3.0 mg/L (Phase 1). Pilot test 7 was conducted to verify the results with a ferric chloride dose of 3.75 mg/L for a filter run up to 16 hours. The effluent arsenic levels were 1.2 ppb after 30 minutes, 1.5 ppb after two hours, 1.2 ppb after four hours and below the detection limit after eight hours; and then increased to 4.3 ppb after 12 hours and 6.4 ppb after 16 hours of run time. The average influent arsenic level of 19.8 ppb was slightly higher than Tests 4 and 5. Based on the data, a coagulant dose of 3.75 mg/L removed arsenic effectively and filter run times of 20 to 24 hours can be expected.

Pilot tests 6 and 8 were conducted to evaluate arsenic removal at a higher coagulant dose of 4.75 mg/L (Figure 3.23). The influent arsenic concentrations of 20.9 and 20 ppb for Tests 6 and 8, respectively, were slightly higher than Pilot tests 4, 5 and 7. Effluent arsenic levels for tests 6 and 8 were 5.3 and 2.3 ppb after 30 minutes, 2.6 and 1.3 ppb after two hours, 2.6 and below the detection limit after four hours, 1.9 and 21.6 ppb after eight hours, 7.1 and 6.3 ppb after 12 hours, and 8.9 and 9.9 ppb after 16 hours. The 21.6 ppb value represents an incorrect, or a mislabeled, sample as the sample was reanalyzed with same answer, and the value is much higher than the overall trend of test run arsenic data. The effluent arsenic levels for pilot tests 6 and 8 were generally higher than pilot tests 4, 5 and 7, and may be attributed to either higher applied arsenic levels, or higher applied suspended solids (higher ferric chloride dose). It appears that a ferric chloride dose of 4.75 mg/L resulted in filter run times of approximately 16 to 18 hours. Based on the results, it can be inferred that a ferric chloride dose of 3.75 mg/L performed better than either 3 or 4.75 mg/L, and is recommended for a coagulation/filtration based treatment process.
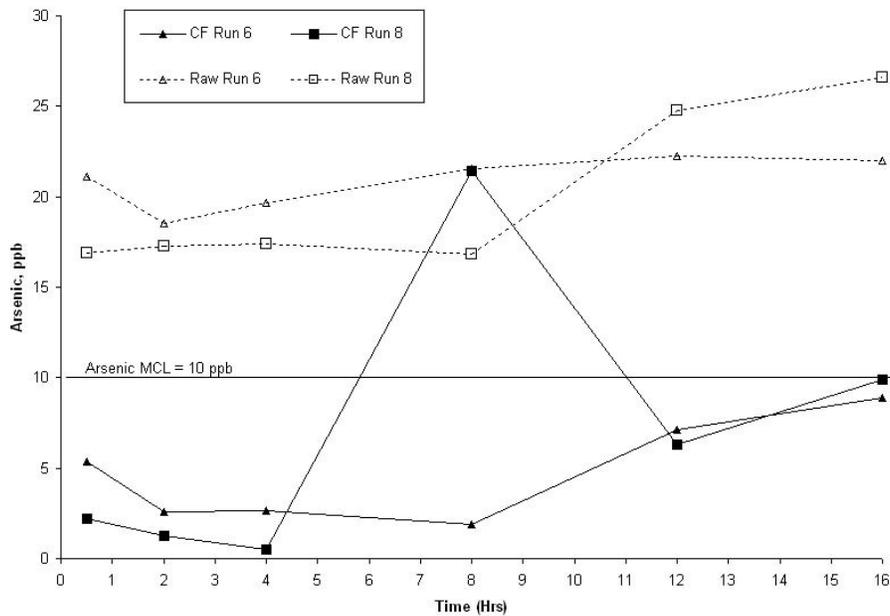
40

**Figure 3.23: Arsenic Removal during C/F Runs at 4.75 mg/L Ferric Chloride**

Based on an average influent turbidity of 1.7 NTU (Table 3.1) and a ferric chloride dose of 3.75 mg/L, approximately 35 pounds of dry solids will be produced per million gallons of treated water. It is assumed that the ratio of total suspended solids and turbidity is one because the suspended data were not available (Crittenden, J., et al., 2005). Assuming a solids concentration of 0.5%, approximately 840 gallons of sludge will be produced.

## 3.7    Summary and Conclusions

Based on pilot testing results of four adsorption media, the iron oxide media E33 was estimated to treat approximately twice the volume of water compared to the ADSORBSIA$^{TM}$GTO$^{TM}$, 2.7 times more than Kemira CFH0818 media, and approximately four times more volume than the npRio. The bed volumes treated as shown in Table 3.2 are based on 100 percent well utilization, and actual media performance will be a function of the actual well utilization. pH adjustment of source water is not expected to increase process performance as source water pH is around 7. Chlorination is required for disinfection and oxidation of arsenite. Generally, adsorption systems are easier to operate than a coagulation/filtration system. Media change-out would depend on well utilization rate, number of contactors operated in either parallel or series mode, and arsenic level. A staggered parallel operation of adsorption contactors results in better utilization of media compared to a single contactor because the individual contactors can be operated to a much higher effluent arsenic level as long as the blended arsenic concentration is below the treatment objective. In a series operation, only a portion of total flow is treated and blended with the untreated flow to increase the bed life. A detailed analysis of a cost effective design and operation strategy is performed during the design phase of the project.

Based on pilot testing results of a coagulation/filtration technology, a ferric chloride dose of 3.75 mg/L without adjusting water pH and a hydraulic loading rate of 8 gpm/ft$^2$ produced acceptable effluent arsenic levels. Under these operating conditions, filter run times of 20 to 24 hours are estimated. Other commercially available filter media may also be utilized in a full-scale application as opposed to the anthracite used in this study. Although ferric chloride (coagulant) dose is not expected to change with the use of different filter media, the filter run times, media head loss and

residual quantities may differ for different filter media. Although a coagulation/filtration ATF requires more operator time, an economic analysis (Chapter 4) should be considered before selecting a final technology.

# 4.0 COST ASSESSMENT

## 4.1 BACKGROUND

Based on the results from this study, an ATF construction and operation and maintenance (O&M) costs were estimated to provide budget level costs for Weatherford Well #30, which is capable of producing 150 gpm water. The construction and O&M costs were estimated for an adsorption ATF using E33 media and a coagulation/filtration ATF. E33 was chosen because it performed the best and has the lowest unit media costs. The capital costs for an adsorption ATF would be the same but O&M costs would vary because of media performance and unit media cost.

## 4.2 Design Assumptions

### 4.2.1 Adsorption ATF

Design assumptions for the 150 gpm adsorption ATF are summarized below:

1. Two vessels, each capable of treating 150 gpm are included to provide redundancy. The vessels may also be used in series to treat only a portion of water flow to increase media life.
    a. Design EBCT: 2.5 minutes per vessel
    b. Design hydraulic loading rate: 7.6 gpm/ft$^2$
    c. Vessel dimensions: 60 inches in diameter by 84 inches in height
2. A manually operated self cleaning pre-filter with a nominal pore size of 50 μm to remove any particulate matter is included.
3. Building costs are not included. Depending on the type of building, the estimated building costs can range from $56,200 (industrial metal shed style) to $150,000 (brick).
4. Adsorption media is backwashed initially to remove fines and whenever necessary based on head loss development during operation. A steel tank is included to store spent filter backwash water. The spent backwash water may be discharged to a sewer, or hauled offsite depending on site specific conditions.
5. Spent media is transferred to a bin or container to remove excess water prior to its disposal to a municipal landfill.
6. To estimate bed life, it is assumed that the well is operated at 50 percent utilization rate.
7. Based on pilot study results, E33 was assumed to treat 73,100 BVs at an assumed influent arsenic level of 20 ppb.
8. E33 unit cost was assumed at $200/cubic feet
9. Power cost: $0.08/kWhr
10. Labor costs:
    a. 520 hours of an operator time at $12/hr
    b. 208 hours of management time at $24/hr

11. Contingencies and allowances:
    a. 10% for instrumentation and control allowance
    b. 15% for electrical allowance
    c. 15% for piping allowance
    d. 8.5% for taxes and bonding
    e. 20% for general contingency
    f. Engineering design, administrative, legal and construction management fees not included
    g. Present worth costs calculated based on 20 years at an effective interest rate of 6%

Table 4.1 summarizes the estimated construction and O&M associated with an adsorption ATF at Weatherford Well #30. The estimated construction cost is $274,000 and does not include any site specific costs such land and unforeseen site issues. The estimated O&M cost is $28,700. The present worth cost for a 150 gpm adsorption ATF is $602,300. The estimated annualized cost for treating 1,000 gallons is estimated at $1.48.

**Table 4.1 Estimated Construction and O&M Costs for Adsorption ATF**

| Construction Cost Summary | |
|---|---:|
| Residuals Handling Facilities | $9,000 |
| Preteatment (Straining) | $11,200 |
| Adsorption Facilities | $129,600 |
| Concrete Support for Treatment Vessels | $20,900 |
| Piping, I&C, Electrical, Yard Piping Allowances | $60,000 |
| Total Facility Cost, $ | $230,700 |
| Contingency, 20% | $46,200 |
| Taxes & Bonding, 8.5% | $23,600 |
| Total Estimated Construction Cost | $300,200 |
| **Annual O&M Costs Summary for E-33 Media** | |
| Annual Power Cost, $/yr | $500 |
| Annual Media Replacement Costs, $/yr | $17,300 |
| Media Replacement Service Cost, $ | $100 |
| Waste Media Disposal Costs, $/yr | $250 |
| Total Estimated Labor Costs, $/yr | $11,200 |
| Equipment Maintenance Costs, $/yr | $3,000 |
| Total Estimated Annual O&M Costs, $/yr | $32,200 |
| Total Present Worth Costs, $ | $669,500 |
| Annualized Costs, $/year | $58,400 |
| Annualized costs/1,000 gallons[1] | $1.48 |

[1.] Based on annual average flow

## 4.2.2 Coagulation/Filtration ATF

Design assumptions for the 150 gpm coagulation/filtration ATF are summarized below:

1. Three pressure vessels, each capable of treating 75 gpm are included to provide redundancy.
    a. Design hydraulic loading rate: 6 gpm/ft$^2$
    b. Vessel dimensions: 48 inches in diameter by 72 inches in height
2. Chemical feed and storage facilities to feed an average ferric chloride dose of 4.0 mg/L are included.
3. pH adjustment is not included.
4. A spent backwash equalization tank is provided. Spent backwash water will be disposed off to a sewer, or hauled off to a wastewater treatment facility. A spent filter backwash recovery system is not included. The estimated costs to haul 5,000 gallons of spent filter backwash water to a wastewater treatment facility within 25 miles of coagulation/filtration ATF is $750. The frequency of spent filter backwash disposal would depend on the filter run length, influent arsenic concentration, ferric chloride dose and well utilization rate. At a well utilization rate of 100 percent and a filter run length of 21 hours, approximately one tanker volume (5000 gallons) of spent filter backwash water would be disposed of per day.
5. A concrete pad is included for installation of the equipment, however, a building is not included.
6. Power cost: $0.08/kWhr
7. Labor costs:
    a. 2080 hours of an operator time at $12/hr
    b. 416 hours of management time at $24/hr
8. Contingencies and allowances:
    a. 10% for instrumentation and control allowance
    b. 15% for electrical allowance
    c. 15% for piping allowance
    d. 8.5% for taxes and bonding
    e. 20% for general contingency
    f. Engineering design, administrative, legal and construction management fees not included
    g. Present worth costs calculated based on 20 years at an effective interest rate of 6%

The estimated construction and O&M costs for a 150 gpm coagulation/filtration ATF are summarized in Table 4.2. The estimated construction cost is $312,400, and do not include any site specific costs such land and unforeseen site issues. The estimated O&M cost is $39,000, and represent higher labor costs associated with a coagulation/filtration facility. The present worth cost for a 150 gpm coagulation/filtration ATF is $759,700. The estimated annualized cost for treating 1,000 gallons is estimated at $1.68. As indicated above, the costs for disposal of spent filter backwash in absence of onsite sewer are not included and can result in significant operational costs.

**Table 4.2 Estimated Construction and O&M Costs for Coagulation/Filtration ATF**

| Construction Capital Cost Summary | |
|---|---|
| Rapid Mixing | $12,000 |
| Granular Media Filters | $117,000 |
| Chemical Feed Systems | $15,800 |
| Backwash Handling | $11,300 |
| Treatment Support Structure | $29,200 |
| Piping, I&C, Electrical, Yard Piping Allowances | $54,600 |
| Total Facility Cost, $ | $239,900 |
| Contingency and Materials Increase, 20% | $48,000 |
| Taxing & Bonding, 8.5% | $24,500 |
| Total Estimated C/F Facility Cost | $312,400 |
| | |
| **Annual O&M Costs Summary** | |
| Annual Power Cost, $/yr | $5,700 |
| FeCl$_3$ Cost, $/yr | $300 |
| Total Estimated Labor Costs, $/yr | $27,000 |
| Equipment Maintenance Costs, $/yr | $6,000 |
| Total Estimated Annual O&M Costs, $/yr | $39,000 |
| Total Present Worth Cost, $ | $759,700 |
| Annualized Costs, $/year | $66,200 |
| Annualized costs/1,000 gallons[1] | $1.68 |

[1] Based on annual average flow

Based on a comparison of the estimated present worth and annualized costs, an adsorption based ATF appears to be more cost effective than a coagulation/filtration based ATF for Well #30. It should be noted that a performance criteria was assumed for E33 media and any deviations from the assumption may result in different estimated costs, and therefore the observed conclusion.

Besides the overall costs, an adsorption based ATF would require less labor, chemicals, residuals generation, and equipment maintenance compared to a coagulation/filtration based ATF.

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# ABBREVIATIONS

| | |
|---|---|
| ATF | arsenic treatment facility |
| AwwaRF | American Water Works Association Research Foundation |
| BV | bed volume |
| C/F | Coagulation/Filtration |
| CWS | Community Water Supply |
| DEQ | Department of Environmental Quality |
| EBCT | empty bed contact time |
| EPDS | entry points to the distribution system |
| FRP | fiber reinforced plastic |
| GIM | granular iron media |
| gpm | gallons per minute |
| GTO | Granular Titanium Oxide |
| IX | Ion Exchange |
| LTS | Legend Technical Services |
| MCL | maximum contaminant level |
| MGD | million gallons per day |
| mg/L | milligrams per liter |
| µg/L | micrograms per liter |
| NCS | Narasimhan Consulting Services, Inc. |
| NSF | National Sanitation Foundation |
| NTNCWS | non-transient non-community water system |
| NTU | nephelometric turbidity units |
| O&M | operations and maintenance |
| ppb | parts per billion |
| POU | point-of-use |
| psi | pounds per square inch |
| PVC | polyvinyl chloride |
| PWS | public water system |
| RCRA | Resource Conservation and Recovery Act |
| SNL | Sandia National Laboratories |
| TCLP | Toxicity Characteristics Leaching Procedure |

TDS   Total Dissolved Solids

USEPA  U.S. Environmental Protection Agency

WERC  A Consortium for Environmental Education and Technology Development

WQL   Water Quality Laboratory

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