

**Arsenic Removal from Drinking Water by Adsorptive Media
U.S. EPA Demonstration Project at Oak Manor Municipal Utility
District at Alvin, TX
Six-Month Evaluation Report**

by

**H. Tien Shiao
Lili Wang
Abraham S.C. Chen**

**Battelle
Columbus, OH 43201-2693**

**Contract No. 68-C-00-185
Task Order No. 0029**

for

**Thomas J. Sorg
Task Order Manager**

**Water Supply and Water Resources Division
National Risk Management Research Laboratory
Cincinnati, Ohio 45268**

**National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268**

DISCLAIMER

The work reported in this document was funded by the United States Environmental Protection Agency (EPA) under Task Order 0029 of Contract 68-C-00-185 to Battelle. It has been subjected to the Agency's peer and administrative reviews and has been approved for publication as an EPA document. Any opinions expressed in this paper are those of the author(s) and do not, necessarily, reflect the official positions and policies of the EPA. Any mention of products or trade names does not constitute recommendation for use by the EPA.

FOREWORD

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

ABSTRACT

This report documents the activities performed and the results obtained from the first six months of the EPA arsenic removal technology demonstration project at the Oak Manor Municipal Utility District (MUD) facility at Alvin, TX. The main objective of the project is to evaluate the effectiveness of the Severn Trent Services (STS) Arsenic Package Unit (APU)-30S in removing arsenic to meet the maximum contaminant level (MCL) of 10 µg/L. Additionally, this project evaluates 1) the reliability of the treatment system for use at small water facilities, 2) the required system operation and maintenance (O&M) and operator skill levels, and 3) the capital and O&M cost of the technology. The project also characterizes water in the distribution system and residuals generated by the treatment process. The types of data collected include system operation, water quality, process residuals, and capital and O&M costs.

After approval of a pilot-study exception request and engineering plans by the Texas Commission of Environmental Quality (TCEQ), the APU-30S system was installed and started up on April 25, 2006. The system consisted of two 63-in-diameter and 86-in-tall adsorption vessels configured in series with 53.6 ft³ of SORB 33™ in the lead vessel and 70.3 ft³ in the lag vessel, gas prechlorination equipment, sample taps, and associated instrumentation. At the design flowrate of 150 gal/min (gpm), the system had a hydraulic loading rate of 6.9 gpm/ft² and an empty bed contact time (EBCT) of 6.2 min. Based on the actual flowrate of only 134 gpm, the system operated at a hydraulic loading of 6.2 gpm/ft² and an EBCT of 6.9 min.

Source water supplied by two wells (Well 1 and 2) had a combined average concentration of 43.8 µg/L for total arsenic, with As(III) as the predominating soluble species at 35.2 µg/L. Iron existed mostly in the particulate form, with concentrations ranging from 34.2 to 100 µg/L and averaging 60.5 µg/L. Total manganese concentrations averaged 54.4 µg/L, existing almost entirely in the soluble form. After prechlorination, As(III) was effectively oxidized to As(V), with concentrations averaging 0.6 and 27.1 µg/L, respectively. Somewhat unexpectedly, Mn(II) also was effectively oxidized, presumably, to MnO₂, leaving only 2.8 µg/L (or 6.5%) in the chlorinated water.

By the end of the first six months of system operation after treating approximately 11,241,500 gal (12,170 bed volumes [BV]) of water (1 BV = 124 ft³ of media in both the lead and lag vessels), arsenic concentration was 10.2 µg/L after the lead vessel and 1.4 µg/L following the lag vessel. Because the arsenic concentration following the lag vessel did not reach 10 µg/L, the media in the lead vessel was not changed out during the first six months of system operation.

Comparison of the distribution system sampling results before and after the system startup showed a considerable decrease in arsenic (38.2 to 2.0 µg/L), iron (115 to <25 µg/L), and manganese concentration (41.8 to 1.3 µg/L). Alkalinity, pH, lead, and copper did not appear to be affected.

Backwash was manually initiated by the operator when differential pressure across Vessel A reached 10 lb/in² (psi), which occurred four times during the six-month period. About 6,058 gal/vessel/event of wastewater was discharged to the roadside ditch during each backwash event. Approximately 14.9 lb of solids were discharged from Vessel A, including 4.2×10^{-5} lb of arsenic, 0.9 lb of iron, and 0.08 lb of manganese. Approximately 2.9 lb of solids were discharged from Vessel B, including 1.5×10^{-4} lb of arsenic, 0.2 lb of iron, and 0.03 lb of manganese. The reasons for the large amount of solids produced are being investigated and will be reported in the Final Performance Evaluation Report.

The capital investment for the system was \$179,750 consisting of \$124,103 for equipment, \$14,000 for site engineering, and \$41,647 for installation, shakedown, and startup. Using the system's rated capacity

of 150 gpm (or 216,000 gal/day [gpd]), the capital cost was \$1,198/gpm (or \$0.83/gpd). This calculation does not include the cost of the building to house the treatment system.

O&M cost, estimated at \$0.21/1,000 gal, included only the incremental cost for labor. There was no incremental electricity cost or chemical consumption cost since gas chlorination was already performed prior to the demonstration study.

CONTENTS

DISCLAIMER	ii
FOREWORD	iii
ABSTRACT	iv
FIGURES	vii
TABLES	vii
ABBREVIATIONS AND ACRONYMS	ix
ACKNOWLEDGMENTS	xi
 Section 1.0 INTRODUCTION	 1
1.1 Background	1
1.2 Treatment Technologies for Arsenic Removal.....	2
1.3 Project Objectives.....	2
 Section 2.0 SUMMARY AND CONCLUSIONS	 5
 Section 3.0 MATERIALS AND METHODS.....	 6
3.1 General Project Approach	6
3.2 System O&M and Cost Data Collection	7
3.3 Sample Collection Procedures and Schedules.....	8
3.3.1 Source Water	9
3.3.2 Treatment Plant Water.....	9
3.3.3 Backwash Water	9
3.3.4 Distribution System Water	9
3.3.5 Residual Solids	9
3.4 Sampling Logistics	11
3.4.1 Preparation of Arsenic Speciation Kits.....	11
3.4.2 Preparation of Sampling Coolers.....	11
3.4.3 Sample Shipping and Handling	11
3.5 Analytical Procedures.....	11
 Section 4.0 SITE BACKGROUND	 13
4.1 Site Description	13
4.1.1 Existing Facility.....	13
4.1.2 Source Water Quality	15
4.1.3 Treated Water Quality	17
4.1.4 Distribution System and Regulatory Monitoring	17
4.2 Treatment Process Description.....	17
4.3 Treatment System Installation.....	24
4.3.1 System Permitting.....	24
4.3.2 Building Construction.....	24
4.3.3 System Installation, Shakedown, and Startup.....	26
4.3.4 Media Loading	28
4.3.5 Punch List Items	28
4.4 System Operation	31
4.4.1 Operational Parameters.....	31
4.4.2 Residual Management	32
4.4.3 Reliability and Simplicity of Operation.....	32
4.5 System Performance.....	35
4.5.1 Treatment Plant Sampling	35

4.5.2 Backwash Water Sampling.....	43
4.5.3 Distribution System Water Sampling	43
4.6 System Cost.....	45
4.6.1 Capital Cost	45
4.6.2 Operation and Maintenance Cost.....	45
Section 5.0 REFERENCES	48

FIGURES

Figure 3-1. Process Flow Diagram and Sampling Schedule and Locations	10
Figure 4-1. Preexisting Chlorine Addition Point and Wells 1 and 2 Blending Point	13
Figure 4-2. Preexisting Storage Tank and Hydropneumatic Tank.....	14
Figure 4-3. Preexisting Polyphosphate Addition Point.....	14
Figure 4-4. Booster Pumps and Entry Piping to Distribution System	15
Figure 4-5. Photograph of APU-30S Arsenic Removal System.....	19
Figure 4-6a. Process Flow Diagram for APU-30S System with Vessel A in Lead Position.....	20
Figure 4-6b. Process Flow Diagram for APU-30S System with Vessel B in Lead Position.....	21
Figure 4-7. Gas Chlorination System.....	23
Figure 4-8. APU-30S System Valve Tree and Piping Configuration	23
Figure 4-9. Valve MB-127 to Supply Additional Treated Water from Hydropneumatic Tank During Backwash	25
Figure 4-10. Small Ditch	25
Figure 4-11. Construction of Concrete Pad with Storage Tank and Hydropneumatic Tank	27
Figure 4-12. Photograph of Piping, Sample Taps, and Chlorine Injection Point Prior to Treatment System	30
Figure 4-13. System Pressure Readings.....	33
Figure 4-14. Concentrations of Various Arsenic Species at IN, AP, TA, and TB Sampling Locations	39
Figure 4-15. Total Arsenic Breakthrough Curves.....	40
Figure 4-16. Chlorine Consumption Based on Chlorine Gas Usage	41
Figure 4-17. Media Replacement and Operation and Maintenance Cost	47

TABLES

Table 1-1. Summary of the Arsenic Removal Demonstration Sites.....	3
Table 3-1. Predemonstration Study Activities and Completion Dates	6
Table 3-2. Evaluation Objectives and Supporting Data Collection Activities	7
Table 3-3. Sampling Schedule and Analyses	8
Table 4-1. Water Quality Data for Oak Manor MUD	16
Table 4-2. Physical and Chemical Properties of SORB 33 TM Media	18
Table 4-3. Design Specifications for STS APU-30S System.....	22
Table 4-4. Freeboard Measurements and Media Volumes in Adsorption Vessels.....	28
Table 4-5. System Inspection Punch-List Items	29
Table 4-6. Summary of APU-30S System Operations	31
Table 4-7. System Instantaneous and Calculated Flowrates	32
Table 4-8. Time Lapse Since Last Backwash.....	33
Table 4-9. Summary of Analytical Results for Arsenic, Iron, and Manganese	36
Table 4-10. Summary of Other Water Quality Sampling Results	37

Table 4-11.	Amount of Mn(II) Precipitated After Chlorination at 11 Arsenic Removal Demonstration Sites	42
Table 4-12.	Backwash Water Sampling Results	43
Table 4-13.	Distribution Water Sampling Results.....	44
Table 4-14.	Capital Investment Cost for APU-30S System	46
Table 4-15.	Operation and Maintenance Cost for APU-30S System	46

ABBREVIATIONS AND ACRONYMS

Δp	differential pressure
AAL	American Analytical Laboratories
Al	aluminum
AM	adsorptive media
APU	arsenic package unit
As	arsenic
ATS	Aquatic Treatment Systems
BET	Brunauer, Emmett, and Teller
BV	bed volume(s)
Ca	calcium
CCR	Consumer Confidence Report
C/F	coagulation/filtration
Cl	chlorine
CRF	capital recovery factor
Cu	copper
DO	dissolved oxygen
EBCT	empty bed contact time
EPA	U.S. Environmental Protection Agency
F	fluoride
Fe	iron
FedEx	Federal Express
FRP	fiberglass reinforced plastic
gpd	gallons per day
gpm	gallons per minute
HIX	hybrid ion exchanger
hp	horsepower
ICP-MS	inductively coupled plasma-mass spectrometry
ID	identification
IX	ion exchange
LCR	(EPA) Lead and Copper Rule
MCL	maximum contaminant level
MDL	method detection limit
MEI	Magnesium Elektron, Inc.
Mg	magnesium
μm	micrometer
Mn	manganese
MUD	Municipal Utility District

mV	millivolts
Na	sodium
NA	not analyzed
NS	not sampled
NSF	NSF International
NTU	nephelometric turbidity units
O&M	operation and maintenance
OIT	Oregon Institute of Technology
ORD	Office of Research and Development
ORP	oxidation-reduction potential
P	phosphorus
P&ID	pipng and instrumentation diagram
Pb	lead
pCi/L	picocuries per liter
psi	pounds per square inch
PLC	programmable logic controller
PO ₄	phosphate
POU	point-of-use
PVC	polyvinyl chloride
QA	quality assurance
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RPD	relative percent difference
RO	reverse osmosis
Sb	antimony
SDWA	Safe Drinking Water Act
SiO ₂	silica
SMCL	secondary maximum contaminant level
SO ₄	sulfate
STS	Severn Trent Services
TBD	to be determined
TCLP	Toxicity Characteristic Leaching Procedure
TCEQ	Texas Commission of Environmental Quality
TDS	total dissolved solids
TOC	total organic carbon
TSS	total suspended solids
UPS	United Parcel Service
V	vanadium
VOC	volatile organic compound(s)

ACKNOWLEDGMENTS

The authors wish to extend their sincere appreciation to the system operator, Mr. Jose Chavez, of Oak Manor Municipal Utility District (MUD) in Alvin, TX. Mr. Chavez monitored the treatment system and collected samples from the treatment and distribution systems on a regular schedule throughout this study period. This performance evaluation would not have been possible without his support and dedication.

Section 1.0 INTRODUCTION

1.1 Project Background

The Safe Drinking Water Act (SDWA) mandates that U.S. Environmental Protection Agency (EPA) identify and regulate drinking water contaminants that may have adverse human health effects and that are known or anticipated to occur in public water supply systems. In 1975 under the SDWA, EPA established a maximum contaminant level (MCL) for arsenic at 0.05 mg/L. Amended in 1996, the SDWA required that EPA develop an arsenic research strategy and publish a proposal to revise the arsenic MCL by January 2000. On January 18, 2001, EPA finalized the arsenic MCL at 0.01 mg/L (EPA, 2001). In order to clarify the implementation of the original rule, EPA revised the rule on March 25, 2003 to express the MCL as 0.010 mg/L (10 µg/L) (EPA, 2003). The final rule requires all community and non-transient, non-community water systems to comply with the new standard by January 23, 2006.

In October 2001, EPA announced an initiative for additional research and development of cost-effective technologies to help small community water systems (<10,000 customers) meet the new arsenic standard and to provide technical assistance to operators of small systems in order to reduce compliance costs. As part of this Arsenic Rule Implementation Research Program, EPA's Office of Research and Development (ORD) proposed a project to conduct a series of full-scale, on-site demonstrations of arsenic removal technologies, process modifications, and engineering approaches applicable to small systems. Shortly thereafter, an announcement was published in the *Federal Register* requesting water utilities interested in participating in Round 1 of this EPA-sponsored demonstration program to provide information on their water systems. In June 2002, EPA selected 17 out of 115 sites to host the demonstration studies.

In September 2002, EPA solicited proposals from engineering firms and vendors for cost-effective arsenic removal treatment technologies for the 17 host sites. EPA received 70 technical proposals for the 17 host sites, with each site receiving one to six proposals. In April 2003, an independent technical panel reviewed the proposals and provided its recommendations to EPA on the technologies that it determined were acceptable for the demonstration at each site. Because of funding limitations and other technical reasons, only 12 of the 17 sites were selected for the demonstration project. Using the information provided by the review panel, EPA, in cooperation with the host sites and the drinking water programs of the respective states, selected one technical proposal for each site.

In 2003, EPA initiated Round 2 arsenic technology demonstration projects that were partially funded with Congressional add-on funding to the EPA budget. In June 2003, EPA selected 32 potential demonstration sites and the Oak Manor Municipal Utility District (MUD) water system in Alvin, TX was one of those selected.

In September 2003, EPA, again, solicited proposals from engineering firms and vendors for arsenic removal technologies. EPA received 148 technical proposals for the 32 host sites, with each site receiving from two to eight proposals. In April 2004, another technical panel was convened by EPA to review the proposals and provide recommendations to EPA with the number of proposals per site ranging from none (for two sites) to a maximum of four. The final selection of the treatment technology at the sites that received at least one proposal was made, again, through a joint effort by EPA, the state regulators, and the host site. Since then, four sites have withdrawn from the demonstration program, reducing the number of sites to 28. Severn Trent Service's (STS) SORB 33TM Arsenic Removal Technology was selected for demonstration at the Oak Manor MUD facility.

As of January 2008, 37 of the 40 systems were operational and the performance evaluation of 26 systems were completed.

1.2 Treatment Technologies for Arsenic Removal

The technologies selected for the Round 1 and Round 2 demonstration host sites include 25 adsorptive media (AM) systems (the Oregon Institute of Technology [OIT] site has three AM systems), 13 coagulation/filtration (C/F) systems, two ion exchange (IX) systems, and 17 point-of-use (POU) units (including nine under-the-sink reverse osmosis [RO] units at the Sunset Ranch Development site and eight AM units at the OIT site), and one system modification. Table 1-1 summarizes the locations, technologies, vendors, system flowrates, and key source water quality parameters (including As, Fe, and pH) at the 40 demonstration sites. An overview of the technology selection and system design for the 12 Round 1 demonstration sites and the associated capital costs is provided in two EPA reports (Wang et al., 2004; Chen et al., 2004), which are posted on the EPA website at <http://www.epa.gov/ORD/NRMRL/wswrd/dw/arsenic/index.html>.

1.3 Project Objectives

The objective of the arsenic demonstration program is to conduct 40 full-scale arsenic treatment technology demonstration studies on the removal of arsenic from drinking water supplies. The specific objectives are to:

- Evaluate the performance of the arsenic removal technologies for use on small systems.
- Determine the required system operation and maintenance (O&M) and operator skill levels.
- Characterize process residuals produced by the technologies.
- Determine the capital and O&M cost of the technologies.

This report summarizes the performance of STS's system at the Oak Manor MUD in Alvin, TX during the first six months from April 25 through October 25, 2006. The types of data collected included system operation, water quality (both across the treatment train and in the distribution system), residuals, and capital and preliminary O&M cost.

Table 1-1. Summary of Arsenic Removal Demonstration Sites

Demonstration Location	Site Name	Technology (Media)	Vendor	Design Flowrate (gpm)	Source Water Quality		
					As (µg/L)	Fe (µg/L)	pH (S.U.)
Northeast/Ohio							
Wales, ME	Springbrook Mobile Home Park	AM (A/I Complex)	ATS	14	38 ^(a)	<25	8.6
Bow, NH	White Rock Water Company	AM (G2)	ADI	70 ^(b)	39	<25	7.7
Goffstown, NH	Orchard Highlands Subdivision	AM (E33)	AdEdge	10	33	<25	6.9
Rollinsford, NH	Rollinsford Water and Sewer District	AM (E33)	AdEdge	100	36 ^(a)	46	8.2
Dummerston, VT	Charette Mobile Home Park	AM (A/I Complex)	ATS	22	30	<25	7.9
Felton, DE	Town of Felton	C/F (Macrolite)	Kinetico	375	30 ^(a)	48	8.2
Stevensville, MD	Queen Anne's County	AM (E33)	STS	300	19 ^(a)	270 ^(c)	7.3
Houghton, NY ^(d)	Town of Caneadea	C/F (Macrolite)	Kinetico	550	27 ^(a)	1,806 ^(c)	7.6
Newark, OH	Buckeye Lake Head Start Building	AM (ARM 200)	Kinetico	10	15 ^(a)	1,312 ^(c)	7.6
Springfield, OH	Chateau Estates Mobile Home Park	AM (E33)	AdEdge	250 ^(e)	25 ^(a)	1,615 ^(c)	7.3
Great Lakes/Interior Plains							
Brown City, MI	City of Brown City	AM (E33)	STS	640	14 ^(a)	127 ^(c)	7.3
Pentwater, MI	Village of Pentwater	C/F (Macrolite)	Kinetico	400	13 ^(a)	466 ^(c)	6.9
Sandusky, MI	City of Sandusky	C/F (Aeralater)	Siemens	340 ^(e)	16 ^(a)	1,387 ^(c)	6.9
Delavan, WI	Vintage on the Ponds	C/F (Macrolite)	Kinetico	40	20 ^(a)	1,499 ^(c)	7.5
Greenville, WI	Town of Greenville	C/F (Macrolite)	Kinetico	375	17	7827 ^(c)	7.3
Climax, MN	City of Climax	C/F (Macrolite)	Kinetico	140	39 ^(a)	546 ^(c)	7.4
Sabin, MN	City of Sabin	C/F (Macrolite)	Kinetico	250	34	1,470 ^(c)	7.3
Sauk Centre, MN	Big Sauk Lake Mobile Home Park	C/F (Macrolite)	Kinetico	20	25 ^(a)	3,078 ^(c)	7.1
Stewart, MN	City of Stewart	C/F&AM (E33)	AdEdge	250	42 ^(a)	1,344 ^(c)	7.7
Lidgerwood, ND	City of Lidgerwood	Process Modification	Kinetico	250	146 ^(a)	1,325 ^(c)	7.2
Midwest/Southwest							
Arnaudville, LA	United Water Systems	C/F (Macrolite)	Kinetico	770 ^(e)	35 ^(a)	2,068 ^(c)	7.0
Alvin, TX	Oak Manor Municipal Utility District	AM (E33)	STS	150	19 ^(a)	95	7.8
Bruni, TX	Webb Consolidated Independent School District	AM (E33)	AdEdge	40	56 ^(a)	<25	8.0
Wellman, TX	City of Wellman	AM (E33)	AdEdge	100	45	<25	7.7
Anthony, NM	Desert Sands Mutual Domestic Water Consumers Association	AM (E33)	STS	320	23 ^(a)	39	7.7
Nambe Pueblo, NM	Nambe Pueblo Tribe	AM (E33)	AdEdge	145	33	<25	8.5
Taos, NM	Town of Taos	AM (E33)	STS	450	14	59	9.5
Rimrock, AZ	Arizona Water Company	AM (E33)	AdEdge	90 ^(b)	50	170	7.2
Tohono O'odham Nation, AZ	Tohono O'odham Utility Authority	AM (E33)	AdEdge	50	32	<25	8.2
Valley Vista, AZ	Arizona Water Company	AM (AAFS50/ARM 200)	Kinetico	37	41	<25	7.8

Table 1-1. Summary of Arsenic Removal Demonstration Sites (Continued)

Demonstration Location	Site Name	Technology (Media)	Vendor	Design Flowrate (gpm)	Source Water Quality		
					As (µg/L)	Fe (µg/L)	pH (S.U.)
Far West							
Three Forks, MT	City of Three Forks	C/F (Macrolite)	Kinetico	250	64	<25	7.5
Fruitland, ID	City of Fruitland	IX (A300E)	Kinetico	250	44	<25	7.4
Homedale, ID	Sunset Ranch Development	POU RO ^(f)	Kinetico	75 gpd	52	134	7.5
Okanogan, WA	City of Okanogan	C/F (Electromedia-I)	Filtronics	750	18	69 ^(c)	8.0
Klamath Falls, OR	Oregon Institute of Technology	POE AM (Adsorbsia/ARM 200/ArsenX ^{np}) and POU AM (ARM 200) ^(g)	Kinetico	60/60/30	33	<25	7.9
Vale, OR	City of Vale	IX (Arsenex II)	Kinetico	525	17	<25	7.5
Reno, NV	South Truckee Meadows General Improvement District	AM (GFH/Kemiron)	Siemens	350	39	<25	7.4
Susanville, CA	Richmond School District	AM (A/I Complex)	ATS	12	37 ^(a)	125	7.5
Lake Isabella, CA	Upper Bodfish Well CH2-A	AM (HIX)	VEETech	50	35	125	7.5
Tehachapi, CA	Golden Hills Community Service District	AM (Isolux)	MEI	150	15	<25	6.9

AM = adsorptive media; C/F = coagulation/filtration; HIX = hybrid ion exchanger; IX = ion exchange; RO = reverse osmosis

ATS = Aquatic Treatment Systems; MEI = Magnesium Elektron, Inc.; STS = Severn Trent Services

(a) Arsenic existing mostly as As(III).

(b) Design flowrate reduced by 50% due to system reconfiguration from parallel to series operation.

(c) Iron existing mostly as Fe(II).

(d) Replaced Village of Lyman, NE site which withdrew from program in June 2006.

(e) Facilities upgraded systems in Springfield, OH from 150 to 250 gpm, Sandusky, MI from 210 to 340 gpm, and Arnaudville, LA from 385 to 770 gpm.

(f) Including nine residential units.

(g) Including eight under-the-sink units.

Section 2.0 SUMMARY AND CONCLUSIONS

Severn Trent Service's APU-30S treatment system has been operating at the Alvin, TX location since April 25, 2006. Based on the information collected during the first six months of operation, the following summary and preliminary conclusions were made relating to the overall project objectives.

Performance of the arsenic removal technology for use on small systems:

- Chlorination was highly effective in oxidizing As(III) to As(V), reducing As(III) concentration from 35.2 µg/L (on average) in raw water to 0.6 µg/L after chlorination. Chlorination also was effective in oxidizing Mn(II), reducing it from 54.0 to 2.8 µg/L.
- SORB 33™ media effectively removed arsenic to 1.4 µg/L after treating 11,241,500 gal, or 12,170 bed volumes (BV), of water. (BV was calculated based on the 124 ft³ of media in both the lead and lag vessels).
- Backwash at an average loading rate of 12.0 gpm/ft² was effective in restoring differential pressure (Δp) across the media beds, reducing it from about 10 psi, a pre-determined backwash trigger point, to an initial level of about 3.5 psi. Although equipped with required automatic features, manually triggered backwashes were preferred by the operator and performed during the six-month study period.
- Since system startup, changes to the water quality in the distribution system occurred, which included significant decreases in arsenic, iron, and manganese concentrations from 38.2 to 2.0 µg/L, from 115 to <25 µg/L, and from 41.8 to 1.3 µg/L, respectively. pH, alkalinity, lead, and copper remained unchanged.

Required system O&M and operator skill levels:

- The daily demand on the operator's time was reasonable, typically about 40 min/day to visually inspect the system and record operational parameters.
- The system was easy to operate and experienced no downtime although operational irregularities were experienced with Vessel A's flowmeter/totalizer, an automatic valve, and system's parallel default settings.

Characteristics of residuals produced by the technology:

- A relatively large quantity of solids was produced during each backwash event, including 14.9 lb from Tank A and 2.9 lb from Tank B based on averaged total suspended solids (TSS) results. Arsenic constituted only a fraction of the solids, i.e., $<1.5 \times 10^{-4}$ lb.

Capital and O&M cost of the technology:

- The capital investment for the system was \$179,750 consisting of \$124,103 for equipment, \$14,000 for site engineering, and \$41,647 for installation, shakedown, and startup. The building was funded by the city and not included in this cost. The unit capital cost was \$1,198/gpm (or \$0.83/gpd) based on a 150-gpm design capacity.
- The O&M cost, estimated at \$0.21/1,000 gal, included only incremental cost for system operation labor.

Section 3.0 MATERIALS AND METHODS

3.1 General Project Approach

Following the predemonstration activities summarized in Table 3-1, the performance evaluation study of the STS treatment system began on April 25, 2006. Table 3-2 summarizes the types of data collected and considered as part of the technology evaluation process. The overall system performance was evaluated based on its ability to consistently remove arsenic to below the target MCL of 10 µg/L through the collection of water samples across the treatment train. The reliability of the system was evaluated by tracking the unscheduled system downtime and frequency and extent of repair and replacement. The unscheduled downtime and repair information were recorded by the plant operator on a Repair and Maintenance Log Sheet.

The O&M and operator skill requirements were evaluated based on a combination of quantitative data and qualitative considerations, including the need for pre- and/or post-treatment, level of system automation, extent of preventative maintenance activities, frequency of chemical and/or media handling and inventory, and general knowledge needed for relevant chemical processes and related health and safety practices. The staffing requirements for the system operation were recorded on an Operator Labor Hour Log Sheet.

The quantity of aqueous and solid residuals generated was estimated by tracking the volume of backwash water produced during each backwash cycle. Backwash water was sampled and analyzed for chemical characteristics.

Table 3-1. Predemonstration Study Activities and Completion Dates

Activity	Date
Introductory Meeting Held	November 2, 2004
Draft Letter of Understanding Issued	January 21, 2005
Final Letter of Understanding Issued	February 8, 2005
Request for Quotation Issued to Vendor	February 14, 2005
Vendor Quotation Received	March 20, 2005
Purchase Order Established	May 3, 2005
Letter Report Issued	May 12, 2005
Exception Request Submitted to TCEQ	July 8, 2005
APU-30S System Shipped	September 4, 2005
Engineering Package Submitted to TCEQ	September 9, 2005
Building Construction Begun	October 6, 2005
Building Completed	November 12, 2005
Exception Request Granted by TCEQ	November 21, 2005
System Permit Granted by TCEQ	December 16, 2005
Study Plan Issued	January 13, 2006
System Installation Completed	March 9, 2006
System Shakedown Completed	March 10, 2006
Performance Evaluation Begun	April 25, 2006

TCEQ = Texas Department of Environmental Quality

Table 3-2. Evaluation Objectives and Supporting Data Collection Activities

Evaluation Objective	Data Collection
Performance	-Ability to consistently meet 10 µg/L arsenic MCL in treated water
Reliability	-Unscheduled system downtime -Frequency and extent of repairs including a description of problems, materials and supplies needed, and associated labor and cost
System O&M and Operator Skill Requirements	-Pre- and post-treatment requirements -Level of automation for system operation and data collection -Staffing requirements including number of operators and laborers -Task analysis of preventative maintenance including number, frequency, and complexity of tasks -Chemical handling and inventory requirements -General knowledge needed for relevant chemical processes and health and safety practices
Residual Management	-Quantity and characteristics of aqueous and solid residuals generated by system operation
System Cost	-Capital cost for equipment, engineering, and installation -O&M cost for chemical usage, electricity consumption, and labor

The cost of the system was evaluated based on the capital cost per gal/min (gpm) (or gal/day [gpd]) of design capacity and the O&M cost per 1,000 gal of water treated. This task required tracking the capital cost for equipment, engineering, and installation, as well as the O&M cost for media replacement and disposal, electricity usage, and labor.

3.2 System O&M and Cost Data Collection

The plant operator performed daily, biweekly, and monthly system O&M and data collection according to instructions provided by the vendor and Battelle. On a daily basis (except for most Saturdays and Sundays), the plant operator recorded system operational data, such as pressure, flowrate, totalizer, and hour meter readings on a Daily System Operation Log Sheet; checked weight of the chlorine gas cylinder; and conducted visual inspections to ensure normal system operations. If any problem occurred, the plant operator contacted the Battelle Study Lead, who determined if the vendor should be contacted for troubleshooting. The plant operator recorded all relevant information, including the problems encountered, course of actions taken, materials and supplies used, and associated cost and labor incurred, on a Repair and Maintenance Log Sheet. On a weekly basis, the plant operator measured several water quality parameters on-site, including temperature, pH, dissolved oxygen (DO), oxidation-reduction potential (ORP), and residual chlorine, and recorded the data on an On-Site Water Quality Parameters Log Sheet. Monthly (or as needed) backwash data also were recorded on a Backwash Log Sheet.

The capital cost for the arsenic removal system consisted of the cost for equipment, site engineering, and system installation. The O&M cost consisted of the cost for electricity consumption and labor. The gas chlorine consumption was tracked on the Daily System Operation Log Sheet. Because the chemical addition system was preexisting, chlorine consumption was not counted towards the O&M cost. Electricity consumption was determined from utility bills. Labor for various activities, such as routine system O&M, troubleshooting and repairs, and demonstration-related work, were tracked using an Operator Labor Hour Log Sheet. The routine system O&M included activities such as completing field logs, replacing the chlorine gas cylinder, ordering supplies, performing system inspections, and others as recommended by the vendor. The labor for demonstration-related work, including activities such as performing field measurements, collecting and shipping samples, and communicating with the Battelle Study Lead and the vendor, was recorded, but not used for the cost analysis.

3.3 Sample Collection Procedures and Schedules

To evaluate system performance, samples were collected at the wellhead, across the treatment system, during APU-30S filter backwash, and from the distribution system. The sample types and locations, number of samples taken, and analytes measured during each sampling event are listed in Table 3-3.

Table 3-3. Sampling Schedule and Analyses

Sample Type	Sample Locations	No. of Samples	Frequency	Analytes	Collection Date(s)
Source Water	IN	1	Once (during initial site visit)	On-site: pH, temperature, DO, and ORP Off-site: As(III), As(V), As (total and soluble), Fe (total and soluble), Mn (total and soluble), U (total and soluble), V (total and soluble), Na, Ca, Mg, Cl, F, NO ₃ , NO ₂ , NH ₃ , SO ₄ , SiO ₂ , PO ₄ , turbidity, alkalinity, TDS, and TOC	11/02/04; additional source water samples taken 02/16/05 (see Table 4-1)
Treatment Plant Water	IN, AC, TA, TB	4	Monthly (first week of each four-week cycle)	On-site: pH, temperature, DO, ORP, and Cl ₂ (free and total) ^(a) Off-site: As(III), As(V), As (total and soluble), Fe (total and soluble), Mn (total and soluble), Ca, Mg, F, NO ₃ , SO ₄ , SiO ₂ , P, turbidity, and alkalinity	See Appendix B
			Monthly (third week of each four-week cycle)	On-site: pH, temperature, DO, ORP, Cl ₂ (free and total) ^(a) Off-site: As (total), Fe (total), Mn (total), SiO ₂ , P, turbidity, and alkalinity	See Appendix B
Backwash Water	Backwash Discharge Line from Each Vessel	2	Monthly or as needed	As(total and soluble), Fe(total and soluble), Mn(total and soluble), pH, TDS, and TSS	See Table 4-12
Distribution Water	One LCR and Two Non-LCR Residences	3	Monthly	As (total), Fe (total), Mn (total), Cu (total), Pb (total), pH, and alkalinity	See Table 4-13
Residual Solids	Spent Media	TBD	TBD	TCLP and total Al, As, Ca, Cd, Cu, Fe, Mg, Mn, Ni, P, Pb, Si, and Zn	TBD

AC = after chlorination, IN = wellhead, TA = after lead vessel, TB = after lag vessel, TBD = to be determined; TCLP = toxicity characteristic leaching procedure

(a) On-site chlorine measurements not collected at IN.

In addition, Figure 3-1 presents a flow diagram of the treatment system along with the analytes and schedules at each sampling location. Specific sampling requirements for analytical methods, sample volumes, containers, preservation, and holding times are presented in Table 4-1 of the EPA-endorsed Quality Assurance Project Plan (QAPP) (Battelle, 2004). The procedure for arsenic speciation is described in Appendix A of the QAPP.

3.3.1 Source Water. During the initial visit to the site on November 2, 2004, one set of raw water samples was collected from Well 2 and speciated using an arsenic speciation kit (see Section 3.4.1). The sample tap was flushed for several minutes before sampling; special care was taken to avoid agitation, which might cause unwanted oxidation. Analytes for the source water samples are listed in Table 3-3. Additional source water samples were taken on February 16, 2005, for Wells 1 and 2.

3.3.2 Treatment Plant Water. During the system performance evaluation study, biweekly water samples were collected across the treatment train by the plant operator for on- and off-site analyses. During the first week of each four-week cycle, samples were collected at the wellhead (IN), after chlorination (AC), after the lead adsorption vessel (TA), and after the lag adsorption vessel (TB) and analyzed for the analytes listed on Table 3-3. During the third week of the four-week cycle, samples were taken from the same four locations and analyzed for the analyte list shown on Table 3-3.

3.3.3 Backwash Water. Backwash water samples were collected from both vessels by the plant operator when the pressure differential across the lead vessel had reached 10 psi. Tubing, connected to the tap on the discharge line, directed a portion of backwash water at about 1 gpm into a clean, 32-gal container over the duration of the backwash for each tank. After the content in the container was thoroughly mixed, composite samples were collected and/or filtered on-site with 0.45- μ m filters. Analytes for the backwash samples are listed in Table 3-3.

3.3.4 Distribution System Water. Water samples were collected from the distribution system to determine the impact of the arsenic treatment system on the water chemistry in the distribution system, specifically, the arsenic, lead, and copper levels. Prior to system startup from March to June 2005, four sets of monthly baseline water samples were collected from three residences, designated as DS1, DS2, and DS3, within the distribution system. The DS1 residence located originally on Oak Manor Drive was sampled only twice in March and April before being changed to another location on Oak Trail. The DS2 residence located originally on Shady Oak Drive was sampled only once in March. Because the home owner was not available to take samples in April, another location on Shady Oak Drive was selected for May and June baseline sampling. The DS3 residence located on Kenny Court was used for all four baseline sampling events. Following system startup, distribution system sampling continued on a monthly basis at the same three locations as discussed.

The homeowners collected samples following an instruction sheet developed according to the *Lead and Copper Monitoring and Reporting Guidance for Public Water Systems* (EPA, 2002). The dates and times of last water usage before sampling and sample collection were recorded for calculation of the stagnation time. All first-draw samples were collected from a cold-water faucet that had not been used for at least 6 hr to ensure that stagnant water was sampled. Analytes for the baseline and monthly samples are listed in Table 3-3.

3.3.5 Residual Solids. Since media replacement did not take place during the initial six months of this demonstration, no spent media samples were collected.

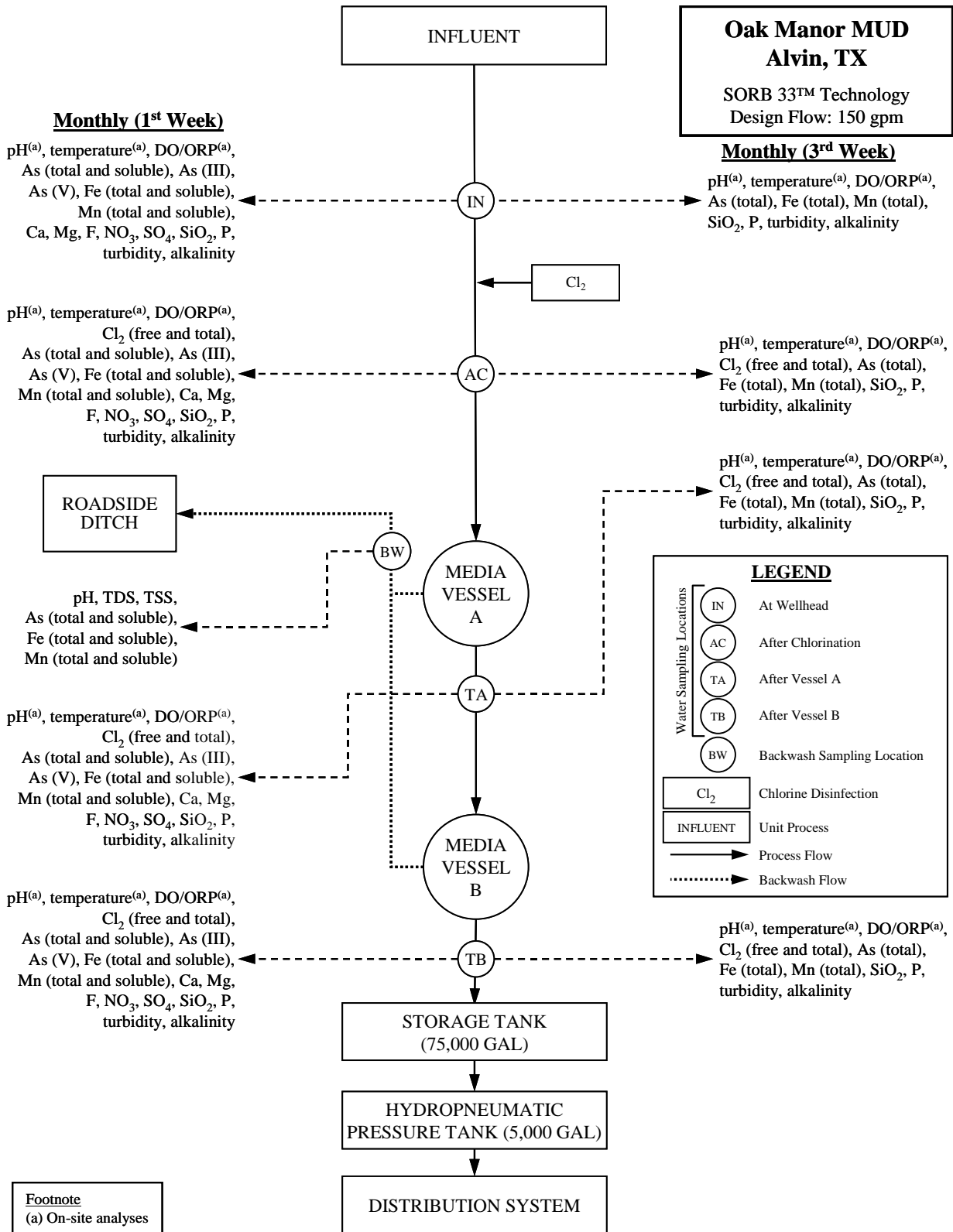


Figure 3-1. Process Flow Diagram and Sampling Schedule and Locations

3.4 Sampling Logistics

3.4.1 Preparation of Arsenic Speciation Kits. The arsenic field speciation method uses an anion exchange resin column to separate the soluble arsenic species, As(V) and As(III) (Edwards et al., 1998). Resin columns were prepared in batches at Battelle laboratories according to the procedures detailed in Appendix A of the EPA-endorsed QAPP (Battelle, 2004).

3.4.2 Preparation of Sample Coolers. For each sampling event, a sample cooler was prepared with the appropriate number and type of sample bottles, disc filters, and/or speciation kits. All sample bottles were new and contained appropriate preservatives. Each sample bottle was affixed with a pre-printed, color-coded label consisting of the sample identification (ID), date and time of sample collection, collector's name, site location, sample destination, analysis required, and preservative. The sample ID consisted of a two-letter code for the specific water facility, sampling date, a two-letter code for a specific sampling location, and a one-letter code designating the arsenic speciation bottle (if necessary). The sampling locations at the treatment plant were color-coded for easy identification. The labeled bottles for each sampling location were placed in separate Ziplock[®] bags and packed in the cooler.

In addition, all sampling- and shipping-related materials, such as disposable gloves, sampling instructions, chain-of-custody forms, prepaid/addressed UPS air bills, and bubble wrap, were included. The chain-of-custody forms and air bills were complete except for the operator's signature and the sample dates and times. After preparation, the sample cooler was sent to the site via FedEx for the following week's sampling event.

3.4.3 Sample Shipping and Handling. After sample collection, samples for off-site analyses were packed carefully in the original coolers with wet ice and shipped to Battelle. Upon receipt, the sample custodian verified that all samples indicated on the chain-of-custody forms were included and intact. Sample IDs were checked against the chain-of-custody forms, and the samples were logged into the laboratory sample receipt log. Discrepancies noted by the sample custodian were addressed with the plant operator by the Battelle Study Lead.

Samples for metal analyses were stored at Battelle's inductively coupled plasma-mass spectrometry (ICP-MS) Laboratory. Samples for other water quality analyses were packed in separate coolers and picked up by couriers from American Analytical Laboratories (AAL) in Columbus, OH and Belmont Labs in Englewood, OH, both of which were under contract with Battelle for this demonstration study. The chain-of-custody forms remained with the samples from the time of preparation through analysis and final disposition. All samples were archived by the appropriate laboratories for the respective duration of the required hold time and disposed of properly thereafter.

3.5 Analytical Procedures

The analytical procedures described in Section 4.0 of the EPA-endorsed QAPP (Battelle, 2004) were followed by Battelle ICP-MS, AAL, and Belmont Labs. Laboratory quality assurance/quality control (QA/QC) of all methods followed the prescribed guidelines. Data quality in terms of precision, accuracy, method detection limits (MDL), and completeness met the criteria established in the QAPP (i.e., relative percent difference [RPD] of 20%, percent recovery of 80 to 120%, and completeness of 80%). The quality assurance (QA) data associated with each analyte will be presented and evaluated in a QA/QC Summary Report to be prepared under separate cover upon completion of the Arsenic Demonstration Project.

Field measurements of pH, temperature, DO, and ORP were conducted by the plant operator using a WTW Multi 340i handheld meter, which was calibrated for pH and DO prior to use following the procedures provided in the user's manual. The ORP probe also was checked for accuracy by measuring

the ORP of a standard solution and comparing it to the expected value. The plant operator collected a water sample in a clean, plastic beaker and placed the WTW probe in the beaker until a stable value was obtained. The plant operator also performed free and total chlorine measurements using Hach chlorine test kits following the user's manual.

Section 4.0 SITE BACKGROUND

4.1 Site Description

4.1.1 Existing Facility. Located at 603 Mohawk Drive, Alvin, Texas, Oak Manor MUD's water system supplies drinking water to about 189 homes from two wells, i.e., Wells 1 and 2, with a combined flowrate of approximately 150 gpm. Well 1, located one mile northeast of the treatment plant, has an average flowrate of 50 gpm. Well 2, located onsite, has an average flowrate of 100 gpm. The average flowrates from both wells were estimated from the facility's historical water usage data collected during July through December 2004.

Prior to the demonstration study, the water system operated for 8 to 9 hr/day with an average and peak daily demand of approximately 74,000 and 97,400 gpd, respectively. The preexisting treatment included gas chlorination to maintain a target total chlorine residual of 1.5 to 2.0 mg/L (as Cl_2) and polyphosphate addition to reach a target dosage of 2.0 mg/L (as P). As shown in Figure 4-1, chlorine was added after the Wells 1 and 2 water combined, but prior to a 75,000-gal storage tank and a 5,000-gal hydropneumatic pressure tank (Figure 4-2). Polyphosphate was added to the Well 1 water just prior to the blending point (Figure 4-3). The well pumps were controlled automatically by a high- and a low-level sensor in the storage tank. Two booster pumps located immediately after the storage tank supplied water to the hydropneumatic tank and distribution system (Figure 4-4) based on a set of low/high pressure settings established for the hydropneumatic tank.



Figure 4-1. Preexisting Chlorine Addition Point and Wells 1 and 2 Blending Point



Figure 4-2. Preexisting Storage Tank (in Foreground) and Hydropneumatic Tank (in Background)



Figure 4-3. Preexisting Polyphosphate Addition Point



Figure 4-4. Booster Pumps and Entry Piping to Distribution System

4.1.2 Source Water Quality. Source water samples were collected and speciated from Well 2 on November 2, 2004, for on- and off-site analyses of the analytes listed on Table 4-1. Additional source water samples also were collected on February 16, 2005, from Well 1, Well 2, and after Wells 1 and 2 combined. The analytical results for all source water sampling events are presented in Table 4-1 and compared to those taken by the facility and submitted to EPA for the demonstration site selection.

Arsenic. Total arsenic concentrations in Wells 1 and 2 source water ranged from 17.4 to 47.4 $\mu\text{g/L}$. The February 16, 2005, sampling results revealed that Well 1 water contained more total arsenic than Well 2 water, with concentrations in Well 1 at 47.7 $\mu\text{g/L}$ and in Well 2 at 17.4 $\mu\text{g/L}$. The sample collected after the blending point had a combined concentration of 34.5 $\mu\text{g/L}$, which was consistent with the average concentration of Wells 1 and 2 before blending, but slightly higher than the 29- $\mu\text{g/L}$ concentration obtained by the facility (although not specified by the facility, it was assumed that this sample was taken after the blending point). Based on the November 2, 2004, speciation results for Well 2, essentially all of the arsenic was in the soluble form. As(III) was the predominating species at 17.6 $\mu\text{g/L}$ (or 94% of total arsenic), indicating the need for oxidation prior to adsorption. The presence of As(III) as the predominating arsenic species was consistent with the low DO and ORP readings, which were measured at 1.7 mg/L and 1 mV, respectively.

Iron and Manganese. Total iron concentrations were 95 and 73 $\mu\text{g/L}$ for the Wells 2 and 1 samples taken on November 2, 2004, and February 16, 2005, respectively. Results for the samples taken from Well 2 and Wells 1 and 2 combined on February 16, 2005, showed elevated iron concentrations at 687 and 317 $\mu\text{g/L}$, respectively. The reason for the high iron concentrations is unknown. Based on the November 2, 2004, speciation results, <40% of total iron existed in the soluble form. The presence of particulate iron in source water was carefully monitored during the demonstration study to determine if the measurement of particulate iron on November 2, 2004, was simply due to inadvertent aeration of the sample during sampling.

Table 4-1. Water Quality Data for Oak Manor MUD

Parameter	Unit	Utility Raw Water Data ^(a)	Battelle Raw Water Data				TCEQ Treated Water Data ^(c)
			Well 2	Well 1	Well 2	Well 1 and 2 Combined ^(b)	
<i>Date</i>		NA	11/02/04	02/16/05	02/16/05	02/16/05	1998–2003
pH	S.U.	7.8	7.8	NS	NS	NS	7.7–8.0
Temperature	°C	NS	23.3	NS	NS	NS	NS
DO	mg/L	NS	1.7	NS	NS	NS	NS
ORP	mV	NS	1	NS	NS	NS	NS
Total Alkalinity (as CaCO ₃)	mg/L	359	377	330	410	379	356–360
Hardness (as CaCO ₃)	mg/L	42	43	NS	NS	NS	42.0–43.3
Turbidity	NTU	NS	0.3	0.3	8.7	2.0	NS
TDS	mg/L	NS	492	526	670	540	526–546
TOC	mg/L	NS	0.7	NS	NS	NS	NS
Nitrate (as N)	mg/L	NS	<0.04	<0.05	<0.05	<0.05	<0.01
Nitrite (as N)	mg/L	NS	<0.04	<0.05	<0.05	<0.05	<0.01
Ammonia (as N)	mg/L	NS	0.2	NS	NS	NS	NS
Chloride	mg/L	91	68.0	120.0	98.0	110.0	89.0–93.0
Fluoride	mg/L	NS	0.8	1.4	1.5	1.4	1.5–1.6
Sulfate	mg/L	2	<1.0	<1.0	2.0	1.0	2.0
Silica (as SiO ₂)	mg/L	NS	16.8	15.8	15.5	16.7	NS
Orthophosphate (as P)	mg/L	NS	<0.06	<0.05	<0.05	<0.05	NS
As (total)	µg/L	29	18.8	47.7	17.4	34.5	28.2–30.7
As (soluble)	µg/L	NS	19.0	NS	NS	NS	NS
As (particulate)	µg/L	NS	<0.1	NS	NS	NS	NS
As (III)	µg/L	NS	17.6	NS	NS	NS	NS
As (V)	µg/L	NS	1.4	NS	NS	NS	NS
Fe (total)	µg/L	62	95	73	687 ^(d)	317 ^(d)	55.0–77.0
Fe (soluble)	µg/L	NS	37	NS	NS	NS	NS
Mn (total)	µg/L	58	61.6	48.0	65.2	55.4	37.5–62.0
Mn (soluble)	µg/L	NS	61.7	NS	NS	NS	NS
U (total)	µg/L	NS	1.5	<0.1	1.5	0.8	NS
U (soluble)	µg/L	NS	1.5	NS	NS	NS	NS
V (total)	µg/L	NS	2.1	1.4	1.2	1.3	NS
V (soluble)	µg/L	NS	1.9	NS	NS	NS	NS
Na (total)	mg/L	201	259	194	273	201	191–210
Ca (total)	mg/L	12	9.3	10.6	12.9	12.0	11.7–13.0
Mg (total)	mg/L	3	4.8	2.9	3.8	3.2	2.0–3.6

TCEQ = Texas Commission of Environmental Quality; NA = not available; NS = not sampled

(a) Provided to EPA for demonstration site selection; well number(s) not specified.

(b) Samples collected before storage tank with no chlorine or polyphosphate addition.

(c) Samples collected at point of entry into distribution system.

(d) Samples reanalyzed with similar results.

In general, adsorptive media technologies are best suited for source waters with relatively low iron levels (e.g., less than 300 µg/L of iron, which is the secondary maximum contaminant level [SMCL] for iron). Above 300 µg/L, taste, odor, and color problems can occur in treated water, along with an increased potential for fouling of the adsorption system components with iron particulates.

Manganese concentrations in source water ranged from 48.0 to 65.2 µg/L. Well 2 water appeared to contain more manganese, with concentrations ranging from 61.6 to 65.2 µg/L, compared to that of Well 1 water at 48.0 µg/L. The average concentration of water from Wells 1 and 2 sampled on February 16, 2005, was consistent with that of the combined well water (i.e., 56.6 versus 55.4 µg/L) and close to the 58.0 µg/L concentration provided by the facility. Based on the November 2, 2004, speciation result, manganese existed entirely in the soluble form.

Silica, Sulfate, and Orthophosphate. As shown in Table 4-1, silica levels ranged from 15.5 to 16.8 mg/L (as SiO₂); sulfate levels ranged from less than the method reporting limit of 1.0 mg/L to 2 mg/L; and orthophosphate levels were all less than the method reporting limit of 0.05 mg/L (as P). Usually, arsenic adsorption can be influenced by the presence of competing anions such as silica, sulfate, and phosphate, but due to the low levels of these constituents, they were not expected to affect arsenic adsorption onto the SORB 33TM media.

Other Water Quality Parameters. A pH value of 7.8 was measured for Well 2 water, which was within the STS target range of 6.0 to 8.0 for arsenic removal via adsorption. Therefore, pH adjustment was not recommended prior to arsenic adsorption. Nitrate and nitrite were not detected in either well. Ammonia at 0.2 mg/L (as N) was measured in Well 2 water. Chloride and fluoride were below their respective SMCLs. Alkalinity ranged from 330 to 410 mg/L. The only total organic carbon (TOC) sample was collected from Well 2 on November 2, 2004, which was measured at 0.7 mg/L. Uranium concentrations ranged from less than the method reporting limit of 0.1 µg/L to 1.5 µg/L, well below its MCL of 30 µg/L. Vanadium concentrations ranged from 1.2 to 2.1 µg/L. Sodium concentrations ranged from 194 to 273 mg/L across both wells. Calcium, magnesium, and hardness were low, ranging from 9.3 to 12.9 mg/L, 2.9 to 4.8 mg/L, and 42 to 43 mg/L (as CaCO₃), respectively. Total dissolved solids (TDS) exceeded its SMCL of 500 mg/L for all February 16, 2005, water samples, ranging from 492 to 670 mg/L.

4.1.3 Treated Water Quality. Historic treated water quality data collected by TCEQ from 1998 to 2003 also are presented in Table 4-1. The treated water samples were collected at the entry point into the distribution system and after polyphosphate and chlorine addition. As expected, the treated water quality data were similar to the source water quality data obtained by Battelle and the facility. Total arsenic concentrations in the treated water ranged from 28.2 to 30.7 µg/L. Total iron was the only constituent that had slightly lower treated water quality results as compared to the source water quality results.

4.1.4 Distribution System and Regulatory Monitoring. Among the three residences selected for distribution system water sampling, only DS3 was part of the Oak Manor MUD's historic sampling network for Lead and Copper Rule (LCR) and monthly bacteriological sampling. Under the LCR, samples were collected from designated taps at 10 residences every three years. Additional regulatory monitoring directed by TCEQ included monthly sampling for coliform and volatile organic compounds (VOCs), and biyearly/quarterly for inorganics, nitrate, and radionuclides.

Based on the information provided by the facility, the distribution system was constructed primarily of 6-in cast-iron pipe. Piping within individual service hookups consisted primarily of ¾- to 1-in polyvinyl chloride (PVC) and ¾- to 1-in galvanized iron. The distribution system was supplied directly by the 75,000-gal storage tank.

4.2 Treatment Process Description

STS provided an Arsenic Package Unit (APU)-30S Arsenic Removal System for the Oak Manor MUD site. The APU is a fixed-bed, down-flow adsorption system used for small water systems with

flowrates ranging from 5 to 150 gpm. The APU uses Bayoxide® E33 media (branded as SORB 33™ by STS), an iron-based adsorptive media developed by Bayer AG, for the removal of arsenic from drinking water supplies. Table 4-2 summarizes vendor-provided physical and chemical properties of the media.

Table 4-2. Physical and Chemical Properties of SORB 33™ Media

<i>Physical Properties</i>	
Parameter	Values
Matrix	Iron oxide composite
Physical Form	Dry pellets
Color	Amber
Bulk Density (lb/ft ³ or g/cm ³)	35 or 0.56
BET Surface Area (m ² /g)	142
Attrition (%)	0.3
Moisture Content (% by weight)	<15
Particle Size Distribution (U.S. Standard Mesh)	10 × 35
Crystal size (Å)	70
Crystal phase	α – FeOOH
<i>Chemical Analysis</i>	
Constituents	Weight %
FeOOH	90.1
CaO	0.27
MgO	1.00
MnO	0.11
SO ₃	0.13
Na ₂ O	0.12
TiO ₂	0.11
SiO ₂	0.06
Al ₂ O ₃	0.05
P ₂ O ₅	0.02
Cl	0.01

BET = Brunauer, Emmett, and Teller

SORB 33™ media is delivered in a dry crystalline form and listed by NSF International (NSF) under Standard 61 for use in drinking water applications. The media exist in both granular and pelletized forms, which have similar physical and chemical properties, except that pellets are denser than granules (i.e., 35 vs. 28 lb/ft³). The pellet form of the media was used for the Oak Manor MUD facility.

The treatment train consists of prechlorination/oxidation and adsorption. The APU-30S Arsenic Removal Treatment System consists of two adsorption vessels, Vessels A and B, arranged in series (Figure 4-5). When the arsenic concentration in the effluent from the lag vessel approaches 10 µg/L, the spent media in the lead vessel is removed and disposed of. After rebedding, this vessel is switched to the lag position. In general, the series operation better utilizes the media capacity when compared to the parallel operation because the lead vessel may be allowed to exhaust completely prior to change-out.

The piping and valve configuration of the APU-30S system consists of electrically actuated butterfly valves to divert raw water flow into either Vessels A or B depending on which is operating as the lead vessel. The piping and instrumentation diagrams (P&IDs) presented in Figures 4-6a and 6b use bolded lines to indicate the process flow for series configuration with Vessels A and B, respectively, in the lead position. Table 4-3 presents key system design parameters.



Figure 4-5. Photograph of APU-30S Arsenic Removal System

The major process components/steps of the APU-30S system include the following:

- **Intake.** Raw water was pumped from the two supply wells and fed to the treatment system via 3-in steel pipe (Figure 4-1). The well pumps were interlocked with the high and low level sensors in the storage tank (Figure 4-2).
- **Prechlorination/Oxidation.** The existing gas chlorination system manufactured by Ecometrics in Silverdale, PA, was used to oxidize As(III), Fe(II), and Mn(II) prior to the adsorption vessels and provide a target total chlorine residual level from 1.5 to 2.0 mg/L (as Cl₂) for disinfection purposes. The chemical feed system consisting of one 150-lb cylinder, a chlorinator unit (sitting on top of the chlorine gas cylinder), and an ejector was located in a secured shed in the close proximity of the treatment system in the fenced area. Figure 4-7 presents composite of pictures of the gas chlorination system. Note that the current chlorine injection point (not pictured) was relocated after the Wells 1 and 2 blending point to >10 ft downstream of the raw water sample tap, after system startup on April 25, 2006 (see Table 4-5). Operation of the chlorine feed system was linked to the well pumps so that gas chlorine was injected only when the wells were on. Chlorine consumption was tracked daily by recording the weight of the chlorine gas cylinder.
- **Adsorption.** The APU-30S system consisted of two 63-in-diameter, 86-in-tall adsorption vessels configured in series. The tanks were made of fiberglass reinforced plastic (FRP), rated for 100-psi working pressure, and skid mounted for ease of shipment and installation. According to the original system design, each vessel was to contain 62 ft³ of media, yielding an empty bed contact time (EBCT) of 3.1 min/vessel at a flowrate of 150 gpm. However, based on STS's onsite measurements on May 17, 2006, Vessels A and B were inadvertently loaded with an uneven amount of media (i.e., 53.6 and 70.3 ft³ for Vessels A and B, respectively). As such, Vessel A had a slightly shorter EBCT than Vessel B (i.e., 2.7 vs. 3.5

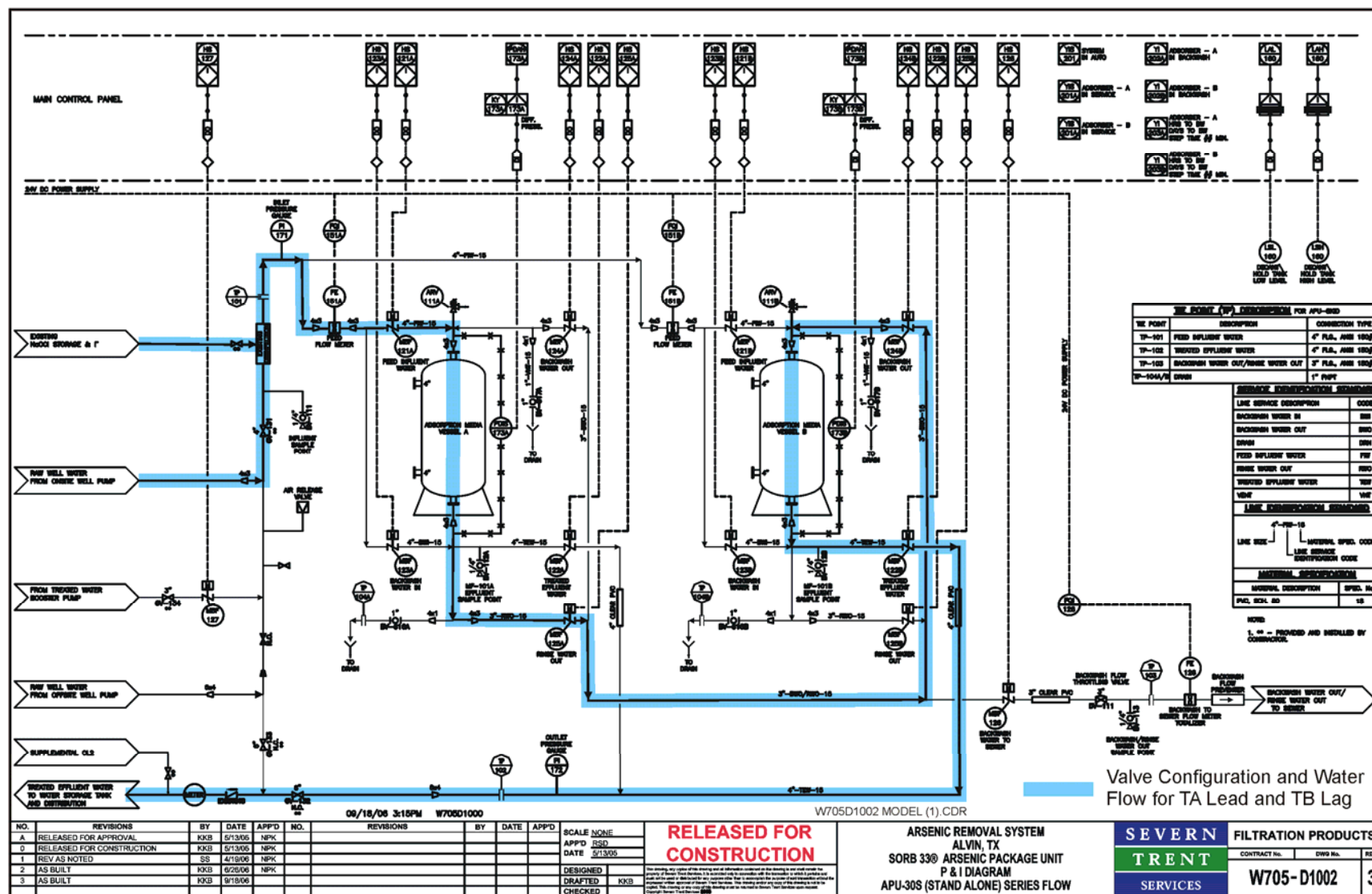


Figure 4-6a. Process Flow Diagram for APU-30S System with Vessel A in Lead Position

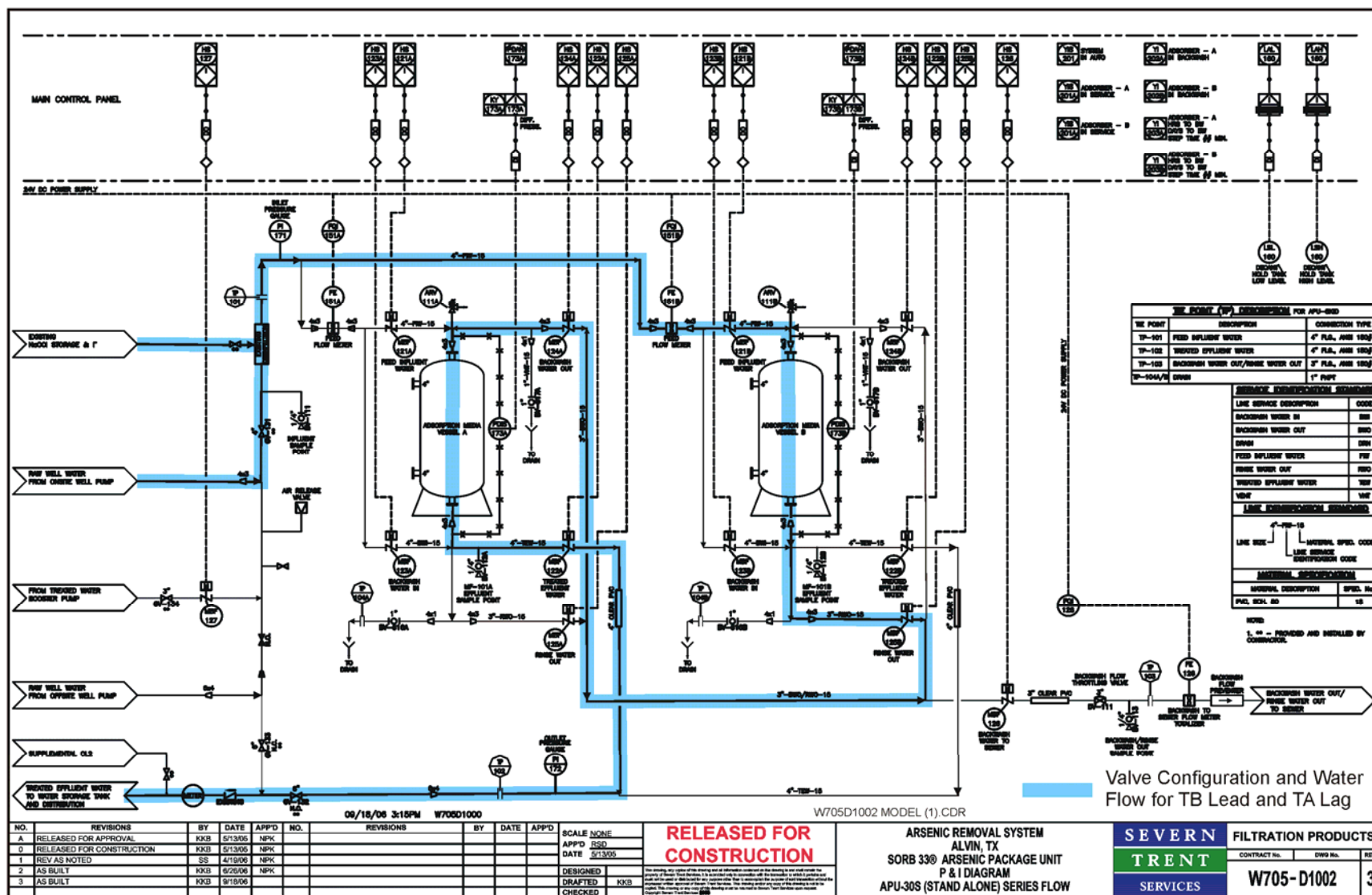


Figure 4-6b. Process Flow Diagram for APU-30S System with Vessel B in Lead Position

Table 4-3. Design Specifications for STS APU-30S System

Parameter	Value	Remarks
Pre-treatment		
Target Total Chlorine Residual (mg/L [as Cl ₂])	1.5 to 2.0	Gas chlorine used
Adsorption Vessels		
Vessel Size (in)	63 D × 86 H	–
Cross-Sectional Area (ft ² /vessel)	21.6	–
Number of Vessels	2	–
Configuration	Series	–
SORB 33™ Adsorption Media		
Media Type	SORB 33™	In pelletized form
Media Quantity (lb)	4,340	Density for pelletized media 35 lb/ft ³
Media Volume (ft ³)	124	62 ft ³ /vessel
Media Bed Depth (in)	32	
Service		
Design Flowrate (gpm)	150	–
Hydraulic Loading Rate (gpm/ft ²)	6.9	–
EBCT for System (min)	6.2	Based on total media volume of 124 ft ³ and system flowrate of 150 gpm (3.1 min/vessel)
Throughput to Lead Vessel Change-out (gal)	47,500,000	Based on vendor revised proposal (STS, March 2005); lead vessel change-out to occur when total arsenic concentration following lead vessel reaches 16 µg/L
Estimated Working Capacity (BV)	51,240	1 BV = 927 gal (based on media in both lead and lag vessels)
Average Use Rate (gal/day)	74,000	Provided by facility
Estimated Media Life (months)	21	Estimated frequency of lead vessel change-out based on average throughput to system
Backwash		
Δp Setpoint (psi)	10	–
Backwash Flowrate (gpm)	210	Minimal recommended flowrate
Hydraulic Loading Rate (gpm/ft ²)	9.7	–
Backwash Frequency (month/backwash)	1	Based on vendor's recommendation
Backwash Duration (min/vessel)	20	–
Forward Flush Flowrate	210	–
Forward Flush Duration (min/vessel)	10	–
Wastewater Production (gal/vessel)	6,300	–

min). Nonetheless, the design EBCT across the system remained unchanged at 6.2 min. The hydraulic loading rate to each adsorption vessel was 6.9 gpm/ft². Each adsorption vessel was interconnected with schedule 80 PVC piping and five electrically actuated butterfly valves, which made up the valve tree as shown in Figure 4-8. In addition to the 10 butterfly valves, the system had two manual diaphragm valves on the backwash line, and six isolation ball valves to divert raw water flow into either vessel, which reversed the lead/lag vessel configuration. Each valve operated independently and the butterfly valves were controlled by a Square D Telemechanique programmable logic controller (PLC) with a Magelis G2220 color touch interface screen.



Figure 4-7. Gas Chlorination System
(Clockwise from the Top: Shed Housing Gas Chlorination System, Gas Cylinder, Chlorine Ejector, and Chlorinator Unit)



Figure 4-8. APU-30S System Valve Tree and Piping Configuration

- **Backwash.** The vendor recommended that the APU-30S system be backwashed on a regular basis to remove particulates and media fines that accumulated in the media beds. Automatic backwash could be initiated by either a time or a Δp setpoint across each vessel. During a backwash cycle, each vessel was backwashed individually, while the second vessel remained off-line. The backwash flowrate, hydraulic loading, duration, and wastewater produced were 210 gpm, 9.7 gpm/ft², 30 min (including 10 min for forward flush), and 6,300 gal (including 2,100 gal for forward flush), respectively. The backwash/forward flush flowrates and the amount of wastewater generated were determined by the flowrate and totalizer readings shown on the PLC. The backwash and forward flush duration was timed and confirmed by the operator. Backwash and forward flush water was mostly supplied by the two supply wells; however, due to their maximum flowrate of 150 gpm, supplemental water had to be drawn from the hydropneumatic pressure tank (Figure 4-9) located just downstream from the adsorption vessels. Backwash wastewater was sent to a small ditch (Figure 4-10) adjacent to the treatment system and subsequently drained into a roadside ditch.
- **Media Replacement.** Replacement of the media in the lead vessel will be scheduled once the arsenic concentration following the lag vessel is approaching 10 µg/L. Once the media in the lead vessel is replaced, flow through the vessels will be switched such that the lag vessel is placed into the lead position and the former lead vessel loaded with virgin media is placed in the lag position. A Toxicity Characteristic Leaching Procedure (TCLP) test will be conducted on the spent media before disposal to determine whether the media can be considered non-hazardous.
- **Storage and Distribution.** The treated water was stored in a 24-ft tall, 75,000-gal storage tank located immediately downstream of the APU-30S treatment system. A low-/high-level sensor pair at 13/19.5 ft controlled the on/off of the well pumps. The booster pumps subsequently pressured and temporarily stored water in a 5,000-gal hydropneumatic tank before water entered the distribution system. The booster pumps switched on and off based on the high and low pressure settings at 40 and 60 psi, respectively. The distribution system was constructed primarily of 6-in cast-iron pipe. Piping within individual service hookups consisted primarily of ¾- 1-in PVC and ¾- 1-in galvanized iron.

4.3 Treatment System Installation

4.3.1 System Permitting. A submittal package was sent by Oak Manor MUD to TCEQ on July 8, 2005, requesting an exception from conducting an on-site pilot study as required under Title 30 Texas Administrative Code (30TAC) 290.42(g). The exception request was required by TCEQ prior to the submission of engineering plans for the installation of the arsenic treatment system. The exception submittal included a written description of treatment technology along with a schematic of the system and relevant pilot- and full-scale data. Subsequently, a permit application package including a process flow diagram of the treatment system, mechanical drawings of the treatment equipment, a schematic of the building footprint and equipment layout, was submitted to TCEQ on September 9, 2005. TCEQ granted its approval for the exception request and system permit application on November 21 and December 16, 2005, respectively. A permit was not required to discharge backwash wastewater to a roadside ditch.

4.3.2 Building Construction. A canopy (Figure 4-5) was built to shield the treatment system from direct sunlight exposure. Construction of the concrete pad (Figure 4-11) began on October 6, 2005, and the canopy was completed on November 12, 2005.



Figure 4-9. Valve MB-127 to Supply Additional Treated Water from Hydropneumatic Tank During Backwash



Figure 4-10. Small Ditch

4.3.3 System Installation, Shakedown, and Startup. The shipment of the APU-30S system arrived at the Oak Manor MUD on September 4, 2005. Upon arrival, STS's subcontractor, Abundant Engineering, off-loaded the system components to a temporary staging area adjacent to the existing treatment facility while the MUD awaited the completion of the concrete pad and issuance of the permit approval. The pelletized media arrived in three super sacks on October 7, 2005. Although each super sack usually has 38 ft³ of media bringing the total media volume to 114 ft³, the actual volume of media shipped to the site was 124 ft³ based on freeboard measurements of the vessels (Section 4.3.4).

Upon receipt of the permit approval on December 16, 2005, Abundant Engineering performed most of the installation work, including connecting the system to the existing inlet and distribution piping. A field engineer from the STS Houston office made three separate trips to the site from January 17 to 19, from March 9 to 10, and on April 5, 2006, to complete system installation and perform system shakedown and startup. System installation, shakedown, and startup were completed on March 9, March 10, and April 25, 2006, respectively.

During the first trip from January 17 to 19, 2006, STS wired the PLC, conducted hydraulic testing on the empty vessels, tested pressure gauges and flowmeters, loaded underbedding gravel and media, measured freeboard heights after backwash, and disinfected the media and the system components with bleach. The hydraulic test was performed at 88 gpm, lower than the design flowrate of 150 gpm. At this flowrate, the inlet and outlet pressure for the treatment system were 14.0 and 6.0 psi, respectively, and the Δp readings across Vessels A and B were 1.2 and 2.0 psi, respectively.

STS recommended a minimum backwash flowrate of 210 gpm (or 9.7 gpm/ft²), which exceeded the maximum well capacity of 150 gpm. The remedy was to modify the preexisting plumbing, including the installation of an automatic valve (MB-127), to deliver the treated water from the hydropneumatic tank to supplement the backwash flow. Also, in order to prevent polyphosphate from entering the adsorption vessels to cause adverse effects on arsenic adsorption, the preexisting polyphosphate addition was relocated downstream of the APU-30S system and, later as discussed below, discontinued due to concerns that polyphosphate in treated water might come in contact with the media during backwash.

STS's field engineer returned to the site from March 9 to 10, 2006, to perform a thorough media backwash with supplemental flow. The backwash flowrates were verified to range from 250 to 270 gpm. Although the polyphosphate addition point had been relocated downstream of the treatment system, concern existed that polyphosphate still could come in contact with the media during backwash. After shutting off polyphosphate addition, backwash and forward flush were performed and system shakedown was completed on March 10, 2006. After chlorinating both vessels, the facility took samples for the bacteriological test. Verbal approval to discharge the treated water into the distribution system was granted by TCEQ on March 14, 2006.

Thereafter, the facility attempted to place the system online, but could not due to the production of red/cloudy treated water. After 80,000 to 100,000 gal (or 86 to 108 BV) of water was used for backwash and forward flush through both vessels, the facility contacted STS for a return visit.

The STS field engineer returned to the site for the third time on April 5, 2006, to troubleshoot the APU-30S system. Vessels A and B were backwashed at 150 gpm for 30 and 40 min, respectively, followed by 20 min of forward flush. Vessel A backwash water cleared after 5 min, and Vessel B soon after. Forward flush for Vessels A and B both cleared after 3 min. Only raw water was used during backwash, although polyphosphate addition was discontinued for over a week prior to STS's return visit. After backwash, both adsorption vessels were opened for freeboard measurements and media observations. The results of the measurements and observations are discussed in Section 4.3.4. The vessels were then resealed and the forward flush through both vessels resumed for about one hour before discharge was directed to the



Figure 4-11. Construction of Concrete Pad with Storage Tank and Hydropneumatic Tank (in Background)

storage tank for distribution. The exact reason as to why the facility was unable to achieve clear water was never determined.

Once all of the activities were completed, polyphosphate addition was restarted downstream of the APU-30S due to complaints of iron in the treated water. On April 17, 2006, the facility shut off the polyphosphate addition again on a permanent basis. The average iron concentration in the treated water remained below the detection limit of 25 µg/L as discussed in Section 4.5.3.

4.3.4 Media Loading. Media loading was performed by STS on January 19, 2006. The media as shipped in super sacks was hoisted to the top of the canopy using a boom truck and loaded through a 12-in × 4-in rigid funnel and a roof hatch into the adsorption vessels partially filled with water. A garden hose was used to completely submerge the media, which was allowed to soak for about 4 hr. After the top hat distributor was reinstalled and top piping reconnected, each vessel was backwashed at 150 gpm for approximately 30 min to remove fines. The freeboard over the top of each media bed was then measured three times and the averages of each vessel along with the calculated media volume are summarized in Table 4-4.

The freeboard measurements taken from the top of the underbedding gravel to the top of the flange openings before media loading were 65.3 and 66.5 in for Vessels A and B, respectively. The freeboard measurements taken from the top of media beds to the top of the flange openings were 36.5 and 37.5 in for Vessels A and B, respectively. As such, 51.8 and 52.3 ft³ of media should have been loaded into the vessels. However, the freeboard measurements taken on April 5, 2006 (when STS returned to the site to troubleshoot a facility's complaint concerning red/cloudy water from the adsorption vessels), and on May 17, 2006 (when STS returned to the site to complete the punch-list items identified by Battelle during its system inspections [see Section 4.3.5]), indicated 52.7 to 53.6 ft³ of media in Vessel A and 69.4 to 70.3 ft³ in Vessel B. The discrepancy in media volume noted in Vessel B was attributed by the vendor to an uneven distribution of three super sack contents to Vessels A and B and an incorrect freeboard measurement of Vessel B after initial media loading on January 19, 2006. To avoid any confusion, it was decided that the media volumes determined on May 17, 2006 (i.e., 43 and 57% in Vessels A and B) should be used for all bed volume calculations.

Table 4-4. Freeboard Measurements and Media Volumes in Adsorption Vessels

Date	Vessel A		Vessel B		Total Volume (ft ³)
	Depth (in)	Volume (ft ³)	Depth (in)	Volume (ft ³)	
01/19/06	36.5	51.8	37.5	52.3	104
04/05/06	36.0	52.7	28.0	69.4	122
05/17/06	35.5	53.6	27.5	70.3	124

It also was noted during STS's April 5, 2006, site visit that the multiple backwashes after media loading did not appear to have affected media integrity. Fine media was observed accumulating at the top of media both with a depth of approximately 1 in. Below this level, the media appeared to be near its original size and shape.

4.3.5 Punch List Items. Battelle performed system inspections and operator training for sample and data collection on April 24 to 25, 2006. The performance evaluation study officially started on April 25, 2006. Table 4-5 summarizes the punch-list items and corrective actions taken from May 22, 2006, to

Table 4-5. System Inspection Punch-List Items

Item No.	Punch-List Item	Corrective Action(s) Taken	Resolution Date
1	Broken Well 2 totalizer	<ul style="list-style-type: none"> Replaced Well 2 totalizer 	05/22/06
2	Raw water sample tap incorrectly located (so that only Well 2 water might be sampled [Figure 4-11])	<ul style="list-style-type: none"> Used existing chlorine injection point (Figure 4-12) for raw water sampling^(a) during first three sampling events on 04/25/06, 05/09/06, and 05/23/06 Relocated raw water sample tap about 0.5 ft after blending point of Wells 1 and 2 (Figure 4-12) and relocated chlorine injection point about 10 ft downstream of the new raw water sample tap for chlorine injection Relocate raw water sample tap to existing chlorine injection point and continued using relocated chlorine injection point 	05/24/06 05/02/07
3	Broken Vessel A flow meter	<ul style="list-style-type: none"> Fixed Vessel A flow meter by removing particles jammed in paddle wheel 	05/17/06
4	Inconsistent Vessel B freeboard measurements taken on 01/19/06 and 04/05/06 by vendor (Section 4.3.4)	<ul style="list-style-type: none"> Retook freeboard measurements for both Vessels A and B 	05/17/06
5	Vessels A and B sample taps (i.e., TA and TB) incorrectly located (so that same water was sampled by both taps)	<ul style="list-style-type: none"> Relocated Vessels A and B sample taps (but still at wrong locations) Corrected sample tap locations 	05/17/06 08/09/06
6	1/8-in tubing from backwash discharge piping to backwash wastewater sample tap	<ul style="list-style-type: none"> Discontinued use of 1/8-in tubing and sample tap and replaced them with a 10-ft garden hose to direct side stream from vessel via a spigot to sample container 	01/07
7	Broken actuator valve 125b (not open for automatic backwash)	<ul style="list-style-type: none"> Replaced actuator valve 125b 	05/17/06
8	Broken actuator valve 123A (not open for automatic backwash)	<ul style="list-style-type: none"> Replaced actuator valve 123A 	08/09/06
9	Missing backwash flow meter/totalizer	<ul style="list-style-type: none"> Installed a backwash flow meter/totalizer 	05/17/06
10	Broken totalizer on treated water line to storage tank	<ul style="list-style-type: none"> Replaced totalizer on treated water line 	07/10/06
11	Parallel vs. series default settings on PLC	<ul style="list-style-type: none"> Investigated PLC default settings, which might not be changed from parallel to series. Power outage will revert system to default setting when left in manual mode [Section 4.3]) 	05/17/06
12	Block vs. unblock mode	<ul style="list-style-type: none"> Held a teleconference with facility representatives, who expressed preference to maintain PLC in unblock mode (i.e., system valves remained open at all times) 	05/19/06
13	Missing as-built drawings for APU-30S system	<ul style="list-style-type: none"> Provided as-built drawings for APU-30S system 	09/21/06
14	Missing as-built site piping and electrical drawings	<ul style="list-style-type: none"> Provided as-built site engineering drawings 	09/21/06

(a) Raw water samples collected after other treatment plant samples at AC, TA, and TB locations had been taken, chlorine injection had been temporarily discontinued, and chlorine injection point had been thoroughly flushed.



Figure 4-12. Photograph of Piping, Sample Taps, and Chlorine Injection Point Prior to Treatment System

September 21, 2006. All punch-list items were addressed by STS and/or the facility by September 21, 2006.

4.4 System Operation

4.4.1 Operational Parameters. The operational parameters for the first six months of system operation were tabulated and are attached as Appendix A. Key parameters are summarized in Table 4-6. From April 25 through October 25, 2006, the system operated for 1,322 hr. This cumulative operating time represents a use rate of about 30% during the first six-month operational period. The system typically operated for a period of 7.2 hr/day (as compared to 8 to 9 hr/day prior to installation of the arsenic treatment system). The average daily demand was about 51,700 gal (versus 74,000 gal provided by the facility prior to the demonstration study) and the peak daily demand occurred on May 14, 2006, at 118,500-gal (compared to 97,400 gpd provided by the facility). Note that the demand calculated over more than one day was not used to determine the peak daily demand.

Because of the difference in media volume in Vessels A and B (i.e., 53.6 ft³ for Vessel A and 70.3 ft³ for Vessel B), the number of bed volumes treated by the system was calculated based on the combined media volume, i.e., 124 ft³, in both vessels.

Table 4-6. Summary of APU-30S System Operations

Operational Parameter	Value/Condition
Duration	04/25/06–10/25/06
Cumulative Operating Time (hr)	1,322
Average (Range) Daily Operating Time (hr)	7.2 (14.8–2.7)
<i>System Operation – Adsorption</i>	
Total Throughput (gal)	11,241,500
Bed Volumes (BV) ^(a)	12,172
Average (Range of) Daily Demand (gpd)	51,700 (21,000–118,500)
Average (Range of) Flowrate (gpm) ^(b)	134 (117–151)
Average (Range of) Hydraulic Loading (gpm/ft ²)	6.2 (5.4–7.0)
Average (Range of) EBCT for System (min) ^(a)	6.9 (6.1–7.9)
Average (Range of) Inlet Pressure (psi)	22.4 (18.0–28.0)
Average (Range of) Outlet Pressure (psi)	5.8 (3.0–8.0)
Average (Range of) Δp across System (psi)	17.0 (13.0–21.0)
Average (Range of) Δp across Vessel A (psi)	5.9 (2.5–10.0)
Average (Range of) Δp across Vessel B (psi)	3.2 (2.3–4.0)
<i>System Operation – Backwash</i>	
Average (Range of) Backwash Flowrate (gpm)	260 (225–280)
Average (Range of) Hydraulic Loading Rate	12.0 (10.4–13.0)
Average (Range of) Backwash Duration (min)	23.3 (20.0–30.0)
Average (Range of) Wastewater Generated (gal)	6,058 (4,500–8,400)

(a) Calculated based on 124 ft³ (or 927 gal) of media in both Vessels A and B.

(b) Instantaneous flowrate readings from Vessel A.

Flowrates through the arsenic treatment system were tracked four ways. Instantaneous flowrate readings were taken from an electromagnetic flowmeter/totalizer installed prior to Vessel A (or lead vessel).

Calculated flowrate values were obtained from hour meter and flow totalizer readings recorded from one each hour meter interlocked to Wells 1 and 2 and four totalizers, including the electromagnetic flowmeter/totalizer installed prior to Vessel A and three preexisting positive displacement type master totalizers installed at two wellheads and on the treated water line.

As shown in Table 4-7, all instantaneous and calculated flowrate readings were similar, with average values ranging from 127 to 134 gpm. The instantaneous readings, chosen to determine the system flowrates and total volume throughput, ranged from 117 to 151 gpm and averaged 134 gpm, which was 10.7% lower than the 150-gpm design value (Table 4-6). Based on the flowrates to the system, the hydraulic loading rates to the adsorption vessels averaged 6.2 gpm/ft² and the EBCTs for the system varied from 6.1 to 7.9 min and averaged 6.9 min. As a result, the actual EBCT was 11.3% higher than the design value of 6.2 min.

Table 4-7. System Instantaneous and Calculated Flowrates

Flowmeter/Totalizer Type and Location	Instantaneous/ Calculated	Flowrate (gpm)	
		Range	Average
Electromagnetic, Prior to Vessel A	Instantaneous	117-147	134
Electromagnetic, Prior to Vessel A	Calculated	78-157	127
Positive Displacement, at Wellheads ^(a)	Calculated	86-150	132
Positive Displacement, on Treated Water Line	Calculated	65-137	134

(a) Sum of Wells 1 and 2 readings.

During the first six months, the system treated approximately 11,241,500 gal of water, equivalent to 12,172 BV, based on the 124-ft³ of media in both vessels.

The APU-30S system pressures were monitored at the system inlet and outlet and across the media beds. As shown in Figure 4-13, for the first three days from April 25 to 27, 2006 (or at throughput up to 1,440 BV), Δp readings across both vessels were low at 3.0 psi, as compared to 1.2 and 2.0 psi across Vessels A and B, respectively, during the hydraulic testing performed without media in the vessels on January 17, 2006. Starting on the fourth day, Δp reading across Vessel A began to rise and a backwash was performed on May 16, 2006, when Δp reached 8.5 psi (or at approximately 2,900 BV of throughput). After backwash, the Δp readings returned to the original level of around 3.5 psi. As shown in Figure 4-13 and Table 4-8, during the first six-month study, four backwashes were performed on both vessels, averaging one backwash every six weeks. Both vessels were backwashed when Δp reached about 10 psi across Vessel A, although Δp readings for Vessel B remained low and rather constant, averaging 3.2 psi for the first six months.

It is postulated that the Δp rise across Vessel A was caused by the accumulation of precipitated solids in the media bed caused by the addition of chlorine before the adsorption vessels. In addition, based on several trip reports provided by STS, sediments produced from the wells also might have accumulated in Vessel A contributing to the observed Δp rise.

4.4.2 Residual Management. Because media replacement was not performed during the first six months of system operation, no spent media was produced in this reporting period.

4.4.3 Reliability and Simplicity of Operation. There was no downtime for the treatment system during the first six-month study period. However, there were operational irregularities related to the APU-30S system's Vessel A flowmeter/totalizer, automatic valve 123A, and system default settings.

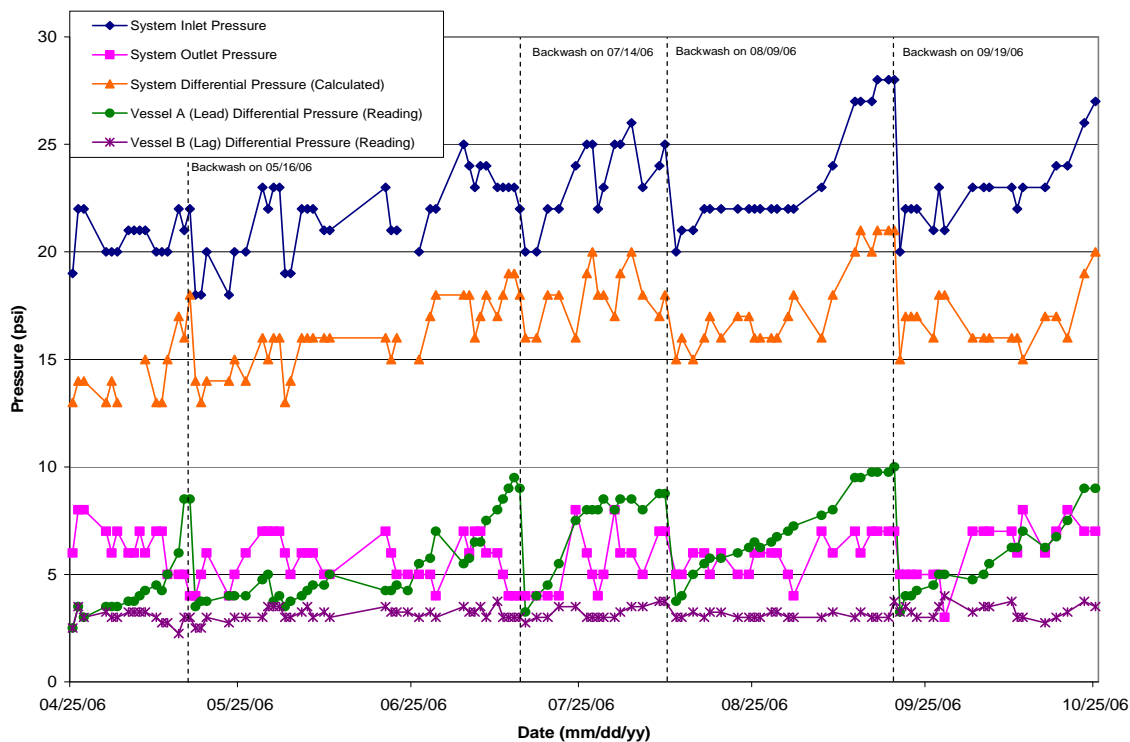


Figure 4-13. System Pressure Readings

Table 4-8. Time Lapse Since Last Backwash

No.	Backwash Date	Duration Since Last Backwash	Total BV Treated	ΔP before Backwash TA/TB (psi)	ΔP after Backwash TA/TB (psi)
1	05/16/06	NA	2,904	8.50/3.00	3.50/2.50
2	07/14/06	8 weeks	6,914	9.00/3.00	3.25/2.75
3	08/09/06	4 weeks	8,314	8.75/3.75	3.75/3.00
4	09/19/06	5 weeks	10,569	10.0/3.75	3.25/3.25

NA = not available

The Vessel A flowmeter/totalizer broke on three separate occasions from April 25 to May 28, June 6, and from September 6 to October 3, 2006, due to wear by either precipitated solids after prechlorination or natural sediments from the wells. The automatic valve 123A failed to open during automatic backwash on July 14, 2006, due to water and humidity accumulating in the valve. The APU-30S system was discovered to be in parallel mode instead of series mode during the vendor's visit from May 16 to 17, 2006. The vendor determined that the system was left in manual mode (for backwash as discussed below), which reverted back to its default parallel mode after a power outage. This occurred three times throughout the first six-month period on June 19, September 5, and September 24, 2006, with the lag vessel treating a total of about 20 BV of raw water from the three events.

During the first three and a half months of system operation, each backwash was initiated/ended by physically opening/closing relevant valves by the operator. This was done to (1) ensure thorough

backwash (i.e., by manually controlling the backwash duration till the effluent water cleared out; Section 4.3.3), (2) circumvent recurring problems with backwash actuator valves 125b and 123a (which would not open in automatic mode), and (3) allow a right amount of water to flow from the hydropneumatic tank to supplement backwash (by manually opening and adjusting an isolation valve on the backwash supplemental line). While it might be necessary to backwash manually as discussed, the automatic control of the system should be utilized to minimize manual operation.

In addition, leaving the system in manual mode would put the system at risk of being reverted back to its default parallel mode after a power outage as discussed above. This, in conjunction with the need to accommodate the operator's request for his physical presence during backwash, prompted the vendor to extend the automatic backwash timer setting from 30 to 120 days in the PLC on August 9, 2006. In doing so, the operator could initiate a backwash, as Δp readings were approaching 10 psi (that usually happened within the 120-day setpoint), by pushing the manual backwash button on the PLC screen. To alleviate the three concerns mentioned above, the following actions were taken: (1) set backwash duration for 20 min and forward flush for 10 min, (2) made onsite observations to ensure correct valve positions, and (3) leave the manual isolation valve open at all times and allow the electrically actuated valve, MB-127, to control the supplemental flowrate. Upon completion of the backwash, the operator reset the system back to the automatic mode.

Operational irregularities also were experienced with the master totalizers on Well 2 and the treated water line. The totalizer on Well 2 was broken from April 25 to May 21, 2006, while the totalizer on the treated water line was broken from April 25 to July 10, 2006, and from August 21 to September 17, 2006.

The system O&M and operator skill requirements are discussed below in relation to pretreatment requirements, levels of system automation, operator skill requirements, preventive maintenance activities, and frequency of chemical/media handling and inventory requirements.

Pre- and Post-Treatment Requirements. Chlorination with the preexisting gas chlorination system (discussed in Section 4.2 and shown in Figure 4-7) was the only pre-treatment required at the Oak Manor MUD. The operator monitored the weight of the chlorine gas cylinder and target residual levels the same way as prior to the arsenic demonstration study.

System Automation. For automatic system operation, the APU-30S system was fitted with electronic flow sensors, flow controllers/valves, pressure transmitters/controllers, and a Square D Telemechanique PLC with a Magelis G2220 color touch interface screen. For example, each adsorption vessel was equipped with a flow sensor and totalizer (i.e., magnetic flowmeter), five electrically actuated butterfly valves, and a pressure transmitter, all of which were capable of transmitting and receiving electronic signals to and from the PLC. Although the PLC was capable of being interlocked with the well pumps, hydropneumatic pressure tank, and/or the storage tank, the Oak Manor MUD elected not to pursue this option due to additional electrical work required for interlocking.

The APU-30S system was capable of automatic backwash triggered by either a timer or a Δp setting. It also allowed the operator to override the automatic setpoint by pushing the manual backwash button on the PLC screen. As described earlier, to ensure a proper backwash, the operator initially conducted backwash manually by physically opening/closing the valves. This practice was replaced with "semi-automatic" backwash via the PLC after August 9, 2006.

The system also had six isolation ball valves to reverse the tank positions from lead to lag and vice versa after each media replacement. Since media replacement would happen rather infrequently, the tank switching operation was not automated.

In addition to regular O&M, operator's awareness and abilities to detect unusual system performance were necessary when troubleshooting system automation failures. The equipment vendor provided hands-on training and a supplemental operations manual to help increase operator's awareness and abilities to detect and cope with any performance irregularities.

Operator Skill Requirements. Under normal operating conditions, the skill requirements to operate the system were minimal. The operator was on-site typically five times a week and spent about 40 min each day to perform visual inspections and record the system operating parameters on the daily log sheets. Normal operation of the system did not require additional skills beyond those necessary to operate the existing water supply equipment.

TCEQ requires that the operator for the treatment system hold at least a TCEQ waterworks operator license. There are four water operator certificate levels, i.e., A, B, C, and D, with Class A being the highest. The certificate levels are based on education, experience, and related training. The operator for the Oak Manor MUD system has a Class C certificate, which requires a high school graduate or equivalent, two years of work experience, and 60 hr of related training (TCEQ, 2007).

Preventive Maintenance Activities. Preventive maintenance tasks included periodic checks of flowmeters and pressure gauges and inspection of system piping and valves. Typically, the operator performed these duties when he was on-site for routine activities.

Chemical Handling and Inventory Requirements. Gas chlorine cylinders were used for prechlorination; the operator ordered chemicals as had been done prior to the installation of the APU-30S system. Typically, four 150-pound cylinders were used per month and the gas chlorine supplier, DXI Industries, refilled the chlorine cylinder onsite.

4.5 System Performance

The performance of the system was evaluated based on analyses of water samples collected from the treatment plant and distribution system.

4.5.1 Treatment Plant Sampling. Table 4-9 summarizes the analytical results of arsenic, iron, and manganese concentrations measured at the four sampling locations across the treatment train. Table 4-10 summarizes the results of other water quality parameters. Appendix B contains a complete set of analytical results through the first six months of operation. The results of the water samples collected throughout the treatment plant are discussed below.

Arsenic. Water samples were collected on 14 occasions (including one duplicate sampling event on August 1, 2006), with field speciation performed during seven of the 14 occasions at IN, AC, TA, and TB sampling locations. Figure 4-14 contains four bar charts showing the concentrations of particulate arsenic, As(III), and As(V) at the four sampling locations for each of the seven speciation events.

Total arsenic concentrations in raw water ranged from 30.2 to 52.5 µg/L and averaged 43.8 µg/L. Particulate As levels were low, ranging from <0.1 to 5.9 µg/L and averaging 3.6 µg/L. Of the soluble fraction, As(III) was the predominating species, ranging from 21.9 to 44.1 µg/L and averaging 35.2 µg/L. As(V) was present, but at lower levels, ranging from 0.2 to 14.2 µg/L and averaging 4.8 µg/L.

After three sets of water samples were collected at the existing chlorine injection point (see Table 4-5), the raw water sample tap was relocated to immediately after the blending point of Wells 1 and 2 on May 24, 2006 (Section 4.3.5). After relocation, the average total arsenic level in source water increased

Table 4-9. Summary of Analytical Results for Arsenic, Iron, and Manganese

Parameter	Sample Location	Unit	Sample Count	Concentration			Standard Deviation
				Minimum	Maximum	Average	
As (total)	IN	µg/L	14	30.2	52.5	43.8	7.0
	AC	µg/L	14	23.5	38.1	31.5	4.1
	TA ^(a)	µg/L	13	0.2	10.9	6.7	3.2
	TB ^(a)	µg/L	13	0.05	4.3	1.0	1.0
As (soluble)	IN	µg/L	7	27.4	45.1	39.9	7.1
	AC	µg/L	7	24.3	30.5	27.7	2.3
	TA ^(a)	µg/L	6	0.05	9.8	6.4	3.7
	TB ^(a)	µg/L	6	0.05	1.5	0.7	0.5
As (particulate)	IN	µg/L	7	<0.1	5.9	3.6	2.1
	AC	µg/L	7	3.4	7.6	5.3	1.5
	TA ^(a)	µg/L	6	0.05	0.9	0.3	0.3
	TB ^(a)	µg/L	6	0.05	0.2	0.1	0.1
As (III)	IN	µg/L	7	21.9	44.1	35.2	9.0
	AC	µg/L	7	<0.1	1.0	0.6	0.3
	TA ^(a)	µg/L	6	0.05	1.1	0.5	0.4
	TB ^(a)	µg/L	6	0.05	0.8	0.5	0.2
As (V)	IN	µg/L	7	0.2	14.2	4.8	4.6
	AC	µg/L	7	23.3	30.0	27.1	2.4
	TA ^(a)	µg/L	6	0.05	8.7	5.8	3.4
	TB ^(a)	µg/L	6	0.05	0.8	0.3	0.3
Fe (total)	IN	µg/L	14	34	100	60	20
	AC	µg/L	14	<25	95	38	25
	TA ^(a)	µg/L	13	<25	<25	<25	–
	TB ^(a)	µg/L	13	<25	65	<25	14.6
Fe (soluble)	IN	µg/L	7	<25	43	<25	13.6
	AC	µg/L	7	<25	<25	<25	–
	TA ^(a)	µg/L	6	<25	<25	<25	–
	TB ^(a)	µg/L	6	<25	<25	<25	–
Mn (total)	IN	µg/L	14	50.0	61.3	54.4	3.1
	AC	µg/L	14	45.4	57.1	51.1	3.5
	TA ^(a)	µg/L	13	1.0	4.0	2.0	0.8
	TB ^(a)	µg/L	13	<0.1	0.9	0.4	0.2
Mn (soluble)	IN	µg/L	7	49.5	61.0	54.0	3.7
	AC	µg/L	7	<0.1	14.5	2.8	5.2
	TA ^(a)	µg/L	6	<0.1	1.2	0.5	0.5
	TB ^(a)	µg/L	6	<0.1	0.4	0.1	0.1

One-half of detection limit used for samples with concentrations less than detection limit for calculations.

(a) Sample results taken on May 23, 2006, not representative of actual water quality at Vessels A and B due to incorrect relocation of both sample taps (Section 4.3.5).

Table 4-10. Summary of Other Water Quality Sampling Results

Parameter	Sample Location	Unit	Sample Count	Concentration			Standard Deviation
				Minimum	Maximum	Average	
Alkalinity (as CaCO ₃)	IN ^(a)	Mg/L	13	318	371	347	12.9
	AC	Mg/L	14	342	390	361	15.8
	TA ^(b)	Mg/L	13	331	399	365	17.8
	TB ^(b)	Mg/L	13	331	392	362	14.9
Fluoride	IN	Mg/L	7	1.2	1.4	1.3	0.1
	AC	Mg/L	7	1.2	1.4	1.4	0.1
	TA ^(b)	Mg/L	6	1.3	1.7	1.4	0.2
	TB ^(b)	Mg/L	6	1.3	1.9	1.5	0.2
Sulfate	IN	Mg/L	7	<1	2	0.8	0.6
	AC	Mg/L	7	1	2	1.7	0.5
	TA ^(b)	Mg/L	6	1	2	1.8	0.4
	TB ^(b)	Mg/L	6	1	2	1.5	0.5
Nitrate (as N)	IN	Mg/L	7	<0.05	<0.05	<0.05	–
	AC	Mg/L	7	<0.05	<0.05	<0.05	–
	TA ^(b)	Mg/L	6	<0.05	<0.05	<0.05	–
	TB ^(b)	Mg/L	6	<0.05	0.20	0.05	0.07
Total P (as P)	IN	µg/L	14	25.2	86.7	42.7	15.1
	AC	µg/L	14	20.4	95.0	43.2	17.0
	TA ^(b)	µg/L	13	<10	95.0	26.5	26.7
	TB ^(b)	µg/L	13	<10	58.7	9.1	14.9
Silica (as SiO ₂)	IN	Mg/L	14	14.4	17.0	15.4	0.6
	AC	Mg/L	14	14.8	16.6	15.7	0.6
	TA ^(b)	Mg/L	13	15.3	17.0	15.9	0.5
	TB ^(b)	Mg/L	13	12.6	16.8	15.6	1.1
Turbidity	IN	NTU	14	0.1	0.8	0.4	0.2
	AC	NTU	14	0.2	0.8	0.4	0.2
	TA ^(b)	NTU	13	0.1	1.2	0.3	0.3
	TB ^(b)	NTU	13	0.1	0.5	0.3	0.2
pH	IN ^(c)	S.U.	13	7.5	8.0	7.7	0.1
	AC ^(c)	S.U.	13	7.3	7.7	7.5	0.1
	TA ^(b, c)	S.U.	12	7.6	8.0	7.7	0.1
	TB ^(b, c)	S.U.	12	7.6	7.9	7.7	0.1
Temperature	IN ^(c)	°C	13	22.8	32.8	25.6	2.6
	AC ^(c)	°C	13	22.3	33.8	25.4	3.0
	TA ^(b, c)	°C	12	22.1	32.1	25.2	2.8
	TB ^(b, c)	°C	12	21.7	30.7	25.0	2.5
Dissolved Oxygen	IN ^(c)	Mg/L	11	1.2	3.0	1.8	0.6
	AC ^(c)	Mg/L	11	1.2	2.3	1.8	0.3
	TA ^(b, c)	Mg/L	10	1.7	4.9	3.2	1.1
	TB ^(b, c)	Mg/L	10	1.5	4.0	2.7	0.8
ORP	IN ^(c)	mV	13	217	437	344	67.4
	AC ^(c)	mV	13	407	675	602	85.9
	TA ^(b, c)	mV	12	292	665	580	111
	TB ^(b, c)	mV	12	397	672	597	94
Free Chlorine (as Cl ₂)	AC ^(c)	Mg/L	13	0.3	3.3	2.1	1.0
	TA ^(b, c)	Mg/L	12	0.1	1.8	1.4	0.5
	TB ^(b, c)	Mg/L	12	0.2	1.8	1.3	0.6

Table 4-10. Summary of Other Water Quality Sampling Results (Continued)

Parameter	Sample Location	Unit	Sample Count	Concentration			Standard Deviation
				Minimum	Maximum	Average	
Total Chlorine (as Cl ₂)	AC ^(c)	Mg/L	13	0.3	3.1	2.1	1.0
	TA ^(b, c)	Mg/L	12	0.2	2.0	1.5	0.5
	TB ^(b, c)	Mg/L	12	0.5	2.0	1.4	0.5
Total Hardness (as CaCO ₃)	IN	Mg/L	7	31.0	44.9	37.8	5.3
	AC	Mg/L	7	30.0	45.9	40.2	6.5
	TA ^(b)	Mg/L	6	31.5	45.4	41.1	5.1
	TB ^(b)	Mg/L	6	32.7	46.6	42.1	4.9
Ca Hardness (as CaCO ₃)	IN	Mg/L	7	18.8	32.7	25.1	5.0
	AC	Mg/L	7	18.0	32.2	26.6	5.7
	TA ^(b)	Mg/L	6	19.0	32.0	27.5	4.5
	TB ^(b)	Mg/L	6	19.8	32.3	28.2	4.4
Mg Hardness (as CaCO ₃)	IN	Mg/L	7	12.1	13.8	12.7	0.6
	AC	Mg/L	7	12.0	15.6	13.6	1.4
	TA ^(b)	Mg/L	6	11.8	15.6	13.5	1.4
	TB ^(b)	Mg/L	6	11.8	16.2	13.9	1.5

One-half of detection limit used for samples with concentrations less than detection limit for calculations.

(a) Outlier on August 29, 2006.

(b) Sample results taken on May 23, 2006, not representative of actual water quality at Vessels A and B due to incorrect relocation of both sample taps (Section 4.3.5).

(c) Onsite water quality parameters not taken on August 1, 2006.

by about 41%, i.e., from 33.2 to 46.8 µg/L (see the complete set of arsenic data in Appendix B and two sets of arsenic speciation data in Figure 4-14).

The increase in total arsenic was attributed to the different arsenic concentrations in Well 1 and Well 2 water (see Table 4-1). Due to its close proximity to the blending point, water samples taken from the relocated sample tap might not have been well mixed and, therefore, were more representative of Well 1 water with higher total arsenic concentrations. In contrast, the raw water sampling location (at the existing chlorine injection point) prior to relocation was located further downstream from the blending point (Figure 4-12) and, therefore, yielded more representative samples of blended water from both wells. The operator continued to sample at the relocated sample tap during the first six-month study period.

After chlorination at AC sampling location, the average As(III) and As(V) concentrations were 0.6 and 27.1 µg/L, respectively, indicating effective oxidation. Free and total chlorine levels at the AC location both averaged 2.1 mg/L (as Cl₂) (see Table 4-10) and their corresponding ORP readings averaged 602 mV, compared to 344 mV in source water. As expected, the relocation of the raw water sample tap on May 24, 2006, did not affect the water samples taken at the AC location. The average total arsenic levels remained unchanged, i.e., averaging 34.7 µg/L before relocation and 30.7 µg/L after relocation. These concentrations were in the same range of the raw water sample results before the raw water sampling location was relocated.

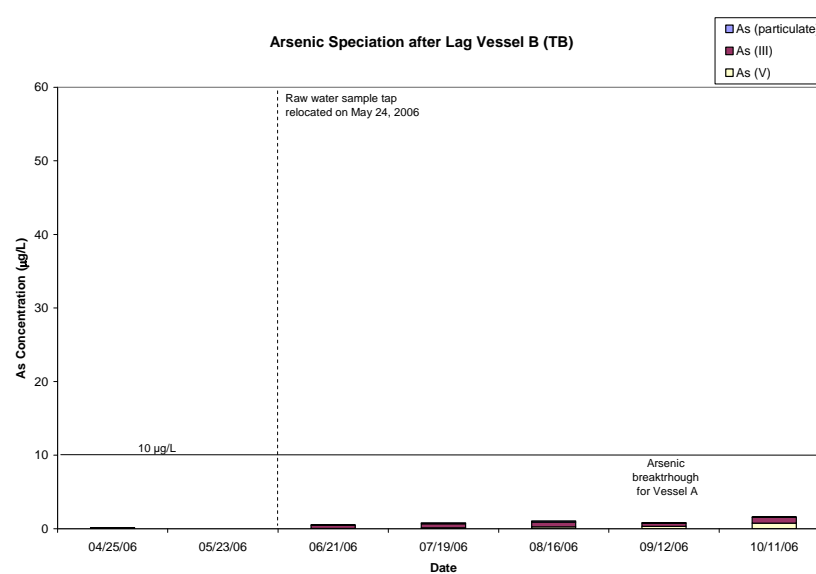
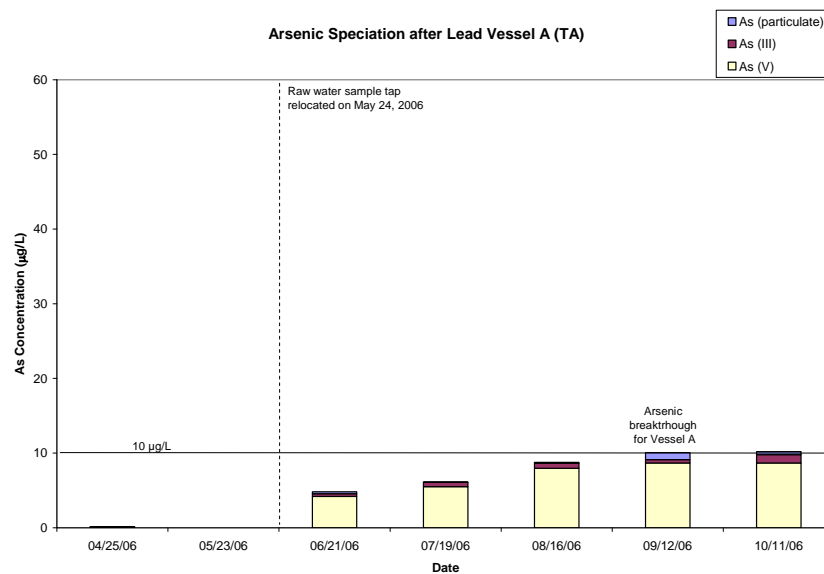
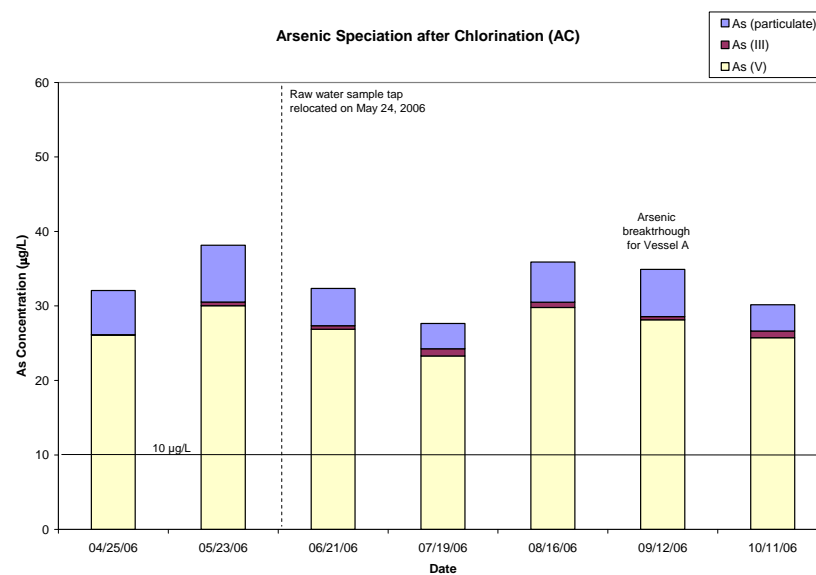
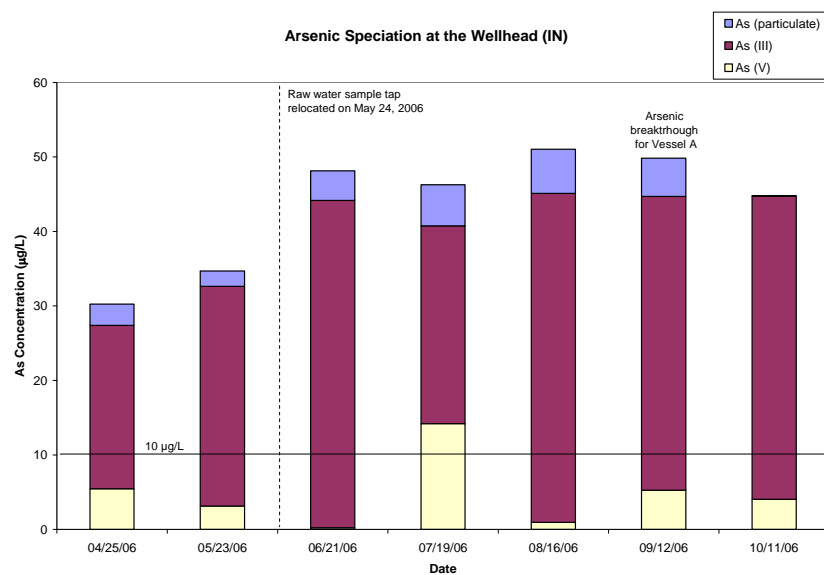


Figure 4-14. Concentrations of Various Arsenic Species at IN, AC, TA, and TB Sampling Locations

Figure 4-15 presents total arsenic breakthrough curves from the lead and lag vessels, along with total arsenic concentrations in raw water and after chlorine addition. The lead vessel, Vessel A, removed the majority of arsenic, existing predominately as As(V) because of prechlorination. On September 12, 2006, after treating approximately 10,240 BV of water, arsenic was 10.0 µg/L following the lead vessel and 0.8 µg/L following the lag vessel. Through the end of the first six months of system operation, the system treated only 12,170 BV, or 11,241,500 gal, of water.

As shown in Figure 4-15, total arsenic concentrations following the lag vessel remained <1.1 µg/L until September 27, 2006, when a concentration spike up to 4.3 µg/L was observed. Total arsenic concentrations decreased back to 1.4 µg/L during the following sampling event on October 11, 2006. The spike might have been caused by a power outage on September 24, 2006, when the system was reverted back to its default parallel configuration (Section 4.4.3).

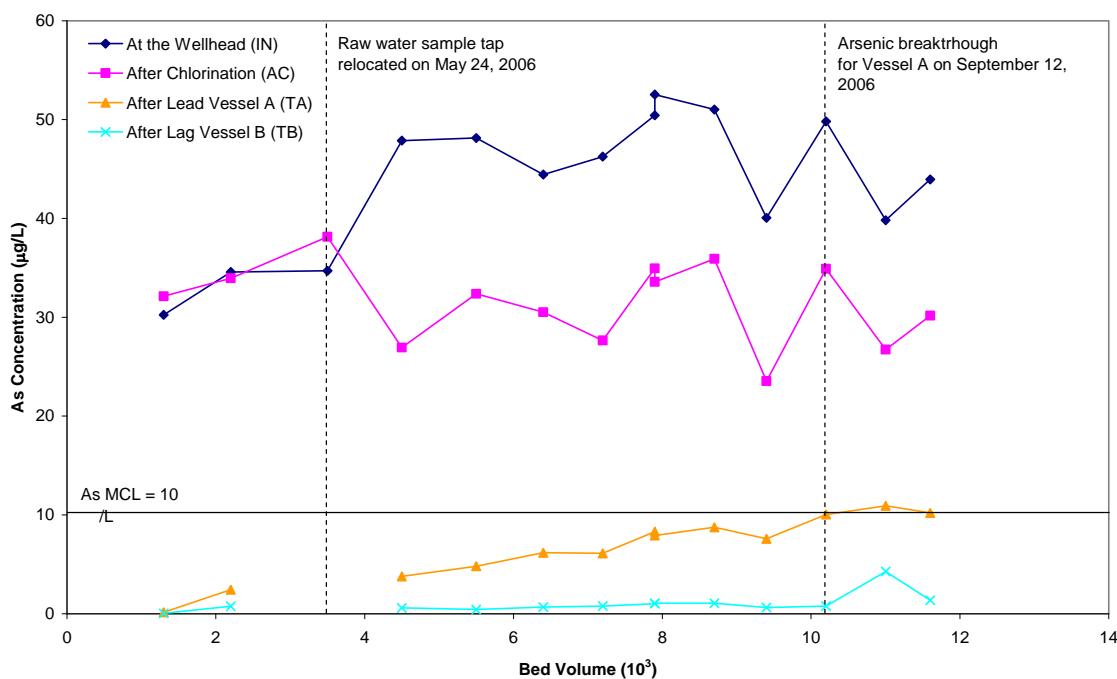


Figure 4-15. Total Arsenic Breakthrough Curves

Total chlorine levels following Vessels A and B averaged 1.5 and 1.4 mg/L (as Cl₂), respectively, with free chlorine levels averaged similarly at 1.4 and 1.3 mg/L (as Cl₂). The corresponding ORP readings averaged 580 and 597 mV, respectively. Both total and free chlorine were lower than the levels measured at the AC location (i.e., 2.1 mg/L [as Cl₂], on average), suggesting some chlorine demand (i.e., 0.6 mg/L [as Cl₂], on average) across the lead vessel. The total chlorine demand for source water included 0.2 mg/L (as Cl₂) for As, Fe, and Mn and 1.4 mg/L (as Cl₂) for ammonia (breakpoint chlorination of 0.2 mg/L [as N] as shown in Table 4-1). As a result, the overall chlorine demand would have been 2.2 mg/L (as Cl₂). The average chlorine consumption calculated based on the chlorine gas usage was 4.5 mg/L (Figure 4-16), which was about 25% higher than the sum of chlorine demand and residuals measured.

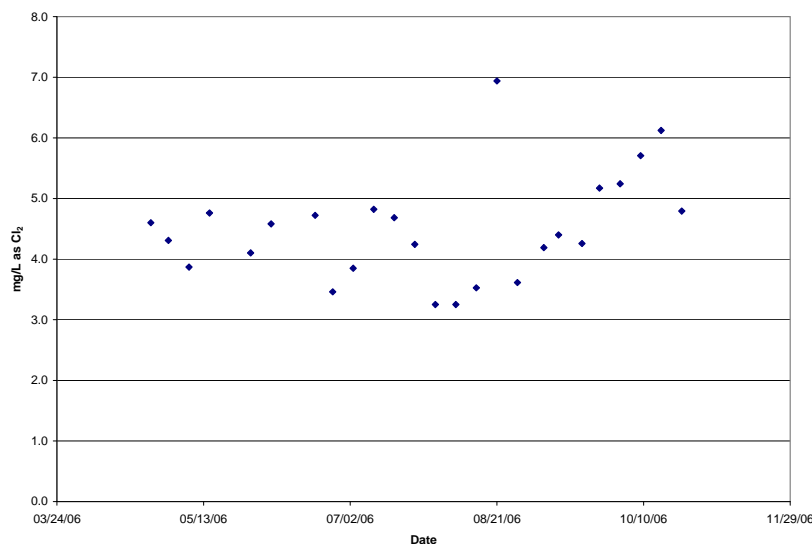


Figure 4-16. Chlorine Consumption Based on Chlorine Gas Usage

Iron. Total iron concentrations in source water ranged from 34 to 100 µg/L and averaged 60 µg/L (Table 4-9), existing mostly as particulate iron. The source water sample taken during the November 2, 2004, site visit, also contained a similar amount of total iron (i.e., 95 µg/L) with over 60% existing as particulate iron. Particulate iron might exist in source water as part of natural sediment or caused by inadvertent aeration of the samples during sampling. The amounts of DO measured in source water, however, were low, ranging from 1.2 to 3.0 mg/L and averaging 1.8 mg/L.

Total iron concentrations in source water were not significantly affected by the relocation of the sample tap on May 24, 2006, with an average decrease of only 11% observed (i.e., 66.1 µg/L before relocation and 58.9 µg/L after relocation). Total iron concentrations following prechlorination were slightly less than those at the wellhead, ranging from less than the method reporting limit of 25 µg/L to 95 µg/L and averaging 38 µg/L. Correspondingly, soluble iron levels (based upon 0.45-µm filters) were <25 µg/L. Total iron concentrations were reduced to an average of <25 µg/L after both Vessels A and B.

Manganese. Total manganese concentrations in source water ranged from 50.0 to 61.3 µg/L and averaged 54.4 µg/L, existing almost entirely in the soluble form (which was consistent with that found in source water samples collected during the November 2, 2004, site visit [Table 4-1]). The amounts of total manganese were not affected by the relocation of the sample tap. After prechlorination, an average of 93.5% of soluble manganese precipitated and formed, presumably, MnO₂ solids. The MnO₂ solids formed along with unoxidized Mn(II) were removed by the media, causing total manganese concentrations to decrease to 2.0 and 0.4 µg/L following the lead and lag vessels, respectively. Note that 0.45-µm disc filters were used to separate solids from the soluble fraction.

The high Mn(II) precipitation rate after chlorination at the Oak Manor MUD reflected rapid oxidation kinetics by chlorine, which was contrary to the findings by most researchers who investigated the oxidation of Mn(II) even with some lengths of contact time (Knocke et al, 1987 and 1990; Condit and Chen, 2006). Varying Mn(II) oxidation kinetics were observed at 11 EPA arsenic removal demonstration sites (Table 4-11), with two sites averaging less than 10% (i.e., Delavan, WI and Bruni, TX), seven sites averaging from 14.6 to 55.0%, and two sites averaging at 93.5 and 70% (i.e., Alvin, TX and Springfield, OH). It is not clear why some source waters had slower oxidation kinetics than others. Based on existing

literature for Mn(II) oxidation with chlorine, the variables affecting Mn(II) oxidization kinetics might include pH, temperature, and contact time. Mn(II) oxidation rates increased at high pH (i.e., 8.0) and high temperature (Knocke et al., 1987). Table 4-11 did not show clear correlation between pH, temperature, and contact time with precipitation rates (McCall et al., 2007). Out of the 13 sites investigated, the Oak Manor MUD had the highest precipitation rates, which might partially be explained by the relatively high temperature readings (average 25.6°C) measured at the site.

Competing Anions. Silica and phosphate are known to influence arsenic adsorption with iron-based media. Silica concentrations in source water ranged from 14.4 to 17.0 mg/L with no significant reductions across the treatment train. Total phosphorous concentrations in source water were somewhat higher, ranging from 25.2 to 86.7 µg/L and averaging 42.7 mg/L. Total phosphorous concentrations were progressively reduced to an average of 26.5 and 9.1 µg/L following Vessels A and B, respectively; suggesting that total phosphorus might compete with arsenic for available adsorptive sites.

Other Water Quality Parameters. All other water quality parameters measured during the first six-month study period were comparable to source water results presented in Table 4-1. As shown in Table 4-10, pH values of raw water varied from 7.5 to 8.0 and averaged 7.7. Arsenic removal by iron-based adsorption media, in general, have greater arsenic removal capacities at near or lower than neutral pH values. Alkalinity, reported as CaCO₃, ranged from 318 to 371 mg/L and averaged 347 mg/L, not including an outlier for raw samples taken on August 29, 2006. The results indicated that the adsorptive media did not affect the amount of alkalinity in the treated water. Sulfate concentrations were consistently low, averaging 0.8 mg/L in source water and 1.5 to 1.8 mg/L across the treatment train. Fluoride levels ranging from 1.2 to 1.9 mg/L in all samples did not appear to have been affected by the SORB 33™ media. Total hardness, existing 66% as calcium hardness and 34% as magnesium hardness, ranged from 31.0 to 44.9 mg/L (as CaCO₃), and also remained unchanged throughout the treatment train. DO levels averaged 1.8 mg/L in source water. Due to a lack of a proper raw sample tap prior to May 24, 2006 (Section 4.3.5), source water was taken at the existing chlorine addition point (see Figure 4-1). DO levels were higher before a proper raw water sample tap was installed, averaging 2.4 mg/L (compared to 1.6 mg/L after installation). DO at the AC location averaged 1.8 mg/L.

Table 4-11. Amount of Mn(II) Precipitated After Chlorination at 11 Arsenic Removal Demonstration Sites

Demonstration Location	Approximate Contact Time	pH	Temperature	Ammonia	TOC	Avg Mn (total/soluble)	Avg Mn (total/soluble)	Avg Mn(II) Precipitated
	min	S.U.	°C	mg/L	mg/L	µg/L	µg/L	%
Bruni, TX	None	8.2	25.6	<detect	0.9	5.0/4.7	3.9/3.5	5.8
Anthony, NM	None	7.7	30.0	None	1.6	9.6/8.9	9.8/6.8	23.5
Brown City, MI	None	8.0	11.6	None	<detect	16.1/15.7	15.0/9.8	31.9
Delavan, WI	2	7.5	13.9	2.9	1.6	19.2/20.1	18.1/17.7	2.7
Sandusky, MI	41	7.2	12.1	0.3	1.5	25.3/26.7	26.0/11.7	55.0
Pentwater, MI	6	8.0	12.6	0.3	2.0	27.3/28.8	30.1/14.3	52.4
Springfield, OH	None	7.3	16.2	0.2	<detect	35.6/36.3	29.5/8.3	70.0
Alvin, TX	None	7.7	25.6	0.2	0.7	54.4/54.0	51.1/2.8	93.5
Rollinsford, NH	None	7.9	14.2	None	<detect	110/124	101/86.5	14.6
Climax, MN	5	7.6	9.1	None	12.0	135/126	130/73.7	35.9
Sabin, MN	7	7.3	13.0	0.2	1.6	346/378	338/228	32.6

Due to the incorrect location of the TA and TB effluent sample taps (Section 4.3.5), these samples had to be taken from each vessel's 1-in drain line until August 9, 2006, before they were correctly installed. Therefore, prior to August 9, 2006, the DO levels averaged 3.8 and 3.1 mg/L for the samples taken at TA

and TB, respectively. Thereafter, the DO levels were lower, averaging 1.9 and 2.0 mg/L at TA and TB, respectively.

4.5.2 Backwash Water Sampling. Table 4-12 presents the analytical results for three monthly backwash water sampling events for both adsorption vessels. pH values ranged from 7.7 to 7.8, similar to those measured for source and treated water. TDS levels ranged from 482 to 532 mg/L and TSS from 5 to 400 mg/L. As expected, TSS values were higher for Vessel A (i.e., 294 mg/L) than for Vessel B (i.e., 57 mg/L). Concentrations of total arsenic, iron, and manganese ranged from 3.2 to 17.0 µg/L, from 0.7 to 25.2 mg/L, and from 79 to 3,570 µg/L, respectively, with the majority of iron and manganese existing as particulate. Assuming that an average of 6,058 gal (as compared to design of 6,300 gal) backwash and fast rinse wastewater was produced from each vessel, at an average flowrate of 260 gpm and duration of 23.3 min, Vessel A would generate about 14.9 lb of solids (including 4.2×10^{-5} lb of arsenic, 0.9 lb of iron, and 0.08 lb of manganese) and Vessel B would generate 2.9 lb of solids (including 1.5×10^{-4} lb of arsenic, 0.2 lb of iron, and 0.03 lb of manganese), for each backwash cycle. The reasons for the large quantity of backwash solids produced are being investigated and will be discussed in the Final Performance Evaluation Report. The quantity of backwash wastewater and backwash solids discharged per vessel will be further monitored during the next six-month study period.

4.5.3 Distribution System Water Sampling. Table 4-13 summarizes the results of the distribution system sampling. Arsenic, iron, and manganese concentrations improved significantly after system startup. Arsenic concentrations decreased, on average, from 38.2 to 2.0 µg/L, iron from 115 to <25 µg/L, and manganese from 41.8 to 1.3 µg/L at each of the three sampling locations. Alkalinity, pH, lead, and copper remained rather unchanged at each location after system startup. Copper concentrations at DS1, however, were much higher than those at DS2 and DS3 (i.e., 498 µg/L, on average, at DS1 compared to 29.7 µg/L at DS2 and 31.0 µg/L at DS3). The operator reported that DS1 had older distribution piping.

Iron concentrations within the distribution system were comparable to those at the entry point (or after the lag vessel), but average arsenic and manganese concentrations within the distribution system increased slightly from 0.9 to 2.0 µg/L and from 0.5 to 1.3 µg/L, respectively.

Table 4-12. Backwash Water Sampling Results

		Vessel A										Vessel B									
		pH	TDS	TSS	As (total)	As (soluble)	As (particulate)	Fe (total)	Fe (soluble)	Mn (total)	Mn (soluble)	pH	TDS	TSS	As (total)	As (soluble)	As (particulate)	Fe (total)	Fe (soluble)	Mn (total)	Mn (soluble)
No.	Date	S.U.	mg/L	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	S.U.	mg/L	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
1	07/14/06	7.7	508	366	17.0	15.9	1.1	25,214	<25	3,570	0.2	7.8	532	150	7.7	1.5	6.2	10,739	<25	1,705	0.4
2	08/09/06	7.7	526	116	16.1	14.7	1.4	3,910	<25	162	1.8	7.7	508	5	3.2	2.6	0.6	662	<25	79	0.4
3	09/19/06	7.7	482	400	10.1	13.9	<0.1	22,591	<25	893	0.6	7.7	500	15	5.1	3.0	2.1	1,437	<25	341	0.2

TDS = total dissolved solids

TSS = total suspended solids

NA = not analyzed

Note operator did not take samples during 05/16/06 backwash

Table 4-13. Distribution Water Sampling Results

Sampling Date		As at Entry Point ⁽ⁱ⁾	Fe at Entry Point ⁽ⁱ⁾	Mn at Entry Point ⁽ⁱ⁾	DS1								DS2								DS3							
					non-LCR								non-LCR								LCR							
					1st Draw								1st Draw								1st Draw							
					Stagnation Time	pH	Alkalinity	As (total)	Fe (total)	Mn (total)	Pb	Cu	Stagnation Time	pH	Alkalinity	As (total)	Fe (total)	Mn (total)	Pb	Cu	Stagnation Time	pH	Alkalinity	As (total)	Fe (total)	Mn (total)	Pb	Cu
No.	Date	µg/L	µg/L	µg/L	hr	S.U.	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L	hr	S.U.	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L	hr	S.U.	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L
BL1	03/16/05 ^(a)	NA	NA	NA	10.0	8.2	379	27.8	<25	40.6	0.6	32.2	6.4	8.1	366	29.6	49	68.3	0.6	20.1	12.0	7.9	379	29.8	<25	34.9	0.3	32.6
BL2	04/20/05 ^(a)	NA	NA	NA	12.0	7.6	369	32.4	<25	32.7	0.8	18.4	Homeowner Not Available								11.8	7.7	368	30.9	<25	19.7	0.1	81.7
BL3	05/18/05	NA	NA	NA	8.6	7.4	379	92.8	815	60.5	0.5	435	8.6	7.7	379	33.0	26	38.3	0.6	59.1	8.0	7.5	357	50.3	268	34.7	0.7	36.5
BL4	06/14/05 ^(b)	NA	NA	NA	11.0	7.7	361	32.4	<25	36.9	0.4	862	7.0	7.7	365	29.6	25	50.9	1.3	28.6	12.0	7.8	356	31.2	<25	42.2	0.8	74.0
Average		NA	NA	NA	10.4	7.7	372	46.3	123	42.7	0.6	337	7.3	7.8	370	30.7	33	52.5	0.8	35.9	10.9	7.7	365	35.5	77	32.9	0.5	56.2
1	05/17/06 ^(c)	0.8	Cold-Water Faucet Not Flushed Before Shutting Off										NA	8.0	363	3.0	<25	1.1	0.5	29.4	NA	7.9	347	3.9	<25	1.4	0.2	25.9
2	06/07/06 ^(d)	0.6	<25	0.9	10.0	7.8	363	1.9	<25	0.3	0.1	624	6.9	7.9	355	2.4	<25	1.3	0.1	36.8	8.5	7.8	359	2.8	<25	3.8	0.5	23.3
3	07/19/06 ^(e)	0.8	<25	0.5	9.0	7.8	353	1.8	<25	0.4	0.3	465	8.0	7.9	361	2.0	<25	2.5	0.6	27.3	8.0	7.8	357	2.1	<25	1.5	0.4	32.4
4	08/15/06 ^(f)	1.1	<25	0.4	10.3	7.7	358	1.4	<25	0.5	0.4	496	6.0	7.9	350	1.6	<25	1.2	0.4	51.3	8.0	7.8	358	2.0	<25	1.7	0.5	41.3
5	09/13/06 ^(g)	0.8	<25	<0.1	9.8	8.0	379	1.2	<25	0.3	0.6	383	7.0	7.9	388	1.3	<25	3.0	0.2	18.5	8.0	7.9	398	1.4	<25	0.2	0.3	18.7
6	10/10/06 ^(h)	1.4	65	0.5	9.3	7.9	385	1.6	<25	0.7	0.6	520	8.2	7.9	387	2.0	<25	1.7	0.6	14.9	10.0	7.8	382	2.0	<25	0.4	0.5	44.6
Average		0.9	<25	0.5	9.7	7.8	368	1.6	<25	0.5	0.4	498	7.2	7.9	367	2.1	<25	1.8	0.4	29.7	8.5	7.8	367	2.4	<25	1.5	0.4	31.0

NS = not sampled

NA = not analyzed

BL = Baseline Sampling

(a) DS1 and DS2 sampled at different locations as discussed in Section 3.3.4.

(b) DS1 sampled on 06/13/05.

(c) DS3 sampled on 05/18/06. Metals at entry point taken on 05/09/06.

(d) Metals at the entry point taken on 06/06/06.

(e) DS2 sampled on 07/25/06.

(f) Metals at the entry point taken on 08/16/06.

(g) Metals at the entry point taken on 09/12/06.

(h) Metals at the entry point taken on 10/11/06.

(i) Metals at entry point (As, Fe, and Mn) taken after Vessel B (Appendix B).

4.6 System Cost

The system cost is evaluated based on the capital cost per gpm (or gpd) of the design capacity and the O&M cost per 1,000 gal of water treated. The capital cost includes the cost for equipment, site engineering, and installation and the O&M cost includes media replacement and disposal, electrical power use, and labor.

4.6.1 Capital Cost. The capital investment for equipment, site engineering, and installation of the treatment system was \$179,750 (see Table 4-14). The equipment cost was \$124,103 (or 69% of the total capital investment), which included \$86,642 for the skid-mounted APU-30S unit, \$18,858 for the E33 media (\$152/ft³ or \$4.35/lb to fill two vessels), \$8,393 for shipping, and \$10,211 for labor.

The engineering cost included the cost for preparing a submittal package for the exception request to system piloting and a follow-up permit application to TCEQ by Oak Manor MUD. The permit submittal package was prepared by SCL Engineering, the District's Engineer (see Section 4.3.1). The engineering cost was \$14,000, or 8% of the total capital investment.

The installation cost included the equipment and labor to unload and install the skid-mounted unit, perform piping tie-ins and electrical work, load, and backwash the media, perform system shakedown and startup, and conduct operator training. The installation cost was \$41,647, or 23% of the total capital investment.

The total capital cost of \$179,750 was normalized to the system's rated capacity of 150 gpm (216,000 gpd), which resulted in \$1,198/gpm (or \$0.83/gpd) of design capacity. The capital cost also was converted to an annualized cost of \$16,967/yr using a capital recovery factor (CRF) of 0.09439 based on a 7% interest rate and a 20-year return period. Assumed that the system operated 24 hours a day, 7 days a week at the system design flowrate of 150 gpm to produce 78,624,000 gal of water per year, the unit capital cost would be \$0.22/1,000 gal. Because the system operated an average of 7.2 hr/day at 134 gpm (see Table 4-6), producing 11,241,500 gal of water during the six-month period, the unit capital cost increased to \$0.75/1,000 gal at this reduced rate of use.

4.6.2 Operation and Maintenance Cost. The O&M cost included the cost for such items as media replacement and disposal, electricity, and labor (Table 4-15). Although media replacement did not take place during the first six months of system operation, the media replacement cost would represent the majority of the O&M cost and was estimated to be \$23,568 to change out the lead and lag vessels. This media change-out cost would include the cost for media for two vessels, freight, labor, travel, and media disposal. This cost was used to estimate the media replacement cost per 1,000 gal of water treated as a function of the projected system run length at the 10 µg/L arsenic breakthrough from the lag vessel (Figure 4-17). Because the actual media change-out most likely will take place only for the lead vessel, a revised cost estimate (or actual) for one vessel will be used for the preparation of the Final Performance Evaluation Report.

Comparison of electrical bills supplied by the utility prior to system installation and since startup did not indicate a noticeable increase in power consumption. Therefore, electrical cost associated with operation of the system was assumed to be negligible.

Under normal operating conditions, routine labor activities to operate and maintain the system consumed an average of 40.4 min/day over the six-month period from April 25 to October 25, 2006 (or 183 days). Therefore, the estimated labor cost was \$0.21/1,000 gal of water treated.

Table 4-14. Capital Investment Cost for APU-30S System

Description	Quantity	Cost	% of Capital Investment
<i>Equipment Cost</i>			
APU-30S Skid Mounted System (Unit)	1	\$86,642	–
E33 adsorptive media (ft ³)	124	\$18,858	–
Shipping	–	\$8,393	–
Vendor Labor	–	\$10,211	–
Equipment Total	–	\$124,103	69%
<i>Engineering Cost</i>			
Subcontractor Labor/ Travel	–	\$14,000	–
Engineering Total	–	\$14,000	8%
<i>Installation Cost</i>			
Vendor Labor	–	\$4,913	–
Vendor Travel	–	\$7,984	–
Subcontractor Labor	–	\$28,750	–
Installation Total	–	\$41,647	23%
Total Capital Investment	–	\$179,750	100%

Table 4-15. Operation and Maintenance Cost for APU-30S System

Cost Category	Value	Assumptions
Volume processed (gal)	11,241,500	April 25 to October 25, 2006
<i>Media Replacement and Disposal Cost</i>		
Media replacement (\$)	\$18,858	Vendor quote for 124 ft ³ for both vessels
Shipping (\$)	\$570	Vendor quote
Vendor Labor/Travel (\$)	\$2,800	Vendor quote
Media disposal (\$)	\$1,040	Vendor quote
Subtotal	\$23,268	Vendor quote
Media replacement and disposal (\$/1,000 gal)	See Figure 4-17	
<i>Electricity Cost</i>		
Electricity (\$/1,000 gal)	\$0.00	Electrical costs assumed negligible
<i>Labor Cost</i>		
Average weekly labor (min)	280	40 min/day; 183 days for first six months of study
Labor (\$/1,000 gal)	\$0.21	Labor rate = \$19.50/hr
Total O&M Cost/1,000 gal	See Figure 4-17	

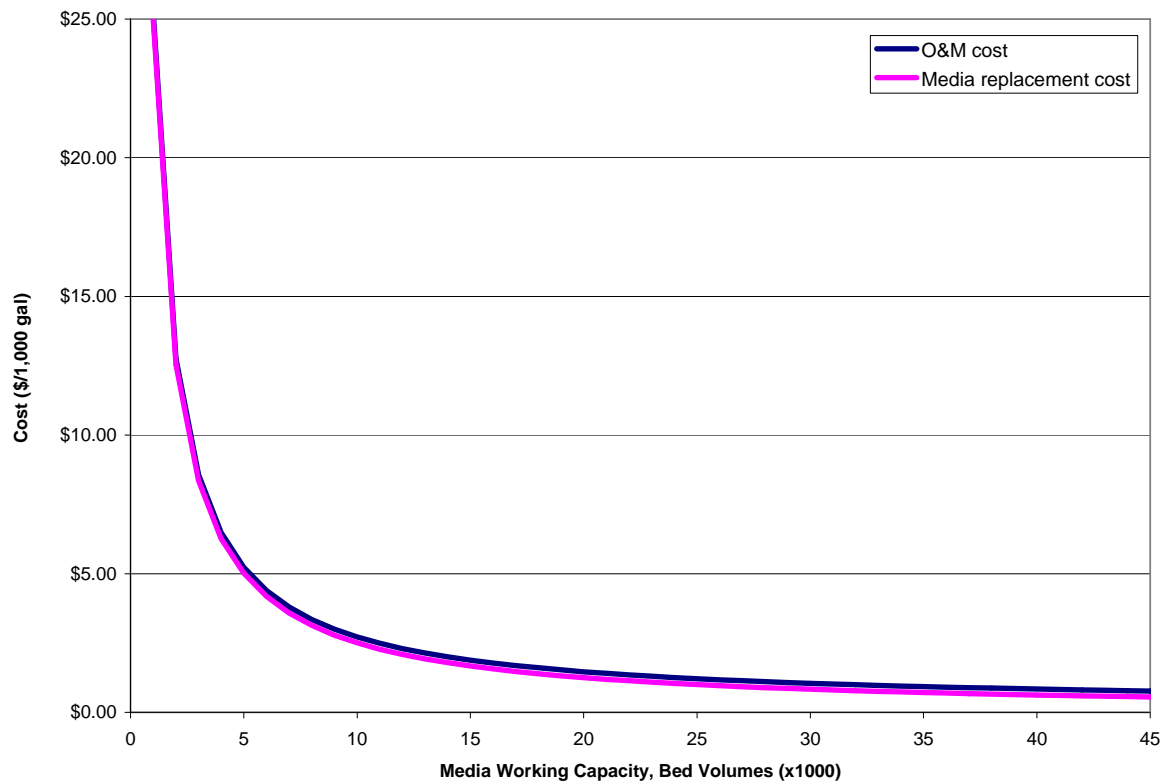


Figure 4-17. Media Replacement and Operation and Maintenance Cost

Section 5.0 REFERENCES

- Battelle. 2004. *Quality Assurance Project Plan for Evaluation of Arsenic Removal Technology*. Prepared under Contract No. 68-C-00-185, Task Order No. 0029, for U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.
- Battelle. 2005. *System Performance Evaluation Study Plan: U.S. EPA Demonstration of Arsenic Removal Technology Round 2 at Alvin, TX*. Prepared under Contract No. 68-C-00-185, Task Order No. 0029, for U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.
- Chen, A.S.C., L. Wang, J.L. Oxenham, and W.E. Condit. 2004. *Capital Costs of Arsenic Removal Technologies: U.S. EPA Arsenic Removal Technology Demonstration Program Round 1*. EPA/600/R-04/201. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.
- Condit, W.E. and A.S.C. Chen. 2006. *Arsenic Removal from Drinking Water by Iron Removal, U.S. EPA Demonstration Project at Climax, MN, Final Performance Evaluation Report*. EPA/600/R-06/152. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.
- Edwards, M., S. Patel, L. McNeill, H. Chen, M. Frey, A.D. Eaton, R.C. Antweiler, and H.E. Taylor. 1998. "Considerations in As Analysis and Speciation." *J. AWWA*, 90(3): 103-113.
- EPA. 2003. Minor Clarification of the National Primary Drinking Water Regulation for Arsenic. *Federal Register*, 40 CFR Part 141.
- EPA. 2002. *Lead and Copper Monitoring and Reporting Guidance for Public Water Systems*. EPA/816/R-02/009. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.
- EPA. 2001. National Primary Drinking Water Regulations: Arsenic and Clarifications to Compliance and New Source Contaminants Monitoring. *Federal Register*, 40 CFR Parts 9, 141, and 142.
- Knocke, W.R., R.C. Hoehn, and R.L. Sinsabaugh. 1987. "Using Alternative Oxidants to Remove Dissolved Manganese from Waters Laden with Organics." *J. AWWA*, 79(3): 75.
- Knocke, W.R., J.E. Van Benschoten, M. Kearney, A. Soborski, and D.A. Reckhow. 1990. *Alternative Oxidants for the Remove of Soluble Iron and Manganese*. Final report prepared for the AWWA Research Foundation, Denver, CO.
- Knocke, W.R., R.C. Hoehn, and R.L. Sinsbaugh. 1992. "Kinetic Modeling of Manganese(II) Oxidation by Chlorine Dioxide and Potassium Permanganate." *Environmental Science and Technology*, 26(7): 1327-1333.
- McCall, S.E., A.S.C. Chen, and L. Wang. 2007. *Arsenic Removal from Drinking Water by Adsorptive Media, U.S. EPA Demonstration Project at Chateau Estates Mobile Home Park in Springfield, OH, Final Evaluation Report*. EPA/600/R-06/152. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH. .
- Sorg, T.J. 2002. "Iron Treatment for Arsenic Removal Neglected." *Opflow*, 28(11): 15.

Severn Trent Services. 2006. *SORB 33TM As Removal Systems with Bayoxide[®] E33 Media Operation and Maintenance Manual APU-30S – City of Alvin, Texas.*

Severn Trent Services. 2006. *SORB 33TM As Removal Systems with Bayoxide[®] E33 Media Vendor Proposal for the APU-30S in Alvin, Texas.*

TCEQ. 2007. *Operator Training and Certification.* <http://www.tceq.state.tx.us/>

Wang, L., W.E. Condit, and A.S.C. Chen. 2004. *Technology Selection and System Design: U.S. EPA Arsenic Removal Technology Demonstration Program Round 1.* EPA/600/R-05/001. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

APPENDIX A

OPERATIONAL DATA

US EPA Arsenic Demonstration Project at Alvin, TX – Daily System Operation Log Sheet

		Well Op Hr	Well 1		Well 2		Vessel A			Vessel B ^(c)				Vessel A & B Total Cum. Bed Volume Treated ^(d)	Vessel/System Pressure			
		Op Time	Usage	Avg Flow	Usage ^(a)	Avg Flow	Flowrate ^(b)	Usage ^(b)	Avg Flow	Flowrate	Usage	Avg Flow	ΔP	no.	Vessel A ΔP	Vessel B ΔP	Sys ΔP	NaOCl Average Dosage
		hr	gal	gpm	gal	gpm	gpm	gal	gpm	gpm	gal	gpm	psi		psi	psi	psig	mg/L
1	04/25/06	7.6	21,000	46	NA	NA	NM	57,041	NA	NM	31	NA	2.50	1,315	2.50	2.50	13	4.8
	04/26/06	8.5	24,000	47	NA	NA	NM	63,750	125	NM	0	0	3.50	1,384	3.50	3.50	14	
	04/27/06	6.5	15,000	38	NA	NA	NM	48,750	125	NM	3	0	3.00	1,437	3.00	3.00	14	
	04/28/06	8.4	26,000	52	NA	NA	off	63,000	125	NM	7	0	off	1,505	off	off	NA	
	04/29/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	
	04/30/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	
2	05/01/06	21.7	60,000	46	NA	NA	NM	162,750	125	NM	29	0	3.25	1,680	3.50	3.25	13	4.3
	05/02/06	4.5	12,000	44	NA	NA	NM	33,750	125	NM	17	0	3.00	1,717	3.50	3.00	14	
	05/03/06	8.6	24,000	47	NA	NA	NM	64,500	125	NM	7	0	3.00	1,786	3.50	3.00	13	
	05/04/06	7.4	20,000	45	NA	NA	off	55,500	125	NM	9	0	off	1,846	off	off	NA	
	05/05/06	11.2	30,000	45	NA	NA	NM	84,000	125	NM	19	0	3.25	1,937	3.75	3.25	NA	
	05/06/06	5.9	14,000	NA	NA	NA	NM	44,250	125	NM	12	0	3.25	1,985	3.75	3.25	NA	
3	05/07/06	6.9	22,000	NA	NA	NA	NM	51,750	125	NM	13	0	3.25	2,040	4.00	3.25	NA	3.9
	05/08/06	9.8	27,000	46	NA	NA	NM	73,500	125	NM	35	0	3.25	2,120	4.25	3.25	15	
	05/09/06	7.7	21,000	45	NA	NA	off	57,750	125	NM	18	0	off	2,182	off	off	NA	
	05/10/06	7.5	20,000	44	NA	NA	NM	56,250	125	NM	137	0	3.00	2,243	4.50	3.00	13	
	05/11/06	10.0	28,000	47	NA	NA	NM	75,000	125	NM	13	0	2.75	2,324	4.25	2.75	13	
	05/12/06	9.3	25,000	45	NA	NA	NM	69,750	125	NM	5	0	2.75	2,399	5.00	2.75	15	
	05/13/06	8.4	27,000	NA	NA	NA	off	63,000	125	NM	7	0	off	2,467	off	off	NA	
4	05/14/06	15.8	39,000	NA	NA	NA	NM	118,500	125	NM	6	0	2.25	2,554	6.00	2.25	17	4.8
	05/15/06	23.4	62,000	44	NA	NA	NM	175,500	125	NM	30	0	3.00	2,784	8.50	3.00	16	
	05/16/06	14.8	39,000	44	NA	NA	NM	111,000	125	NM	10	0	3.00	2,904	8.50	3.00	18	
	05/17/06	9.2	24,000	43	NA	NA	NM	63,500	125	NM	3,595	7	2.50	2,976	3.50	2.50	14	
	05/18/06	10.0	27,000	45	NA	NA	NM	75,000	125	NM	2,226	4	2.50	3,060	3.75	2.50	13	
	05/19/06	7.0	20,000	48	NA	NA	NM	52,500	125	NM	4	0	3.00	3,116	3.75	3.00	14	
	05/20/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	
5	05/21/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	05/22/06	31.1	85,000	46	NA	NA	off	233,250	125	NM	17	0	off	3,368	off	off	NA	4.4
	05/23/06	10.6	29,000	46	53,000	83	NM	NA	129	NM	93	0	2.75	3,456	4.00	2.75	14	
	05/24/06	8.2	22,000	45	40,000	81	NM	NA	126	NM	15	0	3.00	3,523	4.00	3.00	15	
	05/25/06	12.6	36,000	48	63,000	83	off	NA	131	NM	5	0	off	3,630	off	off	NA	
	05/26/06	7.7	20,000	43	38,000	82	NM	NA	126	NM	11	0	3.00	3,693	4.00	3.00	14	
	05/27/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	
	05/28/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	

US EPA Arsenic Demonstration Project at Alvin, TX – Daily System Operation Log Sheet (Continued)

		Well Op Hr	Well 1		Well 2		Vessel A			Vessel B ^(c)				Vessel A & B Total Cum. Bed Volume Treated ^(d)	Vessel/System Pressure			
		Op Time	Usage	Avg Flow	Usage ^(a)	Avg Flow	Flowrate ^(b)	Usage ^(b)	Avg Flow	Flowrate	Usage	Avg Flow	ΔP	no.	Vessel A ΔP	Vessel B ΔP	Sys ΔP	NaOCl Average Dosage
		hr	gal	gpm	gal	gpm	gpm	gal	gpm	gpm	gal	gpm	psi		psi	psi	psig	mg/L
6	05/29/06	34.2	95,000	46	170,000	83	138	NA	123	NM	19	0	3.00	3,979	4.75	3.00	16	4.1
	05/30/06	11.7	28,000	40	52,000	74	139	83,433	119	NM	3	0	3.50	4,069	5.00	3.50	15	
	05/31/06	5.8	17,000	49	18,000	52	147	48,580	140	NM	4	0	3.50	4,121	3.75	3.50	16	
	06/01/06	5.1	16,000	52	26,000	85	0	43,228	141	NM	12	0	3.50	4,168	4.00	3.50	16	
	06/02/06	7.5	20,000	44	40,000	89	139	53,133	118	NM	7	0	3.00	4,225	3.50	3.00	13	
	06/03/06	6.1	15,000	41	31,000	85	141	40,635	111	NM	7	0	3.00	4,269	3.75	3.00	14	
	06/04/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
7	06/05/06	13.8	40,000	48	72,000	87	0	109,902	133	NM	15	0	3.25	4,387	4.00	3.25	16	4.6
	06/06/06	8.5	24,000	47	44,000	86	NM	68,000	133	NM	10	0	3.50	4,461	4.25	3.50	16	
	06/07/06	8.9	25,000	47	45,000	84	141	75,536	141	NM	11	0	3.00	4,536	4.50	3.00	16	
	06/08/06	9.7	26,000	45	49,000	84	0	78,232	134	NM	46	0	off	4,621	off	off	NA	
	06/09/06	7.0	19,000	45	38,000	90	147	58,617	140	NM	9	0	3.25	4,684	4.50	3.25	16	
	06/10/06	9.7	23,000	40	47,000	81	141	80,386	138	NM	6	0	3.00	4,771	5.00	3.00	16	
	06/11/06		NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
8	06/12/06 to 06/19/06 Operator was on vacation and no operational data was taken during this period.																	
	06/17/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	06/18/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
9	06/19/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	06/20/06	85.3	236,000	46	397,000	78	147	633,000	124	NM	4,840	1	3.50	5,459	4.25	3.50	16	4.7
	06/21/06	6.8	20,000	49	40,000	98	139	64,221	157	NM	7	0	3.25	5,528	4.25	3.25	15	
	06/22/06	5.9	13,000	37	27,000	76	141	43,202	122	NM	7	0	3.25	5,575	4.50	3.25	16	
	06/23/06	7.2	22,000	51	40,000	93	0	60,645	140	NM	10	0	off	5,640	off	off	NA	
	06/24/06	5.4	15,000	46	26,000	80	137	45,415	140	NM	5	0	3.25	5,689	4.25	3.25	NA	NA
	06/25/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
10	06/26/06	15.0	41,000	46	77,000	86	144	126,662	141	NM	16	0	3.00	5,826	5.50	3.00	15	3.5
	06/27/06	8.6	24,000	47	44,000	85	0	69,040	134	NM	7	0	off	5,900	off	off	NA	
	06/28/06	10.3	28,000	45	52,000	84	140	84,712	137	NM	13	0	3.25	5,992	5.75	3.25	17	
	06/29/06	7.9	21,000	44	40,000	84	137	63,661	134	NM	14	0	3.00	6,060	7.00	3.00	18	
	06/30/06	8.9	24,000	45	44,000	82	0	71,057	133	NM	7	0	off	6,137	off	off	NA	NA
	07/01/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	07/02/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA

US EPA Arsenic Demonstration Project at Alvin, TX – Daily System Operation Log Sheet (Continued)

		Well Op Hr	Well 1		Well 2		Vessel A			Vessel B ^(c)				Vessel A & B	Vessel/System Pressure			
		Op Time	Usage	Avg Flow	Usage ^(a)	Avg Flow	Flowrate ^(b)	Usage ^(b)	Avg Flow	Flowrate	Usage	Avg Flow	ΔP	Total Cum. Bed Volume Treated ^(d)	Vessel A ΔP	Vessel B ΔP	Sys ΔP	NaOCl Average Dosage
		hr	gal	gpm	gal	gpm	gpm	gal	gpm	gpm	gal	gpm	psi	no.	psi	psi	psig	mg/L
11	07/03/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	07/04/06	26.1	66,000	42	127,000	81	134	179,913	115	NM	28	0	3.50	6,331	5.50	3.50	18	3.8
	07/05/06	8.7	23,000	44	45,000	86	136	71,932	138	NM	8	0	3.25	6,409	5.75	3.25	18	
	07/06/06	6.6	19,000	48	33,000	83	140	54,231	137	NM	7	0	3.25	6,467	6.50	3.25	16	
	07/07/06	5.6	15,000	45	29,000	86	139	45,670	136	NM	8	0	3.50	6,517	6.50	3.50	17	
	07/08/06	7.5	18,000	40	36,000	80	139	57,431	128	NM	4	0	3.00	6,578	7.50	3.00	18	
	07/09/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
12	07/10/06	14.4	41,000	47	76,000	88	133	121,775	141	NM	11	0	3.75	6,710	8.00	3.75	17	4.8
	07/11/06	4.4	12,000	45	22,000	83	144	34,767	132	NM	5	0	3.00	6,747	8.50	3.00	18	
	07/12/06	7.3	18,000	41	37,000	84	137	44,150	101	NM	5	0	3.00	6,795	9.00	3.00	19	
	07/13/06	8.2	23,000	47	42,000	85	138	56,740	115	NM	9	0	3.00	6,856	9.50	3.00	19	
	07/14/06	7.1	19,000	45	38,000	89	131	53,411	125	NM	2	0	3.00	6,914	9.00	3.00	18	
	07/15/06	6.9	19,000	46	33,000	80	138	50,331	122	NM	0	0	2.75	6,968	3.25	2.75	16	
	07/16/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
13	07/17/06	16.7	46,000	46	86,000	86	138	133,384	133	NM	12	0	3.00	7,112	4.00	3.00	16	4.7
	07/18/06	8.7	24,000	46	47,000	90	0	71,494	137	NM	10	0	off	7,189	off	off	NA	
	07/19/06	6.0	14,000	39	32,000	89	141	48,385	134	NM	12	0	3.00	7,241	4.50	3.00	18	
	07/20/06	6.2	18,000	48	29,000	78	0	45,780	123	NM	2	0	off	7,291	off	off	NA	
	07/21/06	4.0	12,000	50	24,000	100	134	36,538	152	NM	6	0	3.50	7,330	5.50	3.50	18	
	07/22/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	07/23/06	13.5	37,000	46	70,000	86	0	108,383	134	NM	10	0	off	7,447	off	off	NA	NA
14	07/24/06	5.7	15,000	44	29,000	85	135	45,273	132	NM	4	0	3.50	7,496	7.50	3.50	16	4.2
	07/25/06	6.2	17,000	46	33,000	89	0	49,913	134	NM	5	0	off	7,550	off	off	NA	
	07/26/06	5.7	15,000	44	29,000	85	137	45,842	134	NM	8	0	3.00	7,599	8.00	3.00	19	
	07/27/06	4.2	11,000	44	22,000	87	136	32,614	129	NM	5	0	3.00	7,634	8.00	3.00	20	
	07/28/06	6.5	19,000	49	35,000	90	127	53,228	136	NM	4	0	3.00	7,692	8.00	3.00	18	
	07/29/06	5.6	14,000	42	31,000	92	132	44,537	133	NM	4	0	3.00	7,740	8.50	3.00	18	
	07/30/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
15	07/31/06	14.3	38,000	44	69,000	80	130	103,736	121	NM	12	0	3.00	7,852	8.00	3.00	17	3.3
	08/01/06	8.3	23,000	46	43,000	86	132	59,525	120	NM	7	0	3.25	7,916	8.50	3.25	19	
	08/02/06	6.7	18,000	45	35,000	87	0	48,433	120	NM	6	0	off	7,968	off	off	NA	
	08/03/06	6.1	16,000	44	32,000	87	141	44,273	121	NM	4	0	3.50	8,016	8.50	3.50	20	
	08/04/06	8.2	23,000	47	42,000	85	0	59,292	121	NM	13	0	off	8,080	off	off	NA	
	08/05/06	3.4	9,000	44	17,000	83	122	24,121	118	NM	3	0	3.50	8,106	8.00	3.50	18	
	08/06/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA

US EPA Arsenic Demonstration Project at Alvin, TX – Daily System Operation Log Sheet (Continued)

		Well Op Hr	Well 1		Well 2		Vessel A			Vessel B ^(c)				Vessel A & B	Vessel/System Pressure			
		Op Time	Usage	Avg Flow	Usage ^(a)	Avg Flow	Flowrate ^(b)	Usage ^(b)	Avg Flow	Flowrate	Usage	Avg Flow	ΔP	Total Cum. Bed Volume Treated ^(d)	Vessel A ΔP	Vessel B ΔP	Sys ΔP	NaOCl Average Dosage
		hr	gal	gpm	gal	gpm	gpm	gal	gpm	gpm	gal	gpm	psi	no.	psi	psi	psig	mg/L
16	08/07/06	14.6	39,000	45	76,000	87	0	106,013	121	NM	10	0	off	8,220	off	off	NA	NA
	08/08/06	6.1	16,000	44	31,000	85	131	44,544	122	NM	9	0	3.75	8,269	8.75	3.75	17	3.3
	08/09/06	5.7	15,000	44	30,000	88	133	41,949	123	NM	5	0	3.75	8,314	8.75	3.75	18	
	08/10/06	10.0	28,000	47	52,000	87	0	62,006	103	NM	439	1	off	8,381	off	off	NA	
	08/11/06	5.3	14,000	44	29,000	91	129	40,250	127	NM	1	0	3.00	8,425	3.75	3.00	15	
	08/12/06	5.4	14,000	43	29,000	90	126	40,415	125	NM	2	0	3.00	8,468	4.00	3.00	16	
	08/13/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
17	08/14/06	17.8	50,000	47	93,000	87	126	132,570	124	NM	12	0	3.25	8,611	5.00	3.25	15	3.5
	08/15/06	7.4	20,000	45	39,000	88	0	55,846	126	NM	7	0	off	8,671	off	off	NA	
	08/16/06	7.3	18,000	41	36,000	82	125	52,297	119	NM	3	0	3.00	8,728	5.50	3.00	16	
	08/17/06	6.9	20,000	48	38,000	92	129	53,956	130	NM	5	0	3.25	8,786	5.75	3.25	17	
	08/18/06	10.1	28,000	46	52,000	86	0	75,778	125	NM	5	0	off	8,868	off	off	NA	
	08/19/06	6.3	18,000	48	37,000	98	130	45,720	121	NM	0	0	3.24	8,917	5.75	3.24	16	
	08/20/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
18	08/21/06	15.3	39,000	42	76,000	83	0	109,715	120	NM	13	0	off	9,036	off	off	NA	6.9
	08/22/06	6.1	17,000	46	32,000	87	126	45,724	125	NM	4	0	3.00	9,085	6.00	3.00	17	
	08/23/06	7.9	22,000	46	41,000	86	0	57,370	121	NM	4	0	off	9,147	off	off	NA	
	08/24/06	4.7	12,000	43	25,000	89	128	34,835	124	NM	4	0	3.00	9,184	6.25	3.00	17	
	08/25/06	6.5	18,000	46	34,000	87	122	47,390	122	NM	5	0	3.00	9,235	6.50	3.00	16	
	08/26/06	5.8	15,000	43	31,000	89	126	36,732	106	NM	0	0	3.00	9,275	6.25	3.00	16	
	08/27/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
19	08/28/06	9.5	26,000	46	50,000	88	124	70,580	124	NM	9	0	3.25	9,351	6.50	3.25	16	3.6
	08/29/06	4.9	13,000	44	26,000	88	133	33,781	115	NM	4	0	3.25	9,388	6.75	3.25	16	
	08/30/06	7.9	22,000	46	42,000	89	0	57,537	121	NM	6	0	off	9,450	off	off	NA	
	08/31/06	5.3	14,000	44	27,000	85	117	38,774	122	NM	4	0	3.00	9,492	7.00	3.00	17	
	09/01/06	6.9	18,000	43	37,000	89	128	50,496	122	NM	5	0	3.00	9,546	7.25	3.00	18	
	09/02/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	09/03/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
20	09/04/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	09/05/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	09/06/06	40.1	108,000	45	206,000	86	NM	314,000	131	NM	1,160	0	3.00	9,886	7.75	3.00	16	4.2
	09/07/06	11.1	29,000	44	56,000	84	NM	85,000	128	NM	9	0	off	9,978	off	off	NA	
	09/08/06	7.6	20,000	44	38,000	83	NM	58,000	127	NM	5	0	3.25	10,040	8.00	3.25	18	
	09/09/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	09/10/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA

US EPA Arsenic Demonstration Project at Alvin, TX – Daily System Operation Log Sheet (Continued)

		Well Op Hr	Well 1		Well 2		Vessel A			Vessel B ^(c)				Vessel A & B Total Cum. Bed Volume Treated ^(d)	Vessel/System Pressure			
		Op Time	Usage	Avg Flow	Usage ^(a)	Avg Flow	Flowrate ^(b)	Usage ^(b)	Avg Flow	Flowrate	Usage	Avg Flow	ΔP	no.	Vessel A ΔP	Vessel B ΔP	Sys ΔP	NaOCl Average Dosage
		hr	gal	gpm	gal	gpm	gpm	gal	gpm	gpm	gal	gpm	psi		psi	psi	psig	mg/L
21	09/11/06	19.2	51,000	44	100,000	87	NM	151,000	131	NM	15	0	off	10,203	off	off	NA	NA
	09/12/06	4.5	12,000	44	23,000	85	NM	35,000	130	NM	4	0	3.00	10,241	9.50	3.00	20	4.4
	09/13/06	5.0	14,000	47	26,000	87	NM	40,000	133	NM	5	0	3.25	10,284	9.50	3.25	21	
	09/14/06	7.4	19,000	43	39,000	88	NM	58,000	131	NM	6	0	off	10,347	off	off	NA	
	09/15/06	4.0	11,000	46	22,000	92	NM	33,000	138	NM	5	0	3.00	10,382	9.75	3.00	20	
	09/16/06	7.1	17,000	40	35,000	82	NM	52,000	122	NM	5	0	3.00	10,438	9.75	3.00	21	
	09/17/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
22	09/18/06	10.6	29,000	46	54,000	85	NM	83,000	131	NM	10	0	3.00	10,528	9.75	3.00	21	4.2
	09/19/06	4.7	13,000	46	25,000	89	NM	38,000	135	NM	4	0	3.75	10,569	10.00	3.75	21	
	09/20/06	7.3	20,000	46	40,000	91	NM	56,000	128	NM	3,243	7	3.25	10,633	3.25	3.25	15	
	09/21/06	4.5	13,000	48	24,000	89	NM	37,000	137	NM	4	0	3.50	10,673	4.00	3.50	17	
	09/22/06	5.7	15,000	44	31,000	91	NM	46,000	135	NM	4	0	3.25	10,722	4.00	3.25	17	
	09/23/06	7.0	19,000	45	39,000	93	NM	58,000	138	NM	3	0	3.00	10,785	4.25	3.00	17	
	09/24/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
23	09/25/06	12.3	36,000	49	65,000	88	NM	101,000	137	NM	4,665	6	off	10,899	off	off	NA	NA
	09/26/06	4.0	10,000	42	23,000	96	NM	33,000	138	NM	0	0	3.00	10,935	4.50	3.00	16	5.2
	09/27/06	3.7	11,000	50	19,000	86	NM	30,000	135	NM	0	0	3.50	10,967	5.00	3.50	18	
	09/28/06	6.7	18,000	45	37,000	92	NM	55,000	137	NM	0	0	4.00	11,026	5.00	4.00	18	
	09/29/06	2.7	7,000	43	14,000	86	NM	21,000	130	NM	0	0	off	11,049	off	off	NA	NA
	09/30/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	off	NA	off	off	NA	NA
	10/01/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
24	10/02/06	18.0	53,000	49	105,000	97	NM	158,000	146	NM	0	0	off	11,219	off	off	NA	NA
	10/03/06	5.2	14,000	45	30,000	96	NM	44,000	141	NM	187	1	3.25	11,267	4.75	3.25	16	5.2
	10/04/06	3.0	9,000	50	17,000	94	0	24,447	136	NM	2	0	off	11,295	off	off	NA	
	10/05/06	5.2	14,000	45	28,000	90	142	41,485	133	NM	6	0	3.50	11,340	5.00	3.50	16	
	10/06/06	6.1	16,000	44	32,000	87	138	46,490	127	NM	3	0	3.50	11,390	5.50	3.50	16	
	10/07/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	10/08/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
25	10/09/06	20.6	56,000	45	110,000	89	0	158,661	128	NM	13	0	off	11,561	off	off	NA	NA
	10/10/06	4.8	13,000	45	27,000	94	133	38,217	133	NM	6	0	3.75	11,602	6.25	3.75	16	5.7
	10/11/06	4.4	12,000	45	24,000	91	131	35,170	133	NM	6	0	3.00	11,640	6.25	3.00	16	
	10/12/06	5.7	15,000	44	30,000	88	133	43,559	127	NM	5	0	3.00	11,687	7.00	3.00	15	
	10/13/06	3.1	9,000	48	17,000	91	0	23,555	127	NM	2	0	off	11,713	off	off	NA	
	10/14/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	10/15/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA

US EPA Arsenic Demonstration Project at Alvin, TX – Daily System Operation Log Sheet (Continued)

		Well Op Hr	Well 1		Well 2		Vessel A			Vessel B ^(c)				Vessel A & B Total Cum. Bed Volume Treated ^(d)	Vessel/System Pressure			
		Op Time	Usage	Avg Flow	Usage ^(a)	Avg Flow	Flowrate ^(b)	Usage ^(b)	Avg Flow	Flowrate	Usage	Avg Flow	ΔP	no.	Vessel A ΔP	Vessel B ΔP	Sys ΔP	NaOCl Average Dosage
		hr	gal	gpm	gal	gpm	gpm	gal	gpm	gpm	gal	gpm	psi		psi	psi	psig	mg/L
26	10/16/06	17.0	45,000	44	91,000	89	121	128,887	126	NM	11	0	2.75	11,852	6.25	2.75	17	6.1
	10/17/06	3.1	8,000	43	17,000	91	0	23,134	124	NM	5	0	off	11,877	off	off	NA	
	10/18/06	4.6	13,000	47	25,000	91	128	34,386	125	NM	6	0	3.00	11,914	6.75	3.00	17	
	10/19/06	4.6	12,000	43	25,000	91	0	33,868	123	NM	3	0	off	11,950	off	off	NA	
	10/20/06	4.5	12,000	44	25,000	93	133	33,448	124	NM	6	0	3.25	11,986	7.50	3.25	16	
	10/21/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
	10/22/06	NA	NA	NA	NA	NA	NM	NA	NA	NM	NA	NA	NM	NA	NM	NM	NA	NA
27	10/23/06	14.9	39,000	44	79,000	88	123	106,917	120	NM	13	0	3.75	12,102	9.00	3.75	19	4.8
	10/24/06	4.8	13,000	45	26,000	90	0	32,111	111	NM	4	0	off	12,136	off	off	NA	
	10/25/06	4.6	12,000	43	24,000	87	126	32,857	119	NM	5	0	3.50	12,172	9.00	3.50	20	

(a) Totalizer on Well 2 broken from 04/25 to 05/21/06.

(b) Vessel A flowmeter and totalizer broken from 04/25 to 05/28/06, 06/06/06, and from 09/06 to 10/03/06.

(c) Vessel B flow meter should not register flow when placed in lag position.

(d) BV for Vessel A and B are 53.6 ft³ (401 gal) and 70.3 ft³ (526 gal), respectively. Total BV is 124 ft³ or 927 gal.

NM = Not Measured; NA = Not Available; off = Well off.

Highlight indicates calculated value.

APPENDIX B
ANALYTICAL DATA TABLES

Analytical Results from Long Term Sampling at Alvin, TX

Sampling Date		04/25/06				05/09/06				05/23/06 ^(a)				06/06/06 ^(b)				06/21/06 ^(c)			
Sampling Location		IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB
Parameter	Unit																				
Bed Volume	10 ³	-	-	1.4		-	-	2.2		-	-	3.5		-	-	4.5		-	-	5.5	
Alkalinity	mg/L ^(a)	361	366	370	370	347	372	363	355	355	347	NA	NA	346	342	367	363	338	359	371	359
Fluoride	mg/L	1.2	1.4	1.3	1.3	-	-	-	-	1.3	1.3	NA	NA	-	-	-	-	1.2	1.2	1.3	1.4
Sulfate	mg/L	1	2	2	2	-	-	-	-	2	2	NA	NA	-	-	-	-	<1	2	2	1
Nitrate (as N)	mg/L	<0.05	<0.05	<0.05	<0.05	-	-	-	-	<0.05	<0.05	NA	NA	-	-	-	-	<0.05	<0.05	<0.05	<0.05
Total P (as P)	mg/L	48.5	42.6	<10	<10	48.2	46.0	10.0	<10	34.4	34.3	NA	NA	51.5	43.4	18.9	<10	44.5	45.9	13.6	<10
Silica (as SiO ₂)	mg/L	15.2	15.7	15.4	15.3	17.0	14.8	16.4	12.6	15.6	16.6	NA	NA	15.4	16.2	16.4	16.5	14.4	14.8	15.3	15.2
Turbidity	NTU	0.6	0.3	0.5	0.4	0.3	0.4	0.2	0.2	0.8	0.3	NA	NA	0.3	0.5	1.2	0.5	0.6	0.6	0.5	0.5
pH	S.U.	7.9	7.6	7.7	7.6	7.9	7.7	8.0	7.9	8.0	7.5	NA	NA	7.8	7.3	7.7	7.6	7.6	7.6	7.7	7.8
Temperature	°C	27.7	28.1	28.3	27.9	32.8	33.8	32.1	30.7	25.0	25.0	NA	NA	27.6	27.2	27.0	27.2	25.8	25.6	24.6	24.5
DO	mg/L	3.0	1.9	2.8	2.0	2.8	1.8	3.5	2.8	1.5	1.7	NA	NA	1.6	1.2	4.2	3.5	2.1	2.0	3.9	3.2
ORP	mV	217	605	619	628	254	548	292	464	321	407	NA	NA	365	556	510	397	302	622	568	477
Free Chlorine	mg/L	-	1.8	1.5	1.5	-	0.3	0.5	0.2	-	0.7	NA	NA	-	0.5	0.1	0.4	-	3.0	1.1	1.1
Total Chlorine	mg/L	-	1.8	1.5	1.6	-	0.3	0.7	0.5	-	0.7	NA	NA	-	0.6	0.2	0.5	-	2.9	1.3	1.2
Total Hardness (as CaCO ₃)	mg/L	44.9	44.4	43.8	44.1	-	-	-	-	31.0	30.0	NA	NA	-	-	-	-	42.5	45.9	44.1	44.5
Ca Hardness (as CaCO ₃)	mg/L	32.7	32.2	32.0	32.3	-	-	-	-	18.8	18.0	NA	NA	-	-	-	-	28.7	30.8	29.6	29.9
Mg Hardness (as CaCO ₃)	mg/L	12.3	12.2	11.8	11.8	-	-	-	-	12.3	12.0	NA	NA	-	-	-	-	13.8	15.1	14.5	14.6
As (total)	µg/L	30.2	32.1	0.2	<0.1	34.6	34.0	2.4	0.8	34.7	38.1	NA	NA	47.9	26.9	3.8	0.6	48.1	32.4	4.8	0.4
As (soluble)	µg/L	27.4	26.2	<0.1	<0.1	-	-	-	-	32.6	30.5	NA	NA	-	-	-	-	44.2	27.3	4.6	0.4
As (particulate)	µg/L	2.9	5.9	<0.1	<0.1	-	-	-	-	2.1	7.6	NA	NA	-	-	-	-	4.0	5.0	0.2	<0.1
As (III)	µg/L	21.9	<0.1	<0.1	<0.1	-	-	-	-	29.5	0.5	NA	NA	-	-	-	-	43.9	0.5	0.4	0.4
As (V)	µg/L	5.5	26.1	<0.1	<0.1	-	-	-	-	3.1	30.0	NA	NA	-	-	-	-	0.2	26.9	4.2	<0.1
Fe (total)	µg/L	72	34	<25	<25	66	42	<25	<25	60	<25	NA	NA	87	69	<25	<25	66	44	<25	<25
Fe (soluble)	µg/L	43	<25	<25	<25	-	-	-	-	<25	<25	NA	NA	-	-	-	-	<25	<25	<25	<25
Mn (total)	µg/L	61.3	57.1	2.5	0.3	59.2	53.8	1.3	0.4	52.3	45.8	NA	NA	56.1	45.4	2.9	0.9	53.6	50.4	2.0	0.4
Mn (soluble)	µg/L	61.0	14.5	1.2	<0.1	-	-	-	-	51.8	1.4	NA	NA	-	-	-	-	52.2	1.1	0.9	0.4

(a) Onsite water quality parameters taken on 05/26/06. (b) Onsite water quality parameters taken on 06/07/06 except for total and free Cl₂ readings. (c) Onsite water quality parameters taken on 06/22/06 except for total and free Cl₂ readings.

IN = influent; AC = after chlorination; TA = after Tank A; TB = after Tank B; TT = combined effluent
 Analytical Results from Long Term Sampling at Alvin, TX

Analytical Results from Long Term Sampling at Alvin, TX (Continued)

Sampling Date		07/05/06 ^(a)				07/19/06				08/01/06 ^(b)				08/16/06				08/29/06			
Sampling Location		IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB
Parameter	Unit																				
Bed Volume	10 ³	-	-	6.4		-	-	7.2		-	-	7.9		-	-	8.7		-	-	9.4	
Alkalinity	mg/L ^(a)	339	352	352	356	340	353	349	353	344	349	357	362	318	343	331	331	NA	384	381	366
Fluoride	mg/L	-	-	-	-	1.4	1.4	1.7	1.9	-	-	-	-	1.4	1.4	1.5	1.4	-	-	-	-
Sulfate	mg/L	-	-	-	-	<1	1	1	1	-	-	-	-	<1	1	2	1	-	-	-	-
Nitrate (as N)	mg/L	-	-	-	-	<0.05	<0.05	<0.05	<0.05	-	-	-	-	<0.05	<0.05	<0.05	0.2	-	-	-	-
Total P (as P)	mg/L	37.8	40.2	12.4	<10	25.2	20.4	<10	<10	35.5	28.9	<10	<10	36.2	39.2	15.9	<10	50.2	53.9	33.0	<10
Silica (as SiO ₂)	mg/L	15.4	16.3	16.0	15.8	15.1	15.2	15.8	15.6	15.5	16.4	17.0	16.5	15.4	15.7	15.6	16.0	14.7	15.2	15.6	15.2
Turbidity	NTU	0.5	0.5	0.2	0.1	0.1	0.5	0.2	0.1	0.2	0.3	0.3	0.2	0.2	0.3	0.2	0.1	0.2	0.3	0.1	0.3
pH	S.U.	7.5	7.4	7.8	7.7	7.6	7.6	7.9	7.7	7.8	7.6	7.9	7.8	7.8	7.6	7.6	7.7	7.6	7.5	7.6	7.7
Temperature	°C	24.5	24.5	24.3	24.4	24.7	23.9	23.4	23.8	26.0	24.7	25.1	24.8	24.3	23.9	24.1	24.1	25.6	25.2	25.0	24.8
DO	mg/L	1.8	1.7	3.3	3.1	1.7	2.3	4.9	4.0	1.4	1.7	3.7	2.9	1.2	1.5	1.8	1.5	1.4	1.7	2.2	2.9
ORP	mV	430	667	461	621	437	459	596	631	345	655	644	652	369	655	651	668	423	660	655	655
Free Chlorine	mg/L	-	3.2	1.8	1.8	-	1.9	1.5	1.8	-	2.3	1.4	0.9	-	2.5	1.8	1.8	-	2.2	1.7	1.5
Total Chlorine	mg/L	-	2.5	1.7	1.7	-	2.2	1.6	1.9	-	2.4	1.4	1.0	-	2.6	1.9	2.0	-	2.1	1.5	1.6
Total Hardness (as CaCO ₃)	mg/L	-	-	-	-	31.1	32.0	31.5	32.7	-	-	-	-	37.4	42.5	40.5	42.9	-	-	-	-
Ca Hardness (as CaCO ₃)	mg/L	-	-	-	-	19.1	19.3	19.0	19.8	-	-	-	-	25.1	29.0	27.8	29.4	-	-	-	-
Mg Hardness (as CaCO ₃)	mg/L	-	-	-	-	12.1	12.7	12.5	13.0	-	-	-	-	12.3	13.5	12.7	13.5	-	-	-	-
As (total)	µg/L	44.4	30.5	6.2	0.7	46.3	27.6	6.1	0.8	50.4	34.9	8.3	1.0	51.0	35.9	8.8	1.1	40.1	23.5	7.6	0.6
As (soluble)	µg/L	-	-	-	-	40.7	24.3	6.1	0.7	-	-	-	-	45.1	30.5	8.6	0.9	-	-	-	-
As (particulate)	µg/L	-	-	-	-	5.5	3.4	<0.1	0.1	-	-	-	-	5.9	5.4	0.1	0.2	-	-	-	-
As (III)	µg/L	-	-	-	-	26.5	1.0	0.6	0.6	-	-	-	-	44.1	0.7	0.7	0.6	-	-	-	-
As (V)	µg/L	-	-	-	-	14.2	23.3	5.5	0.1	-	-	-	-	1.0	29.8	8.0	0.2	-	-	-	-
Fe (total)	µg/L	86	95	<25	<25	100	60	<25	<25	40	<25	<25	<25	52	37	<25	<25	34	42	<25	<25
Fe (soluble)	µg/L	-	-	-	-	<25	<25	<25	<25	-	-	-	-	38	<25	<25	<25	-	-	-	-
Mn (total)	µg/L	52.7	53.5	4.0	0.7	50.0	46.0	2.0	0.5	56.2	50.9	2.5	0.3	52.3	52.7	1.5	0.4	52.0	50.5	1.2	0.1
Mn (soluble)	µg/L	-	-	-	-	49.5	<0.1	0.3	0.1	-	-	-	-	54.9	0.8	0.2	0.1	-	-	-	-

(a) Onsite water quality parameters taken on 07/07/06. (b) Onsite water quality parameters taken on 08/02/06 except for total and free Cl₂ readings.

IN = influent; AC = after chlorination; TA = after Tank A; TB = after Tank B; TT = combined effluent
 Analytical Results from Long Term Sampling at Alvin, TX

Analytical Results from Long Term Sampling at Alvin, TX (Continued)

Sampling Date		09/12/06				09/27/06				10/11/06			
Sampling Location		IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB
Parameter	Unit												
Bed Volume	10 ³	-	-	10.2				11.0		-	-	11.6	
Alkalinity	mg/L ^(a)	352	362	362	362	354	382	388	382	371	390	399	392
		-	-	-	-	-	-	-	-	-	-	-	-
Fluoride	mg/L	1.4	1.4	1.4	1.4	-	-	-	-	1.3	1.4	1.4	1.5
Sulfate	mg/L	<1	2	2	2	-	-	-	-	<1	2	2	2
Nitrate (as N)	mg/L	<0.05	<0.05	<0.05	<0.05	-	-	-	-	<0.05	<0.05	<0.05	<0.05
Total P (as P)	mg/L	38.7	42.8	24.6	<10	86.7	95.0	76.3	58.7	28.1	39.3	19.9	<10
		-	-	-	-	-	-	-	-	-	-	-	-
Silica (as SiO ₂)	mg/L	15.3	15.3	15.7	15.8	14.8	15.7	16.1	15.5	15.9	16.0	15.3	16.5
		-	-	-	-	-	-	-	-	-	-	-	-
Turbidity	NTU	0.2	0.3	0.1	0.2	0.3	0.2	0.2	0.1	0.8	0.8	0.4	0.4
		-	-	-	-	-	-	-	-	-	-	-	-
pH	S.U.	7.7	7.5	7.6	7.6	7.7	7.5	7.6	7.7	7.7	7.5	7.6	7.6
Temperature	°C	23.4	23.1	23.1	23.1	22.8	22.3	22.1	21.7	23.1	22.8	22.8	22.5
DO	mg/L	1.5	2.0	1.7	1.5	NA ^(c)	NA ^(c)	NA ^(c)	NA ^(c)	NA ^(b)	NA ^(b)	NA ^(b)	NA ^(b)
ORP	mV	303	655	639	646	390	660	659	658	317	675	665	672
Free Chlorine	mg/L	-	2.6	1.7	1.6	-	2.9	1.7	1.2	-	3.3	1.8	1.7
Total Chlorine	mg/L	-	2.9	1.7	1.8	-	3.1	2.0	1.4	-	3.1	1.9	2.0
Total Hardness (as CaCO ₃)	mg/L	37.8	40.7	41.2	41.5	-	-	-	-	39.6	45.6	45.4	46.6
Ca Hardness (as CaCO ₃)	mg/L	25.2	26.9	27.2	27.4	-	-	-	-	26.3	30.0	29.8	30.4
Mg Hardness (as CaCO ₃)	mg/L	12.7	13.7	14.0	14.1	-	-	-	-	13.4	15.6	15.6	16.2
As (total)	µg/L	49.8	34.9	10.0	0.8	39.8	26.7	10.9	4.3	44.0	30.2	10.2	1.4
		-	-	-	-	-	-	-	-	-	-	-	-
As (soluble)	µg/L	44.7	28.6	9.1	0.8	-	-	-	-	44.7	26.6	9.8	1.5
As (particulate)	µg/L	5.1	6.3	0.9	<0.1	-	-	-	-	<0.1	3.5	0.4	<0.1
As (III)	µg/L	39.4	0.4	0.4	0.4	-	-	-	-	40.7	0.9	1.1	0.8
As (V)	µg/L	5.3	28.1	8.7	0.3	-	-	-	-	4.1	25.7	8.7	0.8
Fe (total)	µg/L	45	<25	<25	<25	58	43	<25	<25	39	<25	<25	65
		-	-	-	-	-	-	-	-	-	-	-	-
Fe (soluble)	µg/L	<25	<25	<25	<25	-	-	-	-	<25	<25	<25	<25
Mn (total)	µg/L	53.2	50.0	1.3	<0.1	56.6	54.2	2.0	0.6	52.9	52.6	1.0	0.5
		-	-	-	-	-	-	-	-	-	-	-	-
Mn (soluble)	µg/L	52.8	0.7	<0.1	<0.1	-	-	-	-	55.6	0.9	0.2	0.2

IN = influent; AC = after chlorination; TA = after Tank A; TB = after Tank B; TT = combined effluent
 Analytical Results from Long Term Sampling at Alvin, TX