EPA/600/R-06/125
November 2006

Arsenic Removal from Drinking Water by Adsorptive Media
EPA Demonstration Project at Goffstown, NH
Six-Month Evaluation Report

by

Sarah E. McCall
Abraham S.C. Chen
Lili Wang

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, OH 45268

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, OH 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 groundwater; 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 arsenic removal treatment technology demonstration project at the Orchard Highlands Subdivision site at Goffstown, NH. The objectives of the project are to evaluate the effectiveness of AdEdge Technologies' AD-33 media in removing arsenic to meet the new arsenic maximum contaminant level (MCL) of 10 μg/L. Additionally, this project evaluates the reliability of the treatment system (Arsenic Package Unit [APU]-GOFF-LL), the required system operation and maintenance (O&M) and operator's skills, and the capital and O&M cost of the technology. The project also characterizes the water in the distribution system and process residuals produced by the treatment process.

The APU-GOFF-LL treatment system consists of two 18-in.-diameter, 65-in.-tall fiberglass reinforced plastic (FRP) vessels in series configuration, each containing approximately 5 ft^3 of AD-33 media. The media is an iron-based adsorptive media developed by Bayer AG and marketed under the name of AD-33 by AdEdge. The system was designed for a peak flowrate of 10 gal/min (gpm) based on the pump curve provided by the site. The system design had an empty bed contact time (EBCT) of about 3.7 min per vessel based on the 10 gpm flowrate. The actual average flowrate of 13 gpm was 30% higher than the design flowrate. The higher flowrate decreased the EBCT from 3.7 to 2.9 min, which might have contributed, in part, to earlier than expected breakthrough of arsenic.

The AdEdge treatment system began regular operation on April 15, 2005. The data collected include system operation, water quality (both across the treatment train and in the distribution system), process residuals, and capital and O&M cost. Between April 15 and October 22, 2005, the system operated an average of 5 hr/day for a total of 1,032 hr, treating approximately 807,300 gal of water (that contained total arsenic ranging from 24.1 to 34.0 μg/L, and existing almost entirely as As[V]). This volume throughput was equivalent to about 21,600 bed volumes [BV] based on the 5 ft^3 bed volume in the lead adsorption vessel. Total arsenic levels in the treated water following the lead vessel reached 10 μg/L at approximately 19,500 BV. The arsenic level from the lag vessel at the time was <1 μg/L. Concentrations of orthophosphate and silica, which could interfere with arsenic adsorption by competing with arsenate for adsorption sites, ranged from <0.05 to 0.3 mg/L (as PO_4) and from 24.2 to 31.7 mg/L (as SiO_2), respectively, in raw water. Concentrations of iron, manganese, and other ions in raw water were not high enough to impact arsenic removal by the media.

The system was backwashed only once during the first six months of system operation because there had been minimal solids buildup in the vessels and because pressure differential (Δp) across the vessels had remained essentially unchanged at 3 to 6 pounds per square inch (psi). The backwash was initiated manually with each vessel backwashed with the treated water from the 2,000-gal hydropneumatic tank for 20 min at 16 gpm (or 9 gpm/ft^2), producing approximately 320 gal of wastewater. Arsenic concentrations in the backwash water were 30.2 μg/L from the lead vessel and 3.6 μg/L from the lag vessel, compared to the treated water arsenic level of 0.3 μg/L, suggesting desorption from the media. The arsenic desorption might be due to slightly higher pH of the treated water in the hydropneumatic tank following aeration for radon removal.

Comparison of the distribution system sampling results before and after operation of the system showed a significant decrease in arsenic concentration (from an average of 30 μg/L to an average of 1.1 μg/L). The arsenic concentrations in the distribution system were similar to those in the system effluent. Neither lead nor copper concentrations appeared to have been affected by the operation of the system.

The capital investment cost of $34,210 included $22,431 for equipment, $4,860 for site engineering, and $6,910 for installation. Using the system's rated capacity of 10 gpm (14,400 gal/day [gpd]), the capital

cost was $3,421/gpm of design capacity ($2.38/gpd) and equipment-only cost was $2,243/gpm of design capacity ($1.56/gpd).

The O&M cost included only incremental cost associated with the adsorption system, such as media replacement and disposal, electricity consumption, and labor. Although not incurred 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 $4,199 to change out one vessel. This cost was used to estimate the media replacement cost per 1,000 gal of water treated as a function of the projected media run length to the 10 μg/L arsenic breakthrough.

CONTENTS

APPENDICES

FIGURES

TABLES

ABBREVIATIONS AND ACRONYMS

AAL	American Analytical Laboratories
AM	adsorptive media
APU	arsenic package unit
As	arsenic
ATS	aquatic treatment system
BET	Brunauer, Emmett, and Teller
BV	bed volume
Ca	calcium
C/F	coagulation/filtration process
Cl	chlorine
CRF	capital recovery factor
Cu	copper
DO	dissolved oxygen
EBCT	empty bed contact time
EPA	U.S. Environmental Protection Agency
F	fluorine
Fe	iron
FRP	fiberglass reinforced plastic
GFH	granular ferric hydroxide
gpd	gallons per day
gpm	gallons per minute
HIX	hybrid ion exchange
ICP-MS	inductively coupled plasma-mass spectrometry
ID	identification
IX	ion exchange
LCR	Lead and Copper Rule
MCL	maximum contaminant level
MDL	method detection limit
MEI	Magnesium Elektron, Inc.
Mg	magnesium
Mn	manganese
mV	millivolts
Na	sodium
NA	not analyzed
ND	not detectable
NHDES	New Hampshire Department of Environmental Services
NRMRL	National Risk Management Research Laboratory

ABBREVIATIONS AND ACRONYMS (Continued)

O&M	operation and maintenance
OIT	Oregon Institute of Technology
ORD	Office of Research and Development
ORP	oxidation-reduction potential
psi	pounds per square inch
PO_4	orthophosphate
POE	point of entry
PVC	polyvinyl chloride
QA	quality assurance
QAPP	Quality Assurance Project Plan
QA/QC	quality assurance/quality control
RO	reverse osmosis
RPD	relative percent difference
SDWA	Safe Drinking Water Act
SiO_2	silica
SO_4^{2-}	sulfate
STS	Severn Trent Services
TCLP	toxicity characteristic leaching procedure
TDS	total dissolved solids
TOC	total organic carbon
TSS	total suspended solids
U	uranium
V	vanadium

ACKNOWLEDGMENTS

The authors wish to extend their sincere appreciation to Orchard Highlands Subdivision and Mr. John Blumberg, the Chairman of the Board of Directors, who monitored the treatment system and collected samples from the treatment system and distribution system throughout this reporting period. This performance evaluation would not have been possible without his efforts.

1.0 INTRODUCTION

1.1 Background

The Safe Drinking Water Act (SDWA) mandates that the United States Environmental Protection Agency (EPA) identify and regulate drinking water contaminants that may have adverse human health effects and 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 text 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 cost. 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 the first round of this EPA-sponsored demonstration program to provide information on their water systems. In June 2002, EPA selected 17 sites from a list of 115 sites to be the host sites for 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 from 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 Round 1 demonstration program. 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. As of July 2006, 11 of the 12 systems have been operational and the performance evaluation of two systems has been completed.

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 Orchard Highlands Community Water System in Goffstown, NH 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. AdEdge Technologies (AdEdge), using the Bayoxide E33 media developed by Bayer AG, was selected for demonstration at the Orchard Highlands site in September 2004.

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 3 adsorptive media systems), 13 coagulation/filtration systems, 2 ion exchange (IX) systems, 17 point-of-use (POU) units (including 9 residential reverse osmosis [RO] units at the Sunset Ranch Development site and 8 AM units at the OIT site), and 1 system modification. Table 1-1 summarizes the locations, technologies, vendors, system flowrates, and key source water quality parameters (including arsenic, iron, and pH) at the 40 demonstration sites. The technology selection and system design for the 12 Round 1 demonstration sites have been reported in an EPA report (Wang et al., 2004). The capital cost of the 12 Round 1 systems also has been discussed in a separate EPA report (Chen et al., 2004). Both reports are posted on the following EPA Web site: http://www.epa.gov/ORD/NRMRL/arsenic/resource.htm.

1.3 Project Objectives

The objective of the Round 1 and Round 2 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.
- Determine the capital and O&M cost of the technologies.
- Characterize process residuals produced by the technologies.

This report summarizes the performance of the AdEdge system at the Orchard Highlands Subdivision in Goffstown, NH during the first six months from April 15 through October 22, 2005. The data collected included system operational data, water quality data (both across the treatment train and in the distribution system), and capital and preliminary O&M cost data.

Table 1-1. Summary of Round 1 and Round 2 Arsenic Removal Demonstration Locations, Technologies, and Source Water Quality

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(d)	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(b)	7.3
Buckeye Lake, OH	Buckeye Lake Head Start Building	AM (ARM 200)	Kinetico	10	15(a)	1,312(b)	7.6
Springfield, OH	Chateau Estates Mobile Home Park	AM (E33)	AdEdge	150	25(a)	1,615(b)	7.3
Great Lakes/Interior Plains							
Brown City, MI	City of Brown City	AM (E33)	STS	640	14(a)	127(b)	7.3
Pentwater, MI	Village of Pentwater	C/F (Macrolite)	Kinetico	400	13(a)	466(b)	6.9
Sandusky, MI	City of Sandusky	C/F (Aeralater)	USFilter	340	16(a)	1,387(b)	6.9
Delavan, WI	Vintage on the Ponds	C/F (Macrolite)	Kinetico	40	20(a)	1,499(b)	7.5
Greenville, WI	Town of Greenville	C/F (Macrolite)	Kinetico	375	17	7827(b)	7.3
Climax, MN	City of Climax	C/F (Macrolite)	Kinetico	140	39(a)	546(b)	7.4
Sabin, MN	City of Sabin	C/F (Macrolite)	Kinetico	250	34	1,470(b)	7.3
Sauk Centre, MN	Big Sauk Lake Mobile Home Park	C/F (Macrolite)	Kinetico	20	25(a)	3,078(b)	7.1
Stewart, MN	City of Stewart	C/F&AM (E33)	AdEdge	250	42(a)	1,344(b)	7.7
Lidgerwood, ND	City of Lidgerwood	System Modification	Kinetico	250	146(a)	1,325(b)	7.2
Midwest/Southwest							
Lyman, NE	Village of Lyman	C/F (Macrolite)	Kinetico	350	20	<25	7.5
Arnaudville, LA	United Water Systems	C/F (Macrolite)	Kinetico	385	35(a)	2,068(b)	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	Indian Health Services	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(e)	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)	Kinetico	37	41	<25	7.8

Table 1-1. Summary of Round 1 and Round 2 Arsenic Removal Demonstration Locations, Technologies, and Source Water Quality (Continued)

Demonstration Location	Site Name	Technology (Media)	Vendor	Design Flowrate (gpm)	Source Water Quality		
					As (µg/L)	Fe (µg/L)	pH
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)	Kenetico	250	44	<25	7.4
Homedale, ID	Sunset Ranch Development	POU RO(c)	Kinetico	75 gpd	52	134	7.5
Okanogan, WA	City of Okanogan	C/F (Electromedia II)	Filtronics	750	18	69(b)	8.0
Klamath Falls, OR	Oregon Institute of Technology	AM (Adsorbsia/ARM 200/ArsenX) and POU AM(f)	Kinetico	60/60/30	33	<25	7.9
Vale, OR	City of Vale	IX (A520)	Kinetico	525	17	<25	7.5
Reno, NV	South Truckee Meadows General Improvement District	AM (GFH)	USFilter	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; GFH = granular ferric hydroxide; HIX = hybrid ion exchanger; IX = ion exchange
ATS = Aquatic Treatment Systems; MEI = Magnesium Elektron, Inc.; STS = Severn Trent Services
(a) Arsenic existing mostly as As(III).
(b) Iron existing mostly as Fe(II).
(c) Including nine residential units.
(d) System reconfigured from parallel to series operation due to lower flowrate of 40 gpm.
(e) System reconfigured from parallel to series operation due to lower flowrate of 30 gpm.
(f) Including three under-the-sink AM units.

2.0 CONCLUSIONS

Based on the information collected during the first six months of system operation, the following conclusions were made relating to the overall objectives of the treatment technology demonstration study.

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

- Breakthrough of arsenic at 10 μg/L following the lead vessel occurred at approximately 19,500 bed volumes (BV), based on the media bed volume in the lead vessel. The arsenic level from the lag vessel at the time was <1 μg/L. The earlier than expected arsenic breakthrough from the lead vessel was attributed, in part, to the relatively short empty bed contact time (i.e., 2.9 min versus the design value of 3.7 min in each vessel) and competing anions, such as orthophosphate and silica.
- Orthophosphate with concentrations up to 0.3 mg/L (as PO_4) was present in raw water, and was removed to less than its detection limit of 0.05 mg/L until arsenic breakthrough from the lead vessel had reached about 10 μg/L. Orthophosphate apparently competed with arsenic for available adsorption sites on the media, causing arsenic to breakthrough to occur earlier than expected.
- Silica also might have interfered with arsenic adsorption. Its removal by the media was observed immediately after system startup and during one sampling event with an abnormally high concentration detected in an influent sample.
- A significant decrease in arsenic concentration (from an average of 30 μg/L to an average of 1.1 μg/L) was observed in the distribution system. Neither lead nor copper concentrations appeared to have been affected by the operation of the system.
- Neither operational problems nor unscheduled downtime were encountered during the first six months of system operation.

Required system O&M and operator's skill levels:

- The daily demand on the operator was typically 10 min to visually inspect the system and record operational parameters. Due to the small size of the system, operational parameters were recorded only 3 day/wk.
- Operation of the system did not require additional skills beyond those necessary to operate the existing water supply equipment.
- Based on the size of the population served and the treatment technology, the State of New Hampshire requires Level 1A certification for operation of the treatment system.

Process residuals produced by the technology:

- The only process residual produced during the first six months of operation was 640 gal of backwash water from one backwash event. The system was backwashed only once because there had been minimal solids buildup in the vessels and because pressure differential (Δp) across the vessels had remained constant throughout this reporting period.
- The treated water was used for backwash. Arsenic concentrations significantly higher than those in the treated water were measured in the backwash water (i.e., 30.2 and 3.6 μg/L from the lead and lag vessels, respectively). Arsenic might have

been desorbed from the media due to slightly higher pH of the treated water in the hydropneumatic tank following aeration for radon removal.

Cost-effectiveness of the technology:

- Using the system's rated capacity of 10 gpm (14,400 gpd), the capital cost was $3,421/gpm of design capacity ($2.38/gpd) and equipment-only cost was $2,243/gpm of the design capacity ($1.56/gpd).
- Although not incurred during the first six months of system operation, the media replacement cost represented the majority of the O&M cost for the system, and was estimated to be $4,199 to change out one vessel.

3.0 MATERIALS AND METHODS

3.1 General Project Approach

Following the pre-demonstration activities summarized in Table 3-1, the performance evaluation study of the AdEdge treatment system began on April 15, 2005. Table 3-2 summarizes the types of data collected and/or considered as part of the technology evaluation process. The overall performance of the system was determined based on its ability to consistently remove arsenic to the target MCL of 10 μg/L; this was monitored through the collection of biweekly and bimonthly water samples across the treatment train, as described in the Study Plan (Battelle, 2005). The reliability of the system was evaluated by tracking the unscheduled system downtime and the 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.

Table 3-1. Pre-Demonstration Study Activities and Completion Dates

Activity	Date
Introductory Meeting Held	September 13, 2004
Project Planning Meeting Held	November 9, 2004
Draft Letter of Understanding Issued	November 24, 2004
Final Letter of Understanding Issued	December 7, 2004
Request for Quotation Issued to Vendor	January 18, 2005
Vendor Quotation Submitted to Battelle	February 9, 2005
Purchase Order Completed and Signed	March 1, 2005
Engineering Plans Submitted to NHDES	March 3, 2005
Final Study Plan Issued	March 24, 2005
System Permit Issued by NHDES	March 31, 2005
APU Unit Shipped and Arrived	April 12, 2005
System Installation Completed	April 14, 2005
System Shakedown Completed	April 15, 2005
Performance Evaluation Begun	April 15, 2005

NHDES = New Hampshire Department of Environmental Services

The required system O&M and operator skill levels were evaluated based on a combination of quantitative data and qualitative considerations, including any pre-treatment and/or post-treatment requirements, level of system automation, operator skill requirements, task analysis of the preventive maintenance activities, frequency of chemical and/or media handling and inventory requirements, and general knowledge needed for safety requirements and chemical processes. The staffing requirements on the system operation were recorded on a Field Log Sheet.

The cost of the system was evaluated based on the capital cost per gpm (or gpd) of design capacity and the O&M cost per 1,000 gal of water treated. This requires the tracking of the capital cost for equipment, site engineering, and installation, as well as the O&M cost for media replacement and disposal, electrical power use, and labor hours. Data on Goffstown's O&M cost were limited to electricity consumption and labor hours because media replacement did not take place during the six months of system operation.

The quantity of aqueous and solid residuals generated was estimated by tracking the amount of backwash water produced during each backwash cycle and the need to replace the media upon arsenic breakthrough. Backwash water was sampled and analyzed for chemical characteristics.

Table 3-2. General Types of Data

Evaluation Objectives	Data Collection
Performance	-Ability to consistently meet 10 μg/L of arsenic in effluent
Reliability	-Unscheduled downtime for system -Frequency and extent of repairs to include labor hours, problem description, description of materials, and cost of materials
Required O&M and Operator Skill Levels	-Pre- and post-treatment requirements -Level of system automation for data collection and system operation -Staffing requirements including number of operators and labor hours -Task analysis of preventive maintenance to include labor hours per month and number and complexity of tasks -Chemical handling and inventory requirements -General knowledge needed of safety requirements and chemical processes
System Cost	-Capital cost for equipment, site engineering, and installation -O&M cost for chemical and/or media use, electricity consumption, and labor
Residual Management	-Quantity of residuals generated by process -Characteristics of aqueous and solid residuals

3.2 System O&M and Cost Data Collection

The plant operator performed weekly and monthly system O&M and data collection following the instructions provided by the vendor and Battelle. Three times a week, the plant operator recorded system operational data, such as pressure, flowrate, totalizer, and hour meter readings on a Daily Field Log Sheet; and conducted visual inspections to ensure normal system operations. In the event of problems, the plant operator would contact the Battelle Study Lead, who then would determine if AdEdge should be contacted for troubleshooting. Twice a month, the plant operator measured water quality parameters, including pH, temperature, dissolved oxygen (DO), and oxidation-reduction potential (ORP) and recorded the data on a Weekly Water Quality Parameters Log Sheet. Backwash was set to be performed manually by the operator. During this operation period, the system was backwashed only once. The backwash data were recorded on a Backwash Log Sheet.

The O&M cost consisted primarily of electricity and labor cost. Electricity consumption was tracked through the monthly electrical bill that the plant operator received. Labor hours for various activities, such as the routine system O&M, system troubleshooting and repair, and demonstration-related work, were tracked using an Operator Labor Hour Record. The routine O&M included activities such as completing the field logs, performing system inspection, and other miscellaneous routine requirements. The demonstration-related work included activities such as performing field measurements, collecting and shipping samples, and communicating with the Battelle Study Lead. The demonstration-related activities were recorded but not included in the cost analysis.

3.3 Sample Collection Procedures and Schedules

To evaluate the performance of the system, samples were collected from the source, treatment plant, distribution system, and adsorption vessel backwash locations. Table 3-3 provides the sampling schedule and analytes measured during each sampling event. 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).

3.3.1 Source Water Sample Collection. During the initial visit to the site on September 13, 2004, one set of source water samples was collected for detailed water quality analyses (Table 3-3). Source water also was speciated for total and soluble arsenic, iron, and manganese, and As(III) and As(V), and

Table 3-3. Sampling Schedule and Analytes

Sample Type	Sampling Locations[a]	No. of Sampling Locations	Frequency	Analytes	Sampling Date
Source Water	At Wellhead (IN)	1	Once during initial site visit	On-site: pH, temperature, DO, and ORP Off-site: As (total and soluble), As(III), As(V), Fe (total and soluble), Mn (total and soluble), Na, Ca, Mg, U, V, NH_4, NO_3, NO_2, Cl, F, SO_4, SiO_2, PO_4, TDS, TOC, turbidity, and alkalinity	09/13/04
Treatment Plant Water	At Wellhead (IN), After Lead Vessel (TA), After Lag Vessel (TB)	3	Biweekly	On-site: pH, temperature, DO, and ORP Off-site: As (total), Fe (total), Mn (total), F, NO_3, SO_4, SiO_2, PO_4, turbidity, and alkalinity	04/15/05, 05/02/05, 05/16/05, 05/31/05, 06/15/05, 06/27/05, 07/12/05, 07/25/05, 08/08/05, 08/22/05, 09/06/05, 09/20/05, 10/04/05, 10/17/05
			Bi-Monthly	On-site: pH, temperature, DO, and ORP Off-site: As (total and soluble), As(III), As(V), Fe (total and soluble), Mn (total and soluble), Ca, Mg, F, NO_3, SO_4, SiO_2, PO_4, turbidity, and alkalinity	04/15/05, 06/15/05, 08/08/05, 10/17/05
Distribution Water	Three LCR Residences	3	Monthly[b]	pH, alkalinity, As (total), Fe (total), Mn (total), Cu (total), and Pb (total)	Baseline sampling: 01/10/05, 01/25/05, 02/07/05, 03/21/05 Monthly sampling: 05/16/05, 06/13/05, 07/11/05, 08/08/05, 09/06/05, 10/05/05
Backwash Water	Backwash Discharge Line from Each Vessel	2	Sampling based on system performance	pH, TDS, turbidity, As (soluble), Fe (soluble), and Mn (soluble)	08/22/05

(a) Abbreviations in parentheses corresponding to sample locations shown in Figure 4-7.
(b) Four baseline sampling events performed from January 2005 to March 2005 before system became operational.
LCR = Lead and Copper Rule
TOC = total organic carbon

measured for pH, temperature, DO, and ORP on site. The sample tap was flushed for several minutes before sampling; special care was taken to avoid agitation, which might cause unwanted oxidation. Arsenic speciation kits and sample bottles for water quality parameters were prepared as described in Section 3.4.

3.3.2 Treatment Plant Water Sample Collection. During the system performance evaluation study, water samples were collected across the treatment train by the plant operator. Samples were collected biweekly on an 8-wk cycle. For the first three biweekly events, samples were collected at three locations (i.e., at the wellhead [IN], after the lead adsorption vessel [TA], and after the lag adsorption vessel [TB]) and analyzed for the analytes listed under the biweekly treatment plant analyte list in Table 3-3. For the last event, samples were collected for arsenic speciation at the same three locations and analyzed for the analytes listed under the bimonthly treatment plant analyte list in Table 3-3. On-site measurements also were collected at the same locations during each sampling event.

3.3.3 Backwash Water Sample Collection. One backwash water sample was collected on August 22, 2005 from the sample tap installed on the backwash water effluent line from each vessel. Unfiltered samples were sent to American Analytical Laboratories (AAL) for pH, total dissolved solids (TDS), and turbidity measurements. Filtered samples using 0.45-µm disc filters were sent to Battelle's inductively coupled plasma-mass spectrometry (ICP-MS) laboratory for soluble As, Fe, and Mn analyses. Arsenic speciation was not performed for the backwash water samples.

3.3.4 Backwash Solid Sample Collection. Backwash solid samples were not collected in the initial six months of this demonstration. Two to three solid/sludge samples will be collected from the backwash leach area if possible during the course of the second half of the demonstration study. The solid/sludge samples will be collected in glass jars and submitted to TCCI Laboratories for toxicity characteristic leaching procedure (TCLP) testing.

3.3.5 Distribution System Water Sample Collection. Samples were collected from the distribution system by the plant operator to determine the impact of the arsenic treatment system on the water chemistry in the distribution system, specifically, the lead and copper levels. From January to March 2005, prior to the startup of the treatment system, four baseline distribution sampling events were conducted at three locations within the distribution system. Following startup of the arsenic adsorption system, distribution system sampling continued on a monthly basis at the same three locations.

The three residences selected are historical Lead and Copper Rule (LCR) sampling locations serviced by the well. The home-owners of these locations, including the plant operator, collected the baseline and monthly distribution system samples following an instruction sheet developed according to the *Lead and Copper Monitoring and Reporting Guidance for Public Water Systems* (EPA, 2002). The homeowners recorded the date and time of last water use before sampling and the date and time of sample collection for calculation of the stagnation time. All 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 samples coincided with the monthly distribution system water samples as described in Table 3-3. Arsenic speciation was not performed for the distribution system water samples.

3.4 Sampling Logistics

All sampling logistics including arsenic speciation kits preparation, sample cooler preparation, and sample shipping and handling are discussed as follows:

3.4.1 Preparation of Arsenic Speciation Kits. The arsenic field speciation method used an anion exchange resin column to separate the soluble arsenic species, As(V) and As(III) (Edwards et al., 1998). Arsenic speciation kits 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 Sampling Coolers. All sample bottles were new and contained appropriate preservatives. Each sample bottle was labeled with a pre-printed, color-coded, and waterproof label. The sample label consisted of sample identification (ID), sampling date and time, sampler initials, site location, destination of the sample, analysis required, and preservative. The sample ID consisted of a two-letter code for a specific water facility, the sampling date, a two-letter code for a specific sampling location, and a one-letter code for the analysis to be performed. The sampling locations were color-coded for easy identification. For example, red, orange, and yellow were used to designate sampling locations for IN, TA, and TB, respectively. Pre-labeled bottles were placed in one of the plastic bags (each corresponding to a specific sampling location) in a sample cooler. When arsenic speciation samples were to be collected, an appropriate number of arsenic speciation kits also were included in the cooler.

When appropriate, the sample cooler was packed with bottles for the three distribution system sampling locations and/or the two backwash sampling locations (one for each vessel). In addition, a packet containing all sampling and shipping-related supplies, such as latex gloves, sampling instructions, chain-of-custody forms, prepaid FedEx air bills, ice packs, and bubble wrap, also was placed in the cooler. Except for the operator's signature, the chain-of-custody forms and prepaid FedEx air bills had already been completed with the required information. The sample coolers were shipped via FedEx to the facility approximately 1 wk prior to the scheduled sampling date.

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, sample custodians verified that all samples indicated on the chain-of-custody forms were included and intact. Sample label identifications were checked against the chain-of-custody forms and the samples were logged into the laboratory sample receipt log. Discrepancies, if noted, were addressed by the field sample custodian, and the Battelle Study Lead was notified.

Samples for water quality analyses by Battelle's subcontract laboratories were packed in coolers at Battelle and picked up by a courier from AAL (Columbus, OH). The samples for metals analyses, including arsenic speciation, were stored at Battelle's ICP-MS Laboratory. 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 are described in detail in Section 4.0 of the EPA-endorsed QAPP (Battelle, 2004). Field measurements of pH, temperature, DO, and ORP were conducted by the plant operator using a WTW Multi 340i handheld meter, which was calibrated prior to use following the procedures provided in the user's manual. The plant operator collected a water sample in a 400-mL plastic beaker and placed the Multi 340i probe in the beaker until a stable measured value was reached.

Laboratory quality assurance/quality control (QA/QC) of all methods followed the guidelines provided in the QAPP (Battelle, 2004). Data quality in terms of precision, accuracy, method detection limit (MDL), and completeness met the criteria established in the QAPP (i.e., relative percent difference [RPD] of 25%, percent recovery of 75-125%, 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 separately.

4.0 RESULTS AND DISCUSSION

4.1 Facility Description and Pre-Existing Treatment System Infrastructure

The community water system supplies water to 42 homes in the Orchard Highlands Subdivision in Goffstown, NH. Figure 4-1 shows the water treatment building. The water source is a single deep bedrock well drilled to a depth of approximately 800 ft. The flowrate from this supply well was estimated to be approximately 7.5 gal/min (gpm) based on the pump curve provided by the facility. The actual peak flowrate recorded at the site after the installation of the system was 15 gpm with an average flowrate of 13 gpm. The existing system includes an aeration system for radon treatment (Figure 4-2), a 10,000-gal storage tank (Figure 4-3), two booster pumps (Figure 4-4), and a 2,000-gal hydropneumatic pressure tank (Figure 4-5).

Figure 4-1. Pre-Existing Treatment Building at Orchard Highlands Subdivision

4.1.1 Source Water Quality. Source water samples were collected inside the treatment building from two sample taps before and after the aeration unit on September 13, 2004. The analytical results from source water sampling are presented in Table 4-1, and are compared to historic data taken by the facility for the EPA demonstration site selection and by New Hampshire Department of Environmental Services (NHDES). Except for pH and TDS, the analytical results were similar for the samples collected before and after the aeration unit.

Total arsenic concentrations in raw water ranged from 30 to 33 μg/L. Out of 32.7 μg/L of total arsenic, 32.3 μg/L (98.7%) existed as As(V) and only 0.8 μg/L (1.3%) existed as As(III). According to the vendor, the AD-33 media adsorbs As(V) with rapid kinetics and As(III) with slower kinetics. Since the majority of the arsenic was As(V), a pre-oxidation step to convert As(III) to As(V) was not necessary.

Figure 4-2. Aeration System for Radon Treatment

Figure 4-3. 10,000-gal Storage Tank

Figure 4-4. Booster Pumps

Figure 4-5. 2,000-gal Hydropneumatic Pressure Tank

Table 4-1. Orchard Highlands Subdivision Water Quality Data

Parameter	Units	Facility Data	Battelle Data		NHDES Treated Water Data
			Raw	Post-Aeration	
Sampling Date		NA	09/13/04	09/13/04	00-04
pH	S.U.	7.2	6.9	7.5	7.2
Temperature	°C	NA	12.0	13.1	8.0
DO	mg/L	NA	5.1	5.9	NA
ORP	mV	NA	226	235	NA
Total Alkalinity (as $CaCO_3$)	mg/L	44	85	93	44
Hardness (as $CaCO_3$)	mg/L	32	25	31	32
Turbidity	NTU	NA	0.2	0.2	NA
TDS	mg/L	NA	84	248	NA
TOC	mg/L	NA	<0.7	<0.7	NA
Nitrate (as N)	mg/L	NA	<0.04	<0.04	NA
Nitrite (as N)	mg/L	NA	<0.01	<0.01	NA
Ammonia (as N)	mg/L	NA	0.05	<0.05	NA
Chloride	mg/L	<6	1.2	1.1	<6
Fluoride	mg/L	NA	0.3	0.4	0.4
Sulfate	mg/L	6	5.8	5.8	6
Silica (as SiO_2)	mg/L	NA	25.7	25.8	NA
Orthophosphate (as PO_4)	mg/L	NA	0.2	0.3	0.03
As(total)	µg/L	30	32.7	30.5	30-33
As (total soluble)	µg/L	NA	33.1	32.2	NA
As (particulate)	µg/L	NA	<0.1	<0.1	NA
As(III)	µg/L	<0.001	0.8	0.5	NA
As(V)	µg/L	30	32.3	31.7	NA
Fe (total)	µg/L	<100	<25	<25	<100
Fe (soluble)	µg/L	NA	<25	<25	NA
Mn (total)	µg/L	NA	13.5	3.5	<30
Mn (soluble)	µg/L	<30	2.8	2.9	NA
U (total)	µg/L	NA	2.4	1.9	NA
V (total)	µg/L	NA	0.4	0.4	NA
Na (total)	mg/L	8	8	9	8
Ca (total)	mg/L	14	7	9	14
Mg (total)	mg/L	3	2	2	3
Radon	PCi/L	13,100	NA	NA	NA

NA = not analyzed
ND = not detectable

The pH values of raw water samples ranged from 6.9 before aeration to 7.5 after aeration. Aeration might have helped remove some CO_2, thereby increasing the pH values of the aerated water. Nevertheless, these pH values were well within the acceptable pH range of 6.5 to 8.0 for effective arsenic adsorption by the AD-33 media. Therefore, pH adjustment was not recommended.

The adsorptive capacity of the AD-33 media can be impacted by high levels of competing anions such as orthophosphate, silica, vanadate, and fluoride. Orthophosphate concentrations ranged from 0.2 to 0.3 mg/L, which could compete with arsenate for adsorption sites. Concentrations of other competing anions appeared to be low enough not to affect the media's adsorption of arsenic. Iron was not detected (with a reporting limit of 25 µg/L) in raw water; therefore, pre-treatment for iron removal prior to adsorption was not required.

4.1.2 Distribution System. The distribution system consists of a branched drinking water system, supplied by a single deep bed-rock well. Water (from either the bedrock well before the arsenic removal system was installed or the lag adsorption vessel after the system was installed) is treated with an aeration system for radon removal prior to entering a 10,000-gal storage tank. Two booster pumps are located after the storage tank to pump the water into a 2,000-gal pressure tank, which is connected to the distribution system. The distribution system is constructed primarily of polyvinyl chloride (PVC) pipe. The connections to the distribution system and piping within the residences themselves are copper.

Compliance samples from the distribution system are collected for NHDES for quarterly bacterial analysis, and for periodic analysis of inorganic chemicals, nitrates, radiologicals, synthetic organic compounds, and volatile organic compounds (Table 4-1).

4.2 Treatment Process Description

The arsenic package unit (APU) marketed by AdEdge is a fixed-bed down-flow adsorption system used for small water systems in the flow range of 5 to 100 gpm. It uses Bayoxide E33 media (branded as AD-33 by AdEdge), an iron-based adsorptive media developed by Bayer AG, for the removal of arsenic from drinking water supplies. Table 4-2 presents physical and chemical properties of the media. AD-33 media is delivered in a dry crystalline form and listed by NSF International (NSF) under Standard 61 for use in drinking water applications.

For series operation, when the media in the lead vessel completely exhausts its capacity and/or the effluent from the lag vessel reaches 10 µg/L of arsenic, the spent media in the lead vessel is removed and disposed of after being subjected to TCLP testing. After rebedding, the lead vessel is switched to the lag position and the lag vessel is switched to the lead 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.

When comparing the performance of the lead vessel (series operation) with that of two smaller in-parallel vessels of a similarly-sized system (parallel operation), the number of BV treated by the system is calculated based on the media volume in the lead vessel for the series operation and in the two in-parallel vessels for the parallel operation. The calculation does not use the media volume in the lead and lag vessels because this approach considers the two vessels as one large vessel, which has twice as much media than the in-parallel system. The media volume in the lead vessel is equal to the sum of the media volume in each of the two vessels in parallel; the flow through the lead vessel is equal to the sum of the flow through each of the two vessels in parallel; and the EBCT in the lead vessel is the same as EBCT in each of the two vessels in parallel.

The arsenic treatment system (specifically referred to as the APU-GOFF-LL system) at the Orchard Highland Subdivision site consists of two pressure vessels operating in series. Note that the system piping/valving provided does not allow for switching of the lead/lag vessels. The schematic of the system with switchable lead/lag vessels is shown in Figure 4-6. The adsorption vessels receive water directly from the well and the effluent for the adsorption system is further treated by the pre-existing aeration unit for radon removal. Table 4-3 presents the key system design parameters. Figure 4-7 shows the generalized process flow for the system including sampling locations and parameters to be analyzed.

Three key process components are discussed as follows:

- **Intake**. Raw water is pumped from the well and fed into the APU-GOFF-LL system at approximately 13 gpm. The well pump is controlled by a float switch within the 10,000-gal storage tank.

Table 4-2. Physical and Chemical Properties of AD-33 Media[(a)]

Physical Properties	
Parameter	**Value**
Matrix	Iron oxide composite
Physical Form	Dry granules
Color	Amber
Bulk Density (lb/ft^3)	28.1
BET Area (m^2/g)	142
Attrition (%)	0.3
Moisture Content (%)	~ 8 (by weight)
Particle size distribution	10 × 35 mesh
Crystal Size (Å)	70
Crystal Phase	α–FeOOH
Chemical Analysis	
Constituents	**Weight (%)**
FeOOH	90.1
CaO	0.27
MgO	1.00
MnO	0.11
SO_3	0.13
Na_2O	0.12
TiO_2	0.11
SiO_2	0.06
Al_2O_3	0.05
P_2O_5	0.02
Cl	0.01

(a) Provided by Bayer AG.
BET = Brunauer, Emmett, and Teller

- **Adsorption System**. The APU-GOFF-LL system consists of two 18-in.-diameter, 65-in.-tall pressure vessels in series configuration, each containing 5 ft^3 of AD-33 media supported by a gravel underbed. The vessels are fiberglass-reinforced plastic (FRP) construction, rated for 150 pounds per square inch (psi) working pressure, skid-mounted, and piped to a valve rack mounted on a welded frame. The design EBCT for the system is approximately 3.7 min based on a media volume of 5 ft^3/vessel (with a bed depth of 34 in.) and a design flowrate of 10 gpm. Figure 4-8 shows the installed system and Figure 4-9 shows the system control panel.

- **Backwash**. On automatic operation, backwash can be set by time or pressure differential. The system also can be backwashed manually. The adsorption vessels are taken off line for backwash one at a time using the treated water from the 2,000-gal hydropneumatic tank. The purpose of the backwash is to remove particles and media fines accumulating in the beds. The backwash water produced is discharged to an on-site surface drainage field for disposal.

- **Aeration, Storage, and Distribution**. Effluent of the adsorption system is aerated to remove radon before entering the existing 10,000-gal storage tank. Two existing booster pumps are used to pump water from the storage tank to the 2000-gal hydropneumatic tank to ensure adequate supply pressure to the distribution system.

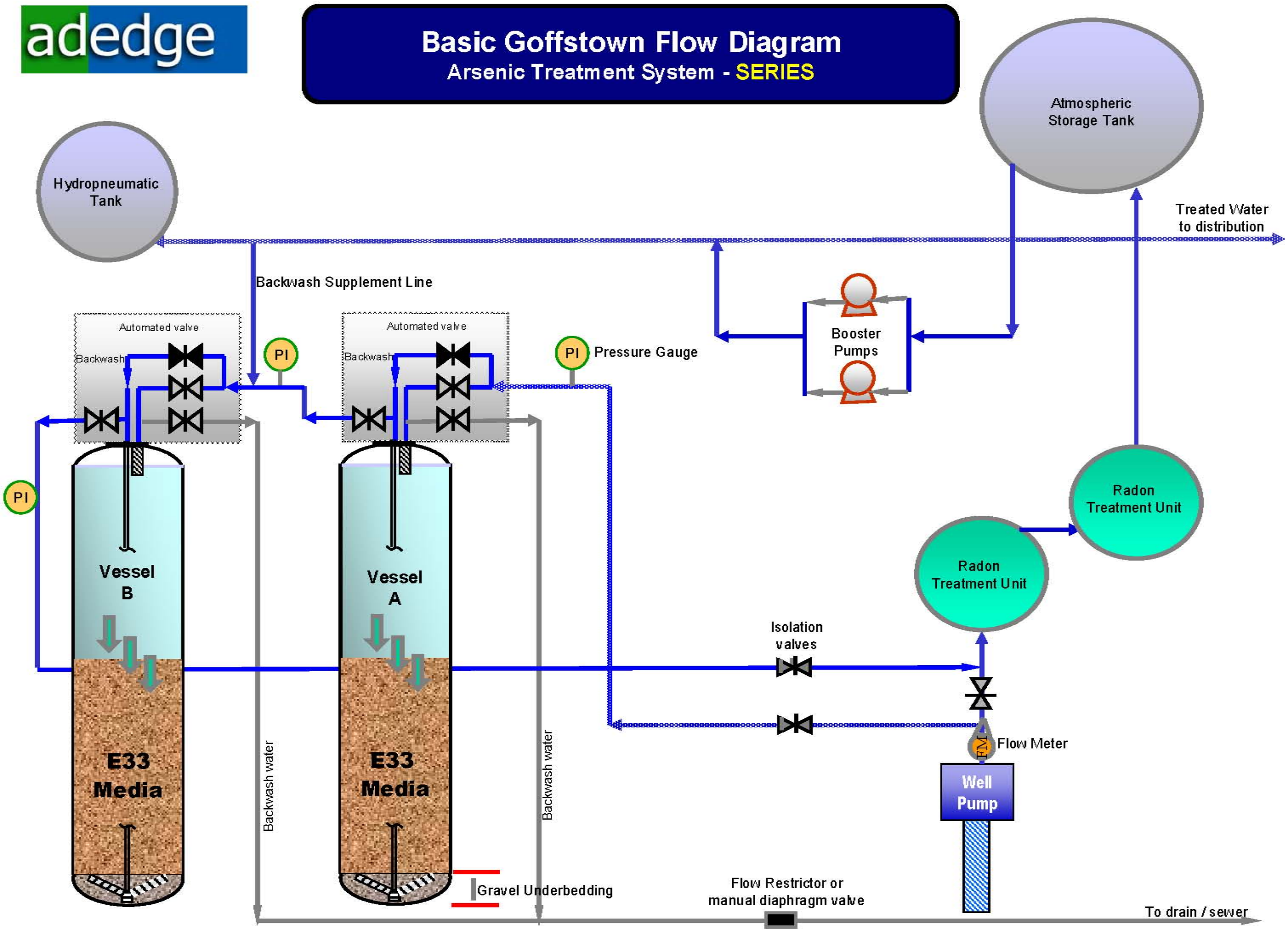


Figure 4-6. Schematic of APU-GOFF-LL System

Table 4-3. Design Features of the APU-GOFF-LL System

Design Parameter	Value	Remarks
Pretreatment	NA	Not required
Adsorbers		
No. of Adsorbers	2	–
Configuration	Series	–
Vessel Size (in)	18 D × 65 H	–
Vessel Cross Sectional Area (ft^2)	1.77	–
Type of Media	Bayoxide E33	–
Quantity of Media (ft^3)	10 (total)	Two vessels, each vessel with 5 ft^3 of media
Media Bed Depth (in)	34	–
Design Flowrate (gpm)	10	Based on 7.5 gpm system use by pump curve supplied by utility
Hydraulic Loading Rate (gpm/ft^2)	5.6	–
EBCT (min)	3.7	Based on 10 gpm flowrate
Backwash		
Backwash Flowrate (gpm)	15.9	–
Backwash Hydraulic Loading Rate (gpm/ft^2)	9	–
Backwash Duration (min/vessel)	20	–
Backwash Water Generated (gal/vessel)	320	–
Design Backwash Frequency	One to two times per month	Set to manual so that backwash sample could be collected
Adsorption System		
Average Throughput to System (gpd)	11,550	Vendor estimated
Estimated Working Capacity (BV)	62,690	Bed volumes to breakthrough at 10 μg/L from lead vessel based on vendor estimate
Bed Volumes (BV/day)	308	Based on throughput of 11,550 gpd, 1 BV = 5 ft^3
Estimated Volume to Breakthrough (gal)	2,344,600	Based on vendor estimated bed volumes to breakthrough at 10 μg/L from lead vessel
Estimated Media Life (months)	6.7	Estimated frequency of change-out of media in lead vessel based on throughput of 11,550 gpd and breakthrough at 10μg/L from lead vessel

4.3 System Installation

The installation of the APU system was completed by Thursty Water Systems, a subcontractor to AdEdge, on April 14, 2005. The following briefly summarizes some of the pre-demonstration activities, including permitting, building preparation, and system offloading, installation, shakedown, and startup.

4.3.1 Permitting. Design drawings and proposal for the proposed treatment system were submitted to the NHDES by AdEdge on March 3, 2005. NHDES granted the treatment system permit on March 31, 2005. NHDES commented that the disposal of the periodic backwash of the media should be consistent with that allowed for the Rollinsford, NH site studied in Round 1 of the EPA's arsenic technology demonstration project; and that the completed installation should be disinfected and tested for bacterial presence before being placed into service.

4.3.2 Building Preparation. The existing building that housed pre-existing treatment system had an adequate building footprint to house the planned arsenic treatment system. Additional preparation was not needed.

4.3.3 Installation, Shakedown, and Startup. The treatment system arrived on-site on April 12, 2005. Figure 4-10 shows a photograph of the system arriving at the site. Several of the PVC connections were damaged during shipping and had to be replaced before system installation. Thursty Water System

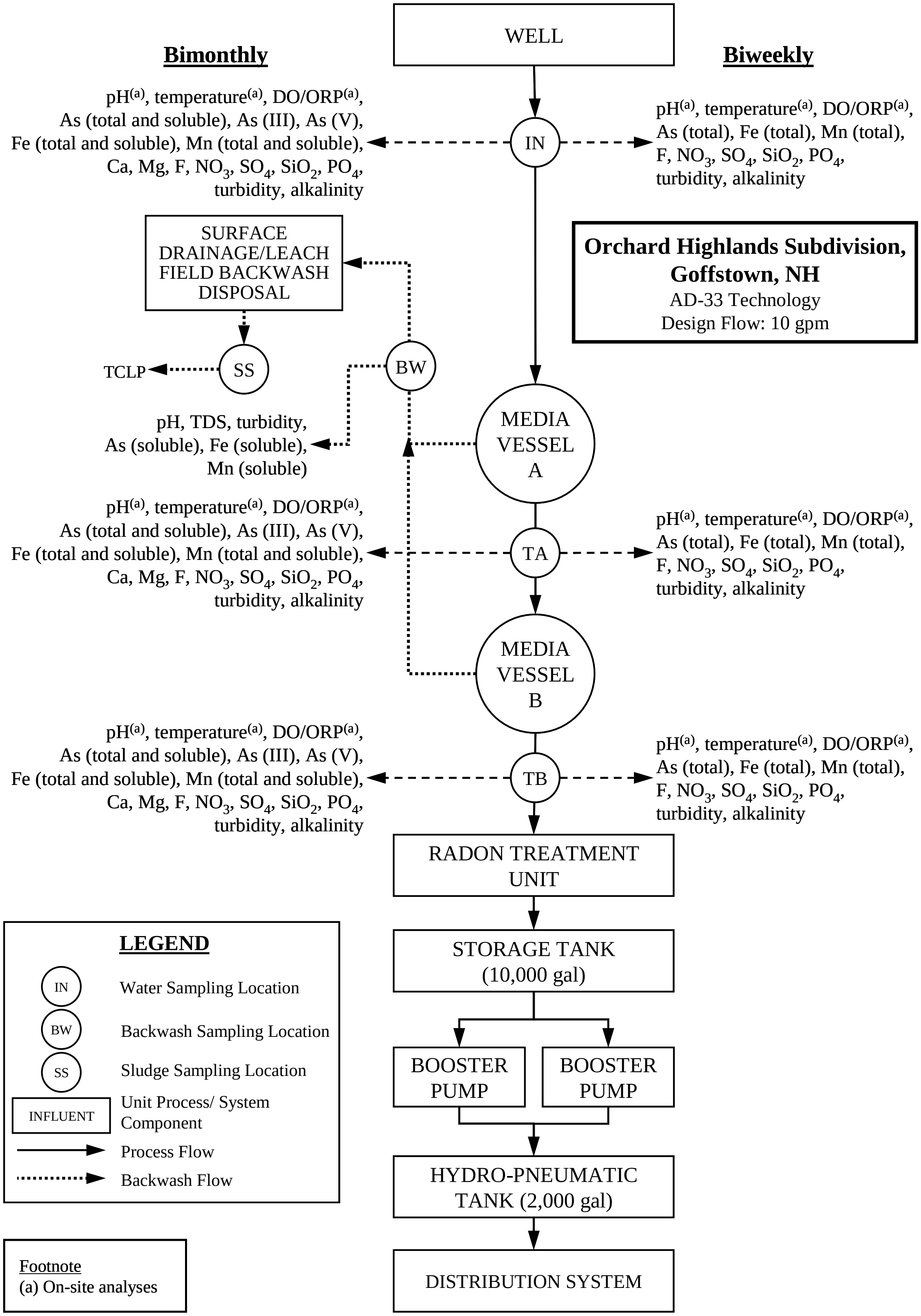


Figure 4-7. Process Flow Diagram and Sampling Locations

Figure 4-8. APU-GOFF-LL Treatment System

and AdEdge were on site for the installation during April 13 through 14, 2005. After media loading, a water sample was collected through the system for bacterial analysis on April 14, 2005. The system was bypassed until the results of the bacterial analysis were received on April 15, 2005. Meanwhile, AdEdge and the local operator performed the system shakedown and startup work, which included media backwash and flow adjustment to approximately 16 gpm for the backwash cycle. Battelle conducted a system inspection and provided operator training on data and sample collection. After the results of the bacterial analysis were forwarded to NHDES, the system was officially brought on-line April 15, 2005.

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 4-4. From April 15 through October 22, 2005, the system operated for 1,032 hr, based on the well pump hour-meter readings collected three times a week. This cumulative operating time represents a use rate of approximately 22% during this 28-wk period. The system typically operated for a period of approximately 5 hr/day.

Figure 4-9. System Control Panel

Figure 4-10. System Being Delivered to Site

Table 4-4. Summary of APU-GOFF-LL System Operation

Operational Parameter	Value / Condition
Duration	04/15/05–10/22/05
Cumulative Operating Time (hr)	1,032
Average Daily Operating Time (hr)	5.4
Throughput (gal)	807,300
Bed Volumes (BV)(a)	21,586
Average (Range of) Flowrate (gpm)	13 (12–15)
Average EBCT (min)(a)	2.9 (5.8 for system)
Range of EBCT (min)(a)	2.5–3.1 (5.0–6.2 for system)
Average (Range of) Inlet Pressure (psi)	27.6 (24–30)
Average (Range of) Outlet Pressure (psi)	10.2 (9–12)
Average (Range of) Δp across Vessel A (psi)	4.8 (range 3–6)
Average (Range of) Δp across Vessel B (psi)	4.3 (range 3.2–6)

(a) Calculated based on 5 ft^3 of media in lead vessel.

During the first six months, the system treated approximately 807,300 gal of water, or 21,586 BV based on the totalizer readings from the lead vessel. Bed volume calculations were performed based on the 5 ft^3 of media in the lead vessel. Flowrates to the system ranged from 12 to 15 gpm and averaged 13 gpm. The highest flowrate occurred when the pump was initially turned on and the flowrate decreased gradually as the well pump operated. The average system flowrate was 30% higher than the 10-gpm design value (Table 4-3), which was derived from the 7.5-gpm supply well flowrate based on the pump curve provided by the facility. Based on the flows to the system, the EBCT for the lead vessel varied from 2.5 to 3.1 min and averaged 2.9 min. As a result, the 3.7-min design EBCT was 30% higher than the actual EBCT.

4.4.2 Backwash. AdEdge recommended that the APU-GOFF-LL system be backwashed, either manually or automatically, approximately once or twice per month. Automatic backwash could be initiated either by timer or by differential pressure (Δp) across the vessels. Due to the steady pressure drop across the vessels of 3 to 6 psi throughout the six months of system operation, the system was backwashed only once when the arsenic concentration in the lead tank was approaching 8 µg/L. This occurred at about 15,000 BV, or 4 months after the system became operational.

4.4.3 Residual Management. Residuals produced by the operation of the system would include backwash water and spent media. Because the media was not replaced during the first six months of system operation, the only residual produced was backwash water. Piping for backwash water from both vessels was combined aboveground before exiting the building through the floor. It then traveled underground and resurfaced behind the treatment building. Backwash water flowed down the surface drainage field and infiltrated to the ground. Any particulates or media fines carried in the backwash water remained in the drainage field.

4.4.4 System/Operation Reliability and Simplicity. There were no operational problems with the APU-GOFF-LL system during the first six-months of operation; the unscheduled downtime for the system was 0% during this study period. The system O&M and operator skill requirements are discussed below in relation to pre- and post-treatment 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. The majority of arsenic at this site existed as As(V). As such, a preoxidation step was not required.

System Automation. The system was fitted with automated controls that would allow for the backwash cycle to be controlled automatically; however, because pressure readings across the adsorption vessels did not rise during the first six months of operation, only one manual backwash was performed. The system piping as currently configured does not allow the lead and lag vessels to switch after rebedding of the lead vessel. Plans have been made to allow the vendor to be on site to reconfigure the piping and valves so that the vessels may be switchable upon media rebedding.

Operator Skill Requirements. Under normal operating conditions, the skill requirements to operate the system were minimal. The operator was on site typically three times a week and spent approximately 10 min each day to perform visual inspection 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. Based on the size of the population served and the treatment technology, the State of New Hampshire requires Level 1A certification for operation of the treatment system.

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

Chemical/Media Handling and Inventory Requirements. No chemical was used as part of the treatment system at Orchard Highlands Subdivision site.

4.5 System Performance

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

4.5.1 Treatment Plant Sampling. Table 4-5 summarizes the analytical results of arsenic, orthophosphate, iron, and manganese concentrations measured at the three sampling locations across the treatment train. Table 4-6 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, with field speciation performed during 4 of the 14 occasions from IN, TA, and TB sampling locations. Figure 4-11 contains three bar charts showing the concentrations of total arsenic, particulate arsenic, As(III), and As(V) at three locations for each of the 4 speciation events. Total arsenic concentrations in raw water ranged from 24.1 to 34.0 μg/L and averaged 29.4 μg/L. As(V) was the predominating species, ranging from 25.3 to 33.0 μg/L and averaging 29.3 μg/L. As(III) and particulate As concentrations were low, averaging 0.6 and 0.1 μg/L, respectively. The arsenic concentrations measured were consistent with those collected previously during source water sampling (Table 4-1).

Table 4-5. Summary of Analytical Results for Arsenic, Orthophosphate, Iron, and Manganese

Parameter	Sampling Location	Unit	Sample Count	Concentration			Standard Deviation
				Minimum	Maximum	Average	
As (total)	IN	(µg/L)	15	24.1	34.0	29.4	3.0
	TA	(µg/L)	15	—(a)			
	TB	(µg/L)	15				
As (soluble)	IN	(µg/L)	4	26.0	33.7	29.9	3.2
	TA	(µg/L)	4	—(a)			
	TB	(µg/L)	4				
As (particulate)	IN	(µg/L)	4	<0.1	0.3	0.1	0.1
	TA	(µg/L)	4	—(a)			
	TB	(µg/L)	4				
As(III)	IN	(µg/L)	4	0.6	0.7	0.6	0.0
	TA	(µg/L)	4	—(a)			
	TB	(µg/L)	4				
As(V)	IN	(µg/L)	4	25.3	33.0	29.3	3.2
	TA	(µg/L)	4	—(a)			
	TB	(µg/L)	4				
Orthophosphate (as PO_4)	IN	(mg/L)	15	<0.05	0.3	0.17	0.13
	TA	(mg/L)	15	—(b)			
	TB	(mg/L)	15				
Fe (total)	IN	(µg/L)	15	<25	<25	<25	0.0
	TA	(µg/L)	15	<25	<25	<25	0.0
	TB	(µg/L)	15	<25	72.5	<25	15.5
Fe (soluble)	IN	(µg/L)	4	<25	<25	<25	0.0
	TA	(µg/L)	4	<25	<25	<25	0.0
	TB	(µg/L)	4	<25	<25	<25	0.0
Mn (total)	IN	(µg/L)	15	0.6	16.7	4	5.0
	TA	(µg/L)	15	<0.1	1.5	0.5	0.4
	TB	(µg/L)	15	<0.1	1.0	0.2	0.3
Mn (soluble)	IN	(µg/L)	4	1.1	1.4	1	0.1
	TA	(µg/L)	4	0.4	1.5	0.9	0.5
	TB	(µg/L)	4	0.3	1.0	0.6	0.4

One-half of detection limit used for samples with concentrations less than detection limit for calculations.
Duplicate samples included in calculations.
(a) Statistics not meaningful for data related to arsenic breakthrough; see data on Figures 4-11 and 4-12.
(b) Statistics not meaningful for data related to orthophosphate breakthrough; see data on Figure 4-13.

Table 4-6. Summary of Water Quality Parameter Sampling Results

Parameter	Sampling Location	Unit	Sample Count	Concentration			Standard Deviation
				Minimum	Maximum	Average	
Alkalinity (as $CaCO_3$)	IN	mg/L	15	33	88	53	14
	TA	mg/L	15	40	63	49	8
	TB	mg/L	15	41	60	49	7
Fluoride	IN	mg/L	15	0.2	0.6	0.4	0.1
	TA	mg/L	15	0.2	0.5	0.4	0.1
	TB	mg/L	15	0.2	0.6	0.3	0.1
Sulfate	IN	mg/L	15	4.6	7.0	5.7	0.9
	TA	mg/L	15	4.6	8.0	5.7	1.0
	TB	mg/L	15	4.6	8.0	5.9	1.0
Nitrate (as N)	IN	mg/L	15	0.05	4.69	0.45	1.18
	TA	mg/L	15	<0.05	1.05	0.25	0.33
	TB	mg/L	15	<0.05	5.06	0.51	1.27
Silica (as SiO_2)	IN	mg/L	15	24.2	31.7	25.5	1.8
	TA	mg/L	15	19.1	26.4	24.6	1.7
	TB	mg/L	15	8.9	26.6	23.5	4.1
Turbidity	IN	NTU	15	<0.1	0.6	0.2	0.2
	TA	NTU	15	<0.1	0.9	0.3	0.3
	TB	NTU	15	<0.1	2.7	0.4	0.6
pH	IN	S.U.	14	6.9	7.5	7.1	0.1
	TA	S.U.	14	7.1	7.4	7.3	0.1
	TB	S.U.	14	7.2	7.5	7.4	0.1
Temperature	IN	°C	14	12.0	15.9	13.5	1.2
	TA	°C	14	12.4	16.5	13.7	1.2
	TB	°C	14	12.4	16.8	14.0	1.4
DO	IN	mg/L	14	4.8	6.5	5.7	0.6
	TA	mg/L	14	3.7	7.2	5.4	0.9
	TB	mg/L	14	4.9	6.4	5.7	0.5
ORP	IN	mV	14	168	219	204	15
	TA	mV	14	183	221	205	11
	TB	mV	14	194	230	210	12
Total Hardness (as $CaCO_3$)	IN	mg/L	4	22	36	27	6
	TA	mg/L	4	24	38	29	7
	TB	mg/L	4	24	37	29	6
Ca Hardness (as $CaCO_3$)	IN	mg/L	4	14	27	18	6
	TA	mg/L	4	16	29	21	6
	TB	mg/L	4	16	26	21	5
Mg Hardness (as $CaCO_3$)	IN	mg/L	4	7.4	9.1	8.3	0.7
	TA	mg/L	4	7.5	9.2	8.4	0.9
	TB	mg/L	4	4.1	11.5	7.9	3.0

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

The total arsenic breakthrough curves shown in Figure 4-12 indicate that the lead vessel removed the majority of arsenic, existing predominately as As(V), in the influent water, leaving only <11.3 µg/L to be further polished by the lag vessel. Breakthrough of total arsenic at 10 µg/L from the lead vessel was first observed during the October 4, 2005 sampling event at approximately 19,500 BV, which represents only 31% of the vendor-estimated working capacity of 62,690 BV (Table 4-4). One contributing factor to the earlier than expected breakthrough was the shorter EBCT (i.e., 2.9 min versus the design value of 3.7 min), which was caused by the higher flowrate experienced by the system (i.e., 13 gpm versus the design value of 10 gpm). However, the 22% reduction in EBCT should not have reduced the media capacity by 69%.

Another factor that might have contributed to the shorter media life was the presence of competing anions, such as orthophosphate and silica, in raw water with concentrations up to 0.3 mg/L (as PO_4) for orthophosphate and 31.7 mg/L (as SiO_2) for silica. As shown in Figure 4-13, orthophosphate was effectively removed to below its detection limit of 0.05 mg/L by the lead vessel up to about 19,500 BV. Coincidentally, as breakthrough of arsenic approached 10 µg/L, orthophosphate also began to break through. Since then, detectable concentrations of 0.1 mg/L were measured following the lead vessel, but were reduced to below its detection limit by the lag vessel. To a lesser extent, silica also competed with arsenic for available adsorptive sites, as evidenced by the reduced silica concentrations observed during the first sampling event on April 15, 2005 and the event on October 4, 2005 when an elevated silica level of 31.7 mg/L (versus an average of 25.5 mg/L) was measured in raw water.

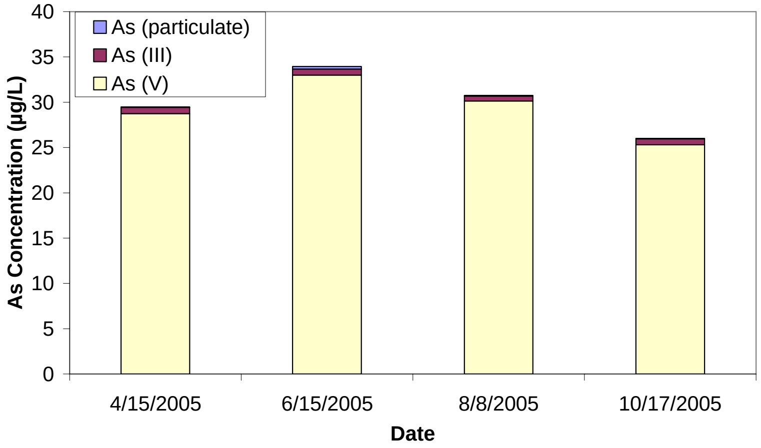
As noted in Section 4.4.1, the system operated for approximately 5 hr/day. This on/off operation, compared with operation 24 hr/day, 7 day/wk might have increased the media capacity due to a relaxation in the concentration gradient following every stoppage. It was not clear if the vendor took this effect into consideration when estimating the media capacity.

By the end of the first six months of system operations, the system treated approximately 21,600 BV of water (equivalent to 807,300 gal). Arsenic breakthrough at this point reached 11.3 and 0.5 µg/L for the lead and lag vessels, respectively. Since then, system operation has continued and the media in the lead vessel will be removed once it is completely exhausted or the breakthrough of the lag vessel reaches 10 µg/L, whichever comes first.

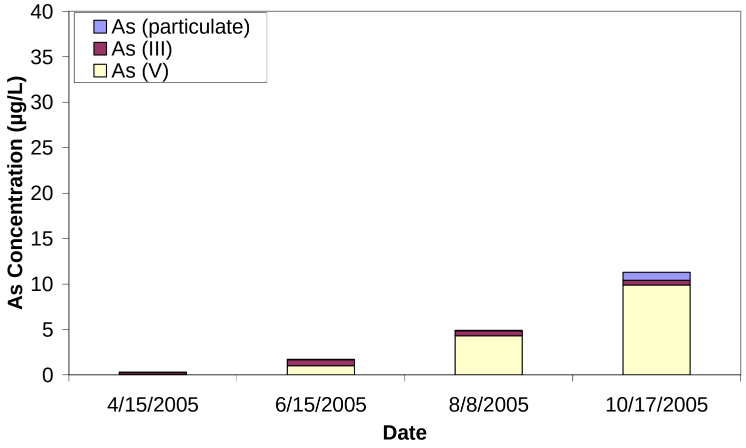
Iron and Manganese. Total iron concentrations in raw water were below its detection limit of 25 µg/L (Table 4-5). Total iron concentrations across the treatment train also were below the detection limit, except for one measurement of 72.5 µg/L at the TB location on September 6, 2005. Total manganese levels ranged from 0.6 to 16.7 µg/L and averaged 4.2 µg/L in raw water. Total manganese concentrations in the effluent from the adsorption vessels showed a decreasing trend, with <1.5 µg/L measured after the lead vessel and <1.0 µg/L after the lag vessel. Soluble manganese concentrations were similar for the 3 sample locations averaging 1.2 µg/L, 0.9 µg/L, and 0.6 µg/L for IN, TA, and TB, respectively.

Other Water Quality Parameters. As shown in Table 4-6, pH values of raw water measured at the IN sample location varied from 6.9 to 7.5 and averaged 7.1. This near neutral pH condition is desirable for adsorptive media which, in general, have a greater arsenic removal capacity when treating water at near neutral pH values. Although not monitored during the first six months of system operation, the pH value after aeration was higher than that before aeration as measured during the initial site visit (Table 4-1). The higher pH values might have caused some arsenic desorption into the backwash water when the aerated water was used to backwash the media. The effect of pH is further discussed in Section 4.5.2.

Arsenic Species at Wellhead (IN)



Arsenic Species after Vessel A (TA)



Arsenic Species after Vessel B (TB)

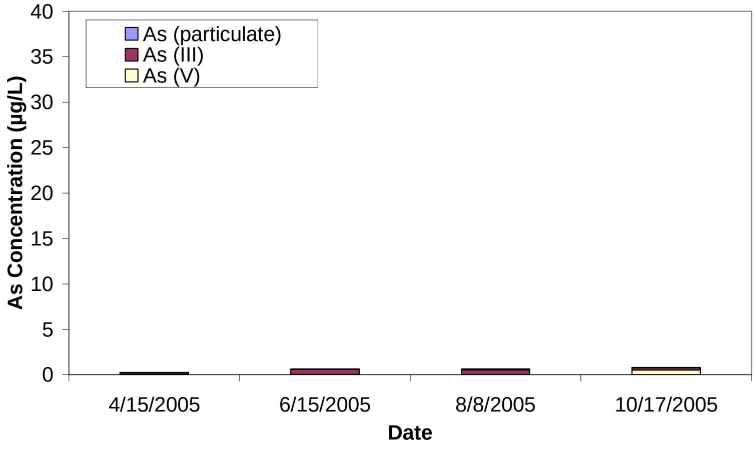


Figure 4-11. Concentrations of Various Arsenic Species at IN, TA, and TB Sampling Locations

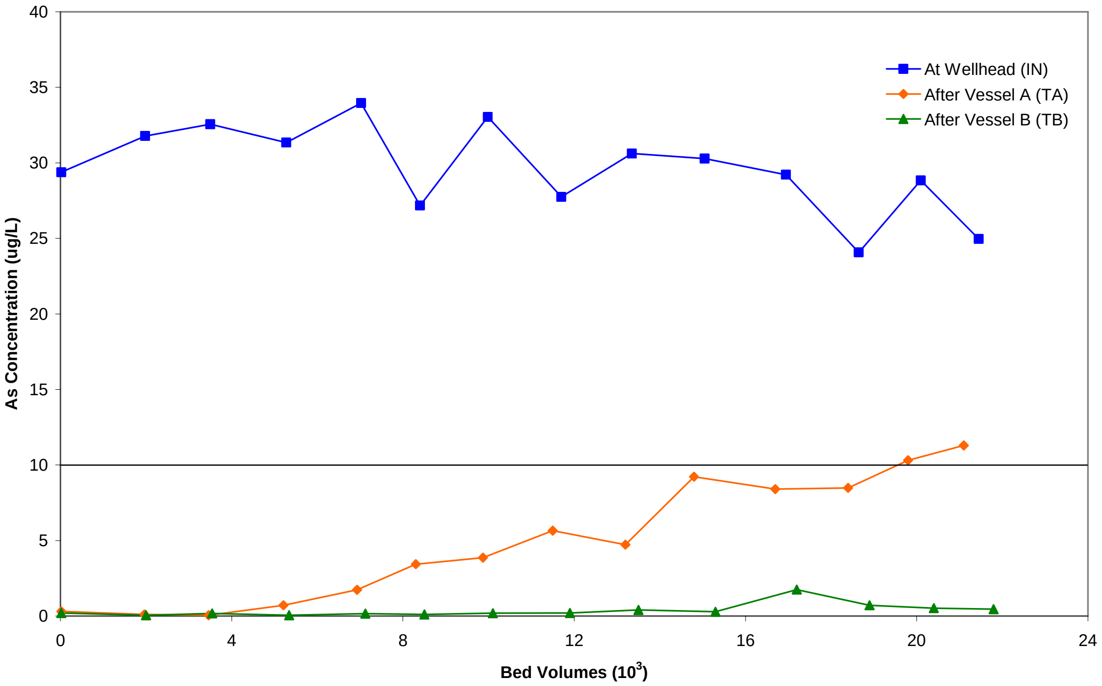


Figure 4-12. Total Arsenic Breakthrough Curves

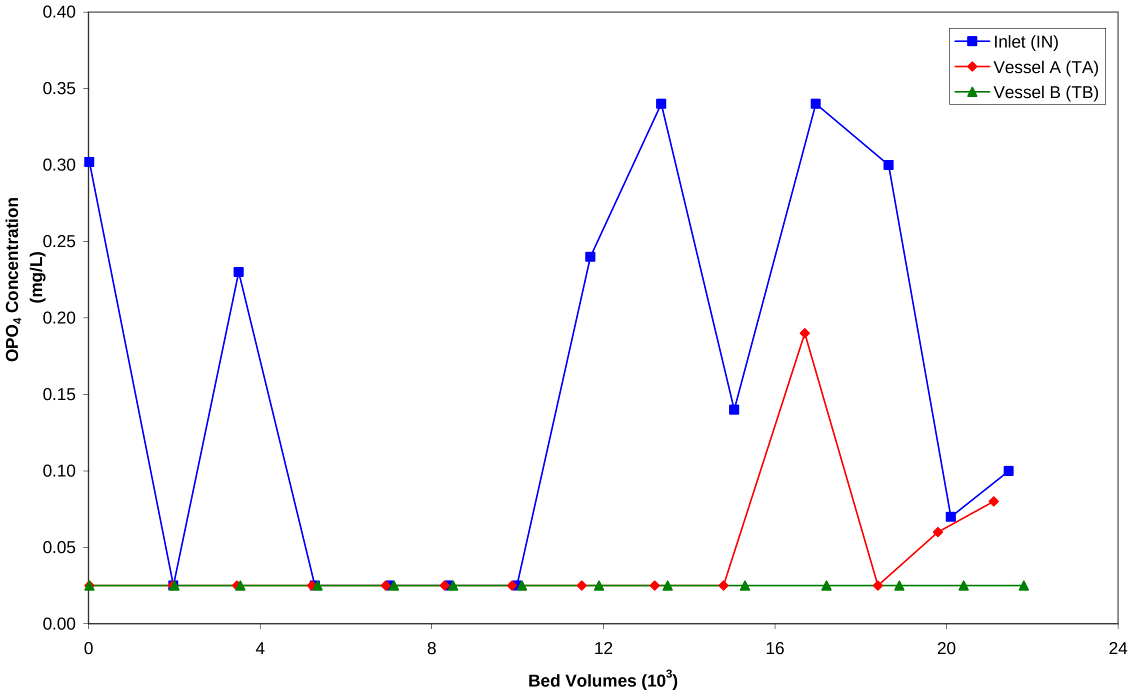


Figure 4-13. Orthophosphate Trend

Alkalinity, reported as $CaCO_3$, ranged from 33 to 88 mg/L. The results indicate that the adsorptive media did not affect the amount of alkalinity in the water after treatment. The treatment plant samples were analyzed for hardness only on speciation weeks. Total hardness ranged from 22 to 38 mg/L (as $CaCO_3$), and also remained constant throughout the treatment train.

Sulfate concentrations ranged from 4.6 to 8.0 mg/L, and remained constant throughout the treatment train. Fluoride results ranged from 0.2 to 0.6 mg/L in all samples. The results indicate that the adsorptive media did not affect the amount of fluoride in the water after treatment.

DO levels ranged from 3.7 to 7.2 mg/L; ORP readings ranged from 168 to 230 mV across all sampling locations. The water pumped from the 800-ft-deep bedrocks appear to be fairly oxidizing.

4.5.2 Backwash Water Sampling. Backwash was performed using the treated water from the 2,000-gal hydropneumatic pressure tank that contained, at the time, no more than 0.3 µg/L of arsenic. The backwash water contained a much higher arsenic level (i.e., 30.2 µg/L from the lead vessel and 3.6 µg/L from the lag vessel), indicating that desorption was occurring. More arsenic was leached from the lead than the lag vessel, apparently caused by the higher arsenic loading in the lead vessel. The arsenic desorption might be due to the slightly higher pH (i.e., 7.5) of the treated water following aeration for radon removal (Table 4-1), although the pH of the backwash water, ranging from 7.1 to 7.2, was similar to that of the treated water (Table 4-6). Turbidity readings from Vessel A were higher than those from Vessel B, most likely because the lead tank had removed the majority of particulates from raw water. The analytical results from the backwash water samples collected are summarized in Table 4-7.

Note that the backwash water sampling procedure will be modified during the next six months of system operation to include the collection of composite samples for total As, Fe, and Mn as well as total suspended solids (TSS). This modified procedure involves diverting a portion of backwash water from the backwash discharge line to a 32-gal plastic container over the duration of the backwash for each vessel and collecting a composite sample from the container after the content had been well mixed. The composite samples also will be filtered using 0.45-µm filters and analyzed for soluble As, Fe, and Mn.

Table 4-7. Backwash Water Sampling Results

	Vessel A (Lead Tank)						**Vessel B (Lag Tank)**					
	pH	**Turbidity**	**TDS**	**As[(a)]**	**Fe[(a)]**	**Mn[(a)]**	**pH**	**Turbidity**	**TDS**	**As[(a)]**	**Fe[(a)]**	**Mn[(a)]**
Date	**S.U.**	**NTU**	**mg/L**	**µg/L**	**µg/L**	**µg/L**	**S.U.**	**NTU**	**mg/L**	**µg/L**	**µg/L**	**µg/L**
08/22/05	7.1	58	90	30.2	<25	1.3	7.2	19	80	3.6	<25	0.3

4.5.3 Distribution System Water Sampling. Prior to the installation/operation of the treatment system, baseline distribution system water samples were collected at three residences on January 10, January 25, February 7, and March 21, 2005. Following the installation of the treatment system, distribution water sampling continued on a monthly basis at the same three residences, with samples collected on May 16, June 13, July 11, August 8, September 6, and October 5, 2005. The results of the distribution system sampling are summarized on Table 4-8.

The most noticeable change in the distribution samples since the system began operation was a decrease in arsenic concentration. Baseline arsenic concentrations ranged from 23.7 to 34.2 µg/L and averaged 30 µg/L for all three locations. After the performance evaluation began, arsenic concentrations were reduced to <2.5 µg/L (averaging 1.1 µg/L), which were similiar to the arsenic conentrations in the system effluent.

Table 4-8. Distribution System Sampling Results

Sampling Event		Treated Water		DS1								DS2								DS3							
		As	pH	Stagnation Time	pH	Alkalinity	As	Fe	Mn	Pb	Cu	Stagnation Time	pH	Alkalinity	As	Fe	Mn	Pb	Cu	Stagnation Time	pH	Alkalinity	As	Fe	Mn	Pb	Cu
No.	Date	µg/L	S.U.	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	01/10/05	NA	NA	8.7	8.2	49	23.7	<25	2.1	0.6	67.7	11.0	8.0	45	24.1	<25	1.9	1.1	82.2	7.8	7.9	48	24.7	<25	1.8	0.4	46.6
BL2	01/25/05	NA	NA	8.0	6.9	49	32.4	<25	2.9	0.7	88.1	9.5	7.2	47	33.2	<25	2.3	0.4	47.2	7.3	7.2	48	34.2	<25	2.5	0.3	38.5
BL3	02/07/05	NA	NA	8.6	7.6	51	31.5	<25	2.7	0.7	84.3	9.0	7.5	52	31.3	<25	2.3	0.6	53.1	6.8	7.5	51	31.6	<25	2.3	0.4	37.8
BL4	03/21/05	NA	NA	8.2	7.5	45	31.4	<25	3.3	0.6	89.0	9.0	7.4	45	31.6	<25	3.0	0.4	89.4	8.3	7.4	47	32.0	<25	3.1	0.4	51.4
1	05/16/05	0.2	7.4	8.7	7.8	55	2.5	<25	1.5	1.3	90.9	9.5	7.7	51	2.5	<25	1.3	2.0	132	8.0	7.8	50	1.7	<25	1.3	0.5	68.9
2	06/13/05	0.2	7.3	8.8	6.6	58	2.3	<25	1.3	1.6	92.5	10.0	6.9	57	2.0	<25	1.3	2.0	113	7.0	7.0	52	1.5	<25	1.5	1.0	66.8
3	07/11/05	0.2	7.4	8.6	6.7	50	1.6	<25	1.1	1.4	92.2	10.0	6.8	48	1.1	<25	0.8	0.7	111	8.5	7.1	48	0.7	<25	0.8	0.7	63.9
4	08/08/05	0.4	7.4	8.6	7.4	47	1.2	<25	1.0	1.3	85.1	8.0	7.3	47	0.9	<25	0.7	0.7	103	7.3	7.3	46	0.6	<25	0.7	0.8	80.8
5	09/06/05	1.7	7.5	8.5	7.0	50	1.1	<25	0.8	0.4	30.8	9.5	7.2	50	0.6	<25	0.4	0.2	16.8	7.3	7.3	51	0.5	<25	0.5	0.2	18.4
6	10/05/05	0.5	7.2	8.3	7.4	50	1.2	<25	0.8	1.3	95.6	10.0	7.4	46	0.9	<25	0.3	1.5	82.7	NA	7.4	50	0.8	<25	0.5	1.1	121

Lead action level = 15 µg/L; copper action level = 1.3 mg/L
The unit for analytical parameters is µg/L except for alkalinity (mg/L as CaCO3).
BL = Baseline Sampling; NA = Not Available.

Lead concentrations ranged from 0.2 to 2.0 µg/L, with none of the samples exceeding the action level of 15 µg/L. Copper concentrations ranged from 16.8 to 132 µg/L, with no samples exceeding the 1,300 µg/L action level. The APU-GOFF-LL system did not seem to affect the Pb or Cu concentrations in the distribution system.

Measured pH ranged from 6.6 to 8.2 and averaged 7.3. Alkalinity levels ranged from 45 to 58 mg/L (as $CaCO_3$). Iron was not detected in any of the samples; manganese concentrations ranged from 0.3 to 3.3 µg/L. The arsenic treatment system did not seem to affect these water quality parameters in the distribution system.

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 Goffstown treatment system was $34,210 (see Table 4-9). The equipment cost was $22,431 (or 66% of the total capital investment), which included $17,171 for the skid-mounted APU-GOFF-LL unit, $3,000 for the AD-33 media ($300/ft^3 or $10.68/lb to fill two vessels), $1,000 for shipping, and $1,260 for labor.

The engineering cost included the cost for preparation of a process flow diagram of the treatment system, mechanical drawings of the treatment equipment, and a schematic of the building footprint and equipment layout to be used as part of the permit application submittal (see Section 4.3.1). The engineering cost was $4,860, or 14% 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 was performed by AdEdge and its local contractor, Thursty Water Systems. The installation cost was $6,910, or 20% of the total capital investment.

The total capital cost of $34,210 was normalized to the system's rated capacity of 10 gpm (14,400 gpd), which resulted in $3,421/gpm of design capacity ($2.38/gpd). The capital cost also was converted to an annualized cost of $3,229/year 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 10 gpm to produce 5,256,000 gal of water per year, the unit capital cost would be $0.61/1,000 gal. Because the system operated an average of 5 hr/day at 13 gpm (see Table 4-4), producing 807,000 gal of water during the six-month period, the unit capital cost increased to $2.00/1,000 gal at this reduced rate of use.

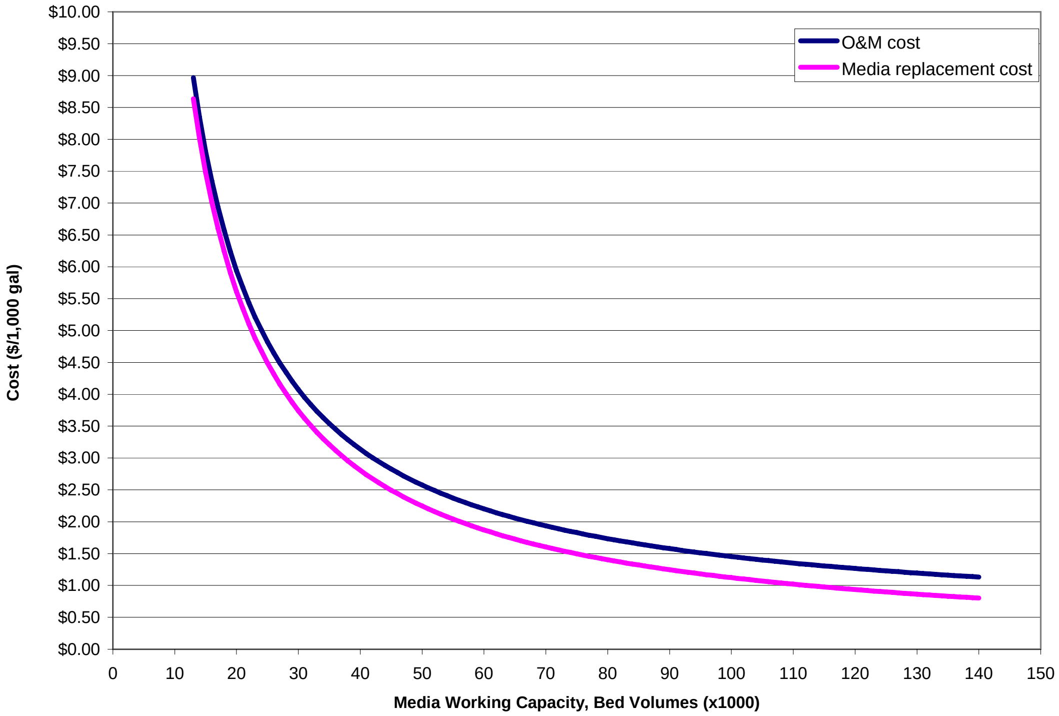
4.6.2 Operation and Maintenance Cost. The O&M cost includes the cost for such items as media replacement and disposal, electricity consumption, and labor (Table 4-10). Although not incurred during the first six months of system operation, the media replacement cost would represent the majority of the O&M cost and was estimated to be $4,199 to change out the lead vessel. This media change-out cost would include the cost for media, freight, labor, travel, spent media analysis, and media disposal fee. This cost was used to estimate the media replacement cost per 1,000 gal of water treated as a function of the projected lead vessel media run length at the 10 µg/L arsenic breakthrough from the lag vessel (Figure 4-14).

Table 4-9. Capital Investment Cost for the APU-GOFF-LL System

Description	Quantity	Cost	% of Capital Investment
Equipment Cost			
APU Skid-Mounted System (Unit)	1	$17,171	–
AD-33 Media (ft^3)	10	$3,000	–
Shipping	–	$1,000	–
Vendor Labor	–	$1,260	–
Equipment Total	–	**$22,431**	**66%**
Engineering Cost			
Vendor Labor	–	$4,860	–
Engineering Total	–	**$4,860**	**14%**
Installation Cost			
Material	–	$2,520	–
Subcontractor	–	$1,950	–
Vendor Labor	–	$1,440	–
Vendor Travel	–	$1,000	–
Installation Total	–	**$6,910**	**20%**
Total Capital Investment	–	**$34,210**	**100%**

Table 4-10. Operation and Maintenance Cost for the APU-GOFF-LL System

Cost Category	Value	Assumptions
Volume processed (kgal)	807	Through October 22, 2005
Media Replacement and Disposal Cost		
Media replacement ($)	1,500	Vendor quote; \$300/ft^3 for 5 ft^3 in lead vessel
Underbedding ($)	154	Vendor quote
Freight ($)	250	Vendor quote
Subcontractor labor ($)	1,050	Vendor quote
Vendor Labor ($)	800	Vendor quote
Media disposal fee ($)	200	Vendor quote
Spent Media Analysis ($)	245	Vendor quote for one TCLP test
Subtotal	4,199	Vendor quote plus spent media analysis
Media replacement and disposal ($/1,000 gal)	See Figure 4-14	Based upon lead vessel media run length at 10-µg/L arsenic breakthrough from lag vessel
Electricity Cost		
Electricity ($/1,000 gal)	$0.001	Electrical costs assumed negligible
Labor Cost		
Average weekly labor (hr)	0.5	30 minutes/per week
Labor ($/1,000 gal)	$0.33	Labor rate = $21/hr
Total O&M Cost/1,000 gal	See Figure 4-14	Based upon lead vessel media run length at 10-µg/L arsenic breakthrough from lag vessel



Note: One bed volume equals 5 ft^3 (37.4 gal) in lead vessel

Figure 4-14. Media Replacement and Operation and Maintenance Cost

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 APU-GOFF-LL system was assumed to be negligible.

Under normal operating conditions, routine labor activities to operate and maintain the system consumed only 30 min per week, as noted in Section 4.4.6. Therefore, the estimated labor cost was $0.31/1,000 gal of water treated.

5.0 REFERENCES

Battelle. 2004. *Revised 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. EPA NRMRL. September 17.

Battelle. 2005. *Final System Performance Evaluation Study Plan: U.S. EPA Demonstration of Arsenic Removal Technology at Goffstown, New Hampshire*. Prepared under Contract No. 68-C-00-185, Task Order No. 0029 for U.S. EPA NRMRL. March 24.

Chen, A.S.C., L. Wang, J. Oxenham, and W. 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. EPA NRMRL, 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* (March): 103-113.

EPA, see United States Environmental Protection Agency.

United States Environmental Protection Agency. 2001. National Primary Drinking Water Regulations: Arsenic and Clarifications to Compliance and New Source Contaminants Monitoring. *Fed. Register*, 66:14:6975. January 22.

United States Environmental Protection Agency. 2002. *Lead and Copper Monitoring and Reporting Guidance for Public Water Systems*. Prepared by U.S. EPA's Office of Water. EPA/816/R-02/009. February.

United States Environmental Protection Agency. 2003. Minor Clarification of the National Primary Drinking Water Regulation for Arsenic. *Federal Register,* 40 CFR Part 141. March 25.

Wang, L., W. Condit, and A. Chen. 2004. *Technology Selection and System Design: U.S. EPA Arsenic Removal Technology Demonstration Program Round 1*. EPA/600/R-05/001. U.S. EPA NRMRL, Cincinnati, OH.

APPENDIX A

OPERATIONAL DATA

Table A-1. EPA Arsenic Demonstration Project at Goffstown, NH - Daily System Operation Log Sheet (Page 1 of 3)

Week No.	Day of Week	Date & Time	Electric Meter	Hour Meter(a)	Actual Run Time	Vessel A Flow Meter							Vessel B Flow Meter			Pressure		ΔP	ΔP	
			KWHR	hr	hr	Flowrate gpm	Totalizer gal	Cum. Bed Volume	Usage gal	Calc. Run Time(b) hr	Average Flowrate gpm	Cum. Run Time hr	Flowrate gpm	Totalizer gal	Cum. Bed Volume	Inlet psig	Outlet psig	Inlet - Outlet psi	Vessel A psi	Vessel B(c) psi
0	Fri	04/15/05 15:40	1860	NA	NA	14.5	729	19	729	1	15	1	14.5	781	21	29	12	17	3	NA
	Sat	04/16/05 07:30	NA	NA	NA	14.7	2400	64	1671	2	15	3	14.3	2443	65	29	12	17	3	NA
	Sun	04/17/05 09:30	1865	NA	NA	12.9	8636	231	6236	8	13	11	13.1	8800	235	28.5	10.5	18	3	NA
1	Mon	04/18/05 11:05	1868	NA	NA	14	14409	385	5773	7	14	18	14.3	14673	392	28	10.5	17.5	4	NA
	Tue	04/19/05 08:00	1870	NA	NA	13.4	17852	477	3443	4	13	22	13.5	18160	486	28	10.5	17.5	5	NA
	Wed	04/20/05 11:30	1873	NA	NA	12.7	22950	614	5098	7	13	29	13.2	23344	624	27	10	17	5	NA
	Thu	04/21/05 08:45	1885	NA	NA	12.2	26486	708	3536	5	12	33	12.5	26948	721	26.5	10.2	16.3	4	NA
	Fri	04/22/05 10:15	1887	NA	NA	13.7	30662	820	4176	5	14	39	14.1	31205	834	28	10.5	17.5	5	NA
	Sat	04/23/05 08:30	1890	NA	NA	14.4	34429	921	3767	4	14	43	14.7	35053	937	29	12	17	5	NA
	Sun	04/24/05 14:55	1893	NA	NA	12.9	41213	1102	6784	9	13	52	13.2	41996	1123	28	10.5	17.5	4	NA
2	Mon	04/25/05 11:30	1896	NA	NA	12.1	45208	1209	3995	6	12	57	12.4	46089	1232	26	10	16	4	NA
	Tue	04/26/05 08:30	1899	NA	NA	12.9	48661	1301	3453	4	13	62	13.3	49619	1327	28	10.2	17.8	5	NA
	Wed	04/27/05 11:00	1901	NA	NA	14.2	53304	1425	4643	5	14	67	14.6	54372	1454	30	10.5	19.5	6	NA
	Thu	04/28/05 10:00	1903	NA	NA	12.6	56709	1516	3405	5	13	72	12.9	57855	1547	27.5	10.2	17.3	5	NA
	Fri	04/29/05 11:30	1905	NA	NA	13.5	60806	1626	4097	5	14	77	13.8	62045	1659	28	10.2	17.8	5.5	NA
	Sat	04/30/05 09:30	1907	NA	NA	14	63839	1707	3033	4	14	80	14.4	65152	1742	29	10.5	18.5	5.5	NA
	Sun	05/01/05 10:00	1909	NA	NA	13.8	67553	1806	3714	4	14	85	14.3	68949	1844	29	10.1	18.9	6	NA
3	Mon	05/02/05 11:15	1913	NA	NA	13.6	73158	1956	5605	7	14	92	13.9	74701	1997	28	10	18	5.5	NA
	Tue	05/03/05 08:45	1915	NA	NA	14.2	76389	2042	3231	4	14	95	14.5	78013	2086	30	11	19	6	NA
	Wed	05/04/05 08:00	1916	NA	NA	13.2	79933	2137	3544	4	13	100	13.6	81647	2183	28	10.2	17.8	5.5	NA
	Thu	05/05/05 09:05	1919	NA	NA	14.1	83394	2230	3461	4	14	104	14.6	85185	2278	29.5	12	17.5	5.8	NA
	Fri	05/06/05 12:45	1921	NA	NA	14.2	87494	2339	4100	5	14	109	14.6	89369	2390	30	11	19	5.9	NA
	Sat	05/07/05 10:00	1923	NA	NA	13.1	90585	2422	3091	4	13	113	13.4	92546	2474	28	10.5	17.5	5.8	NA
	Sun	05/08/05 10:00	1925	NA	NA	12	95033	2541	4448	6	12	119	12.3	97101	2596	26	10	16	4.8	NA
4	Mon	05/09/05 14:30	1929	NA	NA	13	101056	2702	6023	8	13	127	13.3	103288	2762	28	10.2	17.8	5	NA
	Tue	05/10/05 08:00	1931	NA	NA	13.9	103347	2763	2291	3	14	129	14.1	105633	2824	29	11	18	6	NA
	Wed	05/11/05 11:00	1933	NA	NA	13.5	108162	2892	4815	6	14	135	13.8	110580	2957	28	10.2	17.8	5.9	NA
	Thu	05/12/05 10:00	1935	NA	NA	12.5	112010	2995	3848	5	13	140	12.9	114537	3062	27	10	17	5.9	NA
	Fri	05/13/05 13:45	1938	NA	NA	14.1	116385	3112	4375	5	14	146	14.5	119024	3182	29	10.5	18.5	5.5	NA
	Sat	05/14/05 09:30	1940	NA	NA	11.8	119747	3202	3362	5	12	150	12.2	122474	3275	26	10	16	4	NA
	Sun	05/15/05 10:30	1943	NA	NA	12.2	124653	3333	4906	7	12	157	12.5	127522	3410	26	10.2	15.8	4.9	NA
5	Mon	05/16/05 09:00	1946	NA	NA	11.6	129439	3461	4786	7	12	164	12.1	132442	3541	26	10	16	4	NA
	Tue	05/17/05 14:00	1949	NA	NA	13.1	134866	3606	5427	7	13	171	13.3	138019	3690	28	10	18	5.5	NA
	Wed	05/18/05 12:00	1951	NA	NA	14	138653	3707	3787	5	14	175	14.6	141910	3794	29	10.5	18.5	5.9	NA
	Thu	05/19/05 08:00	1953	NA	NA	12	142048	3798	3395	5	12	180	12.5	145393	3888	27	10.5	16.5	4	NA
	Fri	05/20/05 15:00	1957	NA	NA	14.4	147816	3952	5768	7	14	187	14.6	151816	4059	29.5	10.5	19	5.5	NA
	Sat	05/21/05 11:00	1959	NA	NA	12.7	151782	4058	3966	5	13	192	13.1	155403	4155	27	10	17	5.2	NA
6	Tue	05/24/05 11:00	1967	NA	NA	14.2	165420	4423	13638	16	14	208	14.6	169430	4530	30	11	19	6	NA
	Thu	05/26/05 11:00	1972	NA	NA	13.2	174087	4655	8667	11	13	219	13.6	178334	4768	28	10.5	17.5	5.5	NA
	Sat	05/28/05 08:30	1978	NA	NA	12.8	181578	4855	7491	10	13	229	13.1	186037	4974	27.5	10	17.5	5	NA
7	Tue	05/31/05 10:45	1986	NA	NA	12.7	194778	5208	13200	17	13	246	13.2	199630	5338	27	10	17	4	NA
	Thu	06/02/05 08:00	1993	NA	NA	13.4	201319	5383	6541	8	13	254	14.2	206421	5519	29	10.5	18.5	5.5	NA
	Sat	06/04/05 08:30	1999	NA	NA	12.9	208865	5585	7546	10	13	264	13.3	214270	5729	27	10	17	3	NA
8	Tue	06/07/05 08:00	2004	NA	NA	12.9	222922	5960	14057	18	13	282	13.2	228822	6118	27	10	17	4	4
	Thu	06/09/05 08:30	2009	17.1	17.1	13.1	232467	6216	9545	12	13	294	13.3	238609	6380	27	10	17	5	4.5
	Sat	06/11/05 08:30	2018	27.7	10.6	11.3	240924	6442	8457	-	13	305	11.6	247479	6617	25	10	15	3	3.5

Table A-1. EPA Arsenic Demonstration Project at Goffstown, NH - Daily System Operation Log Sheet (Page 2 of 3)

						Vessel A Flow Meter							Vessel B Flow Meter			Pressure		ΔP	ΔP	
Week No.	Day of Week	Date & Time	Electric Meter	Hour Meter[(a)]	Actual Run Time[(b)]	Flowrate	Totalizer	Cum. Bed Volume	Usage	Calc. Run Time	Average Flowrate	Cum. Run Time	Flowrate	Totalizer	Cum. Bed Volume	Inlet	Outlet	Inlet - Outlet	Vessel A	Vessel B[(c)]
			KWHR	hr	hr	gpm	gal		gal	hr	gpm	hr	gpm	gal		psig	psig	psi	psi	psi
9	Mon	06/13/05 11:30	2028	41.6	13.9	14.2	251737	6731	10813	-	13	319	14.3	258394	6909	28	10	18	5.5	5
	Wed	06/15/05 09:00	NA	51.1	9.5	12.5	259252	6932	7515	-	13	328	13.2	266104	7115	27.5	10	17.5	5	4
	Fri	06/17/05 12:00	NA	61.2	10.1	14	267354	7149	8102	-	13	338	14.3	274389	7337	28	10	18	5	5
	Sun	06/19/05 15:30	NA	72.0	10.8	13	276090	7382	8736	-	13	349	13.3	283328	7576	28	10	18	5	4.5
10	Tue	06/21/05 14:00	NA	82.0	10.0	14.1	284086	7596	7996	-	13	359	14.6	291510	7794	29	10.5	18.5	5.5	5
	Thu	06/23/05 08:30	NA	92.2	10.2	10.6	291792	7802	7706	-	13	369	10.8	299426	8006	25	10	15	3	3.2
	Sat	06/25/05 09:30	NA	102.8	10.6	11.9	300045	8023	8253	-	13	380	12.2	307887	8232	26	10	16	4	3.5
11	Mon	06/27/05 08:00	NA	115.7	12.9	11.9	309679	8280	9634	-	12	393	12.4	317810	8498	26	10	16	5	4
	Wed	06/29/05 09:00	NA	128.5	12.8	13.2	319412	8540	9733	-	13	406	13.5	327822	8765	28	10	18	4	4.5
	Sat	07/02/05 09:00	NA	145.8	17.3	11.2	333008	8904	13596	-	13	423	11.6	341786	9139	25	10	15	3	3.5
12	Tue	07/05/05 14:30	NA	162.7	16.9	13.1	346365	9261	13357	-	13	440	13.4	355498	9505	28	10	18	5	4.5
	Thu	07/07/05 09:30	NA	170.8	8.1	14.2	352860	9435	6495	-	13	448	14.5	362168	9684	29	10.5	18.5	5	5
	Sat	07/09/05 09:30	NA	180.1	9.3	13.3	360369	9636	7509	-	13	457	13.7	369876	9890	28	10	18	5	3.5
13	Mon	07/11/05 09:00	NA	191.2	11.1	10.5	369084	9869	8715	-	13	468	10.8	378857	10130	24	9	15	3	3.5
	Wed	07/13/05 14:00	NA	205.6	14.4	12.8	379796	10155	10712	-	12	483	13.2	389916	10426	28	10	18	5	4.5
	Sat	07/16/05 14:30	NA	220.7	15.1	12.5	391514	10468	11718	-	13	498	12.9	402013	10749	27	10	17	4.5	4
14	Tue	07/19/05 13:00	NA	239.2	18.5	13.6	405781	10850	14267	-	13	516	14.3	416782	11144	29	10	19	5	5
	Fri	07/22/05 12:00	NA	256.5	17.3	12.6	418948	11202	13167	-	13	534	13	430405	11508	27	10	17	5.5	4.5
	Sat	07/23/05 10:30	NA	260.8	4.3	12.5	422402	11294	3454	-	13	538	12.8	433976	11604	27	10	17	5	4
15	Mon	07/25/05 08:00	NA	273.5	12.7	12	431780	11545	9378	-	12	551	12.7	443686	11863	26.5	10	16.5	5	3.5
	Wed	07/27/05 12:00	NA	287.5	14.0	12	442514	11832	10734	-	13	565	12.7	454794	12160	27	10	17	5	4.5
	Sat	07/30/05 09:00	NA	302.6	15.1	12	454274	12146	11760	-	13	580	12.4	466970	12486	26	10	16	5	4
16	Tue	08/02/05 13:30	NA	321.1	18.5	13.3	468418	12525	14144	-	13	598	13.5	468418	12525	28	10	18	5.5	5
	Thu	08/04/05 10:00	NA	330.5	9.4	13.8	475728	12720	7310	-	13	608	14.3	475728	12720	28	10	18	4.5	5
	Sat	08/06/05 08:30	NA	339.0	8.5	13.8	482427	12899	6699	-	13	616	14.4	482427	12899	29	10	19	5.5	5
17	Mon	08/08/05 08:00	NA	352.3	13.3	13	492367	13165	9940	-	12	629	13.4	506476	13542	28	10	18	5.5	5
	Wed	08/10/05 09:00	NA	365.1	12.8	10.9	502021	13423	9654	-	13	642	11.4	516496	13810	25	10	15	5	4
	Sat	08/13/05 09:00	NA	381.1	16.0	13.8	514382	13754	12361	-	13	658	14.2	529330	14153	28	10	18	5.5	5
18	Tue	08/16/05 08:30	NA	398.0	16.9	12.9	527347	14100	12965	-	13	675	13.4	542800	14513	28	10	18	5	4.4
	Thu	08/18/05 09:00	NA	407.4	9.4	12.7	534860	14301	7513	-	13	684	13.4	550528	14720	28	10	18	5	4.5
	Sat	08/20/05 08:30	NA	419.3	11.9	12.7	544045	14547	9185	-	13	696	13.3	560103	14976	27	10	17	5	4.5
19	Mon	08/22/05 08:30	NA	434.4	15.1	11.4	554938	14838	10893	-	12	711	11.8	571433	15279	27	10	17	4.5	3.5
	Thu	08/25/05 08:00	NA	454.4	20.0	12.2	569985	15240	15047	-	13	731	12.5	569985	15240	26	10	16	4	4
	Sat	08/27/05 09:30	NA	466.7	12.3	12.5	579564	15496	9579	-	13	744	13	579564	15496	26	10	16	4	4
20	Tue	08/30/05 09:30	NA	484.1	17.4	13.1	592924	15854	13360	-	13	761	13.6	610682	16328	28	10	18	5	4.8
	Thu	08/31/05 08:30	NA	494.2	10.1	11.5	601017	16070	8093	-	13	771	12	619048	16552	25	10	15	3	3.5
	Sat	09/03/05 09:30	NA	504.6	10.4	13.3	609281	16291	8264	-	13	782	13.6	627572	16780	27	10	17	5	4.2
21	Tue	09/06/05 09:00	NA	524.4	19.8	13.1	624840	16707	15559	-	13	801	13.7	642834	17188	27.5	10	17.5	5	4
	Thu	09/08/05 09:30	NA	536.6	12.2	13.7	633600	16941	8760	-	12	814	14	652694	17452	28	10	18	5	4.5
	Sat	09/10/05 09:00	NA	548.2	11.6	13.3	642626	17183	9026	-	13	825	13.5	662004	17701	27	10	17	5	4.3
22	Mon	09/12/05 14:00	NA	566.4	18.2	11.8	655624	17530	12998	-	12	843	12.2	675452	18060	25	10	15	4.2	3.5
	Wed	09/14/05 15:30	NA	576.4	10.0	14.1	663515	17741	7891	-	13	853	14.1	683600	18278	28	10	18	5	6
	Sat	09/17/05 10:00	NA	589.0	12.6	11.8	673593	18011	10078	-	13	866	12.3	694005	18556	25	10	15	4.5	4

Table A-1. EPA Arsenic Demonstration Project at Goffstown, NH - Daily System Operation Log Sheet (Page 3 of 3)

						Vessel A Flow Meter							Vessel B Flow Meter			Pressure		ΔP	ΔP	
Week No.	Day of Week	Date & Time	Electric Meter	Hour Meter(a)	Actual Run Time(b)	Flowrate	Totalizer	Cum. Bed Volume	Usage	Calc. Run Time	Average Flowrate	Cum. Run Time	Flowrate	Totalizer	Cum. Bed Volume	Inlet	Outlet	Inlet - Outlet	Vessel A	Vessel B(c)
			KWHR	hr	hr	gpm	gal		gal	hr	gpm	hr	gpm	gal		psig	psig	psi	psi	psi
23	Tue	09/20/05 09:00	NA	605.8	16.8	13.5	686774	18363	13181	-	13	883	13.8	707606	18920	28	10	18	5	4.5
	Thu	09/22/05 09:30	NA	615.6	9.8	13.7	694629	18573	7855	-	13	893	14	715716	19137	28	10	18	5	4.5
	Sat	09/24/05 08:30	NA	623.9	8.3	14.4	701298	18751	6669	-	13	901	14.7	722600	19321	29	10	19	5	4.7
24	Tue	09/27/05 09:00	NA	639.8	15.9	13.5	713955	19090	12657	-	13	917	14	735641	19670	28	10	18	5	4.7
	Thu	09/29/05 09:30	NA	649.2	9.4	14	721566	19293	7611	-	13	926	14.5	743477	19879	28	10.1	17.9	5	4.9
	Sat	10/01/05 09:15	NA	657.3	8.1	13.1	728269	19472	6703	-	14	934	13.5	750364	20063	27	10	17	4.5	4
25	Tue	10/04/05 09:15	NA	673.4	16.1	13.2	740939	19811	12670	-	13	950	13.7	763411	20412	28	10	18	5	4.2
	Thu	10/06/05 10:15	NA	684.0	10.6	13.5	749348	20036	8409	-	13	961	13.9	772077	20644	28	10	18	3	3.8
	Sat	10/08/05 09:45	NA	692.6	8.6	13.4	756339	20223	6991	-	14	970	13.7	779286	20837	27	10	17	5	4.1
26	Tue	10/11/05 09:30	NA	707.1	14.5	13.8	767896	20532	11557	-	13	984	14.3	791183	21155	28	10.1	17.9	5	5
	Thu	10/13/05 09:40	NA	717.1	10.0	13.4	775977	20748	8081	-	13	994	13.8	799492	21377	28	10	18	4	4.5
	Sun	10/16/05 09:45	NA	729.8	12.7	12.4	786345	21025	10368	-	14	1007	12.8	810170	21662	26	9.5	16.5	3.5	4
27	Mon	10/17/05 09:30	NA	734.7	4.9	14.2	790252	21130	3907	-	13	1012	14.7	814192	21770	28	10	18	5.5	4.5
	Thu	10/20/05 09:30	NA	748.0	13.3	13.1	801173	21422	10921	-	14	1025	13.3	825406	22070	27	10	17	4.5	4.5
	Sat	10/22/05 10:00	NA	755.3	7.3	14	807298	21586	6125	-	14	1032	14.2	831683	22238	28	10.5	17.5	4.5	4.7

Note: BV calculation assumes 5 ft^3 of media per vessel.
NA = data not available
(a) = Hour meter was installed on June 6, 2005.
(b) = Before the hour meter was installed the run time was calculated by dividing the usage by the flowrate.
(c) = Pressure gauge was added on June 6, 2005.

APPENDIX B

ANALYTICAL DATA

Table B-1. Analytical Results from Long-Term Sampling at Goffstown, NH (Page 1 of 3)

Sampling Date		04/15/05[a]			05/02/05[b]			05/16/05[c]			05/31/05[d]			06/15/05[e]		
Sampling Location Parameter	Unit	IN	TA	TB	IN	TA	TB	IN	TA	TB	IN	TA	TB	IN	TA	TB
Bed Volume	BV	-	0.0	0.0	-	2.0	2.0	-	3.5	3.5	-	5.2	5.3	-	6.9	7.1
Alkalinity (as $CaCO_3$)	mg/L	52	54	56	60	60	60	48	56	54	67	63	58	63	57	57
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fluoride	mg/L	0.3	0.4	0.4	0.4	0.5	0.4	0.4	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.5
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sulfate	mg/L	6.4	6.8	7.4	6.3	6.5	6.6	7.0	8.0	8.0	7.0	7.0	7.0	7.0	6.0	6.0
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitrate (as N)	mg/L	0.1	0.1	<0.05	0.1	0.1	0.4	0.1	0.1	0.1	0.1	0.1	0.4	0.1	<0.05	<0.05
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Orthophosphate (as PO_4)	mg/L	0.3	<0.05	<0.05	<0.05	<0.05	<0.05	0.2	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Silica (as SiO2)	mg/L	25.9	19.1	8.9	25.2	25.0	23.7	25.4	25.8	25.4	24.8	25.4	25.3	25.5	26.4	26.6
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Turbidity	NTU	0.3	<0.1	0.2	0.1	<0.1	<0.1	<0.1	0.3	0.1	0.2	0.2	0.2	0.1	0.1	0.1
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH	S.U.	7.1	7.4	7.3	7.1	7.3	7.3	7.1	7.3	7.4	6.9	7.1	7.3	6.9	7.2	7.3
Temperature	°C	13.0	13.1	13.1	13.4	13.1	13.2	12.1	12.7	12.7	12.5	12.4	12.4	13.9	14.1	14.5
DO	mg/L	6.3	7.2	5.8	5.0	5.6	5.0	6.5	6.2	5.9	6.1	5.4	6.4	4.8	4.8	5.4
ORP	mV	215	201	202	212	205	204	212	210	214	213	198	228	219	215	210
Total Hardness (as $CaCO_3$)	mg/L	26.4	32.2	28.8	-	-	-	-	-	-	-	-	-	35.9	37.7	37.1
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca Hardness (as $CaCO_3$)	mg/L	17.3	23.0	24.7	-	-	-	-	-	-	-	-	-	27.2	28.7	25.7
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mg Hardness (as $CaCO_3$)	mg/L	9.1	9.2	4.1	-	-	-	-	-	-	-	-	-	8.7	9.0	11.5
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (total)	µg/L	29.4	0.3	0.2	31.8	0.1	<0.1	32.6	<0.1	0.2	31.3	0.7	<0.1	34.0	1.7	0.2
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (soluble)	µg/L	29.4	0.3	0.2	-	-	-	-	-	-	-	-	-	33.7	1.7	0.2
As (particulate)	µg/L	<0.1	<0.1	<0.1	-	-	-	-	-	-	-	-	-	0.3	<0.1	<0.1
As (III)	µg/L	0.7	0.2	0.2	-	-	-	-	-	-	-	-	-	0.7	0.6	0.6
As (V)	µg/L	28.8	<0.1	<0.1	-	-	-	-	-	-	-	-	-	33.0	1.0	<0.1
Fe (total)	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe (soluble)	µg/L	<25	<25	<25	-	-	-	-	-	-	-	-	-	<25	<25	<25
Mn (total)	µg/L	16.7	1.5	1.0	3.2	0.2	<0.1	0.7	<0.1	<0.1	0.6	0.1	0.1	15.5	0.2	0.2
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mn (soluble)	µg/L	1.4	1.5	1.0	-	-	-	-	-	-	-	-	-	1.1	1.0	0.3

(a) Water quality samples taken on 04/18/05. (b) Water quality measurements taken on 04/29/05. (c) Water quality measurements taken on 05/13/05.

(d) Water quality measurements taken on 05/28/05. (e) Water quality samples taken on 06/13/05. IN = at wellhead; TA = after Vessel A; TB = after Vessel B

Table B-1. Analytical Results from Long-Term Sampling at Goffstown, NH (Page 2 of 3)

Sampling Date		6/27/2005[a]			7/12/2005[b]			7/25/2005[c]			8/8/2005[d]			8/22/2005[e]		
Sampling Location Parameter	**Unit**	**IN**	**TA**	**TB**	**IN**	**TA**	**TB**	**IN**	**TA**	**TB**	**IN**	**TA**	**TB**	**IN**	**TA**	**TB**
Bed Volume	BV	-	8.3	8.5	-	9.9	10.1	-	11.5	11.9	-	13.2	13.5	-	14.8	15.3
Alkalinity (as $CaCO_3$)	mg/L	33 -	41 -	41 -	55 -	55 -	55 -	39 -	40 -	41 -	58 -	41 -	41 -	44 -	45 -	46 -
Fluoride	mg/L	0.3 -	0.3 -	0.3 -	0.4 -	0.3 -	0.3 -	0.3 -	0.3 -	0.3 -	0.5 -	0.3 -	0.2 -	0.3 -	0.3 -	0.3 -
Sulfate	mg/L	5.0 -	5.0 -	6.0 -	6.0 -	6.0 -	6.0 -	5.0 -	5.0 -	6.0 -	6.0 -	5.0 -	5.0 -	5.3 -	5.5 -	5.6 -
Nitrate (as N)	mg/L	4.7 -	1.1 -	5.1 -	0.2 -	0.1 -	0.1 -	0.3 -	0.7 -	0.2 -	0.1 -	0.1 -	0.1 -	0.7 -	0.9 -	0.6 -
Orthophosphate (as PO_4)	mg/L	<0.05 -	<0.05 -	<0.05 -	<0.05 -	<0.05 -	<0.05 -	0.2 -	<0.05 -	<0.05 -	0.3 -	<0.05 -	<0.05 -	0.1 -	<0.05 -	<0.05 -
Silica (as SiO2)	mg/L	25.1 -	25.0 -	24.4 -	25.2 -	25.0 -	25.2 -	24.4 -	23.7 -	23.9 -	25.5 -	25.6 -	24.6 -	25.3 -	24.8 -	24.5 -
Turbidity	NTU	0.2 -	0.2 -	2.7 -	0.2 -	0.2 -	0.3 -	<0.1 -	0.1 -	0.4 -	0.4 -	0.2 -	0.3 -	0.1 -	<0.1 -	0.2 -
pH	S.U.	7.1	7.3	7.4	7.2	7.3	7.4	7.2	7.4	7.5	7.1	7.3	7.4	7.0	7.3	7.4
Temperature	°C	13.9	13.3	13.5	13.3	12.9	13.2	15.2	16.5	16.8	12.9	13.7	14.8	15.9	15.5	15.9
DO	mg/L	5.2	5.1	5.3	4.8	3.7	4.9	5.1	5.4	5.4	5.3	4.5	6.2	6.1	5.5	5.3
ORP	mV	218	217	215	205	221	222	168	183	194	174	189	213	212	207	203
Total Hardness (as $CaCO_3$)	mg/L	- -	- -	- -	- -	- -	- -	- -	- -	- -	23.5 -	23.6 -	23.5 -	- -	- -	- -
Ca Hardness (as $CaCO_3$)	mg/L	- -	- -	- -	- -	- -	- -	- -	- -	- -	15.4 -	15.9 -	15.7 -	- -	- -	- -
Mg Hardness (as $CaCO_3$)	mg/L	- -	- -	- -	- -	- -	- -	- -	- -	- -	8.1 -	7.8 -	7.8 -	- -	- -	- -
As (total)	µg/L	27.2 -	3.4 -	0.1 -	33.0 -	3.9 -	0.2 -	27.8 -	5.7 -	0.2 -	30.6 -	4.7 -	0.4 -	30.3 -	9.2 -	0.3 -
As (soluble)	µg/L	-	-	-	-	-	-	-	-	-	30.7	4.9	0.3	-	-	-
As (particulate)	µg/L	-	-	-	-	-	-	-	-	-	<0.1	<0.1	0.1	-	-	-
As (III)	µg/L	-	-	-	-	-	-	-	-	-	0.6	0.6	0.5	-	-	-
As (V)	µg/L	-	-	-	-	-	-	-	-	-	30.1	4.3	<0.1	-	-	-
Fe (total)	µg/L	<25 -	<25 -	<25 -	<25 -	<25 -	<25 -	<25 -	<25 -	<25 -	<25 -	<25 -	<25 -	<25 -	<25 -	<25 -
Fe (soluble)	µg/L	-	-	-	-	-	-	-	-	-	<25	<25	<25	-	-	-
Mn (total)	µg/L	2.3 -	0.3 -	0.2 -	1.4 -	0.2 -	0.2 -	3.8 -	0.3 -	0.1 -	1.9 -	0.4 -	0.4 -	2.4 -	1.1 -	0.1 -
Mn (soluble)	µg/L	-	-	-	-	-	-	-	-	-	1.2	0.4	0.4	-	-	-

(a) Water quality measurements taken on 06/25/05. (b) Water quality measurements taken on 07/09/05. (c) Water quality measurements taken on 07/23/05.

(d) Water quality measurements were taken on 08/06/05. (e) Water quality measurements taken on 08/20/05.

IN = at wellhead; TA = after Vessel A; TB = after Vessel B

Table B-1. Analytical Results from Long-Term Sampling at Goffstown, NH (Page 3 of 3)

Sampling Date		09/06/05[(a)]			09/20/05[(b)]			10/04/05[(c)]			10/17/05		
Sampling Location Parameter	Unit	IN	TA	TB	IN	TA	TB	IN	TA	TB	IN	TA	TB
Bed Volume	BV	-	16.7	17.2	-	18.4	18.9	-	19.8	20.4	-	21.1	21.8
Alkalinity (as $CaCO_3$)	mg/L	55 -	53 -	50 -	42 43	44 44	44 44	44 -	43 -	44 -	88 -	44 -	41 -
Fluoride	mg/L	0.3 -	0.3 -	0.4 -	0.3 0.3	0.3 0.3	0.3 0.3	0.3 -	0.3 -	0.2 -	0.2 -	0.2 -	0.2 -
Sulfate	mg/L	5.4 -	6.0 -	5.7 -	4.7 4.8	5.0 4.8	5.0 5.0	4.9 -	4.7 -	4.6 -	4.6 -	4.6 -	4.8 -
Nitrate (as N)	mg/L	0.1 -	0.1 -	0.1 -	0.1 0.1	0.1 0.1	0.1 0.2	0.1 -	0.2 -	0.1 -	0.1 -	0.1 -	0.1 -
Orthophosphate (as PO_4)	mg/L	0.3 -	0.2 -	<0.05 -	0.3 0.3	<0.05 0.1	<0.05 <0.05	0.1 -	0.1 -	<0.05 -	0.1 -	0.1 -	<0.05 -
Silica (as SiO2)	mg/L	25.3 -	24.9 -	25.0 -	24.5 24.3	24.4 24.2	23.8 24.2	31.7 -	25.6 -	24.3 -	24.2 -	23.8 -	23.4 -
Turbidity	NTU	0.6 -	0.5 -	0.5 -	0.1 0.1	0.8 0.9	0.4 0.3	0.3 -	0.2 -	0.4 -	0.1 -	0.3 -	0.1 -
pH	S.U.	7.5	7.4	7.5	7.2	7.3	7.4	7.0	7.1	7.2	7.1	7.2	7.2
Temperature	°C	13.9	14.6	14.9	14.6	14.5	15.1	12.0	12.6	13.0	12.1	12.5	12.6
DO	mg/L	6.2	4.9	6.4	6.3	4.7	5.7	6.3	6.2	6.2	6.2	6.3	6.0
ORP	mV	195	196	196	203	212	213	201	215	230	208	198	194
Total Hardness (as $CaCO_3$)	mg/L	- -	- -	- -	- -	- -	- -	- -	- -	- -	21.5 -	23.9 -	26.3 -
Ca Hardness (as $CaCO_3$)	mg/L	- -	- -	- -	- -	- -	- -	- -	- -	- -	14.1 -	16.5 -	18.3 -
Mg Hardness (as $CaCO_3$)	mg/L	- -	- -	- -	- -	- -	- -	- -	- -	- -	7.4 -	7.5 -	8.0 -
As (total)	µg/L	29.2 -	8.4 -	1.7 -	24.1 25.9	8.5 9.5	0.7 0.4	28.8 -	10.3 -	0.5 -	25.0 -	11.3 -	0.5 -
As (soluble)	µg/L	-	-	-	-	-	-	-	-	-	26.0	10.4	0.8
As (particulate)	µg/L	-	-	-	-	-	-	-	-	-	<0.1	0.9	<0.1
As (III)	µg/L	-	-	-	-	-	-	-	-	-	0.6	0.5	0.2
As (V)	µg/L	-	-	-	-	-	-	-	-	-	25.3	9.9	0.5
Fe (total)	µg/L	<25 -	<25 -	72.5 80.4*	<25 <25	<25 <25	<25 <25	<25 -	<25 -	<25 -	<25 -	<25 -	<25 -
Fe (soluble)	µg/L	-	-	-	-	-	-	-	-	-	<25	<25	<25
Mn (total)	µg/L	4.4 -	1.0 -	0.6 -	1.7 4.1	0.4 0.4	<0.1 <0.1	1.1 -	0.4 -	<0.1 -	2.7 -	0.7 -	0.2 -
Mn (soluble)	µg/L	-	-	-	-	-	-	-	-	-	1.1	0.8	0.8

(a) Water quality measurements taken on 09/03/05. (b) Water quality measurements taken on 09/17/05. (c) Water quality measurements taken on 10/01/05.

* = sample was rerun. Second value is rerun results. IN = at wellhead; TA = after Vessel A; TB = after Vessel B