EPA/600/R-11/002
January 2011

Arsenic Removal from Drinking Water by Adsorptive Media
U.S. EPA Demonstration Project at
LEADS Head Start Building in Buckeye Lake, OH
Final Performance Evaluation Report

by

Abraham S.C. Chen[‡]
Jody P. Lipps[§]
Ryan J. Stowe[§]
Brian J. Yates[§]
Vivek Lal[§]
Lili Wang[‡]

[§]Battelle, Columbus, OH 43201-2693
[‡]ALSA Tech, LLC, Columbus, OH 43219-6093

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

for

Thomas J. Sorg
Task Order Manager

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

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

DISCLAIMER

The work reported in this document was funded by the United States Environmental Protection Agency (EPA) under Task Order (TO) 0029 of Contract No. 68-C-00-185 to Battelle. It has been subjected to the Agency's peer and administrative reviews and has been approved for publication as an EPA document. Any opinions expressed in this paper are those of the author(s) and do not, necessarily, reflect the official positions and policies of the EPA. Any mention of products or trade names does not constitute recommendation for use by the EPA.

FOREWORD

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

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

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

Sally Gutierrez, Director
National Risk Management Research Laboratory

ABSTRACT

This report documents the activities performed and the results obtained for the arsenic removal treatment technology demonstration project at Licking Economic Action Development Study (LEADS) Head Start School in Buckeye Lake, Ohio. The objectives of the project were to evaluate: (1) the effectiveness of a Kinetico arsenic removal system using Engelhard/BASF's ARM 200 media in removing arsenic (As) to meet the new arsenic maximum contaminant level (MCL) of 10 µg/L, (2) the reliability of the treatment system, 3) the required system operation and maintenance (O&M) and operator skills, and 4) the capital and O&M cost of the technology. The project also characterized water in the distribution system and residuals produced by the treatment process.

The Kinetico system consisted of two 18-in × 65-in sealed vessels connected in series to treat up to 10 gal/min (gpm) of water. Water supplied from a well was temporarily stored in a 120-gal pressure tank, softened through a water softener, chlorinated with a sodium hypochlorite (NaOCl) solution, and retained in a 120-gal contact tank. Following the contact tank, chlorinated water flowed through the two adsorption vessels, each loaded with 4.5 ft^3 of ARM 200, an iron oxide/iron hydroxide media. At the design flowrate of 10 gpm, the system would yield a hydraulic loading rate of 5.6 gpm/ft^2 and an empty bed contact time (EBCT) of 3.3 min in each vessel. Because of on-demand operation of the system, actual flowrates through the treatment system could not be measured. Based on visual observations during site visits, it was determined that the actual flowrates were much lower than 10 gpm. Therefore, the actual hydraulic loading rates were much lower and the actual EBCTs were much longer than the design values.

The system operated from June 28, 2006, to February 24, 2010, treating approximately 303,200 gal (or 9,000 bed volumes [BV]) of water. Daily use rates averaged 450 gal, compared to 675-gal rate provided by the school. Source water contained 5.5 to 20.5 µg/L of arsenic, existing predominately as soluble As(III), averaging 79% of the soluble arsenic. Ten-µg/L arsenic breakthrough following the two adsorption vessels did not occur during the almost 4 years of operation. The highest arsenic concentration measured after treatment was 1.4 µg/L.

Significantly elevated total trihalomethanes (TTHM) and haloacetic acids (HAA5) were measured in the vessel effluent soon after system startup. Examination of system operating conditions and disinfectant byproduct (DBP) data revealed that the exceedances coincided with elevated chlorine residuals levels at or above 4.4 mg/L (as Cl_2). The results of laboratory column studies suggested that ARM 200 media had the ability to promote TTHM and HAA5 formation, but only with the presence of chlorine and total organic carbon (TOC) in its influent. The increase found in the laboratory was not on the same order as observed onsite. Therefore, the results of the column studies did not totally explain the elevated DBP concentrations observed onsite.

Comparison of distribution system water sampling results before and after system startup showed a significant decrease in arsenic concentration at the two sampling locations during the 12 monthly sampling events. Arsenic concentrations were reduced from an average baseline level of 15.2 µg/L to an average of 1.3 µg/L. In general, arsenic concentrations in the distribution system water were somewhat higher than those measured in the treatment system effluent. Some dissolution and/or resuspension of arsenic might have occurred in the distribution system. Lead and copper levels were well below their respective action levels in the distribution system water both before and after system startup.

The capital investment cost included $10,435 for equipment, $11,000 for site engineering, and $5,820 for installation. Using the system's rated capacity of 10 gpm (or 14,400 gal/day [gpd]), the capital cost was $2,725/gpm (or $1.89/gpd). The annualized capital cost was $2,572/yr based upon a 7% interest rate and

a 20-year return. The unit capital cost was $0.49/1,000 gal assuming the system operated continuously 24 hr/day, 7 days a week at 10 gpm. At the current use rate of approximately 82,500 gal per year, the unit capital cost increased to $31.36/1,000 gal.

The O&M cost included only incremental cost associated with the adsorption system, such as media replacement and disposal (for adsorptive media), electricity consumption, and labor. The unit O&M cost was driven by the cost to replace the spent media as a function of the media run length. Because the media was not replaced during the performance evaluation study, the O&M cost to supply water to the Head Start Building in one year when using ARM 200 media was estimated based on an assumed rebedding cost for the lead vessel.

CONTENTS

DISCLAIMER ii
FOREWORD iii
ABSTRACT iv
APPENDICES vii
FIGURES vii
TABLES viii
ABBREVIATIONS AND ACRONYMS ix
ACKNOWLEDGMENTS xi

1.0 INTRODUCTION 1
1.1 Background 1
1.2 Treatment Technologies for Arsenic Removal 2
1.3 Project Objectives 2

2.0 SUMMARY AND CONCLUSIONS 5

3.0 MATERIALS AND METHODS 6
3.1 General Project Approach 6
3.2 System O&M and Cost Data Collection 7
3.3 Sample Collection Procedures and Schedules 8
3.3.1 Source Water 8
3.3.2 Treatment Plant Water 8
3.3.3 Backwash Wastewater 11
3.3.4 Spent Media 11
3.3.5 Distribution System Water 11
3.3.6 Disinfection Byproducts 11
3.4 Sampling Logistics 16
3.4.1 Preparation of Arsenic Speciation Kits 16
3.4.2 Preparation of Sampling Coolers 16
3.4.3 Sample Shipping and Handling 16
3.5 Analytical Procedures 17

4.0 RESULTS AND DISCUSSION 18
4.1 Facility Description 18
4.1.1 Source Water Quality 19
4.1.2 Distribution System 20
4.2 Treatment Process Description 20
4.3 System Installation 24
4.4 System Operation 25
4.4.1 Operational Parameters 25
4.4.2 Chlorine Addition 26
4.4.3 Media Replacement 26
4.4.4 Residual Management 26
4.4.5 Reliability and Simplicity of Operation 27
4.5 System Performance 28
4.5.1 Treatment Plant Sampling 28
4.5.2 Disinfection Byproducts 37
4.5.3 Backwash Wastewater Sampling 54
4.5.4 Distribution System Water Sampling 55

4.6 System Cost 55
4.6.1 Capital Cost 57
4.6.2 Operation and Maintenance Cost 58

5.0 REFERENCES 60

APPENDICES

APPENDIX A: OPERATIONAL DATA A-1
APPENDIX B: ANALYTICAL RESULTS B-1
APPENDIX C: COLUMN STUDIES ANALYTICAL RESULTS C-1

FIGURES

Figure 3-1. Process Flow Diagram and Sampling Locations 10
Figure 3-2. Column Study Apparatus 14
Figure 3-3. Glass Column Schematic 14
Figure 3-4. Floating Teflon® Lid 15
Figure 4-1. Pre-Existing Treatment System Components at Head Start Building 18
Figure 4-2. Schematic of Arsenic Removal System with Series Configuration 22
Figure 4-3. Adsorptive Media Arsenic Removal System 24
Figure 4-4. Total and Free Chlorine Residuals Measured at Kitchen Sink 27
Figure 4-5. Concentrations of Various Arsenic Species Across Treatment Train 32
Figure 4-6. Total Arsenic Breakthrough Curves 33
Figure 4-7. Total Phosphorus Concentrations Across Treatment Train 34
Figure 4-8. Silica Concentrations Across Treatment Train 35
Figure 4-9. TTHM Concentrations at Kitchen Sink 39
Figure 4-10. HAA5 Concentrations at Kitchen Sink 41
Figure 4-11. Formation of TTHM Across Treatment Train and Distribution System 42
Figure 4-12. Formation of HAA5 Across Treatment Train and Distribution System 42
Figure 4-13. Effects of Water Temperature on TTHM and HAA5 Concentrations at AC Location 43
Figure 4-14. Correlation of TTHM/HAA5 with Free Chlorine Residuals Measured After Contact Tank 44
Figure 4-15. Correlation of TTHM/HAA5 with Free Chlorine Residuals Measured at Kitchen Sink 44
Figure 4-16. TTHM Formation Potential Test Results (AS Water) 48
Figure 4-17. HAA5 Formation Potential Test Results (AS Water) 48
Figure 4-18. THM Formation Potential Test Results in Chlorinated AS Water 49
Figure 4-19. Formation Potential Test Results of HAAs in Chlorinated AS Water 50
Figure 4-20. Column A ARM 200 Chlorine Demand and pH 52
Figure 4-21. TOC Breakthrough from Column A 53
Figure 4-22. TTHM and HAA5 Concentrations in Feed and Column A Effluent 53
Figure 4-23. Comparison of Arsenic Concentrations in System Effluent and Distribution System 57
Figure 4-24. Total O&M and Media Replacement Cost Curves 59

TABLES

Table 1-1. Summary of Arsenic Removal Demonstration Sites 3
Table 3-1. Pre-Demonstration Study Activities and Completion Dates 6
Table 3-2. Evaluation Objectives and Supporting Data Collection Activities 7
Table 3-3. Sampling Schedules and Analyses 9
Table 3-4. Experimental Parameters for DBP Formation Potential Study 12
Table 3-5. Experimental Matrices for DBP Formation Potential Study 13
Table 4-1. Water Quality Data for New Well 19
Table 4-2. Physical and Chemical Properties of Adsorptive Media 20
Table 4-3. Design Specifications of Arsenic Removal System 23
Table 4-4. System Punch-List/Operational Issues and Corrective Action 25
Table 4-5. Summary of System Operations 25
Table 4-6. Summary of Arsenic, Iron, and Manganese Analytical Results 29
Table 4-7. Summary of Water Quality Parameter Measurements 30
Table 4-8. Silica Removal by Adsorptive Media Observed at EPA Arsenic Removal Demonstration Sites 36
Table 4-9. Summary of TTHM Concentrations in Water Samples 38
Table 4-10. Summary of HAA5 Concentrations in Water Samples 40
Table 4-11. Chlorine Demand Test Results (AS Water) 46
Table 4-12. THM Formation Potential Test Results (AS Water) 46
Table 4-13. HAA Formation Potential Test Results (AS Water) 47
Table 4-14. TTHM and HAA5 Concentrations Measured During Column A (Phases II and III) and Column C Studies 51
Table 4-15. TTHM and HAA5 Concentrations Measured During Column B Studies 51
Table 4-16. Backwash Water Analytical Results 55
Table 4-17. Distribution System Sampling Results 56
Table 4-18. Summary of Capital Investment Cost 58
Table 4-19. Summary of O&M Cost 58

ABBREVIATIONS AND ACRONYMS

Δp	differential pressure
AAL	American Analytical Laboratories
AM	adsorptive media
As	arsenic
ATS	Aquatic Treatment Systems
BDCM	bromodichloromathanes
bgs	below ground surface
BV	bed volume(s)
Ca	calcium
CDBM	chlorodibromomathane
C/F	coagulation/filtration
Cu	copper
DBP	disinfection byproduct
DBA	dibromoacetic acid
DCA	dichloroacetic acid
DI	deionized water
DO	dissolved oxygen
DOM	dissolved organic matter
EBCT	empty bed contact time
EPA	U.S. Environmental Protection Agency
F	fluoride
Fe	iron
GFH	granular ferric hydroxide
gpd	gallons per day
gpm	gallons per minute
HAA5	haloacetic acid
HIX	hybrid ion exchanger
Hp	horsepower
ICP-MS	inductively coupled plasma-mass spectrometry
ID	identification
IX	ion exchange
LCR	(EPA) Lead and Copper Rule
LEADS	Licking Economic Action Development Study
LOU	letter of understanding
MCA	monochloroacetic acid
MBA	monobromoacetic acid
MCL	maximum contaminant level

MDL	method detection limit
MEI	Magnesium Elektron, Inc.
Mg	magnesium
Mn	manganese
N/A	not analyzed
Na	sodium
NaOCl	sodium hypochlorite
ND	non detect
NH_3	ammonia
NO_3	nitrate
NPT	National Pipe Thread
NRMRL	National Risk Management Research Laboratory
NSF	NSF International
O&M	operation and maintenance
OEPA	Ohio Environmental Protection Agency
OIT	Oregon Institute of Technology
ORD	Office of Research and Development
ORP	oxidation-reduction potential
P	phosphorus
Pb	lead
POU	point-of-use
PRD	percent relative difference
psi	pounds per square inch
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RO	reverse osmosis
RPD	relative percent difference
RFQ	request for quotation
SDWA	Safe Drinking Water Act
SiO_2	silica
SO_4	sulfate
SS	stainless steel
STS	Severn Trent Services
TCA	trichloroacetic acid
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids
TOC	total organic carbon
TTHM	total trihalomethane
VOC	volatile organic compound

ACKNOWLEDGMENTS

The authors wish to extend their sincere appreciation to the operator of LEADS Head Start in Buckeye Lake, Ohio. The operator monitored the treatment system and collected samples from the treatment system and distribution system on a regular schedule 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 U. S. 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 (As) 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). To clarify the implementation of the original rule, EPA revised the rule on March 25, 2003, to express the MCL as 0.010 mg/L (10 µg/L) (EPA, 2003). The final rule required 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 for reducing 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 published in the *Federal Register* requested water utilities interested in participating in Round 1 of this EPA-sponsored demonstration program to provide information on their water systems. In June 2002, EPA selected 17 out of 115 sites to host the demonstration studies.

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

In 2003, EPA initiated Round 2 arsenic technology demonstration projects that were partially funded with Congressional add-on funding to the EPA budget. In June 2003, EPA selected 32 potential demonstration sites. The water system at Licking Economic Action Development Study (LEADS) Head Start Building in Buckeye Lake, Ohio, 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 two to eight proposals. In April 2004, EPA convened another technical panel to review the proposals and provide recommendations to EPA; the number of proposals per site ranged from none (for two sites) to a maximum of four. Final selection of the treatment technology at sites receiving 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. Kinetico's ARM 200 arsenic removal system was selected for demonstration at the LEADS Head Start building in September 2004.

As of December 2010, 39 of the 40 systems were operational and the performance evaluation study of all 39 systems was completed.

1.2 Treatment Technologies for Arsenic Removal

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

1.3 Project Objectives

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

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

This report summarizes the performance of the Kinetico system at the LEADS Head Start building in Buckeye Lake, OH, from June 28, 2006, through February 24, 2010. The types of data collected included system operation, water quality (both across the treatment train and in the distribution system), residuals, and capital and O&M cost.

Table 1-1. Summary of Arsenic Removal Demonstration Sites

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

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

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

AM = adsorptive media; C/F = coagulation/filtration; GFH = granular ferric hydroxide; HIX = hybrid ion exchanger; IX = ion exchange; RO = reverse osmosis
ATS = Aquatic Treatment Systems; MEI = Magnesium Elektron, Inc.; STS = Severn Trent Services

(a) Arsenic existing mostly as As(III).
(b) Design flowrate reduced by 50% after system was switched from parallel to serial configuration.
(c) Iron existing mostly as Fe(II).
(d) Withdrew from program in 2007. Selected originally to replace Village of Lyman, NE site, which withdrew from program in June 2006.
(e) Faculties upgraded Springfield, OH system from 150 to 250 gpm, Sandusky, MI system from 210 to 340 gpm, and Arnaudville, LA system from 385 to 770 gpm.
(f) Including nine residential units.
(g) Including eight under-the-sink units.

2.0 SUMMARY AND CONCLUSIONS

Based on the information collected during the almost four years of 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:

- ARM 200 adsorptive media was effective in removing arsenic to below its MCL. After 9,000 bed volumes (BV) of system operation, the arsenic concentration remained below the method detection limit (MDL) of 0.1 µg/L. The run length to 10 µg/L could not be determined in the duration of this study.

- Sodium hypochlorite was effective in converting soluble As(III) to soluble As(V).

Formation of disinfection byproducts (DBPs) during treatment:

- Above MCL levels of total trihalomethane (TTHM) and haloacetic acid (HAA5) were detected soon after system startup.

- Formation of DBPs was believed to have been caused by high levels of chlorine residuals in the AM system. There was evidence to suggest that ARM 200 media had the ability to enhance DBP formation but only with the presence of chlorine and total organic carbon (TOC) in its influent.

Simplicity of required system O&M and operator skill levels:

- Very little attention was needed to operate and maintain the system. The weekly demand on the operator was typically 15 min to visually inspect the system and record operational parameters.

- Operation of the treatment system did not require additional skills beyond those necessary to operate the existing water supply equipment.

Process residuals produced by the technology:

- The system did not need to be backwashed on a regular basis.

Technology Costs:

- Using the system's rated capacity of 10 gal/min (gpm) (or 14,400 gal/day [gpd]), the capital cost was $2,725/gpm (or $1.89/gpd).

- The actual O&M cost to supply water to the Head Start building in one year when using ARM 200 media could not be determined because the media was not exhausted during the almost four year evaluation.

3.0 MATERIALS AND METHODS

3.1 General Project Approach

Table 3-1 summarizes pre-demonstration activities and completion dates. The original plan was to install systems in two separate buildings that shared a well. The main building was the LEADS Head Start building, which was estimated to have a peak flowrate of 9 gpm. The second building was a library, which was estimated to have a peak flowrate of 3 gpm. The plan as set forth in the letter of understanding (LOU), request for quotation (RFQ), and engineering plan was to have two appropriately sized systems designed by Kinetico for each of the buildings. Because of concerns over liability issues between the management of the LEADS Head Start Program and the library, the Head Start management decided to drill a new well on January 25, 2006, and to separate its water distribution from the library. Only one 10-gpm system was placed in the Head Start building.

The performance evaluation study of the 10-gpm system began on June 28, 2006, and ended on February 24, 2010. Table 3-2 summarizes the types of data collected and considered as part of the technology evaluation process. The overall system performance was evaluated based on its ability to consistently remove arsenic to below the MCL of 10 μg/L. This was monitored through the collection of water samples across the treatment train, as described in a revised study plan for the one 10-gpm treatment system (Battelle, 2005). The reliability of the system was evaluated by tracking unscheduled system downtime and frequency and extent of repair and replacement. The plant operator recorded unscheduled downtime and repair information on a Repair and Maintenance Log Sheet.

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

Activity	Date
Introductory Meeting Held	August 18, 2004
Project Planning Meeting Held	October 4, 2004
Final Letter of Understanding Issued[(a)]	November 1, 2004
Request for Quotation Issued to Vendor[(a)]	November 5, 2004
Vendor Quotation Received by Battelle[(a)]	November 15, 2004
Purchase Order Completed and Signed[(a)]	December 22, 2004
Engineering Plan Submitted to OEPA[(a)]	February 24, 2005
Final Study Plan Issued[(a)]	March 3, 2005
Comments Received from OEPA[(a)]	March 17, 2005
Sampling of New Well	January 25, 2006
Revised Engineering Plan Submitted to OEPA[(b)]	April 5, 2006
System Permit Issued by OEPA[(b)]	April 10, 2006
New Well Permit Issued by OEPA	May 17, 2006
Purchase Order Revised and Issued[(b)]	May 23, 2006
System Installation Completed[(b)]	June 2, 2006
System Shakedown Completed[(b)]	June 23, 2006
Performance Evaluation Begun	June 28, 2006

OEPA = Ohio Environmental Protection Agency
(a) For two treatment systems in Head Start and library buildings.
(b) For one treatment system in Head Start building.

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

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

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

The 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 task required tracking the capital cost for equipment, site engineering, and installation, as well as the O&M cost for media replacement and disposal, chemical supplies, electrical power use, and labor.

3.2 System O&M and Cost Data Collection

The operator performed system O&M and data collection following the instructions provided by the vendor and Battelle. On a regular basis, the operator recorded system operational data, such as pressure and totalizer readings on a System Operation Log Sheet and conducted visual inspections to ensure normal system operations. If any problems occurred, the operator contacted the Battelle Study Lead, who then determined if Kinetico should be contacted for troubleshooting. The operator recorded all relevant information, including problems encountered, course of actions taken, materials and supplies used, and associated cost and labor incurred on a Repair and Maintenance Log Sheet. On a monthly basis, the operator measured several water quality parameters onsite, including temperature, pH, dissolved oxygen (DO), oxidation-reduction potential (ORP), and residual chlorine, and recorded the data on an Onsite Water Quality Parameters Log Sheet.

The capital cost for the arsenic removal system consisted of the cost for equipment, site engineering, and system installation. The O&M cost consisted of the cost for media replacement, electricity consumption, and labor. Labor for various activities, such as the routine system O&M, troubleshooting and repairs, and demonstration-related work, were tracked using an Operator Labor Hour Log Sheet. The routine system O&M included activities such as completing field logs, ordering supplies, performing system inspections, and others as recommended by the vendor. The labor for demonstration-related work, including activities

such as performing field measurements, collecting and shipping samples, and communicating with the Battelle Study Lead and the vendor, was recorded, but not used for cost analysis.

3.3 Sample Collection Procedures and Schedules

To evaluate system performance, samples were collected at the wellhead, across the treatment plant, and from the distribution system. Table 3-3 provides sampling schedules and analytes measured during each sampling event. Figure 3-1 presents a flow diagram of the treatment system along with the analytes and schedules at each sampling location. Specific sampling requirements for analytical methods, sample volumes, containers, preservation, and holding times are presented in Table 4-1 of the EPA-endorsed Quality Assurance Project Plan (QAPP) (Battelle, 2004). The procedure for arsenic speciation is described in Appendix A of the QAPP.

3.3.1 Source Water. Source water samples from the well shared by the Head Start and library buildings were collected and speciated during the initial site visit on August 18, 2004. Because a new well was drilled for the Head Start building, samples of the new well were collected and speciated on January 25, 2006. Speciation was performed using arsenic speciation kits (see Section 3.4.1). Before sampling, sample taps were flushed for several minutes; special care was taken to avoid agitation, which could cause unwanted oxidation. The samples were analyzed for the analytes listed in Table 3-3.

3.3.2 Treatment Plant Water. During the first six months of system opertion, the operator collected treatment plant water samples every other week (except for four sampling events that took place once every one, three, or four weeks) at four locations across the treatment train, including at the wellhead (IN), after chlorination (AC), and after adsorption vessels (TA and TB). Due to low water usage, sampling frequency was reduced to monthly after December 19, 2006. In February 2007, a sampling tap was added after the water softener (AS) and water samples were collected at five locations from this point forward. Sampling frequency was further reduced to quarterly from May 1, 2007, through the end of the evaluation period. Two Battelle staff members traveled to the site each quarter to collect quarterly samples.

Because analytical data contained a number of inconsistencies during the first several months of system operation (perhaps due to a large water holding capacity [300 to 400 gal] in the treatment system and a small water use rate [675 gpd]), beginning in May 2007, the following steps were taken to ensure that new well water was flowing through the treatment system and that more representative samples were collected during sampling:

- Sampling to be conducted in the middle of the week to avoid any issues with stagnant water in the treatment system on weekends.
- Before sampling, the treatment system to be flushed with approximately 400 gal of water (considering the combined water holding capacity in all system components, including a pressure tank, a water softener, a contact tank, two adsorption vessels, and associated piping) by turning on a mop sink and a kitchen sink at a combined flowrate of approximately 4 gpm.

Speciation samples were taken during every other sampling event for the first six months of system operation. Beginning on December 19, 2006, speciation samples were collected during each sampling event. Initially, samples taken during the speciation sampling events were analyzed for total and soluble arsenic (including As[III] and As[V]), total and soluble iron, and total and soluble manganese (except for two sampling events on June 28 and August 30, 2006, when other analytes listed under non-speciation events as shown below also were analyzed). Samples taken during the non-speciation events were analyzed for total arsenic, total iron, total manganese, calcium, magnesium, fluoride, nitrate, sulfate,

Table 3-3. Sampling Schedules and Analyses

Sample Type	Sample Locations[a]	No. of Samples	Frequency	Analytes	Collection Date(s)
Source Water	IN	1	Once (after new well installation)	Offsite: As (total and soluble), As(III), As(V), Fe (total and soluble), Mn (total and soluble), Ca, Mg, NH_3, TOC, and alkalinity,	08/18/04[b] 01/25/06[c]
Treatment Plant Water	IN, AS, AC, TA, TB	5[d]	Biweekly to Quarterly[e]	Onsite: pH, temperature, DO, ORP, and/or Cl_2 (total and free) Offsite: As (total and soluble), As(III), As(V), Fe (total and soluble), Mn (total and soluble), Ca, Mg, F, NO_3, NH_3, SO_4, SiO_2, P, TOC, turbidity, alkalinity, TTHM, and/or HAA5	See Appendix B
Backwash Wastewater	Backwash Wastewater Discharge Line	1	Once	pH, TDS, TSS, As(total and soluble), Fe (total and soluble), and Mn (total and soluble)	12/13/06
Distribution Water	Two LCR and one non-LCR sinks	3	Monthly[f]	Total As, Fe, Mn, Cu, and Pb, pH and alkalinity	See Table 4-17

(a) Abbreviations corresponding to sample locations shown in Figure 3-1 (IN = at wellhead, AS = after water softener, AC = after chlorination, and TA and TB = after adsorption vessels A and B).
(b) From well shared by Head Start and library buildings.
(c) From new well installed by Head Start.
(d) AS sampling location was added in February 2007.
(e) Biweekly sampling from June 28, 2006, through December 19, 2006; monthly sampling from January 5, 2007, through May 1, 2007; and quarterly sampling from September 19, 2007, through February 24, 2010.
(f) Four baseline sampling events performed before system startup. After system startup, 12 monthly sampling events conducted between August 23, 2006, and September 12, 2007. The non-LCR sampling location in the library building removed from monthly sampling due to removal of that building from demonstration project.
LCR = lead and copper rule

silica, phosphorus, turbidity, and alkalinity. pH, temperature, DO, and ORP were measured onsite during all sampling events. A number of exceptions occurred during sampling and are summarized as follows:

- Starting from December 19, 2006, with the beginning of monthly sampling, all analytes listed above were analyzed during each sampling event.
- Starting from April 5, 2007, ammonia was analyzed for samples collected during each sampling event.

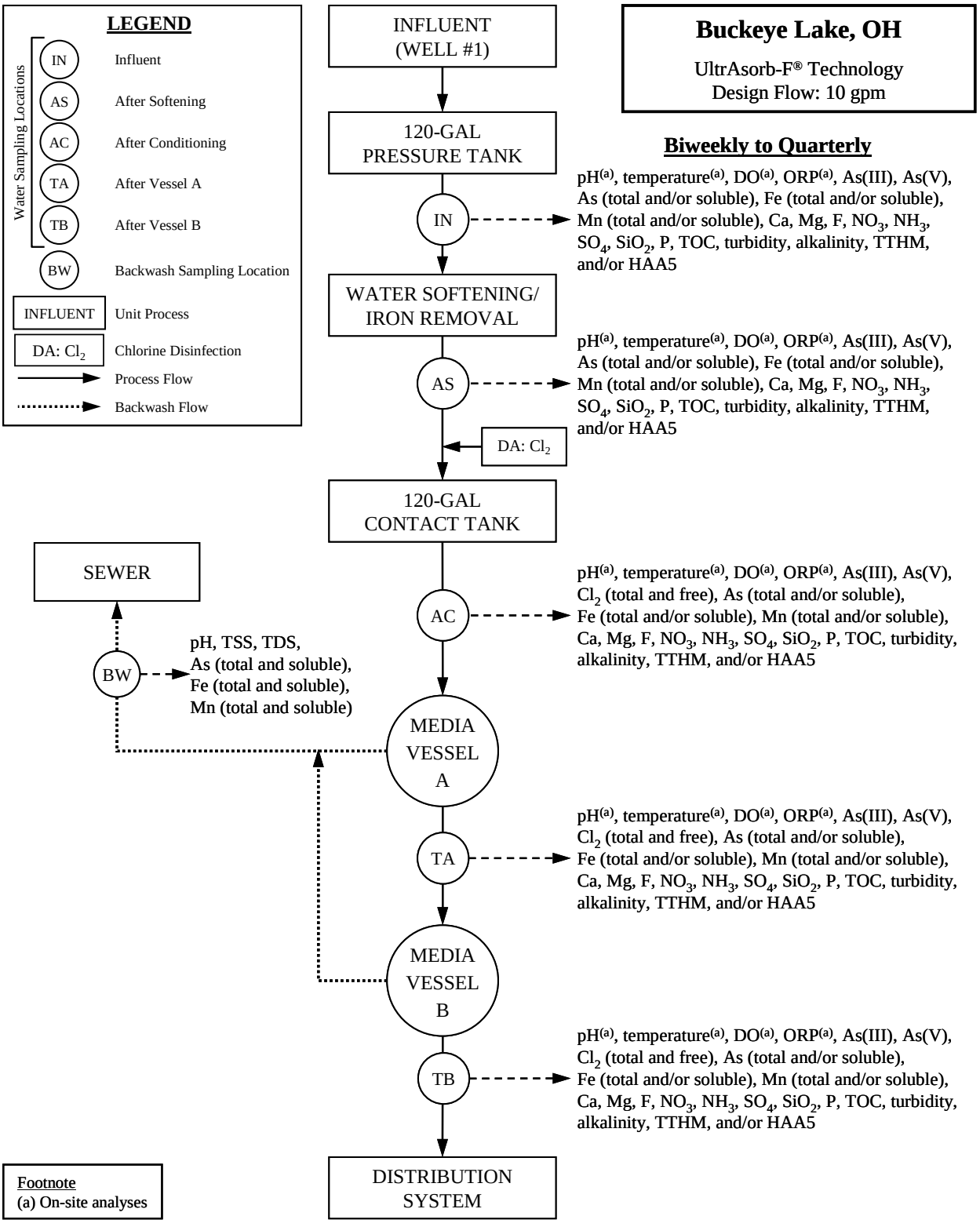


Figure 3-1. Process Flow Diagram and Sampling Locations

- Starting from September 19, 2007, TTHM and TOC were analyzed for samples taken from all sampling locations across the treatment train and at the kitchen sink in the distribution system (DIST). HAA5 also were added to the list of analytes on March 19, 2008.

3.3.3 Backwash Wastewater. The treatment system was backwashed once on December 13, 2006, after approximately six months of system operation. (The operator tried to backwash in September after 3 months of operation; however, because it was not done correctly, the filters were not backwashed). Backwash wastewater samples were collected by directing a portion of backwash wastewater at approximately 1 gpm to a clean, 32-gal container over the duration of backwash for each vessel. This sidestream was produced via plastic tubing connected to a tap on the backwash wastewater discharge line. After the content in the container was thoroughly mixed, composite samples were collected and/or filtered onsite with 0.45-µm disc filters. Analytes for the backwash wastewater samples are listed in Table 3-3.

Because there was no pressure loss across the treatment train, backwashing was not necessary. Therefore, no additional backwashing was done after December 2006.

3.3.4 Spent Media. The media did not reach breakthrough for arsenic during the almost four years of operation. Therefore, no sampling or analysis was performed for spent media.

3.3.5 Distribution System Water. Samples were collected from the distribution system to determine the impact of the arsenic treatment system on the water chemistry in the distribution system, specifically, the arsenic, lead, and copper levels. Prior to system startup from January 2005 to March 2005, four sets of baseline samples were collected from three sampling locations, including two sinks in the Head Start building that were part of the historic sampling network under the Lead and Copper Rule (LCR) and one sink in the library building that was not part of the LCR network. Because the library building was removed from the system performance evaluation study prior to system startup, sampling in the library building was discontinued after completion of baseline sampling. Therefore, only two LCR locations were sampled for distribution system water sampling after system startup. Distribution system water sampling continued on a monthly basis from August 23, 2006, through September 12, 2007.

The distribution system water samples were collected following an instruction sheet developed by Battelle according to the *Lead and Copper Monitoring and Reporting Guidance for Public Water Systems* (EPA, 2002). For the baseline sampling and first four monthly sampling events after system startup, both first draw and flushed samples were collected from the sink faucets. Afterwards, only first draw samples were taken. For the first draw samples, stagnant water was collected from faucets that had not been used for at least six hours. Because the time water was last used before sampling was not known in the Head Start building, staganation time typically could not be determined. The samples were analyzed for the analytes listed in Table 3-3. Arsenic speciation was not performed on the distribution water samples.

3.3.6 Disinfection Byproducts. In September 2007, the operator and Ohio Environmental Protection Agency (OEPA) informed Battelle that TTHM and HAA5 had been exceeding their MCL of 80 µg/L and 60 µg/L, respectively, on several occasions after the treatment system was installed. TTHM concentrations ranged from 37.3 to 220 µg/L from June 2006 through December 2007 and HAA5 concentrations ranged from 39 to 262 µg/L during the same period.

Several steps were taken to define the extent of and determine the cause of the DBP formation, including: (1) sampling across the treatment train for DBPs, (2) conducting a DBP formation potential study on the influent (taken from the AS sampling location) to the adsorption vessels, and (3) conducting a column study. The methods are described below and can be found in greater details in a letter report (Chen and Yates, 2009) and a Test Plan to EPA (Chen et al., 2009b).

Onsite Disinfection Byproducts Sampling. As described in Section 3.3.2, TOC, TTHM, and/or HAA5 were added to the analyte list starting from September 19, 2007, and March 19, 2008, respectively. In addition, historical TTHM, HAA5, and chlorine data were evaluated to assess the cause of the high DBP levels observed in the distribution system.

DBP Formation Potential Study. The formation potential of softened water taken at the AS location was examined following the procedures developed by Summers et al. (1996). Softened water was used for the study because it did not contain soluble iron, which would precipitate during sampling and transit, causing unwanted incidental removal of arsenic and dissolved organic matter (DOM).

Four chlorine doses and four reaction times were tested (Table 3-4). Assuming 0.5-mg/L chlorine demand, 1.5, 2.5, and 4.5 mL of a 1.02 g/L (as Cl_2) NaOCl stock solution was spiked into appropriate amounts of the AS water to achieve target free chlorine residual levels of 1.0, 2.0, and 4.0 mg/L (as Cl_2). The actual chlorine doses were verified by spiking 1.5, 2.5, and 4.5 mL of the stock solution into three 1-L amber bottles filled with deionized (DI) water. Free chlorine concentrations as measured by Hach free chlorine test kits were 1.6, 2.6, and 4.8 mg/L, which were within +4.0 to +6.7% of the target levels. Thus, these spiking amounts were used for the formation potential experiments.

Table 3-4. Experimental Parameters for DBP Formation Potential Study

Parameter/Condition[(a)]	Unit	Values
Chlorine Dosage	mg/L (as Cl_2)	0, 1.6, 2.6, and 4.8
Reaction Time	hr	0, 12, 24, and 48
Temperature	°C	Ambient

(a) Duplicate samples at 48-hr contact time taken for TTHM and HAA5 analyses.

Table 3-5 presents the experimental matrix for the formation potential study. Appropriate aliquots (i.e., 1.5, 2.5, or 4.5 mL) of the NaOCl stock solution were spiked into a series of 1 L, pre-labeled, pre-cleaned amber bottles (i.e., five bottles per chlorine dosage) filled with the AS water. Care was taken to ensure no head-space as the bottles were capped with Teflon®-lined caps. Five additional bottles that did not receive any chlorine were used as controls. The analytical methods, sample volumes, containers, preservation, and holding times are discussed in a letter report to EPA (Chen and Yates, 2009).

Column Study. A series of columns was used to re-create the conditions seen at Buckeye Lake in the laboratory. Columns were loaded separately with:

(1) Virgin ARM 200 media and fed with a softened water, taken at the AS location, chlorinated with approximately 4 mg/L of NaOCl (as Cl_2) – Column A. This column was used to simulate the conditions observed at the Head Start building, examine the TOC breakthrough behavior, and determine if ARM 200 media was indeed responsible for the elevated DBPs observed.

(2) Partially spent ARM 200 media taken from Vessel A and fed with a chlorinated DI water (approximately 4 mg/L of NaOCl [as Cl_2] in DI water) – Column B. This column was used to determine if pre-adsorbed TOC on the media could lead to continued formation of DBPs.

(3) Partially spent ARM 200 media taken from Vessel A and fed with a chlorinated AS water (similar to that described under Column A) – Column C. This column was used to recreate conditions seen at the site.

Table 3-5. Experimental Matrices for DBP Formation Potential Study

Chlorine Dose (mg/L [as Cl_2])	Reaction Time (hr)	Reaction Bottle ID	Measurements				
			Cl_2	pH	Temp	THMs	HAA5
0	0	1	×	×	×		
	12	2	×	×	×		
	24	3	×	×	×		
	48	4	×	×	×	×	×
	48 (Dup)	5	×	×	×		
1.6	0[(a)]	6	×	×	×		
	12	7	×	×	×	×	×
	24	8	×	×	×	×	×
	48	9	×	×	×	×	×
	48 (Dup)	10	×	×	×	×	×
2.6	0[(a)]	11	×	×	×		
	12	12	×	×	×	×	×
	24	13	×	×	×	×	×
	48	14	×	×	×	×	×
	48 (Dup)	15	×	×	×	×	×
4.8	0[(a)]	16	×	×	×		
	12	17	×	×	×	×	×
	24	18	×	×	×	×	×
	48	19	×	×	×	×	×
	48 (Dup)	20	×	×	×	×	×

(a) Time-0 measurements taken about 10 to 20 min after chlorine addition.

The apparatus used for the column studies (see Figure 3-2) consisted of one 5-gal straight-wall polypropylene reservoir (for chlorinated AS water), one 5-gal plastic bucket (for chlorinated DI water), three FMI Q pumps (Model QG50 MB), three 1-in × 12-in glass columns (Ace Glass, Vineland, NJ), and two 5-gal buckets for effluent collection. The glass column assembly was constructed of glass, Teflon®, and stainless steel (SS). Figure 3-3 shows the schematic of a glass column, which had two threaded Teflon® end caps, each fitted with a ¼-in National Pipe Thread (NPT) to ⅛-in compression fitting. Teflon® tubing (⅛ in) and SS Swaglok® fittings were used to make connections to the FMI pumps and waste buckets.

After thoroughly rinsed with DI water to remove fines, a 10-in section of ARM 200 media was packed into a glass column and secured between two glass wool/glass bead end plugs. Before media packing, the bottom end cap was connected to the discharge side of an FMI pump, which was used to fill the column half-way with DI water. Special care was taken to avoid trapping any air bubbles in the Teflon® tubing and, especially, the bottom glass wool/glass bead plug. During media packing, media granules were dispensed slowly into the column using a spatula and the column was tapped to ensure that there were no air bubbles in the media bed. After placing the top end cap, the exit tubing was directed to a 5-gal waste bucket.

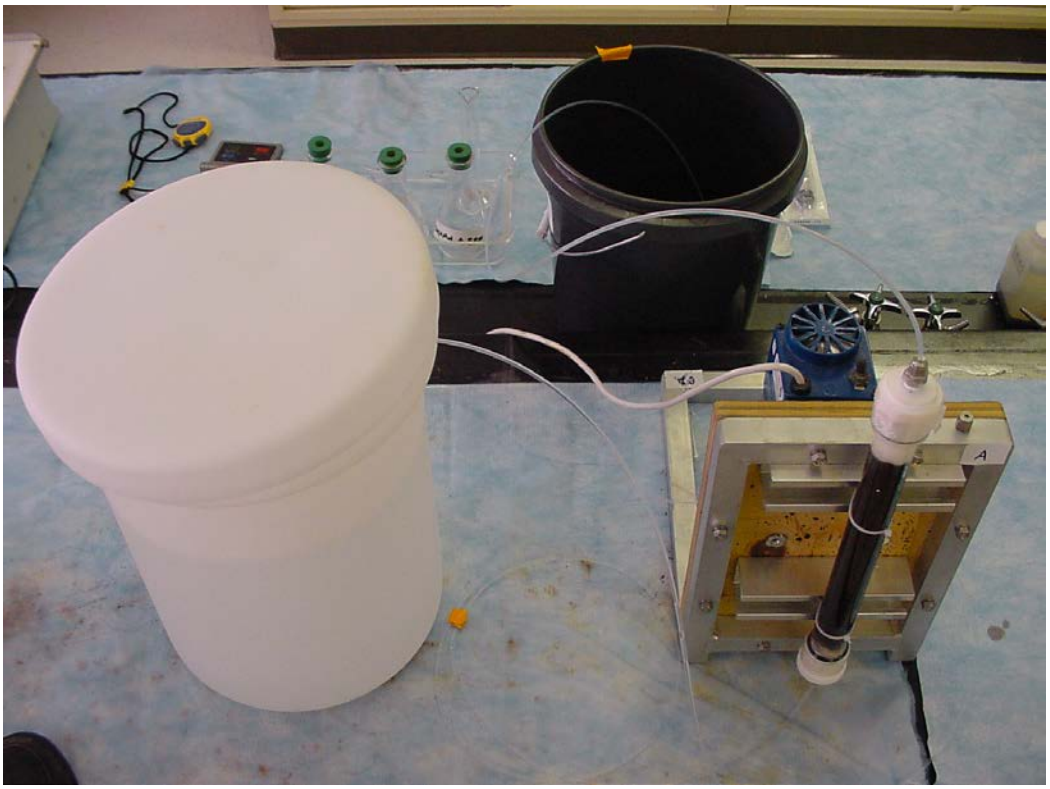


Figure 3-2. Column Study Apparatus

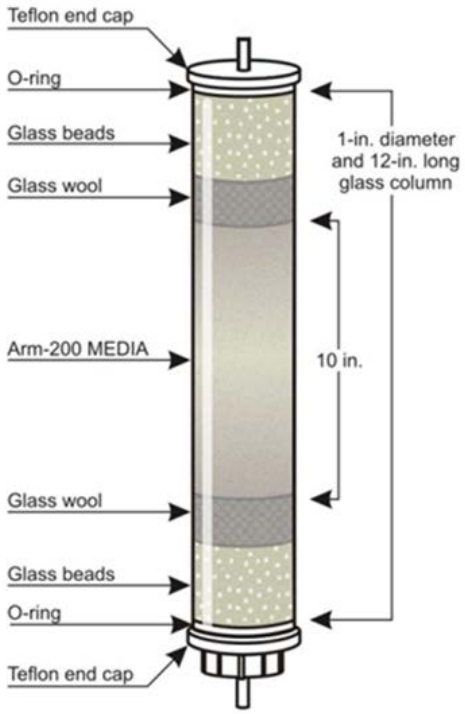


Figure 3-3. Glass Column Schematic

The chlorinated AS water was prepared and stored in 5-gal straight-wall reservoirs. To minimize volitalization of DBPs formed from chlorination, a floating Teflon® lid at 1/64-in thickness (and a diameter just less than that of the reservoir) was placed on the top of the reservoir and allowed to move vertically along with the water level (see Figure 3-4). Efforts were made to ensure that the lid rested flush to the surface of water in the reservoir. A ¼-in opening was drilled in the center of the lid to allow the ⅛-in influent line to pass through. The reservoir was replenished by carefully moving the Teflon® lid aside and slowly pouring in the replenishment solution along the wall of the reservoir. The reservoir and the glass columns were covered in aluminum foil to prevent incident light from entering the apparatus.



Figure 3-4. Floating Teflon® Lid

The columns were operated upflow with a design EBCT of 30 min, which yielded a flowrate of 4.3 mL/min. The upflow configuration was used to avoid accumulation of air bubbles in the coloumn. The target flowrate was attained by adjusting the pump to decrease or increase the flow as necessary.

Before the column studies began, Column A was conditioned with a chlorinated water (approximately 4 mg/L of chlorine [Cl_2] in DI water). Upon chlorine breakthrough at 1.6 mg/L (as Cl_2), samples were collected and analyzed for TOC, TTHM, and HAA5 to determine if the media itself could promote DBP formation in the presence of chlorine. After sample collection, the chlorinated DI water was replaced with a chlorinated AS water. Periodic samples were collected subsequently to evaluate the formation of DBPs due to the presence of TOC and chlroine in the influent water.

Columns B and C were not conditioned as they were loaded with partially spent media from Vessel A, which had already been exposed to chlorine for an extended period prior to media sampling. Samples also were collected periodically from these two columns and analyzed for TOC, TTHM, and HAA5 to evaluate DBP formation.

Effluent samples were collected by placing an effluent tubing into a clean 250-mL Erlenmeyer flask, allowing it to overflow for 10 to 15 min, and quickly filling sample bottles free of headspace with the water in the flask. In this way, potential loss of volatile organic compounds (VOCs) would be diffusion-limited to a small layer near the air/water interface at the top of the flask. One 250-mL flask was sufficient to fill all sample containers required by the studies. Influent samples were collected directly from the plastic bucket by using a 25 mL disposable pipette or from the straight-wall polyethylene (PE) reservoir by inserting the tip of a pipette into the opening in the center of the Teflon® lid (so the lid would not be unnecessarily disturbed). Sampling schedule, sample volumes, containers, preservatives, and hold times for each relevant analyte are discussed in greater detail in the column study test plan (Chen et al., 2009b).

3.4 Sampling Logistics

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

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

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

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

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 or driven to Battelle. Upon receipt, the sample custodian verified that all samples indicated on the chain-of-custody forms were included and intact. Sample IDs were checked against the chain-of-custody forms, and the samples were logged into the laboratory sample receipt log. Discrepancies noted by the sample custodian were addressed with the plant operator by the Battelle Study Lead.

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

3.5 Analytical Procedures

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

Field measurements of pH, temperature, DO, and ORP were conducted by the plant operator or Battelle staff member using a VWR Symphony SP90M5 Handheld Multimeter, which was calibrated for pH and DO prior to use following the procedures provided in the user's manual. The ORP probe also was checked for accuracy by measuring the ORP of a standard solution and comparing it to the expected value. The plant operator collected a water sample in a clean, plastic beaker and placed the Symphony SP90M5 probe in the beaker until a stable value was obtained.

4.0 RESULTS AND DISCUSSION

4.1 Facility Description

The LEADS Head Start building is located at 5312 Walnut Rd. SE, Buckeye Lake, Ohio, approximately 30 miles east of Columbus, Ohio. LEADS Head Start is a preschool with approximately 60 students and staff members. A new well was installed on January 25, 2006, to supply water to the Head Start building. The well was installed to a depth of 125 ft below ground surface (bgs) with a screen set from 121 to 125 ft bgs. Groundwater was delivered at 12 gpm with a ½-horsepower (hp) submersible pump (Aeromotor model A50S-12) set at 100 ft bgs. Figure 4-1 shows the treatment room, which housed a pressure tank (installed when the new well was installed), a water softener, a chlorination module, and a retention tank. The average daily use rate was estimated to be 675 gpd according to the school.



Figure 4-1. Pre-Existing Treatment System Components at Head Start Building
(From left to right: Pressure Tank, Chlorination Module, Retention Tank, and Softening Unit)

Pre-existing treatment at the facility included a dual column IX softening module in series configuration and a chlorination system using dilute sodium hypochlorite solution for disinfection. Water from the well was pumped directly to a 120-gal hydropneumatic tank located in the treatment room prior to the treatment system. After the hydropneumatic tank, water was softened and then chlorinated. Chlorinated water was held in a 120-gal contact tank prior to going to the distribution system.

4.1.1 Source Water Quality. Source water samples from the well shared by the Head Start and the library buildings were collected during the initial site visit on August 18, 2004. Installation of the new well for the Head Start building was completed on January 25, 2006, so another set of samples was collected on that day. Because the new well was installed approximately five months before system startup, little historical data were available. Table 4-1 presents the results of source water analyses and those obtained from OEPA for the new well.

Table 4-1. Water Quality Data for New Well

Parameter	Unit	OEPA Raw Water Data	Battelle Raw Water Data
Date		01/25/06	01/25/06
pH		7.6	N/A
Total Alkalinity(as $CaCO_3$)	mg/L	309	343
Hardness (as $CaCO_3$)	mg/L	266	298
TDS	mg/L	359	N/A
TOC	mg/L	N/A	2.0
Nitrate (as N)	mg/L	<0.1	N/A
Nitrite (as N)	mg/L	<0.1	N/A
Ammonia (as N)	mg/L	N/A	0.9
Chloride	mg/L	<5	N/A
Fluoride	mg/L	0.9	N/A
Sulfate	mg/L	24	N/A
As(total)	µg/L	17.0	15.2
As (soluble)	µg/L	N/A	14.5
As (particulate)	µg/L	N/A	0.7
As(III)	µg/L	N/A	12.1
As(V)	µg/L	N/A	2.4
Fe (total)	µg/L	1,216	1,312
Fe (soluble)	µg/L	N/A	1,241
Mn (total)	µg/L	70.9	83.4
Mn (soluble)	µg/L	N/A	80.3
Na (total)	mg/L	36.3	N/A
Ca (total)	mg/L	70	80.4
Mg (total)	mg/L	22.1	23.5
Pb (total)	µg/L	<5	N/A
Cu (total)	µg/L	<40	N/A

N/A= not available; TDS = total dissolved solids; TOC = total organic carbon

Total arsenic concentrations ranged from 15.2 to 17.0 µg/L. Based on the January 25, 2006, sampling results obtained by Battelle, 14.5 µg/L (or 95%) of total arsenic existed as soluble arsenic and 83% of soluble arsenic was present as As(III).

The pH of source water was 7.6, which is within the acceptable range of 5.5 to 8.0 for arsenic removal by adsorptive media. Therefore, pH adjustment was not required.

Iron concentrations in raw water ranged from 1,216 to 1,312 µg/L, existing mostly as soluble iron. The pre-existing water softener reduced iron concentrations to near or below the MCL of 30 µg/L, as shown

by the data provided by the Head Start, EPA, and vendor (Battelle, 2005). This softening unit was placed upstream of the arsenic removal system.

Manganese concentrations in raw water were high, ranging from 70.9 to 83.4 μg/L. Manganese existed almost entirely as soluble manganese. As much as 0.9 mg/L of ammonia was detected in source water. Soluble manganese and ammonia should be removed by the water softener.

The TOC concentration in source water was 2.0 mg/L, which can react with chlorine to form DBPs. Because the treatment system has a relatively large water holding capacity and a relatively small use rate as noted in Section 3.3.2, resulting residence times after chlorination can be long. Long residence times can contribute to higher DBP concentrations (Rathbun, 1997; Summers et al., 1996).

Other water quality parameters presented in Table 4-1 had sufficiently low concentrations and, therefore, were not expected to affect arsenic adsorption on adsorptive media.

4.1.2 Distribution System. Installed in 1990, the distribution system was constructed primarily of 1-/1.5-in Schedule 80/40 polyvinyl chloride (PVC) and 0.75-in copper pipe. There are no lead pipes or known lead solder in the distribution system. Nonetheless, samples are collected from five taps within the Head Start building every three years under the EPA LCR. Other compliance samples collected from the distribution system include those collected quarterly for bacterial analysis and every three years for VOCs.

4.2 Treatment Process Description

The Kinetico arsenic removal system uses ARM 200, a granular ferric hydroxide media developed by Engelhard Corporation specifically for arsenic adsorption. Table 4-2 lists physical properties of the media. The media has NSF International (NSF) Standard 61 approval for use in drinking water.

Table 4-2. Physical and Chemical Properties of Adsorptive Media

Parameter	ARM 200 
Physical Properties	
Physical Form	Dry granular media
Matrix	ferric oxide/hydroxide
Color	(Dark) brown
Bulk Density (g/cm^3) [lb/ft^3]	0.80[(a)] [50[(a)]]
BET area (m^2/g)	225
Sieve size (U.S. Standard)	20 × 40 mesh
Moisture Content (%)	8
Attrition (%)	<1

(a) As measured by Battelle

The Kinetico arsenic removal system is a fixed-bed adsorption system consisting of two pressure vessels containing ARM 200 media. Figure 4-2 shows a system schematic. Operation of the system involves routine sampling and periodic backwashing of the adsorptive media. When arsenic reaches 10 µg/L following the lag vessel, the media in the lead vessel is replaced with virgin media. The newly-rebedded lead vessel is then placed at the lag position via valving adjustment. Spent media, which is expected to pass the EPA's Toxicity Characteristic Leaching Procedure (TCLP) test, can be disposed of as nonhazardous waste.

The arsenic removal system was constructed using Schedule 80 PVC piping and fittings. Table 4-3 summarizes the design features of the system. Figure 4-3 shows a photograph of the system. The major system components/treatment steps are described as follows:

- **Intake and Pressure Tank.** Raw water pumped from the well was fed to the pre-existing, 120-gal WX-350 Well-X-Trol (by Amtrol) pressure tank via a 1-in copper pipe. The pressure tank operated with low- and high-pressure triggers at 40 and 60 psi, respectively, such that when the pressure fell below 40 psi, the well pump was turned on and when the pressure reached 60 psi, the well pump was turned off.
- **Water Softener.** One CSI Water Treatment Systems dual column IX softening module in series configuration was located after the 120-gal pressure tank. The softener was used to remove calcium, magnesium, iron, manganese, and ammonia from the well water. The water softener was set to regenerate every 300 gal using raw water from the 120-gal pressure tank.
- **Pre-chlorination/Oxidation.** Chlorine was added prior to the arsenic removal system to oxidize As(III) to As(V). The chlorine addition system consisted of a Liquid Metronics Uni-Dose Model U021-281 metering pump with a maximum capacity of 12 gpd, a chlorine injection tap, a flow switch, and a 10-gal polyethylene chemical feed tank (containing a solution of 1 gal of 5.75% NaOCl with 9 gal of water). The flow switch was installed in the water piping and would turn on the pump to inject chlorine when water flow was detected.

  Because As(III) levels in raw water were typically low (<15 µg/L) and because reducing species such as iron, manganese, and ammonia had already been removed by the softener, the chlorine demand was low. The dosage was based on the state-required total and free residual levels of 1 and 0.2 mg/L (as Cl_2), respectively, in the distribution system and the target dose was set at 1 mg/L (as Cl_2). Because the injection rate did not vary with varying flowrates, this pump could not provide a constant residual level throughout the study period.

  To resolve the problem of fluctuating residual levels in the distribution system, a Pulsafeeder Pulsatron E-Plus flow-paced pump and seaMetrics MJ series pulse meter were installed to gain better control over chlorine dosage on November 2, 2009. After installation, chlorine dosage was better controlled, but still fluctuated between 0.7 to 4.9 mg/L (as Cl_2) (with the use of approximately 2,000 to 5,000 mg/L (as Cl_2) of NaOCl solutions). The resulting total and free chlorine residual levels averaged 0.9 and 0.75 mg/L (as Cl_2), respectively.
- **Retention Tank.** Once the water was chlorinated, it was stored in a 120-gal Well-Mate contact tank to ensure sufficient contact times for oxidation and disinfection.
- **ARM 200 Adsorption.** The ARM 200 adsorption system consisted of two Pentair 18 in × 65-in sealed polyethylene vessels in series, each containing 4.5 ft^3 of ARM 200 media. The media (30.5 in) was placed over the bottom distributor. Each vessel had approximately 25 in of freeboard and an upper distributor. The softened and chlorinated water entered the top of

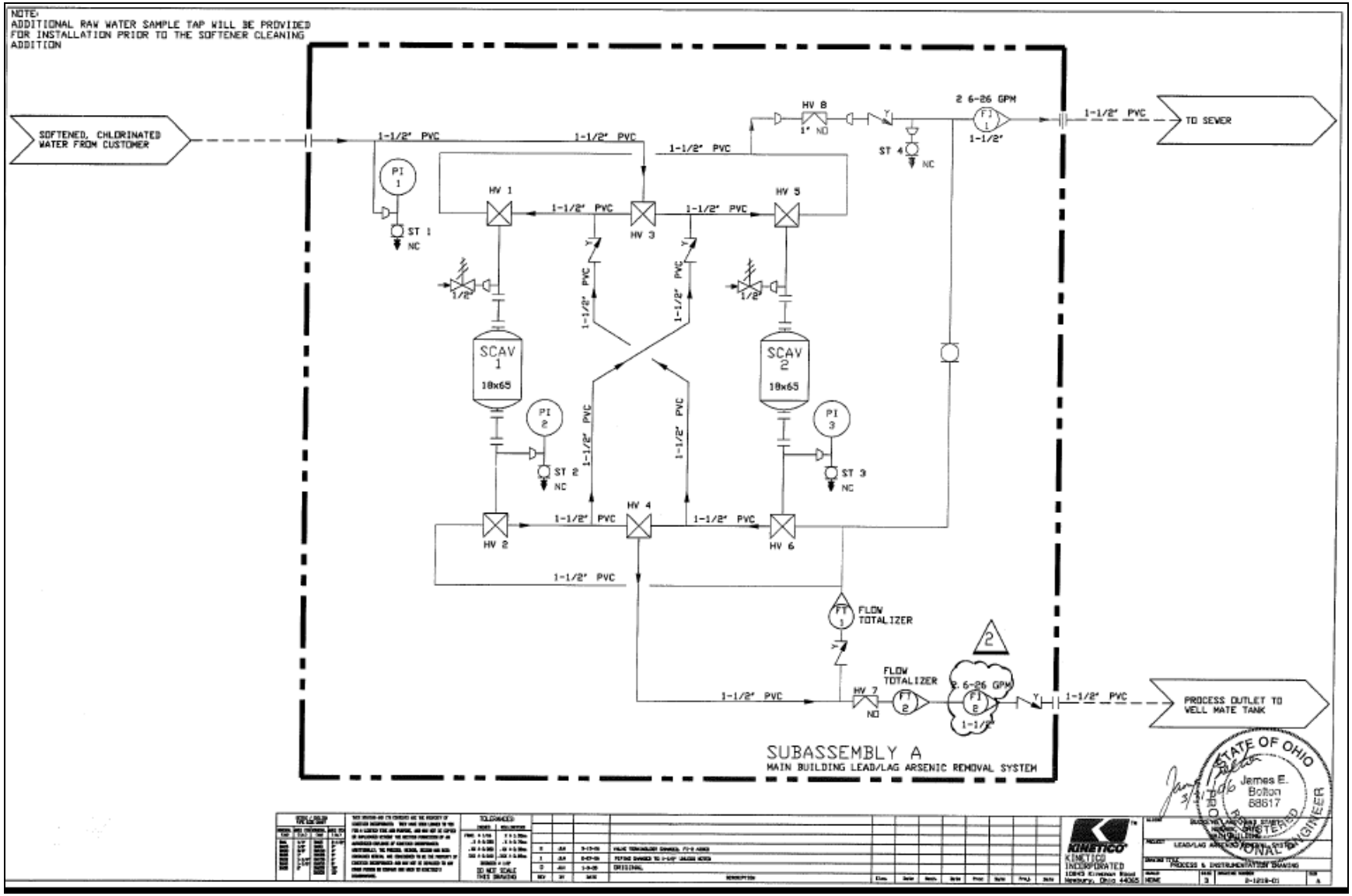


Figure 4-2. Schematic of Arsenic Removal System with Series Configuration

Table 4-3. Design Specifications of Arsenic Removal System

Parameter	Value	Remarks
Adsorption		
Vessel Size (in)	18 D × 65 H	–
Number of Vessels	2	–
Configuration	Series	–
Media Type	ARM 200	Iron oxide/hydroxide
Media Quantity (lb/vessel)	225	–
Media Volume (ft^3/vessel)	4.5	–
Design Flowrate (gpm)	10	–
Hydraulic Loading (gpm/ft^2)	5.6	–
EBCT (min/vessel)	3.3	6.6 min for both vessels
Maximum Use Rate (gpd)	675	Estimate provided by Head Start
Estimated Working Capacity (BV)	35,000	Vendor estimated bed volumes to breakthrough at 10 µg/L from lead tank
Throughput to Breakthrough (gal)	1,179,500	Vendor estimated throughput to breakthrough at 10 µg/L from lead tank (1 bed volume = 4.5 ft^3 or 33.7 gal)
Estimated Media Life (month)	57	Estimated frequency of media changeout in lead tank based on throughput of 675 gpd
Backwash		
Backwash (time/month)	1	Based on pressure drop
Initiating Δp (psi)	6–7	–
Number of Vessels for Backwash	2	–
Hydraulic Loading (gpm/ft^2)	5.6–7.3	–
Backwash Flowrate (gpm)	10–13	–
Backwash Duration (min)	15–20	–
Wastewater Production (gal/vessel)	200	–
Wastewater Production (gal/event)	400	–

the vessel and flowed down through the media and exited the bottom of the vessel. Based on a design flowrate of 10 gpm, the hydraulic loading to the vessels was 5.6 gpm/ft^2 and the EBCT for each vessel was 3.3 min. The vessels were valved so that the positions of the lead and lag vessels could be reversed after the media in the lead vessel was replaced.

Based on the average daily total use rate of about 675 gpd, size of the adsorption vessels, and chemistry of source water, it was expected that the media would last for approximately 57 months before requiring vessel rotation and changeout of the lead vessel. Factors anticipated to play a role in system performance include arsenic concentration, arsenic species, pH, natural organic matter, and concentrations of competing ions present in source water.

- **Backwash Operation.** Backwash piping was installed so that the media could be backwashed to remove particles and fluff the media beds to minimize channeling. The operator monitored inlet and outlet pressure of both vessels and could manually initiate backwashing if differential pressure (Δp) readings across a vessel had increased to about 6 to 7 psi. During the performance evaluation study, Δp readings across the vessels never reached 6 to 7 psi.

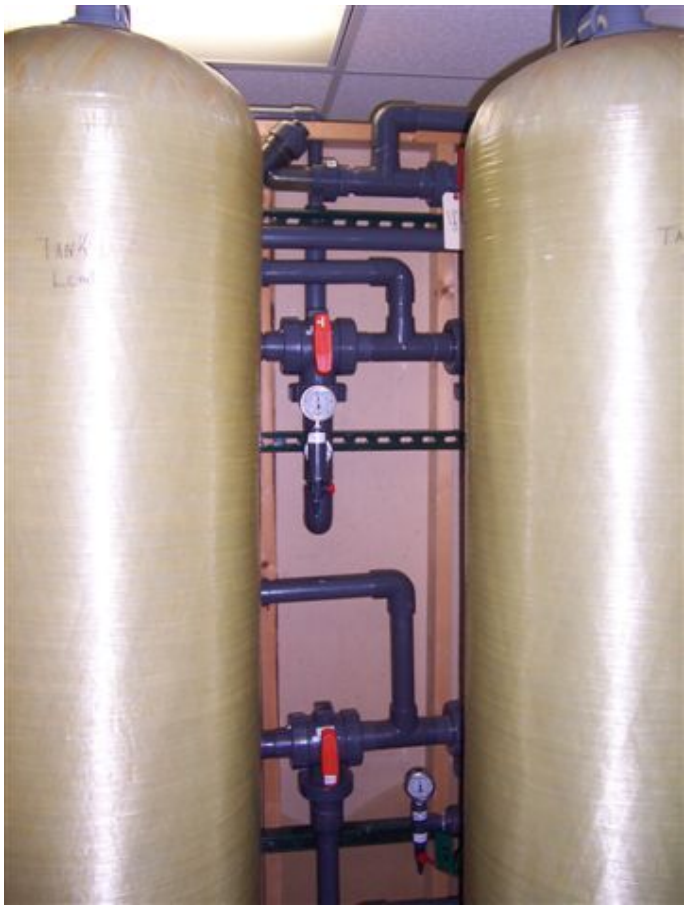


Figure 4-3. Adsorptive Media Arsenic Removal System

- **Media Disposal.** When ARM 200 media exhausts its capacity, the spent media will be removed from the vessels and disposed of at a sanitary landfill after successfully passing EPA's TCLP test. Virgin media will then be loaded into the lead vessel. During the almost four years of system operations, the media did not reach exhaustion.

4.3 System Installation

Engineering plans for the treatment system in the Head Start building were prepared by Kinetico. The plans consisting of a schematic and a written description of the arsenic removal system were submitted to OEPA for approval on April 5, 2006. The approval was granted on April 10, 2006.

The system was installed in the existing treatment room, shown in Figure 4-1, without any addition or modifications. The system consisting of two adsorption vessels, media, piping, valves, gauges, and sample taps was delivered to the site on May 19, 2006. Kinetico met with a subcontractor on May 19, 2006, to plan for system installation. The subcontractor installed the system to the tie-ins at the inlet and entry point to the distribution system. System installation was completed on June 2, 2006, and system shakedown was completed by Kinetico on June 23, 2006.

A Battelle staff member was onsite on June 28, 2006, to inspect the system and train the operator for sampling and data collection. No operational issues were identified during the system inspection.

However, shortly after system startup, the operator identified several issues, which were quickly resolved by the vendor. Table 4-4 summarizes the items identified and corrective actions taken.

Table 4-4. System Punch-List/Operational Issues and Corrective Action

Item No.	Punch List/ Operational Issues	Corrective Action Taken	Resolution Date
1	Pressure Readings higher after Vessels A and B as compared to influent pressure readings	Three new replacement gauges (0-100 psi) shipped by vendor and installed by operator	09/14/06
2	Leak at one pressure gauge	Leak fixed by a vendor's local contractor	09/13/06

4.4 System Operation

4.4.1 Operational Parameters. The operational parameters of the system are tabulated and attached as Appendix A and summarized in Table 4-5. The performance evaluation study began on June 28, 2006, and ended on February 24, 2010, for a total of 1,343 days. Approximately half of the days fell on weekends or during school breaks when there was little or no water usage.

Table 4-5. Summary of System Operations

Operational Parameter	Value/Condition
Performance Evaluation Duration	06/28/06–02/24/10
Daily Run Time (hr/day)	Unknown[(a)]
Total System Operating Time (hr)	Unknown[(a)]
Total Throughput (gal)	303,200
Average Daily Use Rate (gpd)	450
Instantaneous Flowrate (gpm)	<2 (most of times)
EBCT (min/vessel)	>16.8 (most of times)
Hydraulic Loading (gpm/ft^2)	<1.1 (most of times)
Δp Across System (psi)	Negligible

(a) System operated on demand.

The system treated approximately 303,200 gal of water during the study. Based on the total throughput and the estimated number of days the school was in session, the daily use rate averaged 450 gpd, compared to the 675-gpd rate provided by the school.

The system operated on demand at varying flowrates. Instantaneous flowrates were typically showing 0 gpm on the flow meter when the operator was onsite. This also was observed when Battelle staff was onsite collecting water samples each quarter. The flow meter would not register flow less than 2 gpm and there were many situations when water was flowing at a rate less than 2 gpm. Based on site observations, the flowrate was typically below 2 gpm for the majority of the day.

Due to low flow through the system, EBCT values were at least five times greater than the designed EBCT of 3.3 min per vessel for the majority of the day. On June 17, 2009, the pressure tank, which was located upstream of the treatment system, was re-piped to the end of the treatment train. This was done so the system would no longer be on demand to gain better control over the chlorine injection system.

The water softener used raw water from the pressure tank for regeneration. When the pressure tank was placed at the end of the treatment train, the softener could not be regenerated. Therefore, the pressure tank was placed back before the treatment train on September 14, 2009.

No pressure loss across the system was commonly found throughout the system evaluation study. Because the system did not lose pressure, it was not necessary to backwash the media.

4.4.2 Chlorine Addition. The pre-existing chlorine addition system consisted of a day tank filled with a NaOCl solution, a metering pump, a flow switch, and an injection port. When the chlorine tank was replenished, 1 gal of a 5.75% NaOCl solution was mixed with 9 gal of tap water. The metering pump operated at one speed and was turned on when the flow switch detected water flow. Presumably, the same amount of chlorine was injected into the on-demand water stream, thus causing a large variation in chlorine residuals in the treatment and distribution systems.

The operator visited the site once per week and measured chlorine concentrations from the kitchen sink. If the chlorine concentrations were high, he would dilute the chlorine solution in the day tank and if they were low, he would add more NaOCl concentrate to the day tank. This and abovementioned on-demand flow resulted in highly fluctuating chlorine residuals in the treatment and distribution systems as seen in Figure 4-4.

To better control chlorine residuals in the treatment and distribution system, a Battelle staff member began to visit the Head Start building in July 2009 at least once a week to check on chlorine consumption; adjust the metering pump; replenish the chemical day tank, if necessary; and measure chlorine residuals at the AC and/or DIST locations. It was also decided that a paced pump would be better for controlling the chlorine dosage and was installed on November 2, 2009. The NaOCl solution in the day tank was prepared at a chlorine concentration of approximately 4,000 mg/L (as Cl_2). The metering pump was set at 10 pulses per gal of water at 40% and the target dosage was 1 mg/L of chlorine (as Cl_2).

Chlorine concentrations in the distribution system continued to fluctuate after the installation of the paced pump; however, the fluctuation was less than when the metering pump was in operation. From July 2006 through October 2009 during operation of the metering pump, total chlorine concentrations measured at the kitchen sink ranged from 0.0 to 3.5 mg/L (as Cl_2) and averaged 0.8 mg/L (as Cl_2); free chlorine concentrations ranged from 0.0 to 3.4 mg/L (as Cl_2) and averaged 0.8 mg/L (as Cl_2). From November 2009 through February 2010 during operation of the paced pump, total chlorine concentrations ranged from 0.03 to 1.4 mg/L (as Cl_2) and averaged 0.5 mg/L (as Cl_2); free chlorine concentrations ranged from 0.01 to 1.4 mg/L (as Cl_2) and averaged 0.4 mg/L (as Cl_2). Although the average total chlorine residual was below the target of 1.0 mg/L (as Cl_2), the average free chlorine residual was slightly higher than the target of 0.2 mg/L (as Cl_2). In addition, there was no chlorine measurement in the distribution that was above 2 mg/L (as Cl_2), which is believed to attribute to the much lower TTHM and HAA5 concentrations measured in samples collected after November 2009.

4.4.3 Media Replacement. The media did not reach exhaustion during the performance evaluation study and, therefore, it was not replaced.

4.4.4 Residual Management. The only solid residuals produced were backwash wastewater solids. The system was backwashed once on December 13, 2006, after approximately six months of operation. Backwash wastewater collected in a 33-gal drum was given time to settle. The supernatant was then decanted off the top and the solids were collected in a 1-gal container. These solids were not analyzed because less than 1,400 BV of water had been treated at the time of the backwash.

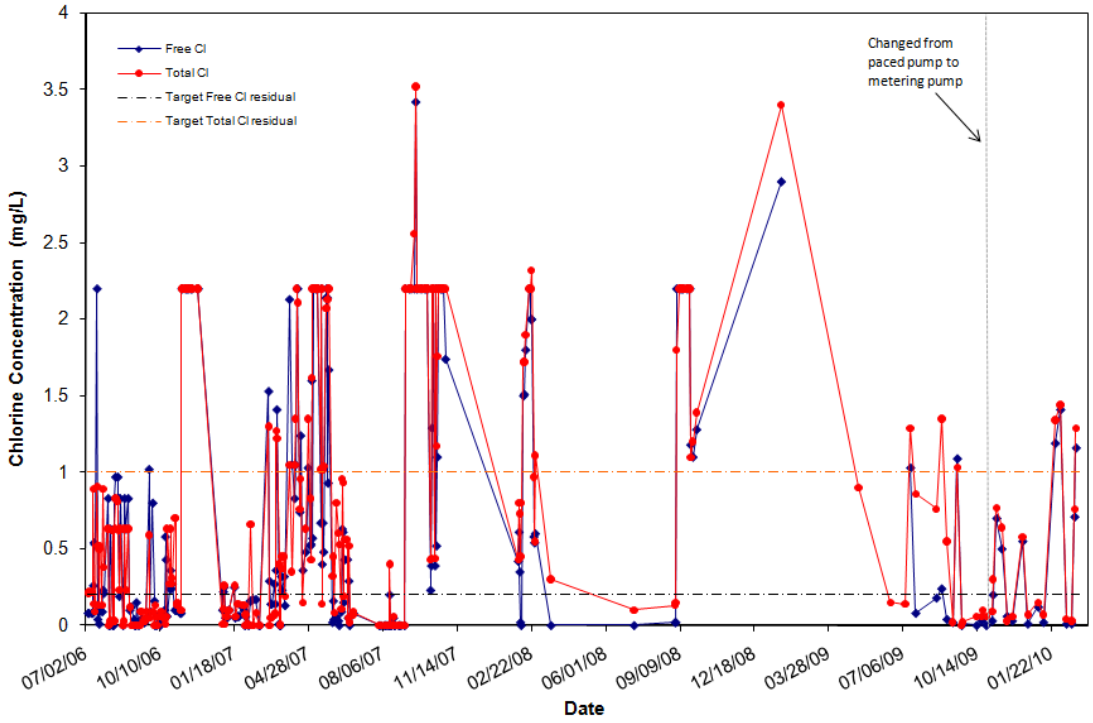


Figure 4-4. Total and Free Chlorine Residuals Measured at Kitchen Sink

During backwash, the lead vessel (Vessel A) was backwashed for approximately 20 min at 10 gpm and the lag vessel (Vessel B) was backwashed for approximately 15 min at a 13 gpm. A total of 200 gal of wastewater was produced through each vessel. The wastewater produced was sent directly to the sewer. Because there was very little pressure drop across the system, backwash was no longer performed during the remainder of the performance evaluation study.

4.4.5 Reliability and Simplicity of Operation. The system required very little effort by the operator. The only problem encountered was the pressure gauges, which read a lower pressure at the influent of the treatment system than after each adsorption vessel. Kinetico installed new pressure gauges on September 14, 2006. Additional discussion regarding system operation and operator skill requirements is provided below.

Pre- and Post-Treatment Requirements. Pretreatment included water softening and chlorination. Both of these pre-treatments existed prior to the installation of the arsenic removal system. Therefore, there were no additional requirements for pre- and post-treatment after the installation of the arsenic removal system.

System Automation. The Kinetico adsorptive media arsenic removal system was a passive system, requiring only the operation of the supply well pump to send groundwater to the pressure tank at the system inlet and through the adsorption vessels to the distribution system. The media vessels themselves did not have automated parts and all valves were manually activated. The only electrical power required was that needed to run the well pump, water softener, and chlorination pump. All of these components were in place prior to the installation of the Kinetico treatment system. The system operation was controlled by the pressure switches in the pressure tank at the system inlet.

Operator Skill Requirements. Under normal operating conditions, the skills required to operate the Kinetico arsenic removal system were minimal. The operation of the system did not appear to require additional skills beyond those necessary to operate the existing system in place at the site.

The level of operator certification is determined by the type and class of the public drinking water systems. OEPA's drinking water rules require all community and non-transient, non-community public drinking water and distribution systems to be classified based on potential health risks. Classifications range from "Class I" (lowest) to "Class IV" (highest) for treatment systems and from "Class I" to "Class II" for distribution systems, depending on such factors as the system's complexity, size, and source water (OEPA, 2006). The Head Start water system is classified as a "Class I" treatment and distribution system. The operator has a "Class IV" license, which is higher than what is need to operate the system.

Preventative Maintenance Activities. The only regularly scheduled preventative maintenance activity recommended by Kinetico was to watch the pressure across the system and backwash the filters as needed. The treatment system operator visited the site approximately once per week for approximately 15 min each visit to check the system for leaks, and record flow, volume, and pressure readings.

4.5 System Performance

The system performance was evaluated based on analyses of samples collected across the treatment train and distribution system. The system ran from June 23, 2006, through February 24, 2010. After almost four years of operation, the system had not reached 10-µg/L breakthrough due mainly to the low water use rate. Arsenic concentrations stayed below 1.5 µg/L following both the lead and lag vessels throughout the entire evaluation period.

4.5.1 Treatment Plant Sampling. The treatment plant water was sampled on 28 occasions including one duplicate and 22 speciation sampling events. Appendix B contains a complete set of analytical results through the almost four years of system operation. Table 4-6 summarizes the arsenic, iron, and manganese results from samples collected across the treatment plant. Table 4-7 summarizes the results of other water quality parameters. The results of the treatment plant sampling are discussed below.

Arsenic. The key parameter for evaluating the effectiveness of the treatment system was the concentration of arsenic in the treated water.

Total arsenic concentrations in raw water ranged from 5.5 to 20.5 µg/L and averaged 15.4 µg/L (Table 4-6). Soluble As(III) was the predominating species, with concentrations ranging from 2.2 to 16.6 µg/L and averaging 11.3 µg/L. Soluble As(V) also was present, averaging 3.0 µg/L. Particulate As was low, averaging 1.8 µg/L. Influent arsenic concentrations measured during the almost four-year study period were consistent with that in the raw water sample collected prior to the study on January 25, 2006.

Figure 4-5 contains four bar charts each showing the concentrations of total As, particulate As, As(III), and As(V) across the treatment train. Because arsenic concentrations remained relatively unchanged between the IN and AS locations, only the IN sampling results are presented in the figure. With the exception of September 28, 2006, March 19, 2008, and September 23, 2009, soluble As(III) was effectively oxidized to soluble As(V) by chlorination. Residual chlorine concentrations were not measured during the September 28, 2006, sampling event. During the September 23, 2009 sampling event, free and total chlorine concentrations were below the MDL at both the AC and DIST locations. This explains why the As(III) concentration remained high at the AC location.

The majority of the arsenic detected after treatment (at the TA and TB locations) was in the soluble As(III) form. This is expected since adsorptive media has been shown to have a higher adsorptive

Table 4-6. Summary of Arsenic, Iron, and Manganese Analytical Results

Parameter (Figure, if any)	Sampling Location	Number of Samples	Concentration (µg/L)			Standard Deviation
			Minimum	Maximum	Average	
As (total) (Figure 4-6)	IN	28	5.5	20.5	15.4	4.0
	AS	13	13.4	20.1	17.6	2.0
	AC	28	9.2	22.4	17.2	2.9
	TA	26	<0.1	1.4	_[a]	
	TB	26	<0.1	1.4		
As (soluble)	IN	22	4.1	17.8	14.3	3.6
	AS	13	13	17.7	15.9	1.2
	AC	22	11.4	19.5	16.0	1.8
	TA	20	<0.1	1.8	-	-
	TB	20	<0.1	1.4	-	-
As (particulate) (Figure 4-5)	IN	22	<0.1	3.7	1.8	1.0
	AS	13	<0.1	3.5	1.8	1.3
	AC	22	<0.1	2.9	1.5	0.9
	TA	20	<0.1	1.0	_[a]	
	TB	20	<0.1	0.9		
As (III) (Figure 4-5)	IN	22	2.2	16.6	11.3	4.9
	AS	13	12.9	17.2	15.3	1.6
	AC	20[b]	<0.1	2.4	0.7	0.5
	TA	20	<0.1	2.0	_[a]	
	TB	20	<0.1	1.9		
As (V) (Figure 4-5)	IN	22	0.3	9.1	3.0	2.9
	AS	13	<0.1	3.8	0.7	1.3
	AC	20[b]	12.3	18.7	15.2	1.8
	TA	20	<0.1	0.2	_[a]	
	TB	20	<0.1	0.1		
Fe (total)	IN	28	855	5,365	2,290	1,204
	AS	13	<25	69	<25	15.7
	AC	28	<25	367	41.9	72.3
	TA	26	<25	86	<25	15.8
	TB	26	<25	48	<25	9.2
Fe (soluble)	IN	21	381	3,882	1,717	832
	AS	12	<25	<25	<25	0.0
	AC	21	<25	369	32.2	77.7
	TA	19	<25	<25	<25	0.0
	TB	19	<25	<25	<25	0.0
Mn (total)	IN	28	61	125	85.7	18.7
	AS	13	<0.1	0.7	0.2	0.2
	AC	28	<0.1	18.4	1.1	3.5
	TA	26	<0.1	0.4	0.1	0.1
	TB	26	<0.1	0.3	0.1	0.1
Mn (soluble)	IN	22	61.9	117	79.8	16.8
	AS	13	<0.1	0.3	0.1	0.1
	AC	22	<0.1	19.2	1.0	4.1
	TA	20	<0.1	0.5	0.1	0.1
	TB	20	<0.1	0.3	0.1	0.1

(a) Statistics not meaningful for data related to breakthrough; see Figure 4-6 for breakthrough curves.
(b) Outliers on 09/28/06 and 09/23/09 not included in calculation.
IN = at wellhead; AS = after softener; AC = after chlorination; TA/TB = after lead/lag vessel
One-half of detection limit used for samples with concentrations less than detection limit for calculations; duplicate samples included in calculations.

Table 4-7. Summary of Water Quality Parameter Measurements

Parameter	Sampling Location	Unit	Number of Samples	Concentration			Standard Deviation
				Minimum	Maximum	Average	
Alkalinity (as $CaCO_3$)	IN	Mg/L	24	299	361	333	16.8
	AS	Mg/L	13	312	354	335	13.9
	AC	Mg/L	24	306	373	342	16.6
	TA[a]	Mg/L	22	305	395	346	24.0
	TB	Mg/L	23	134	423	337	52.3
Ammonia (as N)	IN	Mg/L	12	0.8	1.2	1.0	0.1
	AS	Mg/L	12	<0.05	0.1	<0.05	0.02
	AC	Mg/L	12	<0.05	0.1	<0.05	0.02
	TA	Mg/L	12	<0.05	0.1	<0.05	0.02
	TB	Mg/L	12	<0.05	0.1	<0.05	0.02
Fluoride	IN	Mg/L	24	0.7	1.8	1.1	0.2
	AS	Mg/L	13	0.7	1.2	1.0	0.2
	AC[a]	Mg/L	23	0.8	1.3	1.0	0.1
	TA[a]	Mg/L	22	0.7	1.3	1.0	0.2
	TB	Mg/L	23	0.9	2.4	1.2	0.4
Sulfate	IN	Mg/L	24	33	44	37	2.7
	AS	Mg/L	13	33	38	36	1.4
	AC	Mg/L	24	32	43	37	2.4
	TA	Mg/L	23	32	42	37	2.4
	TB	Mg/L	23	33	160	43	25.7
Phosphorus (as P)	IN[b]	µg/L	23	<10	<10	<10	0.0
	AS	µg/L	13	<10	147	36.6	48.7
	AC	µg/L	24	<10	187	57.4	51.6
	TA	µg/L	23	<10	<10	<10	0.0
	TB	µg/L	23	<10	<10	<10	0.0
Silica (as SiO_2)	IN	Mg/L	24	13.9	17.7	15.3	0.9
	AS	Mg/L	13	13.0	15.5	14.4	0.7
	AC	Mg/L	24	12.9	16.1	14.5	0.8
	TA	Mg/L	23	<0.2	13.4	-[d]	-[d]
	TB[c]	Mg/L	22	<0.2	11.6	-[d]	-[d]
Nitrate (as N)	IN	Mg/L	24	<0.05	0.4	0.05	0.1
	AS	Mg/L	13	<0.05	<0.05	<0.05	0.0
	AC	Mg/L	24	<0.05	0.1	<0.05	0.02
	TA	Mg/L	23	<0.05	0.2	0.05	0.04
	TB	Mg/L	23	<0.05	0.3	0.08	0.1
Temperature	IN	°C	22	13.5	23.8	16.9	2.6
	AS	°C	11	13.9	19.5	15.4	1.6
	AC	°C	22	14.0	21.4	17.4	2.2
	TA	°C	11	14.8	25.0	17.1	2.9
	TB	°C	19	14.3	21.1	17.6	1.9
TOC	IN	Mg/L	8	1.7	2.6	2.0	0.3
	AS	Mg/L	8	1.8	2.5	2.0	0.3
	AC	Mg/L	8	1.7	2.4	2.0	0.2
	TA	Mg/L	8	1.4	1.9	1.7	0.2
	TB	Mg/L	8	1.3	2.4	1.8	0.3
Turbidity	IN	NTU	24	7.5	41	22	9.9
	AS	NTU	13	0.1	3.9	0.7	1.0
	AC	NTU	24	0.2	2.7	0.7	0.5
	TA	NTU	23	<0.1	5.3	0.8	1.0
	TB	NTU	23	<0.1	6.4	1.0	1.4

Table 4-7. Summary of Water Quality Parameter Measurements (Continued)

Parameter	Sampling Location	Unit	Number of Samples	Concentration			Standard Deviation
				Minimum	Maximum	Average	
pH	IN	S.U.	20	6.9	7.7	7.4	0.2
	AS	S.U.	9	7.2	8.2	7.7	0.3
	AC	S.U.	20	7.5	8.0	7.8	0.2
	TA[b]	S.U.	8	7.2	8.1	7.7	0.3
	TB	S.U.	17	7.4	8.1	7.7	0.2
DO	IN	Mg/L	19	1.3	3.6	2.0	0.6
	AS	Mg/L	8	0.7	1.9	1.2	0.4
	AC	Mg/L	19	0.8	4.5	2.0	0.9
	TA	Mg/L	8	1.1	3.0	1.8	0.8
	TB	Mg/L	17	0.8	2.0	1.5	0.4
ORP	IN	mV	20	-79	447	115	199
	AS	mV	9	20	439	188	135
	AC	mV	19	-50	867	645	181
	TA	mV	9	103	741	638	202
	TB	mV	17	-54	990	559	254
Total Hardness (as $CaCO_3$)	IN	Mg/L	23	260	488	303	45
	AS	Mg/L	12	<0.3	2.0	0.8	0.6
	AC	Mg/L	23	<0.3	1.6	0.7	0.4
	TA	Mg/L	22	<0.3	13.6	2.4	3.8
	TB[e]	Mg/L	21	<0.3	22.1	5.8	6.4
Ca Hardness (as $CaCO_3$)	IN	Mg/L	23	166	354	205	38
	AS	Mg/L	12	<0.25	1.8	0.7	0.6
	AC	Mg/L	23	<0.25	1.5	0.6	0.4
	TA	Mg/L	22	<0.25	11.1	1.8	3.2
	TB[e]	Mg/L	21	<0.25	20.9	4.6	5.8
Mg Hardness (as $CaCO_3$)	IN	Mg/L	23	81.5	134	98.3	10.6
	AS	Mg/L	12	<0.1	0.2	<0.1	0.06
	AC	Mg/L	23	<0.1	0.2	<0.1	0.04
	TA	Mg/L	22	<0.1	3.6	0.6	1.0
	TB[e]	Mg/L	21	<0.1	7.0	1.3	2.0

(a) Outlier on 2/24/10 not included in calculations.
(b) Outlier on 11/4/09 not included in calculations.
(c) Outlier on 02/15/07 not included in calculations.
(d) Statistics not meaningful for data related to breakthrough; see Figure 4-8 for breakthrough curves.
(e) Outlier on 10/11/06 not included in calculations.
IN = at wellhead; AS = after water softener; AC = after chlorination; TA/TB = after lead/lag vessel
One-half of detection limit used for samples with concentrations less than detection limit for calculations;
Duplicate samples included in calculations.

capacity for soluble As(V) than soluble As(III). Nonetheless, the elevated soluble As(III) detected at the AC location on September 28, 2006, and September 23, 2009, was almost completely removed by the media (to <0.4 µg/L).

Figure 4-6 presents total arsenic breakthrough curves. The breakthrough curves indicate that ARM 200 media removed arsenic to levels well below the 10-µg/L MCL. Effluent samples collected during the final sampling event on February 24, 2010, contained <0.1 µg/L of total arsenic. The highest total arsenic concentration measured during the almost four-year study period was 1.4 µg/L. The low arsenic concentrations observed were attributed to the low water use rate. Throughout the performance evaluation study, the system treated only 303,200 gal (or 9,000 BV) of water, which was much less than the vendor's estimate of 1,179,500 gal (or 35,000 BV) to reach the MCL. Therefore, it could not be determined if the vendor's estimate was accurate.

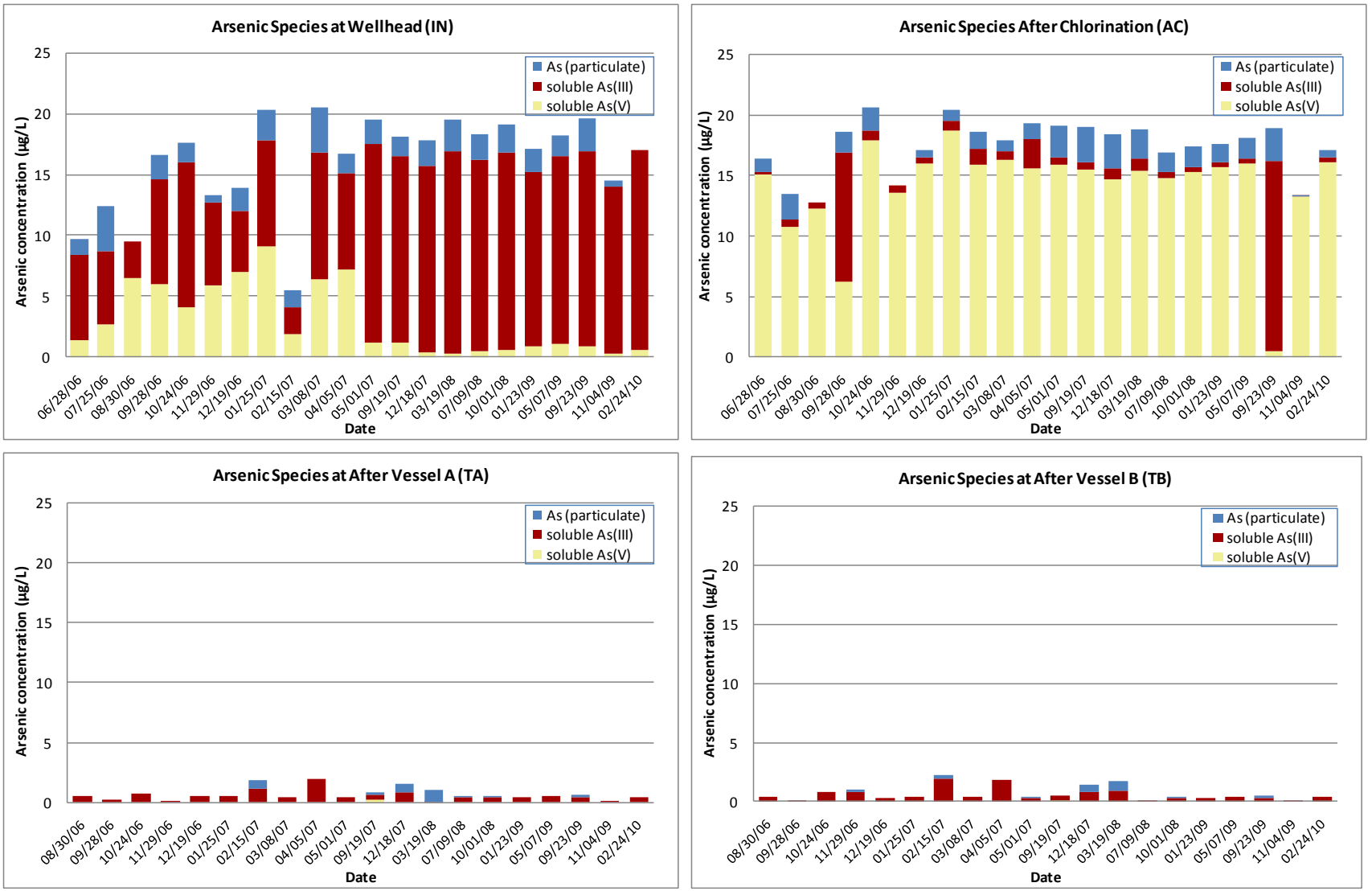
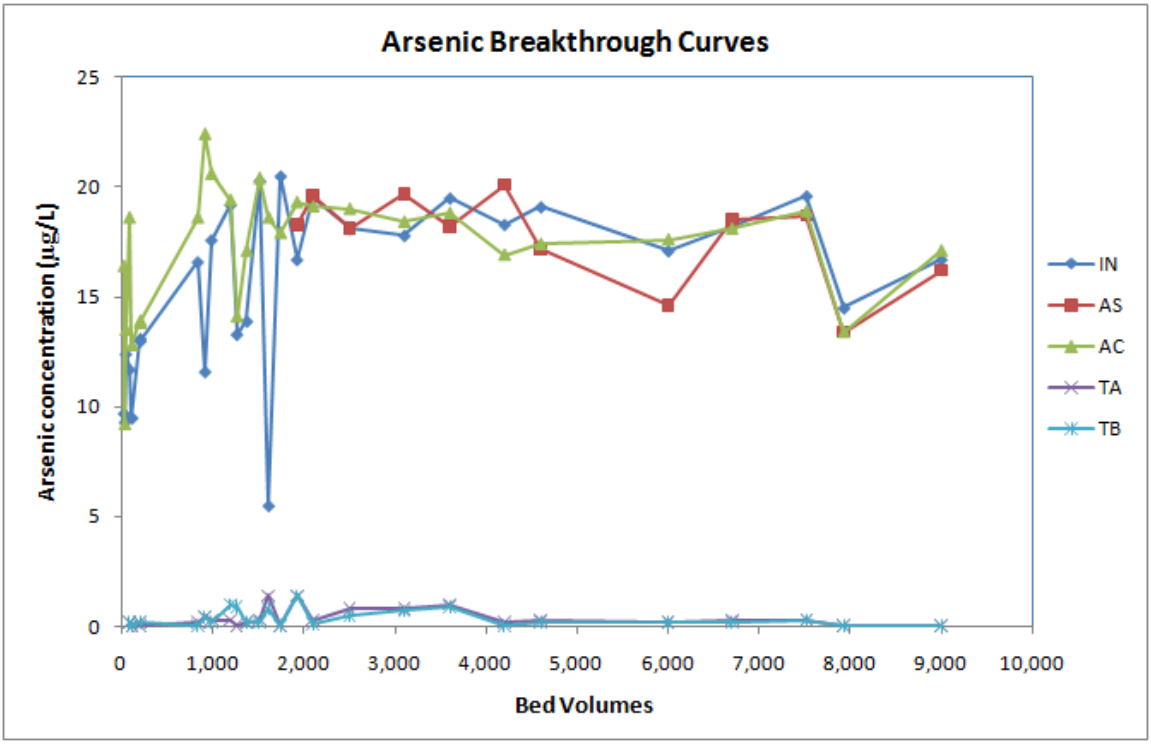


Figure 4-5. Concentrations of Various Arsenic Species Across Treatment Train



Note: Breakthrough curves based upon BV of 4.5 ft^3 for each column

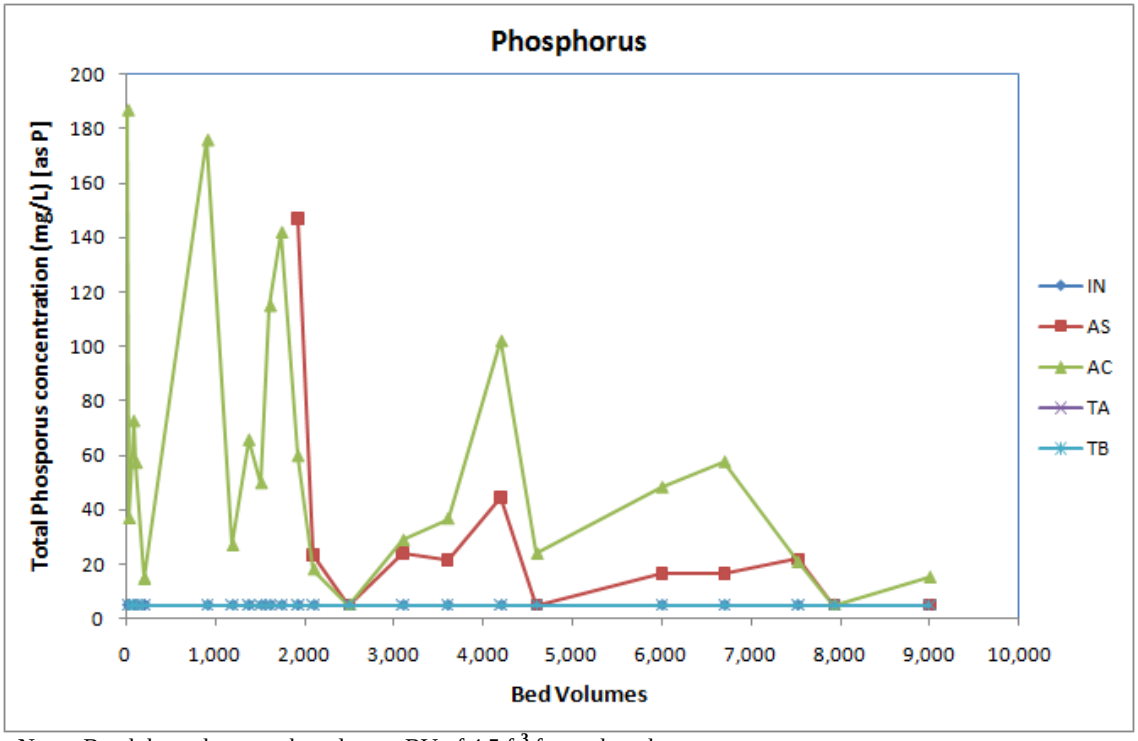
Figure 4-6. Total Arsenic Breakthrough Curves

Iron and Manganese. Total iron levels in source water ranged from 855 and 5,365 µg/L and averaged 2,290 µg/L (Table 4-6). Total iron concentrations were reduced to below the MDL after softening for the majority of sampling events. In the case that iron did show up in one of the sampling locations after the softener (i.e., AS, AC, TA or TB), it was below 200 µg/L in all but one occasion (i.e., iron concentration at the AC location on September 28, 2006, was 367 µg/L). Iron levels remained below the MDL in the treatment system effluent in all but two occasions.

Total manganese levels in source water ranged from 61 and 125 µg/L and averaged 85.7 µg/L (Table 4-6). Similar to iron, manganese also was removed to near completion by the water softener. Concentrations detected after the water softener (AS) ranged from <0.1 to 0.7 µg/L and averaged 0.2 µg/L. Concentrations in the system effluent (TB) were similar to those after the softener (AS).

Competing Anions. Phosphorus and silica, which can adversely affect arsenic adsorption onto adsorptive media, were monitored at sampling locations across the treatment train. Total phosphorus concentrations at the wellhead were below detection (<10 µg/L [as P]) throughout the performance evaluation study. Phosphorus, however, was measured in nine of the 13 samples collected at the AS location and 22 out of 24 samples collected at the AC location. Concentrations at these locations ranged from <10 µg/L to 187 µg/L, which was removed by ARM 200 media to below the MDL as seen at TA and TB (Figure 4-7).

Silica concentrations in source water ranged from 13.9 to 17.7 mg/L (as SiO_2) and averaged 15.3 mg/L (as SiO_2). Silica concentrations remained essentially unchanged, averaging 14.4 and 14.5 mg/L (as SiO_2) after softening and chlorination, respectively. ARM 200 media removed silica from the AC water for the first 2,000 BV before silica began to break through. After 9,000 BV, the silica concentration at TA was



Note: Breakthrough curves based upon BV of 4.5 ft^3 for each tank

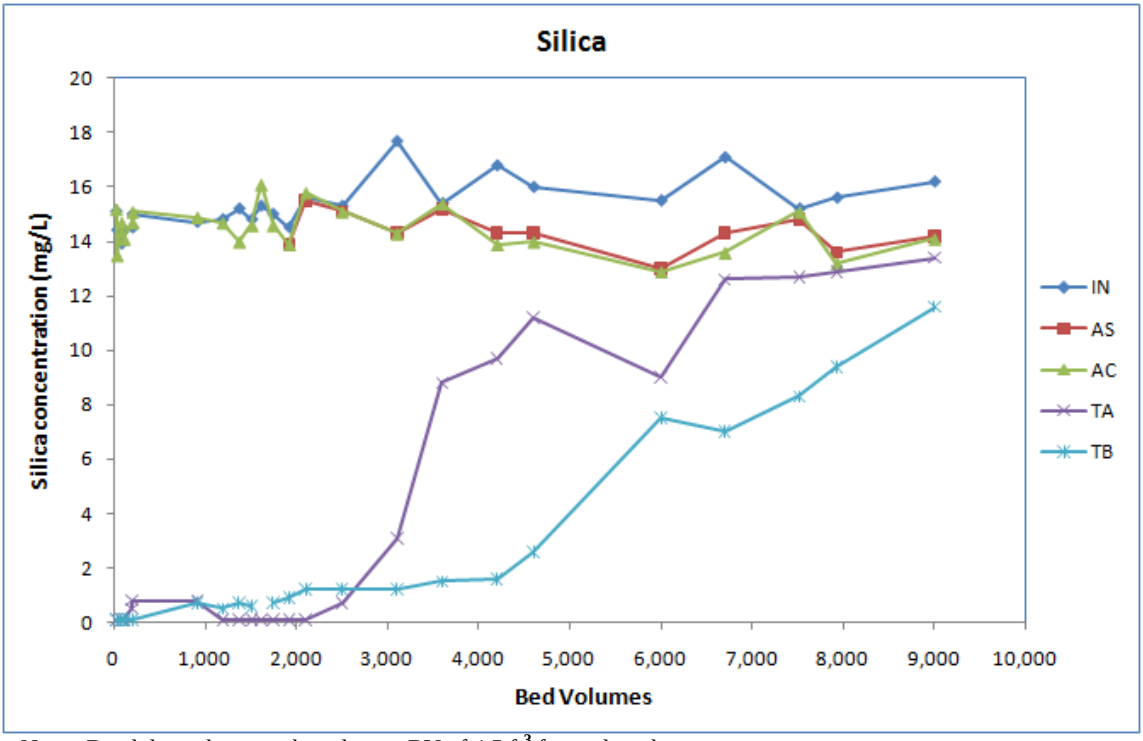
Figure 4-7. Total Phosphorus Concentrations Across Treatment Train

13.4 mg/L (as SiO_2), which was very close to the source water concentration of 16.2 mg/L (as SiO_2). The silica concentration at TB was 11.6 mg/L (as SiO_2) after 9,000 BV (Figure 4-8).

Silica adsorption has been observed at a number of arsenic demonstration sites using adsorptive media (Table 4-8). At Valley Vista, AZ (Valigore et al,, 2007), where ARM 200 also was evaluated, 52% silica removal was observed after treating approximately 800 BV of water. The removal was reduced to 3% at 4,900 BV. Silica removal by iron-based E33 media can be as high as 37% at 800 BV as observed at Brown City, MI (Chen et al., 2008). No additional removal was observed after treating 20,000 BV at Brown City; 2,800 BV at Bruni, TX (Williams et al., 2010); and 900 BV at Wellman, TX (Williams et al., 2009).

A/P 2002 oxidizing media and A/I 2000 adsorptive media, both alumina-based and manufactured by ATS, were observed to remove silica at Dummerston, VT (Lipps et al., 2008), Susanville, CA (Chen et al., 2009a), and Wales, ME (Lipps et al., 2010), with reduction as high as 60% reported at Dummerston. The removal was reduced to 6.5% to near exhaustion after treating approximately 22,600 BV at Susanville, 18,700 BV at Wales, and 16,300 BV at Dummerston. Another alumina-based media, AAFS50, also removed silica at Valley Vista. Removal of two separate adsorption runs did not reach exhaustion until 34,300 or 24,800 BV. The run with high influent pH (i.e., 7.7 vs. 6.9 [on average]) appeared to remove more silica.

At Reno, NV (Cumming et al., 2009), iron-based GFH media reduced silica concentrations from 68.5 to <48.8 mg/L (as SiO_2) at 2,400 BV and reached exhaustion at 5,000 BV. The Reno source water had the highest silica concentration (i.e., 72.6 mg/L as SiO_2 [on average]) measured among the 39 demonstration sites.



Note: Breakthrough curves based upon BV of 4.5 ft^3 for each tank

Figure 4-8. Silica Concentrations Across Treatment Train

Other Water Quality Parameters. Water pH increased from an average of 7.4 in source water to an average of 7.7 after softening. pH values remained essentially unchanged throughout the rest of the treatment train. DO concentrations ranged from 0.7 to 4.5 mg/L and averaged 1.7 mg/L throughout the treatment train. This value is within a tight range of 1.2 and 2.0 mg/L for average DO concentrations across the treatment train. ORP readings varied greatly in raw water, ranging from -79 to 447 mV and averaging 115 mV. Fluctuating ORP readings most likely were caused by the field meter used. ORP readings increased slightly to an average of 188 mV after softening and, as expected, much greater to an average of 645 mV after chlorination. ORP readings decreased slightly after each adsorption vessel, averaging 638 and 559 mV at TA and TB, respectively.

Total hardness (consisting of calcium and magnesium) in source water ranged from 260 to 488 mg/L (as $CaCO_3$) and averaged 303 mg/L (as $CaCO_3$). The water softener removed the majority of the hardness, reducing its concentrations to <0.3 to 2 mg/L (as $CaCO_3$). Total hardness concentrations remained low throughout the remainder of the treatment train.

Nitrate concentrations were typically below detection in source water and throughout the treatment train. Ammonia concentrations in source water ranged from 0.8 to 1.2 mg/L (as N) and averaged 1.0 mg/L (as N). Similar to calcium and magnesium, ammonia was removed by the softener to below the MCL and remained below the MDL throughout the rest of the treatment train.

TOC concentrations in source water ranged from 1.7 to 2.6 mg/L and averaged 2.0 mg/L. As expected, TOC concentrations remained unchanged after chlorination. Following Vessels A and B, 0.2 to 0.3 mg/L of TOC (on average) was removed by ARM 200. Alkalinity, fluoride, and sulfate concentrations remained rather constant across the treatment train.

Table 4-8. Silica Removal by Adsorptive Media Observed at EPA Arsenic Removal Demonstration Sites

Demonstration Site	Adsorptive Media	Average (Range) of Silica Concentration in Source Water (mg/L)	Average (Range) of pH in Source Water (S.U.)	Observed Silica Reduction	Reference
Brown City, MI	E33	9.0 (6.5–14.6)	7.9 (7.6–8.5)	37% reduction at 800 BV[a] Exhaustion at 20,000 BV[a]	Chen, et al., 2008
Bruni, TX	E33	41.5 (39.1–43.9)	7.4 (7.1–8.1) [b]	19% reduction at 600 BV[c] 7% reduction at 1,200 BV[c] Exhaustion at 2,800 BV[c]	Williams, et al., 2010
Dummerston, VT	A/I 2000	12.6 (10.6–16.8)	7.7 (7.0–8.4)	60% reduction at 800 BV[c] Exhaustion at 16,300 BV[c]	Lipps, et al., 2008
Reno, NV	GFH	72.6 (51.5–95.1)	7.1 (6.5–7.9)	30% reduction at 2,400 BV[d] Exhaustion at 5,000 BV[d]	Cumming, et al., 2009
Susanville, CA	A/P 2002[e]	14.1 (12.8–15.7)	8.1 (7.7–8.4)	56% reduction at 3,700 BV[c] 5% reduction at end of run at 22,600 BV[c]	Chen, et al., 2009
Valley Vista, AZ	AAFS50	19.0 (15.7–21.2)	7.7 (7.5–8.4)	19% reduction at 2,500 BV[c] 2% reduction at 34,300 BV[c]	Valigore, et al., 2007
	AAFS50		6.9 (6.6–7.6) [a]	14% reduction at 2,700 BV[c] 3% reduction at 24,800 BV[c]	
	ARM 200		7.7 (7.5–8.4)	52% reduction at 800 BV[c] 3% reduction at 4,900 BV[c] Exhaustion at 14,200 BV[c]	
Wales, ME	A/P 2002[e]	10.5 (9.6–13.3)	8.5 (7.3–8.8)	38% reduction at 2,000 BV[c] 6.5% reduction at end of run at 18,700 BV[c]	Lipps, et al., 2010
	Filox-R[e]			No reduction	
	CFH-12			41% reduction at 4,500 BV[c] Exhaustion at 13,900 BV[c]	
	GFH			42% reduction at 3,500 BV[c] Exhaustion at 10,700 BV[c]	
Wellman, TX	E33	46.8 (42.1–62.1)	7.8 (7.6–8.0)	44% reduction at system startup Exhaustion at 900 BV[f]	Williams, et al., 2007

(a) Bed volumes calculated based on media volume in four adsorption vessels in parallel.
(b) After pH adjustment.
(c) Bed volumes calculated based on media volume in lead vessel.
(d) Bed volumes calculated based on media volume in three adsorption vessels in parallel.
(e) Oxidizing media.
(f) Bed volumes calculated based on media volume in two adsorption vessels in parallel.

4.5.2 Disinfection Byproducts. Prior to installation of the arsenic removal system, the water system at the Head Start building was required to collect distribution system water samples for DBPs because the pre-existing treatment included chlorination. DBPs are a large and diverse class of halogenated organic compounds formed, as first described by Rook (1974), mainly through interaction of chlorine, bromine, and iodine with natural organic matter present in source water. The two classes of DBPs that receive most attention are THMs and HAAs. THMs include chloroform, bromoform, chlorodibromomathane (CDBM), and bromodichloromathanes (BDCM), collectively known as total trihalomethane (TTHM). HAAs include monochloroacetic acid (MCA), dichloroacetic acid (DCA), trichloroacetic acid (TCA), monobromoacetic acid (MBA), and dibromoacetic acid (DBA), collectively known as HAA5. These chemicals were regulated by EPA with an MCL of 80 µg/L for TTHM and 60 µg/L for HAA5. DBPs are found in the finished water from water treatment plants employing chlorination through the introduction of either chlorine gas or sodium hypochlorite (NaOCl).

After system startup, exceedances of TTHM and HAA5 were noticed. Historical DBP data were obtained from OEPA to facilitate the evaluation of conditions before and after system startup. For TTHM, eight compliance samples were collected before system startup and 12 compliance and eight non-compliance samples collected after system startup (see Table 4-9 and Figure 4-9). For HAA5, seven compliance samples were collected before system startup and 12 compliance and seven non-compliance samples collected after system startup (see Table 4-10 and Figure 4-10). Compliance samples were collected at the kitchen sink (DIST) by the Head Start operator and analyzed by AAL. Non-compliance samples were collected across the treatment train at IN, AS, AC, TA, and TB and the kitchen sink (DIST) by Battelle staff members and analyzed by either AAL or EPA's National Risk Management Research Laboratory (NRMRL). Non-compliance samples collected by Battelle are denoted by "*"in Figures 4-9 and 4-10. Where applicable, total and free chlorine concentrations measured at the AC location are noted along with the TTHM and/or HAA5 data in the figures.

Before installation of the arsenic removal system, source water was softened and chlorinated. TTHM concentrations measured at the kitchen sink ranged from 7.0 to 86.1 µg/L and averaged 30.1 µg/L; HAA5 concentrations ranged from 6.3 to 42.0 µg/L and averaged 24.4 µg/L. Except for one TTHM sample taken on July 28, 2004, all TTHM and HAA5 results were below the respective MCLs of 80 and 60 µg/L. The formation of TTHM and HAA5 was the result of interaction between NaOCl and approximately 2 mg/L of natural organic matter in source water after some periods of reaction time (Rathbun, 1997; Summers et al., 1996).

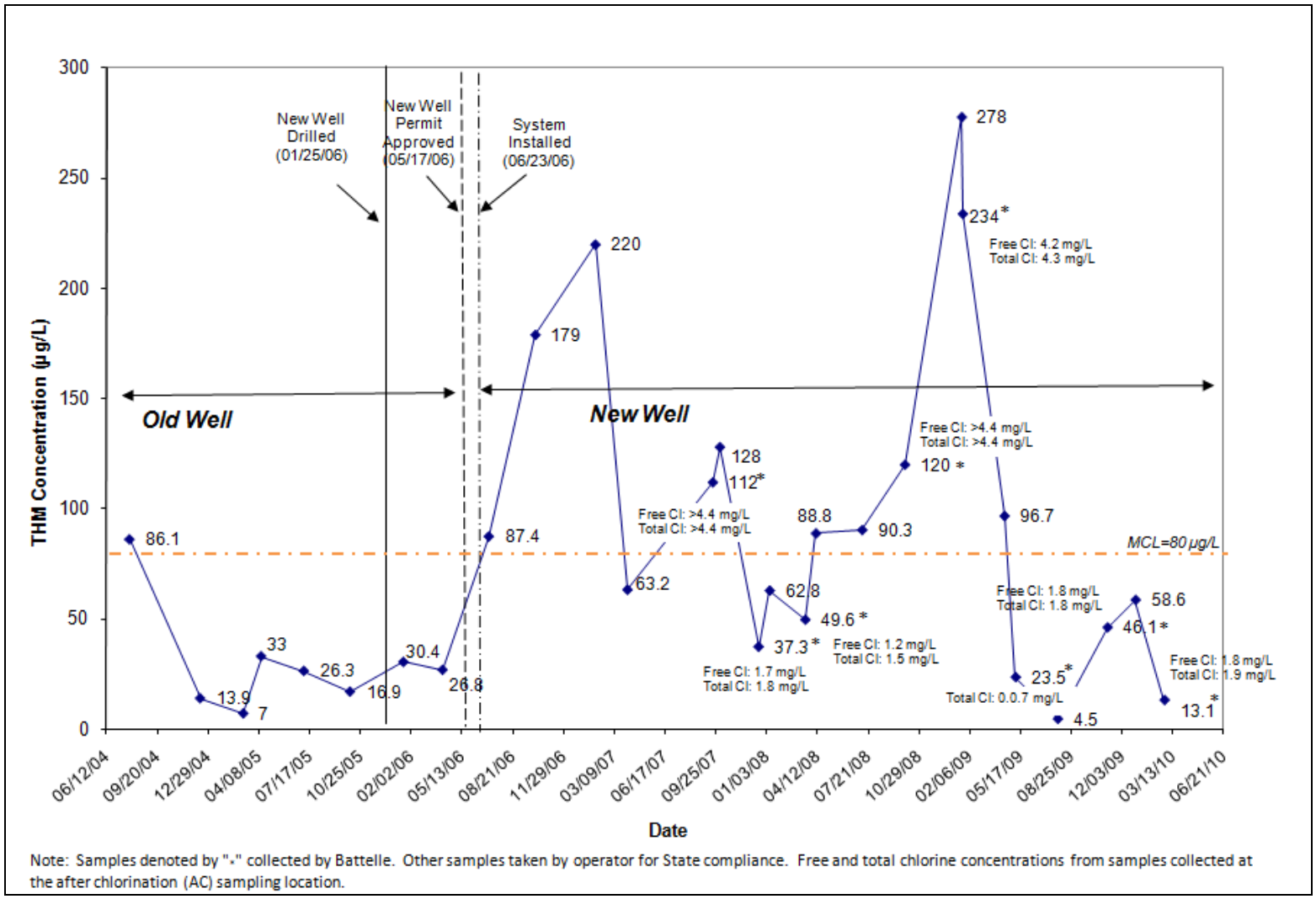
After system startup on June 23, 2006, TTHM concentrations at the kitchen sink drastically increased to 87.4, 179, and 220 µg/L on July 5, 2006; October 5, 2006; and January 31, 2007, respectively; HAA5 concentrations also increased to 187 and 262 µg/L on October 5, 2006, and January 31, 2007. On April 4, 2007, the TTHM concentration decreased to 63.2 µg/L but the HAA5 concentration remained above the MCL at 81.3 µg/L. On September 19, 2007, and March 19, 2008, Battelle began to collect samples across the treatment train and at the kitchen sink for TTHM and HAA5 analyses, respectively. Since then through June 2009 when the system configuration was modified in an effort to curb excessive DBP formation, TTHM and HAA5 concentrations at the kitchen sink had been fluctuating between 23.5 and 278 µg/L and between 13.1 and 489 µg/L, respectively. Among the samples collected since system startup until June 2009, 11 out 16 TTHM samples and 12 out of 15 HAA5 samples exceeded their respective MCLs.

Table 4-9. Summary of TTHM Concentrations in Water Samples

Sampling Date	TTHM Concentration (µg/L)						Data Source
	IN	AS	AC	TA	TB	DIST	
07/28/04	NA	NA	NA	NA	NA	**86.1**	OEPA/AAL
12/14/04	NA	NA	NA	NA	NA	13.9	OEPA/AAL
03/09/05	NA	NA	NA	NA	NA	7.0	OEPA/AAL
04/13/05	NA	NA	NA	NA	NA	33.0	OEPA/AAL
07/06/05	NA	NA	NA	NA	NA	26.3	OEPA/AAL
10/05/05	NA	NA	NA	NA	NA	16.9	OEPA/AAL
01/18/06	NA	NA	NA	NA	NA	30.4	OEPA/AAL
04/05/06	NA	NA	NA	NA	NA	26.8	OEPA/AAL
07/05/06	NA	NA	NA	NA	NA	**87.4**	OEPA/AAL
10/05/06	NA	NA	NA	NA	NA	**179**	OEPA/AAL
01/31/07	NA	NA	NA	NA	NA	**220**	OEPA/AAL
04/04/07	NA	NA	NA	NA	NA	63.2	OEPA/AAL
09/19/07	8.5	<2	10.8	28.2	49.5	**112**	Battelle/NRMRL
10/03/07	NA	NA	NA	NA	NA	**128**	OEPA/AAL
12/18/07	<2	<2	10.8	30.5	43.9	37.3	Battelle/NRMRL
01/09/08	NA	NA	NA	NA	NA	62.8	OEPA/AAL
03/19/08	5.6	2.1	16.3	37.1	39.5	49.6	Battelle/AAL
04/09/08	NA	NA	NA	NA	NA	**88.8**	OEPA/AAL
07/09/08	NA	NA	NA	NA	NA	**90.3**	OEPA/AAL
10/01/08	<2	<2	7.9	18.3	29.2	**120**	Battelle/AAL
01/21/09	NA	NA	NA	NA	**NA**	**278**	OEPA/AAL
01/23/09	<2	<2	20.1	51.0	**152**	**234**	Battelle/AAL
04/15/09	NA	NA	NA	NA	NA	**96.7**	OEPA/AAL
05/07/09	<2	<2	7.0	20.4	49.3	23.5	Battelle/AAL
07/29/09	NA	NA	NA	NA	NA	4.5	OEPA/AAL
11/04/09	<2	<2	11.8	31.5	44.8	46.1	Battelle/AAL
12/29/09	NA	NA	NA	NA	NA	58.6	OEPA/AAL
02/24/10	<2	<2	6.7	9.2	14.1	13.1	Battelle/AAL

Shading indicates samples collected after system startup.
Bold values are MCL exceedances.
IN = at wellhead; AS = after water softener; AC = after chlorination; TA and TB = after adsorption vessels A and B; DIST = kitchen sink
AAL = American Analytical Laboratories; NA = not analyzed; NRMRL = National Risk Management Research Laboratory; OEPA = Ohio Environmental Protection Agency

Figures 4-11 and 4-12 plot TTHM and HAA5 concentrations, respectively, in samples taken across the treatment train and at the kitchen sink by Battelle. From September 19, 2007, through May 7, 2009, TTHM concentrations after chlorination and detention (AC) ranged from 7.0 to 20.1 µg/L and averaged 12.2 µg/L; HAA5 concentrations ranged from 4.1 to 19.4 µg/L and averaged 12.2 µg/L. After adsorption, TTHM concentrations increased significantly to between 18.3 and 51.0 µg/L (30.9 µg/L [on average]) following Vessel A and to between 29.2 and 152 µg/L (60.6 µg/L [on average]) following Vessel B. Similarly, HAA5 concentrations increased to between 11.9 and 55.4 µg/L (28.5 µg/L [on average]) following Vessel A and to between 25.9 and 197 µg/L (81.7 µg/L [on average]) following Vessel B. The use of ARM 200 media appears to have promoted TTHM and HAA5 formation in the presence of TOC and chlorine; prolonged contact with the media appeared to have further enhanced the formation. As noted above, out of the 2.0 mg/L of TOC in source water, about 0.2 to 0.3 mg/L (on average) was removed by ARM 200.



Note: Samples denoted by "*" collected by Battelle. Other samples taken by operator for State compliance. Free and total chlorine concentrations from samples collected at the after chlorination (AC) sampling location.

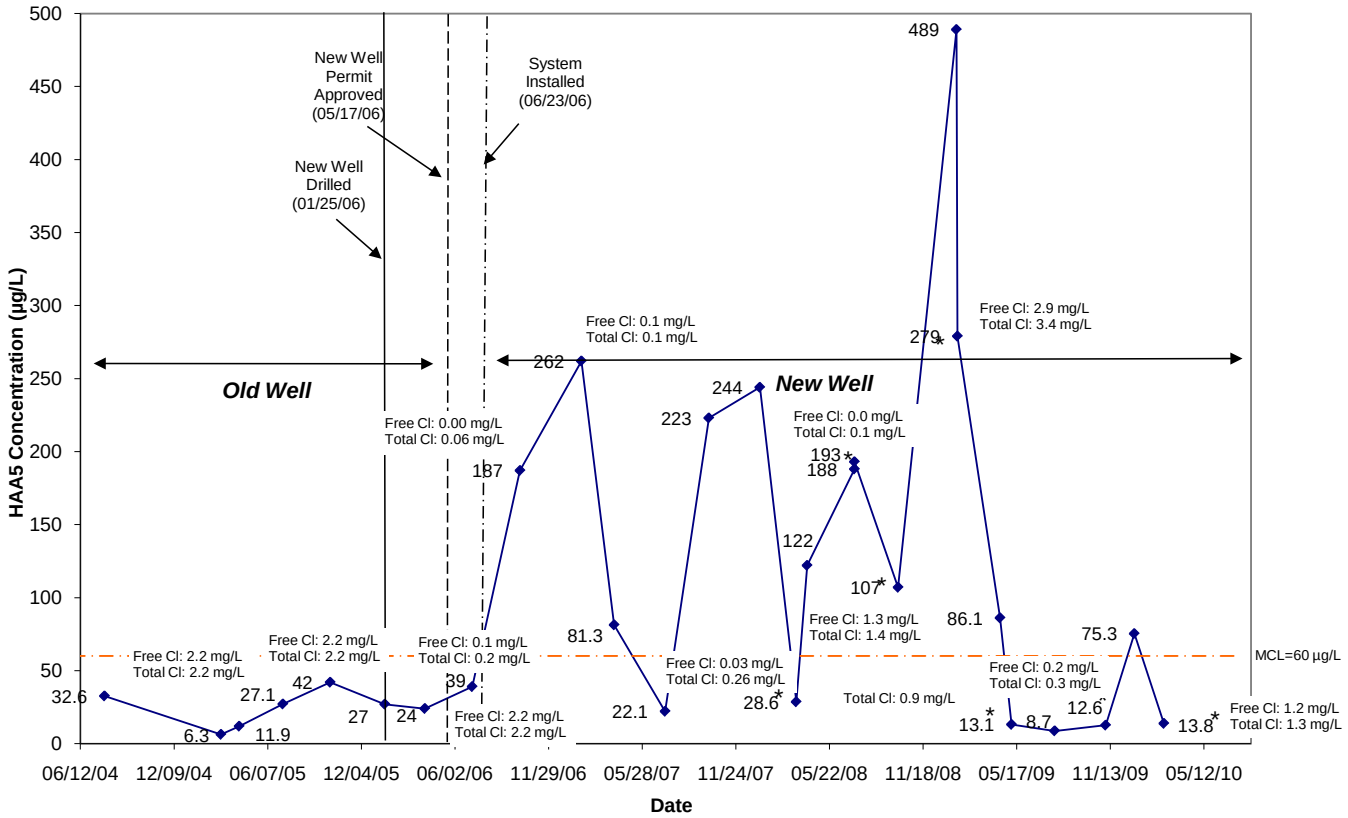
Figure 4-9. TTHM Concentrations at Kitchen Sink

Table 4-10. Summary of HAA5 Concentrations in Water Samples

Sampling Date	HAA5 Concentration (µg/L)						Data Source
	IN	AS	AC	TA	TB	DIST	
07/28/04	NA	NA	NA	NA	NA	32.6	OEPA/AAL
03/09/05	NA	NA	NA	NA	NA	6.3	OEPA/AAL
04/13/05	NA	NA	NA	NA	NA	11.9	OEPA/AAL
07/06/05	NA	NA	NA	NA	NA	27.1	OEPA/AAL
10/05/05	NA	NA	NA	NA	NA	42.0	OEPA/AAL
01/18/06	NA	NA	NA	NA	NA	27.0	OEPA/AAL
04/05/06	NA	NA	NA	NA	NA	24.0	OEPA/AAL
07/05/06	NA	NA	NA	NA	NA	39.0	OEPA/AAL
10/05/06	NA	NA	NA	NA	NA	**187**	OEPA/AAL
01/31/07	NA	NA	NA	NA	NA	**262**	OEPA/AAL
04/04/07	NA	NA	NA	NA	NA	**81.3**	OEPA/AAL
10/03/07	NA	NA	NA	NA	NA	**223**	OEPA/AAL
01/09/08	NA	NA	NA	NA	NA	**244**	OEPA/AAL
03/19/08	<2	<2	10.9	13.7	25.9	28.6	Battelle/AAL
04/09/08	NA	NA	NA	NA	NA	**122**	OEPA/AAL
07/09/08	NA	NA	NA	NA	NA	**188**	OEPA/AAL
07/09/08	<2	<2	19.4	55.4	**94**	**193**	Battelle/AAL
10/01/08	<2	<2	10.6	19.1	36.6	**107**	Battelle/AAL
01/21/09	NA	NA	NA	NA	NA	**489**	OEPA/AAL
01/23/09	<2	<2	16.1	42.6	**197**	**279**	Battelle/AAL
04/15/09	NA	NA	NA	NA	NA	**86.1**	OEPA/AAL
05/07/09	<2	<2	4.1	11.9	55.1	13.1	Battelle/AAL
07/29/09	NA	NA	NA	NA	NA	8.7	OEPA/AAL
11/04/09	<2	<2	3.0	9.5	13.0	12.6	Battelle/AAL
12/29/09	NA	NA	NA	NA	NA	**75.3**	OEPA/AAL
02/24/10	<2	<2	7.3	12.1	20.3	13.8	Battelle/AAL

Shading indicates samples collected after system startup.
Bold values are MCL exceedances.
IN = at wellhead; AS = after water softener; AC = after chlorination; TA and TB = after adsorption vessels A and B; DIST = kitchen sink
AAL = American Analytical Laboratories; NA = not analyzed; NRMRL = National Risk Management Research Laboratory; OEPA = Ohio Environmental Protection Agency

Following the adsorption vessels, the treated water entered the distribution system constructed of PVC and copper. Significant increases in DBP concentrations at the kitchen sink were observed during two sampling events on October 1, 2008, and January 23, 2009, with TTHM and HAA5 concentrations spiked o as high as 234 and 279 µg/L, respectively. Piping leading from the outlet of the arsenic removal system to the kitchen sink included 12.6, 4.6, and 32.6 ft of 1.5 in PVC Schedule 80, 1.0 in PVC Schedule 40, and 0.75 in copper pipe, respectively, which could hold only 2.1 gal of water combined. As such, the extra contact time in the distribution piping would not have contributed to the significant increase in DBP concentrations observed. Water temperature also was contemplated as a potential factor; however, its effect was soon ruled out as shown by Figure 4-13, which plots TTHM and HAA5 concentrations against temperature at the AC sampling location.



Note: Samples denoted by "*" collected by Battelle. Other samples taken by operator for State compliance. Sample was collected by both Battelle for EPA and the operator for State Compliance on 07/09/08. July 2007 data not valid due to system bybpass.

Figure 4-10. HAA5 Concentrations at Kitchen Sink

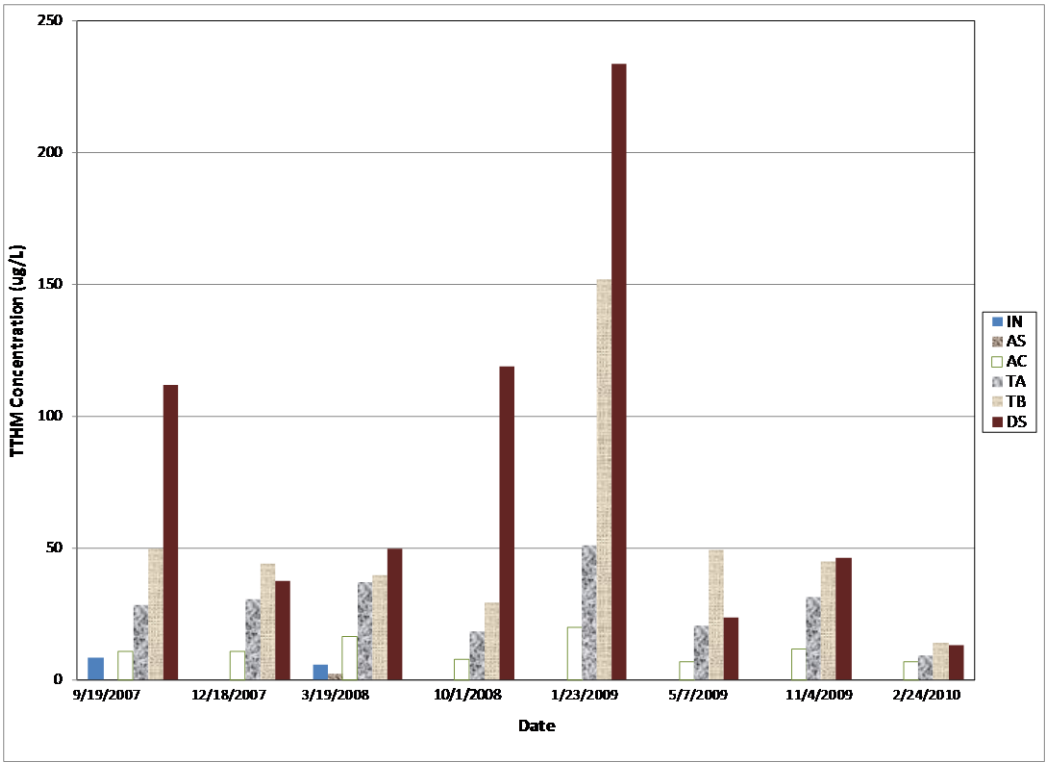


Figure 4-11. Formation of TTHM Across Treatment Train and Distribution System

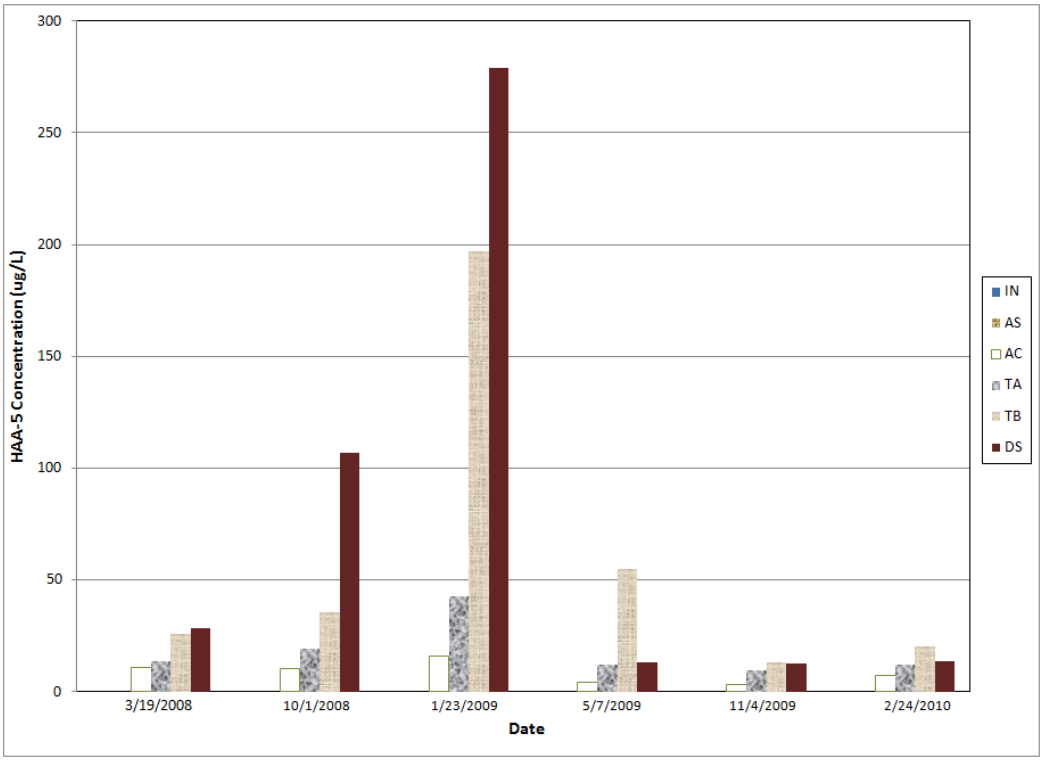


Figure 4-12. Formation of HAA5 Across Treatment Train and Distribution System

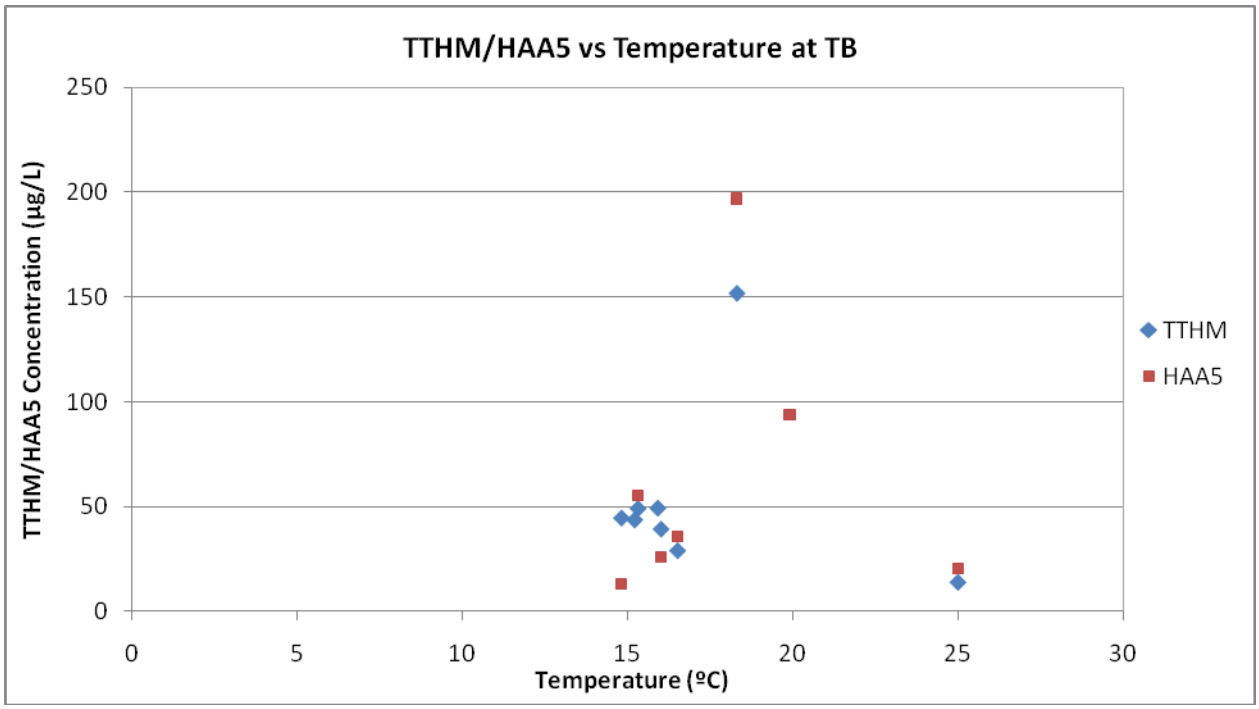


Figure 4-13. Effects of Water Temperature on TTHM and HAA5 Concentrations at AC Location

Differences in water temperature of the samples collected at the kitchen sink might have been caused by how the samples were collected using a single-lever faucet during sampling. It was conceivable that some hot water could have been dispensed depending on the lever position of the faucet. To alleviate any concern, TTHM and HAA5 samples were collected from the kitchen sink in May 2009, with the lever positioned for either hot or cold water. The hot water sample, after being flushed long enough to get the water hot at 44.1ºC, had a TTHM concentration of 5.8 µg/L and a HAA5 concentration of 5.8 µg/L. The cold water sample at 21.8ºC had a TTHM concentration of 40.6 µg/L and a HAA5 concentration was 25.9 µg/L. Therefore, it appears that water temperature did not have much of an effect on TTHM and HAA5 concentrations.

High total and free chlorine residual concentrations were measured at the kitchen sink (DIST) on a number of occasions as shown in Figures 4-9 and 4-10. Even higher total and free chlorine residual levels (with some above the MDL of 4.4 mg/L [as Cl_2]) were measured after the contact tank (AC). (Higher levels of chlorine residuals at AC compared to those at TA and TB indicate chlorine demand across the media beds.) Measured values of TTHM and HAA5 at DIST were correlated to free chlorine residual levels at both AC and DIST and these correlations are presented in Figures 4-14 and 4-15. A linear regression was fit over both sets of data forcing the origin to the fit. These regressions yielded R^2 values of 0.64 and 0.66 for TTHM and 0.62 and 0.26 for HAA5. The low R^2 value of 0.26 was caused mainly by a single data point, i.e., 193 µg/L of HAA5 at 0 mg/L free chlorine residuals, at the kitchen sink. Except for two data points at DIST, higher-than-MCL levels of TTHM and HAA5 occurred only when free chlorine residual levels were over 2 mg/L (as Cl_2).

As noted above, system modifications were implemented as an attempt to curb excessive DBP formation. The first modification involved moving the 120-gal pressure tank from the head to the end of the treatment train to gain better control over chlorine dosing. This modification, completed on June 17, 2009, allowed the system to operate with a constant water flowrate (10 gpm) and a constant chlorine

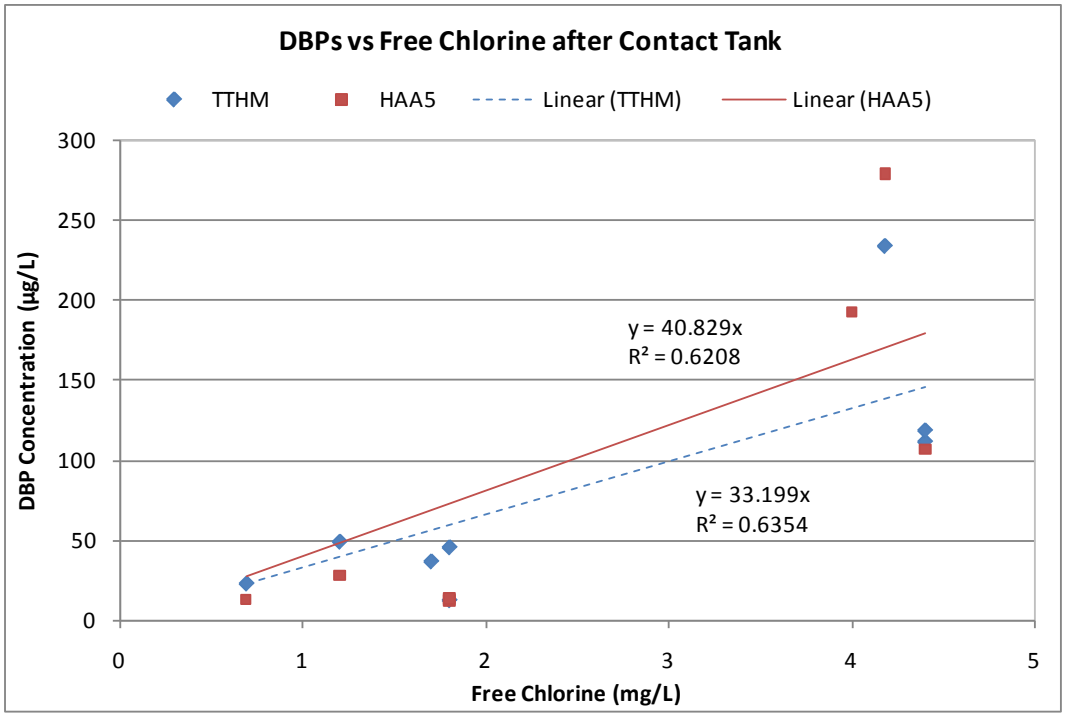


Figure 4-14. Correlation of TTHM/HAA5 with Free Chlorine Residuals Measured After Contact Tank

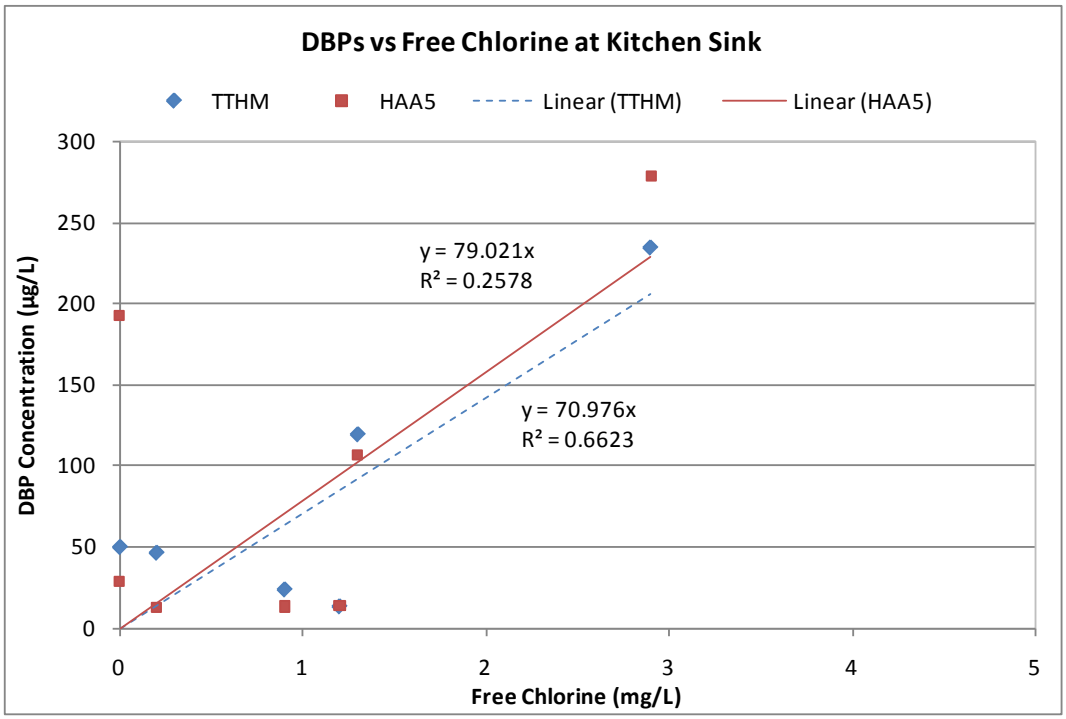


Figure 4-15. Correlation of TTHM/HAA5 with Free Chlorine Residuals Measured at Kitchen Sink

dose rate whenever the well pump was on. (Before this modification, the system was operating on-demand with varying water flowrates and one chlorine dose rate). This, in conjunction with better O&M on the chlorine addition system by a designated Battelle staff member as discussed in Section 4.4.2, allowed the chlorine residuals at AC and DIST to become more constant as shown in Figure 4-4. However, it was discovered soon after the modification that this new system configuration would not allow the water softener to be regenerated properly due to lack of water during most regeneration cycles. (Note that during softener regeneration, water needed for regeneration would be supplied from the pressure tank.) After system reconfiguration, the softener would be regenerated only when the well pump was triggered by low pressure in the pressure tank. Otherwise, the softener would not be regenerated even though the system would still go through the regeneration cycle as though it had. Therefore, the pressure tank was returned to the beginning of the treatment train on September 14, 2009, so that the water softener could be regenerated properly.

The second system modification involved replacing the pre-existing metering pump with a flow-paced pump. This allowed the amount of chlorine addition to be paced with varying water flowrates to the system. This modification, completed on November 2, 2009, resulted in a better control over chlorine dosing, which appeared to help reduce DBP concentrations as shown in Figures 4-9 through 4-12. From November 2, 2009, through the end of DBP sampling on February 24, 2010, TTHM concentrations ranged from 14.1 to 44.8 μg/L following the treatment system and from 13.1 to 58.6 μg/L at the kitchen sink; HAA5 concentrations ranged from 13.0 to 20.3 μg/L following the treatment system and 8.7 to 75.3 μg/L at the kitchen sink. Except for one HAA5 exceedance (75.3 μg/L on December 29, 2009), all DBP measurements were below the respective MCLs of 80 and 60 μg/L.

In summary, exceeded levels of TTHM and HAA5 are thought to be caused by elevated free chlorine residuals in the ARM 200 adsorptive media system. In general, TTHM and HAA5 exceeded the MCL when free chlorine residuals were above approximately 2 mg/L (as Cl_2). Additional testing was conducted in the laboratory to better understand the processes involved in the DBP formation.

Formation Potential Tests. Formation potential tests were conducted in the laboratory on the water collected after softening (from AS location). As noted above, the formation of DBPs requires the presence of organic matter, chlorine and some contact time. Under these conditions, concentrations of DBPs can be quantified and the water can be assigned the so-called "formation potential," given a specific dose of NaOCl and a specific reaction time. The formation potential of a source water also is dictated by the amount and type of oxidizable organic matter (often measured as TOC or via UV 254 nm) in the water. Many types of organic matter are present in natural waters and extensive efforts have been made to identify specific moieties of organic carbon responsible for the formation of DBPs (Joll et al., 2010; Quintana et al., 2010; Bond et al., 2009; Fang et al., 2009; Huang, 2009; Kristiana, 2009; Zhang, 2009; Marhaba, 2000; Oliver, 1980). No attempts were made to identify the types of organic matter for this study. The formation potential also may be affected by the amount of reducing species present in the water and, to a greater extent, the ammonia content of the water (Amy et al., 1984). The presence of ammonia can significantly reduce the DBP formation and ammonia addition has even been suggested as a mitigating action for the formation of DBPs (Bougeard et al., 2010).

Table 4-11 summarizes residual chlorine concentrations in the chlorinated AS water at 0, 12, 24, and 48 hr. The 0-hr measurements were performed approximately 10 to 20 min after 1.6, 2.6, and 4.8 mg/L of chlorine (as Cl_2) had been spiked into respective sample bottles. Thus, the initial chlorine demand of the AS water, measured at 10 min, was 0.78 mg/L (as Cl_2). The 1.6 mg/L of chlorine (as Cl_2) spiked was completely consumed in 48 hr. The 2.6 and 4.8 mg/L of chlorine (as Cl_2) spiked were consumed to close to 0.6 and 2.4 mg/L (as Cl_2), respectively, in 48 hr.

Table 4-11. Chlorine Demand Test Results (AS Water)

Reaction Time (hr)	Chlorine Dosage (mg/L [as Cl_2])			
	0	1.6	2.6	4.8
0	<0.05	0.82	1.80	3.06
12	<0.05	0.27 ± 0.00	1.14 ± 0.02	2.71 ± 0.01
24	<0.05	0.13 ± 0.01	0.83 ± 0.06	2.76 ± 0.03
48	<0.05	<0.05	0.60 ± 0.02	2.38 ± 0.10

Tables 4-12 and 4-13 summarize concentrations of four THMs and five HAAs in the chlorinated AS water. All TTHM and HAA5 concentrations were well below the respective MCL of 60 and 80 µg/L, with TTHM concentrations ranging from 14.9 to 36.8 µg/L and HAA5 concentrations from 7.4 to 19.0 µg/L. These values are rather close to the results of non-compliance sampling conducted by Battelle at AC (which ranged from 7.0 to 20.1 µg/L for TTHM and 4.1 to 19.4 µg/L for HAA5), but somewhat lower than the results of compliance sampling conducted by the Head Start operator before system startup (which ranged from 7.0 to 86.1 µg/L for TTHM and 6.3 to 42.0 µg/L for HAA5). Chloroform was the most abundant THM in the chlorinated AS water while TCA and DCA were the most abundant HAAs. Duplicate samples collected at 48 hr yielded consistent results for both THMs and HAAs with the percent relative difference (PRD) ranging from 0.23 to 15%.

Figures 4-16 and 4-17 presents 3-D plots of TTHM and HAA5 concentrations, respectively, at three chlorine dosages over four reaction times. Figure 4-18 presents concentrations of chloroform, BDCM, DBCM, and TTHM in the chlorinated AS water as a function of reaction time. Figure 4-19 presents concentrations of DCA, TCA, and HAA5 in the chlorinated AS water as a function of reaction time. In general, concentrations of individual THMs/TTHM and individual HAAs/HAA5 increase with chlorine dosage and reaction time.

Table 4-12. THM Formation Potential Test Results (AS Water)

Chlorine Dosage (mg/L [as Cl_2])	Reaction Time (hr)	Compounds (µg/L)				
		Chloroform	BDCM	DBCM	Bromoform	TTHM
1.6	12	10.7	3.3	1.0	<0.5	14.9
	24	13.9	4.5	1.4	<0.5	19.8
	48	14.0	5.3	1.5	<0.5	20.6
	48 (Dup)	14.5	5.4	1.7	<0.5	21.5
2.6	12	15.2	4.5	1.2	<0.5	20.9
	24	18.8	6.2	1.8	<0.5	26.8
	48	22.2	7.5	1.9	<0.5	31.6
	48 (Dup)	22.1	7.6	2.0	<0.5	31.7
4.8	0	<0.5	<0.5	<0.5	<0.5	<2
	12	15.3	5.3	1.3	<0.5	21.9
	24	17.8	6.0	1.6	<0.5	25.4
	48	27.5	7.7	1.7	<0.5	36.8
	48 (Dup)	25.7	7.2	1.9	<0.5	34.8

BDCM = bromodichloromethane; DBCM = dibromochloromethane;
TTHM = total THMs

Table 4-13. HAA Formation Potential Test Results (AS Water)

Chlorine Dosage (mg/L [as Cl_2])	Reaction Time (hr)	Compounds (µg/L)					
		DBA	DCA	MBA	MCA	TCA	HAA5
1.6	12	<1	3.3	<1	<2	4.1	7.4
	24	<1	4.0	<1	<2	4.8	8.8
	48	1.1	4.4	<1	<2	5.2	10.6
	48 (Dup)	1.1	4.4	<1	<2	5.3	10.8
2.6	12	<1	3.7	<1	<2	6.3	10.1
	24	<1	5.3	<1	<2	8.3	13.6
	48	1.0	5.4	<1	<2	7.8	14.2
	48 (Dup)	1.0	6.3	<1	<2	8.5	15.8
4.8	0	<1	<1	<1	<2	<1	<5
	12	<1	4.8	<1	<2	8.6	13.4
	24	<1	6.2	<1	<2	11.3	17.5
	48	<1	7.1	<1	<2	11.9	19.0
	48 (Dup)	<1	6.8	<1	<2	11.0	17.8

DBA = dibromoacetic acid; DCA = dichloroacetic acid;
MBA = monobromoacetic acid; MCA = monochloroacetic acid;
TCA = trichloroacetic acid; HAA5 = sum of all five HAAs

Because the highest concentrations of TTHM and HAA5 formed were 36.8 and 19.0 µg/L, respectively, the elevated DBP concentrations observed in the system effluent and kitchen sink must have been contributed by factors other than TOC concentration, chlorine dosage, and chlorine reaction time. Therefore, additional laboratory tests were conducted to recreate field conditions in the laboratory to determine the cause of the elevated DBP concentrations observed.

Column Studies. A series of column studies was carried out in an attempt to simulate onsite conditions under a controlled laboratory setting. The column studies were divided into three phases for Column A and two phases for Columns B and C. Appendix C contains a complete set of analytical results. Tables 4-14 and 4-15 summarize TTHM and HAA5 results measured during each of the three column studies.

Column A, packed with virgin ARM 200 media, received DI water spiked with 2.4 to 5.4 mg/L of chlorine (as Cl_2) during Phase I of the study (see Figure 4-20). After feeding the column with approximately 2,000 BV of chlorinated DI water, pH values of the column effluent, after initial dips to as low as 4.1, began to approach those of the feed at 7.5 (on average). After that time, total chlorine residuals in the column effluent were still at levels below 1.6 mg/L (as Cl_2), indicating chlorine demand by the media. (Note that because ammonia had been removed by the softener prior to chlorination, total chlorine residuals were at about the same levels as free chlorine residuals.) A sample was then collected and analyzed for DBPs. The results showed only 1.7 and 5.8 µg/L of TTHM and HAA5, respectively, in the column effluent, indicating little or no DBP precursor associated with the media.

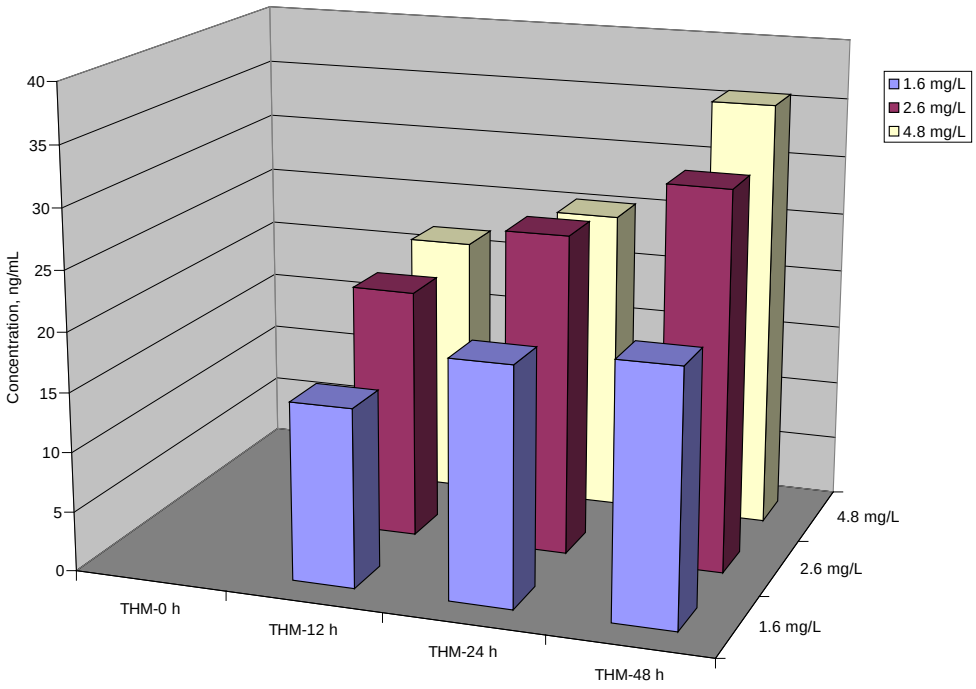


Figure 4-16. TTHM Formation Potential Test Results (AS Water)

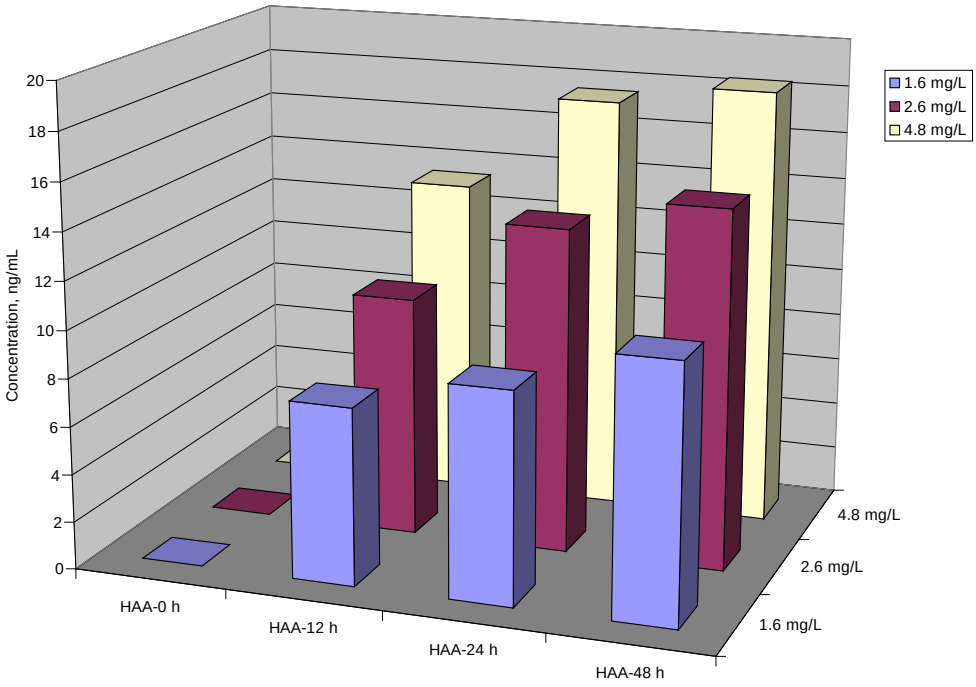
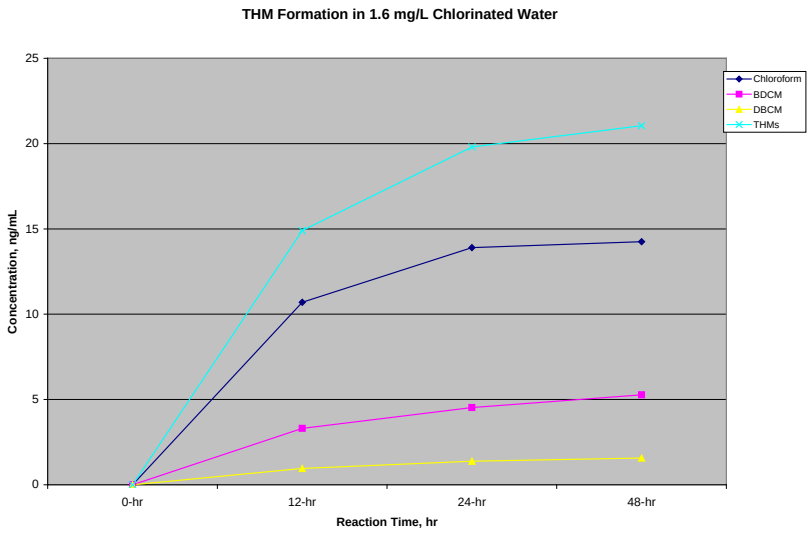
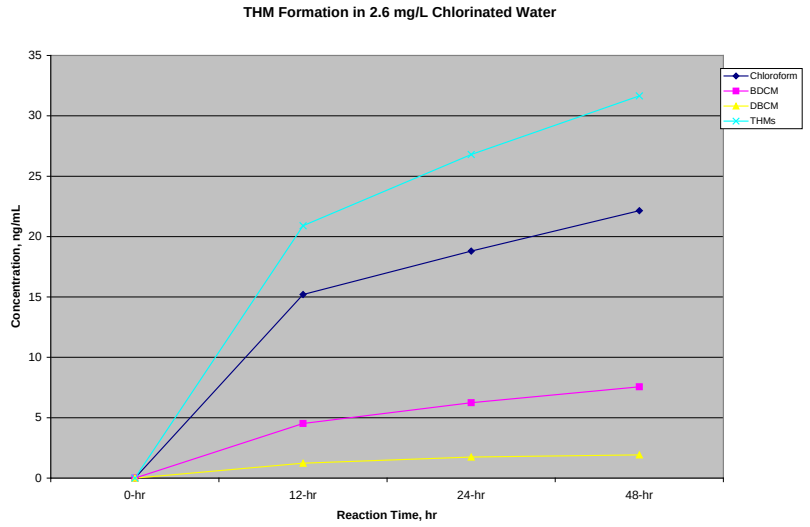


Figure 4-17. HAA5 Formation Potential Test Results (AS Water)





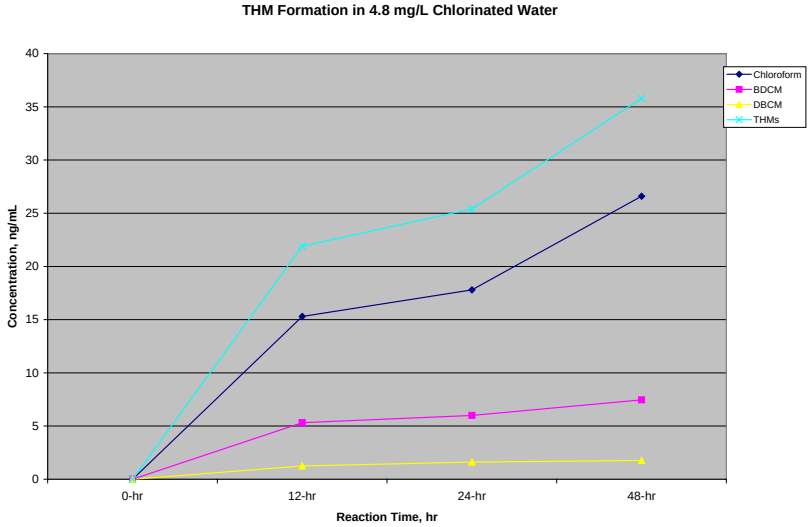


Figure 4-18. THM Formation Potential Test Results in Chlorinated AS Water

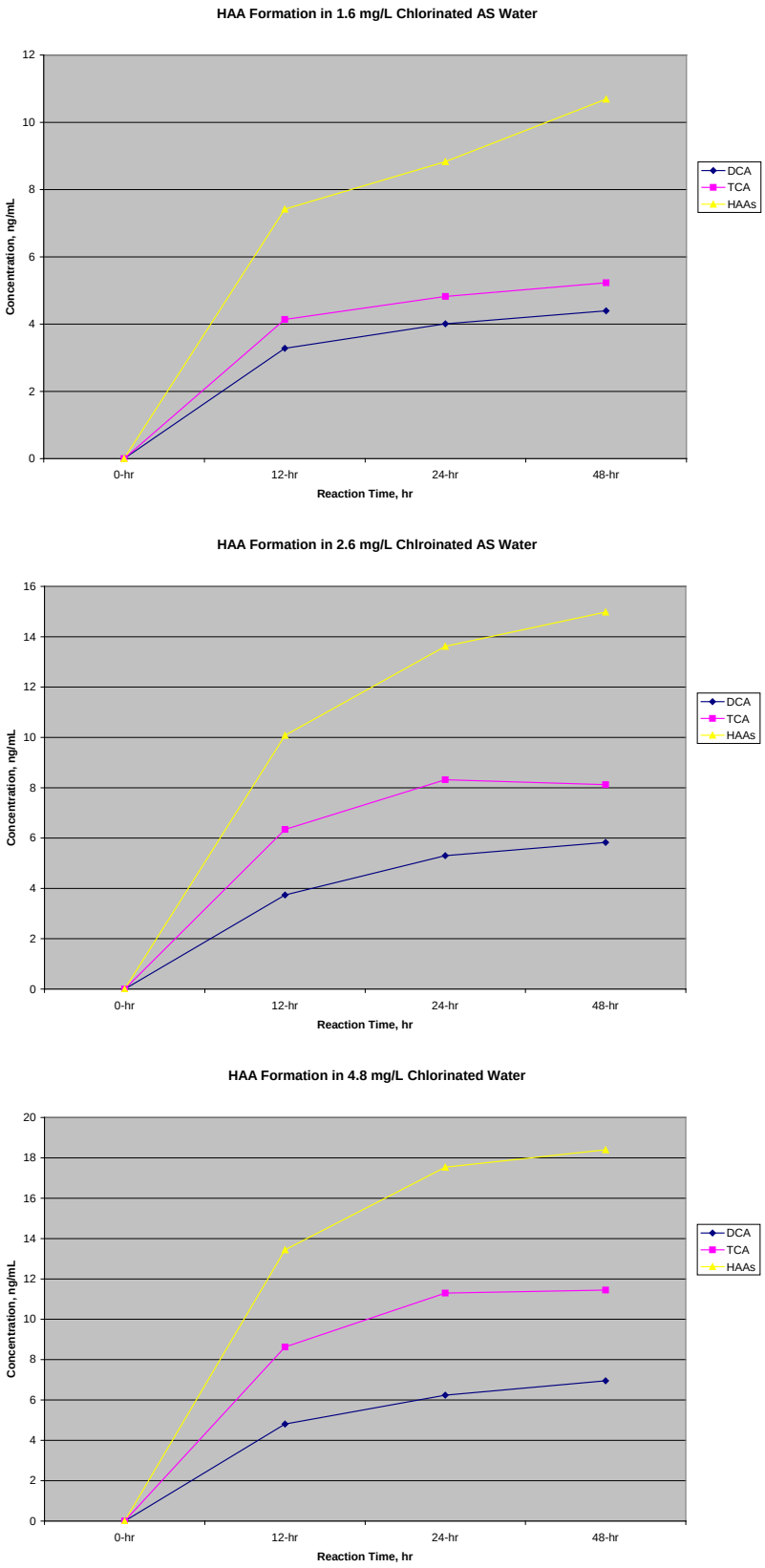


Figure 4-19. Formation Potential Test Results of HAAs in Chlorinated AS Water

Table 4-14. TTHM and HAA5 Concentrations Measured During Column A (Phases II and III) and Column C Studies

Date	Influent			Effluent			
				Column A[(b)]		Column C[(c)]	
	TTHM (µg/L)	HAA5 (µg/L)	Total/Free Chlorine (mg/L)	TTHM (µg/L)	HAA5 (µg/L)	TTHM (µg/L)	HAA5 (µg/L)
08/28/09	NA	NA	3.3/NA	<2.0	5.8	-	-
09/10/09 [(a)]	<2.0	1.9	4.1/0.8	<2.0	3.9	-	-
09/25/09	25.4	13.1	3.3/3.7	73.2	58.3	40.4	24.1
10/09/09	34.5	9.3	4.4/3.8	65.1	24.1	40.6	14.0
10/23/09	29.9	9.8	4.0/3.5	52.6	19.1	35.4	12.3
11/06/09	35.1	10.3	4.2/4.0	51.6	20.2	40.0	12.1
11/13/09	30.0	10.0	4.2/4.4	43.3	16.4	36.2	12.8
11/20/09	40.8	12.2	4.4/4.1	66.9	26.7	53.5	9.2
12/4/09 [(d)]	39.6	12.4	11.1/10.9	55.3	21.4	45.2	17.1
01/15/10	33.4	17.3	10.0/9.5	49.2	22.0	41.3	17.3

(a) Influent to column on September 10, 2009, contained ammonia, which reacted with chlorine to form combined chlorine.
(b) Phase II of Column A began operation on August 28, 2009; influent to column contained 4.0 mg/L of chlorine (as Cl_2).
(c) Column C began operation on September 21, 2009.
(d) Phase III of Column A began operation on December 2, 2009; influent to column contained 10 mg/L of chlorine (as Cl_2).

NA = not available

Table 4-15. TTHM and HAA5 Concentrations Measured During Column B Studies

Date	Influent			Effluent	
	TTHM (µg/L)	HAA5 (µg/L)	Total/Free Chlorine (mg/L)	TTHM (µg/L)	HAA5 (µg/L)
09/25/09	0.8	0.0	4.7/4.6	2.2	1.5
10/09/09	0.9	0.0	4.3/4.1	3.9	0.0
10/23/09	0.0	0.0	4.0/3.8	0.0	0.0
11/06/09	1.1	0.0	4.4/4.2	5.2	2.4
11/13/09	0.0	0.0	3.5/3.9	2.3	0.0
11/20/09	0.7	0.0	5.4/5.3	3.3	1.9
12/4/09 [(a)]	0.9	0.0	10.4/10.3	3.6	2.3
01/15/10	2.3	0.0	9.9/8.5	2.3	0.0

(a) Chlorine concentrations in feed increased to 10 mg/L (as Cl_2).

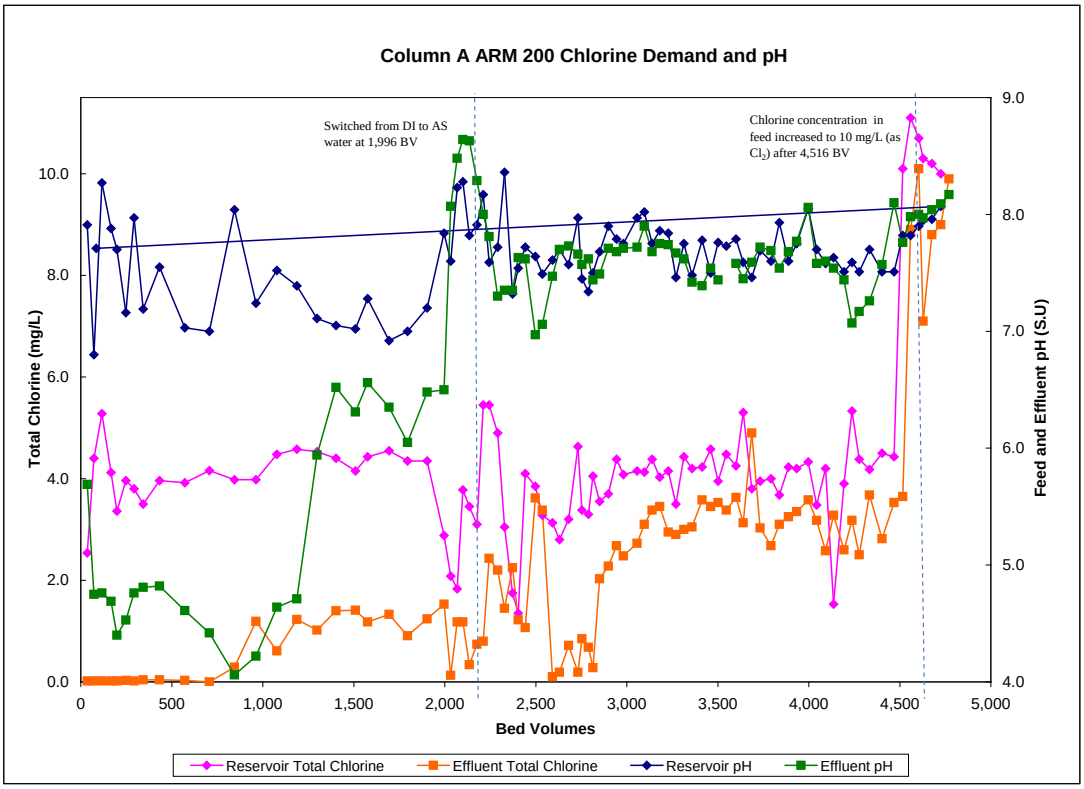


Figure 4-20. Column A ARM 200 Chlorine Demand and pH

During Phase II, the feed to Column A was switched from chlorinated DI water to chlorinated softened water (softened water was taken at AS containing 1.3 to 2.1 mg/L of TOC), but maintained the target total chlorine dose of 4.0 mg/L (as Cl_2). From the formation potential study, it was determined that TOC present in the influent acted as a DBP precursor. Observations made during onsite sampling indicated that ARM 200 might be playing a role in increasing DBP concentrations following the adsorption vessels. The hypothesis was that interaction of chlorine and TOC in the presence of ARM 200 media would increase DBP concentrations above the levels indicated by the formation potential study. This indeed was the case except for one instance on September 10, 2009, when the feed water contained combined chlorine (see Table 4-14) due to the presence of NH_3 in the feed water. The presence of combined chlorine apparently inhibited the formation of TTHM and HAA5, resulting in only <2.0 and 3.9 µg/L of TTHM and HAA5, in the column effluent. Also of note is that the presence of NH_3 in AS water was caused by improper softener regeneration due to the system reconfiguration as described on page 45.

After switching the column influent to chlorinated AS water, some TOC was removed by ARM 200 media during the first 1,500 BV (i.e., from approximately 2,000 to 3,500 BV) but effluent TOC levels reached influent levels throughout the remainder of the column test (Figure 4-21). Meanwhile, TTHM and HAA5 concentrations increased to 73.2 and 58.3 µg/L, respectively (Figure 4-22). The increase in DBP concentration was offset by the increase in DBP formation in the feed itself, which ranged from 25.4 to 40.8 µg/L for TTHM and from 9.3 to 17.3 µg/L for HAA5 during the study. Therefore, net increases in concentration ranged from 13.3 to 47.8 µg/L for TTHM and from 6.1 to 14.6 µg/L for HAA5. Although ARM 200 did increase the DBP concentration as the feed passed through the column, the increase was not of the same magnitude observed at the Head Start building.

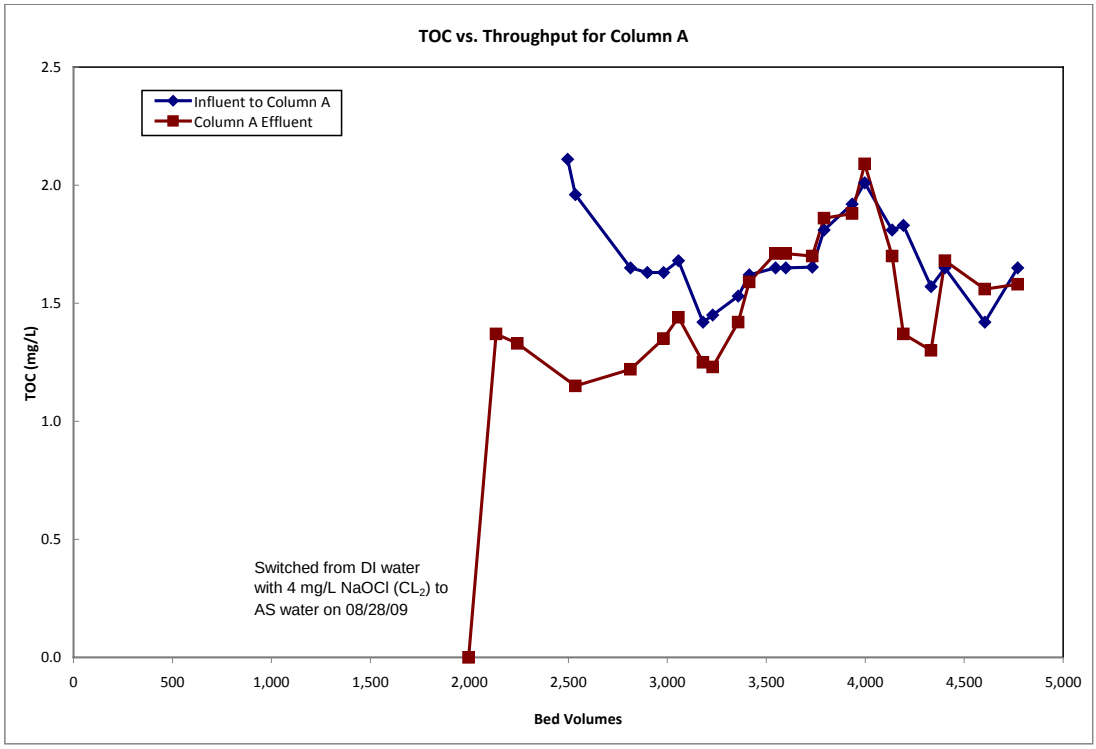


Figure 4-21. TOC Breakthrough from Column A

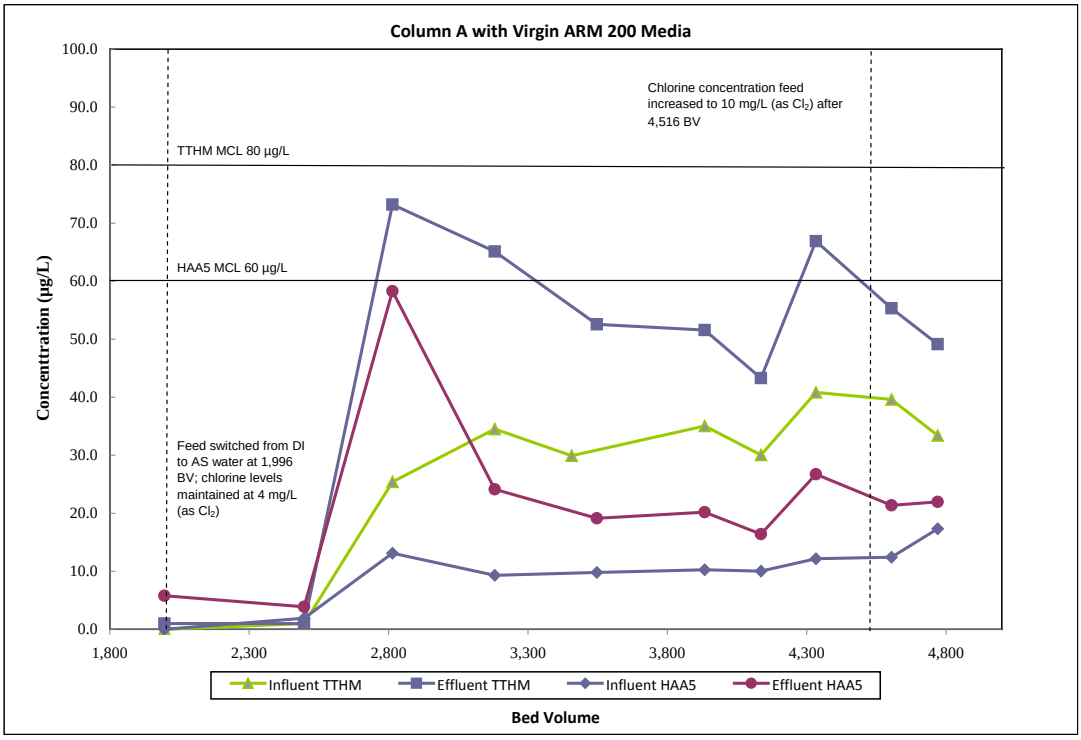


Figure 4-22. TTHM and HAA5 Concentrations in Feed and Column A Effluent

The literature has reported enhanced formation of DBPs in a chlorinated system of organic polymer and clay (Lee et al., 1998). The enhanced formation was thought to be caused by the presence of metal cations on the clay surface. In follow-up work (Lee et al., 2004), DBP formation in the presence of metal-doped montmorillonite was enhanced five times during a 2-hr reaction time and four to 10 times during a 24-hr reaction time. It was hypothesized that the acidic cation-exchanged montmorillonite served as an effective catalyst for the electrophilic organic substitution reaction, which ultimately led to the formation of DBPs. It is not clear if any metal cations on ARM 200 media played a role in increased production of TTHM and HAA5.

During Phase III of the study, chlorine dosages were increased to between10.0 and 10.3 mg/L (as Cl_2) (see Figure 4-20). Net increases in DBP formation after the switch to 10.0 mg/L (as Cl_2) ranged from 15.7 to 15.8 µg/L for TTHM and from 4.6 to 9.0 µg/L for HAA5, which were less than expected.

Column B was packed with the media taken from the top of Vessel A at the Head Start building and was fed with DI water spiked with an average of 4.1 (Phase I) or 10.4 mg/L of chlorine (as Cl_2) (Phase II) throughout the study. As shown in Table 4-15, concentrations in the column effluent were measured from <MDL to 5.2 µg/L for TTHM and from <MDL to 2.4 µg/L for HAA5. These concentrations were only slightly higher than those measured in the chlorinated DI water (i.e., from <MDL to 0.9 µg/L for TTHM and <MDL for HAA5), indicating that adsorbed TOC did not react with chlorine to form DBPs. Increasing chlorine concentrations from 4.1 to 10.4 mg/L (as Cl_2) only slightly increased HAA5 concentrations to 2.3 µg/L.

Packed with the same media as Column B and fed with the chlorinated AS water used for Phases II and III of Column A study, Column C was used to simulate the conditions at the Head Start building. During Phase I with a target chlorine residual level of 4.0 mg/L (as Cl_2), effluent concentrations were measured from 35.4 to 53.5 for TTHM and from 9.2 to 24.1 for HAA5 (Table 4-14). These results were just slightly lower than those seen in Column A when fed with chlorinated AS water. During Phase II, the target chlorine concentration was increased to 10.0 mg/L (as Cl_2). The resulting TTHM and HAA5 concentrations were within the ranges measured during Phase I (4.0 mg/L of chlorine [as Cl_2] in the influent). Therefore, elevated concentrations seen in samples collected at the kitchen sink were unable to be replicated in the laboratory. One factor could be the contact time. The column studies used an EBCT of approximately 30 min, which might have been lower than the reaction times typically observed at the Head Start building. Note that due to low water usage, low flowrates, and high storage capacity after chlorination, a set of procedures had been developed to avoid excessive contact prior to each sampling event as described in Section 3.3.2.

In summary, the results of the laboratory column studies suggest that ARM 200 media with the presence of TOC and free chlorine in the influent has the ability to increase DBP formation. However, this increase was not on the same order as what was observed onsite, even with an influent chlorine concentration of 10.0 mg/L (as Cl_2). Therefore, the results of the column studies cannot explain the elevated DBP concentrations observed at the site. The onsite results seem to indicate that exceeded levels of DBPs can be avoided if levels of chlorine residuals are controlled to below 2 mg/L (as Cl_2).

4.5.3 Backwash Wastewater Sampling. The two adsorption vessels were backwashed once on December 13, 2006, after six months of operation. Table 4-16 presents the analytical results. The wastewater contained 74 to 125 mg/L of total suspended solids (TSS), which was composed mostly of particulate iron (28 to 54 mg/L). Because iron in source water had already been removed to below the MDL by the water softener as demonstrated by the results of most sampling events, the particulate iron found in the backwash wastewater were assumed to be primarily media fines. A small amount of manganese also was washed off the media beds during backwashing.

Table 4-16. Backwash Water Analytical Results

Analytes	Unit	Vessel A	Vessel B
pH	S.U.	7.8	7.5
TDS	mg/L	482	482
TSS	mg/L	125	74
As (total)	µg/L	8.2	1.7
As (soluble)	µg/L	4.6	0.8
As (particulate)	µg/L	3.7	0.9
Fe (total)	µg/L	54,469	28,036
Fe (soluble)	µg/L	721	35.0
Mn (total)	µg/L	317	43.0
Mn (soluble)	µg/L	30.0	0.4

4.5.4 Distribution System Water Sampling. Table 4-17 presents the results of the distribution system water sampling. As expected, prior to system startup, arsenic concentrations in the distribution system were similar to those measured in raw water, ranging from 12.8 to 18.3 µg/L and averaging 15.2 µg/L. After system startup, arsenic concentrations in the distribution system were reduced significantly to <0.1 to 5.0 µg/L and averaged 1.3 µg/L.

During the first 13 months of system operation when distribution system water samples were collected, arsenic concentrations in the distribution system water were somewhat higher than those measured in treatment system effluent (see Figure 4-23). Some dissolution and/or resuspension of arsenic might have occurred in the distribution system.

Lead levels ranged from <0.1 to 0.6 µg/L and averaged 0.3 µg/L in the baseline samples and ranged from <0.1 to 3.4 µg/L and averaged 0.8 µg/L in the samples collected after system startup (excluding the September 13, 2006, sample when the lead level spiked to 8.5 µg/L at the DS3 sampling location). All lead measurements were below the lead action level of 15 µg/L. Copper concentrations ranged from 104 to 796 µg/L and averaged 356 µg/L in the baseline samples and ranged from 11 to 299 µg/L and averaged 90 µg/L in the samples taken after system startup. All copper concentrations measured were below the copper action level of 1,300 µg/L. Lead concentrations in the distribution system water were generally slightly higher than before system startup. Copper concentrations in the distribution system water were significantly lower than those before system startup.

Similar to those in softened water, iron concentrations were below the MDL in the distribution system water samples. Manganese concentrations also were low, averaging 0.5 and 0.8 µg/L before and after system startup. pH values ranged from 7.4 to 8.2, which were similar to the pH values measured after Vessels A and B. Alkalinity values remained rather constant throughout the distribution system.

4.6 System Cost

The cost of the treatment 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 task required tracking capital cost for the equipment, site engineering, and installation and the O&M cost for media replacement and disposal, replacement parts, chemical supply, electricity consumption, and labor. The cost associated with improvements to the building and any other infrastructure was not included in the capital cost. These activities were funded separately by the facility.

Table 4-17. Distribution System Sampling Results

Sampling Event		DS2									DS3																				
	Address	Kitchen Sink									Men's Sink																				
	Sample Type	LCR									LCR																				
	Flushed / 1st Draw	1st Draw									Flushed									1st Draw									Flushed								
	Analytes	Stagnation Time	pH	Alkalinity	As	Fe	Mn	Al	Pb	Cu	Stagnation Time	pH	Alkalinity	As	Fe	Mn	Al	Pb	Cu	Stagnation Time	pH	Alkalinity	As	Fe	Mn	Al	Pb	Cu	Stagnation Time	pH	Alkalinity	As	Fe	Mn	Al	Pb	Cu
No.	Date	hr	S.U.	mg/L	µg/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	µg/L	hr	S.U.	mg/L	µg/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	µg/L
BL1	01/07/05	NS	NS	NS	NS	NS	NS	NS	NS	NS	NA	7.9	343	13.9	<25	5.0	<10	0.2	219	NA	7.8	318	13.1	<25	<0.1	15.2	0.6	796	NA	7.7	322	14.4	<25	<0.1	12.6	0.3	184
BL2	01/28/05	13	7.8	334	12.8	<25	0.5	<10	0.3	619	NA	7.9	326	13.7	<25	0.1	<10	0.1	645	13.17	8.0	334	16.2	<25	<0.1	<10	0.2	199	NA	7.7	334	17.3	<25	<0.1	<10	0.1	121
BL3	02/25/05	15.3	7.8	351	14.3	<25	0.4	<10	0.4	483	NA	7.6	320	14.9	<25	0.1	<10	0.1	551	15.30	7.6	338	14.5	<25	<0.1	<10	0.2	261	NA	7.6	338	15.4	<25	0.2	<10	<0.1	111
BL4	03/21/05	72.0	7.5	326	18.3	<25	<0.1	NA	0.6	405	NA	7.6	343	17.3	<25	<0.1	NA	0.2	400	72	7.5	334	15.7	<25	<0.1	NA	0.4	237	NA	7.6	334	16.2	<25	<0.1	NA	0.1	104
1	08/23/06	NA	8.1	312	1.2	<25	0.2	NA	1.1	40.3	NA	8.1	314	1.0	<25	0.2	NA	1.1	37.1	NA	8.1	318	1.4	<25	<0.1	NA	1.9	28.6	NA	8.1	314	0.9	<25	<0.1	NA	1.9	26.3
2	09/13/06	NA	8.2	358	5.0	<25	4.5	NA	1.1	149	NA	8.2	360	0.4	<25	0.4	NA	3.4	10.7	NA	8.2	358	0.9	<25	0.6	NA	8.5	27.3	NA	8.2	365	1.2	<25	1.4	NA	2.1	29.5
3	10/19/06	NA	7.4	360	1.0	<25	0.4	NA	2.2	61.2	NA	7.6	374	2.0	<25	0.5	NA	0.8	251	NA	7.6	376	0.8	27.1	<0.1	NA	0.8	62.2	NA	7.6	370	0.5	<25	0.2	NA	0.9	60.0
4	11/09/06	NA	7.6	361	2.6	<25	1.4	NA	0.4	183	NA	7.7	355	1.2	<25	2.5	NA	2.9	43.6	NA	7.6	365	0.6	<25	0.2	NA	0.4	51.0	NA	7.7	357	0.9	<25	0.1	NA	0.4	78.6
5	12/19/06	NA	7.9	409	0.5	<25	0.5	NA	0.2	14.7	NS	NS	NS	NS	NS	NS	NS	NS	NS	NA	7.5	393	2.4	<25	0.1	NA	0.2	79.2	NS	NS	NS	NS	NS	NS	NS	NS	NS
6	01/25/07	NA	7.6	324	1.5	<25	1.0	NA	<0.1	66.8	NS	NS	NS	NS	NS	NS	NS	NS	NS	NA	7.6	314	1.0	<25	0.2	NA	0.3	49.3	NS	NS	NS	NS	NS	NS	NS	NS	NS
7	02/15/07	NA	7.6	356	3.6	<25	1.4	NA	0.3	163	NS	NS	NS	NS	NS	NS	NS	NS	NS	NA	7.7	359	2.9	<25	0.4	NA	0.8	96.8	NS	NS	NS	NS	NS	NS	NS	NS	NS
8	03/14/07	NA	7.7	389	1.4	<25	0.9	NA	0.1	166	NS	NS	NS	NS	NS	NS	NS	NS	NS	NA	7.7	369	1.1	<25	<0.1	NA	0.3	101	NS	NS	NS	NS	NS	NS	NS	NS	NS
9	04/11/07	NA	7.6	360	<0.1	<25	0.8	NA	0.2	152	NS	NS	NS	NS	NS	NS	NS	NS	NS	NA	7.7	353	<0.1	<25	0.3	NA	0.3	52.9	NS	NS	NS	NS	NS	NS	NS	NS	NS
10	05/08/07	NA	7.6	369	2.1	<25	0.6	NA	0.5	228	NS	NS	NS	NS	NS	NS	NS	NS	NS	NA	7.6	345	0.6	<25	0.2	NA	0.3	20.8	NS	NS	NS	NS	NS	NS	NS	NS	NS
11	06/06/07	NA	7.4	316	1.2	<25	0.7	NA	<0.1	53.7	NS	NS	NS	NS	NS	NS	NS	NS	NS	NA	7.4	313	0.4	<25	0.7	NA	<0.1	51.1	NS	NS	NS	NS	NS	NS	NS	NS	NS
12	09/12/07	NA	7.9	341	1.3	<25	4.4	NA	0.7	299	NS	NS	NS	NS	NS	NS	NS	NS	NS	NA	7.9	346	0.6	<25	0.5	NA	0.7	161	NS	NS	NS	NS	NS	NS	NS	NS	NS

BL = Baseline Sampling; NS = not sampled

Lead action level = 15 µg/L; copper action level = 1.3 mg/L

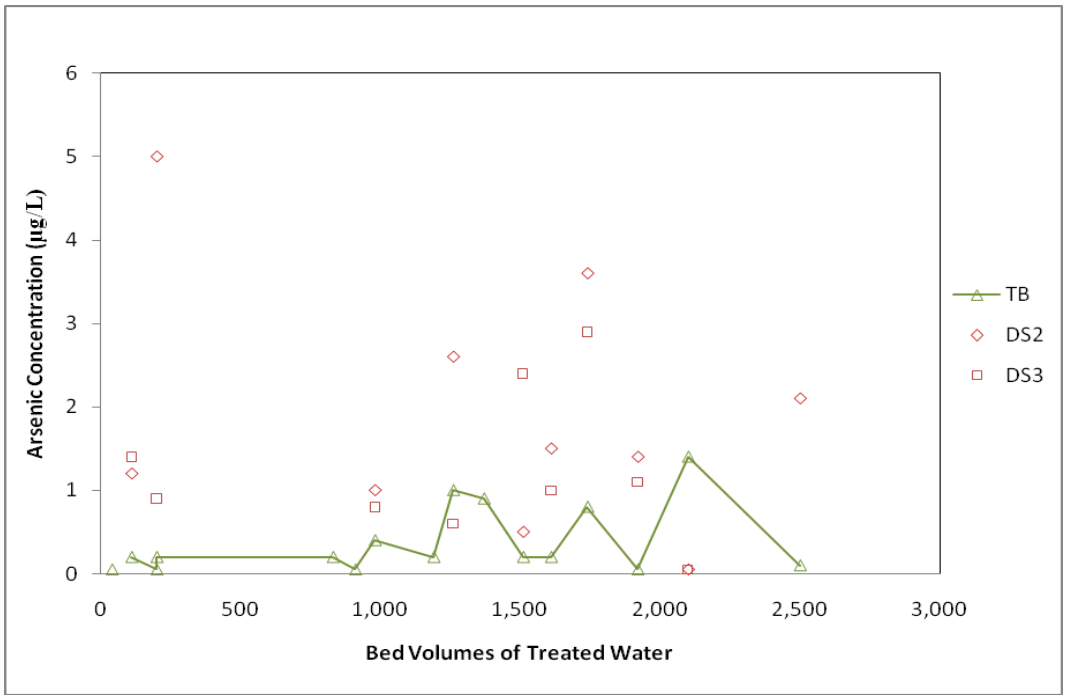


Figure 4-23. Comparison of Arsenic Concentrations in System Effluent and Distribution System

4.6.1 Capital Cost. The capital investment for equipment, site engineering, and installation was $27,255 (see Table 4-18). The equipment cost was $10,435 (or 38% of the total capital investment), which included $4,435 for the treatment system mechanical hardware, $4,000 for 9 ft^3 of ARM 200 media (i.e., $445/$ft^3$ or $8.89/lb), and $2,000 for the vendor's labor and shipping cost.

The engineering cost included the cost for the preparation of the system layout and footprint, design of the piping connections to the entry and distribution tie-in points, and assembly and submission of the engineering plans for the permit application (Section 4.3). The engineering cost was $11,000, or 40% of the total capital investment.

The installation cost included the cost of labor and materials to unload and install the treatment system, complete the piping installation and tie-ins, and perform the system startup and shakedown (Section 4.3). The installation was performed by Kinetico. The installation cost was $5,820, or 22% of the total capital investment.

The total capital cost of $27,255 was normalized to $2,725/gpm ($1.89/gpd) of design capacity using the system's rated capacity of 10 gpm (or 14,400 gpd). The capital cost also was converted to an annualized cost of $2,572/yr using a capital recovery factor of 0.09439 based on a 7% interest rate and a 20-year return period. Assuming that the system operated 24 hr/day, 7 day/week at the design flowrate of 10 gpm to produce 5,256,000 gal of water per year, the unit capital cost would be $0.49/1,000 gal. However, the system processed 303,200 gal of water in 44 months or approximately 82,500 gal/yr. At this reduced rate of operation, the unit capital cost increased to $31.36/1,000 gal of water treated.

Table 4-18. Summary of Capital Investment Cost

Description	Quantity	Cost	% of Capital Investment Cost
Equipment Cost			
Adsorption Vessels	2	$1,450	–
ARM 200 Adsorptive Media (ft^3)	9	$4,000	–
Piping and Valves	1	$2,105	–
Flow Totalizers/Meters	2	$880	–
Procurement, Assembly, Labor	1	$2,000	–
Equipment Total	–	**$10,435**	**38%**
Engineering Cost			
Design/Scope of System (hr)	88	$11,000	–
Engineering Total	–	**$11,000**	**40%**
Installation Cost			
Mechanical Materials	1	$400	–
Vendor Installation Labor	-	$1,000	
Mechanical Subcontractor Labor	-	$4,000	
Vendor Travel	-	$420	–
Installation Total	–	**$5,820**	**22%**
Total Capital Investment	–	**$27,255**	**100%**

4.6.2 Operation and Maintenance Cost. The O&M cost for the Kinetico arsenic removal system included only the incremental cost associated with the treatment system, such as media replacement and disposal, chemical supply, electricity consumption, and labor, as presented in Table 4-19.

In general, for a two-vessel system operating in series, the media in the lead vessel is replaced when the effluent arsenic concentration following the lag vessel reaches the 10-µg/L MCL. Once the lead vessel is rebedded, it is valved into the lag position and the lag vessel becomes the lead vessel. This method allows the media's capacity to be fully utilized before its replacement.

Table 4-19. Summary of O&M Cost

Cost Category	Media Run	Remarks
Volume Processed (gal)	303,200	To end of evaluation period in 44 months
Media Replacement and Disposal		
Unit Media Cost ($/$ft^3$)	$300	4.5 ft^3 of E33 in lead vessel
Subtotal ($)	$4,049	Including media, underbedding, freight, labor, travel, and spent media analysis and disposal
Media Replacement Cost ($/1,000 gal)	See Figure 4-24	
Chemical Usage		
Chemical ($)	$0.0	No additional chemical required
Electricity		
Electricity ($/1,000 gal)	$0.0	No additional electricity required
Labor		
Average Weekly Labor (hr)	0.25	15 min/day, 1 day/week
Labor Cost ($/yr)	$260	$20/hr
Labor Cost ($/1,000 gal)	$3.17	82,000 gal/yr of water treated
Total O&M cost ($/1,000 gal)	See Figure 4-24	

Because the media was not replaced at the Head Start building during the performance evaluation study and because ARM 200 media was no longer available, it was assumed that it would cost $4,049 to change out and dispose of 4.5 ft^3 of media in the lead vessel. This media change-out cost was derived from the cost for rebedding 5 ft^3 of E33 media in the lead vessel at Goffstown, NH, where a similar lead/lag adsorptive media system was evaluated under this demonstration program (McCall, et al., 2009). The $4,049 included the cost for 4.5 ft^3 of E33 media, freight, labor, travel, spent media analysis, and media disposal fee. By averaging the media replacement cost of $4,049 over the media life, the unit cost per 1,000 gal of water treated is plotted as a function of the media life, as shown in Figure 4-24.

There were no additional electricity requirements associated with the treatment system. The well pump and chlorine injection pump were pre-existing and the only equipment present that required electricity. Routine, non-demonstration-related labor activities consumed about 15 min/week as noted in Section 4.4.4. Depending on how the system performs and if any additional troubleshooting is required, the labor incurred will vary. The estimated labor cost for operating and maintaining the arsenic removal system was $3.17/1,000 gal of water treated.

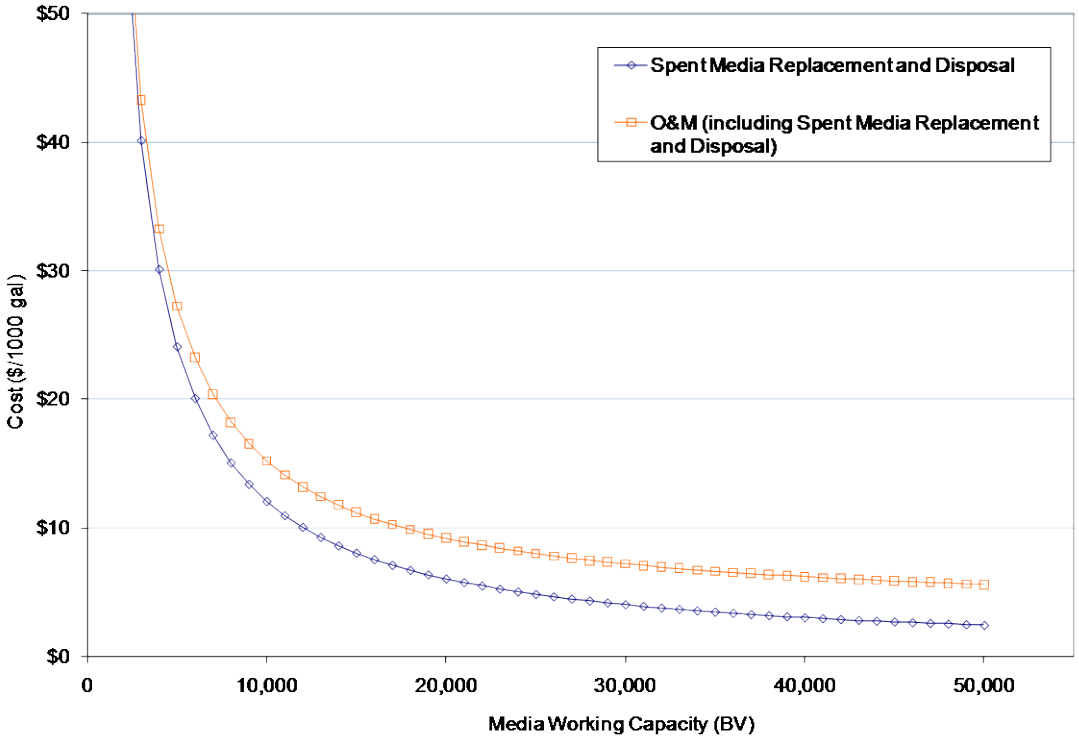


Figure 4-24. Total O&M and Media Replacement Cost Curves

5.0 REFERENCES

Amy, G.L., P.A. Chadik, and P.H. King. 1984. "Chlorine Utilization During Trihalomethane Formation in the Presence of Ammonia and Bromide." *Environ. Sci. Technol.*, 18:781-786.

Battelle. 2004. *Quality Assurance Project Plan for Evaluation of Arsenic Removal Technology*. Prepared under Contract No. 68-C-00-185, Task Order No. 0029, for U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Battelle. 2005. *System Performance Evaluation Study Plan: U.S. EPA Demonstration of Arsenic Removal Technology at the LEADS Head Start Site in Buckeye Lake, OH.* Prepared under Contract No. 68-C-00-185, Task Order No. 0029, for U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Bond, T., O. Henriet, E.H. Goslan, S.A. Parsons, and B. Jefferson. 2009. "Disinfection Byproduct Formation and Fractionation Behavior of Natural Organic Matter Surrogates." *Environ. Sci. Technol.* 43: 5982-5989.

Bougeard, C.M.M., E.H. Goslan, B. Jefferson, and S.A. Parsons. 2010. "Comparison of the Disinfection By-product Formation Potential of Treated Waters Exposed to Chlorine and Monochloramine," *Water Research*, 44: 729-740.

Chen, A.S.C. V. Lal, R.J. Stowe, and B.J. Yates. 2009b. *Test Plan: Disinfection Byproducts Column Studies. U.S. EPA Arsenic Removal Technology Demonstration – Round 2a at Head Start Program Building in Buckeye Lake, OH.* Prepared under Contract No. 68-C-00-185, Task Order No. 0029, for U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Chen, A.S.C., J.P. Lipps, S.E. McCall, and L. Wang. 2009a. *Arsenic Removal from Drinking Water by Adsorptive Media, U.S. EPA Demonstration Project at Richmond Elementary School in Susanville, CA. Final Performance Evaluation Report.* EPA/600/R-09/067. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Chen, A.S.C. and B.J. Yates. 2009. Letter Report: *Disinfection Byproducts Formation Potential of Softened Inlet Water at Buckeye Lake Head Start Program Building.* Prepared under Contract No. 68-C-00-185, Task Order No. 0029, for U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Chen, A.S.C., W.E. Condit, L. Wang, and A.Wang. 2008. *Arsenic Removal from Drinking Water by Adsorptive Media, U.S. EPA Demonstration Project at Brown City, MI. Final Performance Evaluation Report.* EPA/600/R-08/142. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Chen, A.S.C., L. Wang, J.L.Oxenham, and W.E. Condit. 2004. *Capital Costs of Arsenic Removal Technologies: U.S. EPA Arsenic Removal Technology Demonstration Program Round 1.* EPA/600/R-04/201. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Cumming, L.J., A.S.C. Chen, and L. Wang. 2009. *Arsenic Removal from Drinking Water by Adsorptive Media, U.S. EPA Demonstration Project at South Truckee Meadows General Improvement*

District (STMGID), NV. Final Performance Evaluation Report. EPA/600/R-09/016. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Edwards, M., S. Patel, L. McNeill, H. Chen, M. Frey, A.D. Eaton, R.C. Antweiler, and H.E. Taylor. 1998. "Considerations in As Analysis and Speciation." *J. AWWA, 90(3*): 103-113.

EPA. 2001. National Primary Drinking Water Regulations: Arsenic and Clarifications to Compliance and New Source Contaminants Monitoring. *Federal Register*, 40 CFR Parts 9, 141, and 142.

EPA. 2002. *Lead and Copper Monitoring and Reporting Guidance for Public Water Systems*. EPA/816/R-02/009. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

EPA. 2003. Minor Clarification of the National Primary Drinking Water Regulation for Arsenic. *Federal Register*, 40 CFR Part 141.

Fang, J., J. Ma, X. Yang, and C. Shang, C. 2009. "Formation of Carbonaceous and Nitrogenous Disinfection Byproducts from the Chlorination of *Microcyistis aeruginosa*." *Water Research,* 44(6): 1934-1940.

Huang, J., N. Graham, M.R. Templeton, Y. Zhang, C. Collins, and M. Nieuwenhuijsen. 2009. "A Comparison of the Role of Two Blue-Green Algae in THM and HAA Formation." *Water Research,* 43:3009-3018.

Joll, C.A., M.J. Alessandrino, and A. Heitz. 2010. "Disinfection Byproducts Formation from Halogeation of Aqueous Solutions of Terpenoids." *Water Research,* 44: 232-242.

Kristiana, I., H. Gallard, C. Joll, and J.-P. Croue. 2009. "The Formation of Halogen-specific TOX from Chlorination and Chloramination of Natural Organic Matter Isolates." *Water Research,* 43:4177-4186.

Lee, J.F., P.M. Liao, C.K. Lee, H.P. Chao, C.L. Peng, and C.T. Chiu. 2004. "Clay-catalyzed Reactions of Coagulant Polymers During Water Chlorination." *J. Coll. Int. Sci.* 270: 381-387.

Lee, J.F., P.M. Liao, D.H. Tseng, and P.T. Wen. 1998. "Behavior of Organic Polymers in Drinking Water Purification." *Chemosphere*. 37: 1045-1061

Lipps, J.P., A.S.C. Chen, L. Wang, A. Wang, and S.E. McCall. 2010. *Arsenic Removal from Drinking Water by Adsorptive Media, U.S. EPA Demonstration Project at Spring Brook Mobile Home Park in Wales, ME. Final Performance Evaluation Report.* EPA/600/R-10/012. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Lipps, J.P., A.S.C. Chen, S.E. McCall, and L.Wang. 2008. *Arsenic Removal from Drinking Water by Adsorptive Media, U.S. EPA Demonstration Project at Dummerston, VT. Final Performance Evaluation Report.* EPA/600/R-08/081. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Marhaba, T.F. and V. Doanh. 2000. "The Variation of Mass and Disinfection By-product Formation Potential of Dissolved Organic Matter Fractions Along a Conventional Surface Water Treatment Plant," *J. Haz. Mat., 74: 133-147*.

McCall, S.E., A.S.C. Chen, and L. Wang. 2009. *Arsenic Removal from Drinking Water by Adsorptive Media, U.S. EPA Demonstration Project at Goffstown, NH. Final Performance Evaluation Report.* EPA/600/R-09/015. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Ohio EPA. 2006. Chapter 3745-7: Operator Certification for Public Water Systems and Wastewater Treatment Works. Ohio Revised Code. December 21.

Oliver, B.G. and D.B. Shindler. 1980. "Trihalomethane from the Chlorination of Aquatic Algae." *Environ. Sci. Technol.,* 14:1502-1505.

Quintana, J.B., R. Rodil, P. Lopez-Mahia, S. Muniategui-Lorenzo, and D. Prada-Rodreguez. 2010. "Investigating the Chlorination of Acidic Pharmaceuticals and By-product Formation Aided by an Experimental Design Methodology." *Water Research.* 44:243-255.

Rook, J.J. 1974. "Formation of Haloforms During Chlorination of Natural Waters." *Water Treat Exam,* 23: 234-243.

Rathbun, R.E. 1997. "Effect of Reaction Time on the Formation of Disinfection Byproducts." *Chemosphere*. 34(12): 2699-2713.

Summers, R.S., S.M. Hooper, H.M. Shukairy, G. Solarik, and D. Owen. 1996. "Assessing DBP Yield: Uniform Formation Conditions," *J. AWWA.* 88: 80-93.

Valigore, J.M., A.S.C. Chen, and L.Wang. 2007. *Arsenic Removal from Drinking Water by Adsorptive Media, U.S. EPA Demonstration Project at Valley Vista, AZ. Final Performance Evaluation Report.* EPA/600/R-07/133. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

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

Williams, S., A.S.C. Chen, and L. Wang. 2010. *Arsenic Removal from Drinking Water by Adsorptive Media, U.S. EPA Demonstration Project at Webb Consolidated Independent School District in Bruni, TX. Final Performance Evaluation Report*. EPA/600/R-10/040. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Williams, S., A.S.C. Chen, L. Wang, and A.M. Paolucci. 2009. *Arsenic Removal from Drinking Water by Adsorptive Media, U.S. EPA Demonstration Project at Wellman, TX. Final Performance Evaluation Report.* EPA/600/R-09/145. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Zhang, Q., W.-F. Kuang, L.-Y. Liu, K. Li, K.-H. Wong, A.T. Chow, and P.-K. Wong. 2009. "Trihalomethane, Haloacetonitrile and Chloral Hydrate Formation Potentials of Organic Carbon Fractions from Sub-tropical Forest Soils." *J. Haz. Mat.,* 172: 880-887.

APPENDIX A

OPERATIONAL DATA

Table A-1. EPA Arsenic Demonstration Project at LEADS Head Start in Buckeye Lake, OH – Daily System Operational Data

Week No.	Day of Week	Date	Time	ARM 200 System				Pressure			ΔP		ΔP	Chlorine	
				Flowrate	Totalizer	Cum. Bed Volume	Usage	Inlet	After Vessel A	After Vessel B	Across Vessel A	Across Vessel B	Across System	Chlorine Tank Level	Chlorine Solution Feed Rate
				gpm	gal	BVs	gal	psig	psig	psig	psi	psi	psi	gal	L/min
0	Sat	06/24/06	10:00	0	400	12	400	43	38	42	5	-4	1	8	35
1	Mon	06/26/06	9:30	0	400	12	0	45	41	45	4	-4	0	7.5	35
	Wed	06/28/06	11:45	0	599	18	199	47	42	47	5	-5	0	7	31
2	Wed	07/05/06	14:30	0	700	21	101	48	43	49	5	-6	-1	7	35
3	Sun	07/16/06	9:30	0	1,200	36	500	40	36	41	4	-5	-1	12	40
5	Wed	07/26/06	9:47	0	1,400	42	200	44	42	47	2	-5	-3	12	40
	Sun	07/30/06	12:00	0	1,700	51	300	37	38	43	-1	-5	-6	11.5	40
6	Wed	08/02/06	17:00	0	1,900	56	200	36	37	43	-1	-6	-7	11	40
7	Wed	08/09/06	18:15	0	2,100	62	200	31	33	41	-2	-8	-10	10	40
8	Wed	08/16/06	17:00	0	2,300	68	200	33	36	43	-3	-7	-10	9	40
9	Wed	08/23/06	10:00	0	3,100	92	800	44	47	54	-3	-7	-10	8	40
11	Wed	09/06/06	20:00	0	4,300	128	1,200	23	34	41	-11	-7	-18	14	40
12	Thur	09/14/06	15:15	0	5,900	175	1,600	61	62	62	-1	0	-1	11	50
13	Wed	09/20/06	20:00	0	26,400	784	20,500	50	52	52	-2	0	-2	3	50
14	Thur	09/28/06	6:00	0	27,900	829	1,500	49	51	50	-2	1	-1	0	48
15	Thur	10/05/06	5:15	0	29,400	873	1,500	46	48	47	-2	1	-1	13	40
17	Wed	10/18/06	17:00	0	31,900	948	2,500	42	43	42	-1	1	0	8	40
18	Tues	10/24/06	22:00	0	32,900	977	1,000	55	60	61	-5	-1	-6	7	40
19	Wed	11/01/06	16:45	0	35,200	1,046	2,300	50	52	50	-2	2	0	2	40
20	Wed	11/08/06	18:00	0	36,700	1,090	1,500	40	42	42	-2	0	-2	15	40
21	Wed	11/15/06	13:00	0	40,000	1,188	3,300	50	49	48	1	1	2	8	30
23	Wed	11/29/06	20:00	0	42,300	1,257	2,300	50	51	51	-1	0	-1	6	30
24	Wed	12/06/06	17:30	0	43,600	1,295	1,300	45	47	46	-2	1	-1	14	30
26	Wed	12/19/06	10:00	0	46,000	1,367	2,400	54	56	55	-2	1	-1	7	30
27	Wed	12/27/06	11:30	0	46,100	1,370	100	61	62	62	-1	0	-1	7	30
28	Wed	01/03/07	20:30	0	46,800	1,390	700	46	47	45	-1	2	1	15	30

Table A-1. EPA Arsenic Demonstration Project at LEADS Head Start in Buckeye Lake, OH – Daily System Operational Data (Continued)

Week No.	Day of Week	Date	Time	ARM 200 System				Pressure			ΔP		ΔP	Chlorine	
				Flowrate	Totalizer	Cum. Bed Volume	Usage	Inlet	After Vessel A	After Vessel B	Across Vessel A	Across Vessel B	Across System	Chlorine Tank Level	Chlorine Solution Feed Rate
				gpm	gal	BVs	gal	psig	psig	psig	psi	psi	psi	gal	L/min
30	Wed	01/17/07	21:00	0	49,200	1,462	2,400	46	48	47	-2	1	-1	13	30
	Thur	01/18/07	13:00	0	49,400	1,468	200	35	35	35	0	0	0	12	30
31	Mon	01/22/07	12:00	0	49,800	1,480	400	42	35	35	7	0	7	11.5	30
	Thur	01/25/07	6:00	0	50,700	1,506	900	56	58	57	-2	1	-1	11.25	30
32	Mon	01/29/07	8:00	0	51,400	1,527	700	40	40	40	0	0	0	10.5	30
	Wed	01/31/07	11:00	0	51,700	1,536	300	64	65	65	-1	0	-1	10.25	30
33	Wed	02/07/07	17:00	0	52,800	1,569	1,100	41	42	42	-1	0	-1	15	30
34	Thur	02/15/07	18:00	0	54,100	1,607	1,300	44	46	45	-2	1	-1	14	30
35	Wed	02/21/07	20:30	0	54,800	1,628	700	46	47	46	-1	1	0	13	30
36	Wed	02/28/07	19:30	0	57,000	1,693	2,200	56	58	58	-2	0	-2	12	30
37	Wed	03/07/07	15:00	0	58,500	1,738	1,500	51	52	52	-1	0	-1	15	30
38	Wed	03/14/07	21:00	0	61,100	1,815	2,600	36	35	35	1	0	1	13	30
39	Wed	03/21/07	19:30	0	63,100	1,875	2,000	44	46	45	-2	1	-1	37	30
40	Wed	03/28/07	20:00	0	63,700	1,892	600	51	52	52	-1	0	-1	35	30
41	Wed	04/04/07	19:00	0	64,700	1,922	1,000	60	62	62	-2	0	-2	14	30
42	Wed	04/11/07	19:30	0	66,100	1,964	1,400	48	49	48	-1	1	0	13	30
43	Wed	04/18/07	10:00	0	67,400	2,002	1,300	51	53	52	-2	1	-1	10	30
44	Wed	04/25/07	20:30	0	69,700	2,071	2,300	49	51	50	-2	1	-1	7	30
45	Tues	05/01/07	14:15	0	70,900	2,106	1,200	45	46	46	-1	0	-1	6	30
	Wed	05/02/07	20:30	0	71,300	2,118	400	47	48	47	-1	1	0	5	30
46	Tues	05/08/07	9:30	0	72,400	2,151	1,100	59	61	61	-2	0	-2	15	30
47	Wed	05/16/07	10:30	0	74,400	2,210	2,000	48	49	49	-1	0	-1	12	30
48	Wed	05/23/07	18:30	0	76,200	2,264	1,800	41	43	43	-2	0	-2	10	30
49	Wed	05/30/07	20:45	0	76,400	2,270	200	56	57	57	-1	0	-1	9	30
50	Wed	06/06/07	13:00	0	76,500	2,273	100	46	48	47	-2	1	-1	15	30
51	Wed	06/13/07	9:00	0	77,200	2,294	700	42	44	43	-2	1	-1	14	30

Table A-1. EPA Arsenic Demonstration Project at LEADS Head Start in Buckeye Lake, OH – Daily System Operational Data (Continued)

Week No.	Day of Week	Date	Time	ARM 200 System				Pressure			ΔP		ΔP	Chlorine	
				Flowrate	Totalizer	Cum. Bed Volume	Usage	Inlet	After Vessel A	After Vessel B	Across Vessel A	Across Vessel B	Across System	Chlorine Tank Level	Chlorine Solution Feed Rate
				gpm	gal	BVs	gal	psig	psig	psig	psi	psi	psi	gal	L/min
52	Wed	06/20/07	20:00	0	77,200	2,294	0	58	59	59	-1	0	-1	14	30
53	Wed	07/04/07	9:45	0	77,200	2,294	0	49	50	50	-1	0	-1	14	30
54	Wed	07/11/07	5:30	0	77,200	2,294	0	47	48	48	-1	0	-1	14	30
55	Wed	07/18/07	5:30	0	77,200	2,294	0	47	48	48	-1	0	-1	14	30
56	Wed	07/25/07	19:15	0	77,300	2,296	100	59	61	61	-2	0	-2	14	30
57	Wed	08/01/07	13:15	0	77,500	2,302	200	51	52	52	-1	0	-1	13	30
59	Wed	08/15/07	7:30	0	78,100	2,320	600	55	54	55	1	-1	0	13	35
60	Thur	08/23/07	8:15	0	78,700	2,338	600	45	48	46	-3	2	-1	12	35
61	Wed	08/29/07	19:15	0	79,000	2,347	300	53	54	54	-1	0	-1	11	35
62	Wed	09/05/07	19:30	0	80,300	2,386	1,300	50	52	52	-2	0	-2	13	35
63	Wed	09/12/07	20:15	0	83,300	2,475	3,000	41	42	42	-1	0	-1	28	35
64	Wed	09/19/07	15:00	0	85,200	2,531	1,900	57	58	58	-1	0	-1	18	35
65	Wed	09/26/07	9:00	0	86,500	2,570	1,300	57	58	58	-1	0	-1	5	30
66	Wed	10/03/07	22:00	0	88,600	2,632	2,100	42	44	43	-2	1	-1	14	30
67	Wed	10/10/07	7:30	0	89,900	2,671	1,300	45	47	46	-2	1	-1	13	30
68	Wed	10/17/07	12:30	0	91,200	2,709	1,300	51	53	52	-2	1	-1	12	30
69	Wed	10/24/07	20:15	0	93,200	2,769	2,000	42	43	44	-1	-1	-2	8	30
70	Wed	10/31/07	21:00	0	95,000	2,822	1,800	53	54	54	-1	0	-1	5	30
71	Wed	11/07/07	20:00	0	96,600	2,870	1,600	55	56	57	-1	-1	-2	14	30
72	Wed	11/14/07	20:30	0	97,800	2,906	1,200	46	48	47	-2	1	-1	12	30
73	Tues	11/20/07	20:00	0	99,100	2,944	1,300	48	50	49	-2	1	-1	10	35
74	Wed	11/28/07	19:45	0	100,500	2,986	1,400	61	63	63	-2	0	-2	8	35
75	Wed	12/05/07	21:00	0	101,700	3,021	1,200	51	53	52	-2	1	-1	15	35
76	Tues	12/11/07	14:00	0	102,800	3,054	1,100	43	44	43	-1	1	0	13	35
77	Tues	12/18/07	9:30	0	104,100	3,093	1,300	54	55	55	-1	0	-1	12	35
78	Wed	12/19/07	19:30	0	105,200	3,125	1,100	47	48	48	-1	0	-1	10	35

Table A-1. EPA Arsenic Demonstration Project at LEADS Head Start in Buckeye Lake, OH – Daily System Operational Data (Continued)

Week No.	Day of Week	Date	Time	ARM 200 System				Pressure			ΔP		ΔP	Chlorine	
				Flowrate	Totalizer	Cum. Bed Volume	Usage	Inlet	After Vessel A	After Vessel B	Across Vessel A	Across Vessel B	Across System	Chlorine Tank Level	Chlorine Solution Feed Rate
				gpm	gal	BVs	gal	psig	psig	psig	psi	psi	psi	gal	L/min
79	Wed	12/26/07	9:15	0	105,900	3,146	700	51	53	53	-2	0	-2	9	35
80	Wed	01/02/08	21:00	0	106,300	3,158	400	44	46	45	-2	1	-1	8	35
81	Wed	01/09/08	18:30	0	107,500	3,194	1,200	53	54	54	-1	0	-1	12	35
82	Wed	01/16/08	19:00	0	109,100	3,241	1,600	57	58	59	-1	-1	-2	11	35
83	Wed	01/23/08	22:00	0	110,100	3,271	1,000	62	64	64	-2	0	-2	10	35
85	Wed	02/06/08	19:00	0	113,700	3,378	3,600	44	46	45	-2	1	-1	7	35
86	Wed	02/13/08	18:30	0	114,600	3,405	900	46	48	47	-2	1	-1	13	35
87	Wed	02/20/08	19:30	0	115,700	3,437	1,100	58	60	60	-2	0	-2	12	35
88	Wed	02/27/08	18:30	0	117,000	3,476	1,300	44	45	45	-1	0	-1	10	35
89	Wed	03/05/08	19:45	0	118,600	3,523	1,600	48	50	49	-2	1	-1	15	35
90	Wed	03/12/08	19:30	0	120,200	3,571	1,600	44	46	46	-2	0	-2	13	35
91	Wed	03/19/08	10:00	0	121,513	3,610	1,313	58	58	58	0	0	0	11.5	35
92	Wed	03/26/08	20:00	0	122,000	3,624	487	44	46	45	-2	1	-1	10	35
93	Wed	04/02/06	20:30	0	123,200	3,660	1,200	57	58	58	-1	0	-1	8	35
94	Wed	04/09/08	20:30	0	124,700	3,705	1,500	62	64	64	-2	0	-2	13	35
95	Wed	04/16/08	20:30	0	126,100	3,746	1,400	45	46	46	-1	0	-1	11	35
96	Wed	04/23/08	20:00	0	127,700	3,794	1,600	47	49	48	-2	1	-1	8	35
97	Thur	05/01/08	19:00	0	129,200	3,838	1,500	47	49	48	-2	1	-1	5	35
98	Wed	05/07/08	20:30	0	131,100	3,895	1,900	51	52	52	-1	0	-1	3	35
99	Wed	05/14/08	20:15	0	132,800	3,945	1,700	50	52	52	-2	0	-2	14	35
100	Wed	05/21/08	22:45	0	134,400	3,993	1,600	52	54	54	-2	0	-2	12	35
101	Wed	06/04/08	20:30	0	136,600	4,058	2,200	58	60	60	-2	0	-2	15	35
102	Wed	06/11/08	18:30	0	137,800	4,094	1,200	59	62	62	-3	0	-3	13	35
103	Wed	06/18/08	21:10	0	138,900	4,127	1,100	49	51	50	-2	1	-1	11	35
104	Wed	06/25/08	20:00	0	139,800	4,153	900	57	58	59	-1	-1	-2	9	35
105	Wed	07/02/08	18:00	0	140,700	4,180	900	44	45	45	-1	0	-1	8	35

Table A-1. EPA Arsenic Demonstration Project at LEADS Head Start in Buckeye Lake, OH – Daily System Operational Data (Continued)

Week No.	Day of Week	Date	Time	ARM 200 System				Pressure			ΔP		ΔP	Chlorine	
				Flowrate	Totalizer	Cum. Bed Volume	Usage	Inlet	After Vessel A	After Vessel B	Across Vessel A	Across Vessel B	Across System	Chlorine Tank Level	Chlorine Solution Feed Rate
				gpm	gal	BVs	gal	psig	psig	psig	psi	psi	psi	gal	L/min
106	Wed	07/09/08	10:00	0	141,270	4,197	570	43	44	45	-1	-1	-2	15	35
107	Wed	07/16/08	20:30	0	142,400	4,231	1,130	45	46	45	-1	1	0	12.5	35
108	Wed	07/23/08	18:00	0	143,800	4,272	1,400	61	62	63	-1	-1	-2	10	35
110	Wed	08/06/08	19:30	0	145,700	4,329	1,900	42	43	42	-1	1	0	7	35
111	Wed	08/13/06	21:30	0	146,500	4,352	800	49	50	50	-1	0	-1	14	35
112	Wed	08/20/08	19:45	0	146,900	4,364	400	55	56	57	-1	-1	-2	13	35
113	Wed	08/27/08	20:00	0	148,200	4,403	1,300	48	50	49	-2	1	-1	12	35
114	Wed	09/03/08	19:30	0	149,000	4,427	800	48	51	49	-3	2	-1	15	35
115	Wed	09/10/08	19:15	0	150,900	4,483	1,900	43	45	44	-2	1	-1	11	35
116	Wed	09/17/08	20:30	0	152,400	4,528	1,500	52	54	54	-2	0	-2	8	35
117	Wed	09/24/08	20:45	0	154,800	4,599	2,400	60	62	62	-2	0	-2	5	35
118	Wed	10/01/08	10:15	0	156,468	4,648	1,668	45	42	40	3	2	5	2	35
119	Wed	10/08/08	20:00	0	159,100	4,727	2,632	63	64	65	-1	-1	-2	0	35
120	Wed	10/15/08	20:30	0	160,500	4,768	1,400	62	64	64	-2	0	-2	12	35
121	Wed	10/22/08	20:20	0	162,100	4,816	1,600	47	48	48	-1	0	-1	8	35
123	Wed	11/05/08	19:30	0	165,800	4,926	3,700	59	62	62	-3	0	-3	0	35
124	Wed	11/12/08	20:00	0	167,700	4,982	1,900	49	50	50	-1	0	-1	15	35
125	Wed	11/19/08	20:15	0	169,400	5,033	1,700	44	46	45	-2	1	-1	10	35
126	Tues	11/25/08	20:15	0	170,800	5,074	1,400	60	62	62	-2	0	-2	7	35
127	Wed	12/03/08	19:15	0	172,400	5,122	1,600	51	53	52	-2	1	-1	5	35
128	Wed	12/10/08	19:00	0	174,600	5,187	2,200	53	55	55	-2	0	-2	12	35
129	Wed	12/17/08	19:00	0	195,400	5,805	20,800	53	55	55	-2	0	-2	5	35
130	Wed	12/23/08	19:45	0	196,700	5,844	1,300	46	48	48	-2	0	-2	2	35
131	Wed	01/07/09	19:15	0	198,500	5,897	1,800	52	54	53	-2	1	-1	0	35
132	Wed	01/14/09	15:00	0	200,200	5,948	1,700	50	52	52	-2	0	-2	13	35
133	Wed	01/21/09	21:15	0	201,700	5,992	1,500	64	66	66	-2	0	-2	10	35

Table A-1. EPA Arsenic Demonstration Project at LEADS Head Start in Buckeye Lake, OH – Daily System Operational Data (Continued)

Week No.	Day of Week	Date	Time	ARM 200 System				Pressure			ΔP		ΔP	Chlorine	
				Flowrate	Totalizer	Cum. Bed Volume	Usage	Inlet	After Vessel A	After Vessel B	Across Vessel A	Across Vessel B	Across System	Chlorine Tank Level	Chlorine Solution Feed Rate
				gpm	gal	BVs	gal	psig	psig	psig	psi	psi	psi	gal	L/min
133	Fri	01/23/09	9:30	0	202,152	6,006	452	45	44	44	1	0	1	10	35
134	Wed	01/28/09	7:00	0	202,900	6,028	748	52	54	54	-2	0	-2	8	35
135	Wed	02/04/09	20:15	0	204,500	6,075	1,600	61	62	63	-1	-1	-2	15	35
136	Wed	02/11/09	19:30	0	206,900	6,147	2,400	51	53	52	-2	1	-1	12	35
137	Wed	02/18/09	19:00	0	207,700	6,171	800	39	38	37	1	1	2	11	35
138	Wed	02/25/09	18:30	0	208,700	6,200	1,000	43	45	45	-2	0	-2	9	35
139	Wed	03/04/09	19:00	0	210,700	6,260	2,000	47	49	49	-2	0	-2	6	35
140	Wed	03/11/09	19:30	0	212,400	6,310	1,700	50	52	51	-2	1	-1	15	30
141	Wed	03/18/09	20:30	0	214,400	6,370	2,000	54	56	56	-2	0	-2	12	30
142	Wed	03/25/09	20:18	0	216,400	6,429	2,000	51	52	52	-1	0	-1	11	30
143	Wed	04/01/09	21:30	0	216,900	6,444	500	53	56	56	-3	0	-3	11	30
144	Wed	04/08/09	20:30	0	218,200	6,482	1,300	51	53	52	-2	1	-1	13	30
145	Wed	04/15/09	19:30	0	221,700	6,586	3,500	62	64	65	-2	-1	-3	25	35
146	Wed	04/22/09	20:00	0	223,200	6,631	1,500	43	45	44	-2	1	-1	15	35
147	Thur	04/30/09	9:30	0	224,890	6,681	1,690	42	44	44	-2	0	-2	0	35
148	Wed	05/06/09	19:00	0	226,500	6,729	1,610	47	48	48	-1	0	-1	15	35
149	Wed	05/13/09	19:30	0	228,400	6,786	1,900	47	49	48	-2	1	-1	12	35
150	Wed	05/20/09	20:00	0	230,000	6,833	1,600	47	49	49	-2	0	-2	12	35
151	Wed	05/27/09	21:00	0	230,800	6,857	800	58	60	60	-2	0	-2	8	35
152	Wed	06/03/09	20:30	0	231,100	6,866	300	63	65	65	-2	0	-2	8	35
153	Wed	06/10/09	20:00	0	231,500	6,878	400	57	59	59	-2	0	-2	10	35
154	Wed	06/17/09	19:30	0	232,000	6,892	500	47	49	49	-2	0	-2	13	35
155	Wed	06/24/09	20:00	0	232,600	6,910	600	50	51	51	-1	0	-1	14	35
156	Wed	07/01/09	21:00	0	233,100	6,925	500	46	48	47	-2	1	-1	13	35
157	Wed	07/08/09	20:30	0	233,400	6,934	300	42	44	43	-2	1	-1	13	35
158	Wed	07/15/09	21:30	0	234,100	6,955	700	61	63	63	-2	0	-2	12	-

Table A-1. EPA Arsenic Demonstration Project at LEADS Head Start in Buckeye Lake, OH – Daily System Operational Data (Continued)

Week No.	Day of Week	Date	Time	ARM 200 System				Pressure			ΔP		ΔP	Chlorine	
				Flowrate	Totalizer	Cum. Bed Volume	Usage	Inlet	After Vessel A	After Vessel B	Across Vessel A	Across Vessel B	Across System	Chlorine Tank Level	Chlorine Solution Feed Rate
				gpm	gal	BVs	gal	psig	psig	psig	psi	psi	psi	gal	L/min
159	Wed	07/22/09	20:30	0	235,100	6,985	1,000	44	45	44	-1	1	0	12	-
161	Wed	08/05/09	21:30	0	236,400	7,023	1,300	54	56	56	-2	0	-2	10	-
162	Tues	08/11/09	21:30	0	241,400	7,172	5,000	0	0	0	0	0	0	5	-
	Wed	08/12/09	20:30	0	242,200	7,195	800	43	45	44	-2	1	-1	4	-
164	Wed	08/26/09	20:00	0	243,300	7,228	1,100	49	51	50	-2	1	-1	3	-
165	Wed	09/02/09	20:30	0	244,200	7,255	900	60	62	62	-2	0	-2	10	-
166	Wed	09/09/09	20:30	0	245,500	7,294	1,300	49	51	50	-2	1	-1	8	-
167	Wed	09/16/09	20:00	0	249,200	7,403	3,700	52	54	54	-2	0	-2	3	-
168	Wed	09/23/09	13:30	0	253,000	7,516	3,800	44	50	49	-6	1	-5	10	-
169	Tues	10/01/09	7:15	0	255,600	7,594	2,600	44	46	46	-2	0	-2	10	-

NOTE: BV calculation assumes 4.5 ft3 of media per vessel.

APPENDIX B

ANALYTICAL RESULTS

Table B-1. Analytical Results from Long-Term Sampling, Buckeye Lake, OH

Sampling Date		06/28/06			07/12/06				07/25/06			08/23/06				08/30/06					09/13/06			
Sampling Location / Parameter	Unit	IN	AC	TT	IN	AC	TA	TB	IN	AC	TT	IN	AC	TA	TB	IN	AC	TA	TB	TT	IN	AC	TA	TB
Bed Volumes	10^3	-	-	0.0	-	-	-	0.0	-	-	0.0	-	-	-	0.1	-	-	-	-	0.1	-	-	-	0.2
Alkalinity (as $CaCO_3$)	mg/L	318	335	19	322	331	314	134	-	-	-	325	331	348	322	344	353	360	366	369	344	355	371	346
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	344	355	367	351
Ammonia (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fluoride	mg/L	0.9	0.9	0.9	1.8	0.9	1.3	2.4	-	-	-	0.7	1.0	1.1	1.4	1.1	1.0	1.1	1.1	1.3	0.9	0.9	0.9	1.0
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.0	0.9	0.9	1.0
Sulfate	mg/L	34	35	131	37	32	35	160	-	-	-	40	43	42	43	39	38	41	34[a]	43	33	35	35	34
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	35	35	34	36
Nitrate (as N)	mg/L	<0.05	<0.05	<0.05	0.4	<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	<0.05	<0.05
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	<0.05	<0.05	<0.05	0.2
Total P (as P)	µg/L	<10	187	<10	<10	36.8	<10	<10	-	-	-	<10	72.6	<10	<10	<10	57.2	<10	<10	<10	<10	14.4	<10	<10
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	<10	14.7	<10	<10
Silica (as SiO_2)	mg/L	15.1	15.2	<0.2	14.4	13.5	<0.2	<0.2	-	-	-	13.9	14.7	<0.2	<0.2	14.4	14.1	<0.2	<0.2	<0.2	14.5	14.7	0.5	<0.2
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15.0	15.1	0.8	<0.2
Turbidity	NTU	39.0	1.3	1.0	41.0	0.9	0.4	0.4	-	-	-	34.0	0.5	0.2	0.4	39.0	1.1	0.3	<0.1	0.2	15.0	0.6	0.5	0.2
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15.0	0.6	0.6	2.0
TOC	mg/L	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH	S.U.	7.4	7.5	7.0	7.6	7.9	-	7.9	7.5	8.0	8.0	-	-	-	-	7.4	7.6	-	-	7.5	-	-	-	-
Temperature	℃	19.8	21.4	25.0	20.0	20.3	-	20.0	17.8	19.9	20.4	-	-	-	-	19.8	20.0	-	-	24.0	-	-	-	-
DO	mg/L	2.4	1.3	1.4	2.6	2.0	-	1.5	3.6	4.5	1.7	-	-	-	-	1.6	2.1	-	-	1.0	-	-	-	-
ORP	mV	-54	546	375	-36	-50	-	-54	-47	667	420	-	-	-	-	-74	603	-	-	433	-	-	-	-
Free Chlorine	mg/L	-	-	-	-	-	-	0.1	-	-	0.2	-	-	-	0.8	-	-	-	-	0.1	-	-	-	0.0
Total Chlorine	mg/L	-	-	-	-	-	-	0.5	-	-	0.9	-	-	-	0.6	-	-	-	-	0.1	-	-	-	0.0
Total Hardness (as $CaCO_3$)	mg/L	289	0.9	1.0	268	0.3	<0.35	<0.35	-	-	-	294	0.4	0.3	0.3	299	0.6	0.4	0.4	0.4	303	0.6	0.3	0.3
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	306	0.6	0.3	0.3
Ca Hardness (as $CaCO_3$)	mg/L	189	0.8	0.9	178	0.3	<0.25	<0.25	-	-	-	204	0.3	0.3	0.3	199	0.6	0.4	0.3	0.3	212	0.6	<0.25	<0.25
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	213	0.6	<0.25	0.3
Mg Hardness (as $CaCO_3$)	mg/L	99.7	0.1	0.1	90.2	0.1	<0.1	<0.1	-	-	-	89.5	0.1	<0.1	<0.1	101	0.1	<0.1	<0.1	<0.1	90.7	<0.04	<0.04	<0.04
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	92.9	<0.04	<0.04	<0.04
As (total)	µg/L	9.7	16.4	0.4	9.3	9.2	<0.1	<0.1	12.4	13.5	4.7	11.7	18.6	0.2	0.2	11.6	14.4	0.1	<0.1	<0.1	13.1	13.9	0.2	0.2
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	13.0	13.8	<0.1	0.2
As (soluble)	µg/L	8.4	15.3	4.1	-	-	-	-	8.7	11.4	4.3	-	-	-	-	9.5	12.8	<0.1	<0.1	<0.1	-	-	-	-
As (particulate)	µg/L	1.3	1.1	<0.1	-	-	-	-	3.7	2.0	0.4	-	-	-	-	2.1	1.6	0.1	<0.1	<0.1	-	-	-	-
As (III)	µg/L	7.0	0.2	0.2	-	-	-	-	6.0	0.6	0.5	-	-	-	-	3.0	0.5	0.5	0.4	0.4	-	-	-	-
As (V)	µg/L	1.4	15.1	3.9	-	-	-	-	2.7	10.9	3.8	-	-	-	-	6.5	12.3	<0.1	<0.1	<0.1	-	-	-	-
Fe (total)	µg/L	3,974	142	<25	5,365	40	<25	<25	2,495	<25	<25	3,738	29	<25	26	4,840	100	<25	<25	<25	1,600	<25	<25	<25
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1,614	<25	<25	<25
Fe (soluble)	µg/L	3,161	47	<25	-	-	-	-	875	<25	<25	-	-	-	-	3,882	<25	<25	<25	<25	-	-	-	-
Mn (total)	µg/L	112	1.3	2.1	114	0.9	<0.1	<0.1	93.9	0.4	0.2	110	0.3	<0.1	0.1	118	0.7	<0.1	<0.1	<0.1	77.5	0.1	<0.1	<0.1
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	77.7	0.1	<0.1	<0.1
Mn (soluble)	µg/L	114	0.4	1.6	-	-	-	-	92.9	0.4	<0.1	-	-	-	-	117	0.2	<0.1	<0.1	0.2	-	-	-	-

(a) Reanalysis conducted outside of hold time.

IN = At Wellhead, AS = After Water Softener, AC = After Chlorination, TA = After Tank A, TB = After Tank B, DIST = Distribution

Table B-1. Analytical Results from Long-Term Sampling, Buckeye Lake, OH (Continued)

Sampling Date		09/28/06				10/11/06				10/24/06				11/15/06				11/29/06			
Sampling Location / Parameter	Unit	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB
Bed Volumes	10^3	-	-	-	0.8	-	-	-	0.9	-	-	-	1.0	-	-	-	1.2	-	-	-	1.3
Alkalinity (as $CaCO_3$)	mg/L	-	-	-	-	358	373	388	423	-	-	-	-	343	361	371	365	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ammonia (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fluoride	mg/L	-	-	-	-	1.0	0.8	0.7	1.1	-	-	-	-	1.4	1.0	1.0	1.0	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sulfate	mg/L	-	-	-	-	38	37	35	47	-	-	-	-	38	37	36	39	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitrate (as N)	mg/L	-	-	-	-	0.2	<0.05	<0.05	0.2	-	-	-	-	<0.05	<0.05	0.1	0.3	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total P (as P)	µg/L	-	-	-	-	<10	176	<10	<10	-	-	-	-	<10	26.9	<10	<10	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Silica (as SiO_2)	mg/L	-	-	-	-	14.7	14.9	0.8	0.7	-	-	-	-	14.8	14.7	<0.2	0.5	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Turbidity	NTU	-	-	-	-	37.0	1.1	1.1	0.5	-	-	-	-	18.0	1.1	0.6	1.1	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOC	mg/L	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH	S.U.	-	-	-	-	7.5	7.9	-	7.4	-	-	-	-	7.6	7.9	-	7.9	-	-	-	-
Temperature	℃	-	-	-	-	19.6	19.6	-	19.3	-	-	-	-	15.9	15.9	-	16.2	-	-	-	-
DO	mg/L	-	-	-	-	2.3	2.6	-	2.0	-	-	-	-	1.7	3.5	-	1.5	-	-	-	-
ORP	mV	-	-	-	-	-56	700	-	485	-	-	-	-	447	716	-	689	-	-	-	-
Free Chlorine	mg/L	-	-	-	-	-	-	-	0.0	-	-	-	-	-	-	-	2.2	-	-	-	2.2
Total Chlorine	mg/L	-	-	-	-	-	-	-	0.1	-	-	-	-	-	-	-	2.2	-	-	-	2.2
Total Hardness (as $CaCO_3$)	mg/L	-	-	-	-	295	1.6	1.4	67.8	-	-	-	-	265	0.5	<0.3	17.5	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca Hardness (as $CaCO_3$)	mg/L	-	-	-	-	192	1.4	1.3	48.1	-	-	-	-	166	0.5	<0.25	17.1	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mg Hardness (as $CaCO_3$)	mg/L	-	-	-	-	103	0.2	<0.1	19.6	-	-	-	-	98.7	0.04	<0.04	0.4	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (total)	µg/L	16.6	18.6	0.2	<0.1	11.6	22.4	0.4	0.4	17.6	20.6	0.3	0.2	19.2	19.4	0.3	1.0	13.3	14.1	<0.1	0.9
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (soluble)	µg/L	14.6	16.9	0.2	<0.1	-	-	-	-	16.0	18.7	0.3	0.2	-	-	-	-	12.7	14.2	<0.1	0.7
As (particulate)	µg/L	2.0	1.7	0.1	<0.1	-	-	-	-	1.6	1.9	<0.1	<0.1	-	-	-	-	0.6	<0.1	<0.1	0.2
As (III)	µg/L	8.6	10.7	0.2	0.1	-	-	-	-	11.9	0.8	0.7	0.8	-	-	-	-	6.8	0.6	<0.1	0.8
As (V)	µg/L	6.0	6.2	<0.1	<0.1	-	-	-	-	4.1	17.9	<0.1	<0.1	-	-	-	-	5.9	13.6	<0.1	<0.1
Fe (total)	µg/L	2,667	367	<25	47	4,058	118	<25	<25	2,352	46	<25	<25	2,117	46	<25	48	1,738	26	<25	<25
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe (soluble)	µg/L	2,585	369	<25	<25	-	-	-	-	2,154	<25	<25	<25	-	-	-	-	1,653	<25	<25	<25
Mn (total)	µg/L	91.7	18.4	0.2	0.1	125	3.6	0.1	<0.1	87.5	0.7	<0.1	<0.1	82.9	0.5	<0.1	0.2	80.9	0.3	<0.1	<0.1
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mn (soluble)	µg/L	93.8	19.2	0.2	<0.1	-	-	-	-	85.4	0.2	<0.1	<0.1	-	-	-	-	80.1	<0.1	<0.1	<0.1

IN = At Wellhead, AS = After Water Softener, AC = After Chlorination, TA = After Tank A, TB = After Tank B, DIST = Distribution

Table B-1. Analytical Results from Long-Term Sampling, Buckeye Lake, OH (Continued)

Sampling Date		12/19/06[a]				01/25/07[b]				02/15/07[c]					03/08/07[d]			
Sampling Location		IN	AC	TA	TB	IN	AC	TA	TB	IN	AS	AC	TA	TB	IN	AC	TA	TB
Parameter	Unit																	
Bed Volumes	10^3	-	-	-	1.4	-	-	-	1.5	-	-	-	-	1.6	-	-	-	1.7
Alkalinity (as $CaCO_3$)	mg/L	361	363	395	415	299	306	305	308	352	352	349	361	352	354	361	353	366
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ammonia (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fluoride	mg/L	1.2	1.3	1.2	1.2	1.2	0.9	0.9	1.2	1.1	1.0	0.9	0.9	1.2	1.0	1.1	1.0	1.0
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sulfate	mg/L	44	42	38	46	39	40	39	40	37	33	37	34	35	36	37	36	36
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitrate (as N)	mg/L	<0.05	<0.05	0.1	0.2	<0.05	0.1	0.1	0.1	0.1	<0.05	0.1	0.1	0.1	<0.05	<0.05	<0.05	<0.05
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total P (as P)	µg/L	<10	65.6	<10	<10	<10	49.7	<10	<10	<10	140	115	<10	<10	<10	142	<10	<10
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Silica (as SiO_2)	mg/L	15.2	14.0	<0.2	0.7	14.8	14.6	<0.2	0.6	15.3	14.8	16.1	<0.2	12.1	15.0	14.6	<0.2	0.7
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Turbidity	NTU	37.0	0.8	1.2	1.5	18.0	0.7	0.7	0.8	7.5	0.6	0.9	1.0	2.4	19.0	0.8	0.7	1.1
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOC	mg/L	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH	S.U.	7.6	7.9	-	7.8	7.3	7.5	-	7.4	7.5	-	7.7	-	7.7	7.5	7.8	-	7.5
Temperature	℃	19.5	19.0	-	18.5	14.6	15.8	-	17.2	16.6	-	17.9	-	17.8	18.0	19.8	-	19.5
DO	mg/L	1.6	2.3	-	2.0	2.5	1.7	-	1.6	1.6	-	1.9	-	1.1	2.1	2.2	-	1.4
ORP	mV	-47	625	-	990	405	681	-	501	345	-	683	-	647	438	694	-	535
Free Chlorine	mg/L	-	-	-	-	-	-	-	0.1	-	-	-	-	0.2	-	-	-	NA
Total Chlorine	mg/L	-	-	-	-	-	-	-	0.1	-	-	-	-	0.1	-	-	-	NA
Total Hardness (as $CaCO_3$)	mg/L	301	0.5	0.3	7.0	307	0.7	3.0	13.6	295	0.6	0.6	1.9	7.9	297	1.1	2.4	10.9
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca Hardness (as $CaCO_3$)	mg/L	200	0.4	0.3	6.9	207	0.6	0.6	8.2	204	0.5	0.5	0.1	5.4	195	1.0	1.2	8.0
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mg Hardness (as $CaCO_3$)	mg/L	101	0.1	<0.04	0.1	100	0.1	2.4	5.4	90.8	0.1	0.1	1.8	2.5	102	0.1	1.3	2.9
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (total)	µg/L	13.9	17.1	0.2	0.2	20.3	20.4	0.3	0.2	5.5	16.5	18.6	1.4	0.8	20.5	17.9	<0.1	<0.1
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (soluble)	µg/L	12.0	16.5	0.2	0.2	17.8	19.5	0.3	0.2	4.1	16.3	17.2	0.6	0.5	16.8	17.0	<0.1	<0.1
As (particulate)	µg/L	1.9	0.6	0.1	<0.1	2.4	0.8	<0.1	<0.1	1.3	0.2	1.4	0.8	0.3	3.7	0.9	<0.1	<0.1
As (III)	µg/L	5.0	0.5	0.5	0.3	8.7	0.8	0.5	0.4	2.2	13.1	1.3	1.1	1.9	10.4	0.7	0.4	0.4
As (V)	µg/L	7.0	16.0	<0.1	<0.1	9.1	18.8	<0.1	<0.1	1.9	3.3	15.9	<0.1	<0.1	6.4	16.3	<0.1	<0.1
Fe (total)	µg/L	4,057	<25	<25	<25	1,401	<25	86	<25	855	69	<25	48	<25	1,365	<25	<25	<25
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe (soluble)	µg/L	3,124	<25	<25	<25	1,451	<25	<25	<25	381	<25	<25	<25	<25	1,343	<25	<25	<25
Mn (total)	µg/L	117	0.3	<0.1	0.3	66.2	0.2	0.4	<0.1	68.9	0.7	0.3	0.4	<0.1	68.2	<0.1	<0.1	<0.1
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mn (soluble)	µg/L	117	0.2	<0.1	0.3	68.8	0.2	0.4	0.3	67.7	0.3	0.1	0.1	<0.1	68.1	<0.1	<0.1	<0.1

(a) Onsite measurements taken on 12/27/06. (b) Onsite measurements taken on 01/31/07. (c) Onsite measurements taken on 02/28/07. (d) Onsite measurements taken on 03/28/07.

IN = At Wellhead, AS = After Water Softener, AC = After Chlorination, TA = After Tank A, TB = After Tank B, DIST = Distribution

Table B-1. Analytical Results from Long-Term Sampling, Buckeye Lake, OH (Continued)

Sampling Date		04/05/07 [a]					05/01/07					09/19/07 [b]						12/18/07					
Sampling Location / Parameter	Unit	IN	AS	AC	TA	TB	IN	AS	AC	TA	TB	IN	AS	AC	TA	TB	DIST	IN	AS	AC	TA	TB	DIST
Bed Volumes	10^3	-	-	-	-	1.9	-	-	-	-	2.1	-	-	-	-	2.5	-	-	-	-	-	3.1	-
Alkalinity (as $CaCO_3$)	mg/L	331	340	352	338	338	345	354	352	352	335	350	346	352	354	352	-	322	320	327	320	324	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ammonia (as N)	mg/L	0.9	<0.05	<0.05	<0.05	<0.05	0.8	<0.05	<0.05	<0.05	<0.05	1.1	<0.05	<0.05	<0.05	<0.05	-	1.2	0.1	0.1	0.1	0.1	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fluoride	mg/L	1.1	0.9	1.1	1.0	1.5	1.1	0.7	0.9	1.0	1.0	1.0	0.9	1.1	1.1	1.2	-	0.9	0.9	0.8	0.8	0.9	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sulfate	mg/L	37	37	39	39	37	35	36	37	37	36	36	36	36	37	37	-	37	37	36	35	36	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitrate (as N)	mg/L	<0.05	<0.05	<0.05	<0.05	0.1	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.2	-	<0.05	<0.05	<0.05	<0.05	<0.05	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total P (as P)	µg/L	<10	147	59.7	<10	<10	<10	23.6	18.0	<10	<10	<10	<10	<10	<10	<10	-	<10	24.0	28.7	<10	<10	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Silica (as SiO_2)	mg/L	14.5	13.9	13.9	<0.2	0.9	15.6	15.5	15.8	<0.2	1.2	15.3	15.1	15.1	0.7	1.2	-	17.7	14.3	14.3	3.1	1.2	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Turbidity	NTU	19.0	0.9	0.8	0.6	0.8	11.0	0.7	0.3	1.1	1.8	22.0	3.9	2.7	5.3	6.4	-	17.0	0.7	0.9	0.9	0.4	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOC	mg/L	-	-	-	-	-	-	-	-	-	-	1.8	1.8	1.9	1.4	1.3	1.0	4.3	1.9	1.8	1.7	5.9	8.7
Total HAA5		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total THM		-	-	-	-	-	-	-	-	-	-	8.5	ND	10.8	28.2	49.5	112	ND	ND	10.8	30.5	43.9	37.3
pH	S.U.	7.5	-	7.7	-	7.6	7.5	7.7	7.8	7.7	7.8	7.7	7.7	7.8	7.7	7.5	-	7.7	7.8	7.8	7.7	7.9	-
Temperature	℃	16.4	-	17.5	-	17.4	15.3	15.2	15.5	16.0	16.7	15.0	19.5	15.8	15.9	21.1	-	13.5	14.1	15.3	15.2	16.5	-
DO	mg/L	1.4	-	2.5	-	1.8	1.5	1.9	2.8	1.8	1.0	1.9	1.2	1.7	1.1	2.0	-	2.1	1.6	1.6	3.0	1.0	-
ORP	mV	391	-	704	-	722	175	439	738	712	263	251	271	721	741	736	-	228	225	644	691	681	-
Free Chlorine	mg/L	-	-	-	-	-	0.1	0.0	3.5	1.7	0.3	0.0	0.0	>4.4	>4.4	3.4	-	-	-	1.7	2.1	1.2	-
Total Chlorine	mg/L	-	-	-	-	-	0.1	0.0	4.4	1.9	0.3	0.0	0.0	>4.4	>4.4	3.5	-	-	-	1.8	2.2	1.4	-
Total Hardness (as $CaCO_3$)	mg/L	273	0.9	0.9	0.9	5.0	296	0.5	0.3	0.8	2.6	260	0.4	0.4	0.4	0.4	-	290	0.2	0.2	0.4	0.8	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca Hardness (as $CaCO_3$)	mg/L	176	0.9	0.8	0.6	3.7	193	0.4	0.3	<0.3	2.1	171	<0.25	<0.25	<0.25	<0.25	-	192	0.1	0.1	0.3	0.7	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mg Hardness (as $CaCO_3$)	mg/L	97.0	0.1	0.1	0.2	1.2	103	0.1	<0.04	0.8	0.5	88.9	<0.1	<0.1	<0.1	0.1	-	97.6	<0.1	<0.1	<0.1	<0.1	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (total)	µg/L	16.7	18.3	19.3	1.4	1.4	19.5	19.6	19.1	0.3	0.1	18.1	18.1	19.0	0.8	0.5	-	17.8	19.7	18.4	0.8	0.7	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (soluble)	µg/L	15.1	16.8	18.0	1.8	1.4	17.5	16.4	16.5	0.3	<0.1	16.5	15.0	16.1	0.6	0.5	-	15.7	16.2	15.6	0.1	0.1	-
As (particulate)	µg/L	1.6	1.5	1.3	<0.1	<0.1	2.0	3.2	2.6	<0.1	0.1	1.6	3.1	3.0	0.2	<0.1	-	2.2	3.5	2.8	0.6	0.6	-
As (III)	µg/L	7.9	13.0	2.4	2.0	1.8	16.3	16.4	0.6	0.4	0.3	15.3	15.2	0.6	0.4	0.4	-	15.3	16.6	0.9	0.8	0.8	-
As (V)	µg/L	7.1	3.8	15.6	<0.1	<0.1	1.2	<0.1	15.9	<0.1	<0.1	1.2	<0.1	15.5	0.2	<0.1	-	0.4	<0.1	14.7	<0.1	<0.1	-
Fe (total)	µg/L	1,800	<25	<25	<25	<25	1,489	<25	<25	<25	<25	2,170	<25	<25	<25	<25	-	2,630	<25	<25	<25	<25	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe (soluble)	µg/L	1,760	<25	<25	<25	<25	1,345	<25	<25	<25	<25	1,295	<25	<25	<25	<25	-	1,411	<25	<25	<25	<25	-
Mn (total)	µg/L	74.7	0.2	0.2	<0.1	<0.1	74.7	<0.1	<0.1	<0.1	<0.1	97.7	<0.25	<0.25	0.4	<0.25	-	92.2	<0.1	<0.1	0.2	<0.1	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mn (soluble)	µg/L	75.2	0.3	0.3	0.2	0.2	74.1	<0.1	<0.1	<0.1	<0.1	69.0	<0.25	0.4	0.5	0.5	-	73.2	<0.1	<0.1	<0.1	<0.1	-

(a) Onsite measurements taken on 04/25/07. (b) TOC samples were collected on 10/10/07.

IN = At Wellhead, AS = After Water Softener, AC = After Chlorination, TA = After Tank A, TB = After Tank B, DIST = Distribution

Table B-1. Analytical Results from Long-Term Sampling, Buckeye Lake, OH (Continued)

Sampling Date		03/19/08						07/09/08						10/01/08						01/23/09					
Sampling Location		IN	AS	AC	TA	TB	DIST	IN	AS	AC	TA	TB	DIST	IN	AS	AC	TA	TB	DIST	IN	AS	AC	TA	TB	DIST
Parameter	Unit																								
Bed Volumes	10^3	-	-	-	-	3.6	-	-	-	-	-	4.2	-	-	-	-	-	4.6	-	-	-	-	-	6.0	-
Alkalinity (as $CaCO_3$)	mg/L	321	329	331	323	325	-	325	328	339	325	323	-	308	312	314	314	314	-	310	319	326	342	333	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ammonia (as N)	mg/L	0.9	<0.05	<0.05	<0.05	<0.05	-	1.1	<0.05	<0.05	<0.05	<0.05	-	1.0	<0.05	<0.05	<0.05	<0.05	-	1.0	<0.05	<0.05	<0.05	<0.05	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fluoride	mg/L	0.9	0.9	1.0	0.9	0.9	-	1.0	1.0	1.1	1.0	1.0	-	1.0	1.1	1.1	1.1	1.0	-	1.1	1.2	1.2	1.2	1.3	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sulfate	mg/L	43.1	37.8	36.2	37.5	37.5	-	32.7	33.6	32.5	31.7	32.8	-	36.4	35.4	37.3	37.1	37.2	-	34.6	36.3	34.5	35.0	37.1	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitrate (as N)	mg/L	<0.05	<0.05	<0.05	<0.05	<0.05	-	<0.05	<0.05	<0.05	<0.05	<0.05	-	<0.05	<0.05	<0.05	<0.05	<0.05	-	<0.05	<0.05	<0.05	<0.05	<0.05	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total P (as P)	µg/L	<10	21.4	36.6	<10	<10	-	<10	44.5	102	<10	<10	-	<10	<10	23.8	<10	<10	-	<10	16.5	48.2	<10	<10	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Silica (as SiO_2)	mg/L	15.4	15.2	15.4	8.8	1.5	-	16.8	14.3	13.9	9.7	1.6	-	16.0	14.3	14.0	11.2	2.6	-	15.5	13.0	12.9	9.0	7.5	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Turbidity	NTU	20.0	0.5	0.4	0.5	0.6	-	19.0	0.2	0.2	0.2	0.1	-	17.0	0.1	0.2	0.2	<0.1	-	26.0	0.1	0.2	<0.1	<0.1	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOC	mg/L	2.6	2.5	2.4	1.6	2.4	2.2	NA [a]	NA [a]	NA [a]	NA [a]	NA [a]	NA [a]	2.1	2.1	2.2	1.6	1.7	-	1.9	1.8	1.9	1.9	1.9	-
Total HAA5	µg/L	<2	<2	10.9	13.7	25.9	28.6	<2	<2	19.4	55.4	94.0	193	<2	<2	10.6	19.1	35.6	107	<2	<2	16.1	42.6	197	279
Total THM	µg/L	5.6	2.1	16.3	37.1	39.5	49.6	NA [a]	NA [a]	NA [a]	NA [a]	NA [a]	NA [a]	<2	<2	7.9	18.3	29.2	119	<2	<2	20.1	51.0	152	234
pH	S.U.	7.4	7.2	7.5	7.2	7.5	7.2	NA [b]	NA [b]	NA [b]	NA [b]	NA [b]	NA [b]	7.5	8.2	7.8	7.8	8.1	7.9	NA [c]	NA [c]	NA [c]	NA [c]	NA [c]	NA [c]
Temperature	℃	15.6	16.9	15.5	16.0	17.7	15.3	23.8	15.8	19.2	19.2	19.9	22.7	16.2	15.0	15.6	16.5	17.3	22.3	14.8	14.4	18.2	18.3	19.4	19.3
DO	mg/L	1.8	0.7	0.8	1.1	0.8	0.9	1.4	1.4	1.3	2.1	1.7	1.1	2.0	1.2	1.1	2.9	1.7	1.3	1.8	1.1	1.3	1.2	1.3	1.0
ORP	mV	130	232	661	684	505	583	9.4	269	697	709	548.2	328	-60.6	111	693	696	708	527	-49	20.1	737	737	754	756
Free Chlorine	mg/L	-	-	1.2	0.7	0.3	0.0	-	-	4.0	3.4	0.2	0.0	-	-	>4.4	>4.4	>4.4	1.3	-	-	4.18	>4.4	3.34	2.9
Total Chlorine	mg/L	-	-	1.5	0.5	0.3	0.3	-	-	>4.4	1.8	0.2	0.1	-	-	>4.4	>4.4	>4.4	1.4	-	-	4.32	3.22	3.24	3.4
Total Hardness (as $CaCO_3$)	mg/L	262	0.2	0.2	0.2	0.2	-	351	0.6	0.4	0.4	0.6	-	NA	NA	NA	NA	NA	-	302	0.9	0.8	11.3	8.1	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca Hardness (as $CaCO_3$)	mg/L	174	<0.06	<0.06	<0.06	<0.06	-	269	0.5	0.3	0.3	0.5	-	NA	NA	NA	NA	NA	-	207	0.8	0.7	7.7	1.1	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mg Hardness (as $CaCO_3$)	mg/L	88.1	<0.1	<0.1	<0.1	<0.1	-	81.3	<0.1	<0.1	<0.1	<0.1	-	NA	NA	NA	NA	NA	-	95	<0.1	<0.1	3.6	7.0	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (total)	µg/L	19.5	18.2	18.8	1.0	0.9	-	18.3	20.1	16.9	0.2	<0.1	-	19.1	17.2	17.4	0.3	0.2	-	17.1	14.6	17.6	0.2	0.2	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (soluble)	µg/L	16.9	16.4	16.4	<0.1	<0.1	-	16.2	17.7	15.3	0.1	<0.1	-	16.8	15.1	15.7	0.2	0.1	-	15.2	14.6	16.1	0.2	0.2	-
As (particulate)	µg/L	2.7	1.9	2.4	0.9	0.8	-	2.1	2.5	1.6	<0.1	<0.1	-	2.3	2.1	1.7	<0.1	<0.1	-	1.9	<0.1	1.5	<0.1	<0.1	-
As (III)	µg/L	16.6	16.5	1.0	<0.1	0.9	-	15.7	17.2	0.5	0.4	<0.1	-	16.2	15.1	0.4	0.4	0.3	-	14.3	13.9	0.4	0.4	0.3	-
As (V)	µg/L	0.2	<0.1	15.4	<0.1	<0.1	-	0.5	0.5	14.9	<0.1	<0.1	-	0.6	<0.1	15.4	<0.1	<0.1	-	0.9	0.8	15.7	<0.1	<0.1	-
Fe (total)	µg/L	1,911	<25	<25	<25	<25	-	1,432	<25	<25	<25	<25	-	1,280	<25	<25	<25	<25	-	1,654	<25	<25	<25	<25	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe (soluble)	µg/L	1,351	<25	<25	<25	<25	-	NA	NA	NA	NA	NA	-	1,245	<25	<25	<25	<25	-	1,632	<25	<25	<25	<25	-
Mn (total)	µg/L	81.9	<0.1	1.5	<0.1	<0.1	-	74.4	<0.1	<0.1	<0.1	<0.1	-	66.5	0.1	0.1	<0.1	<0.1	-	77.8	0.2	0.1	<0.1	<0.1	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mn (soluble)	µg/L	73.1	<0.1	<0.1	<0.1	<0.1	-	74.4	<0.1	<0.1	<0.1	<0.1	-	66.6	0.1	<0.1	<0.1	<0.1	-	77.5	<0.1	<0.1	<0.1	<0.1	-

(a) Sample pH too low to conduct TOC and Total THM analysis, (b) measurements not taken due to meter error (ERR 107), (c) measurements not taken due to calibration error.

IN = At Wellhead, AS = After Water Softener, AC = After Chlorination, TA = After Tank A, TB = After Tank B, DIST = Distribution

Table B-1. Analytical Results from Long-Term Sampling, Buckeye Lake, OH (Continued)

Sampling Date		05/07/09						09/23/09						11/04/09						02/24/10[a]					
Sampling Location		IN	AS	AC	TA	TB	DIST	IN	AS	AC	TA	TB	DIST	IN	AS	AC	TA	TB	DIST	IN	AS	AC	TA	TB	DIST
Parameter	Unit																								
Bed Volumes	10^3	-	-	-	-	6.7	-	-	-	-	-	7.5	-	-	-	-	-	7.9	-	-	-	-	-	9.0	-
Alkalinity (as $CaCO_3$)	mg/L	344	351	349	349	344	-	318	324	324	332	332	-	332	341	341	339	343	-	331	334	336	34	341	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ammonia (as N)	mg/L	1.0	<0.05	<0.05	<0.05	<0.05	-	1.0	<0.05	<0.05	<0.05	<0.05	-	0.9	<0.05	<0.05	<0.05	<0.05	-	1.0	<0.05	<0.05	<0.05	<0.05	<0.05
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fluoride	mg/L	1.1	1.1	1.1	1.1	1.2	-	1.1	1.0	1.1	1.0	1.0	-	1.1	0.8	1.1	1.3	1.0	-	1.2	1.2	5.0	3.3	1.9	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sulfate	mg/L	36.9	37.3	37.8	39.9	37.6	-	36.7	36.1	36.6	36.3	36.9	-	39.0	36.0	39.9	38.3	36.3	-	37.3	37.8	41.0	37.5	38.1	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitrate (as N)	mg/L	<0.05	<0.05	<0.05	<0.05	<0.05	-	<0.05	<0.05	<0.05	<0.05	<0.05	-	<0.05	<0.05	<0.05	<0.05	<0.05	-	<0.05	<0.05	<0.05	<0.05	<0.05	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total P (as P)	µg/L	<10	16.7	57.5	<10	<10	-	<10	21.9	20.7	<10	<10	-	62.4	<10	<10	<10	<10	-	<10	<10	15.1	<10	<10	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Silica (as SiO_2)	mg/L	17.1	14.3	13.6	12.6	7.0	-	15.2	14.8	15.1	12.7	8.3	-	15.6	13.6	13.2	12.9	9.4	-	16.2	14.2	14.1	13.4	11.6	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Turbidity	NTU	15.0	0.2	0.3	0.5	0.6	-	14.0	0.3	0.2	0.2	0.2	-	18.0	0.2	0.4	0.5	0.3	-	16.0	0.6	0.8	0.5	0.7	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOC	mg/L	1.8	1.9	1.9	1.7	1.9	1.6	1.7	1.8	1.7	1.7	1.7	1.7	2.3	2.4	1.9	1.9	1.9	1.9	1.9	1.8	1.8	1.7	1.8	1.8
Total HAA5	µg/L	<2	<2	4.1	11.9	55.1	13.1	NS	NS	NS	NS	NS	NS	0.0	0.0	3.0	9.5	13.0	12.6	0.0	0.0	7.3	12.1	20.3	13.8
Total THM	µg/L	<2	<2	7.0	20.4	49.3	23.5	NS	NS	NS	NS	NS	NS	0.0	0.0	11.8	31.5	44.8	46.1	0.0	0.0	6.7	9.2	14.1	13.1
pH	S.U.	7.2	7.5	7.6	7.5	7.5	7.5	6.9	8.0	8.0	8.1	8.1	8.0	7.1	7.7	7.8	6.4	7.7	-	7.3	7.5	7.5	7.5	7.6	-
Temperature	℃	15.0	14.8	15.2	15.3	15.5	18.4	16.1	15.5	15.3	16.1	15.2	19.5	14.2	14.5	15.1	14.8	15.0	-	14.4	13.9	14.0	25.0	14.3	-
DO	mg/L	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	1.3	0.8	1.0	1.2	0.8	-
ORP	mV	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	NA[c]	-12.0	99.1	NA[c]	103.2	114.7	125.5	-105.3	109.1	553.2	597.3	298.1	-	-78.5	30.2	603.9	671.4	671.3	-
Free Chlorine	mg/L	-	-	-	-	-	-	-	-	0.0	-	-	0.0	-	-	1.8	-	-	0.2	-	-	1.8	-	-	1.2
Total Chlorine	mg/L	-	-	0.69	0.82	0.82	0.9	-	-	0.0	-	-	0.0	-	-	1.8	1.0	0.1	0.3	-	-	1.9	-	-	1.3
Total Hardness (as $CaCO_3$)	mg/L	15.0	0.2	0.3	0.5	0.6	-	293	0.6	0.6	13.5	12.4	-	488	2.1	1.7	8.8	22.1	-	311	1.6	1.5	3.2	6.0	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca Hardness (as $CaCO_3$)	mg/L	205	1.2	1.1	4.0	6.3	-	194	0.5	0.5	11.1	8.5	-	354	1.8	1.5	8.5	20.9	-	210	1.5	1.4	3.1	5.8	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mg Hardness (as $CaCO_3$)	mg/L	116	0.2	0.1	0.1	0.5	-	99	0.1	0.1	2.5	3.9	-	134	0.2	0.1	0.3	1.2	-	102	<0.1	<0.1	<0.1	0.2	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (total)	µg/L	18.2	18.5	18.1	0.3	0.2	-	19.6	18.7	18.9	0.3	0.3	-	14.5	13.4	13.4	<0.1	<0.1	-	16.7	16.2	17.1	<0.1	<0.1	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (soluble)	µg/L	16.5	16.4	16.4	0.3	0.2	-	16.9	16.0	16.2	0.1	<0.1	-	14.0	13.0	13.3	<0.1	<0.1	-	17.0	16.7	16.5	<0.1	<0.1	-
As (particulate)	µg/L	1.7	2.1	1.8	<0.1	<0.1	-	2.7	2.7	2.7	0.2	0.2	-	0.5	0.4	<0.1	<0.1	<0.1	-	<0.1	<0.1	0.6	<0.1	<0.1	-
As (III)	µg/L	15.4	16.5	0.4	0.5	0.4	-	16.0	15.7	15.7	0.4	0.3	-	13.7	12.9	<0.1	<0.1	<0.1	-	16.4	16.8	0.4	0.4	0.4	-
As (V)	µg/L	1.1	<0.1	15.9	<0.1	<0.1	-	0.8	0.4	0.5	<0.1	<0.1	-	0.3	<0.1	13.2	<0.1	<0.1	-	0.6	<0.1	16.1	<0.1	<0.1	-
Fe (total)	µg/L	1,736	<25	<25	26	<25	-	1,125	<25	35	<25	<25	-	1,462	<25	<25	<25	<25	-	1,202	<25	<25	<25	<25	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe (soluble)	µg/L	1,500	<25	<25	<25	<25	-	1,129	<25	<25	<25	<25	-	1,544	<25	<25	<25	<25	-	1,228	<25	<25	<25	<25	-
Mn (total)	µg/L	73.8	<0.1	0.1	0.2	<0.1	-	61.0	<0.1	0.3	<0.1	<0.1	-	69.2	0.3	0.2	0.3	0.14	-	63.5	0.1	<0.1	<0.1	<0.1	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mn (soluble)	µg/L	70.7	<0.1	0.2	<0.1	<0.1	-	61.9	<0.1	0.2	<0.1	<0.1	-	71.2	0.2	0.2	0.2	0.1	-	64.5	<0.1	<0.1	<0.1	<0.1	-

(a) Total THM & HAA5 re-collected on 03/22/10.

IN = At Wellhead, AS = After Water Softener, AC = After Chlorination, TA = After Tank A, TB = After Tank B, DIST = Distribution

APPENDIX C

COLUMN STUDIES ANALYTICAL RESULTS

Table C-1. Concentrations of Arsenic, TOC, Ammonia, THMs, and HAAs in Columns A and C Feed Prepared with AS Water and 4 or 10 mg/L of Chlorine (as Cl_2)

Date	Total Arsenic (µg/L)	Soluble Arsenic (µg/L)	TOC (mg/L)	Ammonia - Hach (mg/L)[a]	Ammonia (mg/L)[a]	Chloroform (µg/L)	Bromodichloro-methane (µg/L)	Dibromochloro-methane (µg/L)	Bromoform (µg/L)	TTHM (µg/L)
8/28/2009[c]	NA	NA	<1.00[b]	NA	0.61	NA	NA	NA	NA	NA
8/31/2009	NA	NA	NA	NA	0.65	NA	NA	NA	NA	NA
9/1/2009	NA	NA	1.37	NA	NA	NA	NA	NA	NA	NA
9/3/2009	NA	NA	NA	NA	1.34	NA	NA	NA	NA	NA
9/4/2009	NA	NA	1.33	NA	NA	NA	NA	NA	NA	NA
9/10/2009 [d]	NA	NA	2.11	NA	NA	1.68	<0.500	<0.500	<0.500	<2.00
9/11/2009	8.28	NA	1.96	NA	NA	NA	NA	NA	NA	NA
9/25/2009	15.40	NA	1.65	NA	<0.05	18.60	5.60	1.24	<0.500	25.40
9/30/2009	NA	NA	1.63	NA	NA	NA	NA	NA	NA	NA
10/2/2009	NA	NA	1.63	NA	NA	NA	NA	NA	NA	NA
10/6/2009	NA	NA	1.68	NA	NA	NA	NA	NA	NA	NA
10/9/2009	14.20	NA	1.42	NA	NA	25.50	7.41	1.62	<0.500	34.53
10/13/2009	NA	NA	1.45	NA	NA	NA	NA	NA	NA	NA
10/16/2009	NA	NA	1.53	NA	NA	NA	NA	NA	NA	NA
10/20/2009	NA	NA	1.62	0.06	NA	NA	NA	NA	NA	NA
10/23/2009	15.90	15.50	1.65	NA	NA	21.89	6.49	1.52	<0.500	29.90
10/27/2009	NA	NA	1.65	0.01	NA	NA	NA	NA	NA	NA
10/30/2009	NA	NA	1.65	0.00	NA	NA	NA	NA	NA	NA
11/3/2009	NA	NA	1.81	0.00	NA	NA	NA	NA	NA	NA
11/6/2009	16.70	16.20	1.92	0.01	NA	25.30	8.05	1.70	<0.500	35.05
11/10/2009	NA	NA	2.01	0.02	NA	NA	NA	NA	NA	NA
11/13/2009	15.70	16.10	1.81	0.00	NA	21.11	7.41	1.52	<0.500	30.04
11/17/2009	NA	NA	1.83	0.36	NA	NA	NA	NA	NA	NA
11/20/2009	15.50	16.20	1.57	0.01	NA	27.69	10.46	2.69	<0.500	40.84
11/24/2009	NA	NA	1.65	0.11	NA	NA	NA	NA	NA	NA
12/4/2009 [e]	16.00	16.10	1.42	0.11	NA	29.18	8.77	1.67	<0.500	39.62
1/15/2010	16.2	16.6	1.65	NA	NA	24.63	7.22	1.54	<0.500	33.39

Table C-1. Concentrations of Arsenic, TOC, Ammonia, THMs, and HAAs in Columns A and C Feed Prepared with AS Water and 4 or 10 mg/L of Chlorine (as Cl_2) (Continued)

Date	THM Plus (µg/L as $CHCl_3$)	Dibromoacetic Acid (µg/L)	Dichloroacetic Acid (µg/L)	Monobromoacetic Acid (µg/L)	Monochloroacetic Acid (µg/L)	Trichloroacetic Acid (µg/L)	HAA5 (µg/L)[b]
8/28/2009[c]	NA	NA	NA	NA	NA	NA	NA
8/31/2009	NA	NA	NA	NA	NA	NA	NA
9/1/2009	NA	NA	NA	NA	NA	NA	NA
9/3/2009	NA	NA	NA	NA	NA	NA	NA
9/4/2009	NA	NA	NA	NA	NA	NA	NA
9/10/2009[d]	NA	<1.00	1.92	<1.00	<2.00	<1.00	1.92
9/11/2009	NA	NA	NA	NA	NA	NA	NA
9/25/2009	26	<1.00	5.47	<1.00	<2.00	7.64	13.11
9/30/2009	26	NA	NA	NA	NA	NA	NA
10/2/2009	NA	NA	NA	NA	NA	NA	NA
10/6/2009	34	NA	NA	NA	NA	NA	NA
10/9/2009	10	<1.00	4.61	<1.00	<2.00	4.70	9.31
10/13/2009	NA	NA	NA	NA	NA	NA	NA
10/16/2009	0	NA	NA	NA	NA	NA	NA
10/20/2009	0	NA	NA	NA	NA	NA	NA
10/23/2009	0	<1.00	4.64	<1.00	<2.00	5.17	9.81
10/27/2009	37	NA	NA	NA	NA	NA	NA
10/30/2009	11	NA	NA	NA	NA	NA	NA
11/3/2009	NA	NA	NA	NA	NA	NA	NA
11/6/2009	NA	<1.00	5.42	<1.00	<2.00	4.85	10.27
11/10/2009	NA	NA	NA	NA	NA	NA	NA
11/13/2009	NA	<1.00	5.33	<1.00	<2.00	4.69	10.02
11/17/2009	NA	NA	NA	NA	NA	NA	NA
11/20/2009	NA	<1.00	5.22	<1.00	<2.00	6.93	12.15
11/24/2009	NA	NA	NA	NA	NA	NA	NA
12/4/2009 [e]	NA	<1.00	5.37	<1.00	<2.00	7.04	12.41
1/15/2010	NA	<1.00	7.61	<1.00	<2.00	9.70	17.32

(a) Ammonia samples taken during AS water sampling at Head Start building.
(b) Sum of concentrations of individual acids.
(c) Feed changed from DI to AS water; continued to maintain 4 mg/L Cl_2 in water.
(d) As water contained ammonia from 08/28/09 through 09/11/09 due to improper regeneration of softener; ammonia reacted with chlorine to form combined chlorine, which inhibited DPB formation.
(e) On 12/2/09, chlorine concentration in feed increased to 10 mg/L (as Cl_2).
NA = Not Analyzed
Questionable results flagged in red

Table C-2. Concentrations of Arsenic, TOC, Ammonia, THMs, and HAAs in Column B Feed Prepared with DI water and 4 or 10 mg/L of Chlorine (as Cl_2)

Date	Total Arsenic (µg/L)	Soluble Arsenic (µg/L)	TOC (mg/L)	Ammonia - Hach (mg/L)[a]	Ammonia (mg/L)[a]	Chloroform (µg/L)	Bromodichloro-methane (µg/L)	Dibromochloro-methane (µg/L)	Bromoform (µg/L)
9/25/2009	0.18	NA	<1.00	NA	NA	0.80	<0.500	<0.500	<0.500
9/30/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
10/2/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
10/6/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
10/9/2009	<0.10	NA	<1.00	NA	NA	0.91	<0.500	<0.500	<0.500
10/13/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
10/16/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
10/20/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
10/23/2009	<0.1	<0.1	<1.00	NA	NA	<0.500	<0.500	<0.500	<0.500
10/27/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
10/30/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
11/3/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
11/6/2009	0.50	0.17	<1.00	NA	NA	1.08	<0.500	<0.500	<0.500
11/10/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
11/13/2009	0.16	0.13	<1.00	NA	NA	<0.500	<0.500	<0.500	<0.500
11/17/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
11/20/2009	0.13	0.11	<1.00	NA	NA	0.66	<0.500	<0.500	<0.500
11/24/2009	NA	NA	<1.00	NA	NA	NA	NA	NA	NA
12/4/2009[c]	0.13	0.20	< 1.00	NA	NA	0.85	<0.500	<0.500	<0.500
1/15/2010	0.3	0.1	<1.00	NA	NA	2.30	<0.500	<0.500	<0.500

Table C-2. Concentrations of Arsenic, TOC, Ammonia, THMs, and HAAs in Column B Feed Prepared with DI water and 4 or 10 mg/L of Chlorine (as Cl_2) (Continued)

Date	TTHM (µg/L)	THM Plus (µg/L as $CHCl_3$)	Dibromoacetic Acid (µg/L)	Dichloroacetic Acid (µg/L)	Monobromoacetic Acid (µg/L)	Monochloroacetic Acid (µg/L)	Trichloroacetic Acid (µg/L)	HAA5 (µg/L)[(b)]
9/25/2009	0.80	0	<1.00	<1.00	<1.00	<2.00	<1.00	0.00
9/30/2009	NA	0	NA	NA	NA	NA	NA	NA
10/2/2009	NA	NA	NA	NA	NA	NA	NA	NA
10/6/2009	NA	13	NA	NA	NA	NA	NA	NA
10/9/2009	0.91	0	<1.00	<1.00	<1.00	<2.00	<1.00	0.00
10/13/2009	NA	NA	NA	NA	NA	NA	NA	NA
10/16/2009	NA	0	NA	NA	NA	NA	NA	NA
10/20/2009	NA	8	NA	NA	NA	NA	NA	NA
10/23/2009	0.00	0	<1.00	<1.00	<1.00	<2.00	<1.00	0.00
10/27/2009	NA	0	NA	NA	NA	NA	NA	NA
10/30/2009	NA	29	NA	NA	NA	NA	NA	NA
11/3/2009	NA	NA	NA	NA	NA	NA	NA	NA
11/6/2009	1.08	NA	<1.00	<1.00	<1.00	<2.00	<1.00	0.00
11/10/2009	NA	NA	NA	NA	NA	NA	NA	NA
11/13/2009	0.00	NA	<1.00	<1.00	<1.00	<2.00	<1.00	0.00
11/17/2009	NA	NA	NA	NA	NA	NA	NA	NA
11/20/2009	0.66	NA	<1.00	<1.00	<1.00	<2.00	<1.00	0.00
11/24/2009	NA	NA	NA	NA	NA	NA	NA	NA
12/4/2009[(c)]	0.85	NA	<1.00	<1.00	<1.00	<2.00	<1.00	0.00
1/15/2010	2.30	NA	<1.00	<1.00	<1.00	<2.00	<1.00	0.00

(a) Ammonia samples are taken before use from the buckets brought from Buckeye Lake, not the reservoir itself. Ammonia values represent maximum values applicable between ammonia samples.

(b) Sum of HAA-5 calculated as sum of values of individual components. Values BRL are treated as nil (as per EPA 552.2).

(c) On 12/2/09, chlorine concentration in feed increased to 10 mg/L (as Cl2).

NA = Not Analyzed.

Questionable results flagged in red.

Table C-3. Arsenic, TOC, THMs, and HAAs Concentrations in Effluent from Column A Packed with Virgin ARM 200 Media

Date	Total Throughput (BV)	AS Water Throughput (BV)	Total Arsenic (µg/L)	Soluble Arsenic (µg/L)	TOC (mg/L)	Chloroform (µg/L)	Bromodichloro-methane (µg/L)	Dibromochloro-methane (µg/L)	Bromoform (µg/L)	TTHM (µg/L)
8/28/2009[a]	1996	0	<0.1	NA	<1.00	1.74	<0.500	<0.500	<0.500	<2.00
9/1/2009	2135	139	NA	NA	1.37	NA	NA	NA	NA	NA
9/4/2009	2243	247	NA	NA	1.33	NA	NA	NA	NA	NA
9/10/2009[c]	2497	501	NA	NA	NA	1.81	<0.500	<0.500	<0.500	<2.00
9/11/2009	2536	540	0.45	NA	1.15	NA	NA	NA	NA	NA
9/25/2009	2814	818	0.31	NA	1.22	60.20	10.90	2.12	<0.500	73.20
9/30/2009	2851	855	NA	NA	2.51	NA	NA	NA	NA	NA
10/2/2009	2981	985	NA	NA	1.35	NA	NA	NA	NA	NA
10/6/2009	3056	1060	NA	NA	1.44	NA	NA	NA	NA	NA
10/9/2009	3181	1185	<0.10	NA	1.25	53.24	9.98	1.90	<0.500	65.12
10/13/2009	3229	1233	NA	NA	1.23	NA	NA	NA	NA	NA
10/16/2009	3358	1362	NA	NA	1.42	NA	NA	NA	NA	NA
10/20/2009	3414	1418	NA	NA	1.59	NA	NA	NA	NA	NA
10/23/2009	3547	1551	0.11	<0.1	1.71	42.29	8.56	1.71	<0.50	52.56
10/27/2009	3599	1603	NA	NA	1.71	NA	NA	NA	NA	NA
10/30/2009	3733	1737	NA	NA	1.70	NA	NA	NA	NA	NA
11/3/2009	3792	1796	NA	NA	1.86	NA	NA	NA	NA	NA
11/6/2009	3934	1938	0.88	0.67	1.88	39.82	9.70	2.06	<0.500	51.58
11/10/2009	3997	2001	NA	NA	2.09	NA	NA	NA	NA	NA
11/13/2009	4136	2140	0.40	0.35	1.70	32.73	8.94	1.62	<0.500	43.29
11/17/2009	4193	2197	NA	NA	1.37	NA	NA	NA	NA	NA
11/20/2009	4333	2337	2.47	0.28	1.30	50.85	13.18	2.87	<0.500	66.90
11/24/2009	4403	2407	NA	NA	1.68	NA	NA	NA	NA	NA
12/4/2009[d]	4604	2608	0.47	0.45	1.56	43.07	10.51	1.73	<0.500	55.31
1/15/2010	4770	2774	0.4	0.5	1.58	38.32	9.17	1.67	<0.500	49.16

Table C-3. Arsenic, TOC, THMs, and HAAs Concentrations in Effluent from Column A Packed with Virgin ARM 200 Media (Continued)

Date	THM Plus (µg/L as $CHCl_3$)	Dibromoacetic Acid (µg/L)	Dichloroacetic Acid (µg/L)	Monobromoacetic Acid (µg/L)	Monochloroacetic Acid (µg/L)	Trichloroacetic Acid (µg/L)	HAA5 (µg/L)[b]
8/28/2009[a]	NA	1.19	2.20	<1.00	<1.00	2.39	5.78
9/1/2009	NA	NA	NA	NA	NA	NA	NA
9/4/2009	NA	NA	NA	NA	NA	NA	NA
9/10/2009[c]	NA	<1.00	3.89	<1.00	<2.00	<1.00	3.89
9/11/2009	NA	NA	NA	NA	NA	NA	NA
9/25/2009	0	<1.00	32.70	<1.00	<2.00	25.60	58.30
9/30/2009	0	NA	NA	NA	NA	NA	NA
10/2/2009	NA	NA	NA	NA	NA	NA	NA
10/6/2009	15	NA	NA	NA	NA	NA	NA
10/9/2009	20	<1.00	13.76	<1.00	<2.00	10.36	24.12
10/13/2009	20	NA	NA	NA	NA	NA	NA
10/16/2009	0	NA	NA	NA	NA	NA	NA
10/20/2009	14	NA	NA	NA	NA	NA	NA
10/23/2009	2	<1.00	10.50	<1.00	<2.00	8.63	19.12
10/27/2009	0	NA	NA	NA	NA	NA	NA
10/30/2009	46	NA	NA	NA	NA	NA	NA
11/3/2009	NA	NA	NA	NA	NA	NA	NA
11/6/2009	NA	<1.00	11.67	<1.00	<2.00	8.52	20.20
11/10/2009	NA	NA	NA	NA	NA	NA	NA
11/13/2009	NA	<1.00	9.39	<1.00	<2.00	7.02	16.41
11/17/2009	NA	NA	NA	NA	NA	NA	NA
11/20/2009	NA	<1.00	15.76	<1.00	<2.00	10.96	26.71
11/24/2009	NA	NA	NA	NA	NA	NA	NA
12/4/2009[d]	NA	<1.00	10.34	<1.00	<2.00	11.03	21.37
1/15/2010	NA	<1.00	12.04	<1.00	<2.00	9.91	21.95

(a) Ammonia samples taken during AS water sampling at Head Start building.
(b) Sum of concentrations of individual acids.
(c) As water contained ammonia from 08/28/09 through 09/11/09 due to improper regeneration of softener; ammonia reacted with chlorine to form combined chlorine,which inhibited DPB formation.
(d) On 12/2/09, chlorine concentration in feed increased to 10 mg/L (as Cl2).
NA = Not Analyzed
Questionable results are flagged in red

Table C-4. Arsenic, TOC, THMs, and HAAs Concentrations in Effluent from Column B Packed with ARM 200 Media Taken from System in Head Start Building

Date	Total Throughput (BV)	Total Arsenic (µg/L)	Soluble Arsenic (µg/L)	TOC (mg/L)	Chloroform (µg/L)	Bromodichloro-methane (µg/L)	Dibromochloro-methane (µg/L)	Bromoform (µg/L)
9/25/2009	174	36.00	NA	<1.00	2.21	<0.500	<0.500	<0.500
9/30/2009	263	NA	NA	<1.00	NA	NA	NA	NA
10/2/2009	346	NA	NA	<5.00	NA	NA	NA	NA
10/6/2009	407	NA	NA	<1.00	NA	NA	NA	NA
10/9/2009	544	9.27	NA	<1.00	3.93	<0.500	<0.500	<0.500
10/13/2009	597	NA	NA	<1.00	NA	NA	NA	NA
10/16/2009	732	NA	NA	<1.00	NA	NA	NA	NA
10/20/2009	786	NS	NA	<1.00	NA	NA	NA	NA
10/23/2009	925	0.17	0.16	<1.00	<0.500	<0.500	<0.500	<0.500
10/27/2009	980	NA	NA	<1.00	NA	NA	NA	NA
10/30/2009	1117	NA	NA	<1.00	NA	NA	NA	NA
11/3/2009	1173	NA	NA	<1.00	NA	NA	NA	NA
11/6/2009	1306	0.97	0.56	<1.00	5.19	<0.500	<0.500	<0.500
11/10/2009	1363	NA	NA	<1.00	NA	NA	NA	NA
11/13/2009	1498	0.52	0.68	<1.00	2.30	<0.500	<0.500	<0.500
11/17/2009	1555	NA	NA	<1.00	NA	NA	NA	NA
11/20/2009	1693	0.51	0.59	<1.00	3.27	<0.500	<0.500	<0.500
11/24/2009	1802	NA	NA	<1.00	NA	NA	NA	NA
12/4/2009[(b)]	1992	0.60	0.61	< 1.00	3.61	<0.500	<0.500	<0.500
1/15/2010	2164	1.4	1.4	<1.00	2.30	<0.500	<0.500	<0.500

Table C-4. Arsenic, TOC, THMs, and HAAs Concentrations in Effluent from Column B Packed with ARM 200 Media Taken from System in Head Start Building (Continued)

Date	TTHM (µg/L)	THM Plus (µg/L as $CHCl_3$)	Dibromoacetic Acid (µg/L)	Dichloroacetic Acid (µg/L)	Monobromoacetic Acid (µg/L)	Monochloroacetic Acid (µg/L)	Trichloroacetic Acid (µg/L)	HAA5 (µg/L)[a]
9/25/2009	2.21	23	<1.00	1.52	<1.00	<2.00	<1.00	1.52
9/30/2009	NA	23	NA	NA	NA	NA	NA	NA
10/2/2009	NA	NA	NA	NA	NA	NA	NA	NA
10/6/2009	NA	54	NA	NA	NA	NA	NA	NA
10/9/2009	3.93	13	<1.00	<1.00	<1.00	<2.00	<1.00	0.00
10/13/2009	NA	1	NA	NA	NA	NA	NA	NA
10/16/2009	NA	0	NA	NA	NA	NA	NA	NA
10/20/2009	NA	48	NA	NA	NA	NA	NA	NA
10/23/2009	0.00	0	<1.00	<1.00	<1.00	<2.00	<1.00	0.00
10/27/2009	NA	0	NA	NA	NA	NA	NA	NA
10/30/2009	NA	38	NA	NA	NA	NA	NA	NA
11/3/2009	NA	NA	NA	NA	NA	NA	NA	NA
11/6/2009	5.19	NA	<1.00	2.39	<1.00	<2.00	<1.00	2.39
11/10/2009	NA	NA	NA	NA	NA	NA	NA	NA
11/13/2009	2.30	NA	<1.00	<1.00	<1.00	<2.00	<1.00	0.00
11/17/2009	NA	NA	NA	NA	NA	NA	NA	NA
11/20/2009	3.27	NA	<1.00	1.90	<1.00	<2.00	<1.00	1.90
11/24/2009	NA	NA	NA	NA	NA	NA	NA	NA
12/4/2009[b]	3.61	NA	<1.00	2.29	<1.00	<2.00	<1.00	2.29
1/15/2010	2.30	NA	<1.00	<1.00	<1.00	<2.00	<1.00	0.00

(a) Sum of concentrations of individual acids.
(b) On 12/2/09, chlorine concentration in feed increased to 10 mg/L (as Cl2).
NA = Not Analyzed.
Questionable results are flagged in red.

Table C-5. Arsenic, TOC, THMs, and HAAs Concentrations in Effluent from Column C Packed with ARM 200 Media Taken from System in Head Start Building

Date	Total Throughput (BV)	Total Arsenic (µg/L)	Soluble Arsenic (µg/L)	TOC (mg/L)	Chloroform (µg/L)	Bromodichloro-methane (µg/L)	Dibromochloro-methane (µg/L)	Bromoform (µg/L)
9/25/2009	168	13.60	NA	1.63	30.50	8.21	1.74	<0.500
9/30/2009	287	NA	NA	1.72	NA	NA	NA	NA
10/2/2009	373	NA	NA	2.35	NA	NA	NA	NA
10/6/2009	423	NA	NA	1.66	NA	NA	NA	NA
10/9/2009	555	21.50	NA	1.41	30.85	7.94	1.81	<0.500
10/13/2009	607	NA	NA	1.44	NA	NA	NA	NA
10/16/2009	745	NA	NA	1.41	NA	NA	NA	NA
10/20/2009	799	NS	NA	1.58	NA	NA	NA	NA
10/23/2009	936	21.70	21.90	1.61	26.95	6.90	1.58	<0.50
10/27/2009	991	NA	NA	1.65	NA	NA	NA	NA
10/30/2009	1131	NA	NA	1.72	NA	NA	NA	NA
11/3/2009	1187	NA	NA	1.85	NA	NA	NA	NA
11/6/2009	1322	22.30	22.30	1.82	29.82	8.44	1.76	<0.500
11/10/2009	1380	NA	NA	1.97	NA	NA	NA	NA
11/13/2009	1516	18.80	17.90	1.78	26.53	8.05	1.63	<0.500
11/17/2009	1571	NA	NA	1.64	NA	NA	NA	NA
11/20/2009	1695	5.33	6.21	1.28	38.73	12.00	2.80	<0.500
11/24/2009	1755	NA	NA	1.57	NA	NA	NA	NA
12/4/2009[(b)]	1941	12.50	12.30	1.39	34.19	9.40	1.63	<0.500
1/15/2010	2104	15.0	15.1	1.58	31.32	8.20	1.73	<0.500

Table C-5. Arsenic, TOC, THMs, and HAAs Concentrations in Effluent from Column C Packed with ARM 200 Media Taken from System in Head Start Building (Continued)

Date	TTHM (µg/L)	THM Plus (µg/L as $CHCl_3$)	Dibromoacetic Acid (µg/L)	Dichloroacetic Acid (µg/L)	Monobromoacetic Acid (µg/L)	Monochloroacetic Acid (µg/L)	Trichloroacetic Acid (µg/L)	HAA5 (µg/L)[a]
9/25/2009	40.40	31	<1.00	12.70	<1.00	<2.00	11.40	24.10
9/30/2009	NA	34	NA	NA	NA	NA	NA	NA
10/2/2009	NA	NA	NA	NA	NA	NA	NA	NA
10/6/2009	NA	30	NA	NA	NA	NA	NA	NA
10/9/2009	40.60	38	<1.00	7.07	<1.00	<2.00	6.89	13.96
10/13/2009	NA	17	NA	NA	NA	NA	NA	NA
10/16/2009	NA	29	NA	NA	NA	NA	NA	NA
10/20/2009	NA	0	NA	NA	NA	NA	NA	NA
10/23/2009	35.43	0	<1.00	6.05	<1.00	<2.00	6.23	12.28
10/27/2009	NA	41	NA	NA	NA	NA	NA	NA
10/30/2009	NA	31	NA	NA	NA	NA	NA	NA
11/3/2009	NA	NA	NA	NA	NA	NA	NA	NA
11/6/2009	40.02	NA	<1.00	7.80	<1.00	<2.00	6.26	12.06
11/10/2009	NA	NA	NA	NA	NA	NA	NA	NA
11/13/2009	36.21	NA	<1.00	7.10	<1.00	<2.00	5.73	12.82
11/17/2009	NA	NA	NA	NA	NA	NA	NA	NA
11/20/2009	53.53	NA	<1.00	<1.00	<1.00	<2.00	9.17	9.17
11/24/2009	NA	NA	NA	NA	NA	NA	NA	NA
12/4/2009[b]	45.22	NA	<1.00	8.17	<1.00	<2.00	8.89	17.09
1/15/2010	41.25	NA	<1.00	7.61	<1.00	<2.00	9.70	17.32

(a) Sum of concentrations of individual acids.
(b) On 12/2/09, chlorine concentration in feed increased to 10 mg/L (as Cl2).
NA = Not Analyzed.
Questionable results are flagged in red.