

**Arsenic Removal from Drinking Water by Coagulation/Filtration
U.S. EPA Demonstration Project at Village of Pentwater, MI
Six-Month Evaluation Report**

by

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Sally Gutierrez, Director
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ABSTRACT

This report documents the activities performed during and the results obtained from the first six months of the EPA arsenic removal technology demonstration project at the Village of Pentwater, MI facility. The main objective of the project is to evaluate the effectiveness of Kinetico's FM-260-AS treatment system using Macrolite[®] media in removing arsenic to meet the new arsenic maximum contaminant level (MCL) of 10 µg/L. Additionally, this project evaluates the reliability of the treatment system for use at small water facilities, the required system operation and maintenance (O&M) and operator skill levels, and the cost-effectiveness of the technology. The project also characterizes water in the distribution system and residuals generated by the treatment process. The types of data collected include system operation, water quality (both across the treatment train and in the distribution system), process residuals, and capital and O&M costs.

After engineering plan review and approval by the state, the FM-260-AS treatment system was installed and became operational on November 22, 2005. The system consisted of one 96-in-diameter, 96-in-tall steel contact tank and two 60-in-diameter, 96-in-tall steel pressure tanks configured in parallel. Each pressure tank contained 40 ft³ of Macrolite[®] media, which is a spherical, low density, chemically inert ceramic media designed for filtration rates up to 10 gpm/ft². The system used an existing chlorination system to oxidize As(III) and Fe(II) and the contact tank to improve the formation of As(V)-laden particles prior to entering the pressure filters. The system operated at approximately 353 gal/min (gpm) for 3.2 hr/day, producing 12,714,000 gal of water through May 22, 2006. The flowrate corresponded to a contact time of 6.8 min and a filtration rate of 9 gpm/ft². A number of issues related to backwash operation were experienced and are being addressed by the vendor. The resolution of these issues will be further discussed in the Final Performance Evaluation Report.

The source water had an average pH of 8.0 and contained 15.3 to 21.8 µg/L of total arsenic. The predominant species was As(III) with an average concentration of 17.2 µg/L. Total iron concentrations ranged from 346 to 510 µg/L, which existed primarily in the soluble form with an average concentration of 367 µg/L. Raw water soluble iron and soluble arsenic concentrations corresponded to a ratio of 21:1. Total arsenic concentrations in treated water ranged from 7.8 to 15.6 µg/L and averaged 10.0 µg/L. To further reduce arsenic concentrations in treated water, provisions were made to enable supplemental iron addition. This condition will be initiated after backwash issues are resolved by the vendor and evaluated in the Final Performance Evaluation Report.

Comparison of the distribution system sampling results before and after the system startup demonstrated a considerable decrease in arsenic (16.5 to 8.8 µg/L), iron (192 to <25 µg/L), manganese (23.8 to 11.5 µg/L), and copper (131 to 70.4 µg/L) concentrations. Alkalinity, pH, and lead concentrations did not appear to be affected.

Filter tank backwash occurred automatically about 3 time/tank/week triggered by 24-hr service time, 48-hr standby time, or 22-psi differential pressure setpoints, whichever occurred first. Due to low operational time of the treatment system, the majority of backwash cycles was initiated by the standby time setpoint. Approximately 403,900 gal of wastewater, or 3.2% of the amount of water treated, was generated during the first six months. Under normal operating conditions, the backwash wastewater contained 24 to 106 mg/L of total suspended solids (TSS), 1.5 to 29.5 mg/L of iron, 66 to 1,206 µg/L of manganese, and 30 to 610 µg/L of arsenic, with the majority existing as particulates. The highest amount of solids discharged per backwash cycle was approximately 0.96 lb, including 0.235 lb of iron, 0.009 lb of manganese, and 0.005 lb of arsenic.

The capital investment for the system was \$334,573 consisting of \$224,994 for equipment, \$30,929 for site engineering, and \$78,650 for installation, shakedown, and startup. Using the system's rated capacity of 400 gpm (or 576,000 gal/day [gpd]), the capital cost was \$836/gpm (or \$0.58/gpd). This calculation does not include the cost of the building to house the treatment system.

O&M cost, estimated at \$0.22/1,000 gal, included only the incremental cost for electricity and labor. Since chlorination already existed prior to the demonstration study, the incremental cost for chemical usage will only be incurred for iron addition once initiated. The associated costs for iron addition will be discussed in the Final Performance Evaluation Report.

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ABBREVIATIONS AND ACRONYMS

Δp	differential pressure
AA	activated alumina
AAL	American Analytical Laboratories
Al	aluminum
AM	adsorptive media
As	arsenic
ATS	Aquatic Treatment Systems
bgs	below ground surface
BV	bed volume(s)
C/F	coagulation/filtration
Ca	calcium
Cl	chlorine
CRF	capital recovery factor
Cu	copper
DBPR	Disinfection Byproducts Rule
DO	dissolved oxygen
EPA	U.S. Environmental Protection Agency
F	fluoride
Fe	iron
FEATS	Field Evaluation and Technical Support
FeCl ₃	ferric chloride
FedEx	Federal Express
gpd	gallons per day
gpm	gallons per minute
H ₂ SO ₄	sulfuric 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
MCL	maximum contaminant level
MDEQ	Michigan Department of Environmental Quality
MDL	method detection limit
MEI	Magnesium Elektron, Inc.
Mg	magnesium
μm	micrometer

Mn	manganese
mV	millivolts
Na	sodium
NA	not analyzed
NaOCl	sodium hypochlorite
ND	not detected
NS	not sampled
NSF	NSF International
NTU	nephelometric turbidity units
O&M	operation and maintenance
OIP	operator interface panel
OIT	Oregon Institute of Technology
ORD	Office of Research and Development
ORP	oxidation-reduction potential
P	phosphorus
P&ID	piping and instrumentation diagram
Pb	lead
pCi/L	picocuries per liter
psi	pounds per square inch
PLC	programmable logic controller
PO ₄	phosphate
POU	point-of-use
PVC	polyvinyl chloride
QA	quality assurance
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RPD	relative percent difference
RO	reverse osmosis
Sb	antimony
SDWA	Safe Drinking Water Act
SiO ₂	silica
SMCL	secondary maximum contaminant level
SO ₄	sulfate
STS	Severn Trent Services
TBD	to be determined
TDS	total dissolved solids
THM	trihalomethanes
TOC	total organic carbon
TSS	total suspended solids
UPS	uninterruptible power supply
V	vanadium

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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 that are known or anticipated to occur in public water supply systems. In 1975 under the SDWA, EPA established a maximum contaminant level (MCL) for arsenic at 0.05 mg/L. Amended in 1996, the SDWA required that EPA develop an arsenic research strategy and publish a proposal to revise the arsenic MCL by January 2000. On January 18, 2001, EPA finalized the arsenic MCL at 0.01 mg/L (EPA, 2001). In order to clarify the implementation of the original rule, EPA revised the rule on March 25, 2003 to express the MCL as 0.010 mg/L (10 µg/L) (EPA, 2003). The final rule 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 in order to reduce compliance costs. As part of this Arsenic Rule Implementation Research Program, EPA's Office of Research and Development (ORD) proposed a project to conduct a series of full-scale, on-site demonstrations of arsenic removal technologies, process modifications, and engineering approaches applicable to small systems. Shortly thereafter, an announcement was published in the *Federal Register* requesting water utilities interested in participating in Round 1 of this EPA-sponsored demonstration program to provide information on their water systems. In June 2002, EPA selected 17 out of 115 sites to host the demonstration studies.

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

In 2003, EPA initiated Round 2 arsenic technology demonstration projects that were partially funded with Congressional add-on funding to the EPA budget. In June 2003, EPA selected 32 potential demonstration sites and the community water system in the Village of Pentwater, MI was one of those selected.

In September 2003, EPA again solicited proposals from engineering firms and vendors for arsenic removal technologies. EPA received 148 technical proposals for the 32 host sites, with each site receiving from two to eight proposals. In April 2004, another technical panel was convened by EPA to review the proposals and provide recommendations to EPA with the number of proposals per site ranging from none (for two sites) to a maximum of four. The final selection of the treatment technology at the sites that received at least one proposal was made, again, through a joint effort by EPA, the state regulators, and the host site. Since then, four sites have withdrawn from the demonstration program, reducing the number of sites to 28. Kinetico's Macrolite[®] Arsenic Removal Technology was selected for demonstration at the Pentwater facility. As of June 2007, 36 of the 40 demonstrations have been initiated with 21 performance evaluations completed.

1.2 Treatment Technologies for Arsenic Removal

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

1.3 Project Objectives

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

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

This report summarizes the performance of the Kinetico system at the Village of Pentwater in Michigan during the first six months from November 22, 2005 through May 22, 2006. The types of data collected included system operation, water quality (both across the treatment train and in the distribution system), residuals, and capital and preliminary O&M cost.

Table 1-1. Summary of Arsenic Removal Demonstration Sites

Demonstration Location	Site Name	Technology (Media)	Vendor	Design Flowrate (gpm)	Source Water Quality		
					As (µg/L)	Fe (µg/L)	pH (S.U.)
<i>Northeast/Ohio</i>							
Wales, ME	Springbrook Mobile Home Park	AM (A/I Complex)	ATS	14	38 ^(a)	<25	8.6
Bow, NH	White Rock Water Company	AM (G2)	ADI	70 ^(b)	39	<25	7.7
Goffstown, NH	Orchard Highlands Subdivision	AM (E33)	AdEdge	10	33	<25	6.9
Rollinsford, NH	Rollinsford Water and Sewer District	AM (E33)	AdEdge	100	36 ^(a)	46	8.2
Dummerston, VT	Charette Mobile Home Park	AM (A/I Complex)	ATS	22	30	<25	7.9
Felton, DE	Town of Felton	C/F (Macrolite)	Kinetico	375	30 ^(a)	48	8.2
Stevensville, MD	Queen Anne's County	AM (E33)	STS	300	19 ^(a)	270 ^(c)	7.3
Houghton, NY ^(d)	Town of Caneadea	C/F (Macrolite)	Kinetico	550	27 ^(a)	1,806 ^(c)	7.6
Newark, OH	Buckeye Lake Head Start Building	AM (ARM 200)	Kinetico	10	15 ^(a)	1,312 ^(c)	7.6
Springfield, OH	Chateau Estates Mobile Home Park	AM (E33)	AdEdge	250 ^(e)	25 ^(a)	1,615 ^(c)	7.3
<i>Great Lakes/Interior Plains</i>							
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
<i>Midwest/Southwest</i>							
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	Indian Health Services	AM (E33)	AdEdge	145	33	<25	8.5
Taos, NM	Town of Taos	AM (E33)	STS	450	14	59	9.5
Rimrock, AZ	Arizona Water Company	AM (E33)	AdEdge	90 ^(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.)
<i>Far West</i>							
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)	Filtronic	750	18	69 ^(c)	8.0
Klamath Falls, OR	Oregon Institute of Technology	POE AM (Adsorbis/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 process; C/F = coagulation/filtration; HIX = hybrid ion exchanger; IX = ion exchange process; RO = reverse osmosis

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

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

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

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

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

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

(f) Including nine residential units.

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

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2.0 SUMMARY AND CONCLUSIONS

Kinetico's FM-260-AS treatment system with Macrolite[®] media was installed and operated at Village of Pentwater, MI since November 22, 2005. Based on the information collected during the first six months of operation, the following preliminary conclusions were made relating to the overall project objectives.

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

- Without supplemental iron addition, the system may not remove arsenic to <10 µg/L. The average soluble iron to soluble arsenic ratio in raw water was 21:1, which is on the borderline with the rule of thumb value of 20:1.
- Chlorination is effective in oxidizing As(III) to As(V), reducing the As(III) concentration from 14.6 µg/L (on average) in raw water to 0.4 µg/L (on average) after the contact tank.
- The system can be operated at a high filtration rate of 9 gpm/ft² (on average) with minimum particulate leakage observed in the pressure filter effluent.
- The treatment system has improved water quality in the distribution system. A considerable decrease in arsenic (16.5 to 8.8 µg/L), iron (192 to <25 µg/L), manganese (23.8 to 11.5 µg/L), and copper (131 to 70.4 µg/L) concentrations was observed. Alkalinity, pH, and lead concentrations did not appear to be affected.

Required system O&M and operator skill levels:

- Although the daily demand on the operator was only 30 min, a significant amount of time and effort was required to troubleshoot several backwash related issues.
- Flow meters and totalizers may provide erroneous readings due to incorrect meter calibration. It would be prudent to verify these readings, especially if and when the system is performing out of design specifications.

Characteristics of residuals produced by the technology:

- The amount of wastewater produced was equivalent to about 3.2% of the amount of water treated. This generation rate is higher than that from a similar, but smaller system at Climax, MN, where 1.9 to 2.4% was observed (Condit and Chen, 2006). The backwash generation rate will continue to be monitored after all backwash issues are resolved.
- Approximately 0.96 lb of residual solids was produced during each backwash cycle, including 0.235 lb of iron, 0.009 lb of manganese, and 0.005 lb of arsenic.

Cost-effectiveness of the technology:

- The capital investment for the system was \$334,573, consisting of \$224,994 for equipment, \$30,929 for site engineering, and \$78,650 for installation, shakedown, and startup. The building cost was not included in the capital investment, since it was funded by the village.
- The unit capital cost was \$836/gpm (or \$0.58/gpd) based on a design capacity of 400 gpm.
- The O&M cost, estimated at \$0.22/1,000 gal, included only incremental cost for electricity and labor.

3.0 MATERIALS AND METHODS

3.1 General Project Approach

Following the predemonstration activities summarized in Table 3-1, the performance evaluation study of the Kinetico treatment system began on November 22, 2005. Table 3-2 summarizes the types of data collected and considered as part of the technology evaluation process. The overall system performance was evaluated based on its ability to consistently remove arsenic to below the target MCL of 10 µg/L through the collection of water samples across the treatment train. The reliability of the system was evaluated by tracking the unscheduled system downtime and frequency and extent of repair and replacement. The unscheduled downtime and repair information were recorded by the plant operator on a Repair and Maintenance Log Sheet.

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

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

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

Table 3-1. Predemonstration Study Activities and Completion Dates

Activity	Date
Introductory Meeting Held	August 31, 2004
Draft Letter of Understanding Issued	October 19, 2004
Final Letter of Understanding Issued	November 4, 2004
Request for Quotation Issued to Vendor	November 10, 2004
Vendor Quotation Received	December 2, 2004
Purchase Order Established	February 1, 2005
Letter Report Issued	March 1, 2005
Engineering Package Submitted to MDEQ	March 29, 2005
Study Plan Issued	March 30, 2005
System Permit Granted by MDEQ	May 31, 2005
Building Construction Permit Granted by Oceana County	August 17, 2005
Building Construction Began	August 19, 2005
Building Completed and FM-260-AS System Shipped	October 21, 2005
System Installation Completed	November 4, 2005
System Shakedown Completed	November 11, 2005
Performance Evaluation Began	November 22, 2005

MDEQ = Michigan Department of Environmental Quality

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

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

3.2 System O&M and Cost Data Collection

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

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

3.3 Sample Collection Procedures and Schedules

To evaluate system performance, samples were collected at the wellhead, across the treatment plant, during Macrolite[®] filter backwash, and from the distribution system. The sampling schedules and analytes measured during each sampling event are listed in Table 3-3. In addition, Figure 3-1 presents a

Table 3-3. Sampling Schedule and Analyses

Sample Type	Sample Locations^(a)	No. of Samples	Frequency	Analytes	Collection Date(s)
Source Water	At Wellhead (IN)	1	Once (during initial site visit)	On-site: pH, temperature, DO, and ORP Off-site: As (total, soluble, and particulate), As(III), As(V), total and soluble Fe, Mn, U, and V, Na, Ca, Mg, Cl, F, SO ₄ , SiO ₂ , PO ₄ , NH ₃ , NO ₂ , NO ₃ , TOC, TDS, turbidity, and alkalinity	08/31/04
Treatment Plant Water	At Wellhead (IN), after Contact Tank (AC), after Tank A (TA), and after Tank B (TB)	4	Weekly	On-site ^(b) : pH, temperature, DO, ORP, Cl ₂ (free and total). Off-site: total As, Fe, Mn, and P, SiO ₂ , turbidity, and alkalinity	11/29/05, 12/08/05, 12/12/05, 01/11/06, 01/17/06, 01/23/06, 02/06/06, 02/14/06, 02/22/06, 03/07/06, 03/14/06, 03/20/06, 04/10/06, 04/18/06, 04/24/06, 05/09/06, 05/16/06
	At Wellhead (IN), after Contact Tank (AC), and after Tanks A and B Combined (TT)	3	Monthly	Same as weekly analytes shown above plus the following: Off-site: As (soluble and particulate), As(III), As(V), Fe (soluble), Mn (soluble), Ca, Mg, F, NO ₃ , SO ₄ , NH ₃ , and TOC	11/22/05, 01/04/06, 01/31/06, 03/01/06, 04/03/06, 05/02/06
Backwash Water	Backwash discharge line	2	Monthly	As (total, soluble, and particulate), total and soluble Fe and Mn, pH, TDS, and TSS	12/08/05, 01/04/06, 02/06/06, 03/07/06, 04/12/06, 05/09/06
Distribution Water	Three non-LCR residences	3	Monthly	Total As, Fe, Mn, Cu, and Pb, pH, and alkalinity	Baseline sampling ^(c) : 02/22/05, 03/22/05, 04/19/05, 05/26/05 Monthly sampling: 12/13/05, 01/17/06, 02/14/06, 03/14/06, 04/18/06, 05/16/06
Residual Solids	Backwash solids from each tank	2	Twice	TCLP metals and total Al, As, Ca, Cd, Cu, Fe, Mg, Mn, Ni, P, Pb, Si, and Zn	TBD

(a) Abbreviation corresponding to sample location in Figure 3-1.

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

(c) Sampling events performed before system startup.

TBD = to be determined.

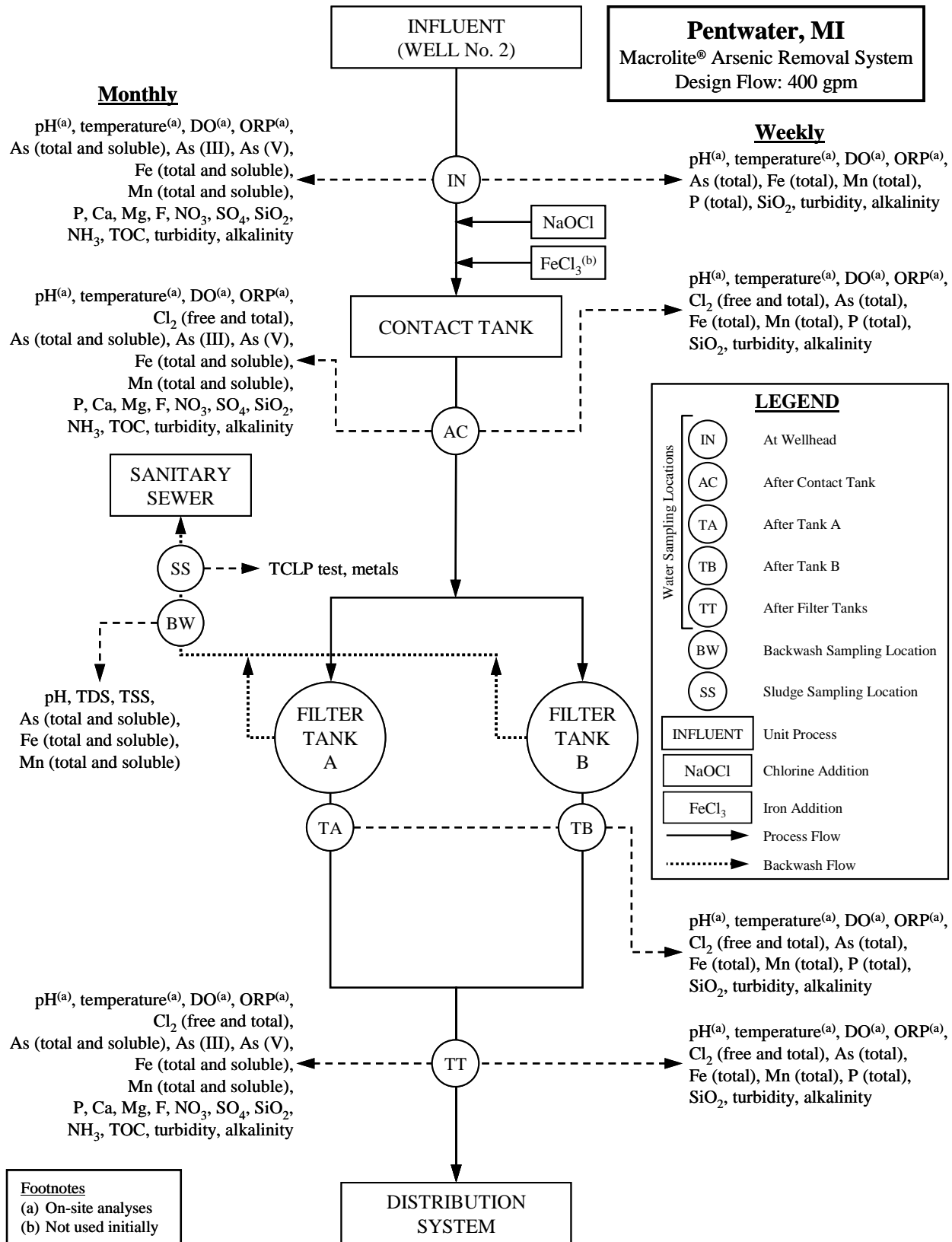


Figure 3-1. Process Flow Diagram and Sampling Schedule and Locations

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

3.3.1 Source Water. During the initial site visit, one set of source water samples was collected and speciated using an arsenic speciation kit (Section 3.4.1). The sample tap was flushed for several minutes before sampling; special care was taken to avoid agitation, which might cause unwanted oxidation. Analytes for the source water samples are listed in Table 3-3.

3.3.2 Treatment Plant Water. During the system performance evaluation study, the plant operator collected samples weekly, on a four-week cycle, for on- and off-site analyses. For the first week of each four-week cycle, samples taken at the wellhead (IN), after the contact tank (AC), and after Tanks A and B combined (TT), were speciated on-site and analyzed for the analytes listed in Table 3-3 for monthly treatment plant water. For the next three weeks, samples were collected at IN, AC, after Tank A (TA), and after Tank B (TB) and analyzed for the analytes listed in Table 3-3 for the weekly treatment plant water.

3.3.3 Backwash Water. Backwash water samples were collected monthly by the plant operator. Tubing, connected to the tap on the discharge line, directed a portion of backwash water at approximately 1 gpm into a clean, 32-gal container over the duration of the backwash for each tank. After the content in the container was thoroughly mixed, composite samples were collected and/or filtered on-site with 0.45- μ m filters. Analytes for the backwash samples are listed in Table 3-3.

3.3.4 Distribution System Water. 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 the system startup from February to May 2005, four sets of baseline distribution water samples were collected from three residences within the distribution system. Following the system startup, distribution system sampling continued on a monthly basis at the same three locations.

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

3.3.5 Residual Solids. Residual solids produced by the treatment process included backwash solids, which were not collected during the initial six months of this demonstration.

3.4 Sampling Logistics

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

3.4.2 Preparation of Sample Coolers. For each sampling event, a sample cooler was prepared with the appropriate number and type of sample bottles, disc filters, and/or speciation kits. All sample bottles were new and contained appropriate preservatives. Each sample bottle was affixed with a pre-printed, colored-coded label consisting of the sample identification (ID), date and time of sample

collection, collector's name, site location, sample destination, analysis required, and preservative. The sample ID consisted of a two-letter code for the specific water facility, sampling date, a two-letter code for a specific sampling location, and a one-letter code designating the arsenic speciation bottle (if necessary). The sampling locations at the treatment plant were color-coded for easy identification. The labeled bottles for each sampling location were placed in separate Ziplock[®] bags and packed in the cooler.

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

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

Samples for metal analyses were stored at Battelle Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) Laboratory. Samples for other water quality analyses were packed in separate coolers and picked up by couriers from American Analytical Laboratories (AAL) in Columbus, OH and TCCI Laboratories in New Lexington, OH, both of which were under contract with Battelle for this demonstration study. The chain-of-custody forms remained with the samples from the time of preparation through analysis and final disposition. All samples were archived by the appropriate laboratories for the respective duration of the required hold time and disposed of properly thereafter.

3.5 Analytical Procedures

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

Field measurements of pH, temperature, DO, and ORP were conducted by the plant operator using a handheld field meter, which was calibrated for pH and DO prior to use following the procedures provided in the user's manual. The ORP probe also was checked for accuracy by measuring the ORP of a standard solution and comparing it to the expected value. The plant operator collected a water sample in a clean, plastic beaker and placed the probe in the beaker until a stable value was obtained. The plant operator also performed free and total chlorine measurements using Hach chlorine test kits following the user's manual.

4.0 RESULTS AND DISCUSSION

4.1 Facility Description

Three wells (Wells No. 1, 2, and 3) owned by the Village of Pentwater supplied water to a population of about 1,000, which increased during the summer months with the influx of tourists and summer residents. Well No. 2 was primarily used to meet the village's daily demand, and Wells No. 1 and 3 were used as backup wells to meet the peak demand of 300,000 gpd. Typical daily operational time was 16 to 18 hr during the summer and 4 to 5 hr during the winter.

Well No. 2, selected for this demonstration study, was a 10-in-diameter, 235-ft-deep well screened from 195 to 235 ft below ground surface (bgs) with a static water level at 40 ft bgs. The well was equipped with a 30-horsepower (hp) submersible pump rated for 250 gpm at 300 ft of total dynamic head (TDH). Operating at a reduced TDH of 184 ft, Well No. 2 had a capacity of approximately 350 gpm, which was notably less than the 420 gpm expected based on the pump curve.

Prior to the installation of the arsenic removal system, treatment consisted of only chlorine and polyphosphate addition, which was carried out in the Well No. 2 pump house (Figure 4-1). A 15% NaOCl solution stored in a 55-gal drum was injected at 2 to 3 mg/L at the wellhead using a 1.0-gal/hr (gph) pump to attain a chlorine residual of approximately 0.5 mg/L. A phosphate mixture (i.e., 85% polyphosphate and 15% orthophosphate) also was added at 2 mg/L using a 2.5-gph pump for iron sequestration and corrosion control. The treated water was stored in a 150,000-gal water tower with level sensors for pump control.



Figure 4-1. Existing Facility and System Components
(Clockwise from Top: Well No. 2 Pump House, Water Tower, Polyphosphate Drum, Wellhead Totalizer, and Piping and Chlorine Addition Equipment)

4.1.1 Source Water Quality. Source water samples were collected from Well No. 2 on August 31, 2004. The results of the source water analysis, along with those provided by the facility, vendor, and Michigan Department of Environmental Quality (MDEQ), are presented in Table 4-1.

Historically, total arsenic concentrations in source water ranged from 17 to 24 µg/L. Based on the August 30, 2004 sampling results, arsenic existed primarily as As(III) (i.e., 11.1 of 13.4 µg/L), most likely a result of the reducing conditions of the source water (i.e., low DO and ORP). A small amount of arsenic also was present as particulate arsenic (i.e., 0.2 µg/L) and As(V) (i.e., 2.1 µg/L). Because the treatment process relied upon coprecipitation and adsorption of As(V) onto iron solids, prechlorination was required to oxidize As(III) to As(V). The presence of 0.3 mg/L of ammonia and 2.5 mg/L of total organic carbon (TOC) potentially could impact the prechlorination dosage. Hence, chlorine residual, ammonia, and TOC were monitored during the performance evaluation study.

Iron concentrations in source water ranged from 300 to 600 µg/L, which existed almost entirely as soluble iron based on the August 30, 2004 sampling results. For effective adsorption of arsenic onto iron solids, the general recommendations are that the soluble iron concentration is at least 20 times greater than the soluble arsenic concentration (Sorg, 2002), and that the pH value of source water falls in the range between 5.5 and 8.5 although improved performance may be observed at the lower end of this range. The results obtained on August 30, 2004 indicated a soluble iron to soluble arsenic ratio of 35:1 and a pH range of 6.9 to 7.9. Therefore, no provisions were made for iron addition or pH adjustment.

Other source water quality parameters also were analyzed (Table 4-1). Among those with detectable concentrations were chloride (i.e., 130 to 165 mg/L), fluoride (i.e., 0.4 to 0.7 mg/L), selenium (i.e., 6 to 8 µg/L), sodium (i.e., 51 to 73 mg/L), calcium and magnesium hardness (i.e., 180 to 252 mg/L [as CaCO₃]), barium (i.e., 90 to 110 µg/L), chromium (i.e., 10 µg/L), and manganese (i.e., 32.4 to 80 µg/L, which exceeded the secondary MCL [SMCL] of 0.05 mg/L). The combined radium concentration (i.e., 0.3 and 0.1 pCi/L of Ra-226 and 228, respectively) was below the 5.0-pCi/L MCL.

4.1.2 Distribution System. The distribution system at the Village of Pentwater consisted of a mostly looped distribution line linked to the primary supply well (i.e., Well No. 2) and two backup wells (i.e., Wells No. 1 and 3). Based on a conversation with the utility operator, the distribution system was a combination of 6- and 8-in-diameter ductile iron and sand cast iron piping. Three residences served by these wells were selected by the plant operator for the distribution system sampling. These locations were not part of Pentwater's historic sampling network for EPA's Lead and Copper Rule (LCR) due to limited availability of such homes year-round.

The Village samples water from the distribution system monthly for bacteria analysis, semi-annually for trihalomethanes (THMs) and acetic acid analysis under EPA's Disinfection Byproducts Rule (DBPR), and once every three years for lead and copper analysis at 10 residences under EPA's LCR. The wells also are sampled periodically for arsenic and other constituents.

4.2 Treatment Process Description

Kinetico provided a FM-260-AS Arsenic Removal system for the Village of Pentwater site. The treatment train included prechlorination/oxidation, coprecipitation/adsorption, and Macrolite[®] pressure filtration. Macrolite[®], a spherical, low density, chemically inert, ceramic media manufactured by Kinetico, is designed to allow for filtration rates up to 10 gpm/ft² and approved for use in drinking water applications under NSF International (NSF) Standard 61. The physical properties of Macrolite[®] are summarized in Table 4-2.

Table 4-1. Well No. 2 Source Water Quality Data

Parameter	Unit	Facility Data	Kinetico Data	Battelle Data	MDEQ Data
Date	-	NA	11/06/03	08/31/04	04/08/00 - 02/26/04
pH	S.U.	NA	7.9	6.9	NA
Temperature	°C	NA	NA	13.7	NA
DO	mg/L	NA	NA	1.3	NA
ORP	mV	NA	NA	-97	NA
Alkalinity (as CaCO ₃)	mg/L	NA	144	141	NA
Hardness (as CaCO ₃)	mg/L	188	204	252	180-211
Turbidity	NTU	NA	NA	2.3	NA
TDS	mg/L	NA	NA	450	NA
TOC	mg/L	NA	NA	2.5	NA
Nitrate (as N)	mg/L	NA	NA	<0.04	<0.4
Nitrite (as N)	mg/L	NA	NA	<0.01	<0.05
Ammonia (as N)	mg/L	NA	NA	0.3	NA
Chloride	mg/L	148	144	130	140-165
Fluoride	mg/L	NA	0.7	0.4	0.5-0.7
Sulfate	mg/L	<5	<4	1	<5
Silica (as SiO ₂)	mg/L	NA	17.1	11.1	NA
Orthophosphate (as P)	mg/L	NA	<0.5	<0.1	NA
As (total)	µg/L	18.0	17.0	13.4	17.0-24.0
As (soluble)	µg/L	NA	NA	13.2	NA
As (particulate)	µg/L	NA	NA	0.2	NA
As(III)	µg/L	NA	NA	11.1	NA
As(V)	µg/L	NA	NA	2.1	NA
Ba (total)	µg/L	NA	NA	NA	90-110
Cr (total)	µg/L	NA	NA	NA	10
Ca (total)	mg/L	NA	47.5	56	NA
Fe (total)	µg/L	550	530	466	300-600
Fe (soluble)	µg/L	NA	NA	465	NA
Mg (total)	mg/L	NA	21	27	NA
Mn (total)	µg/L	NA	80	32.4	NA
Mn (soluble)	µg/L	NA	NA	32.6	NA
Na (total)	mg/L	58	67	83	51-73
Se (total)	µg/L	NA	NA	NA	6-8
U (total)	µg/L	NA	NA	<0.1	NA
U (soluble)	µg/L	NA	NA	<0.1	NA
V (total)	µg/L	NA	NA	1.4	NA
V (soluble)	µg/L	NA	NA	1.0	NA
Ra-226	pCi/L	NA	NA	NA	0.3
Ra-228	pCi/L	NA	NA	NA	0.1

Note: MDEQ data also reported non-detect levels of Be, Cd, Hg, Ni, Pb, Sb, and Tl.
TDS = total dissolved solids; TOC = total organic carbon; NA = not analyzed

Table 4-2. Physical Properties of M2 Macrolite® Media

Property	Value
Color	Variable
Uniformity Coefficient	1.1
Sphere Size Range (mm) [mesh]	0.21 – 0.42 [40 × 70]
Nominal Size (mm)	0.3
Bulk Density (g/cm ³) [lb/ft ³]	0.86 [54]
Specific Gravity	2.05

The FM-260-AS system was composed of one contact tank, two pressure filtration tanks arranged in parallel, and associated instrumentation to monitor pressure, flowrate, and turbidity (continuous turbidity monitoring was performed only during backwash). The system also was equipped with a central control panel that housed a touch screen operator interface panel (OIP), a programmable logic controller (PLC), a modem, and an uninterruptible power supply (UPS). The PLC automatically controlled the system by actuating polyvinyl chloride (PVC) pneumatic valves using a 7.5-horsepower (hp) compressor. The system also featured schedule 80 PVC solvent bonded plumbing and all of the necessary isolation and check valves and sampling ports. Figure 4-2 is a simplified system piping and instrumentation diagram (P&ID). Figures 4-3 and 4-4 contain photographs of the key system components and control and instrumentation, respectively. The system’s design specifications are summarized in Table 4-3. The major process steps are presented as follows:

- **Intake.** Raw water was pumped from Well No. 2 at approximately 350 gpm. The system was equipped with two 200-gpm flow-limiting devices (i.e., one installed after each pressure filtration tank) to prevent overrun and piping to bypass the treatment system (Figure 4-3).
- **Chlorination.** The existing chlorine feed system was used to oxidize As(III) to As(V) and Fe(II) to Fe(III) and maintained a total chlorine residual of approximately 1.3 mg/L (as Cl₂) throughout the treatment train. The feed system consisted of a 55-gal day tank containing a 15% NaOCl solution and a chemical feed pump with a maximum capacity of 1.0 gph.
- **Coprecipitation/Adsorption.** It was anticipated at system startup that enough natural iron existed in source water to effectively remove soluble arsenic through coprecipitation/adsorption of As(V) with/onto iron solids formed after chlorination. However, analytical results collected during the first six months of operation indicated that arsenic removal might be improved via supplemental addition of ferric chloride (FeCl₃) to the chlorinated water (Section 4.5.1). An iron addition system, purchased in April 2006, included a 55-gal polyethylene tank with secondary containment, a 1/20-hp overhead mixer, and a 3.15-gph chemical metering pump. Iron addition will commence during the second six months of system operation.

One 96-in-diameter, 96-in-tall epoxy-lined steel tank, designed to allow 6 min of contact time, was used to improve the formation of iron flocs prior to pressure filtration. The 2,400-gal tank had 6-in top and bottom flanges, which connected to the exit and inlet piping, respectively, for an upflow configuration.

- **Pressure Filtration.** Floc removal from the contact tank effluent was achieved via downflow filtration through two 60-in-diameter, 96-in-tall pressure tanks configured in

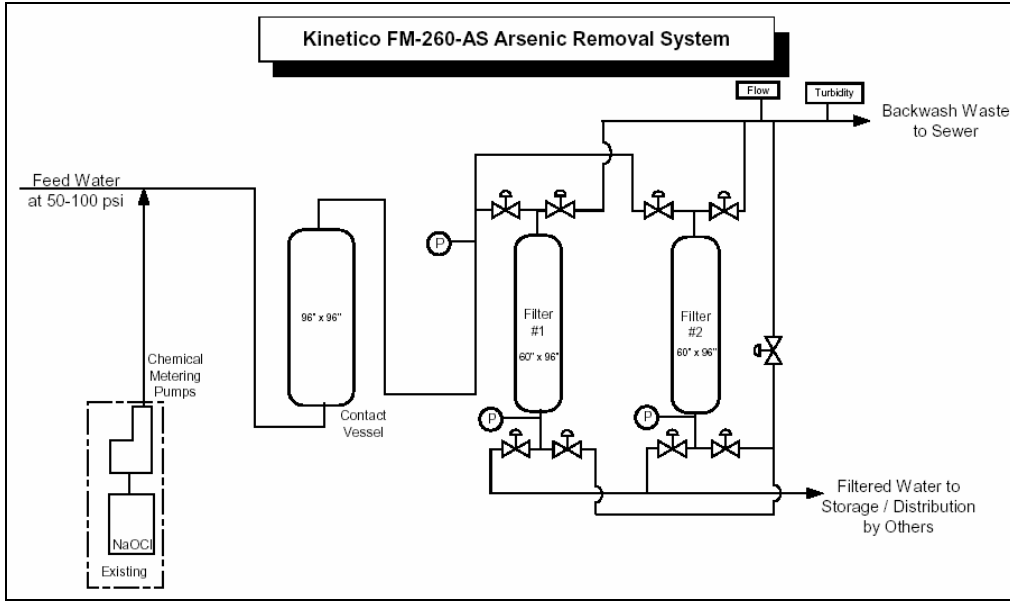


Figure 4-2. Schematic of Kinetico’s FM-260-AS System



Figure 4-3. Treatment System Components
 (Clockwise from Top: Well No. 2 Entry and Bypass Piping; Two Filter Tanks and a Contact Tank; Filter Tank Laterals and Viewing Window; and Backwash Discharge Piping to Building Sump)



Figure 4-4. Control and Instrumentation

(Clockwise from Left: Control Panel Housing PLC; Turbidimeter Display; Compressor; and Sample Tap and Pressure Gauge)

Table 4-3. Design Specifications for Kinetico’s FM-260-AS System

Parameter	Value	Remarks
<i>Pretreatment</i>		
Chlorine Dosage (mg/L [as Cl ₂])	2-3	–
Iron Dosage (mg/L [as Fe])	0	Not used during the first six months
<i>Contact</i>		
Tank Quantity	1	–
Tank Size (in)	96 D × 96 H	–
Tank Volume (gal)	2,400	–
Contact Time (min)	6	–
<i>Filtration</i>		
Tank Quantity	2	Parallel configuration
Tank Size (in)	60 D × 96 H	–
Tank Cross Section (ft ²)	19.6	–
Media Volume (ft ³ /tank)	40	24-in bed depth of Macrolite®
Peak Flowrate (gpm)	400	Typically expected
Filtration Rate (gpm/ft ²)	10	200 gpm/tank
Δp across Tank (psi)	10-12	Across one clean filter
Maximum Production (gpd)	576,000	Based on peak flow, 24 hr/day
Hydraulic Utilization (%)	52	Estimated based on 300,000-gal peak daily demand in summer
<i>Backwash</i>		
Frequency	Variable	Based on PLC setpoints for Δp across tank, run time, and standby time
Hydraulic Loading Rate (gpm/ft ²)	8-10	157-196 gpm
Wastewater Production (gpd)	Variable	Based on PLC setpoints for minimum and maximum backwash time and turbidity

D = diameter; H = height.

parallel. Each tank contained 40 ft³ (or 24 in) of 40 × 60 mesh Macrolite[®] media loaded on top of fine garnet underbedding filled to 1 in above the 0.006-in slotted, stainless steel wedge-wire underdrain. The epoxy-lined steel pressure tanks featured windows for media and backwash observation and were rated for a working pressure of 150 pounds per square inch (psi). The tanks were floor mounted and piped to a valve rack mounted on a welded, stainless steel frame. The flow through each tank was regulated to less than 200 gpm using a flow-limiting device to prevent filter overrun. System operation with both tanks in service could produce a total flowrate of 400 gpm.

- **Filter Backwash.** Backwash removed particulates accumulating in the filter tanks, thereby reducing pressure buildup. The filter tanks were automatically backwashed in succession in an upflow configuration based on service time, run time, and/or differential pressure (Δp) setpoints. The water was drained from the first filter tank before a 2-min air sparge at 100 pounds per square inch gage (psig). After a 4-min settling period, the filter tank was backwashed with treated water from the distribution system until reaching a turbidity threshold setpoint (i.e., 20 nephelometric turbidity units [NTU]) as measured using a Hach[™] turbidimeter. The resulting wastewater was sent to a sump that emptied into the sanitary sewer. After the backwash step, the filter tank underwent filter-to-waste for 2 min using water from the contact tank before returning to feed service.

4.3 Treatment System Installation

This section provides a summary of the system installation, startup, and shakedown activities and the associated prerequisites including permitting and building construction.

4.3.1 System Permitting. The system engineering package, prepared by Kinetico and Wade Trim, included a system design report and associated general arrangement and a P&ID for the FM-260-AS system, electrical and mechanical drawings and component specifications, and building construction drawings detailing connections from the system to the entry piping and the village's water and sanitary sewer systems. The engineering package was certified by a Professional Engineer registered in the State of Michigan and submitted to MDEQ for review and approval on March 29, 2005. After MDEQ's review comments were addressed, the package was resubmitted along with a permit application on May 19, 2005. A water supply construction permit was issued by MDEQ on May 31, 2005, and fabrication of the system began thereafter.

4.3.2 Building Construction. A permit for building construction was applied for by the village and issued by Oceana County on August 17, 2005. Construction began on the following day and was completed on October 21, 2005. The building was 37 ½ ft × 33 ½ ft with sidewall and roof peak heights of 16 and 22.7 ft, respectively. The foundation had a 42-in-depth overlain with a 6-in concrete slab. A 12-ft-wide overhead door enabled ease of equipment placement and installation. Wastewater discharge was facilitated with a 1,500-gal underground sump that emptied by gravity into the sanitary sewer. Figure 4-5 shows the new building constructed adjacent to the existing Well No. 2 pump house. In addition to electrical and plumbing connections, a phone line also was installed on January 19, 2006 with service available on February 22, 2006 to enable the equipment vendor to dial into the modem in the control panel for any troubleshooting.

4.3.3 System Installation, Startup, and Shakedown. The FM-260-AS treatment system was delivered to the site on October 21, 2005. The vendor, through its subcontractor, performed the off-loading and installation of the system, including connections to the entry and distribution piping and electrical interlocking. System installation, hydraulic testing, and media loading were completed on November 4, 2005. System startup and shakedown activities that lasted until November 11, 2005



Figure 4-5. New Building Constructed Next to Existing Well No. 2 Pump House

included PLC testing, instrument calibration, prolonged backwashing to remove Macrolite[®] media fines, chlorine disinfection and residual testing, and operator training on system O&M. The treatment system remained off through November 21, 2005 pending bacteriological results.

Battelle performed system inspections and operator training on sample and data collection on November 21 and 22, 2005. As a result of the system inspections, several punch-list items were identified, some of which appeared to have failed relevant MDEQ requirements and system design specifications. Table 4-4 summarizes the items identified and corrective actions taken. While most of the punch-listed items were resolved by December 2005, several problems related to filter backwash, as discussed in Section 4.4.2, continued to surface throughout the six-month study period.

4.3.4 Iron Addition Modification. Initial sampling results across the treatment train indicated a need for iron addition to further reduce arsenic concentrations to less than the 10- $\mu\text{g/L}$ MCL. Battelle requested a quote for such capabilities on December 6, 2005 and follow-on permitting and equipment supply services on January 23, 2006. An approval for iron addition was granted by MDEQ on April 20, 2006, and the equipment was delivered to the site and installed by the operator on May 8, 2006. Iron addition was not initiated by the end of the first six months of system operation due to on-going backwash problems (Section 4.4.2).

4.4 System Operation

4.4.1 Coagulation/Filtration Operation. The operational parameters for the first six months of the system operation are tabulated and attached as Appendix A with the key parameters summarized in Table 4-5. From November 22, 2005 through May 22, 2006, the system operated for 572 hr, producing 12,714,000 gal based on hour meter and flow totalizer readings on the control panel. (Note that the hour meter was interlocked with the well pump and that the flow meter/totalizer was installed downstream of the pressure filters.) The average daily demand was 70,200 gal, equivalent to approximately 3.2 hr/day of operational time and a utilization rate of 13% over the 26-week period.

Table 4-4. System Inspection Punch-List Items

Item No.	Punch-List Item Description	Corrective Action(s) Taken	Resolution Date
1	Elevate discharge piping to at least 2 times piping diameter off of floor	<ul style="list-style-type: none"> Elevated discharge piping as required 	12/15/05
2	Provide metal, saddled sample tap at combined effluent location	<ul style="list-style-type: none"> Provided metal sample tap at combined effluent location with PVC saddle 	12/15/05
3	Pipe air release valves to drain to keep water off of floor	<ul style="list-style-type: none"> Piped air release valves to drain 	12/15/05
4	Enable contact tank to be drained	<ul style="list-style-type: none"> Installed ball valve between contact tank inlet (at bottom of contact tank) and treatment system inlet valve 	12/15/05
5	Coordinate modem/phone line hookup with facility	<ul style="list-style-type: none"> Completed modem/phone line connection (Section 4.3.2) Dialed into PLC for modifications (Section 4.4.1) 	01/19/06 02/22/06
6	Correct backwash flowrate readings	<ul style="list-style-type: none"> Attempted to increase flowrate to specified range by adjusting diaphragm valve (Section 4.4.2) Added tank stagger time to PLC to prevent/reduce sump overflow (Section 4.4.2) Measured flowrate with portable meter, recalibrated flow meter, and adjusted diaphragm valve (Section 4.4.2) Installed 150-gpm flow restrictors and replaced lost media (Section 4.4.2) 	12/06/05 03/10/06 05/15/06 TBD
7	Review/revise PLC field settings as appropriate	<ul style="list-style-type: none"> Changed PLC settings (Section 4.4.2) Recommended field setting changes due to recurring sump overflow (Section 4.4.2; Table 4-6) 	12/15/05 03/10/06

TBD = to be determined

Table 4-5. FM-260-AS Treatment System Operational Parameters

Parameter	Value
Operational Period	11/22/05–05/22/06
<i>Pretreatment Operation</i>	
Chlorine Dosage (mg/L [as Cl ₂])	1.3
Iron Dosage (mg/L [as Fe])	TBD
<i>Coagulation/Filtration Operation</i>	
Total Operating Time (hr)	572
Average Operating Time (hr/day)	3.2
Throughput (gal)	12,714,000
Average Demand (gpd)	70,200
Service Time between Backwash Cycles ^(a) (hr)	3–14
Throughput between Backwash Cycles ^(a) (gal)	74,000–276,000
Average Flowrate [Range] (gpm)	353 [345–365]
Average Contact Time [Range] (min)	6.8 [6.6–7.0]
Average Filtration Rate [Range] (gpm/ft ²)	9.0 [8.8–9.3]
Average Δp across Each Tank [Range] (psi)	6 [4–15]
Average Δp across System [Range] (psi)	20 [14–24]

Table 4-5. FM-260-AS Treatment System Operational Parameters (Cont'd)

Parameter	Value
<i>Backwash Operation</i>	
Average Frequency (time/tank/week)	3 ^(a)
Number of Cycles (Tank A/Tank B)	110/107
Average Flowrate [Range] (gpm)	213 [170–280] ^(b)
Average Hydraulic Loading Rate [Range] (gpm/ft ²)	10.9 [8.7–14.3] ^(b)
Average Duration [Range] (min/tank)	5 [5–7] ^(b)
Average Backwash Volume [Range] (gal/tank)	1,150 [840–2,100] ^(c)
Filter to Waste Volume (gal/tank)	700
Average Wastewater Produced [Range] (gal/tank)	1,850 [1,540–2,800] ^(c)

(a) Based on 24-hr service time and/or 48-hr standby time since 12/15/05.

(b) Based on monthly data from Backwash Log Sheet.

(c) Based on all cycles. Three backwashes which appeared to occur for <5 min possibly due to incomplete backwash or recording errors not included in range.

TBD = to be determined

Flowrates of the system were tracked by both instantaneous readings of the flow meter and calculated values based on hour meter and flow totalizer readings on the control panel. As shown in Figure 4-6, large discrepancies were observed between the instantaneous readings and calculated values since the system startup through February 22, 2006, when the hour meter display was modified to add one decimal place for tenths of an hour. During this period, the calculated values, denoted as “×” in Figure 4-6, scattered extensively from 304 to 950 gpm. After the decimal place was added, the calculated flowrates fell in a much tighter range, with values ranging from 339 to 392 gpm and averaging 374 gpm (excluding two outliers at 198 and 449 gpm on May 12 and 15, 2006, respectively) until the end of this reporting period.

The instantaneous flowrate readings, denoted as “•” in Figure 4-6, ranged from 382 to 405 gpm and averaged 391 gpm from the system startup through May 15, 2006. During the vendor’s site visit on May 15, 2006 to troubleshoot “low” backwash flowrates (Section 4.4.2), it was noticed that the paddle wheel flow meter was calibrated with an incorrect, factory-supplied K factor (i.e., 19.457), thus resulting in erroneously high flowrate and totalizer readings during this period. After being recalibrated with a revised K factor of 17.553, the flow meter read 355 gpm on May 17, 2006, compared to an average of 391 gpm beforehand. As a result, the original and corrected calibration values were used to adjust the previously obtained instantaneous flowrate and totalizer readings to reflect actual flowrates and throughputs. The revised instantaneous flowrate readings for the entire six-month period ranged from 345 to 365 gpm and averaged 353 gpm.

Due to the changes to totalizer readings, flowrate values were re-calculated and plotted in Figure 4-6. As shown in the figure, the revised calculated values, denoted as “▪,” ranged from 306 to 353 gpm and averaged 340 gpm (except for two outliers at 178 and 405 gpm on May 12 and 15, 2006, respectively) since the decimal place had been added on February 22, 2006. The revised calculated values were somewhat lower than the revised instantaneous readings, which were used as the system flowrates throughout this performance evaluation report.

The 353-gpm flowrate corresponded to a contact time of 6.8 min and a filtration rate of 9 gpm/ft², compared to the design values of 6 min and 10 gpm/ft², respectively (Table 4-3). The Δp readings ranged from 14 to 24 psi across the system and 4 to 15 psi across each tank. Few particulates or media fines accumulated in the filters between two consecutive backwash events due to the backwash frequency of approximately 3 time/tank/week and low service time of 3.2 hr/day.

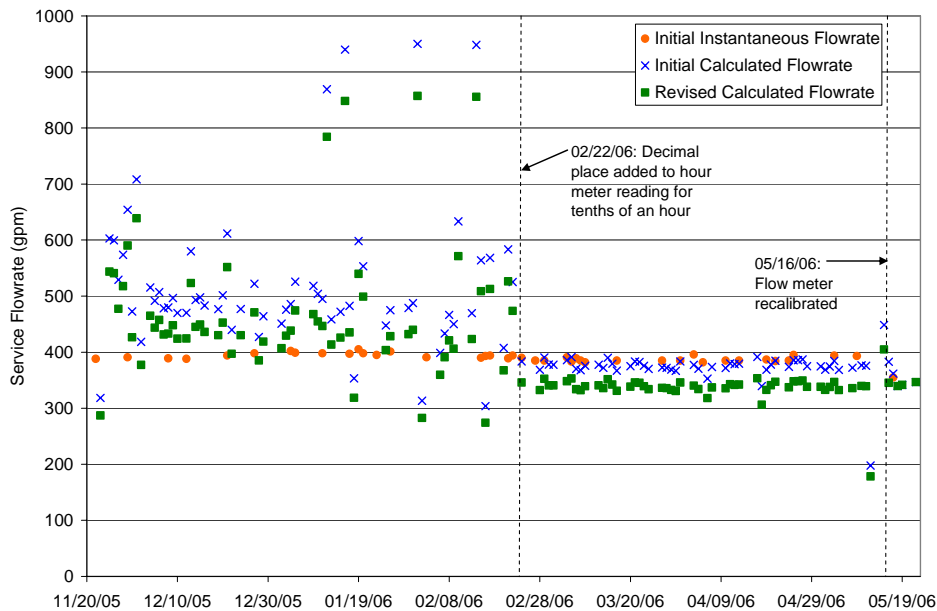


Figure 4-6. Service Flowrates According to Initial and Revised Calibration Values

4.4.2 Backwash Operation. The Macrolite[®] pressure filtration tanks were automatically backwashed according to three PLC setpoints: Δp , standby time, and service time. Due to short daily operational time, the majority of the backwash cycles were triggered by the standby time. Occasionally, manual backwash cycles also were initiated but only for testing and sampling of backwash water and solids. The backwash duration for each tank was affected by the minimum and maximum backwash time settings and the ability of the backwash water to meet the turbidity threshold setting as measured by an in-line Hach[™] turbidimeter. If the backwash water failed to meet the set threshold prior to reaching the maximum backwash time, the backwash failure alarm had to be acknowledged and a successful backwash cycle had to be conducted before the tank might return to the service mode. Backwash was followed by a 2-min filter-to-waste rinse to remove any particulates from the tank.

The pressure filters were backwashed relatively frequently during the first six months of system operation including 110 backwash cycles for Tank A and 107 backwash cycles for Tank B. Backwash flowrates, initially shown on the touch screen OIP as 60 to 104 gpm due to the use of an incorrect K factor (i.e., 7.354), were actually 170 to 295 gpm after the flow meter had been recalibrated using a revised K factor of 20.554 (Figure 4-7). As a result, the hydraulic loading rates for backwash were 8.7 to 14.3 gpm/ft². (The implications of these observations are discussed below.) With each backwash cycle lasting for 5 to 7 min, the amount of wastewater produced ranged from 1,540 to 2,800 gal/tank, including 700 gal/tank produced during the filter-to-waste rinse. (Note that three backwashes which appeared to occur for less than 5 min possibly due to incomplete backwash or recording errors are not included in the range.) The amount of wastewater produced was equivalent to 3.2% of the total amount of water treated.

Backwash-related issues experienced during the first six months of system operation included backwash setting modifications, backwash alarms, media loss, and sump overflow. Table 4-6 summarizes the PLC settings for the backwash process at system startup and two subsequent modifications on December 15, 2005 and March 10, 2006. Initially, the PLC was set in the field to backwash with a standby time trigger of 12 hr, which resulted in frequent backwash (i.e., at least 1 time/tank/day) even though the filter service time during this 12-hr period ranged from only 1 to 5 hr/day. In addition, the field-set turbidity threshold

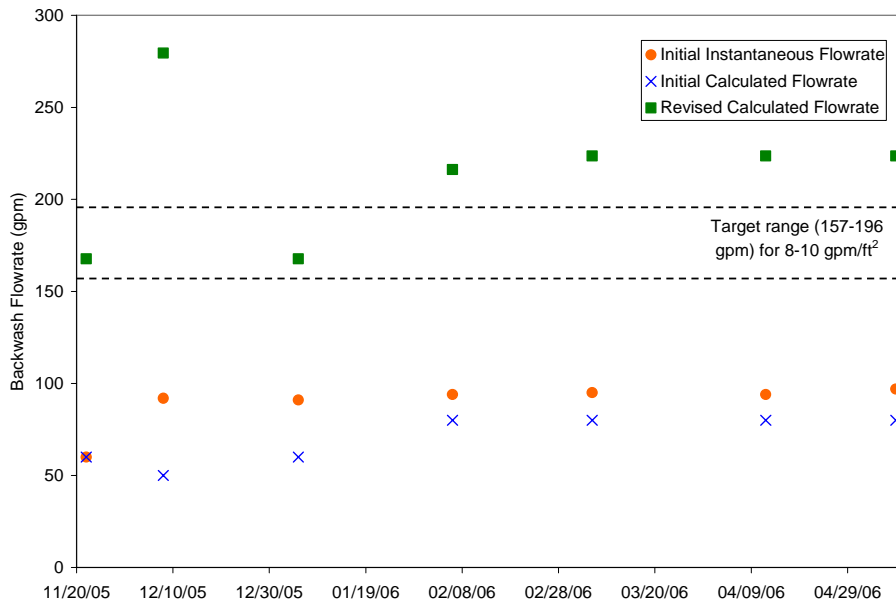


Figure 4-7. Backwash Flowrates According to Initial and Revised Calibration Values

Table 4-6. Summary of PLC Settings for Backwash Operations

Parameter (for Each Tank)	Date		
	11/22/05 ^(a)	12/15/05	03/10/06
Drain Time (min)	4	2	4
Service Time Trigger (hr)	24	24	24
Standby Time Trigger (hr)	12	48	48
Δp Trigger (psi)	18	22	22
Minimum Backwash Time (min)	5	5	5
Maximum Backwash Time (min)	16	20	10
Turbidity Threshold (NTU)	65.5	20	20
Low Flowrate Threshold (gpm)	5	120	75
Filter-to-Waste Time (min)	2	2	2
Backwash Stagger Time (min)	-	-	5

(a) Initial field settings.

of 65.5 NTU was significantly higher than the factory setpoint of 20 NTU, and the low flowrate alarm level of 5 gpm was well below the 157 to 196 gpm (8 to 10 gpm/ft²) design values.

On December 15, 2005, several changes were made to the November 22, 2005 field settings, including increasing standby time trigger, Δp trigger, maximum backwash time, and low flowrate threshold, and decreasing turbidity threshold. With these changes, the backwash frequency decreased to approximately 3 time/tank/week. On March 10, 2006, additional changes were made to decrease the maximum backwash time and add stagger time to allow the sump additional drain time between tank backwashes. These changes were made in an attempt to alleviate concerns over recurring sump overflow problems

during backwash since system startup, which, in turn, were based on the erroneous flowrate readings from the incorrectly calibrated flow meter.

The low flowrate threshold also was decreased on March 10, 2006 due in part to a backwash alarm experienced on March 2, 2006, caused by insufficient flow from the water tower. Previously unacknowledged backwash alarms caused the system to remain in the standby mode, which prevented the system from supplying water to the water tower. The plant operator bypassed the treatment system, refilled the water tower with untreated water from Well No. 2, and restarted the system with vendor assistance on March 3, 2006.

Due to incorrect calibration of the backwash flow meter, the backwash flowrate readings were substantially lower than the design values. This problem, not identified until the vendor's site visit on May 15, 2006, had created a great deal of confusion concerning backwash flowrate, sump capacity, and media loss. Prior to the May 15, 2006 site visit, the maximum attainable backwash flowrate was thought to be only 104 gpm (which, in fact, was 295 gpm with proper meter calibration). At the "low" 104-gpm backwash flowrate, recurring overflow was observed from the building sump, which was designed for a discharge capacity of at least 150 gpm according to the Village Engineer. Further, some Macrolite[®] media was found in and around the sump after each backwash, with the loss confirmed and measured during the vendor's May 15, 2006 visit to be 3 and 4 in (or 5 and 7 ft³) from Tanks A and B, respectively. Prior to the vendor's site visit, several attempts had been made to verify the accuracy of flowrate readings (including using a portable flow meter) and to establish strategies to overcome problems associated with the "underdesigned" sump (including decreasing the maximum backwash time and low flowrate threshold and adding stagger time to allow the sump additional drain time between consecutive backwash cycles). After the flow meter was recalibrated, the backwash flowrate was adjusted to 180 gpm using a diaphragm valve. It also was determined that the filter-to-waste rinse was actually performed at approximately 350 gpm instead of the 200-gpm design value because all of the influent flow was going through one tank during this step.

Therefore, contrary to the initial thoughts, sump overflow was more likely attributable to incorrect backwash settings due to erroneous flowrates and the surge experienced during the filter-to-waste rinse. Similarly, the media loss was likely caused by the excessive backwash flowrates (ranging from 170 to 295 gpm [8.7 to 15.0 gpm/ft²]) experienced by the pressure filters. To prevent overflow, the vendor recommended on May 17, 2006 to use a 150-gpm flow restrictor on each filter-to-waste discharge line to reduce the surge. The replacement of lost media, installation of flow restrictors, and any changes in backwash operation will be discussed in the Final Performance Evaluation Report.

4.4.3 Residual Management. The only residuals produced by the Macrolite[®] Arsenic Removal System were backwash wastewater and filter-to-waste rinse water. Wastewater from backwash was discharged to the building sump, which emptied by gravity to the sanitary sewer. According to the backwash flow totalizer, 250,700 gal of wastewater were produced during the pressure filter backwash. Based on a flowrate of 350 gpm and a duration of 2 min/tank for 217 backwash cycles, 151,900 gal of filter-to-waste rinse water also were produced. (Note that a flow meter was not able to be installed on the filter-to-waste discharge line due to anticipated complications caused by high solids content.) Therefore, over 402,000 gal of wastewater, or 3.2% of the treated water, was generated as a result of this pressure filtration process.

4.4.4 Reliability and Simplicity of Operation. Inability to achieve acceptable arsenic removal due to insufficient iron levels in source water (Sections 4.5.1.1 and 4.5.1.2) and erroneous backwash flowrates resulting in media loss and sump overflow (Section 4.4.2) were the primary sources of concern during this reporting period. Other O&M issues encountered included problems with the prechlorination.

The total amount of system downtime for troubleshooting problems with the prechlorination and backwash was no more than 1% of the operational time.

4.4.4.1 Pre- and Post-Treatment Requirements. Prechlorination with 15% NaOCl solution was performed at the pump house using the existing equipment to oxidize As(III) and Fe(II) and provide chlorine residuals to the distribution system. In addition to tracking the depth of the NaOCl solution in the day tank, the operator measured chlorine residuals to ensure that adequate residuals existed throughout the treatment train. Insufficient chlorine was dosed from February 21 to March 9, 2006 due to provision of an off-spec solution by a chemical supplier. This period of non-treatment could have been shortened if low free and total chlorine measurements were noticed earlier.

Analytical results from the first six months of system operation also indicated that iron addition should be employed for more effective arsenic removal. Iron addition, using 38 to 42% FeCl₃ will commence upon resolution of several backwash issues (Section 4.4.2) and will be discussed in the Final Performance Evaluation Report. No post-treatment requirements existed.

4.4.4.2 System Automation. The FM-260-AS Arsenic Removal System was automatically controlled by the PLC in the central control panel. The control panel contained a modem and a touch screen OIP that facilitated monitoring of system parameters, changing of system setpoints, and checking the alarm status. Service time, standby time, and Δp settings (Table 4-6) automatically dictated when the tanks should be backwashed. The touch screen OIP also enabled the operator to manually initiate the backwash sequence.

4.4.4.3 Operator Skill Requirements. Under normal operating conditions, the daily demand on the operator was about 30 min for visual inspection of the system and recording of operational parameters, such as pressure, volume, flowrate, and chemical usage on field log sheets. In Michigan, operator certifications are classified on a level of 1 (least complex) to 4 (most complex). The primary operator was Limited Water Treatment Level 3 (D-3) and Water Distribution Level 3 (S-3) certified. After receiving proper training during the system startup, the operator understood the PLC, knew how to use the touch screen OIP, and was able to work with the vendor to troubleshoot and perform minor on-site repairs.

4.4.4.4 Preventative Maintenance Activities. The vendor recommended several routine maintenance activities to prolong the integrity of the treatment system (Kinetico, 2005). Preventative maintenance tasks included recording pressures, flows, chemical drum levels, and visually checking for leaks, overheating components, proper manual valve positioning and pumps' lubricant levels, and any unusual conditions daily. The vendor recommended weekly checking for trends in the recorded data which might indicate a decline in system performance, and semi-annually servicing and inspecting ancillary equipment and replacing worn components. Cleaning and replacement of sensors and replacement of o-ring seals and gaskets of valves should be performed as needed.

4.4.4.5 Chemical Handling and Inventory Requirements. Prechlorination was required for effective treatment since system startup. The operator tracked the NaOCl usage daily, coordinated the solution supply, and refilled the day tank as-needed.

4.5 System Performance

The performance of the Macrolite[®] FM-260-AS Arsenic Removal System was evaluated based on analyses of water samples collected from the treatment plant, backwash lines, and distribution system.

4.5.1 Treatment Plant Sampling. The treatment plant water was sampled on 25 occasions including two duplicate events and six speciation events during the first six months of system operation. Table 4-7 summarizes the analytical results for arsenic, iron, and manganese. Table 4-8 summarizes the results of the other water quality parameters. Three sets of samples (including two weekly and one monthly speciation) collected from February 22 to March 7, 2006, when insufficient chlorine residuals existed due to the use of an off-spec NaOCl solution, are not included in the statistical calculations in Tables 4-7 and 4-8, but included in the data plots. Appendix B contains a complete set of analytical results. The results of the water samples collected across the treatment plant are discussed below.

Table 4-7. Summary of Arsenic, Iron, and Manganese Results^(a)

Parameter	Location	Sample Count	Concentration (µg/L)			Standard Deviation
			Minimum	Maximum	Average	
As (total) (Figure 4-9)	IN	25	15.3	21.8	17.7	1.4
	AC	22	14.4	25.4	19.0	2.9
	TA	17	7.8	15.6	10.2	1.8
	TB	17	8.1	11.9	10.0	1.1
	TT	5	8.4	12.0	9.5	1.5
As (soluble)	IN	6	15.5	18.3	17.2	1.0
	AC	5	9.2	12.9	11.1	1.3
	TT	5	8.2	11.6	9.3	1.4
As (particulate) (Figure 4-8)	IN	6	<0.1	0.9	0.3	0.3
	AC	5	4.9	8.1	6.3	1.3
	TT	5	<0.1	1.1	0.4	0.4
As(III) (Figure 4-8)	IN	6	8.7	17.1	14.6	3.1
	AC	5	<0.1	1.4	0.4	0.6
	TT	5	0.2	1.6	0.6	0.5
As(V) (Figure 4-8)	IN	6	1.2	6.8	2.7	2.1
	AC	5	9.1	11.5	10.6	0.9
	TT	5	7.7	10.1	8.7	0.9
Fe (total) (Figure 4-10)	IN	25	346	510	427	34
	AC	22	344	902	515	144
	TA	16 ^(b)	<25	<25	<25	0.0
	TB	17	<25	31.9	<25	4.7
	TT	5	<25	66.2	34.4	22.6
Fe (soluble)	IN	5 ^(c)	249	433	367	87.4
	AC	5	<25	<25	<25	0.0
	TT	5	<25	<25	<25	0.0
Mn (total)	IN	25	23.9	31.7	27.5	1.7
	AC	22	21.5	46.3	29.7	5.5
	TA	17	6.4	17.3	10.8	2.8
	TB	17	6.2	15.6	10.4	2.2
	TT	5	9.0	22.2	13.1	5.2
Mn (soluble)	IN	6	25.5	32.9	28.6	2.5
	AC	5	9.1	10.9	10.2	0.7
	TT	5	9.0	22.2	13.2	5.2

(a) Results for three sampling events without sufficient chlorine addition during 02/22/06 to 03/07/06 not included in AC, TA, TB, and TT calculations.

(b) One outlier (i.e., 483 µg/L on 11/29/05) not included in calculations.

(c) One outlier (i.e., 45.2 µg/L on 03/01/06) not included in calculations.

One-half of detection limit used for non-detect results and duplicate samples included for calculations.

Table 4-8. Summary of Other Water Quality Parameter Results

Parameter	Sampling Location	Unit	Sample Count	Minimum	Maximum	Average	Standard Deviation
Alkalinity (as CaCO ₃)	IN	mg/L	25	141	167	149	6
	AC	mg/L	22	142	154	149	4
	TA	mg/L	17	141	158	150	5
	TB	mg/L	17	141	159	151	6
	TT	mg/L	5	144	154	150	5
Fluoride	IN	mg/L	6	0.4	0.6	0.5	0.1
	AC	mg/L	5	0.4	0.5	0.4	0.1
	TT	mg/L	5	0.4	0.5	0.4	0.1
Sulfate	IN	mg/L	6	<1	<1	<1	0.0
	AC	mg/L	5	<1	<1	<1	0.0
	TT	mg/L	5	<1	<1	<1	0.0
Nitrate (as N)	IN	mg/L	6	<0.05	<0.05	<0.05	0.0
	AC	mg/L	5	<0.05	0.1	0.0	0.04
	TT	mg/L	5	<0.05	0.1	0.0	0.04
Total P (as PO ₄)	IN	mg/L	25	<0.03	0.2	0.17	0.04
	AC	mg/L	22	<0.03	0.4	0.20	0.08
	TA	mg/L	17	<0.03	0.7	0.10	0.15
	TB	mg/L	17	<0.03	0.1	0.07	0.03
	TT	mg/L	5	<0.03	0.2	0.08	0.05
Silica (as SiO ₂)	IN	mg/L	25	10.2	11.7	11.2	0.3
	AC	mg/L	22	10.5	12.3	11.3	0.4
	TA	mg/L	17	10.2	12.5	11.2	0.5
	TB	mg/L	17	10.7	11.9	11.2	0.4
	TT	mg/L	5	10.9	11.5	11.2	0.2
Turbidity	IN	NTU	25	1.7	3.9	2.5	0.4
	AC	NTU	22	0.2	2.6	0.9	0.6
	TA	NTU	17	<0.1	4.7	0.8	1.1
	TB	NTU	17	<0.1	1.5	0.6	0.4
	TT	NTU	5	<0.1	1.6	0.7	0.6
TOC	IN	mg/L	3	1.9	1.9	1.9	0.0
	AC	mg/L	2	1.9	1.9	1.9	0.0
	TT	mg/L	2	1.9	1.9	1.9	0.0
pH	IN	S.U.	20	7.5	8.3	8.0	0.2
	AC	S.U.	18	7.9	8.4	8.0	0.1
	TA	S.U.	13	7.8	8.3	8.0	0.1
	TB	S.U.	13	7.7	8.3	8.0	0.2
	TT	S.U.	5	7.9	8.6	8.2	0.3
Temperature	IN	°C	20	11.5	15.0	12.6	0.9
	AC	°C	18	11.7	14.0	12.6	0.6
	TA	°C	13	12.1	13.2	12.6	0.3
	TB	°C	13	12.1	13.6	12.7	0.5
	TT	°C	5	12.0	14.5	13.4	1.3
DO	IN	mg/L	19	0.8	3.7	1.8	0.8
	AC	mg/L	17	0.5	2.0	1.1	0.4
	TA	mg/L	12	0.6	1.7	1.3	0.3
	TB	mg/L	12	0.7	4.1	1.6	0.9
	TT	mg/L	5	0.9	3.7	2.0	1.3

Table 4-8. Summary of Other Water Quality Parameter Results (Cont'd)

Parameter	Sampling Location	Unit	Sample Count	Minimum	Maximum	Average	Standard Deviation
ORP	IN	mV	20	-3	473	302	110
	AC	mV	18	303	523	422	64
	TA	mV	13	310	516	420	63
	TB	mV	13	318	523	428	58
	TT	mV	5	403	511	443	41
Free Chlorine (as Cl ₂)	AC	mg/L	16	0.1	1.5	0.6	0.4
	TA	mg/L	12	0.2	1.3	0.6	0.4
	TB	mg/L	12	0.0	1.0	0.5	0.3
	TT	mg/L	4	0.2	0.9	0.7	0.4
Total Chlorine (as Cl ₂)	AC	mg/L	16	1.1	1.9	1.3	0.2
	TA	mg/L	12	1.1	1.8	1.3	0.2
	TB	mg/L	12	1.2	1.8	1.3	0.2
	TT	mg/L	4	1.0	1.5	1.3	0.2
Total Hardness (as CaCO ₃)	IN	mg/L	6	190	212	202	9.6
	AC	mg/L	5	195	215	205	8.4
	TT	mg/L	5	177	217	202	15.7
Ca Hardness (as CaCO ₃)	IN	mg/L	6	104	118	113	4.8
	AC	mg/L	5	106	122	115	5.8
	TT	mg/L	5	98.5	121	113	8.6
Mg Hardness (as CaCO ₃)	IN	mg/L	6	77.2	99.9	89.8	7.7
	AC	mg/L	5	79.7	95.9	90.0	6.2
	TT	mg/L	5	78.8	96.0	88.9	8.8

(a) Results for three sampling events without sufficient chlorine addition during 02/22/06 to 03/07/06 not included in AC, TA, TB, and TT calculations.

One-half of detection limit used for non-detect results and duplicate samples included for calculations.

4.5.1.1 Arsenic. Figure 4-8 presents the results of six speciation events and Figure 4-9 shows total arsenic concentrations measured across the treatment train. Total arsenic concentrations in raw water ranged from 15.3 to 21.8 µg/L, with As(III) as the predominant species. Low levels of As(V) and particulate As also were present, averaging 2.7 and 0.3 µg/L, respectively. Total arsenic concentrations measured during this six-month period were slightly higher than that of the raw water sample collected on August 31, 2004 (Table 4-1).

The analytical results for water samples collected from February 22 to March 7, 2006 indicated insufficient chlorine addition for As(III) oxidation (Figures 4-8 and 4-9). For all other events, the results obtained after prechlorination and the contact tank indicated that As(III) was effectively oxidized to As(V). Average concentrations of As(III), As(V), and particulate As were 0.4, 10.6, and 6.3 µg/L, respectively. The high As(V) levels in water after the contact tank indicated incomplete adsorption of As(V) onto iron solids. Ideally, high levels of particulate As and low to non-detectable levels of As(III) and As(V) should exist prior to entering the pressure filters.

With sufficient chlorine addition, total arsenic concentrations after the pressure filtration at the TA, TB, and TT sampling locations ranged from 7.8 to 15.6 µg/L and averaged 10.0 µg/L. It became evident soon after startup that the treatment system was not able to consistently remove arsenic to less than 10 µg/L. This observation was supported by the fact that the ratio of soluble iron to soluble arsenic was just over 21:1, which was on the borderline with the rule of thumb ratio of 20:1 for effective arsenic removal. Two

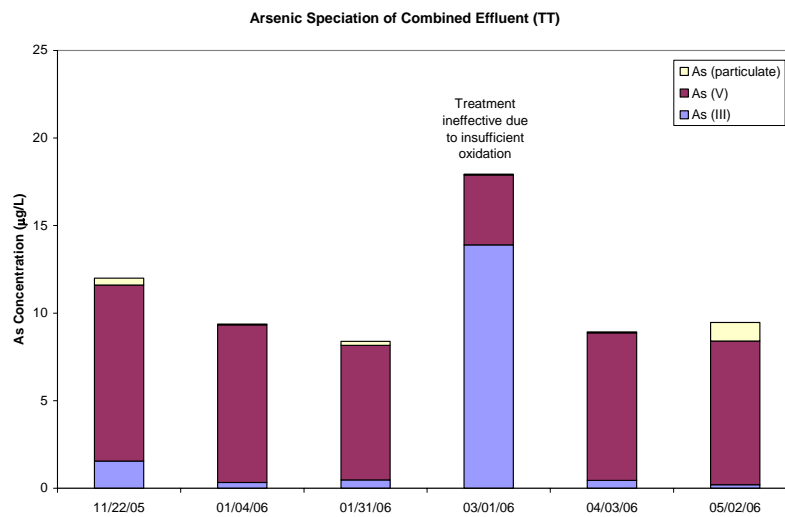
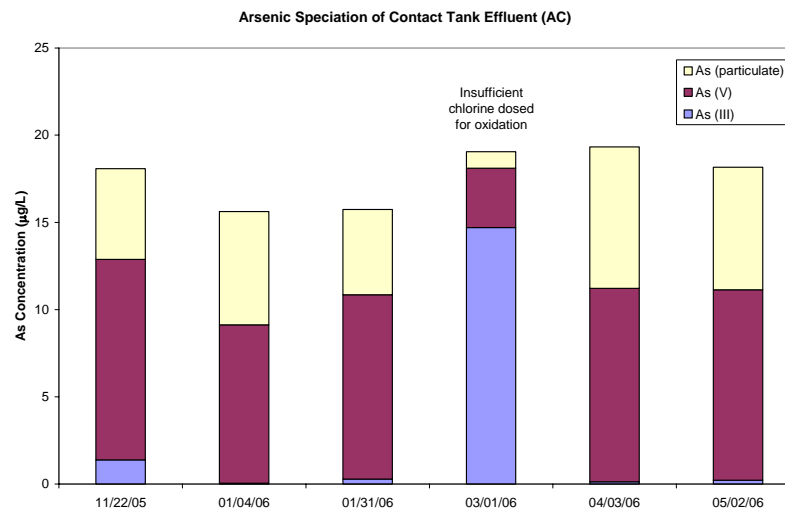
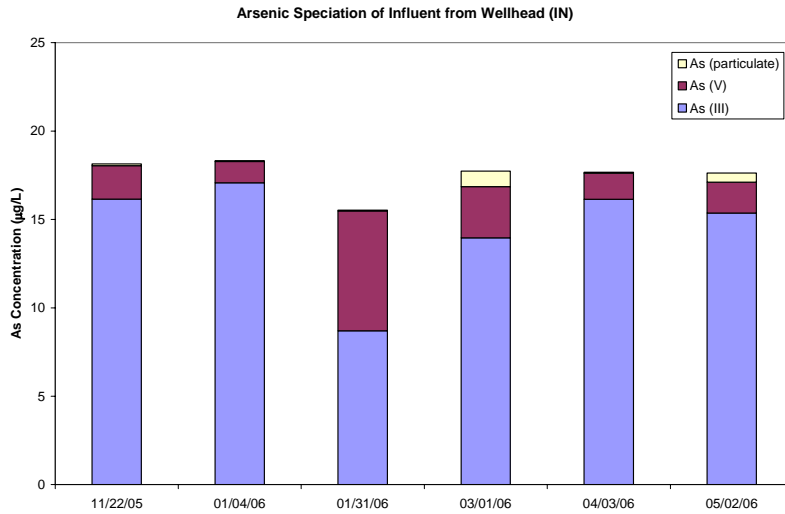


Figure 4-8. Arsenic Speciation Results at Wellhead (IN), After Contact Tank (AC), and After Tanks A and B Combined (TT)

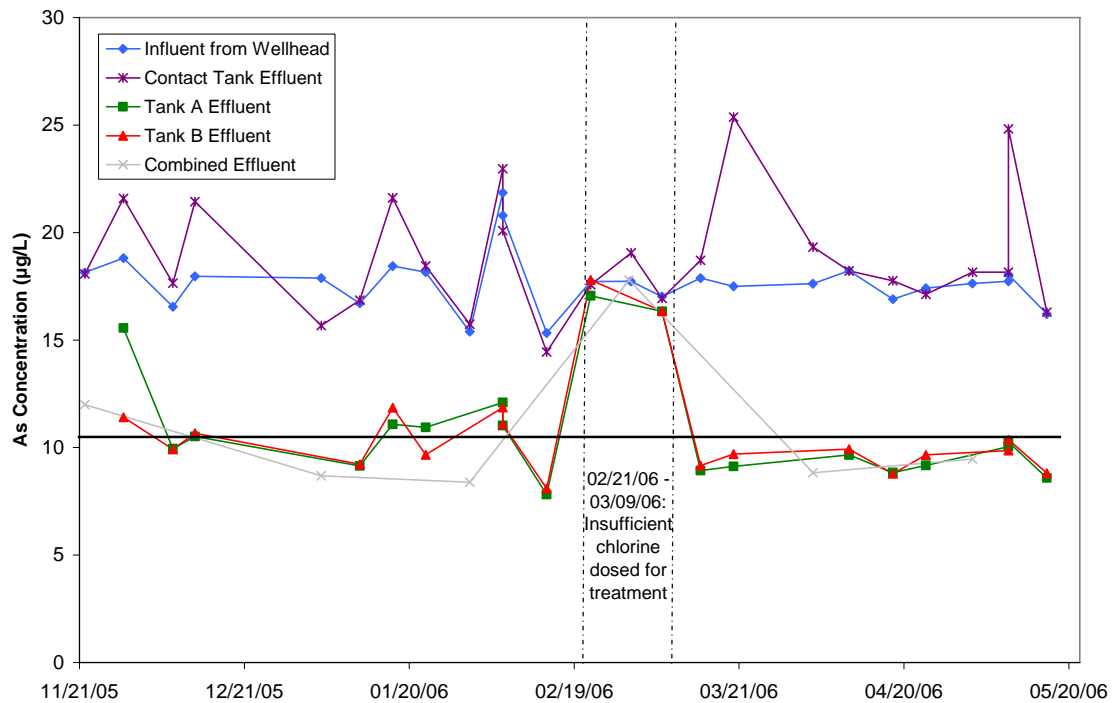


Figure 4-9. Total Arsenic Concentrations Across Treatment Train

weeks after the commencement of weekly sampling on December 6, 2005, planning began for an iron addition system as part of the pretreatment for this pressure filtration system.

4.5.1.2 Iron. Figure 4-10 presents total iron concentrations measured across the treatment train. Total iron concentrations in raw water ranged from 346 to 510 µg/L, which existed primarily in the soluble form with an average concentration of 367 µg/L (not including one outlier of 45.2 µg/L on March 1, 2006). As noted above, average soluble iron and average soluble arsenic concentrations in raw water (Table 4-7) corresponded to a ratio of 21:1, which was just over the 20:1 target ratio for effective arsenic removal (Sorg, 2002). It was possible that factors such as pH and/or other water quality parameters affected the arsenic removal capacity of the iron solids.

The treated water exhibited low iron concentrations, mostly near and/or less than 25 µg/L, except for one exceedance of 483 µg/L at the TA location on November 29, 2005. Soluble iron concentrations were <25 µg/L in treated water. These low iron levels indicated that iron was effectively removed by the Macrolite[®] pressure filters and that little or no particulate breakthrough had occurred during the 3 to 14 hr of service time.

After successful resolution of all backwash issues (Section 4.4.2), iron addition using FeCl₃ will be initiated at 0.5 mg/L (as Fe). The feed rate of the pump and/or stock solution concentration will be adjusted, as necessary, to consistently reduce effluent arsenic concentrations to below the 10-µg/L arsenic MCL. Stock solution samples will be collected and analyzed periodically to ensure proper solution preparation and strength.

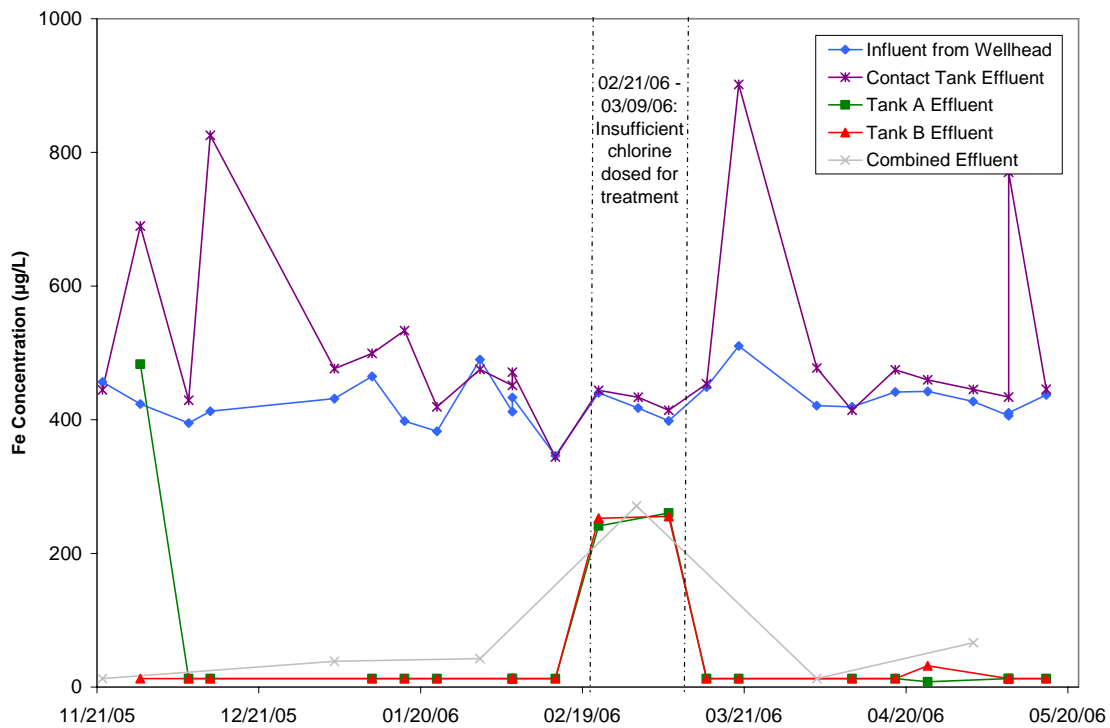


Figure 4-10. Total Iron Concentrations Across Treatment Train

4.5.1.3 Manganese. Manganese concentrations in raw water ranged from 23.9 to 31.7 µg/L, which existed primarily in the soluble form at an average concentration of 28.6 µg/L. With prechlorination and contact time, approximately 64% of the soluble manganese was converted to particulate manganese (i.e., 10.2 µg/L soluble Mn and 18.4 µg/L particulate Mn after the contact tank). Previous studies also have found that incomplete oxidation of Mn(II) occurs using free chlorine at pH values less than 8.5 (Knocke et al., 1987 and 1990; Condit and Chen, 2006). Macrolite® does not promote manganese removal unless present in the particulate form, so soluble levels after the contact tank were similar to total levels after the pressure filters.

4.5.1.4 pH, DO, and ORP. pH values in raw water ranged from 7.5 to 8.3 and averaged 8.0. This range was significantly higher than what was measured by Battelle during source water sampling on August 31, 2004 (i.e., 6.9 [Table 4-1]). Average DO levels across the treatment train were low, ranging from 1.1 to 2.0 mg/L. As a result of prechlorination, average ORP levels increased from 302 millivolts (mV) in raw water to over 400 mV after the contact tank.

4.5.1.5 Chlorine and Ammonia. Chlorine residuals measured at the TA, TB, and TT locations were comparable to those measured at the AC location, indicating little or no chlorine consumption through the pressure filters. Ammonia was sampled on one occasion on May 2, 2006 (Appendix B). The significant difference between free and total chlorine levels (i.e., 0.6 and 1.3 mg/L [as Cl₂]) and decrease in ammonia from 0.4 to 0.3 mg/L at the AC location indicated formation of chloramines after chlorine addition. However, the presence of 0.3 mg/L of ammonia after the contact tank contradicted the fact that 0.6 mg/L of free chlorine (on average as Cl₂) also existed at this location, because all ammonia should have reacted with NaOCl before free chlorine would form.

4.5.1.6 Other Water Quality Parameters. Alkalinity, fluoride, sulfate, nitrate, silica, TOC, temperature, and hardness levels remained consistent across the treatment train and were not affected by the treatment process (Table 4-8). TOC levels were 1.9 mg/L in raw water and remained unchanged across treatment train. Total phosphorus (as PO₄) decreased from an average concentration of 0.2 mg/L in raw water and after the contact tank to 0.1 mg/L after the pressure filters. Turbidity also decreased from 2.5 to <1.0 NTU with treatment.

4.5.2 Backwash Water Sampling. Table 4-9 presents the analytical results of four monthly backwash water sampling events. The results for the January and February 2006 sampling events are not included in the table because these samples were collected from an incorrect sampling tap. Among the four sampling events reported, relatively low values of total metals, TSS, and TDS were observed for Events 1 and 2, most likely due to the timing of the sampling (i.e., these manual backwash cycles were initiated soon after the pressure filters had just been backwashed automatically by the PLC [thus having fewer solids in backwash water for sampling]). Event 2 also was collected on March 7, 2006 when insufficient chlorine was added for oxidation as discussed in Section 4.5.1.1. The implication was that the backwash was performed without proper prechlorination, as evident by the somewhat elevated soluble arsenic, iron, and manganese concentrations in the backwash water.

The backwash water of Events 1, 3, and 4, characteristic of normal operating conditions, ranged from 7.9 to 8.0 for pH, 252 to 646 mg/L for TDS, and 24 to 106 mg/L for TSS. Concentrations of total arsenic, iron, and manganese ranged from 30 to 610 µg/L, 1.5 to 29.5 mg/L, and 66 to 1,206 µg/L, respectively, with the majority existing as particulate.

Assuming that the Event 4 results are representative of the backwash water from all backwash cycles, and that 1,150 gal of backwash water is produced from each backwash cycle, approximately 0.96 lb of solids would be generated and discharged per backwash cycle, including 0.235 lb of iron, 0.009 lb of manganese, and 0.005 lb of arsenic. The amount of solids to be discharged during backwash will be further monitored during the next months of system operation.

4.5.3 Distribution System Water Sampling. Table 4-10 summarizes the results of the distribution system sampling. The water quality was similar among the three residences except at the DS3 residence, which exhibited lower lead and copper concentrations than the other two residences. Water quality significantly improved after the treatment system began operation. Arsenic, iron, manganese, and copper concentrations decreased from average baseline levels of 16.5, 192, 23.8, and 131 µg/L to 8.8, <25, 11.5, and 70.4 µg/L, respectively, after system startup. Alkalinity, pH, and lead concentrations remained fairly consistent. The water in the distribution system was comparable to that of the treatment system effluent. Thus, the treatment system appeared to have beneficial effects on the water quality in the distribution system.

4.6 System Cost

The system cost 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. Capital cost of the treatment system included cost for equipment, engineering, and system installation, shakedown, and startup. O&M cost included cost for chemicals, electricity, and labor. Cost associated with the building including the sump, sanitary sewer connections, and water system telemetry was not included in the capital cost because it was not included in the scope of this demonstration project and was funded separately by the village.

Table 4-9. Backwash Water Sampling Results

Sampling Event	Tank A										Tank B										
	pH	TDS	TSS	Total As	Soluble As	Particulate As	Total Fe	Soluble Fe	Total Mn	Soluble Mn	pH	TDS	TSS	Total As	Soluble As	Particulate As	Total Fe	Soluble Fe	Total Mn	Soluble Mn	
No.	Date	S.U.	mg/L	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	S.U.	mg/L	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
1	12/08/05	8.0	252	26	30.0	8.2	21.8	1,564	<25	68.1	10.6	8.0	414	24	31.1	8.5	22.6	1,546	<25	66.1	11.4
2	03/07/06 ^(a)	8.0	390	34	30.5	16.2	14.3	2,023	158	30.2	26.6	8.0	370	11	24.6	14.4	10.2	1,791	92.4	35.4	28.3
3	04/12/06	8.0	428	78	383	11.3	371	25,116	141	658	16.7	8.0	646	39	215	10.0	205	18,599	92.8	373	15.0
4	05/09/06	7.9	430	106	610	12.8	597	29,521	251	1,206	20.6	7.9	636	94	396	11.3	385	19,883	155	824	16.0

(a) Prechlorination not performed on treated water used for backwash during normal operation (02/21/06 - 03/09/06).

Table 4-10. Distribution System Sampling Results

Sampling Event	DS1									DS2							DS3								
	Residence - 1st draw									Residence - 1st draw							Residence - 1st draw								
	Stagnation Time	pH	Alkalinity	As	Fe	Mn	Pb	Cu	Stagnation Time	pH	Alkalinity	As	Fe	Mn	Pb	Cu	Stagnation Time	pH	Alkalinity	As	Fe	Mn	Pb	Cu	
No.	Date	hrs	S.U.	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L	hrs	S.U.	mg/L	µg/L	µg/L	µg/L	µg/L	hrs	S.U.	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L	
BL1	02/22/05	8.0	7.2	158	15.6	144	29.4	3.2	56.5	10.5	7.2	158	12.4	<25	21.2	0.3	199	7.3	7.6	153	15.7	315	26.4	0.1	8.0
BL2	03/22/05 ^(a)	6.6	7.8	155	17.8	145	25.2	0.9	151	7.8	8.2	160	23.8	232	8.2	2.6	586	7.5	7.8	155	17.7	284	29.4	<0.1	10.3
BL3	04/19/05	8.0	7.9	155	14.7	144	24.8	0.4	113	7.5	7.9	155	14.2	123	23.8	0.8	202	7.5	7.9	155	17.6	382	29.8	<0.1	3.8
BL4	05/26/05	8.8	7.7	156	16.1	241	23.0	<0.1	32.6	7.5	7.8	156	18.0	188	18.7	0.9	209	7.0	7.9	156	15.0	93.7	26.3	<0.1	4.9
1	12/13/05	8.5	8.0	150	8.5	<25	8.2	<0.1	44.7	8.0	8.1	158	9.6	<25	0.9	1.3	58.6	7.0	8.0	150	10.2	<25	11.7	<0.1	2.3
2	01/17/06	9.5	7.9	154	9.0	<25	9.4	1.5	165	6.8	8.0	154	10.2	<25	12.1	<0.1	4.4	8.0	8.2	154	10.2	<25	13.0	0.1	3.8
3	02/14/06	8.8	8.0	138	7.6	<25	8.5	<0.1	47.1	7.5	8.0	146	4.9	<25	9.5	0.9	176	Homeowner Not Available							
4	03/14/06	6.5	8.0	149	8.6	<25	28.0	5.5	92.1	51.5	8.0	132	11.7	<25	25.1	0.1	26.3	7.5	8.0	145	8.8	<25	14.9	0.1	2.8
5	04/18/06	8.3	8.1	154	7.7	<25	11.5	0.1	125	8.7	8.4	154	11.0	36.5	1.3	0.9	134	8.0	8.1	154	8.6	27.0	10.0	<0.1	3.5
6	05/16/06	8.3	7.9	146	8.0	<25	8.9	<0.1	105	7.8	8.0	146	5.7	<25	11.9	0.6	202	7.5	7.9	142	9.1	<25	11.2	<0.1	3.6

(a) DS2 samples collected on 03/21/05.

BL = baseline sampling; NA = data not available

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

Alkalinity measured in mg/L as CaCO₃.

4.6.1 Capital Cost. The capital investment for the FM-260-AS system was \$334,573 (Table 4-11). The equipment cost was \$224,994 (or 67% of the total capital investment), which included cost for an iron addition system, a contact tank, two pressure tanks, 80 ft³ of Macrolite[®], instrumentation and controls, miscellaneous materials and supplies, labor, and system warranty. The system warranty cost covered the cost for repair and replacement of defective system components and installation workmanship for a period of twelve months after system startup.

The engineering cost covered the cost for preparing the required permit application submittal, including a process design report, a general arrangement drawing, P&IDs, electrical diagrams, interconnecting piping layouts, tank fill details, and a schematic of the PLC panel, and obtaining the required permit approval from MDEQ. The engineering cost was \$30,929, which was 9% of the total capital investment.

Table 4-11. Capital Investment for Kinetico’s FM-260-AS System

Description	Cost	% of Capital Investment Cost
<i>Equipment</i>		
Tanks, Valves, and Piping	\$122,315	–
Macrolite [®] Media (80 ft ³)	\$20,607	–
Instrumentation and Controls	\$25,123	–
Air Scour System	\$6,305	–
Iron Addition System	\$3,395	–
Additional Sample Taps and Totalizers/Meters	\$2,002	–
Labor	\$42,747	–
Freight	\$2,500	–
Equipment Total	\$224,994	67%
<i>Engineering</i>		
Labor	\$28,679	–
Subcontractor	\$2,250	–
Engineering Total	\$30,929	9%
<i>Installation, Shakedown, and Startup</i>		
Labor	\$16,200	–
Subcontractor	\$57,500	–
Travel	\$4,950	–
Installation, Shakedown, and Startup	\$78,650	24%
Total Capital Investment	\$334,573	100%

The installation, shakedown, and startup cost covered the labor and materials required to unload, install, and test the system for proper operation. All installation activities were performed by Kinetico’s subcontractor, and startup and shakedown activities were performed by Kinetico with the operator’s assistance. The installation, startup, and shakedown cost was \$78,650, or 24% of the total capital investment.

The total capital cost of \$334,573 was normalized to \$836/gpm (\$0.58/gpd) of design capacity using the system’s rated capacity of 400 gpm (or 576,000 gpd). The total capital cost also was converted to a unit cost of \$0.15/1,000 gal using a capital recovery factor (CRF) of 0.09439 based on a 7% interest rate and a 20-yr return period. This calculation assumed that the system operated 24 hr/day at its rated capacity. Since the system operated at approximately 353 gpm (Table 4-5), producing 12,714,000 gal of water during the six-month period, the total unit cost increased to \$1.24/1,000 gal.

A 37 ½ ft × 33 ½ ft building with a sidewall height of 16 ft was constructed by the Village of Pentwater to house the treatment system (Section 4.3.2). The total cost of the building and supporting utilities was approximately \$120,000, which, as noted above, was not included in the capital cost.

4.6.2 O&M Cost. O&M costs included chemical usage, electricity consumption, and labor for a combined unit cost of \$0.22/1,000 gal (Table 4-12). No cost was incurred for repairs because the system was under warranty. Since chlorination was already performed prior to the demonstration study, incremental chemical cost will only be incurred for iron addition once initiated during the remainder of the one-year study period. The associated cost for iron addition will be discussed in the Final Performance Evaluation Report.

Electrical power consumption was calculated based on the difference between the average monthly cost from electric bills before and after building construction and system startup. The difference in cost was approximately \$147.50/month or \$0.07/1,000 gal of water treated.

The routine, non-demonstration related labor activities consumed 30 min/day (Section 4.4.4.3). Based on this time commitment and a labor rate of \$30/hr, the labor cost was \$0.15/1,000 gal of water treated.

Table 4-12. O&M Cost for Kinetico’s FM-260-AS System

Category	Value	Remarks
Volume Processed (1,000 gal)	12,714	From 11/22/05 through 05/22/06
<i>Chemical Usage</i>		
37-42% FeCl ₃ Unit Cost (\$/lb)	\$0.37	610 lb drum including tax, surcharges, and drum deposit
FeCl ₃ Consumption (lb/1,000 gal)	0.03	Anticipated
Chemical Cost (\$/1,000 gal)	TBD	
<i>Electricity Consumption</i>		
Electricity Cost (\$/month)	\$147.50	Average incremental consumption after system startup; including building heating and lighting
Electricity Cost (\$/1,000 gal)	\$0.07	
<i>Labor</i>		
Labor (hr/week)	2.5	30 min/day, 5 day/week
Labor Cost (\$/1,000 gal)	\$0.15	Labor rate = \$30/hr
Total O&M Cost (\$/1,000 gal)	\$0.22	Not including FeCl ₃ usage

TBD = to be determined

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APPENDIX A
OPERATIONAL DATA

US EPA Arsenic Demonstration Project at Pentwater, MI - Daily System Operation

Week No.	Date	Well #2 Meter	Run Time	15% Cl ₂ Tank Level	Cl ₂ Usage	Totalizer to Treatment			Pressure Filtration							Flow rate	Totalizer to Distribution				Backwash						
						Meter	Daily Flow	Avg Flow rate	Influent	Outlet Tank A	Outlet Tank B	Effluent	Inlet-TA	Inlet-TB	Inlet-Effluent		gpm	Meter	Daily Flow	Cum. Flow	Avg Flow rate	Tank A	Tank B	Cum. Volume	Daily Volume	Since Last BW	
																										Run Time	Standby Time
22	04/17/06	201.0	13.5	18.3	7.1	476634	314	388	NA	NA	NA	NA	NA	NA	NA	NA	892.9	286	9371	353	94	93	247.6	5.0	0.0/0.0	0.7/0.4	
	04/18/06	205.4	4.4	17.3	1.8	476722	88	333	NA	NA	NA	NA	NA	NA	NA	NA	973.7	81	9452	306	94	93	247.6	0.0	3.9/3.9	20.0/19.8	
	04/19/06	209.8	4.4	16.0	2.2	476822	100	379	80	71	72	58	9	8	22	349	1061.5	88	9540	332	94	93	247.6	0.0	8.3/8.3	47.2/42.0	
	04/20/06	214.4	4.6	14.8	2.2	476922	100	362	NA	NA	NA	NA	NA	NA	NA	NA	1155.6	94	9634	341	95	94	250.1	2.5	2.6/2.5	13.0/12.7	
23	04/21/06	219.1	4.7	13.0	3.1	477031	109	387	80	72	72	58	8	8	22	346	1253.4	98	9731	347	95	94	250.1	0.0	7.3/7.2	34.7/34.5	
	04/24/06	231.5	12.4	9.8	5.8	477308	277	372	81	73	72	58	8	9	23	347	1504.4	251	9982	337	96	95	252.7	2.5	10.4/10.0	42.6/42.6	
	04/25/06	234.5	3.0	9.0	1.3	477376	68	378	77	72	72	58	5	5	19	356	1567.0	63	10045	348	97	96	255.2	2.5	0.0/2.6	0.0/13.7	
	04/26/06	238.5	4.0	7.8	2.2	477468	92	383	NA	NA	NA	NA	NA	NA	NA	NA	1650.6	84	10129	348	98	96	256.3	1.1	4.0/6.7	16.5/30.4	
24	04/27/06	242.4	3.9	6.3	2.7	477558	90	385	NA	NA	NA	NA	NA	NA	NA	NA	1732.3	82	10210	349	98	97	257.4	1.1	7.9/1.2	36.3/1.9	
	04/28/06	246.4	4.0	5.3	1.8	477647	89	371	NA	NA	NA	NA	NA	NA	NA	NA	1813.5	81	10292	338	99	97	258.8	1.4	1.2/5.2	7.7/21.0	
	05/01/06	261.9	15.5	1.8	6.2	477993	346	372	NA	NA	NA	NA	NA	NA	NA	NA	2128.0	314	10606	338	100	98	261.3	2.5	4.1/8.1	19.0/33.1	
	05/02/06	266.0	4.1	30.3	NA	478083	90	366	NA	NA	NA	NA	NA	NA	NA	NA	2209.8	82	10688	333	100	99	262.7	1.4	8.2/0.0	36.4/23.0	
25	05/03/06	271.4	5.4	29.0	2.2	478204	121	373	NA	NA	NA	NA	NA	NA	NA	NA	2319.2	109	10797	338	101	99	263.8	1.1	2.7/5.4	7.5/21.8	
	05/04/06	274.2	2.8	28.0	1.8	478264	60	357	79	72	71	58	7	8	21	355	2377.5	58	10856	347	101	99	263.8	0.0	5.5/8.2	24.2/38.5	
	05/05/06	280.0	5.8	26.3	3.1	478395	131	376	NA	NA	NA	NA	NA	NA	NA	NA	2493.2	116	10971	332	101	100	265.2	1.4	11.3/1.3	42.9/8.9	
	05/08/06	299.8	19.8	20.5	10.2	478835	440	370	NA	NA	NA	NA	NA	NA	NA	NA	2892.1	399	11370	336	103	101	269.2	3.9	1.6/6.3	3.2/17.5	
26	05/09/06	304.4	4.6	18.8	3.1	478941	106	384	77	72	72	58	5	5	19	355	30.9	NA	11401	NA	104	102	271.4	2.2	0.0/0.0	2.0/0.4	
	05/10/06	310.1	5.7	17.0	3.1	479068	127	371	NA	NA	NA	NA	NA	NA	NA	NA	147.1	116	11517	340	105	102	273.1	1.7	4.4/5.7	16.3/18.8	
	05/11/06	314.1	4.0	16.0	1.8	479164	96	400	NA	NA	NA	NA	NA	NA	NA	NA	228.5	81	11599	339	105	102	273.1	0.0	8.8/9.7	34.3/36.8	
	05/12/06	319.7	5.6	15.0	1.8	479281	117	348	NA	NA	NA	NA	NA	NA	NA	NA	288.4	60	11659	178	106	103	275.9	2.8	1.5/2.7	4.3/6.7	
27	05/15/06	333.3	13.6	11.3	6.7	479586	305	374	NA	NA	NA	NA	NA	NA	NA	NA	618.7	330	11989	405	107	104	278.7	2.8	2.6/4.1	12.9/15.4	
	05/16/06	337.4	4.1	10.3	1.8	479680	94	382	NA	NA	NA	NA	NA	NA	NA	NA	703.7	85	12074	345	107	104	278.7	0.0	0.0/8.3	0.0/28.4	
	05/17/06	341.4	4.0	8.8	2.7	479776	96	400	78	72	73	58	6	5	20	355	866.8	163	12237	NA	108	105	101.3	1.6	4.0/0.8	15.6/2.4	
	05/18/06	346.4	5.0	7.5	2.2	479884	108	360	NA	NA	NA	NA	NA	NA	NA	NA	968.6	102	12339	339	108	105	101.3	0.0	9.0/5.7	37.1/24.4	
05/19/06	352.0	5.6	5.3	4.0	480067	183	545	NA	NA	NA	NA	NA	NA	NA	NA	1083.4	115	12454	342	109	105	102.6	1.3	2.7/11.2	6.6/42.4		
27	05/22/06	368.2	16.2	1.0	7.5	480368	301	310	NA	NA	NA	NA	NA	NA	NA	NA	1420.3	337	12790	347	110	107	106.4	3.8	4.3/0.0	10.6/0.0	

Average calculated flowrates before 02/22/06 not accurate due to hour meter limitations.

Flowrate and Totalizer to Distribution Meter readings before 05/16/06 proportionally calculated due to incorrect initial calibration.

Highlighted columns indicate calculated values.

NA = data not available

APPENDIX B
ANALYTICAL DATA TABLES

Analytical Results from Long-Term Sampling at Pentwater, MI

Sampling Date		11/22/05			11/29/05				12/08/05				12/12/05				01/04/06		
Sampling Location		IN	AC	TT	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TT
Parameter	Unit																		
Alkalinity	mg/L ^(a)	141	154	154	150	154	154	158	154	150	154	154	154	154	150	145	150	150	154
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fluoride	mg/L	0.5	0.4	0.4	-	-	-	-	-	-	-	-	-	-	-	-	0.4	0.4	0.4
Sulfate	mg/L	<1	<1	<1	-	-	-	-	-	-	-	-	-	-	-	-	<1	<1	<1
Nitrate (as N)	mg/L	<0.05	<0.05	<0.05	-	-	-	-	-	-	-	-	-	-	-	-	<0.05	<0.05	<0.05
Total P (as PO ₄)	mg/L ^(b)	0.2	0.2	0.2	0.2	0.4 ^(d)	0.7 ^(d)	0.1	0.2	0.2	0.1	0.1	0.2	0.3	0.1	0.1	0.2	0.2	0.1
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Silica (as SiO ₂)	mg/L	11.4	11.7	11.3	11.4	11.5	11.5	11.5	11.2	10.5	11.1	10.7	11.2	11.1	11.1	10.9	11.6	11.1	11.1
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Turbidity	NTU	2.6	0.6	<0.1	1.8	0.4	0.5	0.7	2.3	0.4	0.1	0.2	1.7	0.2	<0.1	<0.1	1.9	0.7	0.5
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOC	mg/L	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH	S.U.	8.3	8.3	8.6	8.1	8.1	8.1	8.0	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	8.3	8.4	8.1
Temperature	°C	12.2	12.3	12.0	11.5	12.3	12.5	12.1	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	15.0	14.0	14.3
DO	mg/L	0.9	1.2	0.9	3.3	0.9	1.6	4.1	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	2.4	1.9	3.7
ORP	mV	-3	496	424	91	469	516	511	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	187	523	511
Free Chlorine	mg/L	-	2.0+ ^(c)	2.0+ ^(c)	-	2.0+ ^(c)	2.0+ ^(c)	2.0+ ^(c)	-	NA ^(e)	NA ^(e)	NA ^(e)	-	NA ^(e)	NA ^(e)	NA ^(e)	-	1.5	0.8
Total Chlorine	mg/L	-	2.0+ ^(c)	2.0+ ^(c)	-	2.0+ ^(c)	2.0+ ^(c)	2.0+ ^(c)	-	NA ^(e)	NA ^(e)	NA ^(e)	-	NA ^(e)	NA ^(e)	NA ^(e)	-	1.5	1.2
Total Hardness	mg/L ^(a)	210	215	217	-	-	-	-	-	-	-	-	-	-	-	-	202	207	210
Ca Hardness	mg/L ^(a)	118	122	121	-	-	-	-	-	-	-	-	-	-	-	-	113	114	117
Mg Hardness	mg/L ^(a)	92.1	92.6	96.0	-	-	-	-	-	-	-	-	-	-	-	-	89.0	92.4	93.9
As (total)	µg/L	18.1	18.1	12.0	18.8	21.6 ^(d)	15.6 ^(d)	11.4	16.5	17.7	9.9	9.9	18.0	21.4	10.5	10.7	17.9	15.7	8.7
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As (soluble)	µg/L	18.0	12.9	11.6	-	-	-	-	-	-	-	-	-	-	-	-	18.3	9.2	9.3
As (particulate)	µg/L	0.1	5.2	0.4	-	-	-	-	-	-	-	-	-	-	-	-	<0.1	6.5	<0.1
As (III)	µg/L	16.2	1.4	1.6	-	-	-	-	-	-	-	-	-	-	-	-	17.1	<0.1	0.3
As (V)	µg/L	1.9	11.5	10.1	-	-	-	-	-	-	-	-	-	-	-	-	1.2	9.1	9.0
Fe (total)	µg/L	456	445	<25	423	690 ^(d)	483 ^(d)	<25	395	429	<25	<25	413	826	<25	<25	431	476	38.5
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe (soluble)	µg/L	433	<25	<25	-	-	-	-	-	-	-	-	-	-	-	-	422	<25	<25
Mn (total)	µg/L	28.5	27.8	10.8	27.0	30.7 ^(d)	17.3 ^(d)	9.8	27.7	26.9	11.7	10.8	27.4	35.9	6.8	7.0	24.8	27.6	9.0
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mn (soluble)	µg/L	28.9	10.5	11.0	-	-	-	-	-	-	-	-	-	-	-	-	25.5	9.1	9.0

(a) As CaCO₃. (b) As PO₄. (c) Residual was estimated by operator based on color of solution with reagent. (d) Rerun analysis indicated similar results.

(e) Water quality parameter not measured.

Analytical Results from Long-Term Sampling at Pentwater, MI

Sampling Date		01/11/06				01/17/06 ^(d)				1/23/2006 ^(e)				01/31/06			02/06/06 ^(f)			
Sampling Location	Parameter	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TT	IN	AC	TA	TB
	Unit																			
Alkalinity	mg/L ^(a)	154	145 ^(c)	154	158	154	154	158	150	167	150	154	154	148	152	144	150	150	150	150
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	146	150	150
Fluoride	mg/L	-	-	-	-	-	-	-	-	-	-	-	-	0.4	0.4	0.4	-	-	-	-
Sulfate	mg/L	-	-	-	-	-	-	-	-	-	-	-	-	<1	<1	<1	-	-	-	-
Nitrate (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	-	-	<0.05	<0.05	<0.05	-	-	-	-
Total P (as PO ₄)	mg/L ^(b)	<0.05	<0.05	<0.05	<0.05	0.1	0.2	<0.05	0.1	0.2	0.2	0.1	0.1	0.1	0.1	<0.05	0.2	0.2	0.1	0.1
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.2	0.2	0.1
Silica (as SiO ₂)	mg/L	11.1	11.2	11.4	11.3	11.5	11.2	11.6	11.6	11.0	10.8	11.2	11.3	11.3	10.6	11.5	10.9	11.5	11.2	11.1
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11.4	11.5	11.1
Turbidity	NTU	2.5	0.6	0.6	0.4	2.7	0.6	2.2	1.1	2.9	2.0	4.7	1.0	2.6	0.9	1.6	2.5	0.7	0.3	0.5
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.5	0.7	0.3
TOC	mg/L	-	-	-	-	-	-	-	-	-	-	-	-	2.0	1.6 ^(g)	2.5 ^(g)	-	-	-	-
pH	S.U.	8.1	8.0	7.9	8.0	8.0	8.0	8.0	7.9	8.1	8.3	8.3	8.3	8.0	8.0	8.5	8.0	8.0	8.0	8.0
Temperature	°C	12.6	12.6	12.9	12.6	12.0	12.4	12.9	13.6	12.1	12.1	12.4	12.6	13.8	13.5	14.5	12.2	12.3	12.8	13.1
DO	mg/L	1.3	1.1	1.1	1.2	0.8	0.5	1.4	1.1	1.2	0.8	1.7	0.7	3.7	1.7	1.5	1.9	0.9	1.5	1.1
ORP	mV	331	403	400	478	264	437	444	413	322	487	471	466	397	395	443	302	311	318	364
Free Chlorine	mg/L	-	0.4	0.3	1.0	-	0.2	0.4	0.9	-	0.3	0.2	0.6	-	0.4	0.9	-	1.1	0.6	0.2
Total Chlorine	mg/L	-	1.2	1.3	1.3	-	1.2	1.2	1.2	-	1.1	1.1	1.2	-	1.3	1.0	-	1.2	1.2	1.2
Total Hardness	mg/L ^(a)	-	-	-	-	-	-	-	-	-	-	-	-	191	197	197	-	-	-	-
Ca Hardness	mg/L ^(a)	-	-	-	-	-	-	-	-	-	-	-	-	114	117	117	-	-	-	-
Mg Hardness	mg/L ^(a)	-	-	-	-	-	-	-	-	-	-	-	-	77.2	79.7	79.9	-	-	-	-
As (total)	µg/L	16.7	16.9	9.1	9.2	18.4	21.6	11.1	11.9	18.2	18.5	10.9	9.7	15.4	15.7	8.4	21.8	23.0	12.1	11.9
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20.8	20.1	11.0
As (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	-	-	15.5	10.9	8.2	-	-	-	-
As (particulate)	µg/L	-	-	-	-	-	-	-	-	-	-	-	-	<0.1	4.9	0.2	-	-	-	-
As (III)	µg/L	-	-	-	-	-	-	-	-	-	-	-	-	8.7	0.3	0.5	-	-	-	-
As (V)	µg/L	-	-	-	-	-	-	-	-	-	-	-	-	6.8	10.6	7.7	-	-	-	-
Fe (total)	µg/L	465	499	<25	<25	398	534	<25	<25	383	419	<25	<25	490	475	42.4	412	451	<25	<25
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	433	471	<25
Fe (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	-	-	297	<25	<25	-	-	-	-
Mn (total)	µg/L	26.1	28.1	14.3	15.6	25.4	29.4	13.8	13.0	25.9	26.4	9.7	11.5	31.7	31.4	11.4	26.9	27.6	12.4	10.9
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	27.2	27.3	12.0
Mn (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	-	-	32.9	10.9	11.9	-	-	-	-

(a) As CaCO₃. (b) As PO₄. (c) Reanalyzed outside of hold time. (d) Water quality measurements taken on 01/19/06. (e) Water quality measurements taken on 01/26/06. (f) Water quality measurements taken on 02/09/06. (g) Result is an estimated concentration.

Analytical Results from Long-Term Sampling at Pentwater, MI

Sampling Date		02/14/06 ^(c)				02/22/06 ^(d)				03/01/06 ^(d)			03/07/06 ^(d,f)				03/14/06			
Sampling Location	Parameter	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TT	IN	AC	TA	TB	IN	AC	TA	TB
	Unit																			
Alkalinity	mg/L ^(a)	150	146	146	158	146	146	146	150	145	145	149	145	149	149	145	145	145	145	145
Fluoride	mg/L	-	-	-	-	-	-	-	-	0.5	0.5	0.5	-	-	-	-	-	-	-	-
Sulfate	mg/L	-	-	-	-	-	-	-	-	<1	<1	<1	-	-	-	-	-	-	-	-
Nitrate (as N)	mg/L	-	-	-	-	-	-	-	-	<0.05	<0.05	<0.05	-	-	-	-	-	-	-	-
Total P (as PO ₄)	mg/L ^(b)	0.2	0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.2	0.2	0.1	0.1
Silica (as SiO ₂)	mg/L	11.0	11.4	10.7	11.2	11.6	11.4	12.4	11.7	11.1	12.0	11.7	10.8	10.9	11.2	10.4	10.2	11.1	10.2	10.8
Turbidity	NTU	3.0	1.5	1.0	1.5	2.5	4.0	2.1	1.9	3.9	5.6	5.8	2.9	5.1	2.6	2.5	2.5	0.9	0.7	1.0
TOC	mg/L	-	-	-	-	-	-	-	-	1.9	1.9	1.9	-	-	-	-	-	-	-	-
pH	S.U.	7.9	7.9	7.8	7.8	8.1	8.1	8.1	8.1	NA ^(e)	NA ^(e)	NA ^(e)	7.5	8.1	8.1	8.1	8.0	8.0	8.0	8.0
Temperature	°C	12.6	11.7	12.1	12.2	12.1	12.2	12.5	12.4	NA ^(e)	NA ^(e)	NA ^(e)	12.7	12.1	13.4	11.9	13.1	12.4	13.2	13.6
DO	mg/L	1.6	1.3	1.5	1.3	2.4	2.6	2.0	2.5	NA ^(e)	NA ^(e)	NA ^(e)	2.0	1.1	2.9	1.8	2.2	2.0	1.3	1.8
ORP	mV	288	303	310	318	265	268	273	287	NA ^(e)	NA ^(e)	NA ^(e)	257	261	264	259	473	494	501	523
Free Chlorine	mg/L	-	0.3	0.4	0.4	-	0.0	0.0	0.0	-	NA ^(e)	NA ^(e)	-	0.3	0.3	0.3	-	0.4	0.4	0.6
Total Chlorine	mg/L	-	1.2	1.2	1.2	-	0.0	0.1	0.1	-	NA ^(e)	NA ^(e)	-	1.0	1.0	1.0	-	1.9	1.8	1.7
Total Hardness	mg/L ^(e)	-	-	-	-	-	-	-	-	212	215	211	-	-	-	-	-	-	-	-
Ca Hardness	mg/L ^(e)	-	-	-	-	-	-	-	-	112	114	112	-	-	-	-	-	-	-	-
Mg Hardness	mg/L ^(e)	-	-	-	-	-	-	-	-	99.9	101	99.3	-	-	-	-	-	-	-	-
As (total)	µg/L	15.3	14.4	7.8	8.1	17.7	17.6	17.1	17.8	17.7	19.1	17.8	17.0	16.9	16.3	16.3	17.9	18.7	8.9	9.2
As (soluble)	µg/L	-	-	-	-	-	-	-	-	16.9	18.1	17.9	-	-	-	-	-	-	-	-
As (particulate)	µg/L	-	-	-	-	-	-	-	-	0.9	0.9	<0.1	-	-	-	-	-	-	-	-
As (III)	µg/L	-	-	-	-	-	-	-	-	14.0	14.7	13.9	-	-	-	-	-	-	-	-
As (V)	µg/L	-	-	-	-	-	-	-	-	2.9	3.4	4.0	-	-	-	-	-	-	-	-
Fe (total)	µg/L	346	344	<25	<25	440	444	241	253	418	434	271	398	414	260	255	449	454	<25	<25
Fe (soluble)	µg/L	-	-	-	-	-	-	-	-	45.2 ^(g)	355	167	-	-	-	-	-	-	-	-
Mn (total)	µg/L	23.9	21.5	11.1	11.3	28.9	28.7	28.9	29.4	27.6	28.4	29.1	27.7	28.8	28.8	27.9	28.4	28.0	7.5	7.4
Mn (soluble)	µg/L	-	-	-	-	-	-	-	-	27.1	28.2	28.5	-	-	-	-	-	-	-	-

(a) As CaCO₃. (b) As PO₄. (c) Water quality measurements taken on 02/17/06. (d) Insufficient chlorine dosed for treatment due to off-spec solution per communication with operator. Chlorine solution replaced on 03/09/06. (e) Water quality measurement not recorded. (f) Water quality measurements taken on 03/09/06. (g) Reanalysis indicated similar result.

Analytical Results from Long-Term Sampling at Pentwater, MI

Sampling Date		03/20/06				04/03/06			04/10/06				04/18/06				04/24/06 ^(c)			
Sampling Location	Parameter	IN	AC	TA	TB	IN	AC	TT	IN	AC	TA	TB	IN	AC	TA	TB	IN	AC	TA	TB
	Unit																			
Alkalinity	mg/L ^(a)	145	145	145	145	146	146	146	145	145	141	141	153	153	153	158	154	154	154	159
Fluoride	mg/L	-	-	-	-	0.5	0.5	0.5	-	-	-	-	-	-	-	-	-	-	-	-
Sulfate	mg/L	-	-	-	-	<1	<1	<1	-	-	-	-	-	-	-	-	-	-	-	-
Nitrate (as N)	mg/L	-	-	-	-	<0.05	<0.05	<0.05	-	-	-	-	-	-	-	-	-	-	-	-
Total P (as PO ₄)	mg/L ^(b)	0.2	0.3	0.1	0.1	0.2	0.2	0.1	0.2	0.2	<0.05	<0.05	0.2	0.2	0.1	0.1	0.1	0.2	<0.05	0.1
Silica (as SiO ₂)	mg/L	11.4	11.8	10.9	11.4	11.1	11.6	11.2	11.2	11.3	10.9	10.7	10.5	11.2	10.9	10.8	11.4	11.0	10.7	11.2
Turbidity	NTU	2.3	1.0	0.3	0.3	2.4	1.6	0.9	2.9	2.6	1.4	1.5	2.6	0.7	0.3	0.5	2.1	0.6	0.4	0.4
TOC	mg/L	-	-	-	-	1.9	1.9	1.9	-	-	-	-	-	-	-	-	-	-	-	-
pH	S.U.	7.9	8.0	7.9	7.9	7.7	8.1	7.9	8.0	7.9	8.0	7.9	7.9	8.0	8.0	8.0	7.9	8.0	7.9	7.7
Temperature	°C	11.7	12.1	12.5	12.6	14.3	14.0	14.1	12.7	12.6	12.4	12.3	12.7	12.7	12.8	12.7	11.9	12.6	12.8	12.7
DO	mg/L	2.0	0.8	1.2	1.2	1.0	1.0	1.0	NA ^(d)	NA ^(d)	NA ^(d)	NA ^(d)	1.3	1.1	1.1	2.7	1.1	1.1	1.1	1.5
ORP	mV	325	476	461	456	353	401	403	363	402	385	379	330	432	409	415	349	373	444	427
Free Chlorine	mg/L	-	0.3	1.3	0.5	-	0.2	0.2	-	0.1	1.2	0.9	-	1.1	0.7	0.0	-	0.3	0.2	0.6
Total Chlorine	mg/L	-	1.8	1.8	1.8	-	1.6	1.5	-	1.4	1.3	1.5	-	1.3	1.4	1.3	-	1.2	1.3	1.3
Total Hardness	mg/L ^(a)	-	-	-	-	190	195	177	-	-	-	-	-	-	-	-	-	-	-	-
Ca Hardness	mg/L ^(a)	-	-	-	-	104	106	98.5	-	-	-	-	-	-	-	-	-	-	-	-
Mg Hardness	mg/L ^(a)	-	-	-	-	86.6	89.2	78.8	-	-	-	-	-	-	-	-	-	-	-	-
As (total)	µg/L	17.5	25.4	9.1	9.7	17.6	19.3	8.8	18.2	18.2	9.7	9.9	16.9	17.8	8.8	8.8	17.4	17.1	9.2	9.7
As (soluble)	µg/L	-	-	-	-	17.6	11.2	8.9	-	-	-	-	-	-	-	-	-	-	-	-
As (particulate)	µg/L	-	-	-	-	<0.1	8.1	<0.1	-	-	-	-	-	-	-	-	-	-	-	-
As (III)	µg/L	-	-	-	-	16.1	0.1	0.4	-	-	-	-	-	-	-	-	-	-	-	-
As (V)	µg/L	-	-	-	-	1.5	11.1	8.4	-	-	-	-	-	-	-	-	-	-	-	-
Fe (total)	µg/L	510	902	<25	<25	421	477	<25	419	414	<25	<25	441	475	<25	<25	442	460	<25	31.9
Fe (soluble)	µg/L	-	-	-	-	432	<25	<25	-	-	-	-	-	-	-	-	-	-	-	-
Mn (total)	µg/L	29.1	46.3	6.4	6.2	26.2	26.9	22.2	25.6	25.4	9.0	9.6	27.3	28.1	9.8	10.1	29.0	28.7	10.2	11.0
Mn (soluble)	µg/L	-	-	-	-	28.2	10.5	22.2	-	-	-	-	-	-	-	-	-	-	-	-

(a) As CaCO₃. (b) As PO₄. (c) Water quality measurements taken on 04/25/06. (d) DO probe not operational.

Analytical Results from Long-Term Sampling at Pentwater, MI

Sampling Date		05/02/06			5/9/2006 ^(c)				05/16/06			
Sampling Location		IN	AC	TT	IN	AC	TA	TB	IN	AC	TA	TB
Parameter	Unit											
Alkalinity	mg/L ^(a)	146	150	150	147	142	142	147	142	146	146	146
		-	-	-	142	147	147	147	-	-	-	-
Ammonia	mg/L	0.4	0.3	0.3	-	-	-	-	-	-	-	-
Fluoride	mg/L	0.6	0.5	0.5	-	-	-	-	-	-	-	-
Sulfate	mg/L	<1	<1	<1	-	-	-	-	-	-	-	-
Nitrate (as N)	mg/L	<0.05	0.1	0.1	-	-	-	-	-	-	-	-
Total P (as PO ₄)	mg/L ^(b)	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	<0.05	<0.05
		-	-	-	0.2	0.3	0.1	0.1	-	-	-	-
Silica (as SiO ₂)	mg/L	11.4	10.9	10.9	11.5	12.3	12.1	11.9	11.4	11.2	11.1	10.9
		-	-	-	11.7	11.6	12.5	11.7	-	-	-	-
Turbidity	NTU	2.3	0.5	0.6	2.4	0.6	0.2	0.4	2.3	0.6	0.2	0.4
		-	-	-	2.2	0.5	0.3	0.3	-	-	-	-
TOC	mg/L	1.9	1.9	1.9	-	-	-	-	-	-	-	-
pH	S.U.	8.1	7.9	8.2	7.7	8.0	7.9	7.9	7.8	8.0	8.0	7.9
Temperature	°C	12.2	12.1	12.0	12.2	12.4	12.3	12.5	12.3	12.4	12.3	12.2
DO	mg/L	1.1	1.5	3.2	1.3	0.8	0.6	0.9	1.6	1.0	1.0	1.2
ORP	mV	438	455	436	333	375	376	415	370	356	421	396
Free Chlorine	mg/L	-	1.2	0.9	-	1.1	0.3	0.5	-	0.6	0.5	0.3
Total Chlorine	mg/L	-	1.3	1.3	-	1.3	1.3	1.3	-	1.2	1.2	1.2
Total Hardness	mg/L ^(a)	208	210	209	-	-	-	-	-	-	-	-
Ca Hardness	mg/L ^(a)	114	114	113	-	-	-	-	-	-	-	-
Mg Hardness	mg/L ^(a)	94.4	95.9	96.0	-	-	-	-	-	-	-	-
As (total)	µg/L	17.6	18.2	9.5	17.7	18.2	10.0	9.9	16.2	16.3	8.6	8.8
		-	-	-	18.1	24.8	10.3	10.4	-	-	-	-
As (soluble)	µg/L	17.1	11.1	8.4	-	-	-	-	-	-	-	-
As (particulate)	µg/L	0.5	7.0	1.1	-	-	-	-	-	-	-	-
As (III)	µg/L	15.4	0.2	0.2	-	-	-	-	-	-	-	-
As (V)	µg/L	1.7	10.9	8.2	-	-	-	-	-	-	-	-
Fe (total)	µg/L	427	445	66.2	406	434	<25	<25	437	446	<25	<25
		-	-	-	410	770	<25	<25	-	-	-	-
Fe (soluble)	µg/L	249	<25	<25	-	-	-	-	-	-	-	-
Mn (total)	µg/L	27.7	28.4	11.7	29.8	29.5	10.3	9.9	28.3	28.3	10.3	11.4
		-	-	-	29.1	42.6	10.3	10.2	-	-	-	-
Mn (soluble)	µg/L	29.3	10.1	11.8	-	-	-	-	-	-	-	-

(a) As CaCO₃. (b) As PO₄. (c) Water quality measurements taken on 05/10/06.