



Arsenic Removal from Drinking Water by Iron Removal

USEPA Demonstration Project at Climax, MN

Project Summary

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A project to demonstrate Kinetico's Macrolite® pressure filtration process' ability to remove arsenic from drinking water was conducted at a water system in Climax, MN. The project objectives were to evaluate: (1) the effectiveness of Kinetico's Macrolite® pressure filtration process in removing arsenic to meet the new arsenic maximum contaminant level (MCL) of 10 micrograms per liter ($\mu\text{g/L}$), (2) the reliability of the treatment system, (3) the required system operation and maintenance (O&M) and operator's skills, and 4) the capital and O&M costs of the technology. The project also characterized water in the distribution system and process residuals produced by the treatment system.

Introduction

Amended in 1996, the Safe Drinking Water Act (SDWA) required that the United States Environmental Protection Agency (EPA) develop an arsenic research strategy and publish a proposal to revise the arsenic MCL. On March 25, 2003, EPA revised the rule text to express the MCL as 0.010 mg/L (10 $\mu\text{g/L}$) and to require all community and non-transient, noncommunity water systems to comply with the new standard by January 23, 2006 (EPA, 2003).

In October 2001, EPA announced an initiative for additional research and development of cost-effective technologies to help small community water systems (those with less than 10,000 customers) meet the new arsenic MCL, and to provide technical assistance to small system operators to reduce compliance costs. As part of this Arsenic Rule Implementation Research Program, EPA's Office of Research and Development proposed a project to conduct a series of full-scale, onsite demonstrations of arsenic removal technologies, process modifications, and engineering approaches applicable to small systems.

Site Information

The water system in Climax, MN supplies drinking water to 264 community members. Two wells in a Quaternary Buried Artesian aquifer provide the groundwater. Each well is 141 feet deep with 15 feet of slotted screen. Well 1 has a capacity of 140 gallons per minute (gpm), and Well 2 has a capacity of 160 gpm. The wells are alternated monthly to meet the peak daily demand of 105,000 gallons per day (gpd). Both pumps are used during fire emergencies with a full capacity of 300 gpm. The treatment system originally consisted of a gas chlorine feed to reach a target chlorine residual level of 0.6 mg/L. The water is fluoridated to a target level of 1.0 mg/L.

Source water samples were collected on July 30, 2003 from the West Well. The results of the source water analyses are presented in Table 1. Based on the July 30, 2003 sampling results, as much as 90 percent of the total arsenic existed as arsenic (III) and 10 percent existed as particulate arsenic. Almost all of the iron concentration in the source water existed as soluble iron. A rule of thumb is that the soluble iron concentration should be at least 20 times the soluble arsenic concentration for effective removal of arsenic onto iron solids. The results from the July 30, 2003 sampling event indicated that the soluble iron level was approximately 16 times the soluble arsenic level. Because the natural iron content in the source water was close to the target ratio, the initial plan was to operate the system without supplemental iron addition.

Arsenic Treatment System

The treatment train for the Climax system includes oxidation, co-precipitation/adsorption, and Macrolite® pressure filtration (see Figure 1 for the process flowchart and Figure 2 for a photograph of the Macrolite® FM-236-AS Arsenic Removal System). Macrolite® is a low-density, spherical, and chemically inert ceramic media that is designed for a high-rate filtration up to 10 gpm per square foot. The media, manufactured by Kinetico, is approved for use in drinking water applications under NSF Standard 61. Table 2 summarizes the design features of the Macrolite® pressure filtration system. The major process steps and system components include:

- **Oxidation**—The liquid sodium hypochlorite feed system consisted of a day tank and a chemical feed pump with a maximum capacity of 6 gallons per hour. The operator tracked the operation of the

Table 1. Climax, MN Source Water Quality		
Parameter	Unit	Value
pH		7.4
Total Alkalinity (as CaCO ₃)	mg/L	304.0
Hardness (as CaCO ₃)	mg/L	227.6
Chloride	mg/L	190.0
Fluoride	mg/L	1.7
Sulfate	mg/L	120.0
Silica (as SiO ₂)	mg/L	27.3
Orthophosphate (as PO ₄)	mg/L	<0.10
As (Total)	µg/L	38.7
As (Soluble)	µg/L	34.6
As(III)	µg/L	34.8
As(V)	µg/L	<0.1
Total Fe	µg/L	546.3
Total Al	µg/L	<10
Total Mn	µg/L	128.3
Total V	µg/L	0.4
Total Na	mg/L	177.2

* The mention of trade names does not constitute endorsement.

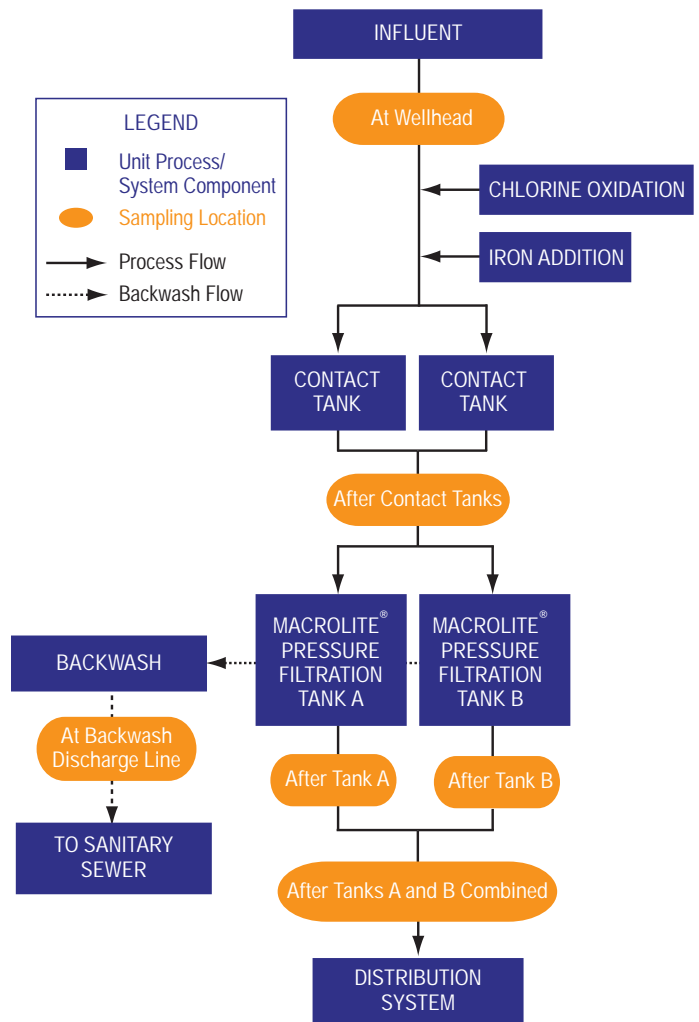


Figure 1. Process Flow (140 gpm) Diagram and Sampling Locations

chemical feed system by measuring free and total chlorine across the treatment train.

- **Co-Precipitation/Adsorption with Supplemental Iron Addition**—Beginning on January 3, 2005, an iron addition system was used to inject a target dose of 0.5 mg/L of iron after the prechlorination tap



Figure 2. Macrolite® Pressure Filtration System (Control Panel [1], Macrolite® Filters [2, 3], and Contact Tanks [4, 5])

Table 2. Design Specifications for the Macrolite® FM-236-AS Pressure Filtration System

Parameter	Value	Remarks
Prechlorination Dosage (mg/L [as Cl ₂])	1.2	The chlorine dosage was adjusted to provide a chlorine residual in the distribution water of 0.6 mg/L.
Supplemental Iron Dosage (mg/L [as Fe])	0.5	Implemented on January 3, 2005
Contact Vessels		
No. Vessels	2	Arranged in parallel
Vessel Size (inch)	42 D × 72 H	345 gallons each tank
Contact Time (minutes/vessel)	5	—
Filtration Vessels		
No. Vessels	2	Arranged in parallel
Vessel Size (inch)	36 D × 72 H	264 gallons each tank
Media Quantity (ft ³ /vessel)	14	24-inch bed depth of 40/60 mesh Macrolite® media in each vessel
Filtration Rate (gpm/ft ²)	10	—
Pressure Drop (psi)	15	Across a clean bed
Backwash Initiating Pressure (psi)	20	Across bed at end of filter run
Throughput before Backwash (gallons)	Variable	Based on PLC settings for pressure, run time, or standby set points.
Backwash Hydraulic Loading (gpm/ft ²)	8 to 10	—
Backwash Duration (minutes)	Variable	Based on PLC settings for minimum and maximum backwash times (e.g., 7 to 15 minutes from factory set points).
Wastewater Production (gallons)	Variable	See above
System Design Flowrate (gpm)	140	A flow-limiting device regulated flow through each vessel to less than 70 gpm to prevent filter overrun and system damage.
Maximum Daily Production (gpd)	201,600	Based on peak flow, 24 hours per day
Hydraulic Utilization (%)	52	Estimated based on a historic peak daily demand of 105,000 gpd

using a ferric chloride solution. The iron addition system included one 55-gallon polyethylene tank with containment, an overhead mixer, a 2.5-gallons per hour chemical metering pump, and a 600-pound capacity drum scale. The operator used daily readings of the weight of the day tank to measure the consumption of ferric chloride solution.

- **Contact**—The two 345-gallon contact tanks were constructed of fiberglass-reinforced plastic and had 6-inch top and bottom flanges. The water passed through the contact tanks in an upflow configuration.
- **Pressure Filtration**—Pressure filtration involved downflow filtration through two vessels arranged in parallel. The vessels, equipped with 6-inch top and bottom flanges, were mounted on a polyurethane-coated steel frame. The Macrolite® media in each vessel was underlain by a fine garnet fill layered 1 inch above the 0.006-inch slotted stainless steel wedge-wire underdrain.
- **Backwash Operations**—The filter was automatically backwashed in an upflow configuration when the pressure drop across the bed had reached 20 pounds per square inch (psi). The backwash was also triggered by the length of time the unit had been in service and/or in stand-by mode. During backwash, the water in one of the filtration vessels was first drained from the vessel and the filter was then sparged with air for 2 minutes at a pressure of

100 pounds per square inch gauge. After a 5-minute settling period, the filtration vessel was backwashed with treated water at a flowrate of approximately 55 gpm (8 gpm per square foot) until the turbidity of the backwash water had reached a target threshold level of 6 nephelometric turbidity units (NTU) based on the factory setting. The backwash was conducted one vessel at a time and the resulting wastewater was sent to a sump and then to the sanitary sewer. After backwash, the filtration vessel underwent a filter-to-waste cycle for 5 minutes before returning to the service mode.

The Macrolite® treatment system is fully automated with an operator interface, programmable logic controller (PLC), and modem housed in a central control panel. The control panel is connected to various instruments used to track system performance, including inlet and outlet pressure after each filter, system flowrate, backwash flowrate, and backwash turbidity with a Hach™ high range turbidimeter. All major functions of the treatment system are automated and would require only minimal operator oversight and intervention if all functions are operating as intended. Under normal operating conditions, the skill set required to operate the system was limited to observation of the process equipment integrity and operating parameters such as pressure, flow, and system alarms. The daily demand on the operator was about 30 minutes to visually inspect the system and record the operating parameters on the

log sheets. The operator also performed O&M activities such as cleaning the turbidimeter photo cell, monitoring backwash operational issues, and working with the vendor to troubleshoot and perform minor on-site repairs. All plumbing for the system is Schedule 80 PVC and the skidded unit is pre-plumbed with the necessary isolation valves, check valves, sampling ports, and other features. A 5-hp, 60-gallon vertical air compressor is included in the system.

System Performance

The performance of the Macrolite® FM-236-AS Arsenic Removal System was evaluated based on analyses of water samples collected from the treatment plant, distribution system, and backwash lines. The treatment plant water was sampled on 53 occasions (including four duplicate sampling events) during the one-year demonstration period.

Arsenic Removal. The total arsenic levels across the treatment train over the duration of the one-year period are illustrated in Figure 3. Total arsenic levels in raw water ranged from 31.2 to 51.4 µg/L. From August 11, 2004 to January 2, 2005, total arsenic levels in the treated water ranged from 9.7 to 19.0 µg/L, averaging 14.7 µg/L. Insufficient natural iron was present in the raw water to achieve effective arsenic removal to below the 10 µg/L MCL. After supplemental iron addition was implemented, total arsenic levels in the treated water were reduced to 6.0 to 9.3 µg/L, averaging 7.4 µg/L, with no exceedances of arsenic above the 10 µg/L level for the remainder of the study period.

Figure 4 shows the arsenic speciation results. The total arsenic concentration in the raw water averaged 36.5 µg/L that consisted predominately of soluble arsenic. Of the soluble fraction, 35.8 µg/L was arsenic (III) and 2.1 µg/L arsenic (V). These results compared well with those of the July 30, 2003 source water sampling.

After prechlorination and the contact tanks, the soluble fraction of the arsenic decreased to an average 14.7 µg/L and the particulate fraction to 24.1 µg/L. Of the soluble arsenic, 12.2 µg/L (83 %) was arsenic (V) indicating effective oxidation of arsenic (III) to arsenic (V) with chlorine. Most of the particulate arsenic was removed

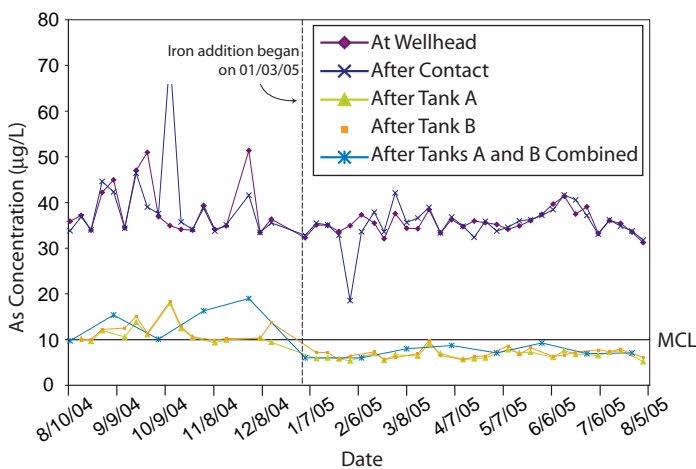


Figure 3. Total Arsenic Concentrations Across Treatment Train

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by the filters. Because of insufficient natural iron in the raw water, however, the arsenic concentration in the combined filter effluent ranged from 9.7 µg/L to 19.0 µg/L and averaged 14.1 µg/L (primarily soluble arsenic) that was above the 10 µg/L arsenic MCL.

After the start of supplement iron addition, the particulate arsenic of the water from the contact tanks averaged 23.4 µg/L and the soluble arsenic averaged 11.7 µg/L with the soluble arsenic being 83% arsenic (V). The

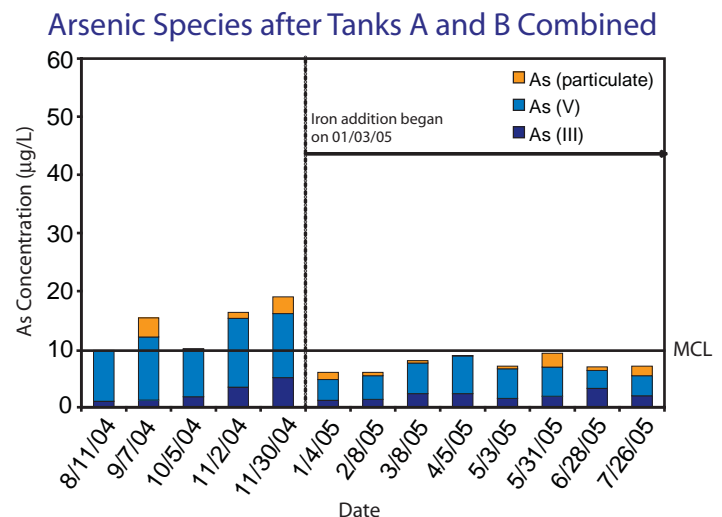
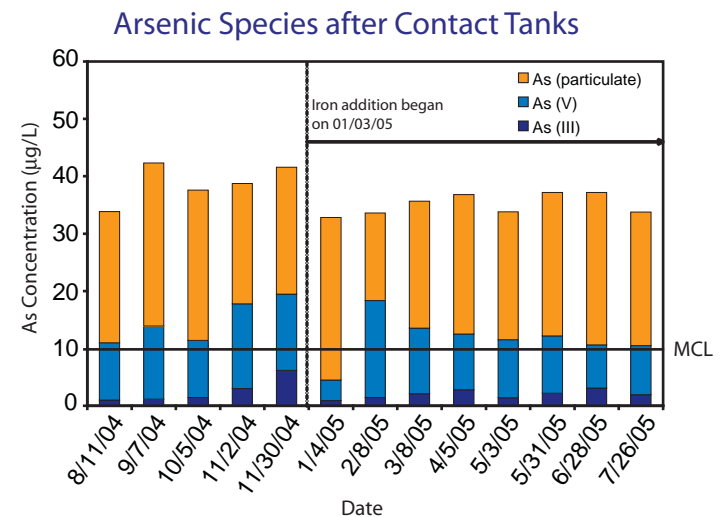
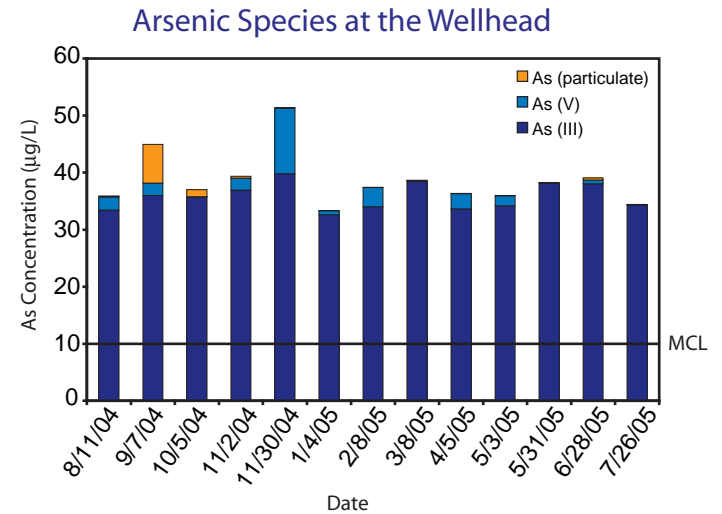


Figure 4. Concentrations of Arsenic Species

total arsenic in the combined filter effluent averaged 7.4 µg/L with 6.5 µg/L (88%) of the effluent arsenic being soluble arsenic. Particulate arsenic levels in the treated water were low, ranging from less than 0.1 to 2.4 µg/L and averaging 0.9 µg/L. The reduction of some of the soluble arsenic (V) through the filters suggests that the iron particles accumulated within the filters had some additional adsorptive capacity for arsenic (V) removal.

Iron Removal. Figure 5 shows the total iron levels across the treatment train over the duration of the study period. Total iron levels in the raw water ranged from 361 to 1,209 µg/L and averaged 540 µg/L. Iron in the raw water existed primarily in the soluble form and averaged 485 µg/L. The average soluble iron and soluble arsenic levels in the source water corresponded to an iron:arsenic ratio of 13:1, which was below the target ratio of 20:1 for effective arsenic removal. As expected, iron existed solely in the particulate form after prechlorination and the contact tanks.

Manganese Removal. Total manganese levels in raw water ranged from 112 to 218 µg/L with an outlier at 505 µg/L. Manganese in raw water existed primarily in the soluble form at levels ranging from 112 to 145 µg/L. After prechlorination and the contact tanks, soluble manganese concentrations decreased to 59.0 to 89.1 µg/L. An average of 42 percent of the soluble manganese was precipitated to particulate manganese. Unlike MnOx-coated media, Macrolite® does not promote Mn(II) removal via adsorption with the presence of chlorine. Only particulate manganese was filtered out by the Macrolite® filters, leaving soluble manganese in the treated water at levels ranging from 55.5 to 91.5 µg/L.

Other Water Quality Parameters. Dissolved oxygen levels remained low across the treatment train, with average values ranging from 1.3 to 1.7 mg/L, but oxidation-reduction potential values significantly increased after chlorine addition ranging from -63 to -128 mV before chlorination to 121 to 382 mV after chlorination. The pH values of the raw water and treated water had average values of 7.5 and 7.4, respectively. Average alkalinity results ranged from 313 to 326

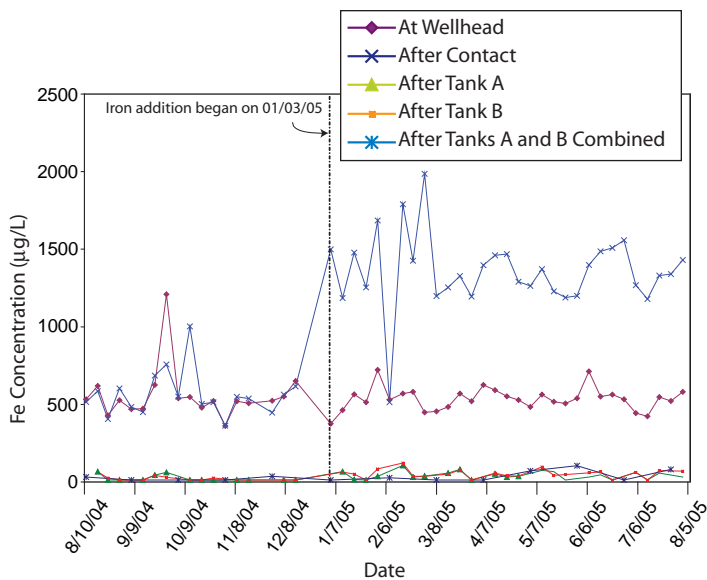
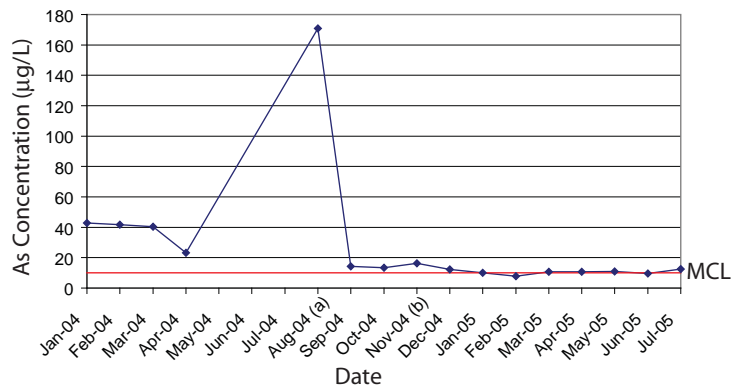


Figure 5. Total Iron Concentrations Across Treatment Train

mg/L (as CaCO₃) across the treatment train. Average total hardness (i.e., the sum of calcium hardness and magnesium hardness) ranged from 229 to 232 mg/L across the treatment train. The water had predominantly calcium hardness. The corresponding free and total chlorine concentrations after the contact tanks averaged 0.9 and 1.9 mg/L, respectively. Fluoride concentrations were not affected by the Macrolite® filtration. Fluoride averaged 1.0 mg/L in the combined effluent samples after the fluoridation step. Average sulfate concentrations ranged from 121 to 123 mg/L across the treatment train. The silica (as SiO₂) concentration remained at approximately 28 mg/L across the treatment train.

Distribution Water. The distribution system sampling showed that pH values did not change significantly after the system became operational. Alkalinity levels ranged from 198 to 331 and from 294 to 339 mg/L (as CaCO₃) before and after startup, respectively. Arsenic concentrations in the baseline samples averaged 37.0 µg/L and were consistent with those in the raw water. After system startup, arsenic levels in the distribution system averaged 14.1 µg/L before iron addition and 10.3 µg/L after iron addition. Figure 6 shows the average arsenic concentration at the three distribution system sampling points. Since system startup, iron levels in the distribution system decreased from an average of 286 µg/L in baseline samples to an average of 43.2 µg/L before iron addition and 74.7 µg/L after iron addition. These values were still higher than the corresponding average iron levels in the treated water. The arsenic and iron data may suggest solubilization, destabilization, and/or desorption of particles within the distribution system (Lytle, 2005).

The manganese levels in the distribution system samples decreased from an average of 65.6 µg/L in the baseline samples to 33.8 µg/L after system startup. In general, total manganese levels in the distribution samples were lower than those in the treated water (averaged 83.4 µg/L). This may be due to further oxidation of Mn(II) and adsorption and/or coating onto metal oxide scales in the distribution system. System operation did not appear to affect lead levels in the distribution system. Copper concentrations in the distribution system averaged 155 mg/L in the baseline samples and 266 mg/L after system startup. The copper levels increased overall after system



(a) A flush of red water was seen during sample collection.
(b) DS2 was taken on 12/07/04 for this sampling event.

Figure 6. Average Arsenic Concentration at Distribution System Sampling Locations

Table 3. Summary of Backwash Parameters

Backwash Parameters Per Vessel	Minimum	Median	Maximum
Initial Field Settings (08/11/04–01/14/05)^(a)			
Backwash Duration (min)	18	18	53 ^(c)
Water Quantity Generated (gal)	800	900	2,650 ^(c)
Modified Field Setting (01/14/05–08/12/05)^(b)			
Backwash Duration (min)	5	10	306 ^(c)
Water Quantity Generated (gal)	250	500	15,300 ^(c)
(a) Backwash events: 70 for Vessel A and 71 for Vessel B.			
(b) Backwash events: 119 for Vessel A and 115 for Vessel B, not including multiple successive events caused by backwash malfunctions.			
(c) Backwash control malfunctions caused repeat backwash cycles to occur on the same day.			

startup, and one sample exceeded the 1,300 µg/L action level. The treatment system did not appear to impact the factors that can increase the solubility of copper in drinking water in contact with plumbing fixtures (e.g., low pH, high temperature, and soft water with fewer dissolved minerals).

Backwashing. Table 3 summarizes data related to the backwash duration and backwash water quantity produced under the initial and modified field settings from August 11, 2004 through January 14, 2005 and from January 14, 2005 through August 12, 2005, respectively. The backwash flowrate for both time periods was approximately 50 gpm or 7 gpm/ft², which is lower than the 8 to 10 gpm/ft² design value. The backwash flowrate was lowered in the field at startup to avoid media loss that was observed when a higher flowrate was used such as the factory set point of 75 gpm.

Table 4 summarizes the analytical results from the twelve backwash water sampling events. Prior to iron addition, soluble arsenic and iron concentrations in the backwash water averaged 16.0 µg/L and 21.0 µg/L, respectively. After iron addition, soluble arsenic concentrations decreased and averaged 8.4 µg/L, while soluble iron concentrations increased and averaged 75.4 µg/L (excluding the July 27, 2005 data that had uncharacteristically high soluble arsenic, iron, and manganese). After iron addition, the soluble iron levels in the backwash water increased due to equilibrium with the higher total iron levels (e.g., iron particulates) in the backwash water. However, the soluble arsenic levels decreased, due to increased adsorption onto the iron particulates. For the last sampling event on November 15, 2005, total suspended solids (TSS) and total arsenic, iron, and manganese also were analyzed for the composite sample collected. The results showed total iron levels in the backwash water at 74.2 to 97.6 mg/L and total arsenic levels at 1.42 to 1.85 mg/L. TSS levels in the backwash water ranged from 188 to 278 mg/L.

The Toxicity Characteristic leaching Procedure (TCLP) results of the backwash solids showed no detectable arsenic concentrations in the leachate. Concentrations of cadmium, chromium, lead, mercury, selenium, and silicon were also below the detection limit. Only barium

Table 4. Backwash Water Sampling Results

Parameter	Unit	Value Type	Pre Iron Addition	Post Iron Addition
pH	S.U.	Minimum	7.1	7.3
		Maximum	7.9	7.6
		Average	7.6	7.5
Turbidity	NTU	Minimum	7.6	14
		Maximum	60	140
		Average	41.6	93.4
Total Dissolved Solids	mg/L	Minimum	758	646
Soluble As	µg/L	Minimum	12.3	6.4
		Maximum	21.6	25.6
		Average	16.0	10.5
Soluble Fe	µg/L	Minimum	<25	25.7
		Maximum	39.9	771
		Average	21.0	164.3
Soluble Mn	µg/L	Minimum	24.9	65.6
		Maximum	413	118
		Average	119.65	79.6
One-half of the detection limit was used for non-detect samples for calculations.				

showed detectable concentrations ranging from 0.189 to 0.231 mg/L. The TCLP regulatory limit set by EPA is 5 mg/L for arsenic and 100 mg/L for barium.

System Costs

The cost of the system was evaluated based on the capital cost per gpm (or gpd) of design capacity and the O&M cost per 1,000 gallons of water treated. The costs associated with the building, sanitary sewer connections, and other discharge-related infrastructure were not included in the treatment system costs. These costs were funded separately by the demonstration site.

Capital Costs. Table 5 summarizes the capital investment for the Climax system. The equipment costs include the costs for the Macrolite[®] media, contact tanks, filtration skid, instrumentation and controls, labor (including activities for the system shakedown), system warranty, freight, and sales tax. The system warranty included repair and/or replacement of any equipment or installation workmanship for twelve months after system startup. The engineering costs include the costs for preparing a process design report and the required engineering plans. The installation costs include the costs for labor and materials for system unloading and anchoring, plumbing, and mechanical and electrical connections.

The total capital cost of \$270,530 was normalized to the system's rated capacity of 140 gpm (201,600 gpd), which resulted in \$1,932 per gpm (\$1.34 per gpd). The total capital cost of \$270,530 was converted to a unit cost of

Description	Cost
Equipment Costs (59%)	\$159,419
Media, Filter Skid, and Tanks	\$66,210
Air Compressor	\$2,346
Control Panel	\$11,837
Labor	\$43,005
Warranty	\$11,950
Additional Flowmeter/Totalizers	\$2,622
Iron Addition Equipment	\$5,259
Freight and Sales Tax	\$16,190
Engineering Costs (15%)	\$39,344
Labor	\$38,094
Subcontractor	\$1,250
Installation Costs (26%)	\$71,767
Labor	\$12,914
Travel	\$6,163
Subcontractor	\$52,690
Total Capital Investment (100%)	\$270,530

\$0.35/1,000 gallons, using a capital recovery factor of 0.9439 based on a 7 percent interest rate and a 20-year return period (Chen et al., 2004). These calculations assumed that the system operated 24 hours a day, 7 days a week, at the system design flowrate of 140 gpm. The system operated only 5.6 hours a day and produced 13,829,000 gallons of water during the study period. At this reduced usage rate, the total unit cost was increased to \$1.85/1,000 gallons.

Operation and Maintenance Costs. Table 6 summarizes O&M costs, which include costs associated with chemical supply, electricity, and labor. Because the system was under warranty during the one-year study period, no costs were incurred for repairs to the system. Chlorination was performed prior to the demonstration study so the incremental cost for the sodium hypochlorite solution was assumed to be negligible. The usage rate for the ferric chloride stock solution was approximately 80 gallons or 900 pounds per year. The incremental power costs were estimated based on the change in electric utility bills for a one-year timeframe before and after the treatment plant installation and do not include propane costs to heat the building. Under normal operating conditions, the skill requirements to operate the system were minimal, with a typical daily demand on the operator of 30 minutes. The operator performed activities such as cleaning the turbidimeter photocell, monitoring backwash operational issues, and working with the vendor to troubleshoot and perform on-site repairs. Remote monitoring of the treatment system by the vendor was effective in troubleshooting problems.

Based on this time commitment and a labor rate of \$21/hour, the labor cost was \$0.22/1,000 gallons of water treated. The total O&M cost was approximately \$0.29/1,000 gallons.

Cost Category	Value	Assumptions
Volume processed (1,000 gallons)	13,829	From 08/16/04 through 08/12/05
Chemical Usage (10%)		
Ferric Chloride Unit Price (\$/pound)	\$0.40	35% ferric chloride in a 600-lb drum.
Ferric Chloride Consumption Rate (pounds/1,000 gallons)	0.065	80 gallons or 900 pounds annually
Chemical cost (\$/1,000 gallons)	\$0.03	
Electricity (14%)		
Power use (\$/1,000 gallons)	\$0.04	Based on additional costs after treatment plant startup.
Labor (76%)		
Average weekly labor (hours)	2.5	30 minutes/day; 5 days/week
Labor cost (\$/1,000 gallons)	\$0.22	Labor rate = \$21/hour
Total O&M Cost (\$1,000 gallons)	\$0.29	—

Conclusions

The Climax, MN demonstration project confirmed that iron removal is an effective way to remove arsenic from water. Additionally, when natural iron levels are insufficient for desired arsenic removal, ferric iron can be added to the water after the oxidant feed (for arsenic [III] oxidation). Removing iron from source water improves water quality in the distribution system and reduces flushing frequency.

Battelle submitted the full report in fulfillment of EPA Contract 68-C-00-185, Task Order 0019.

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