Arsenic Removal from Drinking Water by Adsorptive Media

USEPA Demonstration Project at Springfield, OH

Project Summary

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A project to demonstrate AdEdge Technologies' AD-33 media's ability to remove arsenic was conducted at the Chateau Estates Mobile Home Park at Springfield, OH. The project objectives were to evaluate: (1) the effectiveness of the AdEdge Technologies' AD-33 media in removing arsenic to meet the new arsenic maximum contaminant level (MCL) of 10 micrograms per liter (µg/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 cost of the technology. The project also characterizes the water in the distribution system and process residuals produced by the treatment process.

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 milligrams per liter (mg/L), or 10 µg/L, and to require all community and nontransient, 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 has a total of 226 connections and serves a population of approximately 600 in the Chateau Estates Mobile Home Park Community in Springfield, OH. Source water is groundwater supplied from two bedrock wells. The West Well produces about 130 gallons per minute (gpm). The East Well produces about 90 gpm. Both wells are 8 inches in diameter and were originally installed to a depth of 100 feet. In 2001, the East Well was extended to a depth of 220 feet. The pre-existing water treatment system consisted of chlorination using a 12.5% sodium hypochlorite solution and addition of polyphosphate as a sequestering agent for corrosion and scale control. Before the installation of the water treatment system, the West Well typically operated for approximately 5 hours per day and produced 40,000 gallons of water.

Source water samples were collected on August 5, 2004, for the West Well and on September 9, 2004, for the East Well. The results of the analyses are presented in Table 1. Arsenic in the West Well existed almost entirely as arsenic (III); while arsenic in the East Well existed as arsenic (III), arsenic (V), and particulate arsenic. Total arsenic concentration in the West Well was much higher than that in the East Well (i.e., 24.6 versus 14.6 μg/L).

Arsenic Treatment System

The treatment system consists of two integrated units referred to as an AD-26 pretreatment system and an AD-33 arsenic package unit (APU) adsorption system. The AD-26 pretreatment system uses a manganese dioxide mineral media commonly used for oxidation and filtration of iron and manganese. Pretreatment is followed in series by the APU adsorption system for arsenic removal. Figure 1 contains a process flowchart including sampling locations. Figure 2 contains photo of the AD-26 treatment system.

Raw water was first treated with chlorine for disinfection and oxidation. Chlorine precipitates soluble iron and converts arsenic (III) to arsenic (V). The arsenic (V) formed was adsorbed onto the precipitated iron solids, which in turn, were filtered out by the AD-26 media.

The AD-26 pretreated water was sent to the APU system as a polishing step. The APU is a fixed bed adsorption system that uses Bayoxide E33 media, an iron-based adsorptive media. Once reaching capacity, the spent media may be removed and disposed of after being tested for EPA's TCLP test.

Table 1. Springfield, OH Source Water Quality

Parameter	Unit	West Well	East Well
pH		NA	7.3
Total Alkalinity (as $CaCO_3$)	mg/L	319	343
Hardness (as $CaCO_3$)	mg/L	381	291
Chloride	mg/L	14	1.4
Fluoride	mg/L	1.5	0.8
Sulfate	mg/L	27	15
Silica (as SiO_2)	mg/L	19.4	17.5
Orthophosphate	mg/L	<0.10	<0.10
Total As	μg/L	24.6	14.6
As (particulate)	μg/L	0.3	5.7
As(III)	μg/L	24.7	6.1
As(V)	μg/L	<0.1	2.8
Total Fe	μg/L	1,615	636
Total Mn	μg/L	18.5	62.3
Total V	μg/L	0.2	0.41
Total Na	mg/L	11.3	14.8

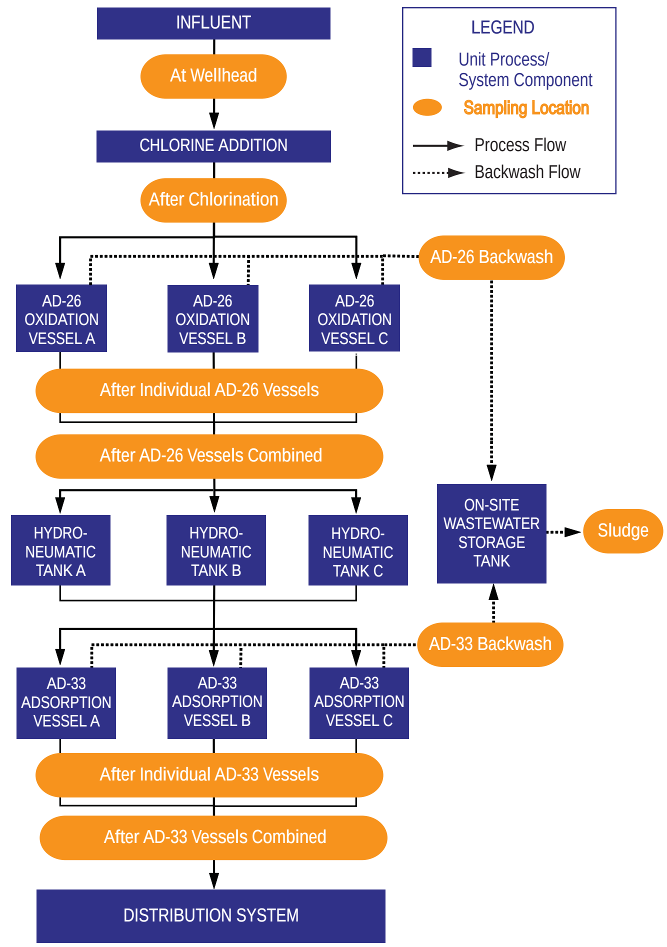

Figure 1. Process Flow (250 gpm) Diagram and Sampling Locations

Both the AD-26 oxidation/filtration and the APU systems are skid-mounted, each comprising of three carbon steel pressure vessels. The AD-26 and AD-33 media are both certified under NSF Standard 61. Table 2 presents the key system design parameters. Key process components include:

- **Intake—**Raw water was pumped from the supply wells, alternating every cycle.

Figure 2. AD-26 Treatment System

- **Chlorination—**An automatic chlorine injection system was used to chlorinate the water by injecting 12.5% liquid sodium hypochlorite solution to the 4-inch PVC line. The proper operation of the feed system was tracked by the operator through measurements of free and total chlorine across the treatment train and at the entry point. In spite of repeated efforts, the automatic chlorine monitor/controller failed to control free and total chlorine residuals within the target level of 1.0 mg/L (as Cl_2).

- **Iron/Manganese Removal—**Prechlorinated water entered the AD-26 oxidation/filtration system at an average flowrate of 130 gpm. The AD-26 system consisted of three 36-inch-diameter, 60-inch-sidewall height carbon steel pressure vessels configured in parallel. Each vessel was filled with 31 inches (19 cubic feet) of media, which was underlain by 7 inches (5 cubic feet) of fine underbedding. Electrically actuated butterfly valves and a centralized programmable logic controller (PLC) unit controlled the AD-26 system.

- **Hydropneumatic Tanks—**The filtered water from the AD-26 system entered the three hydropneumatic storage tanks. Each tank had a storage capacity of 528 gallons for a total capacity of 1,584 gallons.

- **Arsenic Adsorption—**Upon demand, the water stored in the hydropneumatic tanks flowed through the AD-33 adsorption system. During a pre-demonstration water demand study, flowrates ranged from 18.1 to 58.2 gpm and averaged 33.0 gpm. The APU system consisted of three 48-inch-diameter, 60-inch-sidewall height carbon steel pressure vessels configured in parallel. Each APU vessel contained approximately 38 cubic feet (114 cubic feet total) of AD-33 media. The estimated media empty bed contact time (EBCT) of 25.8 minutes is at least 5 times higher than the vendor's recommendation.

- **Backwash—**Both the AD-26 and APU systems required backwashing. Each vessel was backwashed one at a time using water stored in the hydropneumatic tanks. Initially, the backwash wastewater was stored in two on-site 6,000-gallon storage tanks and hauled off-site for disposal on a weekly basis. On September 14, 2006, the facility was connected to the sewer system.

Table 2. Design Specifications for the AdEdge Treatment System

Parameter	Value	Remarks
Influent Specifications		
Peak Design Flowrate (gpm)	250	System upsized from 150 gpm at Park Owner's request and expense
Average Throughput to System (gpd)	40,000	—
Prechlorination		
Chlorine Dosage (mg/L [as Cl_2])	2.5	1.0 mg/L residual chlorine within distribution system
AD-26 Oxidation/Filtration		
Number of Vessels	3	Arranged in parallel
Vessel Size (inch)	36 D × 60 H	—
Media Quantity (ft^3/vessel)	19	57 ft^3 total of AD-26 media
Flowrate through Each Vessel (gpm)	43	Total flowrate of 130 gpm
Backwash Flowrate through Each Vessel (gpm)	130	18.4 gpm/ft^2
Backwash Duration (minutes)	15	Per vessel
Backwash Frequency (times/week)	3	Actual frequency determined during system operation
Media Life (years)	4	Vendor provided estimate
AD-33 Adsorption		
Number of Vessels	3	Arranged in parallel
Vessel Size (inch)	48 D × 60 H	—
Media Quantity (ft^3/vessel)	38	114 ft^3 total of AD-33 (Bayoxide E33) media
Flowrate through Each Vessel (gpm)	on-demand	Average of 33 gpm measured prior to study
Empty Bed Contact Time (minutes/vessel)	25.8	Based on average on-demand flowrate
Backwash Flowrate (gpm)	127	10 gpm/ft^2
Backwash Duration (minutes)	15	Per vessel
Backwash Frequency (times/60 days)	1	Actual frequency determined during system operation
Bed Volumes (BV)/Day	47	Based on throughput of 40,000 gpd, 1 BV = 114 ft^3
Working Capacity (BV)	83,500	Based on vendor estimate for breakthrough at 10 µg/L
Volume to Breakthrough (gallons)	71,200,000	Vendor provided estimate
Media Life (years)	4.9	Based on estimated media working capacity of 83,500 BVs and average throughput of 40,000 gpd

- **Media Replacement—**When the AD-33 adsorptive media exhausts its capacity, the spent media will be removed and disposed. Virgin media will be loaded into the vessels.

The skills required to operate the APU-250 system were relatively complex due to the problems associated with the chlorine injection. The operator needed to adjust the dosage of the chlorine, adjust the metering pump, and change out the master chip within the control panel.

Under normal operating conditions, the operator spent approximately 20 minutes daily to perform visual inspection and record the system operating parameters on the Daily Field Log Sheets. The operator also performed routine weekly and monthly maintenance according to the users' manual to ensure proper system operation. Normal operation of the system did not appear to require additional skills beyond those necessary to operate the existing water supply equipment. Ohio public water systems serving more than 250 people must have a certified operator. Chateau Estates has a Class III water system operator with Class IV being the highest.

The only chemical required for the system operation was the sodium hypochlorite solution. Every week approximately 15 gallons of the solution was added to the 75-gallon chlorine tank.

System Performance

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

Arsenic Removal. Figure 3 contains four bar charts showing the concentrations of total arsenic, particulate arsenic, arsenic (III), and arsenic (V) at the wellhead, after chlorination, and in the combined effluent from the AD-26 and AD-33 vessels, respectively. Total arsenic concentrations in raw water averaged 22.7 µg/L of the soluble fraction. Arsenic (III) was the predominating species, averaging 16.9 µg/L. Arsenic (V) and particulate arsenic concentrations were low, averaging 1.7 and 2.8 µg/L, respectively.

Total arsenic concentrations were higher in West Well than East Well (26.9 versus 20.2 µg/L on average). Unlike what was observed during the source water sampling events, arsenic (III) was the predominating species in both wells. The presence of elevated particulate arsenic and particulate iron during some speciation events and the East Well source water sampling, most likely was caused by inadvertent aeration of the samples.

Chlorine oxidized arsenic (III) to arsenic (V) that, in turn, was attached effectively, to iron solids to form particulate arsenic. The samples collected downstream of the chlorine injection point showed a decrease in the average soluble arsenic concentration from 18.5 µg/L to 6.4 µg/L and an increase in average particulate arsenic concentration from 2.8 µg/L to 15.3 µg/L. The majority of particulate arsenic was filtered out by the AD-26 media, leaving only 0.5 to 2.1 µg/L of total arsenic, existing mainly as arsenic (V). Total arsenic concentrations in the treated water after the AD-33 vessels were reduced to less than 0.5 µg/L. Figure 4 presents arsenic breakthrough curves from the AD-26 and AD-33 systems.

Free and total chlorine were monitored. After chlorination, free and total chlorine levels averaged 1.7 mg/L and 1.5 mg/L (as Cl_2), respectively. The residual chlorine measured after the AD-26 and AD-33 vessels indicated little or no chlorine consumption through the vessels. Repeated attempts had been made to reduce the levels of free and total chlorine residuals to the target levels of 1.5 and 1 mg/L (as Cl_2). The cartridge filter placed just before the chlorine monitor/control module appeared to control the chlorine levels.

Iron Removal. Total iron concentrations at the wellhead averaged 1,102 µg/L. Iron concentrations following the prechlorination step were similar with concentrations averaging 1,171 µg/L. Iron was removed from the treatment train with concentrations ranging from less than the method detection limit of 25 µg/L to 25.3 µg/L after the AD-26 vessels and less than the method detection limit of 25 µg/L after the AD-33 vessels. Dissolved iron levels ranged from 217 to 1,475 µg/L at the wellhead. After prechlorination, except for one outlier at 838 µg/L occurring on July 26, 2006, dissolved iron levels ranged from less than the method detection limit of 25 µg/L to 32.8 µg/L. Dissolved iron levels were always less than the method detection limit after the AD-33 vessels. The backwash frequency of once every three days appeared to be adequate.

Manganese Removal. Total manganese levels in source water averaged 35.6 µg/L and existed almost entirely in the soluble form. After prechlorination, over 70% on average of soluble manganese was precipitated, presumably, to form MnO_2 solids, which, along with unoxidized Mn^{2+}, were removed by the AD-26 media to less than 0.7 µg/L. Total manganese concentrations were further reduced to 0.2 µg/L after the AD-33 adsorptive media.

The amount of Mn^{2+} that precipitated upon chlorination varied extensively during the 13 speciation events, with 9 events ranging from 85.0 to 98.0%, 2 ranging from 48.8 to 57.6%, and the remaining 2 ranging from 1.1 to 5.8%.

Other Water Quality Parameters. The pH values of raw water measured at the wellhead varied from 6.9 to 7.5. The pH values remained essentially unchanged after the AD-26 and AD-33 vessels. Alkalinity, total hardness, sulfate, and silica (as SiO_2) remained constant throughout the treatment train. Fluoride concentrations did not appear to be affected by the AD-33 media. Total phosphorous (as PO_4) was below the detection limit of 0.01 mg/L for all samples.

Distribution Water. Prior to the installation/operation of the treatment system, first draw baseline distribution system water samples were collected at three locations (two residences and the mobile park clubhouse). Following the installation of the treatment system, distribution water sampling continued on a monthly basis. The results of the distribution system sampling are summarized in Table 3.

The most noticeable change in the distribution samples after system startup was the decrease in arsenic, iron, and manganese concentrations. Baseline arsenic concentrations averaged 23.7 µg/L for all three locations. After system startup, arsenic concentrations were reduced to an average of 1.6 µg/L. The baseline iron averaged 1,359. After the treatment system became operational, iron concentrations decreased to less than the method detection limit of 25 µg/L in all samples except for three. Manganese had a similar trend with baseline concentrations averaging 15.2 µg/L and after startup samples averaging 0.2 µg/L.

Lead concentrations ranged from less than 0.1 to 5.2 µg/L. Copper concentrations ranged from 0.3 to 1,353 µg/L; one sample exceeded the 1,300 µg/L action level during baseline sampling. The arsenic treatment system does not seem to affect the lead or copper concentrations in the distribution system.

Measured pH values averaged 7.5, and alkalinity levels ranged from 198 to 364 mg/L (as $CaCO_3$). The arsenic treatment system does not seem to affect these water quality parameters in the distribution system.

Backwash Water.

Backwash was performed using the AD-26 treated water stored in the hydropneumatic tanks. The results of the unfiltered sample analysis are presented in Table 4. The first AD-26 vessel was sampled during 12 monthly events, while the second and third vessels, were sampled on the last eleven and last eight sampling events, respectively. Total dissolved solids (TDS) concentrations averaged 408 mg/L. Total suspended solids (TSS) concentrations averaged 83.4 mg/L. The several unusually low TSS values measured during backwash of each AD-26 vessel were thought to be the result of insufficient mixing of the backwash wastewater. Note that lower TSS values also had lower particulate arsenic, iron, and manganese concentrations. The majority of the total arsenic, iron and manganese in the backwash wastewater were in the particulate form.

Assuming that 83 mg/L of TSS (average of all TSS values except for the outliers) was produced in 6,000 gallons of backwash wastewater, approximately 4.2 pounds of solids would be discharged during each AD-26 backwash event. The solids discharged would be composed of 0.02, 1.51, and 0.03 pounds of arsenic, iron, and manganese, respectively, assuming 450 µg/L of particulate arsenic, 30,100 µg/L of particulate iron, and 500 µg/L of particulate manganese in the backwash wastewater.

The AD-33 vessels were backwashed four times, generating approximately 6,050 gallons of wastewater. After reviewing the system operation, it was determined that the media would not need to be backwashed on a regular basis and that backwashing frequency would be determined based on system pressures. Backwash samples were not taken.

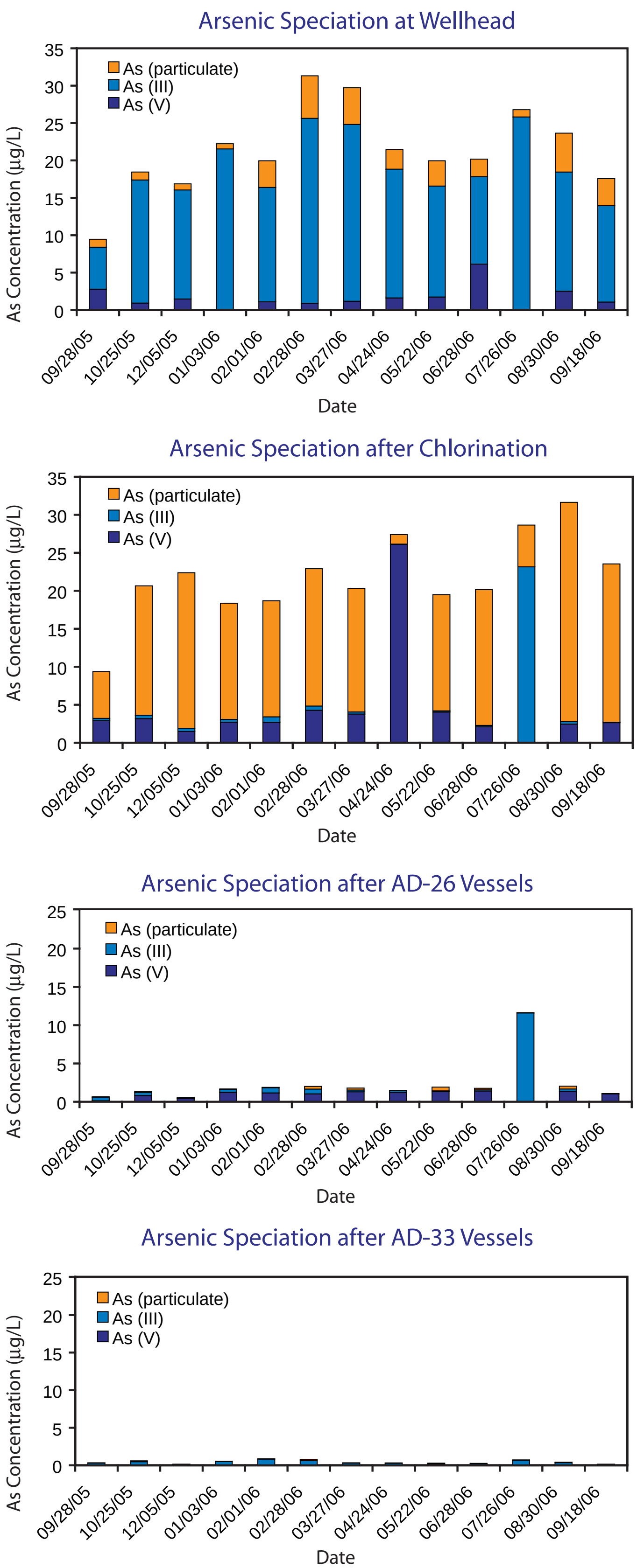

Figure 3. Concentrations of Arsenic Species

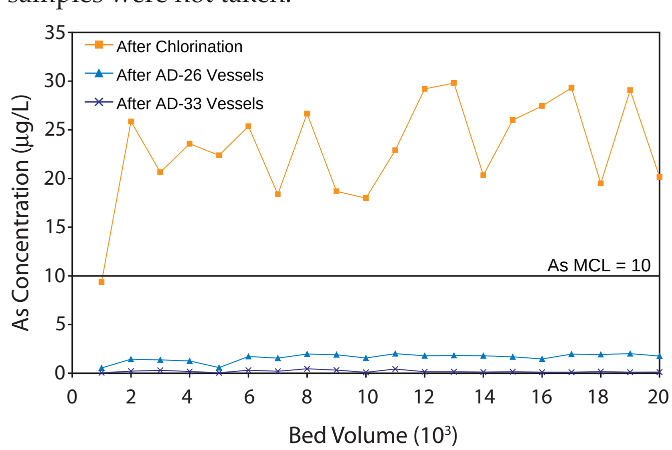

Figure 4. Total Arsenic Breakthrough Curves

Table 3. Average Distribution System Sampling Results

Sampling Event		pH	Alkalinity	Arsenic	Iron	Manganese	Lead	Copper
No.	Date	S.U.	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L
Average Baseline	Apr 05–Jul 05	7.4	346.8	23.7	1359.8	15.2	1.4	401.1
1	Oct 05	7.5	349.0	2.5	12.5	0.1	0.2	6.7
2	Nov 05	7.8	289.0	2.3	12.5	0.1	0.2	67.4
3	Dec 05	7.5	347.7	2.3	12.5	0.1	0.2	64.5
4	Jan 06	7.4	353.3	2.3	17.7	0.3	1.0	106.9
5	Feb 06	7.4	329.3	1.6	12.5	0.1	0.1	37.8
6	Mar 06	7.6	340.7	1.0	12.5	0.1	0.7	65.4
7	Apr 06	7.5	333.3	1.1	27.8	0.4	0.9	55.1
8	May 06	7.5	331.7	1.0	12.5	0.2	0.3	45.0
9	Jun 06	7.4	330.7	1.3	12.5	0.1	1.0	79.6
10	Jul 06	7.4	342.0	1.1	12.5	0.2	1.2	67.7
11	Aug 06	7.4	331.3	1.3	17.1	0.2	1.0	35.8
12	Sep 06	7.5	348.0	1.3	12.5	0.1	1.2	79.4

One-half of the detection limit was used for non-detect samples for calculations.

System Cost

The cost of the system is based on the capital cost per gpm (or gpd) of the design capacity and the O&M cost per 1,000 gallons of water treated. At his own cost, the park owner upgraded the system from 150 gpm to 250 gpm in response to the Ohio EPA's redundancy requirement and for future growth.

Capital Costs. Table 5 summarizes the capital investment for the system. The equipment cost included $144,136 for the 150-gpm system (EPA-funded) and $68,690 for the system upgrades (facility-funded). The $68,690 of equipment upgrades covered the cost of upgrading the AD-26 and AD-33 vessels and adding 21 cubic feet of AD-26 and 38 cubic feet of AD-33 media, three new hydropneumatic tanks, and a chlorine injection system including a chlorine monitor/controller module.

The engineering cost included the cost for the preparation of a process flow diagram of the treatment system, mechanical drawings of the treatment equipment, and a schematic of the building footprint and equipment layout.

Table 4. Backwash Water Sampling Results

Parameter	Unit	Min	Max	Average
pH	S.U.	4.4	7.7	7.4
TDS	mg/L	360	476	409
TSS	mg/L	9	262	72
As (total)	µg/L	71	1,089	402
As (soluble)	µg/L	2.2	7.2	4.1
As (particulate)	µg/L	68.9	1,084	398
Fe (total)	µg/L	5,237	59,656	26,450
Fe (soluble)	µg/L	43.8	279.0	120.3
Mn (total)	µg/L	51.1	1,357	446
Mn (soluble)	µg/L	0.4	5.3	2.4

The installation cost included the equipment and labor to unload and install the skid-mounted units, perform piping tie-ins and electrical work, and load and backwash the media.

The capital cost of $292,252 was normalized to $1,170/gpm ($0.81 gpd) of design capacity using the system's rated capacity of 250 gpm (or 360,000 gpd). The capital cost also was converted to an annualized cost of $27,590/year using a capital recovery factor (CRF) of 0.09439 based on a 7% interest rate and a 20-year return period.

Table 5. Summary of Capital Investment

Description	Cost
Equipment Costs (73%)	**$212,826**
AD-26 Media (36 ft3) and three 30-inch diameter fiberglass vessels on skid*	$53,656
AD-33 Media (76 ft3) and three 42-inch diameter fiberglass vessels on skid*	$82,640
Totalizer for Backwash Line	$990
One-Year O&M Support and Manuals	$3,640
Additional Sample Taps	$675
Freight	$2,535
Equipment for Upgrade to APU-250 System (Paid by Owner)	$68,690
Engineering Costs (9%)	**$27,528**
Labor, Travel, and Materials	$22,454
System Upgrade (Paid by Owner)	$5,074
Installation Costs (18%)	**$51,899**
Labor, Travel, and Materials	$27,025
System Upgrade (Paid by Owner)	$24,874
Total Capital Investment (100%)	**$292,253**

* Also includes gravel underbedding, process valves and piping, and instrumentation and controls.

Assuming that the system operated 24 hours/day, 7 days/week at the design flowrate of 250 gpm, the unit capital cost would be $0.21/1,000 gallons. During the year long demonstration, the system produced 16,873,000 gallons of water; at this reduced usage rate, the unit capital cost increased to $1.64/1,000 gallons.

Operation and Maintenance Costs.

The O&M cost is summarized in Table 6. Although media replacement did not occur during the study, the media replacement cost would represent the majority of the O&M cost. The AD-26 media has a 10-year life expectancy before replacement. At the current water use rate (i.e., 16,873,000 gallons for one year), the system would treat 169 million gallons of water in a 10-year period. Therefore, the AD-26 media replacement cost would be $0.08/1,000 gallons of water treated. The AD-33 media has a 4-year life expectancy. The estimated cost of replacing the 114 cubic feet of AD-33 media is $34,230, including the cost for media, freight, labor, travel expenses, and media disposal. This cost was used to estimate the media replacement cost per 1,000 gallons of water treated as a function of the projected media run length to the 10-μg/L arsenic breakthrough (Figure 5).

Table 6. O&M Costs

Cost Category	Value	Assumptions
Volume Processed (1,000 gallons)	16,873	Through 09/24/06
AD-26 Media Replacement and Disposal ($13,140)		
Media unit cost ($/ft^3)	150	Vendor quote
Media volume (ft^3)	57	To fill three 36-inch diameter vessels
Underbedding gravel ($)	1,040	Vendor quote
Labor ($)	1,950	Vendor quote
Freight ($)	705	Vendor quote
Waste disposal and analysis ($)	985	Vendor quote
Cost ($/1,000 gallons)	*0.08*	*10-year media life, treating 169 million gallons*
AD-33 Media Replacement and Disposal ($34,230)		
Media unit cost ($/ft^3)	260	Vendor quote
Media volume (ft^3)	114	To fill three 48-in diameter vessels
Other costs ($)	4,680	Same additional costs as AD-26 Media
Cost ($/1,000 gallons)	*See Figure 5*	
Chemical Usage		
Chemical cost ($/1,000)	0.17	Approximately $2,800 for one year
Electricity		
Power use ($/1,000 gallons)	0.001	Electrical costs assumed negligible
Labor		
Average weekly labor (hour)	2.33	20 minutes/day
Labor cost ($/1,000 gallons)	0.16	Labor rate = $21/hr
Total O&M Cost ($/1,000 gallons)	See Figure 5	0.08 + AD-33 replacement cost + 0.17 + 0.16

The cost for chlorination was approximately $2,800 or $0.17/1,000 gallons of water treated. Electrical costs were assumed to be negligible because electrical bills prior to system installation and since startup did not indicate any noticeable increase in power consumption. Under normal operating conditions, routine labor activities to operate and maintain the system consumed 20 minutes per day (2.33 hours per week). Assuming a $21 per hour rate, the estimated labor cost is $0.16/1,000 gallons of water treated.

Conclusions

The Chateau Estates demonstration project confirmed that chlorination effectively oxidized arsenic (III) and iron (II) and formed arsenic-laden particles filterable by the AD-26 media. The AD-26 system alone was capable of reducing total arsenic concentrations to less than 2.5 μg/L. Chlorination also was effective in precipitating Mn(II) without an extended contact time, converting 85 to 98% of Mn^{2+} to MnO_2 in 9 of the 13 speciation events. The AD-33 system worked as a polisher, reducing total arsenic concentrations from 2.1 μg/L to less than 0.5 μg/L.

Battelle submitted the full report in fulfillment Contract 68-C-00-185, Task Order 0029.

References

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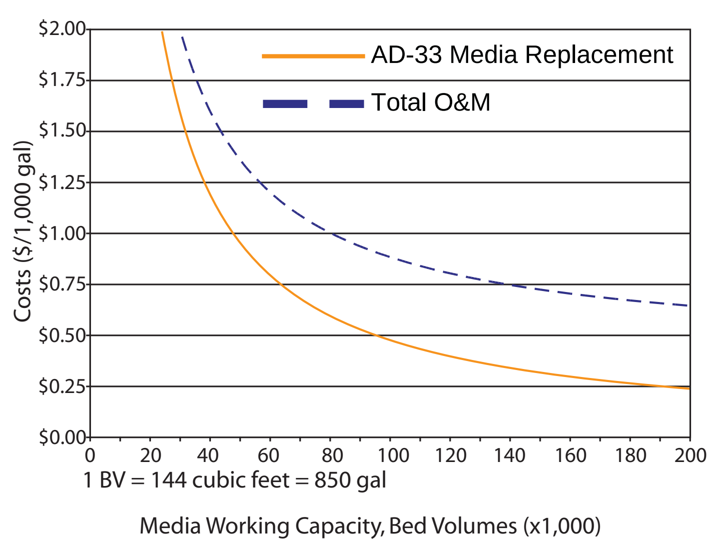

Figure 5. Media Replacement Cost Curves

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