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Arsenic/Radium Removal from Drinking Water by the HMO Process
U.S. EPA Demonstration Project at Greenville, WI

PROJECT SUMMARY

Abraham S.C. Chen, Ryan Stowe, and Lili Wang

In 2003, the town of Greenville, Wisconsin was selected for the Round 2 U.S. Environmental Protection Agency (EPA) Arsenic Demonstration Program and a Kinetico Macrolite® pressure filtration system was selected for its ability to remove arsenic. Well reconstruction prior to the planned arsenic study, however, resulted in changes in water quality that resulted in a decrease in arsenic to below the 10-µg/L maximum contaminant level (MCL) and an increase in radium to above the combined MCL of 5 pCi/L (at around 9 pCi/L). With the changes in water quality (high radium), the treatment process was modified to include the addition of hydrous manganese oxide (HMO) for radium removal. Between August 3, 2007 and April 19, 2010, system performance was evaluated in two phases. The first study conducted between August 3, 2007, and January 14, 2008, collected system operational, performance, and cost data on arsenic removal. Operational data included system pressures, flowrates, filter run lengths, and filter backwashing. Operation and maintenance (O&M) cost was tracked and analyzed per 1,000 gal of water treated. A special study that focused entirely on the system's ability to remove radium followed a year later between May 29, 2009, and April 19, 2010.

Introduction

Starting in 2003, U.S. EPA conducted an Arsenic Demonstration Program that consisted of a series of full-scale, on-site demonstration projects to remove arsenic from drinking water at 50 locations in 26 states. The goal of this program was to evaluate the performance and determine the cost (capital and operating) of the technologies demonstrated to help small drinking water systems meet the new MCL. The specific objectives of these projects were to: (1) evaluate the performance of arsenic removal technologies for use on small systems, (2) determine the required system O&M and operator skill levels, (3) characterize process residuals produced by the technologies, and (4) determine the capital and O&M cost of the technologies. The program consisted of three rounds of projects: 12 projects in Round 1, 28 projects in Round 2, and 10 projects in Round 2a.

The town of Greenville, Wisconsin was selected for the demonstration program in the second round of the program. The town had approximately 5,000 residents and their drinking water was supplied by three wells designated as Wells No. 2, 3, and 4. Well No. 2 (500 ft deep) was not used because of elevated arsenic and iron concentrations and, therefore, it was selected for the arsenic demonstration project. Well No. 2 water was first sampled on September 21, 2004, during the initial site visit by an EPA contractor, Battelle, and results of the water analyses are shown in Table 1. As shown in the table, the arsenic concentration was 34 µg/L, with the soluble fraction (12.2 µg/L) consisting of 85% As(III) and 15% As(V). The iron level was extremely high at 14.5 mg/L.

Two vendor proposals were submitted for the demonstration project from which a Kinetico proposal was selected. The Kinetico treatment system proposed for demonstration was an iron removal filtration process using Macrolite® as the filtration media. Macrolite® is a low-density, spherical, and chemically inert ceramic media designed for a high-rate filtration up to 10 gpm/ft^2. The media, originally manufactured by Kinetico, but currently marketed by Fairmont Minerals, is approved for use in drinking water applications under NSF Standard 61.

After isolating the upper section (305/308 ft) of Well No. 2, the utility conducted a 72-hr pumping test on February 25, 2005. The test results on the water samples collected at the end of the pumping test found the total arsenic concentration at 16.9 µg/L and the iron concentration at 7.8 mg/L; both values were approximately half of the levels found during the initial site visit five months earlier (September 21, 2004).

Table 1. Analytical Results of Well No. 2 Water

Parameter	Unit	Test Results		
		During Initial Visit	**During 72-hr Pump Test[(a)]**	**After Well Reconstruction**
Sampling Date (Time)		09/21/04	02/25/05 (at 71 hr)	04/06/06
pH	S.U.	7.3	NA	7.5
Temperature	°C	11	NA	NA
DO	mg/L	0.68	NA	NA
ORP	mV	-113	NA	NA
Total Alkalinity (as $CaCO_3$)	mg/L	235	NA	240
Hardness (as $CaCO_3$)	mg/L	300	240	258
Turbidity	NTU	89	NA	NA
TDS	mg/L	308	NA	320
TOC	mg/L	1.0	NA	NA
Nitrate (as N)	mg/L	<0.04	NA	0.03
Nitrite (as N)	mg/L	<0.01	NA	<0.01
Ammonia	mg/L	<0.05	NA	NA
Chloride	mg/L	3.6	NA	4.5
Fluoride	mg/L	<0.1	NA	0.17
Sulfate	mg/L	40	NA	32
Silica (as SiO_2)	mg/L	28.3	NA	NA
Orthophosphate	mg/L	<0.06	NA	NA
Phosphorus (as P)	µg/L	NA	NA	NA
As (total)	µg/L	34.0	16.9	9.7
As (soluble)	µg/L	12.2	10.8	NA
As (particulate)	µg/L	22.1	6.1	NA
As (III)	µg/L	10.4	8.8	NA
As (V)	µg/L	1.8	2.0	NA
Fe (total)	mg/L	14.5	7.8	6.2
Fe (soluble)	mg/L	7.8	7.4	NA
Mn (total)	µg/L	46	51.1	59.0
Mn (soluble)	µg/L	54	49.8	NA
U (total)	µg/L	2.9	1.2	NA
U (soluble)	µg/L	NA	1.0	NA
V (total)	µg/L	7.4	1.2	NA
V (soluble)	µg/L	NA	0.5	NA
Na (total)	mg/L	12.0	9.8	9.8
Ca (total)	mg/L	56	49.1	54.0
Mg (total)	mg/L	39	28.5	30.0
Ra-226	pCi/L	4.1	1.6	4.1
Ra-228	pCi/L	5.0	3.0	4.0

(a) Well puckered between 305 and 308 ft; samples taken by end of pump test at 71 hr.

During December 2005, the well was reconstructed to seal off an upper aquifer (St. Peter sandstone from 110 to 220 below ground surface [bgs]) to try to improve the water quality. The well was sampled on April 6, 2006, and the arsenic level was found to be 9.7 µg/L (below the arsenic MCL) and the iron level was slightly lower at 6.2 mg/L. Unfortunately, the combined radium (226 plus 228) concentration increased to 8.1 pCi/L (above the radium MCL).

Six months later in October 2006, an AquaStream sand removal device was installed because of a sediment problem. A new submersible pump was installed at the same time at 175 ft bgs. Although the arsenic concentration of Well No. 2 was now slightly below the MCL after well reconstruction, the demonstration project continued because of the high level of total radium. With the major focus now on radium removal and a minor focus on arsenic, the Macrolite® filtration system was modified slightly by including hydrous manganese oxide (HMO) addition, which is effective for radium removal. The removal of natural iron also was expected to reduce arsenic to even lower levels in the treated water.

Although treatment system installation, startup and shakedown was complete by March 9, 2007, the performance evaluation study did not begin until August 2007 because of a pipe break at the outlet end of the contact tanks caused by high system inlet pressure (~200 psi) and the failure of two safety features, i.e., a pressure relief valve and a high pressure switch. To ensure proper system operation, a variable frequency drive (VFD) was installed and the pressure relief valve was re-oriented to prevent sediment from entering the valve.

Because arsenic concentration in the well water was below the MCL, the performance evaluation study was reduced from the normal one-year demonstration period to only six months from August 2007 to early January 2008 with the focus on arsenic removal and system operation. During the six-month arsenic removal study, radium removal was monitored by the facility. A follow-up special study on radium removal by the treatment system was conducted by Battelle from May 2009 through April 2010.

System performance (arsenic) data were collected similar to the other arsenic demonstration projects. The types of data collected included system operation, water quality (both across the treatment train and in the distribution system), residuals, and capital and O&M cost. This report summarizes the activities performed during and the results obtained from the two study periods.

Materials and Methods

Arsenic Treatment System

The treatment train included prechlorination, HMO addition, adsorption/co-precipitation, and Macrolite® pressure filtration. Figure 1 shows a photograph of the treatment system and Table 2 summarizes relevant system design specifications. The major process steps and system components include:

- **Prechlorination** – The existing chlorine gas feed system was used to oxidize soluble As(III) and Fe(II) and maintain a target total chlorine residual level of 0.5 mg/L (as Cl_2). The system consisted of two 150-lb cylinders with a chlorinator unit on each cylinder, an ejector, an automatic switchover system, and a scale (to track chlorine consumption).
- **HMO Addition** – Following prechlorination, a 3% HMO (or MnO_2) pre-formed with manganese sulfate ($MnSO_4$) and potassium permanganate ($KMnO_4$) was added for radium removal. The HMO addition system consisted of a chemical feed pump, a 325-gal polyethylene chemical day tank, an overhead tank mixer, a day tank scale, and a static mixer. The target HMO level was 1.75 mg/L (as MnO_2).

Figure 1. Three Macrolite® Filters (forground) and One Contact Tank (background)

Table 2. Design Specifications for Greenville Macrolite® Pressure Filtration System

Parameter	Value	Remarks
Pretreatment		
Prechlorination Dosage (mg/L [as Cl_2])	5.5	For a target free chlorine residual of 0.5 mg/L (as Cl_2)
HMO Dosage (mg/L [as MnO_2])	1.75	Based on pilot test results from Well No. 4
Contact		
No. of Tanks	2	Arranged in parallel
Tank Size (in)	63 D × 86 H	850 gal each tank
Contact Time (min)	4.5	Based on 375-gpm design flowrate
Filtration		
No. of Vessels	3	In parallel
Vessel Size (in)	48 D × 72 H	–
Media Volume (ft^3/vessel)	25	24-in bed depth of 40/60 US standard mesh Macrolite®
Hydraulic Loading Rate (gpm/ft^2)	10	Based on 125-gpm/vessel flowrate
Differential Pressure Across Vessel (psi)	15	Across a clean bed
Hydraulic Utilization (%)	33	Typical operating time 8 hr/day
Backwash		
Initiating Pressure (psi)	25	Across bed at end of filter run
Initiating Standby Time (hr)	48	–
Initiating Service Time (hr)	24	–
Backwash Rate (gpm/ft^2)	8–10	100 to 125 gpm
Minimum Backwash Time (min)	5	–
Maximum Backwash Time (min)	18	–
Turbidity Set Point (NTU)	20	To terminate backwash

- **Adsorption/Co-precipitation** – The pretreated water passed through two 850-gal fiberglass reinforced plastic (FRP) tanks configured in parallel for 4.5 min of contact time based on a peak flowrate of 375 gpm.

- **Pressure Filtration** – Pressure filtration involved downflow filtration through three 150 psi-rated FRP vessels arranged in parallel. The vessels were floor mounted and piped to a valve rack on a stainless steel frame. Each filtration vessel was filled with 24 in (or 25 ft^3) of 40/60 U.S. standard mesh Macrolite® media underlain by 30/40 U.S. standard mesh garnet fill. The flow through each vessel was regulated to 125 gpm, yielding a filtration rate of 10-gpm/ft^2.

  Filter backwashing was triggered by a 25-psi pressure drop, a 24-hr service time, or a 48-hr standby time. The filters were backwashed one at a time. To begin a backwash, water in a filter was drained and the filter was air sparged for 4 min. After settling for 5 min, the filter was backwashed with treated water at 100 to 125 gpm (8 to 10 gpm/ft^2) until the turbidity of backwash wastewater had reached a target threshold level of 20 nephelometric turbidity units (NTU). The filter then underwent a filter-to-waste rinse for 3 min before returning to service. Wastewater was sent to a 3,000 gal equalization tank and then the sanitary sewer.

- **Post-treatment** –Sodium silicate was applied for corrosion control at a target dosage of 2.6 mg/L (as NaSi) and fluoride was added at a target dosage of 0.88 mg/L (as F).

The system engineering package, prepared by the town's engineer, Earth Tech, was submitted to the Wisconsin Department of Natural Resources (WDNR) on November 7, 2005, and a system construction permit was issued by WDNR on March 8, 2006. A supplemental submittal on HMO addition was filed on November 8, 2006, and the approval was granted on November 20, 2006. Installation of the system by Kinetico began on October 23, 2006, after successful AquaStream installation and well development. All system startup and shakedown activities were complete by March 9, 2007.

System O&M and Cost Data Collection

The plant operator performed daily, weekly, and monthly system O&M and data collection. On a regular basis, the plant operator recorded system operational data such as pressure, flowrate, totalizer, and hour meter readings and conducted visual inspections to ensure normal system operations. In case of problems, the plant operator contacted Battelle and/or the vendor for troubleshooting and corrective actions. The capital cost for the system consisted of the cost for equipment, site engineering, and installation. The O&M cost consisted of the cost of chemical supplies, electricity, and labor. The operator tracked labor for routine system O&M, troubleshooting, and repairs. The demonstration-related work was recorded, but not used for cost analysis.

Sample Collection and Analyses

During the six-month arsenic removal study from August 13, 2007, through January 14, 2008, eight sets of water samples were collected. Each set consisted of samples from three locations of the treatment plant (see Figure 2): (1) influent source water (IN), (2) after contact tanks (AC) and, (3) the combined effluent from the three filters (TT). Water samples were analyzed onsite for pH, temperature, and dissolved oxygen. Water samples sent to the Battelle laboratory were analyzed for total alkalinity, hardness, turbidity, nitrate, fluoride, sulfate, silica, phosphorus, arsenic, iron, and manganese. In addition, four sets of the samples were speciated for arsenic (particulate, dissolved, As[III] and As[V]) and for total and soluble iron and manganese.

Each month for four months, a filter backwash wastewater sample was collected from a side stream of each filter's wastewater discharge line over the duration of a backwash. These backwash water samples

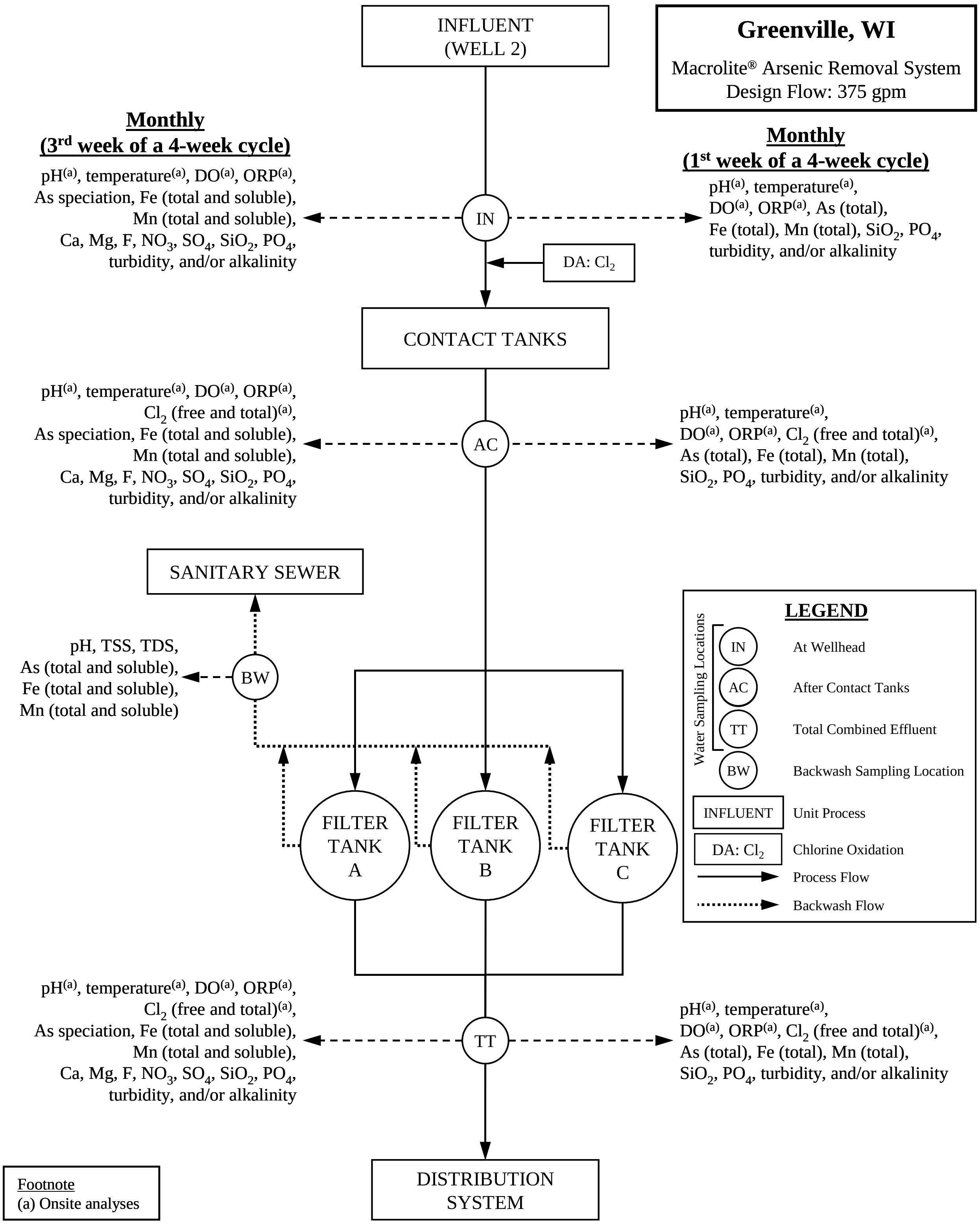

Figure 2. Process Flow Diagram and Sampling Schedules

(12) were analyzed for pH, total suspended solids (TSS), total dissolved solids (TDS), total arsenic, iron and manganese, and soluble arsenic, iron and manganese. All backwash wastewater was discharged to the town's sewer system.

Four sets of weekly baseline distribution system water samples were collected before system startup from two residences within the town's historic Lead and Copper Rule (LCR) sampling network and one non-LCR residence. Following system startup, four monthly samples were collected from the same three locations to determine the impact of the arsenic treatment system on the water quality in the distribution system. Sampling followed an instruction sheet developed in accordance with the *LCR Monitoring and Reporting Guidance for Public Water Systems* (EPA, 2002). These distribution water samples were analyzed for pH, alkalinity, arsenic, iron, manages, lead and copper.

During the one-year special radium removal study from May 2009 through April 2010, only monthly radium samples were collected and analyzed by Battelle.

All relevant sampling logistics for preparation of arsenic speciation kits, sample containers, sample coolers, and sample shipping and handling, as well as specific requirements for analytical methods, sample volumes, containers, preservation, and holding times were addressed in an EPA-endorsed Quality Assurance Project Plan (QAPP) (Battelle, 2004).

Results

System Operation

From August 3, 2007, through January 14, 2008, the system operated for a total of 625 hr during the 162 days (less 3 days when the system was taken offline due to a leak on the backwash discharge line), treating approximately 10,830,000 gal of water. During this time period, daily run time averaged 3.9 hr/day and the average daily water demand was 66,852 gal/day (gpd). System instantaneous flowrates ranged from 197 to 347 gpm and averaged 285 gpm, compared to the 289-gpm average flowrate calculated based on the total water production and total system run time. The system design flowrate was 375 gpm. Average chlorine and HMO dose rates were 3.7 mg/L (as Cl_2) and 1.7 mg/L (as MnO_2), respectively, compared to the target dose rates of 5.5 mg/L (as Cl_2) and 1.75 mg/L (as MnO_2), respectively. The target chlorine dose rate was calculated based on 6.2 mg/L of soluble Fe(II), which was much higher than the 2.0 mg/L (on average) measured during the performance evaluation study. The system was backwashed for a total of 112 times, equivalent to 0.7 time/day (or 0 to 2 time/day). Because the average daily run time was 3.9 hr/day, the average filter run length was 5.6 hr.

The system was fully automated with an operator interface, programmable logic controller (PLC), and modem housed in a central control panel. The control panel was connected to various instruments used to track system performance, including inlet and outlet pressure for each filter, system flowrate, backwash flowrate, and backwash turbidity. All major functions of the treatment system were automated and required only minimal operator oversight and intervention if all functions were 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 approximately 2 hr to visually inspect the system, record the operating parameters on the log sheets, and collect and analyze water samples. The operator also performed O&M activities such as monitoring backwash operational issues and working with the vendor to troubleshoot and perform minor on-site repairs.

System Performance

Arsenic, Iron, and Manganese Removal. Figures 3 and 4 present arsenic and iron test results, respectively, conducted on the sets of water samples collected across the treatment train during the arsenic removal study. The Well No. 2 source water contained 4.8 to 7.0 µg/L of total arsenic, existing mostly as soluble As(III). The well water also had 1.8 to 2.3 mg/L of total iron and 29.4 to 32.6 µg/L of total manganese, existing almost entirely in soluble form. With the addition of chlorine at a pH value of 7.3 (on average), arsenic was converted to mostly particulate arsenic, which was removed by the Macrolite® filters to below 1.4 µg/L. Total iron concentrations also were reduced to just above the MCL of 25 µg/L by the filters. The highest iron concentration measured in the filter effluent was 100 µg/L, indicating some iron breakthrough from the filters. Table 3 provides ranges and averages of all test results conducted on the water samples.

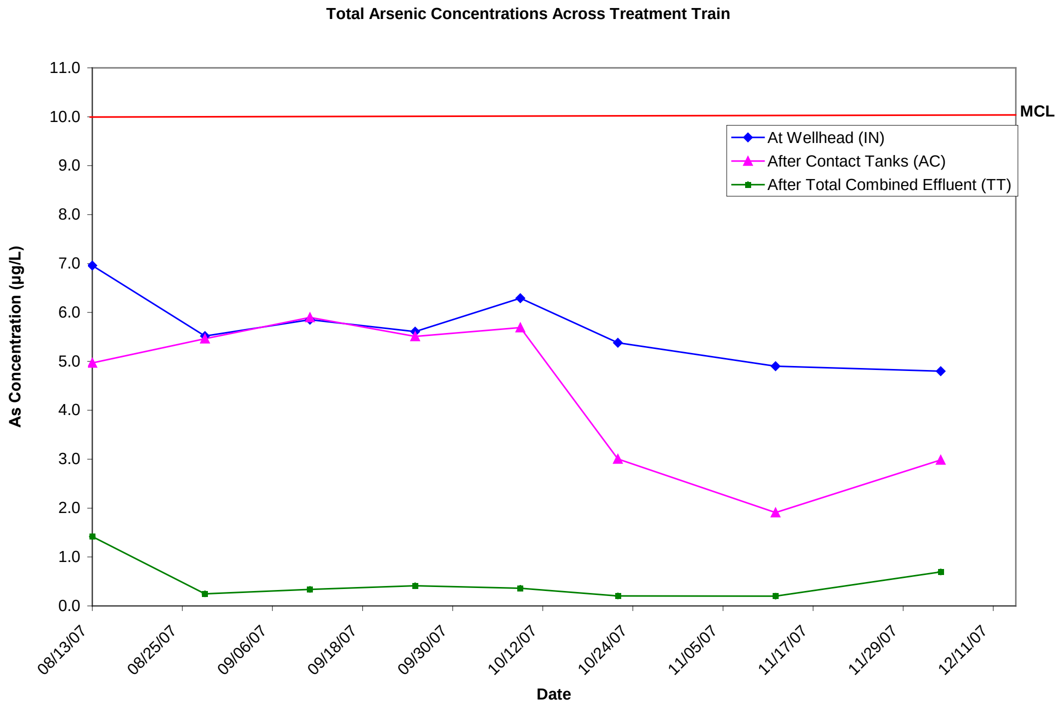

Figure 3. Total Arsenic Concentrations Across Treatment Train

After prechlorination, HMO addition, and the contact tanks, average total manganese concentrations increased from 30.6 to 399 µg/L (excluding two outliers on September 11 and 25, 2007, with unusually low manganese levels after HMO addition) due to HMO addition. Total manganese concentrations were reduced to 7.7 µg/L after Macrolite® filtration, indicating little manganese breakthrough from the filters even with the combined loading of iron and HMO solids.

Radium Removal. After Well No. 2 reconstruction, radium levels in source water increased up to 9.0 pCi/L. With HMO addition to the filtration process, the total radium level decreased to 3.2 pCi/L. After this initial confirmation by Battelle, the facility assumed the responsibility for radium sampling and analysis up until the special study conducted about two years later. The data collected by the facility from July 2007 through January 2008 ranged 2.1 to 3.4 pCi/L and averaged 2.9 pCi/L.

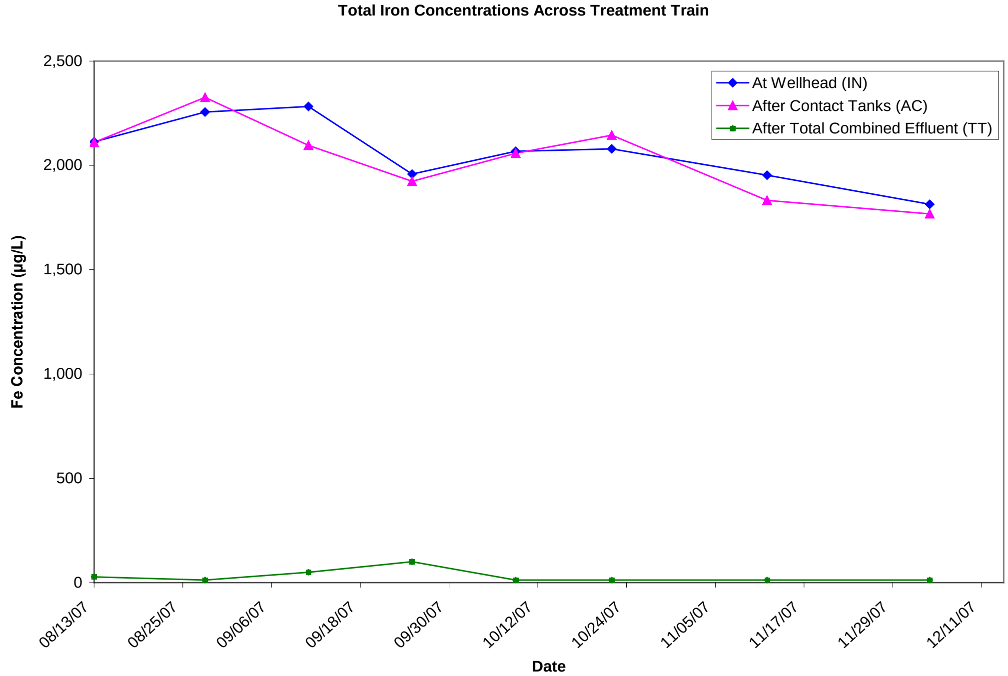

Figure 4. Total Iron Concentrations Across Treatment Train

Table 3. Summary of Test Results on Samples Collected During Arsenic Removal Study from August 3, 2007, Through January 14, 2008

Parameter	Unit	Source Water Range (Average)	After Contact Tanks Range (Average)	After Filters Range (Average)
pH	S.U.	7.2–7.4 (7.3)	7.1–7.3 (7.2)	7.1–7.3 (7.2)
Temperature	°C	10.8–18.5 (14.5)	11.0–18.6 (14.1)	10.9–18.6 (14.5)
DO	mg/L	1.4–2.6 (1.9)	1.3–2.5 (1.7)	1.2–2.1 (1.7)
Total Alkalinity[(a)]	mg/L	271–297 (281)	265–294 (277)	266–302 (276)
Hardness[(a)]	mg/L	295–366 (314)	273–389 (317)	267–386 (315)
Turbidity	NTU	26.0–36.0 (30.2)	1.8–13.0 (6.2)	0.4–1.6 (0.8)
Nitrate (as N)	mg/L	<0.05–0.8 (0.2)	<0.05 (<0.05)	<0.05–0.4 (0.1)
Fluoride	mg/L	0.2–0.3 (0.3)	0.2–0.5 (0.3)	0.2–0.6 (0.3)
Sulfate	mg/L	16.0–17.0 (17.0)	17.0–22.0 (19.3)	17.0–23.0 (19.8)
Silica (as SiO_2)	mg/L	12.3–13.6 (13.1)	12.7–13.6 (13.0)	12.0–29.0 (15.3)
Phosphorus (as P)	µg/L	18.5–49.5 (33.4)	19.8–46.2 (31.6)	<10 (<10)
As (total)	µg/L	4.8–7.0 (5.7)	1.9–5.9 (4.4)	0.2–1.4 (0.5)
As (soluble)	µg/L	4.0–5.2 (4.7)	0.2–0.4 (0.3)	0.1–0.2 (0.2)
As (particulate)	µg/L	0.4–1.1 (0.8)	1.5–5.7 (3.8)	<0.1–0.5 (0.2)
As (III)	µg/L	3.0–4.8 (4.1)	0.1–0.3 (0.2)	<0.1–0.3 (0.1)
As (V)	µg/L	0.3–1.0 (0.6)	<0.1–0.2 (<0.1)	<0.1 (<0.1)
Fe (total)	mg/L	1.8–2.3 (2.1)	1.8–2.3 (2.0)	<0.025–0.1 (0.028)
Fe (soluble)	mg/L	1.8–2.2 (2.0)	<0.025–0.064 (0.025)	<0.025 (<0.025)
Mn (total)	µg/L	29.4–32.6 (30.6)	28.9–798 (318)	0.8–22.3 (7.7)
Mn (soluble)	µg/L	27.7–29.5 (28.5)	2.1–7.6 (5.3)	0.3–2.3 (1.4)
Ca (total)	mg/L	53.6–62.4 (57.2)	54.4–64.8 (58.0)	50.8–65.6 (56.8)
Mg (total)	mg/L	33.3–51.2 (41.5)	33.3–55.1 (41.7)	32.3–53.9 (42.0)

(a) as $CaCO_3$.

A special follow-up radium removal study was conducted on the treatment system by Battelle that consisted of colleting 11 effluent sample from May 2009 through April 2010. Table 4 presents analytical results of this special study.

Table 4. Radium Test Results, May, 2009 – April, 2010

Date	Ra-226 (pCi/L)			Ra-228 (pCi/L)			*Total Radium*[(a)] *at TT* (pCi/L)
Location	**IN**	**AC**	**TT**	**IN**	**AC**	**TT**	
05/29/09	6.1	5.2	3.0	4.1	3.4	1.3	4.3
06/30/09	6.2	5.2	4.2	3.5	4.2	1.8	6.0
07/29/09	5.0	5.0	3.2	3.9	4.3	2.6	5.7
08/25/09	7.5	5.8	0.3	4.2	4.0	3.0	3.3
09/24/09	6.3	6.1	3.2	4.2	4.0	3.0	6.2
10/26/09	8.6	8.0	5.1	3.6	3.8	2.3	7.4
11/24/09	6.8	7.1	6.7	3.1	4.5	2.5	9.1
01/05/10	6.2	5.1	1.8	2.1	2.0	0.5	2.3
02/10/10	9.5	7.5	1.4	3.4	3.4	1.1	2.5
03/17/10	5.9	2.9	2.3	3.2	1.9	1.7	4.0
04/19/10	7.3	7.8	0.8	2.9	2.2	0.4	1.3
Average	**6.8**	**5.8**	**3.1**	**3.5**	**3.4**	**2.0**	**4.7**

(a) Combined Ra-226 and Ra-228 in pCi/L.

Ra-226 levels in raw water ranged from 5.0 to 9.5 pCi/L and averaged 6.8 pCi/L while Ra-228 levels were slightly lower, ranging from 2.1 to 4.2 pCi/L and averaging 3.5 pCi/L. Both Ra-226 and 228 levels remained relatively unchanged after HMO additions at the AC sample location. After filtration, levels in the treated water ranged from 0.3 to 6.7 pCi/L for Ra-226 and from 0.4 to 3.0 pCi/L for Ra-228. Average radium levels in the treated water were 3.1 and 2.0 pCi/L for Ra-226 and Ra-228, respectively.

The HMO target dosage was 1.75 mg/L (as MnO_2). In order for the dosing pumps to work properly, the HMO solution had to be diluted, which resulted in a lower feed rate. The lower feed rate led to a decrease in radium removal and an increase in total radium levels to above 5 pCi/L on five of the first seven sampling occasions during the study period. In December 2009, the town hired a local engineering firm to check the HMO feed rate and dosage. The firm discovered that the actual dosage (i.e., 0.5 to 0.7 mg/L [as MnO_2]) was lower than the target dosage to achieve the required total radium removal and increased the dosage to approximately 1.0 mg/L (as MnO_2) in January 2010. After the increase in the HMO dosage, total radium levels in the filter effluent were reduced to 1.3 to 4.0 pCi/L. However, addition of HMO at 1.0 mg/L (as MnO_2) added extra loading to the filters, causing solids to breakthrough from the filters prematurely.

Backwashing. Table 5 summarizes the data collected on filter backwash times and backwash water quantity produced under the field settings. Backwash flowrates averaged 83 gpm or 6.6 gpm/ft^2, which is lower than the 8 to 10 gpm/ft^2 design value.

Table 5. Summary of Backwash Parameters

Backwash Parameters	Minimum	Maximum	Average
Backwash Duration (min/vessel)	8	18	11
Backwash Flowrate (gpm/vessel)	78	87	83
Water Quantity Generated (gal/vessel)	749	1260	899
Hydraulic Loading (gal/ft^2)	6.2	6.9	6.6

Table 6 summarizes analytical results of backwash sampling. As expected, total arsenic, iron, and manganese existed mainly in the particulate form. Assuming a TSS level of 278 mg/L and a total wastewater production volume of 2,700 gal per backwash event, 2,840 g of solids, consisting of 0.7 g, 742g, 104 g of arsenic, iron, and manganese would have been produced and discharged to the sewer.

Table 6. Backwash Water Sampling Results

Parameter	Unit	Range (Average)
pH	S.U.	7.4–7.5 (7.4)
Total Suspended Solids (TSS)	mg/L	196–384 (272)
Total Dissolved Solids (TDS)	mg/L	268–296 (278)
As (total)	µg/L	24.5–149 (70.4)
As (soluble)	µg/L	0.1–0.6 (0.3)
Fe (total)	mg/L	38.8–118 (72.6)
Fe (soluble)	mg/L	<25–113 (32.5)
Mn (total)	µg/L	5,912–14,820 (10,175)
Mn (soluble)	µg/L	0.5–26.3 (8.8)

Note: One-half of detection limit used for non-detect samples for calculation.

Distribution Water. Table 7 presents distribution system water sampling results. Arsenic concentrations in the distribution system baseline samples collected prior to startup of the treatment system averaged 1.3 µg/L. Because the distribution samples were collected prior to the completion of Well No. 2 reconstruction, the water samples represented the water from Wells No. 3 and/or 4 that contained little arsenic. After system startup, arsenic levels in the distribution system averaged 1.3 µg/L, which is slightly higher than the 0.5 µg/L level in the filter effluent. Iron levels in the distribution after system startup were mostly below the MCL of 25 µg/L with one outlier as high as 138 µg/L. Manganese levels in the distribution system samples decreased from an average baseline level of 1.9 µg/L to 1.5 µg/L after system startup. The use of HMO apparently did not impart manganese to the distribution water. System operation appeared to slightly elevate copper and lead concentrations from the baseline levels. Lead concentration increased from 3.6 µg/L to 7.2 µg/L after startup, while copper levels increased from 144 to 163 µg/L.

System Cost

Capital Cost. Capital investment for the Greenville system was $332,584, including $196,542 for equipment, $48,057 for site engineering, and $87,985 for system installation, shakedown, and startup. The total capital cost, not including the HMO addition system, was normalized to the system's rated capacity of 375 gpm (540,000 gpd), which resulted in $886.89 per gpm ($0.62 per gpd). The total capital cost was converted to an annualized cost of $31,392.60/yr using a capital recovery factor of 0.09439 based on a 7 percent interest rate and a 20-year return period. Assuming that the system operates 24 hr a day, 7 days a week, at the system design flowrate of 375 gpm, the unit capital cost would be $0.16/1,000 gal of water treated. The system operated at 289 gpm for 3.9 hr/day (on average) and would have produced an estimated 24,683,500 gal of water in a year. At this reduced usage rate, the unit capital cost was increased to $1.27/1,000 gal.

Operation and Maintenance Cost. The O&M cost included expenditures associated with electricity and labor. Because the system was under warranty during the five-month study period, no cost was incurred

Table 7. Distribution System Sampling Results

Sampling No.	Date	Stagnation Time	pH	Alkalinity	As	Fe	Mn	Pb	Cu
		hr	S.U.	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L
DS1 (Non-LCR Residence)									
BL1	02/21/06	8.5	7.4	311	0.5	<25	11.3	2.9	56.4
BL2	02/28/06	8.2	7.5	321	0.5	<25	2.8	1.2	27.7
BL3	03/07/06	8.7	7.6	319	0.5	<25	2.2	1.6	54.1
BL4	03/15/06	8.2	7.5	310	0.2	<25	1.3	1.7	95.3
	Average	8.4	7.5	315	0.4	<25	4.4	1.9	58.4
1	09/25/07	9.3	7.4	314	0.3	<25	2.0	10.0	206
2	10/09/07	9.3	7.5	299	0.4	<25	1.5	11.7	214
3	11/06/07	9.0	7.5	306	0.2	<25	0.8	3.6	183
4	12/04/07	9.5	7.6	308	0.4	<25	0.6	1.8	111
	Average	9.3	7.5	307	0.3	<25	1.2	6.8	178
DS2 (LCR Residence)									
BL1	02/21/06	14.0	7.7	323	1.8	<25	0.8	5.2	287
BL2	02/28/06	14.5	7.6	329	2.1	<25	1.7	1.5	40.3
BL3	03/07/06	15.3	7.7	328	2.0	<25	2.3	1.5	38.3
BL4	03/15/06	13.8	7.8	338	1.1	<25	0.4	20.7	487
	Average	14.4	7.7	330	1.7	<25	1.3	7.2	214
1	09/25/07	14.0	7.4	352	2.0	<25	0.9	6.7	95.4
2	10/09/07	14.5	7.5	325	2.1	<25	1.6	6.7	86.3
3	11/06/07	14.0	7.6	327	1.7	<25	1.8	5.7	125
4	12/04/07	14.0	7.9	324	2.0	28.1	2.6	5.6	89.5
	Average	14.1	7.6	332	1.9	16.4	1.7	6.2	99.0
DS3 (LCR Residence)									
BL1	02/21/06	7.5	7.7	328	1.9	<25	<0.1	1.5	141
BL2	02/28/06	7.6	7.7	333	1.9	<25	<0.1	1.1	132
BL3	03/07/06	8.0	7.7	328	1.8	<25	<0.1	1.1	154
BL4	03/15/06	8.5	7.7	338	1.1	<25	<0.1	3.3	210
	Average	7.9	7.7	332	1.7	<25	<0.1	1.7	159
1	09/25/07	7.8	7.5	348	1.7	<25	<0.1	8.7	222
2	10/09/07	8.0	7.5	305	2.1	138	5.0	16.8	231
3	11/06/07	8.0	7.7	329	1.9	34.4	1.2	4.0	204
4	12/04/07	8.0	7.7	325	1.7	27.4	0.5	4.9	186
	Average	7.9	7.6	327	1.8	70.8	1.7	8.6	211
Overall Baseline Ave.		10.2	7.6	326	1.3	<25	1.9	3.6	144
Overall Sampling Ave.		10.4	7.6	322	1.3	33.2	1.5	7.2	163

for repairs. Chlorination was performed prior to the demonstration study so the incremental cost for the gas chlorination system was negligible. Pre-formed HMO was funded, in part, by the facility and since HMO addition was not part of the original system design, the associated cost was not included for the cost analysis. The incremental power cost was estimated based on the change in electric utility bills for a five-month period before and after system startup and did not include natural gas cost to heat the building. The power cost was estimated to be $0.03/1,000 gal of water treated (assuming an annual production of 24,401,000 gal). Under normal operating conditions, the skill requirements to operate the system were minimal, with a typical daily demand on the operator of 2 hr over a 5-day workweek. Based on this time commitment and a labor rate of $24/hr, the labor cost was $0.51/1,000 gal of water treated. Therefore, the total O&M cost was $0.54/1,000 gal.

Conclusions

The Greenville, Wisconsin demonstration project showed that the Macrolite® pressure filtration system was capable of reducing arsenic concentrations in source water from around 6 μg/L to less than 0.5 μg/L with iron levels in the source water of around 2 mg/L. With the addition of HMO, the filtration system also was found effective in reducing total radium to below 5 pCi/L using a proper HMO dosage. If the proper dosage is not maintained, radium levels in the system effluent can increase above the radium MCL of 5 pCi/L. Added loadings from HMO addition can cause solids to breakthrough from the filters prematurely, making it difficult to maintain sustainable system operation. The treatment system did not appear to have any significant detrimental impact on the levels of copper or lead in distribution water.

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