

**Arsenic Removal from Drinking Water
by Iron Removal and Adsorptive Media
U.S. EPA Demonstration Project at Stewart, MN
Six-Month Evaluation Report**

by

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Sally Gutierrez, Director
National Risk Management Research Laboratory

ABSTRACT

This report documents the activities performed and the results obtained from the first six months of the EPA arsenic removal technology demonstration project at the Stewart, MN facility. The main objective of the project is to evaluate the effectiveness of Siemens' Type II AERALATER[®] system for iron removal and AdEdge Technologies' Arsenic Package Unit (APU)-300 system for subsequent arsenic removal. The effectiveness is evaluated based on the system's ability to remove arsenic to below the new arsenic maximum contaminant level (MCL) of 10 µg/L. Further, this project also 1) evaluates the reliability of the treatment system for use at small water facilities, 2) determines the required system operation and maintenance (O&M) and operator skill levels, 3) characterizes process residuals generated by the treatment process, and 4) determines the capital and O&M cost of the technology. 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 cost.

The 250-gal/min (gpm) treatment system consists of an AERALATER[®] pretreatment unit and an APU-300 arsenic removal unit. Used for iron removal, the 11-ft diameter × 26-ft carbon steel AERALATER[®] package unit is composed of an aeration tower, a detention tank, and a four-cell gravity filter in one stacked circular configuration. The effluent from the gravity filter is subsequently polished with AD-33 media, an iron-based adsorptive media developed by Bayer AG for arsenic removal. The APU-300 system consists of two skid-mounted 63-in × 86-in fiberglass vessels configured in parallel. Each vessel contains 64 ft³ of pelletized AD-33 media supported by gravel underbedding.

The treatment system began routine operation on January 18, 2006. Through the period from January 30 to August 1, 2006, the system treated approximately 10,039,000 gal of water with an average run time of 4.9 hr/day. The average daily demand was 54,822 gal with the peak daily demand of 126,779 gal occurring on July 12, 2006. Water to the treatment system was supplied by two wells (i.e., Wells No. 3 and 4) each operating at an average flowrate of 194 and 184 gpm, respectively, on an alternating basis. These reduced flowrates resulted in longer contact times (i.e., 44 to 46 min versus the design value of 34 min) within the AERALATER[®] detention tank and lower hydraulic loading rates (i.e., 1.9 to 2.0 gpm/ft² versus the design value of 2.6 gpm/ft²) to the gravity filter. The corresponding flowrates measured through the APU-300 system also resulted in longer empty bed contact time (EBCT) (i.e., 4.6 to 6.8 min compared to the design value of 3.8 min) in each vessel. No significant operational or mechanical issues were experienced during the six-month study period.

The source water contained 35.5 to 56.4 µg/L of total arsenic, with As(III) at an average concentration of 34.9 µg/L as the predominant species. With NaMnO₄ addition prior to aeration (based on February 2, 2006 data), most As(III) was oxidized to As(V), which, along with the pre-existing As(V), was partially adsorbed onto and co-precipitated with iron solids also formed during this preoxidation step, resulting in 57% As(V) removal. The arsenic-laden iron solids were effectively removed by the gravity filter, achieving approximately 60% total arsenic and 100% total iron removal. The untreated arsenic was present mostly as As(V) at 17.2 µg/L, which was subsequently removed by the AD-33 media during the polishing step. The higher-than-expected amount of As(V) in the gravity filter effluent was thought to have been caused by the relatively high levels of pH, competing anions (such as phosphorous and silica), and total organic carbon in source water.

NaMnO₄ addition was inadvertently discontinued after one week of operation due to problems with the chemical feed pump. Total arsenic removal was 34% and the iron removal rate 100% across the gravity filter. The oxidation of Fe(II) was accomplished through aeration. It was also observed that the oxidation of As(III) to As(V) was occurring at a rate of over 95% across the gravity filter due to natural biological processes with only 1.2 µg/L of As(III) in the filter effluent. The As(V) concentration averaged 24.5

µg/L after the gravity filter. Nitrification was also observed to within the gravity filter, but was not related to the microbially-mediated As(III) oxidation as noted in this report.

In both cases, the levels of As(V) remained above 10 µg/L in the gravity filter effluent, which required further polishing in the APU-300 unit. Through 10,900 bed volume (BV), the effluent arsenic concentration averaged 3.1 µg/L in the APU-300 effluent.

Comparison of the distribution system sampling results before and after system startup showed a significant decrease in arsenic concentration from an average of 31.2 to 5.5 µg/L. However, the average arsenic concentration in the distribution system at 5.5 µg/L was higher than the average arsenic concentration of 0.9 µg/L following the AD-33 adsorption vessels. Iron and manganese also were significantly reduced in the distribution system.

AERALATER[®] backwash was manually initiated by the operator on a weekly basis. The APU-300 system was backwashed manually on two occasions during the six-month study period. Approximately 168,900 gal of wastewater, or 1.7% of the quantity of the treated water, was generated during the first six months from the AERALATER[®]. The AERALATER[®] backwash water contained, on average, 108 mg/L of total suspended solids (TSS), 46 mg/L of iron, 415 µg/L of arsenic, and 68 µg/L of manganese with the majority existing as particulate. The average amount of solids discharged per backwash cycle was approximately 6.1 lb, which was composed of 2.6 lb of elemental iron, 0.004 lb of elemental manganese, and 0.02 lb of elemental arsenic. In addition, 13,472 gal of wastewater were generated by the APU-300 unit or 0.1% of the quantity of treated water.

The capital investment for the system was \$367,838, consisting of \$273,873 for equipment, \$16,520 for site engineering, and \$77,445 for installation, shakedown, and startup. Using the system's rated capacity of 250 gpm or 360,000 gal/day (gpd), the capital cost was \$1,471 per gpm of design capacity (\$1.02/gpd). This calculation did not include the cost of the building to house the treatment system. The O&M cost consisted primarily of the media replacement cost, which was estimated by the vendor at \$41,370 to change out the AD-33 media. The O&M cost is presented as a function of potential media run length and will be refined in the Final Evaluation Report once the actual bed volumes to breakthrough become available.

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ABBREVIATIONS AND ACRONYMS

AAL	American Analytical Laboratories
Al	aluminum
AM	adsorptive media
APU	arsenic package unit
As	arsenic
bgs	below ground surface
BV	bed volume(s)
Ca	calcium
CAOs	chemolithoautotrophic arsenite oxidizers
C/F	coagulation/filtration
Cl	chlorine
CRF	capital recovery factor
Cu	copper
DBP	disinfection by-products
DO	dissolved oxygen
DOM	dissolved organic matter
EBCT	empty bed contact time
EPA	U.S. Environmental Protection Agency
F	fluoride
Fe	iron
FedEx	Federal Express
GCSP	Greene County Southern Plant
GFH	granular ferric hydroxide
gpd	gallons per day
gpm	gallons per minute
gph	gallons per hour
HAA5	haloacetic acids
HAO	heterotrophic arsenite oxidizers
H ₂ SO ₄	sulfuric acid
hp	horsepower
ICP-MS	inductively coupled plasma-mass spectrometry
ID	identification
IX	ion exchange
kgal	kilo gallons
LCR	(EPA) Lead and Copper Rule

MCL	maximum contaminant level
MDH	Minnesota Department of Health
MDL	method detection limit
Mg	magnesium
µm	micrometer
Mn	manganese
mV	millivolts
Na	sodium
NA	not applicable
ND	not detected
NS	not sampled
NSF	NSF International
NTU	nephelometric turbidity units
O&M	operation and maintenance
OIT	Oregon Institute of Technology
ORD	Office of Research and Development
ORP	oxidation-reduction potential
P&ID	process and instrumentation diagram
Pb	lead
pCi	pico curie
psi	pounds per square inch
PLC	programmable logic controller
PO ₄	orthophosphate
POE	point-of-entry
POU	point-of-use
PVC	polyvinyl chloride
QA	quality assurance
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RO	reverse osmosis
RPD	relative percent difference
Sb	antimony
SDWA	Safe Drinking Water Act
SiO ₂	silica
SMCL	secondary maximum contaminant level
SO ₄	sulfate
STS	Severn Trent Services
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids
THM	trihalomethanes
TOC	total organic carbon
TSS	total suspended solids
V	vanadium
VOC	volatile organic compound

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1.0 INTRODUCTION

1.1 Background

The Safe Drinking Water Act (SDWA) mandates that 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 requires 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 be the host sites for 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 from 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. As of March 2007, 11 of the 12 systems have been operational and the performance evaluation study for seven systems has been completed.

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 at the City of Stewart in Minnesota was one of those selected.

In September 2003, EPA 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. Two technologies were selected for demonstration at the Stewart, MN facility including Siemens' (formerly known as USFilter) Type II AERALATER® for iron removal followed by AdEdge Technologies' AD-33 adsorptive media for arsenic removal.

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 costs 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 Siemens' Type II AERALATER[®] and AdEdge Arsenic Package Unit (APU)-300 systems at Stewart, MN during the first six months from February 2 through August 1, 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 Round 1 and Round 2 Arsenic Removal Demonstration Locations, Technologies, and Source Water Quality

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)	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

The Siemens' AERALATER[®] and AdEdge Technologies' AD-33 APU-300 units were installed and operated at Stewart, MN since January 18, 2006. Based on the information collected during the first six months of operation, a summary of the system performance and the preliminary conclusions are provided as follows:

Performance of the arsenic removal technology:

- The aeration step in the AERALATER[®] unit was effective in oxidizing soluble iron, converting 100% of the soluble iron to iron solids. Aeration, however, was only minimally effective in oxidizing As(III), converting less than 26% (on average) of As(III) to As(V).
- NaMnO₄, added as an oxidant prior to aeration, effectively oxidized As(III), converting over 90% of As(III) to As(V). Of the As(V) in the contact section of the AERALATER[®], only 57% became attached to the iron solids formed during the preoxidation step, presumably via adsorption and co-precipitation. The relatively low As(V) removal rate was probably the result of the relatively elevated pH (i.e., 8.2), competing anions (such as 1.0 mg/L of total phosphorous [as PO₄] and 27.6 mg/L of Si [as SiO₂]) and total organic carbon (i.e., 6.7 mg/L) in raw water.
- Without the addition of NaMnO₄, over 95% of As(III) was oxidized to As(V) within the AERALATER[®] filter, presumably, via microbial-mediated natural pathways, leaving only 1.2 µg/L of As(III) in the filter effluent. Nitrification also occurred within the gravity filter and AD-33 adsorption vessels about 69 days after system startup. Because As(III) oxidation was observed within 40 days of system startup, it was very likely that oxygen, instead of nitrate, was the electron acceptor for the microbial-mediated As(III) oxidation process. This speculation was supported by the observation that over 47% of DO was consumed across the gravity filter soon after the system startup, with average concentrations decreasing from 5.3 mg/L in the filter influent to 2.8 mg/L in the filter effluent. A separate study conducted at Battelle using filtered groundwater and filter media obtained from the Greene County Southern Plant in Beaver Creek, OH that also demonstrated co-occurrence of As(III) oxidation and nitrification across its sand filters, indicated that nitrification might not be linked directly to As(III) oxidation and that some arsenite oxidizers most likely were responsible for the oxidation process observed.
- The As(V) formed in the filter via natural pathways was partially removed by adsorbing to the pre-formed iron particles in the filter. The average removal rate was 28%, which was much lower than the 57% As(V) removal rate observed during the preoxidation step. This observation further confirms that oxidation of iron and arsenic must occur at the same time in order to achieve good arsenic removal.
- The AERALATER[®] filter was highly effective in removing particulate matter. Without NaMnO₄ addition, 34% of total arsenic was removed, compared to 60% removed with the use of NaMnO₄ in the preoxidation step. Aeration alone in the AERALATER[®] system was sufficient to accomplish complete iron removal. No particulate iron breakthrough was observed from the AERALATER[®] filter, suggesting adequate filter backwash frequency.
- Out of the 27.0 µg/L of total arsenic (on average) in the AERALATER[®] filter effluent, 23.4 µg/L was present as As(V) and 1.2 µg/L as As(III). Arsenic was subsequently removed in the polishing step by the AD-33 media. After approximately 10,900 BV of throughput, total arsenic concentrations in the adsorption vessel effluent averaged 3.1 µg/L. Because of the high As(V) concentrations observed in the filter effluent, further studies are needed to

determine if preoxidation and even supplemental iron addition would be warranted when considering the overall O&M cost – that is, the cost associated with preoxidation, iron addition, and media replacement for a longer AD-33 run length versus that with media replacement for a shorter AD-33 run length.

- The treatment system has improved water quality in the distribution system. A considerable decrease was observed in arsenic (from 31.2 to 5.5 µg/L), iron (from 376 to 56 µg/L), and manganese (from 2.2 to 0.1 µg/L) concentrations in distribution system water before and after the system startup. However, arsenic concentrations were slightly higher in the distribution system than in the treatment plant effluent that may have been the result of solubilization, destabilization, and/or desorption of arsenic from pipe surfaces.

Required system operation and maintenance and operator's skill levels:

- Daily operation of the system did not require additional skills beyond those necessary to operate the existing water supply equipment. The daily demand on the operator was only 10 min/day for routine operations.
- The AERALATER[®] system did not include automatic backwash triggers. This level of automation was available from Siemens, but was not selected for this site by the vendor. Because the system was backwashed only once a week, manual backwash seemed to be acceptable to the plant operator. The time required was 31 min per backwash event. At sites requiring more frequent backwash, manual backwash may become an issue.

Characteristics of residuals produced by the technology:

- Residuals produced by the operation of the treatment system include backwash wastewater from the AERALATER[®] gravity filter, backwash wastewater from the AD-33 adsorption vessels, and spent AD-33 media. Because the media was not replaced during the first six months of system operation, the only residual produced was backwash wastewater from both units.
- The gravity filter was backwashed on a weekly basis and the AD-33 adsorption vessels were backwashed with the treated water twice during the six-month study period. The amount of wastewater produced was equivalent to about 1.8% of the amount of water treated (168,900 or 1.7% from the AERALATER[®] and 13,472 gal or 0.1% from the APU-300 unit).
- The amount of solids produced per filter backwash cycle was 6.1 lb that included 2.6 lb of elemental iron, 0.004 lb of elemental manganese, and 0.02 lb of elemental arsenic.

Cost-effectiveness of the technology:

- The capital investment for the system was \$367,838, including \$273,873 for equipment, \$16,520 for site engineering, and \$77,445 for installation, shakedown, and startup. The building cost incurred by the City of Stewart was not included in the capital investment cost.
- Using the system's rated capacity of 250 gpm or 360,000 gpd, the capital cost was \$1,471/gpm (\$1.02/gpd) of design capacity.
- Although not incurred during the first six months of system operation, the AD-33 media replacement cost would represent the majority of the O&M cost for the system and was estimated to be \$41,370 to change out the AD-33 media.

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 treatment system began on February 2, 2006. 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	08/30/04
Draft Letter of Understanding Issued	11/18/04
Final Letter of Understanding Issued	12/10/04
Request for Quotation Issued to Vendor	01/21/05
Vendor Quotation Received	03/15/05
Purchase Order Established	03/29/05
Letter Report Issued	03/09/05
Engineering Package Submitted to MDH	03/21/05
System Permit Granted by MDH	06/20/05
Building Construction Permit Granted	06/13/05
Building Construction Began	07/01/05
APU-300 Unit Shipped/Arrived	09/06/05
AERALATER [®] Shipped/Arrived	09/16/05
System Installation/Shakedown Completed	01/18/06
Study Plan Issued	01/24/06
Performance Evaluation Began	02/02/06
Building Construction Completed	02/09/06

MDH = Minnesota Department of Health

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
Cost-Effectiveness	-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 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. Weekly 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 media replacement, electricity consumption, and labor. Electricity consumption was determined from utility bills. Labor for various activities, such as routine system O&M, troubleshooting and repairs, and demonstration-related work, were tracked using an Operator Labor Hour Log Sheet. The routine system O&M included activities, such as completing field logs, ordering supplies, performing system inspections, and others as recommended by the vendor. The labor for demonstration-related work, including activities such as performing field measurements, collecting and shipping samples, and communicating with the Battelle Study Lead and the vendor, was recorded, but not used for the cost analysis.

3.3 Sample Collection Procedures and Schedules

To evaluate system performance, samples were collected at the wellhead, across the treatment plant, at the AERALATER[®] backwash discharge sump, 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 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,

Table 3-3. Sampling Schedule and Analyses

Sample Type	Sample Location ^(a)	No. of Samples	Frequency	Analyte	Sampling Date
Source Water	At Wellhead (IN)	1	Once (during initial site visit)	On-site: pH, temperature, DO, and ORP Off-site: As (total, soluble, particulate), As(III), As(V), Fe (total and soluble), Mn (total and soluble), V (total and soluble), U (total and soluble), Na, Ca, Mg, Cl, F, NO ₃ , NO ₂ , NH ₃ , SO ₄ , SiO ₂ , PO ₄ , Ra-226, Ra-228, alkalinity, turbidity, TDS, and TOC	08/30/04
Treatment Plant Water	At Wellhead (IN), after Contact (AC), after Gravity Filter (AF), after Vessel A (TA), after Vessel B (TB)	5	Weekly	On-site: pH, temperature, DO, and ORP Off-site: As (total), Fe (total), Mn (total), P (total), SiO ₂ , alkalinity, and turbidity	02/14/06, 02/21/06, 03/06/06, 03/14/06, 03/21/06, 04/04/06, 04/11/06, 04/18/06, 05/02/06, 05/09/06, 05/16/06, 05/30/06, 06/06/06, 06/13/06, 06/27/06, 07/05/06, 07/11/06, 07/25/06, 08/01/06
	At Wellhead (IN), after Contact (AC), after Gravity Filter (AF), At Vessels A and B Combined (TT)	4	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 , NH ₃ , SO ₄ , SiO ₂ , and TOC	02/02/06, 02/27/06, 03/28/06 ^(c) , 04/25/06, 05/24/06, 06/20/06, 07/18/06
Backwash Water	At Backwash Discharge Sump	2	Monthly	As (total and soluble), Fe (total and soluble), Mn (total and soluble), pH, TDS, and TSS	03/01/06, 03/22/06, 04/12/06, 05/31/06, 06/28/06, 07/26/06
Distribution Water	Three Non-LCR Residences	3	Monthly	Total As, Fe, Mn, Cu, and Pb, pH, and alkalinity	Baseline sampling ^(c) : 02/16/05, 03/16/05, 04/13/05, 05/18/05 Monthly sampling: 02/22/06, 03/21/06, 04/18/06, 05/16/06, 06/13/06, 07/11/06
Residual Solids	At Backwash Water Discharge Sump	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) Sampling events performed before system startup.

(c) Sampling events before 04/25/06 taken from TA or TB tap due to absence of combined effluent sample tap.

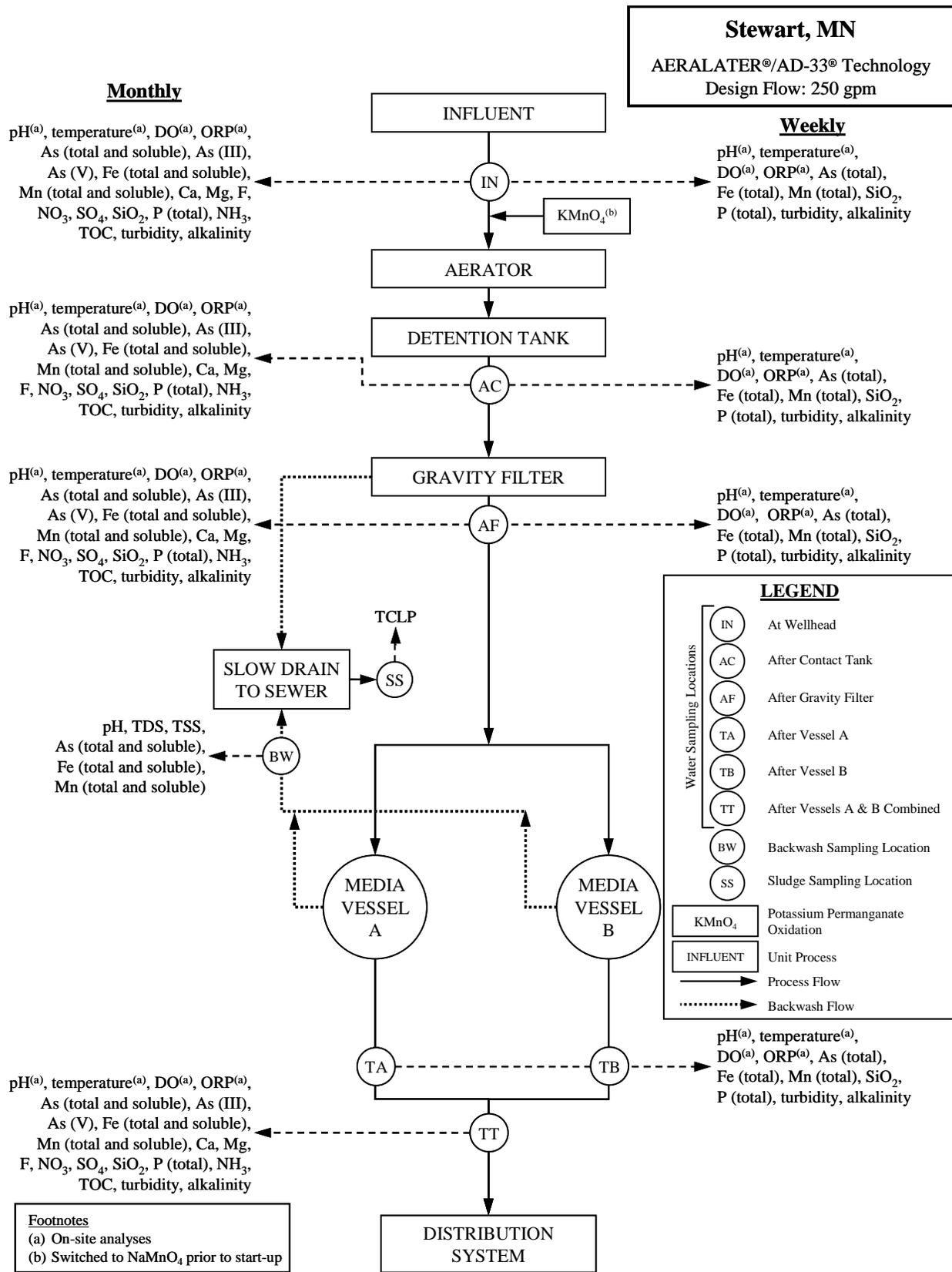


Figure 3-1. Process Flow Diagram and Sampling Schedule and Locations

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 visit to the site, one set of source water samples was collected and speciated using an arsenic speciation kit (see 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), after AERALATOR[®] gravity filter (AF), and after APU-300 Vessels 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, AF, and after APU-300 Tanks A (TA) and B (TB) and analyzed for the analytes listed in Table 3-3 for the weekly treatment plant water.

3.3.3 Backwash Water. AERALATER[®] backwash water samples were collected monthly by the plant operator. Because of lack of a sampling tap on the backwash water discharge line, grab samples were taken directly from the backwash water discharge sump during each of the six monthly backwash events. One aliquot was collected as is and the other filtered on-site with 0.45- μ m disc filters. Analytes for the backwash samples are listed in Table 3-3. Arsenic speciation was not performed for the backwash water samples.

During the second half of the one-year study period, composite samples of backwash water will be collected. A clean, 32-gal plastic container will be filled from the discharge sump and the contents thoroughly mixed using a mixing rod. One aliquot will be collected as is and the other filtered on-site with 0.45- μ m disc filters. The samples will be analyzed for the same set of analytes performed during the first six-month study period.

The APU-300 system was backwashed manually twice during the first six-month study period; however, no samples were collected. One set of composite backwash water samples will be collected during the next six month period. These samples will be collected from a sampling device similar to the one used for AERALATER[®] filter backwash. The only difference will be that a side stream of backwash water will be directed from a sample tab on the APU-300 backwash water discharge line to the plastic container. Filtered and unfiltered samples will be analyzed for the same set of analytes listed under backwash water.

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 and spent media, 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 locations 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 and analyzed at Battelle's inductively coupled plasma-mass spectrometry (ICP-MS) laboratory. Samples for other water quality parameters were packed in separate coolers and picked up by couriers from American Analytical Laboratories (AAL) in Columbus, Ohio, and TCCI Laboratories in New Lexington, Ohio, 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 VWR Symphony SP90M5 handheld multimeter, which was calibrated for pH and DO prior to use following the procedures provided in the user's manual. The ORP probe also was checked for accuracy by measuring the ORP of a standard solution and comparing it to the expected value. The plant operator collected a water sample in a clean, plastic beaker and placed the SP90M5 probe in the beaker until a stable value was obtained.

4.0 RESULTS AND DISCUSSION

4.1 Facility Description

The water treatment system at Stewart, MN, supplies drinking water to approximately 600 community members. The water source is groundwater from two wells (Wells No. 3 and 4). Wellheads 3 and 4 are shown in Figures 4-1 and 4-2, respectively. The static water level of the wells ranges from 20 to 30 ft below ground surface (bgs). Each well is 8-in in diameter and extends to a depth of approximately 370 ft bgs. Well No. 3 has a 50-ft screen length and is equipped with a 20-horsepower (hp) submersible pump with a capacity of approximately 350 gpm. Well No. 4 has a 52-ft screen length and a 15-hp submersible pump with a capacity of approximately 275 gpm. The average daily demand is 48,600 gpd and the peak daily demand is 125,300 gpd. Use of these two wells is alternated automatically based on the water tower level. Typically, each well runs for about 12,000 to 15,000 gal per cycle.

The pre-existing treatment consisted of chlorination, fluoridation, and polyphosphate addition. Chlorination was accomplished with a gas chlorine feed system to provide chlorine residuals in the distribution system. The target residual level was 1.1 mg/L for total chlorine (as Cl₂). The water also was fluoridated to a target level of 1.3 mg/L. Blended polyphosphates were added for iron sequestration and corrosion control. Figure 4-3 shows the chemical feed pumps and associated tanks within the pump house. Figure 4-4 shows the entry piping from Wells No. 3 and 4 and the tubing from the chemical feed pumps. The pre-existing equipment shown in Figures 4-3 and 4-4 was replaced with new equipment of similar sizes as part of the pre- and post-treatment, as described in Section 4.2. The treated water is stored in a nearby 65,000-gal water tower shown in Figure 4-5.



Figure 4-1. Wellhead 3 at Stewart, MN (near orange flag in center of photo)



Figure 4-2. Wellhead 4 at Stewart, MN (in front of small brown shed)

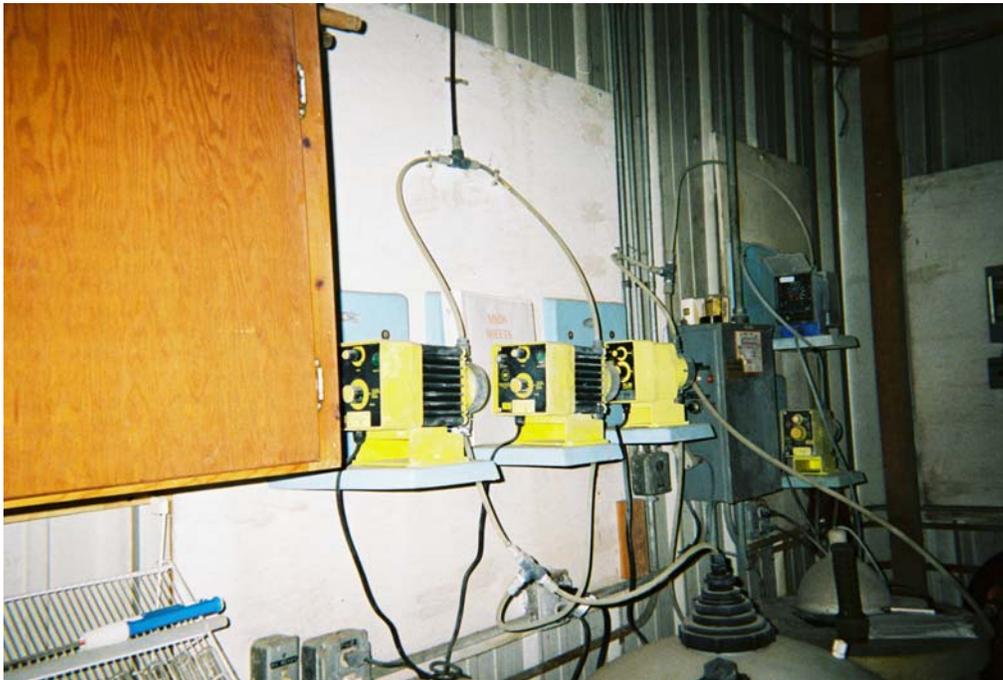


Figure 4-3. Existing Chemical Addition Equipment at Stewart, MN



Figure 4-4. Existing Chemical Addition and Entry Piping with Flow Totalizer and Pressure Gauge at Stewart, MN



Figure 4-5. A 65,000-Gal Water Tower at Stewart, MN

4.1.1 Source Water Quality. Source water samples were collected from Well No. 3 on August 30, 2004, by Battelle for detailed water quality characterization; the analytes of interest are presented in Table 3-3. In addition, pH, temperature, DO, and ORP were measured on-site using a VWR Symphony SP90MS handheld multimeter. The source water also was filtered for soluble arsenic, iron, manganese, uranium, and vanadium and speciated for As(III) and As(V) using the field speciation method modified from Edwards et al. (1998) by Battelle. The analytical results from the source water sampling event are presented in Table 4-1 and compared to historic data taken by the facility.

The proposed treatment train for the City of Stewart included oxidation with potassium permanganate (KMnO₄), iron removal using gravity filtration, and arsenic adsorption with AD-33 media. Several factors were anticipated to play a role in the pretreatment process for iron removal, including natural iron concentration, pH, turbidity, natural organic matter, ammonia, anions, and cations. Factors that may affect arsenic removal via adsorption include arsenic concentration, arsenic speciation, pH, and other competing anions.

Arsenic. Total arsenic concentrations in source water ranged from 39.0 to 41.7 µg/L. Based on August 30, 2004 sampling results from Well No. 3, out of 41.7 µg/L of total arsenic, 31.9 µg/L existed as As(III), 1.0 µg/L as As(V), and 8.8 µg/L as particulate As. Therefore, As(III) was the predominating species in groundwater. The proposed treatment process was to use KMnO₄, as originally designed, but switched to NaMnO₄ just before the system startup by the City, to oxidize As(III) to As(V) prior to iron removal and AD-33 adsorption. Oxidant addition was discontinued after the discovery of a naturally occurring oxidation process developed within the AERALATER[®] filter (see detailed discussion in Section 4.5.1.1). Upon oxidation, As(V) was removed via adsorption onto and/or co-precipitation with iron solids during the iron removal pretreatment step. The remaining As(V) was then removed via adsorption onto the AD-33 media.

Iron and Manganese. In general, adsorptive media technologies are best suited to source waters with relatively low iron levels (i.e., less than 300 µg/L, which is the secondary maximum contaminant level [SMCL] for iron). Above 300 µg/L, taste, odor, and color problems can occur in treated water, along with an increased potential for fouling of the adsorption system. The proposed treatment process at Stewart, MN relied on aeration and gravity filtration to remove elevated levels of iron in source water. This iron removal process also resulted in the removal of some As(V) in the water. Iron concentrations in source water ranged from 1,344 to 1,400 µg/L, which existed almost entirely as soluble iron. Total manganese in source water ranged from 24 to 27 µg/L, which was below the SMCL of 50 µg/L.

pH. pH values of source water ranged from 7.7 to 7.8, which were near the upper end of the target range of 6.0 to 8.0 for optimal arsenic adsorption onto the AD-33 media.

TOC and Ammonia. The source water contained elevated levels of total organic carbon (TOC) (ranging from 6.8 to 7.2 mg/L) and ammonia (at 1.7 mg/L). To avoid the formation of disinfection by-products (DBPs) and high chlorine consumption, the treatment process used NaMnO₄, instead of chlorine, for As(III) oxidation. However, as mentioned above, oxidant addition was later discontinued because iron removal was accomplished through aeration and As(III) oxidation attained via a naturally occurring process.

Competing Anions. The adsorption of arsenic onto iron solids and AD-33 media also may be influenced by the presence of competing anions such as silica, sulfate, and phosphate. At the Stewart, MN site, silica levels ranged from 24.0 to 26.6 mg/L (as SiO₂) and sulfate levels ranged from <5 to 7.4 mg/L. These concentrations were low enough not to pose a significant problem for effective arsenic adsorption. The orthophosphate level was 0.02 mg/L; however, as discussed in Section 4.5.1.6, total phosphorous level

Table 4-1. City of Stewart, MN Water Quality Data

Parameter	Unit	Concentration		
		Utility Raw Water Data ^(a)	Battelle Well NO. 3 Raw Water Data	MDH Treated Water Data ^(b)
<i>Sampling Date</i>		Not Specified	08/30/04	10/16/01-10/18/04
pH	S.U.	7.8	7.7	7.7–7.8
DO	mg/L	NS	2.2	NS
ORP	mV	NS	-86	NS
Alkalinity (as CaCO ₃)	mg/L ^(a)	415	424	410–420
Hardness (as CaCO ₃)	mg/L ^(a)	230	246	<240
Turbidity	NTU	NS	7	<1–7.2
TDS	mg/L	NS	462	NS
TOC	mg/L	6.8	7.2	6.7–6.8
Total N (Nitrate + Nitrite)	mg/L	NS	NS	<0.05
Nitrate (as N)	mg/L	NS	<0.04	NS
Nitrite (as N)	mg/L	NS	<0.01	NS
Ammonia (as N)	mg/L	NS	1.7	NS
Chloride	mg/L	6.5	7.2	6.3–6.8
Fluoride	mg/L	NS	0.4	0.5–4.0
Sulfate	mg/L	7.4	<5.0	7.0–14.0
Silica (as SiO ₂)	mg/L	24.0	26.6	23.0–24.0
Orthophosphate (as PO ₄)	mg/L	0.02	<0.1	NS
As (total)	µg/L	39.0	41.7	34.0–43.0
As (soluble)	µg/L	NS	32.9	NS
As (particulate)	µg/L	NS	8.8	NS
As(III)	µg/L	39	31.9	NS
As(V)	µg/L	<0.1	1.0	NS
Fe (total)	µg/L	1,400	1,344	1,200–1,500
Fe (soluble)	µg/L	NS	1,359	NS
Mn (total)	µg/L	24.0	27.0	22.0–25.0
Mn (soluble)	µg/L	NS	28.0	NS
U (total)	µg/L	NS	<0.1	NS
U (soluble)	µg/L	NS	<0.1	NS
V (total)	µg/L	NS	<0.1	NS
V (soluble)	µg/L	NS	<0.1	NS
Na (total)	mg/L	87	87	84–89
Ca (total)	mg/L	46	56	44–48
Mg (total)	mg/L	28	26	26–29
Ra-226	pCi/L	NS	<1.0	NS
Ra-228	pCi/L	NS	<1.0	<0.77 ^(c)
Gross-Alpha	pCi/L	NS	NS	1.6–2.7 ^(c)
Gross-Beta	pCi/L	NS	NS	<1.1–1.5 ^(c)
Radon	pCi/L	NS	NS	358–531 ^(c)

(a) Provided to EPA for demonstration study site selection.

(b) Water from Wells No. 3 and 4 after chlorine, fluoride, and polyphosphate addition.

(c) Radiochemistry based on data collected from 12/14/92 through 10/18/04.

NS = Not Sampled; MDH= Minnesota Department of Health; TDS = Total Dissolved Solids; TOC = Total Organic Carbon

was elevated at 0.90 mg/L (as PO₄) and could compete with arsenic for available adsorption sites onto iron solids and AD-33 media.

Other Water Quality Parameters. Alkalinity, hardness, sodium, and total dissolved solids (TDS) levels in source water were all elevated. Alkalinity values ranged from 415 to 424 mg/L (as CaCO₃); hardness values ranged from 230 to 246 mg/L (as CaCO₃); and sodium and TDS concentrations (in August 30, 2004 sample) were 87 and 462 mg/L. Other water quality parameters, including nitrate, nitrite, chloride, fluoride, uranium, vanadium, were below their respective detection limits or SMCLs. Radium was measured at less than the detection limit of <1.0 pCi/L.

4.1.2 Treated Water Quality and Distribution System. Historic water samples were taken from both Wells No. 3 and 4, but after chlorination, fluoridation, and polyphosphate addition; therefore, the analytical results obtained from the Minnesota Department of Health (MDH) are included in Table 4-1 as treated water data. These water samples were collected from residences, businesses (stores), city hall, and the treatment plant from October 16, 2001, through October 18, 2004.

Historic As levels detected within the distribution system ranged from 34.0 to 43.0 µg/L; iron levels ranged from 1,200 to 1,500 µg/L, and manganese levels ranged from 22 to 25 µg/L. These concentrations were similar to those measured in raw water. Results of other water quality parameters measured historically also were very close to those found in the raw water samples collected by the facility and Battelle.

The distribution system at Stewart, MN is supplied only by Wells No. 3 and 4. Water from Wells No. 3 and 4 is blended within the distribution system and the 65,000-gal water tower. Based on the distribution system blueprint, the mains for the water distribution system are primarily constructed of 6-in to 8-in cast iron. Other connections within the distribution system include ¾-in to 2-in galvanized iron, 2-in copper, and 2-in polyvinyl chloride (PVC) piping. Three locations were selected for both baseline and distribution system sampling after system startup. The locations were selected as part of the City's historic sampling network for the Lead and Copper Rule. Compliance samples also include quarterly sampling for arsenic, coliform, total chlorine residual, and fluoride and annual sampling for nitrate, volatile organic compounds (VOCs), trihalomethanes (THMs), haloacetic acids (HAA5), turbidity, TOC, alkalinity, and radionuclides.

4.2 Treatment Process Description

The 250-gpm treatment system at Stewart, MN consists of pre-treatment for iron removal followed by adsorption with AD-33 media for arsenic removal (Figure 4-6). This section provides a detailed description of the Siemens' Type II AERALATER[®] system for iron removal and AdEdge's APU-300 system for arsenic adsorption.

Due to elevated iron levels in source water, the adsorption system is preceded by a Siemens' Type II AERALATER[®] system for iron (and some arsenic) removal via oxidation and filtration. Figure 4-7 shows the 11-ft diameter AERALATER[®] system, which is a packaged unit for oxidation, detention, and gravity filtration. The AERALATER[®] system includes an aeration chamber, a detention tank, and four filter cells. The treatment processes involved permanganate oxidation (with the oxidant added at inlet piping to the AERALATER[®] system), aeration, adsorption/co-precipitation of As(V) onto/with iron solids, and gravity filtration with anthracite and silica sand. The filtration media are approved for use in drinking water applications under NSF International (NSF) Standard 61. More details on the Siemens' Type II AERALATER[®] system are provided below.

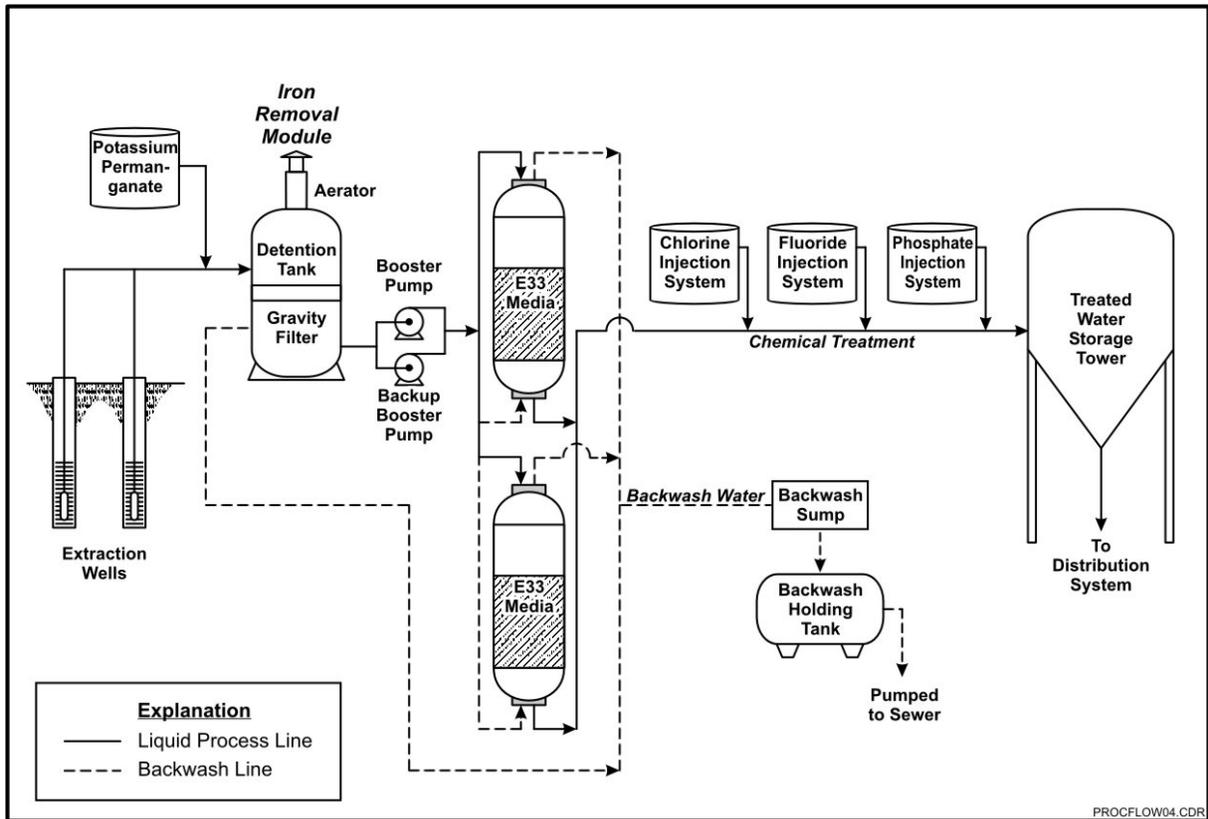


Figure 4-6. Schematic of AERALATER® and APU-300 Systems at Stewart, MN



Figure 4-7. AERALATER® (left) and APU-300 Systems (right) at Stewart, MN

The soluble As(V) that remains in the treated water after the AERALATER[®] system is further treated by the AdEdge APU-300 system. Designed for arsenic removal for small systems in the flow range of 10 to 300 gpm, the APU series is a fixed-bed adsorption system. As groundwater is pumped through fixed-bed pressure vessels, soluble arsenic is adsorbed onto the media, thus reducing the soluble arsenic concentration to below the 10 µg/L MCL. The APU-300 adsorption system consists of two 63-in diameter, 86-in tall vessels configured in parallel (see Figure 4-7). Each vessel contains 64 ft³ of pelletized Bayoxide[®] E33 media (branded as AD-33 by AdEdge). This iron-based adsorptive media was developed by Bayer AG for the removal of arsenic from drinking water supplies. Table 4-2 presents the physical and chemical properties of the media. The AD-33 media is delivered in a dry crystalline form and listed by NSF under Standard 61 for use in drinking water applications. AD-33 is available in both granular and pelletized forms. The pelletized media used at the Stewart, MN site is 25% denser than the granular media (35 vs. 28 lb/ft³). Both media are reported by the vendor to have similar arsenic adsorption capacities on a per pound basis. After reaching its capacity, the spent media is removed and disposed of as nonhazardous waste after passing EPA's toxicity characteristic leaching procedure (TCLP) test. The media life depends upon the arsenic concentration, pH, and concentrations of interfering ions in the influent water.

Table 4-2. Physical and Chemical Properties of AD-33 Media

Parameter	Value
<i>Physical Properties</i>	
Matrix	Iron oxide/Hydroxide
Physical form	Dry pelletized media
Color	Amber/rust
Bulk Density (lb/ft ³)	35
Bulk Density (g/cm ³)	0.56
BET Area (m ² /g) ^(a)	142
Attrition (%) ^(a)	0.3
Moisture Content (%)	5% by weight
Particle size distribution (U.S. Standard Mesh)	14 × 18 (1.0 to 1.4 mm)
Crystal Size (Å) ^(a)	70
Crystal Phase ^(a)	α-FeOOH
<i>Chemical Analysis^(a)</i>	
Constituents	Weight (%)
FeOOH	90.1
CaO	0.27
MgO	1.00
MnO	0.11
SO ₃	0.13
Na ₂ O	0.12
TiO ₂	0.11
SiO ₂	0.06
Al ₂ O ₃	0.05
P ₂ O ₅	0.02
Cl	0.01

Data Source: Bayer AG

(a) For dry granular media

Table 4-3 presents design features of the treatment system at Stewart, MN. The major process components of the treatment system are described as follows:

- **Intake.** Raw water is pumped from Wells No. 3 and 4, alternately, and fed into the entry piping to the Siemens Type II AERALATER[®] unit. The well pumps are turned on and off based on the low and high level settings of 23 and 27 ft of H₂O, respectively, in the water tower.
- **Oxidation.** The original design called for the use of a 2 % KMnO₄ solution and a 2.5-gal/hr diaphragm metering pump to oxidize As(III) and Fe(II). The target oxidant dosage was 0.5 mg/L (as Mn). However, modifications were made to include the use of a 20% liquid NaMnO₄ solution and a 1-gal/hr metering pump by the City prior to system startup. In addition to the metering pump with adjustable stroke length and speed, the chemical feed system included a 150-gal polyethylene day tank and an overhead mixer. The addition of NaMnO₄ was discontinued after the system startup because the oxidation of As(III) was accomplished even without the use of any oxidant.
- **Iron Removal.** Siemens' Type II AERALATER[®] was used as a pretreatment step for iron removal. Constructed of carbon steel, the 11-ft diameter package unit was designed to allow oxidation, detention, and gravity filtration to all occur in a single unit. The system components were assembled in a stacked circular configuration, with an aeration chamber on the top, a detention tank in the middle, and four filter cells in the base (Figure 4-8). The details of these process components are described as follows:
 - **Aeration.** Air for the aluminum aeration unit was supplied by a ½-hp blower with a capacity of 855 ft³/min (cfm) at a 3/8-in static pressure. The influent water was aerated as it passed over a network of 1¼-in PVC slats supported by a stainless steel grid.
 - **Contact.** The 11-ft diameter by 11.5-ft high steel detention tank provided 34 min of contact time to improve the formation of filterable iron flocs. The total detention time of 34 min was based on the total volume of 8,550 gal in the detention tank and the freeboard above the filter.
 - **Filtration.** The four filter cells sitting at the base of the circular unit had a total cross-sectional area of 95 ft². Therefore, operating the system at the design flowrate of 250 gpm would result in a hydraulic loading rate of 2.6 gpm/ft². The filtration bed in each filter cell consisted of one each 12-in layer of 0.6 to 0.8 mm anthracite and 0.45 to 0.55 mm sand, which were supported by a 14-in layer of gravel underbedding. A steel plate underdrain was located under the gravel with media retaining strainers.
 - **Backwash.** The filter cells were backwashed manually once per week to remove filtered particles from the filter media (the system did not have automatic backwash capabilities). Each cell was backwashed individually at 285 gpm (or 12 gpm/ft²) using filtered water from the other cells. To initiate the manual backwash, the influent valve on the first cell was closed and the corresponding backwash valve was opened. The backwash was continued until visual observation indicated that the backwash water had reached a “light straw” color. As a result, the duration of the backwash varied based upon operator observations. Upon completion, the backwash valve was closed and the influent valve on the first cell was re-opened. The same procedure was followed for the remaining filter cells. All filter cells had to be backwashed on the same day to ensure consistent

Table 4-3. Design Features of Type II AERALATER® and APU-300 Systems

Parameter	Value	Remarks
<i>Preoxidation</i>		
Oxidant Used	2% KMnO ₄	Changed to 20% NaMnO ₄ by City before system startup
<i>AERALATER® Pretreatment</i>		
Design Flowrate (gpm)	250	–
AERALATER® Diameter (ft)	11	–
AERALATER® Height (ft)	26	–
Aerator Cross-Sectional Area (ft ²)	95	–
Detention Tank Size (ft)	11 D × 11.5 H	–
Detention Tank Volume (gal)	8,550	Including freeboard above filter
Detention Time (min)	34	–
Media Volume (ft ³)	190	24-in bed depth (12-in anthracite and 12-in sand)
Hydraulic Loading Rate to Filter (gpm/ft ²)	2.6	–
Backwash Flowrate (gpm)	285	–
Backwash Hydraulic Loading (gpm/ft ²)	12	–
Backwash Frequency (time/week)	1	–
Backwash Duration (min)	~8	Variable based on visual observation
Wastewater Production (gal/filter cell)	2,250	Per vendor estimate
<i>APU-300 Adsorbers</i>		
Vessel Size (in)	63 D × 86 H	–
Cross-Sectional Area (ft ² /vessel)	21.6	Based on 62-in inner diameter
No. of Vessels	2	–
Configuration	Parallel	–
Media Type	AD-33	Pelletized media
Media Volume (ft ³)	128	36-in bed depth or 64 ft ³ /vessel
Pressure Drop (psi)	4 psi	Across a clean bed
<i>APU-300 Service</i>		
Design Flowrate (gpm)	250	–
Hydraulic Loading (gpm/ft ²)	5.8	–
EBCT (min)	3.8	–
Estimated Working Capacity (BV)	82,500	Projected by vendor
Throughput To Breakthrough (gal)	79,000,000	1 BV = 958 gal
Average Use Rate (gal/day)	48,600	–
Estimated Media Life (months)	53	Estimated frequency of change-out at 13.5% utilization
<i>APU-300 Backwash</i>		
Pressure Differential Set Point (psi)	10	–
Backwash Flowrate (gpm)	200	–
Backwash Hydraulic Loading Rate (gpm/ft ²)	9.3	–
Backwash Frequency (per quarter)	1	Per vendor recommendations
Backwash Duration (min/vessel)	15	–
Fast Rinse Duration (min/vessel)	5	–
Wastewater Production (gal/vessel)	4,000	–

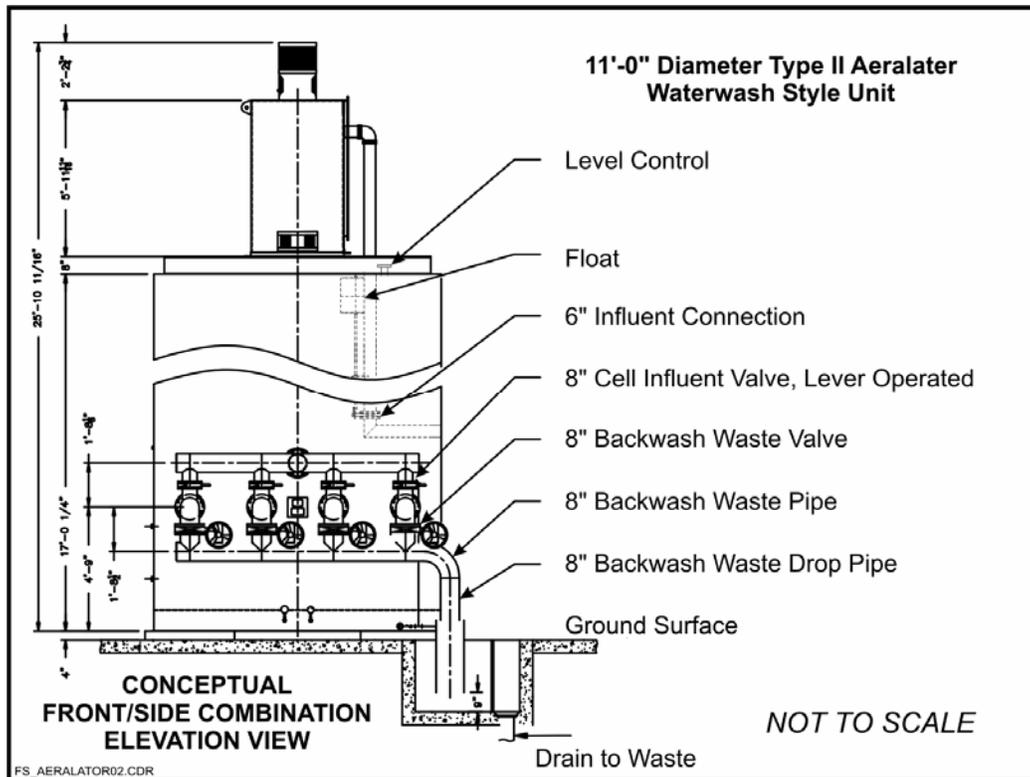


Figure 4-8. Schematic of Type II AERALATER® System (Based on General Arrangement Drawing Provided by Siemens)

performance of the filter. After all four cells were backwashed, the system effluent valve was re-opened and the system returned to service. The backwash water produced was discharged to a sump and then drained by gravity to two backwash water holding tanks before being pumped to the sewer system.

- **Adsorption.** The AdEdge APU-300 system was fed by two 15-hp high service pumps to provide pressurized flow to the water tower. The high service pumps were controlled to start and stop operation based on the water level in the AERALATER® detention tank. The APU-300 adsorption system consisted of two 63-in diameter, 86-in tall vessels configured in parallel, each containing 64 ft³ of pelletized AD-33 media supported by gravel underbedding. Figure 4-9 shows the schematic of the APU-300 system. The adsorption vessels were constructed of composite fiberglass with a polyethylene liner and rated for 150 pounds per square inch (psi) working pressure. The system was skid mounted and piped to a valve rack mounted on a polyurethane-coated, welded frame. The service, backwash, and media replacement are described in more detail below.
 - **Service.** Water flowed downward through the packed AD-33 media beds. Flow to each vessel was measured and totaled to record the volume of water treated. The pressure differential through each vessel also was monitored. Based on a design flowrate of 250 gpm, the empty bed contact time (EBCT) for each vessel was 3.8 min and the hydraulic loading to each vessel was approximately 5.8 gpm/ft².

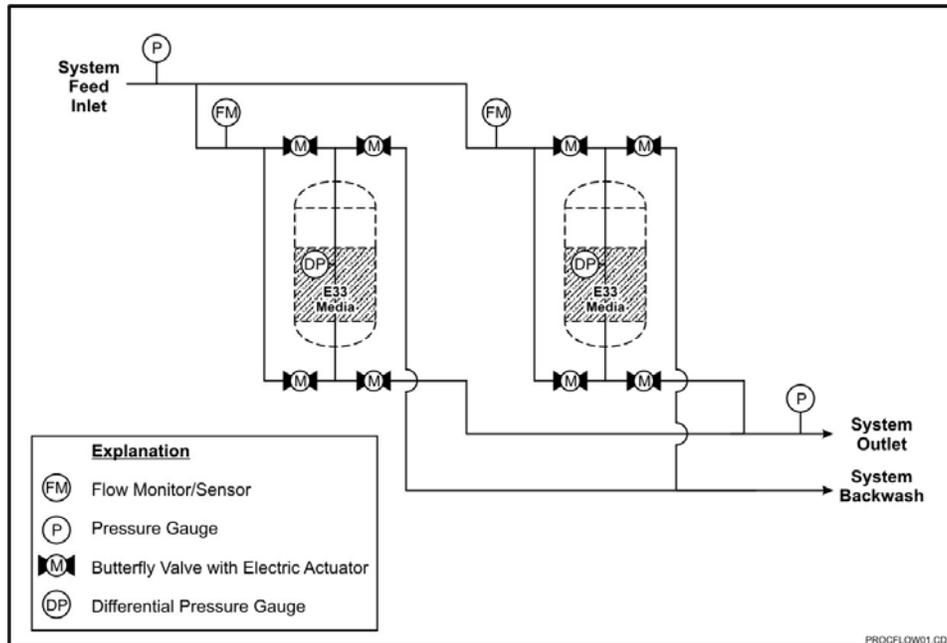


Figure 4-9. Schematic of APU-300 System (Based on Process and Instrumentation Diagram Provided by AdEdge)

- **Backwash.** Based upon a set time period or a set pressure differential, the adsorption vessels were taken off-line one at a time for a manual backwash using raw water from the wells. The system was equipped with an automatic backwash trigger based on time or differential pressure, but this feature was disabled. The purpose of the backwash was to remove particulates and media fines built up in the beds and to uncompress the media beds. While one vessel was backwashed, the other vessel remained in service. Each vessel was backwashed at a flow rate of approximately 200 gpm (or 9.3 gpm/ft²). The backwash water generated was discharged to a sump and then drained by gravity to two backwash water holding tanks before being pumped to the sewer system.
- **Media Replacement.** When the AD-33 media arsenic removal capacity is exhausted, the spent media will be removed from the vessels and disposed off-site. Virgin media is then loaded back into each vessel. Based on the vendor's estimate, the media will be changed out after treating approximately 79 million gal or every 53 months (based on an estimated daily use rate of 48,600 gal for the system and influent arsenic concentrations of 20 to 27 µg/L). The actual media change-out will be based on the system performance and media exhaustion. The spent media, which most likely will pass the EPA's TCLP test for toxicity, will be disposed of as nonhazardous waste.
- **Post-Treatment Chemical Feed.** After the APU-300 system, the treated water underwent post-chlorination, fluoridation, and polyphosphate addition. Post-chlorination was carried out with a gas chlorine injection system, which consisted of two 150-lb chlorine gas cylinders, an electronic scale, a flow controller, and a 3-hp chlorine booster pump. Post-chlorination helped maintain a target total chlorine residual level of 1.1 mg/L (as Cl₂) in the distribution system. Fluoride was added at a target level of 1.3 mg/L using a 0.58-gph maximum capacity diaphragm chemical metering pump and a 65-gal polyethylene storage tank. Blended polyphosphates were added with a 0.58-gal maximum capacity diaphragm chemical metering pump and a 50-gal polyethylene storage tank for corrosion control.

4.3 Treatment System Installation

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

4.3.1 System Permitting. The system engineering package, prepared by AdEdge and Bolton & Menk, Inc., included a system design report and associated general arrangement and piping and instrumentation diagrams (P&IDs) for the Type II AERALATER[®] and APU-300 systems, electrical and mechanical drawings and component specifications, and building construction drawings detailing connections from the system to the entry piping and the City's water and sanitary sewer systems. The engineering package was certified by a Professional Engineer registered in the State of Minnesota and submitted to MDH for review and approval on March 21, 2005. After MDH's review comments were incorporated, the revised package was resubmitted on May 20, 2005. A water supply construction permit was issued by MDH on June 20, 2005, and fabrication of the system began thereafter.

4.3.2 Building Construction. A permit for building construction was applied for by the City and issued on June 13, 2005. Building construction began on July 1, 2005, and was completed on February 9, 2006. The concrete block building had a 55.3 ft × 24.7 ft footprint with a sidewall height of 14 ft (see Figure 4-10). The AERALATER[®] aeration tower protrudes through the building roof where two 16-in diameter access hatches also were installed for adsorptive media loading. In addition to housing the treatment system, the building contains a fluoride room, a chemical room, a bathroom, and some office/laboratory space. Wastewater discharge is facilitated with a 4 ft × 2 ft × 2 ft (120 gal) underground sump that empties by gravity into two 12,500 gal pre-cast concrete holding tanks. Each holding tank is equipped with a 2-hp sump pump with a design capacity of 50 gpm for transferring backwash water to the sanitary sewer system.

4.3.3 System Installation, Startup, and Shakedown. Although building construction was still on going, the site was prepared for delivery of the treatment systems by September 2005. Both units were shipped and arrived prior to roof construction to facilitate placement in the building. The APU-300 system arrived on September 6, 2005 and the AERALATER[®] system arrived on September 16, 2006. The vendor, through its subcontractor, performed the off-loading and installation of the systems, including connections to the entry and distribution piping and electrical interlocks. Figure 4-11 shows the off-loading of the AERALATER[®] unit by crane.

Subsequent to the treatment system delivery, construction work to finish the building and associated piping and electrical infrastructure continued through February 9, 2006. Siemens arrived on-site for mechanical checkout of the AERALATER[®] installation on January 4, 2006. AdEdge was on-site from January 4 to 11, 2006, for mechanical checkout of the APU-300 installation and start-up activities, including hydraulic testing, media loading, initial backwashing, and system disinfection. After the bacteriological test results were received and passed, the systems began to operate manually with the treated water sent to the distribution system starting from January 18, 2006. Manual operation of the systems continued until the City's contractor completed the electrical wiring and control setpoints for the well pumps and high service pumps. The operator began to record operational data on January 30, 2006.

Battelle staff traveled to Stewart, MN to perform system inspections and operator training from February 1 to 3, 2006, with the first set of treatment plant samples taken on February 2, 2006. A punch list was identified during the trip and later forwarded to AdEdge on February 16, 2006. The issues to be addressed included replacement of a headloss gauge on the AERALATER[®] system, installation of a combined effluent sample tap downstream of the APU-300 system and upstream of post-chlorination, disabling of the APU-300 system automatic backwash, calibration of flow meters for the APU-300



Figure 4-10. Building with AERALATER® Tower (top), Backwash Sump (bottom left), and Backwash Water Holding Tanks (bottom right) at Stewart, MN



Figure 4-11. Off-Loading and Placement of AERALATER® Unit at Stewart, MN

system, and changes of combined flow totalizer PLC programming for the APU-300 system. These issues were subsequently resolved by the vendor by August 2006.

4.4 System Operation

The operational parameters for the first six months of the system operation were tabulated and are attached as Appendix A. Key parameters are summarized in Table 4-4. From January 30, 2006, to August 1, 2006, the system operated for 890 hr, producing 10,039,000 gal based on wellhead flow totalizer readings. The wells were operated on an alternating basis with Well No. 3 operating for 432.4 hr and Well No. 4 for 457.6 hr. The average daily demand was 54,822 gal and the average operation time was 4.9 hr/day. Given the full design capacity of 250 gpm (360,000 gpd), this represents an average hydraulic utilization rate of 15% on a daily basis. The peak daily demand was 126,779 gal, which occurred on July 12, 2006. The system operation is discussed further below in terms of the hydraulic performance of the AERALATER[®] and APU-300 systems.

Table 4-4. Treatment System Operational Parameters for Stewart, MN

Parameter	Value		
	January 30, 2006 to August 1, 2006		
Operational Period	January 30, 2006 to August 1, 2006		
Wellhead Operations	Well No. 3	Well No. 4	Total
Total Operating Time (hr)	432.4	457.6	890.0
Average Operating Time (hr/day)	2.4	2.5	4.9
Throughput (kgal)	5,012	5,027	10,039
Average Demand (gpd)	27,436	27,532	54,822
Peak Demand (gpd)	85,225	87,300	126,779
AERALATER[®] Iron Removal Operations	Well 3	Well 4	Total
Average Flowrate [Range] (gpm) ^(a)	194 [121–215]	184 [134–210]	–
Average Contact Time [Range] (min)	44 [40–71]	46 [41–64]	–
Average Filtration Rate [Range] (gpm/ft ²)	2.0 [1.3–2.2]	1.9 [1.4–2.2]	–
Average Δp across Filter (ft H ₂ O)	–	–	<1.5
Median Throughput between Backwash [Range] (kgal)	–	–	367.1 [217.1–739.4]
Median Run Time between Backwash [Range] (hr)	–	–	32 [19–65]
Median Backwash Frequency [Range] (day/backwash)	–	–	7 [5–15]
APU-300 Adsorption Operations	Tank A	Tank B	Total
Throughput (kgal)	5,282	5,177	10,459
Throughput (BV)	11,031	10,814	10,922
Average Flowrate [Range] (gpm) ^(b)	90 [73–104]	88 [70–103]	179 [143–207]
Average EBCT [Range] (min)	5.3 [4.6–6.5]	5.4 [4.6–6.8]	5.3 [4.6–6.6]
Δp across tank/system (psi)	0	0	1 to 2

(a) Average flowrate based on readings of individual wellhead mechanical flow totalizers and hour meter.

(b) Average flowrate based on weekly readings of instantaneous flowrate from each vessel using digital paddlewheel flow meters.

4.4.1 AERALATER[®] Operations. With an average flowrate of 189 gpm between the two wells, the AERALATER[®] system was run at approximately 76% of its full design capacity of 250 gpm. The flowrate to the AERALATER[®] system varied slightly based on which well pump was operational. When Well No. 3 was operational, the flowrate readings ranged from 121 to 215 gpm and averaged 194 gpm. At these flowrates, the contact times ranged from 40 to 71 min and averaged 44 min (compared to a

design value of 34 min), and the hydraulic loading rates to the filter ranged from 1.3 to 2.2 gpm/ft² and averaged 2.0 gpm/ft² (compared to the design value of 2.6 gpm/ft²). When Well No. 4 was operational, the flowrate readings ranged from 134 to 210 gpm and averaged 184 gpm. This corresponded to a contact time of 41 to 64 min and a hydraulic loading rate of 1.4 to 2.2 gpm/ft². In general, the contact time was higher, but the hydraulic loading rate was lower than the respective design value.

During this time period, a total number of 25 backwash events took place. The operator manually backwashed the AERALATER[®] system approximately once per week with the number of days per backwash ranging from 5 to 15. During the filter run cycles, less than 1.5 ft of H₂O headloss was measured across the filter media beds. The run times between two consecutive backwash events ranged from 19 to 65 hr and the media run time was 32 hr. The throughput between two consecutive backwash events ranged from 217,100 to 739,400 gal and the median throughput was 367,100 gal. The throughput to the filter varied based on the amount of run time required to meet the water demand during the week.

4.4.2 APU-300 Operations. The APU-300 system processed approximately 10,459,000 gal or 10,922 BV of water from January 30 through August 1, 2006, based on the readings from the individual digital paddle-wheel flow totalizers installed on the effluent piping downstream from the adsorption vessels. In general, the throughput readings obtained via the paddle-wheel flow totalizers were 5.6% higher than those from the mechanical totalizers at the wellheads given the wellhead throughput and estimated backwash water volume. Based on the readings for the individual vessels, Vessel A processed 11,031 BV (5,282,000 gal) and Vessel B processed 10,814 BV (5,177,000 gal) of water. The average flowrates were 90 and 88 gpm for Vessels A and B, respectively, indicating balanced flow between the two vessels. The flowrates were recorded at least once per week by the operator based on the instantaneous readouts on the digital paddlewheel flow meter for each vessel. According to the flowrates measured, the system operated at approximately 71% of its design capacity. The EBCTs for Vessels A and B averaged 5.3 and 5.4 min, which are higher than the design value of 3.8 min. Throughout the six-month operational period, the differential pressure across the media beds and across the entire system remained low at 1.0 to 2.0 psi, suggesting effective particulate removal by the AERALATER[®] system. The two manual backwash events that took place during this study period are discussed in detail below.

4.4.3 Backwash Operations. Both the AERALATER[®] and APU-300 systems required backwash. Because the AERALATER[®] system was used as pre-treatment to remove iron particles, it was backwashed as often as once per week. The APU-300 system did not experience elevated differential pressures above the 10-psi setpoint and, therefore, was backwashed only twice during the first six-month study period. Both units used treated water for backwash. Table 4-5 summarizes key operational parameters related to system backwash for both systems.

During the six-month study period, 25 manual backwash events were initiated, generating approximately 168,900 gal of backwash water based on the readings obtained via the wellhead totalizer readings before and after backwash. The amount of wastewater produced represents 1.7% of the volume of water processed during this time period. The average backwash flowrate was 224 gpm, or 9.4 gpm/ft², which was about 21% lower than the design value of 284 gpm or 12 gpm/ft². The duration for each backwash event (for all four cells) ranged from 13 to 45 min and averaged 31 min, which is very close to the vendor-provided value of 8 min/cell or 32 min/event. The backwash duration varied because backwash was manually controlled by the operator based on visual observations of the backwash water color. The backwash was discontinued when the backwash water had reached a “light straw” color. The average amount of wastewater produced was 6,756 gal per backwash event, compared to 9,000 gal per event provided by the vendor.

Table 4-5. Summary of Backwash Operations at Stewart, MN

Parameter	Value
<i>AERALATER[®] Backwash Operations</i>	
Total Number of Backwash Events	25
Total Volume of Backwash Wastewater Produced (gal)	168,900
Median Frequency of Backwash [Range] (day)	7 [5–15]
Average Flowrate [Range] (gpm)	224 [173–386]
Average Hydraulic Loading Rate [Range] (gpm/ft ²)	9.4 [7.3–16.3]
Average Duration [Range] (min)	31 [13–45]
Average Backwash Wastewater Volume [Range] (gal/event)	6,756 [2,600–12,400]
<i>APU-300 Backwash Operations</i>	
Total Number of Backwash Events	2
Total Volume of Backwash Wastewater (gal) ^(a)	13,472
Backwash Duration (min)	15
Fast Rinse Duration (min)	3
Average Backwash Wastewater Volume [Range] (gal/vessel)	2,935 ^(b) [2,799–4,668]

(a) Backwash water volumes including fast rinse wastewater.

(b) Average values do not include Vessel A backwash initiated and then halted on February 2, 2006.

For the APU-300 system, it was recommended that the AD-33 media be backwashed approximately once every 45 days to loosen up the media bed. The system was equipped with an automatic backwash control that initiated backwash either by a 45-day time trigger or by a differential pressure trigger set at 10 psi across each vessel. It was necessary to disable this automatic backwash feature due to the process control configuration of the well pumps and high service pumps at the Stewart, MN site. Per communication with the operator during the startup trip in February 2006, it was determined that there was no wiring connection between the APU-300 programmable logic controller (PLC) and the City of Stewart’s PLC that controlled the well pumps and high service pumps. Therefore, if an automatic backwash was called for while the well pumps and high service pumps were off, there would not be adequate flow to the APU-300 units to accomplish the backwash. For this reason, the automatic backwash capability was disabled in the PLC on February 2, 2006, and the operator performed each backwash of the APU-300 unit with a manual trigger. The backwash trigger was initiated manually twice during the six months of system operation on February 2, 2006, and February 23, 2006, as described below.

The event on February 2, 2006, occurred during startup activities to confirm proper installation and setup of the system. During this event, it was noted that further adjustments were required to the PLC settings and to the backwash flowrate to meet design specifications. During the backwash of Vessel A on February 2, 2006, a higher than specified backwash flowrate of greater than 275 gpm (or 13 gpm/ft²) was noted along with visual observation of media loss discharged through the backwash line. Shortly after initiation of backwash, the operator throttled back the flowrate to approximately 181 gpm (or 8.6 gpm/ft²), a value below the design flowrate of 200 gpm (or 9.5 gpm/ft²). It also was noted that the backwash and fast rinse time setpoints required adjustment in the PLC. Therefore, the backwash of Vessel A was halted after 28 min to make these adjustments. The backwash time was changed from 1,200 sec (20 min) to 900 sec (15 min) to match the design value of 15 min. The fast rinse time also was adjusted from 1,500 sec (25 min) to 180 sec (3 min) to be closer to the design value 5 min. During this backwash event, Vessels A and B generated 4,668 and 2,979 gal of wastewater, respectively. The operator subsequently performed a manual backwash event on February 23, 2006, that generated 3,026

and 2,799 gal from Vessels A and B, respectively. Except for Vessel A on February 2, 2006, backwash produced less amounts of wastewater than the design value of 4,000 gal/vessel.

During the first six-months of system operation, backwash of the adsorption vessels produced 13,472 gal of wastewater, which represents 0.12% of the total amount of water processed. Because no elevated differential pressure readings across the vessels occurred, it was decided not to backwash the adsorption vessels for the remainder of the six month time period.

4.4.4 Residual Management. The residuals produced by the treatment system at Stewart, MN included wastewater produced from the gravity filter and adsorption vessels. Wastewater produced was discharged to the building sump, which emptied by gravity to two holding tanks and was then pumped to the sanitary sewer. The total volume of wastewater produced was 182,372 gal, which represents a wastewater generation rate of approximately 1.8%. The AD-33 media was not exhausted during the first six months of system operation, so there were no residuals associated with spent media.

4.4.5 Reliability and Simplicity of Operation. No significant scheduled or unscheduled downtime has been required since installation of the treatment system. The simplicity of system operation and operator skill requirements are discussed including pre- and post treatment requirements, levels of system automation, operator skill requirements, preventative maintenance activities, and frequency of chemical/media handling and inventory requirements.

4.4.5.1 Pre- and Post-Treatment Requirements. Due to the high TOC and ammonia levels in source water, KMnO_4 , instead of chlorine, was originally selected to oxidize As(III) and Fe(II). Prior to system startup, however, the operator indicated his preference of using liquid NaMnO_4 instead of powdered KMnO_4 . Subsequently, a modification of the initial design was implemented by the City in December 2005 to include the use of a 20% liquid NaMnO_4 solution with a 1-gph chemical metering pump. To achieve the target dosage, the chemical metering pump operated with a 25% stroke and 2.5% speed settings. Based on measurements with a calibration cylinder, these settings corresponded to a 0.092-gph application rate, equivalent to only 9.2% of the pump's maximum capacity. The pump size and low settings contributed to difficulties in controlling the NaMnO_4 dose and the pump appeared to have lost prime after February 2, 2006. Without NaMnO_4 injection, it was observed that iron continued to be removed, presumably by aeration and that As(III) continued to be oxidized to As(V) via unidentified processes within the AERALATER[®] gravity filter (see Section 4.5.1.1). No post-treatment requirements existed related to the arsenic removal system.

4.4.5.2 System Automation. The wellhead and high service pumps were automatically controlled by a PLC installed by the City. The AERALATER[®] system did not require significant automation other than the level sensors in the detention tank that controlled the operation of the high service pumps. The AERALATER[®] system did not include automatic backwash triggers, which could be added as a system upgrade. Because the system needed to be backwashed only weekly, the lack of automation for the gravity filter backwash was not a significant inconvenience. However, this lack of automation would likely be an issue at a site requiring more frequent backwash. As noted in Section 4.4.3, it was necessary to disable the automatic backwash capability of the APU-300 system. It was determined that there was no wiring connection between the APU-300 PLC and the City's PLC that controlled the well pumps and high service pumps. Therefore, if an automatic backwash was called for while the well pumps and high service pumps were off, there would not be adequate flow to the adsorption vessels to accomplish the backwash. The City decided not to pursue a change to the control system and manually backwash the adsorption vessels when required.

4.4.5.3 Operator Skill Requirements. Under normal operating conditions, the daily demand on the operator was approximately 10 min for visual inspection of the system and recording of operational data,

such as pressure, volume, and flowrate on field log sheets. The manual backwash operations required an average of 31 min of the operator's time once per week. This is equivalent to approximately 1.7 hr of labor per week. 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.

For the state of Minnesota, there are five water operator certificate class levels, i.e., A, B, C, D, and E (A being the highest). The certificate levels are based on education, experience, and system characteristics, such as water source, treatment processes, water storage volume, number of wells, and population affected. The certified water operator for the City of Stewart has a Class C certificate. Class C requires a high school diploma or equivalent with at least three years of experience in operation of Class A, B, or C systems or a bachelor's degree from an accredited institution with at least one year of experience in the operation of a Class A, B, C, or D systems.

4.4.5.4 Preventative Maintenance Activities. Recommended maintenance activities for the AERALATER[®] system include annual inspection of the aerator internals and slats to monitor iron build-up and perform cleaning if necessary, a complete interior inspection every two years by Siemens, and mechanical and electrical aerator blower checks if performance issues arise. Preventative maintenance tasks for the APU-300 system recommended by the vendor included monthly inspection of the control panel; quarterly checking and calibration of flow meters; biannual inspection of actuator housings, fuses, relays, and pressure gauges; and annual inspection of the butterfly valves. The vendor recommended checking the actuators at each backwash event to ensure that the valves were opening and closing in the proper sequence. Further, inspection of the adsorber laterals and replacement of the underbedding gravel was recommended to be performed concurrent with the media replacement. During this six month time period, two relays that controlled the electrically-actuated valves on the APU-300 system were replaced using spare relays existing in the PLC panel. No other significant repair and maintenance activities were reported during this reporting period.

4.4.5.5 Chemical Handling and Inventory Requirements. No chemical handling requirements were necessary because iron removal occurred by aeration and oxidation of As(III) to As(V) was occurring within the AERALATER[®] filter (see Section 4.5.1.1). Chemical handling of NaMnO₄ was required initially from January 18 to February 2, 2006.

4.5 System Performance

The performance of the AERALATER[®] and APU-300 systems were evaluated based on analyses of water samples collected from the treatment plant, backwash lines, and distribution system.

4.5.1 Treatment Plant. The treatment plant water was sampled on as many as 28 occasions including two duplicate events and seven speciation events during the first six months of system operation. Table 4-6 summarizes the analytical results for As, Fe, and Mn. Table 4-7 summarizes the results of the other water quality parameters. Appendix B contains a complete set of analytical results. The results of the water samples collected throughout the treatment plant are discussed below.

4.5.1.1 Arsenic. Figure 4-12 presents the results of seven speciation events and Figure 4-13 shows total arsenic concentrations measured across the treatment train. Total arsenic concentrations in raw water ranged from 35.5 to 56.4 µg/L with As(III) at 27.9 to 40.7 µg/L existing as the predominant species. Low levels of As(V) and particulate arsenic also were present, averaging 4.5 µg/L and 4.4 µg/L, respectively. Total arsenic concentrations measured during this study period varied in a wider range than those measured historically (i.e., 39.0 to 41.7 µg/L) as shown in Table 4-1.

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

Parameter	Sampling Location	Sample Count	Concentration (µg/L)			Standard Deviation
			Minimum	Maximum	Average	
As (total)	IN	28	35.5	56.4	42.2	6.0
	AC	28	33.5	56.9	41.9	5.5
	AF	28	19.8	38.7	27.0	4.8
	TA	23	0.4	7.4	-(a)	-(a)
	TB	22	0.3	9.2	-(a)	-(a)
	TT	4	<0.1	2.3	-(a)	-(a)
As (soluble)	IN	7	34.1	44.6	39.3	4.2
	AC	7	21.3	44.9	33.8	7.0
	AF	7	18.5	29.2	24.7	3.5
	TA	2	0.4	0.5	-(a)	-(a)
	TB	1	0.2	0.2	-(a)	-(a)
	TT	4	<0.1	3.0	-(a)	-(a)
As (particulate)	IN	7	0.5	8.5	4.4	2.6
	AC	7	<0.1	31.1	11.3	9.6
	AF	7	<0.1	12.3	4.6	5.2
	TA	2	<0.1	0.3	-(a)	-(a)
	TB	1	<0.1	<0.1	-(a)	-(a)
	TT	4	<0.1	0.2	-(a)	-(a)
As (III)	IN	7	27.9	40.7	34.9	4.4
	AC	7	4.2	27.3	22.2	8.1
	AF	7	<0.1	2.9	1.2	1.0
	TA	2	0.6	1.7	-(a)	-(a)
	TB	1	0.9	0.9	-(a)	-(a)
	TT	4	<0.1	0.6	-(a)	-(a)
As (V)	IN	7	1.4	7.0	4.5	2.1
	AC	7	6.1	23.2	11.7	6.1
	AF	7	17.2	26.4	23.4	3.3
	TA	2	<0.1	<0.1	-(a)	-(a)
	TB	1	<0.1	<0.1	-(a)	-(a)
	TT	4	<0.1	2.5	-(a)	-(a)
Fe (total)	IN	28	993	1,491	1,173	111
	AC	28	983	1,309	1,145	91.3
	AF	28	<25	27.4	<25	3.1
	TA	23	<25	337	26.7	67.6
	TB	22	<25	524	35.8	109
	TT	4	<25	<25	<25	-
Fe (soluble)	IN	7	412	1,335	904	292
	AC	7	<25	68.5	<25	21.1
	AF	7	<25	<25	<25	-
	TA	2	<25	<25	<25	-
	TB	1	<25	<25	<25	-
	TT	4	<25	<25	<25	-
Mn (total) ^(b)	IN	27	19.8	44.3	23.7	4.4
	AC	27	20.3	31.4	24.1	2.3
	AF	27	21.9	47.8	29.8	6.6
	TA	23	10.7	31.2	24.9	5.3
	TB	21	7.2	33.2	26.4	6.7
	TT	4	26.4	34.2	29.6	3.3
Mn (soluble) ^(b)	IN	6	20.7	26.1	23.7	1.9
	AC	6	20.3	25.6	23.9	2.0
	AF	6	22.0	41.3	28.5	7.1
	TA	2	17.5	26.0	21.8	6.1
	TT	4	26.7	35.1	29.5	3.8

(a) Average and standard deviation not meaningful for arsenic breakthrough data.

(b) Results from February 2, 2006, sampling event with NaMnO₄ addition not included.

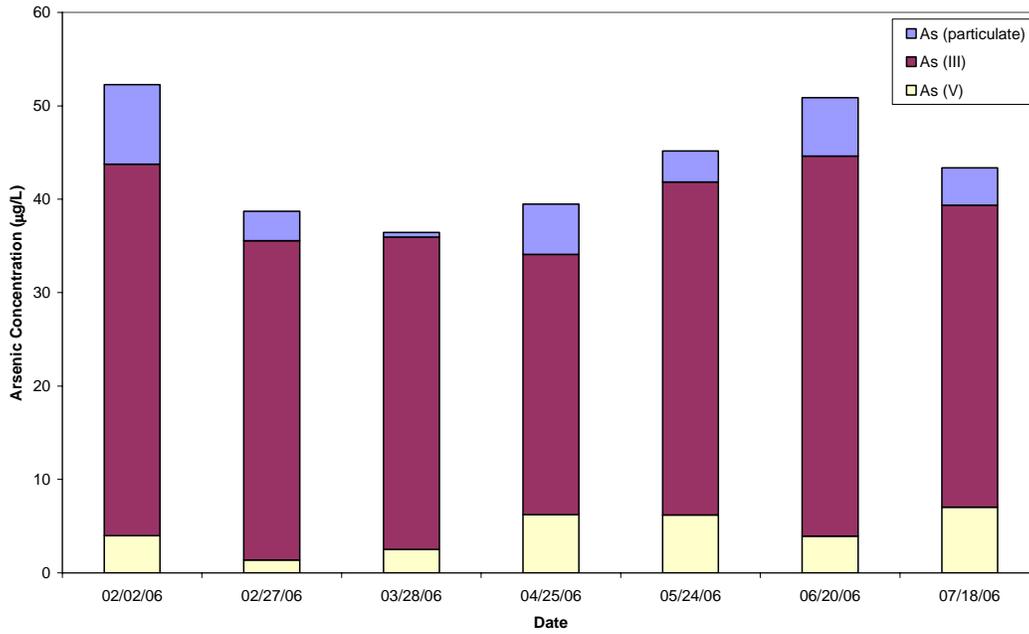
Table 4-7. Summary of Other Water Quality Parameter Results

Parameter	Sampling Location	Unit	Sample Count	Concentration			Standard Deviation
				Minimum	Maximum	Average	
Alkalinity (as CaCO ₃)	IN	mg/L	28	408	454	424	10.6
	AC	mg/L	28	410	447	424	10.5
	AF	mg/L	28	410	448	425	8.8
	TA	mg/L	23	400	454	423	13.3
	TB	mg/L	22	367	444	420	15.3
	TT	mg/L	4	416	427	421	4.6
Ammonia (as N)	IN	mg/L	11	1.0	1.9	1.6	0.3
	AC	mg/L	11	1.1	1.9	1.6	0.3
	AF	mg/L	11	0.9	1.7	1.3	0.2
	TA	mg/L	6	0.6	1.4	1.0	0.3
	TB	mg/L	5	0.4	1.7	1.0	0.5
	TT	mg/L	4	1.0	1.2	1.1	0.1
Fluoride	IN	mg/L	7	0.3	0.6	0.5	0.1
	AC	mg/L	7	0.3	0.5	0.4	0.1
	AF	mg/L	7	0.3	0.6	0.4	0.1
	TA	mg/L	2	0.4	0.4	0.4	0.0
	TB	mg/L	1	0.3	0.3	0.3	-
	TT	mg/L	4	0.4	0.6	0.5	0.1
Sulfate	IN	mg/L	7	<1	<1	<1	-
	AC	mg/L	7	<1	<1	<1	-
	AF	mg/L	7	<1	<1	<1	-
	TA	mg/L	2	<1	<1	<1	-
	TB	mg/L	1	<1	<1	<1	-
	TT	mg/L	4	<1	<1	<1	-
Nitrate (as N)	IN	mg/L	11	<0.05	<0.05	<0.05	-
	AC	mg/L	11	<0.05	<0.05	<0.05	-
	AF	mg/L	11	<0.05	0.44	0.16	0.15
	TA	mg/L	6	<0.05	1.68	0.53	0.62
	TB	mg/L	5	<0.05	1.58	0.53	0.62
	TT	mg/L	4	0.28	0.49	0.37	0.10
Total P (as PO ₄)	IN	mg/L	28	0.25	1.07	0.90	0.15
	AC	mg/L	28	0.78	1.05	0.89	0.06
	AF	mg/L	28	0.27	0.39	0.33	0.04
	TA	mg/L	23	<0.03	0.75	0.06	0.15
	TB	mg/L	22	<0.03	1.03	0.08	0.21
	TT	mg/L	4	<0.03	0.06	<0.03	0.03
Silica (as SiO ₂)	IN	mg/L	28	23.3	28.3	25.6	1.2
	AC	mg/L	28	23.1	28.2	25.3	1.1
	AF	mg/L	27	23.0	28.1	25.1	1.1
	TA	mg/L	23	23.3	28.3	25.4	1.2
	TB	mg/L	22	23.5	28.6	25.4	1.2
	TT	mg/L	4	24.8	27.0	25.5	1.1
Turbidity	IN	NTU	28	4.1	15.0	6.6	2.4
	AC	NTU	28	4.3	15.0	9.2	2.0
	AF	NTU	28	0.4	1.5	0.8	0.3
	TA	NTU	23	0.4	2.2	0.8	0.5
	TB	NTU	22	0.3	3.5	1.1	0.8
	TT	NTU	4	0.4	0.9	0.7	0.2

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

Parameter	Sampling Location	Unit	Sample Count	Concentration			Standard Deviation
				Minimum	Maximum	Average	
TOC	IN	mg/L	6	6.2	6.7	6.4	0.2
	AC	mg/L	6	6.2	7.1	6.5	0.4
	AF	mg/L	6	6.2	6.8	6.4	0.2
	TA	mg/L	1	6.1	6.1	6.1	-
	TT	mg/L	3	6.1	6.6	6.4	0.3
pH	IN	S.U.	26	7.4	8.2	7.9	0.2
	AC	S.U.	26	7.8	8.5	8.2	0.2
	AF	S.U.	26	7.7	8.9	8.2	0.2
	TA	S.U.	20	7.8	8.4	8.1	0.1
	TB	S.U.	20	7.9	8.4	8.2	0.1
	TT	S.U.	5	7.7	8.2	8.1	0.2
Temperature	IN	°C	26	10.1	16.6	11.7	1.4
	AC	°C	26	10.1	13.1	11.3	0.7
	AF	°C	26	10.5	19.3	12.0	1.7
	TA	°C	20	10.6	14.3	11.9	1.1
	TB	°C	20	10.5	15.4	12.0	1.2
	TT	°C	5	10.8	11.7	11.5	0.4
Dissolved Oxygen	IN	mg/L	25	0.5	1.9	1.0	0.5
	AC	mg/L	24	3.8	7.9	5.3	0.9
	AF	mg/L	24	1.6	5.0	2.8	1.0
	TA	mg/L	18	1.9	4.7	2.9	0.7
	TB	mg/L	18	1.9	5.7	3.1	1.0
	TT	mg/L	5	2.4	6.2	3.2	1.6
ORP	IN	mV	26	-36.6	404	194	141
	AC	mV	26	95.9	349	232	71.3
	AF	mV	26	108	386	216	66.3
	TA	mV	20	88.7	323	189	63.9
	TB	mV	20	83.9	321	186	67.0
	TT	mV	5	137	264	180	51.9
Total Hardness (as CaCO ₃)	IN	mg/L	7	200	237	217	13.6
	AC	mg/L	7	189	236	211	16.3
	AF	mg/L	7	206	235	217	10.3
	TA	mg/L	2	209	210	210	0.6
	TB	mg/L	1	214	214	214	-
	TT	mg/L	4	206	240	222	13.7
Ca Hardness (as CaCO ₃)	IN	mg/L	7	101	119	112	6.1
	AC	mg/L	7	95.0	118	108	9.4
	AF	mg/L	7	102	120	111	6.4
	TA	mg/L	2	103	104	104	0.1
	TB	mg/L	1	113	113	113	-
	TT	mg/L	4	104	122	114	8.3
Mg Hardness (as CaCO ₃)	IN	mg/L	7	94.0	117	105	10.5
	AC	mg/L	7	93.9	118	103	9.8
	AF	mg/L	7	93.6	117	106	7.7
	TA	mg/L	2	105	106	106	0.7
	TB	mg/L	1	101	101	101	-
	TT	mg/L	4	99.8	119	108	9.1

Arsenic Speciation at the Wellhead (IN)



Arsenic Speciation after Contact Tank (AC)

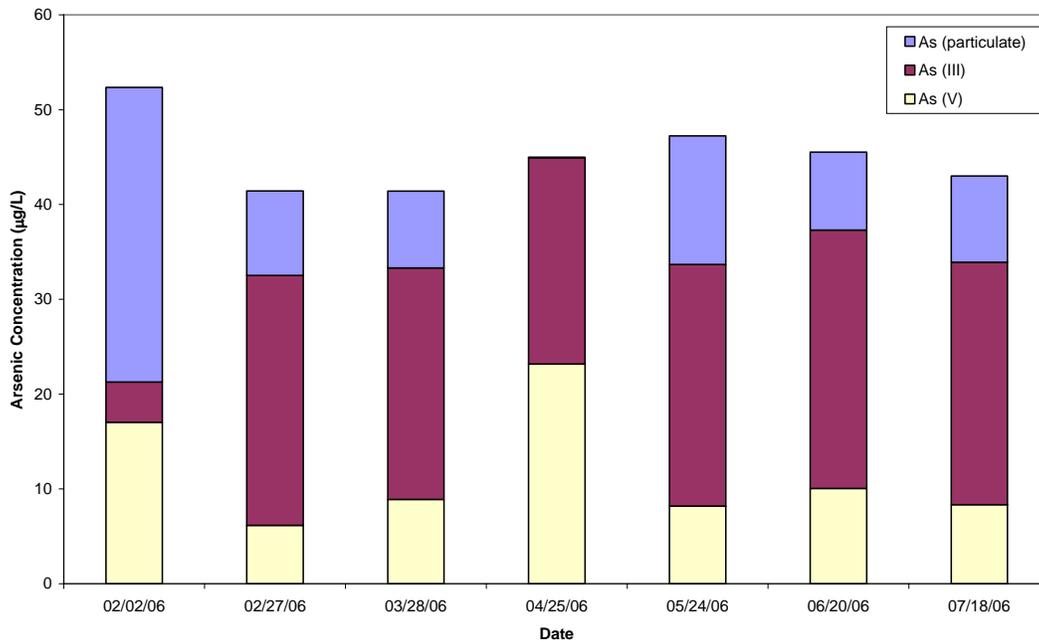
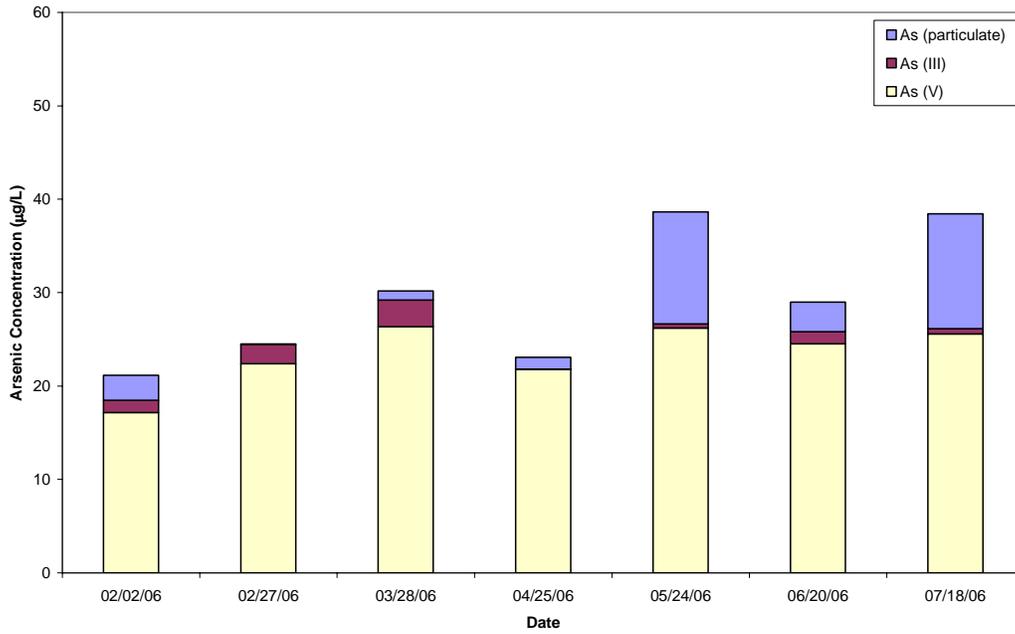
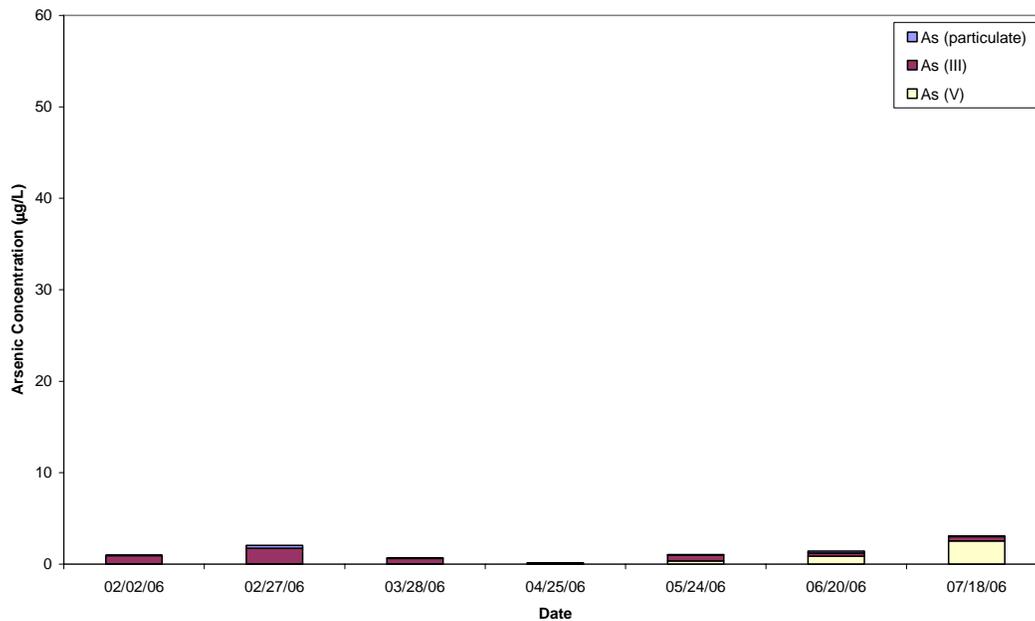


Figure 4-12. Arsenic Speciation Results at Wellhead (IN), After Contact Tank (AC), After Filtration (AF), and After Vessels A and B Combined (TT)

Arsenic Speciation after Filtration (AF)



Arsenic Speciation after Combined Effluent (TT)



Note: Samples from 02/02/06 taken from TB and 02/27/06, 03/28/06 taken from TA due to absence of combined effluent tap.

Figure 4-12. Arsenic Speciation Results at Wellhead (IN), After Contact Tank (AC), After Filtration (AF), and After Vessels A and B Combined (TT) (Continued)

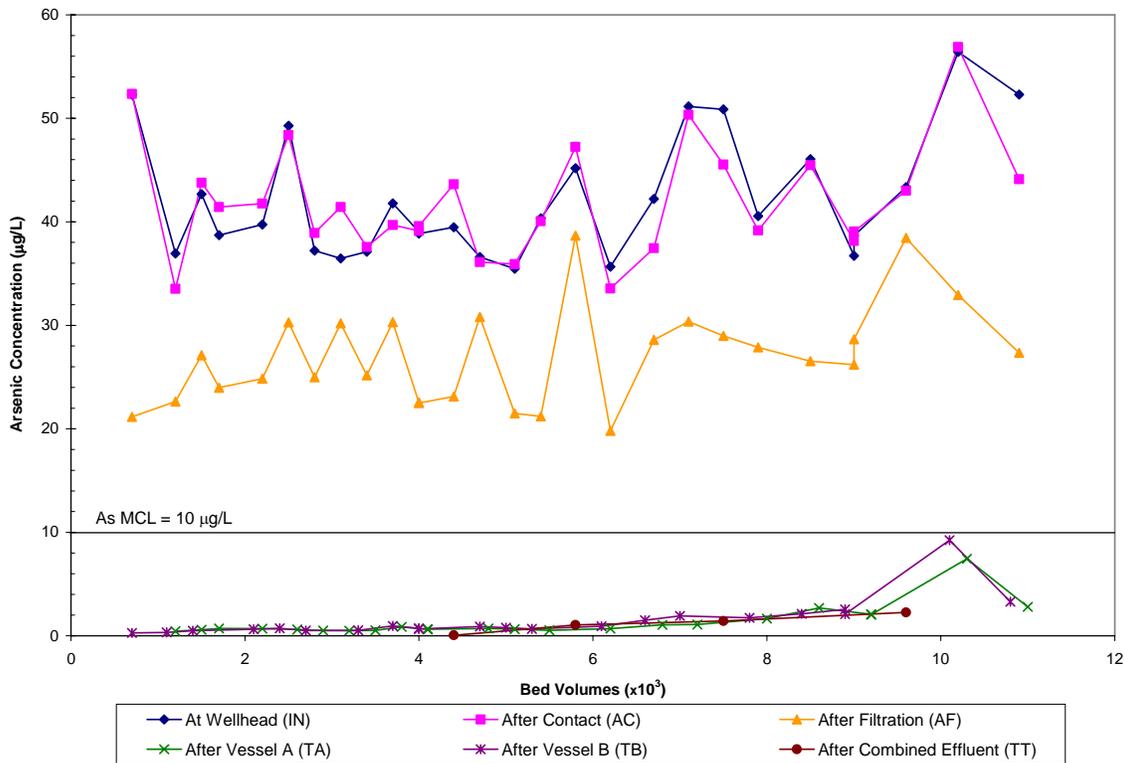


Figure 4-13. Total Arsenic Concentrations Across Treatment Train

Arsenic Removal with NaMnO_4 Addition. Upon completion of shakedown and startup on January 18, 2006, the treatment system was operated with the addition of NaMnO_4 for As(III) and Fe(II) oxidation. However, the NaMnO_4 addition was disrupted due to loss of prime within one week after the first sampling and speciation event on February 2, 2006, based on the measurements of solution level and consumption rate in the chemical day tank.

For the February 2, 2006, sampling event, out of 52.3 $\mu\text{g/L}$ of total arsenic in raw water, 39.8 $\mu\text{g/L}$ was present as As(III). Iron at 1,240 $\mu\text{g/L}$ existed almost entirely as soluble iron. The As(III) and Fe(II) concentrations were decreased to 4.2 and < 25 $\mu\text{g/L}$, respectively, following NaMnO_4 preoxidation, aeration, and detention. About 0.51 mg/L of NaMnO_4 (as Mn) was believed to have been added to raw water based on the difference in total Mn concentrations between the IN and AC sampling locations. This amount was close to the stoichiometrically-estimated dosage of 0.42 mg/L (as Mn) based on February 2, 2006, raw water data, and, therefore, should be sufficient to oxidize most, if not all, As(III) and Fe(II) in raw water. It should be noted, however, that the NaMnO_4 target dosage was estimated based mainly on the levels of soluble As, Fe, and Mn in raw water (see data in Appendix B) and that the elevated TOC level at 6.7 mg/L could add to the oxidant demand as to be discussed in Section 4.5.1.3. The As(V) thus formed, along with the pre-existing As(V), was adsorbed onto and/or co-precipitated with the iron solids formed during the preoxidation step, resulting in 31.1 $\mu\text{g/L}$ of particulate arsenic after the detention tank.

The February 2, 2006, AC location results also indicated the presence of a significant amount of As(V), i.e., 17.0 $\mu\text{g/L}$, after the detention tank, suggesting insufficient naturally occurring iron in raw water for more complete As(V) treatment to below the 10- $\mu\text{g/L}$ MCL. The concentration ratio of soluble iron to soluble arsenic in raw water was 26:1 on February 2, 2006, which was over the 20:1 target ratio for

effective arsenic removal via iron removal process (Sorg, 2002). The relatively inefficient As(V) removal observed might be attributed to the relatively high levels of pH (i.e., 8.2), competing anions (1.0 mg/L of total phosphorous [as PO₄] and 27.6 mg/L of Si [as SiO₂]), and TOC (i.e., 6.7 mg/L) in raw water, all of which could adversely impact the As(V) removal by natural iron solids.

The February 2, 2006, results also showed that the gravity filter was highly effective in removing particulate matter, leaving only 2.7 µg/L of particulate arsenic and below the detection limit of iron in the filter effluent. Also present in the filter effluent were 17.2 µg/L of As(V) and 1.3 µg/L of As(III). As expected, As(V) in the filter influent was left essentially untreated. However, As(III) concentrations were reduced from 4.2 to 1.3 µg/L across the filter bed. Conversion of As(III) to As(V) in the gravity filter also was observed during the subsequent sampling events after the addition of NaMnO₄ had been inadvertently discontinued due to a pump problem. This unexpected finding is discussed in the following paragraphs.

Arsenic Removal without NaMnO₄ Addition. As noted above, after the February 2, 2006, sampling event, the NaMnO₄ metering pump lost prime, thus inadvertently discontinuing NaMnO₄ addition for As(III) oxidation. The disruption of chemical addition was confirmed by both the lack of chemical consumption in the NaMnO₄ day tank and the decrease in Mn concentrations in the AC samples taken after the detention tank starting from the second sampling event on February 14, 2006.

As typified by the results of the first speciation event on February 27, 2006, since discontinuation of NaMnO₄ addition, very little As(III) conversion occurred via aeration, with 34.2 µg/L in raw water and 26.4 µg/L following aeration and detention. This observation was consistent with the general notion that aeration was not effective in oxidizing As(III) (Ghurye and Clifford, 2001). Nonetheless, some As(III) oxidation still occurred, with As(V) concentrations increasing from 1.4 to 6.1 µg/L and particulate arsenic concentrations from 3.2 to 8.9 µg/L after aeration and detention. The amount of particulate arsenic formed via aeration was 5.7 µg/L (i.e., the difference of 3.2 and 8.9 µg/L on February 27, 2006), compared to 22.6 µg/L (i.e., the difference of 8.5 and 31.1 µg/L) formed following NaMnO₄ preoxidation and aeration on February 2, 2006. Note that the levels of soluble iron in February 2 and 27, 2006, raw water samples were comparable at 1,159 and 1,193 µg/L, respectively.

As discussed in the *Design Manual for the Removal of Arsenic from Drinking Water Supplies by Iron Removal Process* (Hoffman et al., 2006), the use of a chemical oxidant and the point of chemical oxidant addition are critical to optimize arsenic removal via iron removal process. Research has shown that iron particles that were formed in the presence of As(V), like the case of preoxidation with NaMnO₄, had more capacity to remove As(V) than pre-formed iron particles, as with the case of aeration. Edwards (1994) reported that pre-formed iron hydroxides only reached 1/5 to 1/6 of the maximum adsorption density for iron hydroxides formed in the presence of As(V). The differences in adsorption densities were attributed to certain mechanisms, i.e., strictly surface adsorption versus adsorption and co-precipitation. Lytle and Snoeyink (2003) also observed that arsenic removal was lower with pre-formed iron solids, as opposed to the ideal case of oxidizing both Fe(II) and As(III) at the same time. Consequently, the oxidation of iron and arsenic should occur at the same time to achieve ideal arsenic removal.

The February 27, 2006 speciation results also showed that, even without the use of NaMnO₄, most As(III) in the filter influent was oxidized to As(V) within the gravity filter, with the As(V) concentration elevated to 22.4 µg/L and particulate arsenic reduced to <0.01 µg/L in the filter effluent. The amount of As(V) in the filter effluent suggested that a portion of the As(V) formed in the filter along with that already existing in the filter influent was removed, presumably, by attaching to the iron solids accumulating in the filter. Removal of As(V) also was observed during the other five subsequent speciation events, with removal rates ranging from 13% to 51% and averaging 28%. These As(V) removal rates were lower than the 57%

As(V) removal rate achieved on February 2, 2006, following NaMnO_4 preoxidation. Adsorption of As(V) on pre-formed iron solids, as discussed above, probably explained why the removal rates were lower.

As observed above, the gravity filter was effective in removing particulate iron and arsenic, as indicated by $<25 \mu\text{g/L}$ of iron and $<3.2 \mu\text{g/L}$ of particulate arsenic (except for two cases) in the filter effluent throughout this part of study period. Because As(III) was unexpectedly oxidized to As(V) in the filter under natural conditions, it was decided to continue the study without the NaMnO_4 addition.

In summary, after the use of NaMnO_4 was discontinued, the average As(III) and As(V) concentrations following the contact tank (AC) were 25.1 and 10.8 $\mu\text{g/L}$, respectively. The average As(III) level in the gravity filter (AF) decreased to 1.2 $\mu\text{g/L}$ and As(V) increased to 24.5 $\mu\text{g/L}$ (only including data after February 2, 2006). As shown by Figure 4-13, on average, approximately 34% of total arsenic was removed by the gravity filter, lower than the 60% occurred during the single sampling event on February 2, 2006, with NaMnO_4 addition. Arsenic exiting the gravity filter was removed by the AD-33 media in the APU-300 system. After approximately 10,900 BV of throughput, the effluent arsenic concentrations were 2.8 and 3.3 $\mu\text{g/L}$ following Vessels A and B, respectively. There was one outlier event on July 25, 2006, as discussed below where total arsenic at 7.4 to 9.2 $\mu\text{g/L}$ and total iron at 337 to 534 $\mu\text{g/L}$ were observed in the respective effluent. However, by the next sampling event on August 1, 2006, the effluent concentration returned to an average of 3.1 $\mu\text{g/L}$ and the trend of gradual arsenic breakthrough resumed as typically would be expected with an adsorption system (see Figure 4-13).

Microbial-Mediated As(III) Oxidation. Since the NaMnO_4 addition was ceased, As(III) was unexpectedly oxidized to As(V) in the gravity filter apparently via certain natural pathways. Figure 4-14 shows the biogeochemical cycle of arsenic as it is transformed between the As(III) and As(V) states in the environment. This transformation often is mediated by microbial activities. Several researchers have reported the presence of As(III)-oxidizing bacteria in natural waters, including surface water and groundwater (Oremland and Stolz, 2003; Battaglia-Brunet et al., 2002; Hambsch et al., 1995), with over 30 strains of microorganisms identified. These microorganisms are categorized in two groups, i.e., heterotrophic arsenite oxidizers (HAOs) and chemolithoautotrophic arsenite oxidizers (CAOs) based on the pathways involved in arsenite oxidation. The term heterotroph means that the microbe uses organic carbon substrates for its biomass growth, while the term autotroph means that the microbe uses inorganic carbon (e.g. CO_2) for its biomass growth. These two types of microorganisms oxidize As(III) through the following mechanisms (Oremland and Stoltz, 2003):

- **Heterotrophic Arsenite Oxidizers.** The HAOs primarily oxidize As(III) as a detoxification reaction that converts As(III) to As(V) at the cell membrane. This helps to inhibit its entry into the cellular structure. This reaction does not create energy or biomass for the HAO microbe.
- **Chemolithoautotrophic Arsenite Oxidizers.** The CAOs use As(III) as an electron donor to reduce oxygen or nitrate and to use the energy to fix CO_2 into biomass. The term chemolithoautotroph refers to the microbe that uses chemical reactions for energy (“chemo”) and uses inorganic electron donors (“litho”) to fix CO_2 into biomass (“autotroph”).

Through research efforts under a separate task order, researchers at EPA and Battelle observed similar naturally-occurring As(III) oxidation processes in a gravity sand filter following aeration at the Greene County Southern Plant (GCSP) in Beaver Creek, OH. Raw water at the Plant contained 45.9 and 2,280 $\mu\text{g/L}$ of total arsenic and iron, both existing almost entirely in the soluble form. Upon aeration and

filtration, As(III) concentrations were reduced from 37.2 µg/L (on average) in the filter influent to 1.2 µg/L (on average) in the filter effluent. As(V) removal across the filter bed was 77%, much higher than the 28% observed at the Stewart, MN facility without NaMnO₄ preoxidation (Wang, 2006a). Higher As(V) removal at the GCSP was likely due to the lower pH value at 7.5, which is more favorable for As(V) adsorption onto iron solids, and the <10 µg/L of total phosphorous, which eliminated a source of competing species for As(V) removal. At the GCSP, the oxidation of As(III) co-occurred with nitrification in the filter bed, which converted almost 100% of the 1.2 mg/L of NH₃ (as N) (on average) in the filter influent to NO₃⁻ in the filter effluent (Wang, 2006a; Lytle et al., 2007). Nitrification, however, was determined not to be directly responsible for As(III) oxidation under an internally-funded research project at Battelle. The results of this study will be further discussed under Section 4.5.1.5.

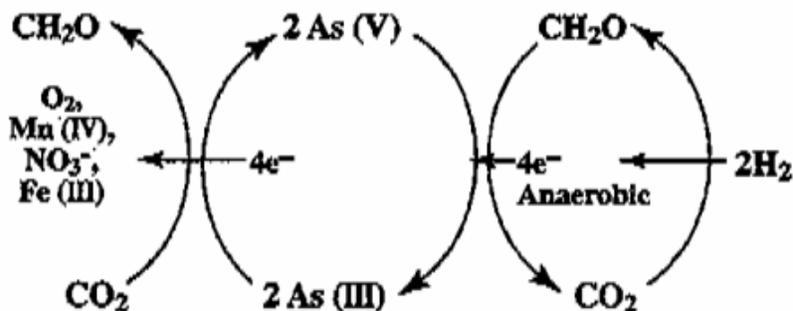


Figure 4-14. Biogeochemical Cycle of Arsenic (Oremland et al., 2002)

At the Stewart, MN site, the average As(III) levels declined from 22.2 µg/L in the filter influent to 1.2 µg/L in the filter effluent. The reduction of DO concentrations from 5.3 mg/L after aeration to 2.8 mg/L after the filter suggested that oxygen was the most likely electron-donor in a biologically mediated process and that aerobic conditions persist throughout the filter. A portion of DO removal also might be attributed to the nitrification process that occurred, although this process was shown unrelated to the As(III) oxidation at the GCSP as described below in Section 4.5.1.5.

4.5.1.2 Iron. Figure 4-15 presents total iron concentrations measured across the treatment train. Total iron concentrations in raw water ranged from 993 to 1,491 µg/L, which existed primarily in the soluble form with concentrations averaging at 904 µg/L. The average soluble iron and soluble arsenic concentrations in raw water corresponded to a ratio of 23:1, which was just over the 20:1 target ratio for effective arsenic removal (Sorg, 2002). As discussed above, relatively high pH values and/or high concentrations of competing anion and TOC in raw water might affect the arsenic removal capacity of the natural iron solids.

It appears that aeration alone in the AERALATER[®] unit was sufficient to accomplish complete Fe(II) oxidation. Soluble iron concentrations after aeration and the detention tank were <25 µg/L; complete conversion of soluble iron to particulate iron was achieved with 1,145 µg/L (on average) of particulate iron following the detention tank. The AERALATER[®] filter was effective in removing particulate iron, reducing the iron concentrations to close to or below its detection limit of 25 µg/L over the six month study period. No particulate iron breakthrough was observed from the gravity filter, indicating adequate filter backwash frequency.

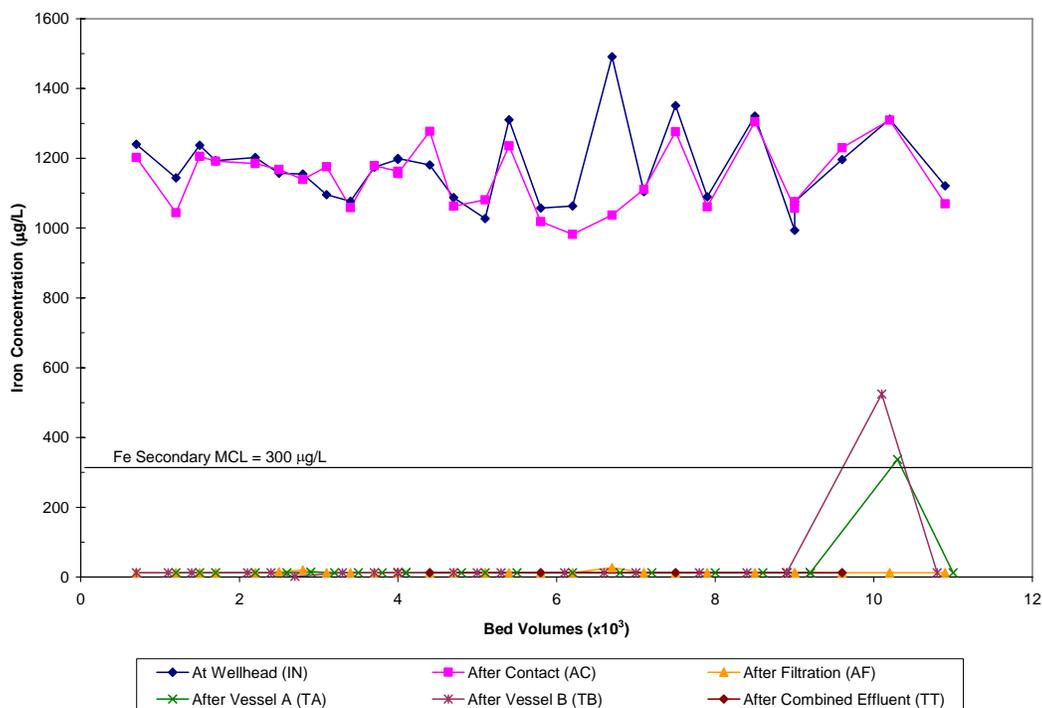


Figure 4-15. Total Iron Concentrations Across Treatment Train

Following the APU-300 adsorption vessels, iron levels remained at <25 µg/L with the exception of one outlier event on July 25, 2006, when total iron (as particulate) appeared to breakthrough from Vessels A and B at 337 and 524 µg/L, respectively. It was not clear what had caused the elevated iron concentrations observed. The system appeared to operate properly at the time with differential pressure across the system remained as low as 1 psi. On the subsequent sampling event on August 1, 2006, the total iron levels from Vessels A and B returned to <25 µg/L.

4.5.1.3 Manganese. Manganese concentrations in raw water ranged from 19.8 to 44.3 µg/L, which existed primarily in the soluble form at an average concentration of 23.7 µg/L. Mn removal is discussed below for treatment system performance both with and without NaMnO₄ addition. For the first sampling event on February 2, 2006, the NaMnO₄ feed pump was operational and a total Mn concentration of 541 µg/L was measured after preoxidation, aeration, and detention. The total Mn concentration following the AERALATER[®] gravity filter (AF) was elevated at 127 µg/L, which existed entirely as soluble Mn. The presence of elevated soluble Mn in the filter effluent was unexpected, because the amount of NaMnO₄ added was very close to the stoichiometric dosage of 0.42 mg/L (as Mn) for the February 2, 2006, raw water and should have been completely consumed and converted to MnO₂ solids during the preoxidation step.

The presence of “soluble Mn,” instead of MnO₂ solids, was probably caused by the presence of high TOC levels in raw water. It is possible that the “soluble Mn” exiting the filter, in fact, was present in the colloidal form that could not be effectively removed by the filter and the 0.45-µm disc filters during speciation. Researchers have reported that high levels of dissolved organic matter (DOM) in source water can form fine colloidal MnO₂ particles, which may not be filterable by conventional gravity or pressure filters (Knocke et al., 1991). Similar observation also was made at another EPA arsenic demonstration

site at Sauk Centre, MN, where elevated levels of “soluble Mn” at up to 1,062 µg/L were observed following the contact tank and Macrolite® pressure filters as the KMnO₄ dosage was progressively decreased from 3.8 to 1.4 mg/L (as Mn) due to concerns over overdosing. (Note that similar to the Stewart, MN system, KMnO₄ was used for the Sauk Centre, MN system to preoxidize as much as 23 and 2,691 µg/L of As(III) and Fe(II), respectively, due to the presence of 4.0 mg/L of TOC.) “Soluble Mn” eventually was reduced as low as 2.5 µg/L as the KMnO₄ dosage was increased to 5.6 mg/L (as Mn). This was due to the fact that by increasing the KMnO₄ dosage the effect of DOM on Mn(II) oxidation was overcome and more filterable particles were formed (Shiao et al., 2007).

At the Stewart site, because the high Mn levels at 127 µg/L exiting the gravity filter occurred only for a very short duration, their effects on arsenic adsorption on the AD-33 media should be minimal. Mn, possibly present in the colloidal form, appeared to have been removed by the AD-33 media, with total Mn levels of 3.7 µg/L measured following the adsorption vessels on February 2, 2006. However, these elevated colloidal Mn levels in the treated water could have become an issue for media performance if NaMnO₄ dosing had continued at the same dosage rate as on February 2, 2006. If it is later decided to restart the NaMnO₄ addition, a jar test is recommended to determine the NaMnO₄ dosage that would be high enough to overcome the effects of DOM in raw water and minimize Mn effluent levels to the AD-33 media. At other EPA demonstration sites with pre-chlorination, such as the Rollinsford, NH site, high Mn loading was found to coat and/or foul the AD-33 media (Oxenham et al., 2005). At this site, the presence of free chlorine promoted the removal of Mn(II) onto the AD-33 media surface.

After the February 2, 2006, sampling event when the NaMnO₄ chemical feed pump lost prime, manganese levels after the contact tank (AC) declined dramatically to levels close to the influent levels at 21 µg/L by the next sampling event on February 14, 2006 (see Figure 4-16). Total Mn levels exiting the AERALATER® filter continued to be elevated at 37.2 to 47.8 µg/L relative to influent levels until March 6, 2006. From February 2 until March 6, 2006, manganese removal across the AD-33 adsorption vessels continued for approximately 2,500 BV and then became equal to the influent values by March 14, 2006. These results suggest that the AD-33 media had only a limited capacity for Mn removal (present as Mn²⁺ ions). As discussed in Section 4.5.1.1, the NaMnO₄ addition was not resumed during the remainder of the study period.

4.5.1.4 pH, DO, and ORP. pH values of raw water ranged from 7.4 to 8.2 and averaging 7.9. pH values increased slightly from an average value of 7.9 at the wellhead to 8.2 after the AERALATER® filter. Aeration probably contributed to this increase in pH. DO levels averaged 1.0 mg/L in raw water and increased to an average value of 5.3 mg/L after aeration. DO concentrations decreased by about 47% to an average value of 2.8 mg/L across the AERALATER® filter. The aerobic biological processes responsible for As(III) oxidation and nitrification processes might have consumed some of the DO in the filter influent (Sawyer et al., 2003). The average DO levels after the APU-300 system ranged from 2.9 to 3.2 mg/L, essentially the same as those that went into the system. ORP levels followed a similar pattern with an initial increase from 194 mV (on average) in raw water to 232 mV after aeration and the detention tank. Again, due to the biological processes, ORP readings decreased slightly to 216 mV (on average) after the AERALATER® filter. ORP levels ranged from 180 to 189 mV after the APU-300 system.

4.5.1.5 Ammonia and Nitrate. Eleven sampling events took place for ammonia and nitrate during this study period. Figure 4-17 presents ammonia and nitrate concentrations across the treatment train. In raw water, ammonia concentrations ranged from 1.0 to 1.9 mg/L (as N) and averaged 1.6 mg/L (as N); nitrate concentrations were consistently less than the method reporting limit of 0.05 mg/L (as N). Following aeration and detention, ammonia and nitrate concentrations remained essentially unchanged, although up to 0.3 mg/L (as N) of concentration increases or decreases were observed for ammonia between the IN

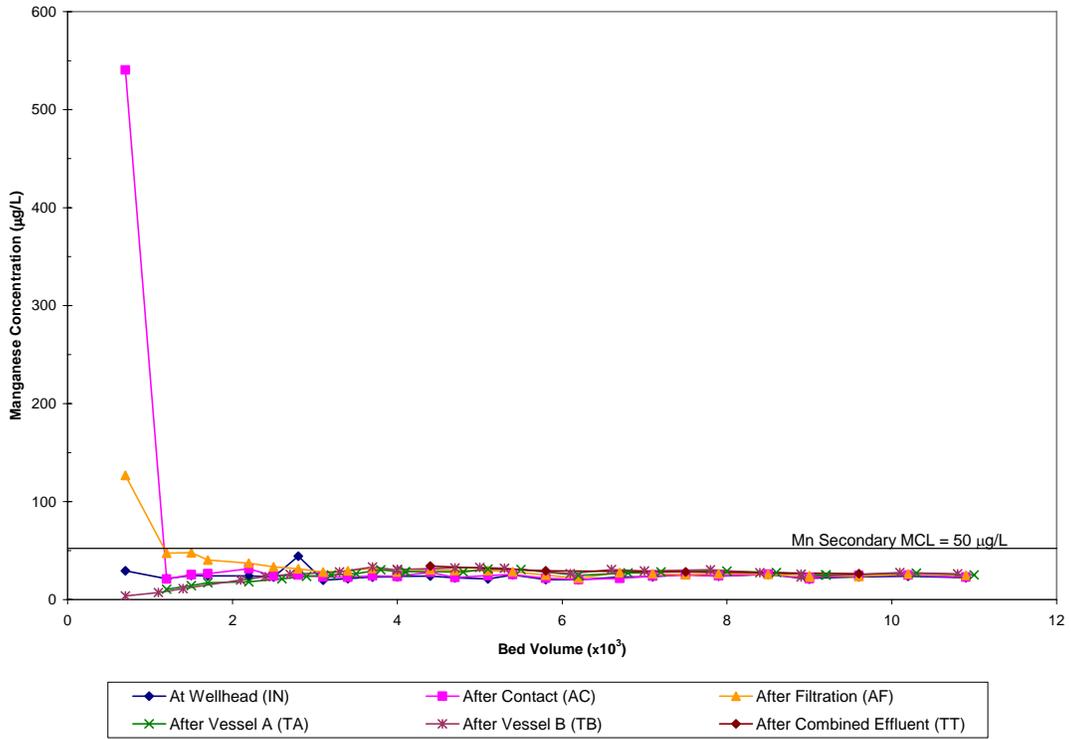


Figure 4-16. Total Manganese Concentrations Across Treatment Train

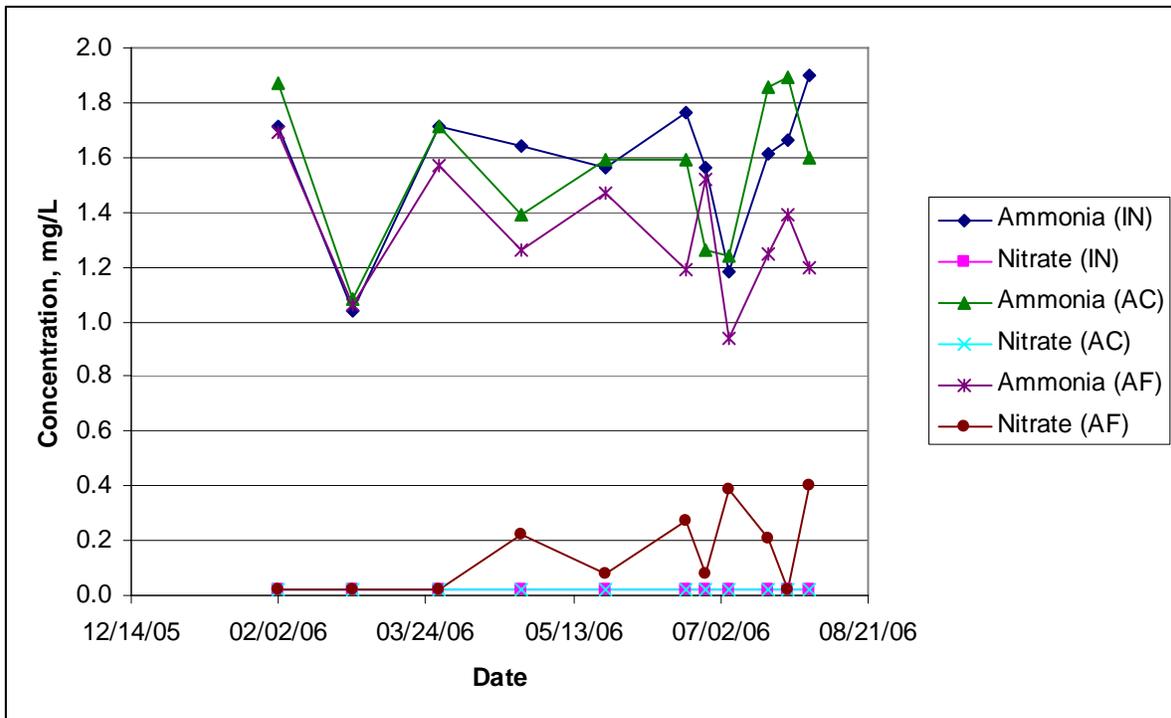


Figure 4-17. Ammonia Removal via Nitrification Across AERALATER[®] Filter

and AC sampling locations. After 69 days of system operation on March 28, 2006, some ammonia removal was observed across the gravity filter and AD-33 adsorption vessels. Ammonia removal across the gravity filter increased from 0.1 mg/L (as N) on Days 69 to 126 to as much as 0.4 mg/L (as N) after Day 153. After Day 69, ammonia removal across the AD-33 adsorption vessels remained at 0.1 to 0.3 mg/L (as N).

Nitrate concentrations remained below 0.05 mg/L (as N) until April 25, 2006, or 97 days after the system startup, and then increased to as high as 0.4 mg/L (as N) across the gravity filter and to 0.2 mg/L across the adsorption vessels. The concentration changes between ammonia and nitrate appear to have a stoichiometric relationship at these sampling locations.

The decreasing ammonia and DO concentrations and increasing nitrate concentrations indicate that significant nitrification was occurring within the gravity filter and AD-33 adsorption vessels after approximately 69 to 97 days of system operation. The 69 day timeframe was based on the observation of ammonia removal, while the 97 day timeframe was based on detectable levels of nitrate in the gravity filter effluent. Under the aerobic conditions in the AERALATER[®] filter, nitrifiers, including *Nitrosomonas* and *Nitrobacters*, can convert ammonia to nitrite and then to nitrate following the reaction equations (Sawyer et al., 2003):



Through research efforts funded separately by EPA and Battelle, researchers have observed similar nitrification processes occurring in gravity filters at the GCSP in Beaver Creek, OH that has a similar treatment train (i.e., aeration and gravity filtration) to the Stewart, MN system (Lytle et al., 2007; Wang, 2006a). In addition, As(III) to As(V) oxidation also was observed possibly through biologically-mediated processes. Based on laboratory column tests conducted with filtered raw water and filter media obtained from the GCSP, it was observed that As(III) oxidation continued to occur even after the nitrification processes had been completely inhibited by lowering the influent pH values to < 5.0 (Clark et al., 1977). This suggests that nitrification is not necessary for the microbial-mediated As(III) oxidation to occur (Wang, 2006b). The same study also showed that, after the filter media in the column had been sterilized with HgCl₂, the pathways responsible for As(III) oxidation apparently were disrupted, thus allowing As(III) to breakthrough from the column with the same amount of As(III) measured both in the column influent and effluent. Furthermore, because significant nitrification was not observed for 97 days compared to 40 days for As(III) oxidation, it was very likely that oxygen, instead of nitrate was the electron acceptor for the microbial-mediated As(III) oxidation process. As discussed above, there was a 47% DO removal rate across the filter with approximately 2.8 mg/L of O₂ in the filter effluent, suggesting the persistence of aerobic conditions through the filter.

4.5.1.6 Other Water Quality Parameters. Alkalinity, fluoride, sulfate, silica, TOC, temperature, and hardness levels remained consistent across the treatment train and were not significantly affected by the treatment process (Table 4-7). TOC levels were elevated at 6.4 mg/L in raw water and remained unchanged across the treatment train. Although high TOC levels might have contributed to the oxidant demand, they did not appear to have been adsorbed onto iron solids. Total phosphorus (as PO₄) decreased from an average concentration of 0.90 mg/L in raw water to an average concentration of 0.33 mg/L after the AERALATER[®] filter. Removal of total phosphorus (as PO₄) also occurred on the AD-33 media with its concentrations reduced to less than 0.1 mg/L (as PO₄) after the AD-33 adsorption vessels in most cases. Turbidity also decreased from 6.6 nephelometric turbidity units (NTU) in the raw water to <1.0 NTU after the AERALATER[®] filter and APU-300 system.

4.5.2 Backwash Water Sampling. Table 4-8 presents the analytical results of six monthly backwash water sampling events for two AERALATER[®] filter cells. The backwash water ranged from 7.9 to 8.1 for pH, 404 to 454 mg/L for TDS, and 28 to 260 mg/L for TSS. The wide range in TSS values observed was attributed to the fact that grab samples were taken directly from the backwash water discharge dump. The average TSS level over this time period was 108 mg/L. Concentrations of total arsenic, iron, and manganese ranged from 168 to 844 µg/L, 17 to 111 mg/L, and 41 to 109 µg/L, respectively, with the majority existing as particulate. Assuming that 6,756 gal of backwash water was produced, on average, from each backwash cycle for four filter cells, approximately 6.1 lb of solids (including 0.02 lb of arsenic, 2.6 lb of iron, and 0.004 lb of manganese) would be generated and discharged per backwash cycle. The quantity of backwash water and amount of backwash solids to be discharged during AERALATER[®] filter backwash will be further monitored during the next six months of system operation with composite backwash samples.

The quantity of backwash water and amount of backwash solids generated during AD-33 adsorption vessels backwash also will be determined during the next six months of system operation with composite backwash samples.

4.5.3 Distribution System Water Sampling. Table 4-9 summarizes the results of the distribution system water sampling. The water quality was similar among the three residences, except for relatively high iron levels on three occasions at DS3 after system startup. Water quality significantly improved after the treatment system began operation. Arsenic, iron, and lead concentrations decreased from average baseline levels of 31.2, 376, and 2.2 µg/L to 5.5, 56, and 0.11 µg/L, respectively, after system startup. Alkalinity, pH, manganese, and copper concentrations remained fairly consistent. Thus, the treatment system appeared to have beneficial effects on the water quality in the distribution system. In general, the arsenic levels were significantly higher in the distribution system water compared to the treatment system effluent (i.e., 5.5 µg/L versus 0.9 µg/L on average), although still below the 10 µg/L MCL. Higher iron levels also were observed in the distribution system water compared to the treatment system effluent (i.e., 56 µg/L versus <25 µg/L on average).

4.6 System Cost

The cost of the system was evaluated based on the capital cost per gpm (or gpd) of the design capacity and the O&M cost per 1,000 gal of water treated. This required the tracking of the capital cost for the equipment, site engineering, and installation and the O&M cost for media replacement and disposal, electricity consumption, and labor. These costs do not include building costs or instrumentation and control upgrades installed by the City of Stewart.

4.6.1 Capital Cost. The capital investment for equipment, site engineering, and installation for the 250-gpm treatment system was \$367,838. The equipment cost was \$273,873 (or 74.4% of the total capital investment), which included \$125,555 for a Siemens' Type II AERALATER[®] system, \$126,482 for a skid-mounted APU-300 system, \$17,952 for ancillary equipment, and \$3,884 for freight (as shown in Table 4-10). The Siemens' Type II AERALATER[®] system included a 11-ft diameter steel unit (which was composed of an aerator, a fan, a detention tank, and a four-cell filter for a total of \$77,000), process valves and piping (\$32,060), instrumentation and controls (\$7,420), 190 ft³ of sand (\$8,400), and other materials (\$675). The APU-300 system included two skid-mounted fiberglass vessels (\$45,360), process valves and piping (\$19,460), instrumentation and controls (\$20,860), 128 ft³ of AD-33 media (\$32,000 or \$250/ft³), and \$8,802 for other materials.

Table 4-8. Backwash Water Sampling Results

Sampling Event		BW1										BW2									
		Backwash Filter Cell No. 1										Backwash Filter Cell No. 2									
		pH	TDS	TSS	As (total)	As (soluble)	As (particulate)	Fe (total)	Fe (soluble)	Mn (total)	Mn (soluble)	pH	TDS	TSS	As (total)	As (soluble)	As (particulate)	Fe (total)	Fe (soluble)	Mn (total)	Mn (soluble)
No.	Date	S.U.	mg/L	mg/L	µg/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
1	03/01/06 ^(a)	8.1	426	92	209	NA	NA	25,897	NA	69.2	NA	8.1	416	36	231	NA	NA	28,765	NA	78.2	NA
2	03/22/06	8.0	432	104	255	23.2	232	31,173	33.5	48.8	26.8	8.0	422	46	176	26.8	149	18,262	37.8	42.2	26.3
3	04/12/06	8.0	428	28	215	28.5	187	18,889	25.8	41.2	28.1	8.0	420	38	168	30.2	138	16,691	47.8	42.9	25.3
4	05/31/06	8.0	454	130	654	29.6	624	55,791	245	70.0	19.5	8.0	436	260	844	26.7	817	73,492	143	86.4	19.0
5	06/28/06	7.9	430	214	835	39.7	795	110,886	206	109	24.3	8.0	404	122	538	30.9	507	69,635	158	103	24.3
6	07/26/06	7.9	428	126	456	38.3	417	52,912	76.7	64.9	24.0	7.9	426	100	403	59.1	343	50,511	133	64.2	24.6

(a) Filtered samples were not collected by the operator.
 TDS = total dissolved solids; TSS = total suspended solids; NA = not analyzed

Table 4-9. Distribution System Sampling Results

No. of Sampling Events	Address	DS1								DS2								DS3								
		520 Croyden Street								321 Martha Street								730 Powers Street								
		LCR								LCR								LCR								
		1st Draw								1st Draw								1st Draw								
Sample Type	Flushed / 1st Draw	Sampling Date	Stagnation Time (hrs)	pH	Alkalinity	As	Fe	Mn	Pb	Cu	Stagnation Time (hrs)	pH	Alkalinity	As	Fe	Mn	Pb	Cu	Stagnation Time (hrs)	pH	Alkalinity	As	Fe	Mn	Pb	Cu
BL1		02/16/05	9.0	7.6	436	27.0	337	21.4	0.8	130	8.5	7.6	414	37.2	1,317	23.2	19.8	0.5	9.0	7.6	418	27.2	311	23.6	1.0	130
BL2		03/16/05 ^(b)	8.5	7.7	466	29.3	404	21.6	0.9	159	10.0 ^(a)	7.5	433	37.1	548	23.0	<0.1	56.3	8.5	7.7	433	29.8	197	20.1	0.5	143
BL3		04/13/05	8.0	7.7	424	30.1	206	26.5	1.1	202	10.0	7.7	424	31.8	174	25.9	0.2	125	8.0	7.7	446	29.7	427	25.7	1.4	162
BL4		05/18/05	9.0	7.7	428	30.5	169	21.3	0.5	105	9.4 ^(a)	7.9	428	33.8	193	21.4	<0.1	195	8.3	7.7	428	30.4	230	22.3	0.5	118
1		02/22/06	8.5	7.9	416	7.8	<25	10.7	<0.1	85.4	7.0	7.9	416	9.9	<25	11.7	<0.1	179	9.8	7.9	420	17.8	<25	17.5	<0.1	103
2		03/21/06	7.8	7.8	406	2.1	<25	20.9	<0.1	35.9	9.5	7.8	410	4.2	<25	16.0	<0.1	131	8.0	7.9	419	9.9	250	20.2	0.4	177
3		04/18/06	8.5	8.0	438	3.5	<25	26.4	0.1	70.4	9.5	7.9	438	4.1	62.8	22.9	<0.1	154	8.8	7.9	434	4.7	249	25.3	0.3	222
4		05/16/06	9.0	7.8	409	3.1	<25	26.9	<0.1	103	9.8	7.8	405	3.5	<25	28.2	<0.1	106	11.5	7.7	405	4.7	<25	29.4	<0.1	184
5		06/13/06	Homeowner did not collect sample								7.0	7.7	433	4.1	<25	30.2	<0.1	338	8.0	7.6	429	3.7	203	30.1	<0.1	226
6		07/11/06	8.0	7.6	419	3.2	<25	24.9	<0.1	91.7	7.5	7.7	415	3.9	<25	23.2	0.4	292	6.3	7.5	415	3.7	45.4	28.4	0.1	203

(a) Estimate provided by the homeowner.
 (b) DS1 sampled on 03/22/05.
 NS = not sampled; NA = not analyzed; BL = Baseline Sampling.

Table 4-10. Capital Investment Cost for Siemens and AdEdge Treatment System

Description	Quantity	Cost	% of Capital Investment Cost
<i>Equipment Costs</i>			
Siemens Type II AERALATER®			
11-ft Diameter Steel, Epoxy-Lined Unit Including Aerator, Fan, Detention tank, and Filter	1	\$77,000	–
Filter Media (ft ³)	190	\$8,400	–
Process Valves and Piping	1	\$32,060	–
Instrumentation and Controls	1	\$7,420	–
Additional Sample Taps	1	\$675	–
<i>Subtotal</i>		\$125,555	–
AdEdge APU-300 System			
63-in Diameter Fiberglass Vessels on Skid	2	\$45,360	–
AD-33 Media (ft ³)	128	\$32,000	–
Gravel Underbedding	1	\$1,540	–
Process Valves and Piping	1	\$19,460	–
Instrumentation and Controls	1	\$20,860	–
Totalizer for Backwash Line	2	\$2,422	–
O&M Manuals	–	\$1,080	–
One-Year O&M Support	–	\$3,760	–
<i>Subtotal</i>		\$126,482	–
Ancillary Equipment			
KMnO ₄ Feed System	1	\$4,192	–
Booster Pumps	2	\$6,580	–
Motor Controls/MCC/HOA for Pumps	1	\$6,850	–
In-Line Mixer	1	\$330	–
<i>Subtotal</i>		\$17,952	–
Freight			
Freight–AD33 Media (lb)	4,460	\$780	–
Freight–Filter Media (lb)	10,000	\$680	–
Freight–System (lb)	26,000	\$2,112	–
Freight–Ancillary Equipment	1	\$312	–
<i>Subtotal</i>		\$3,884	–
Equipment Total	–	\$273,873	74.4%
<i>Engineering Cost</i>			
Vendor Labor	–	\$4,534	
Vendor Travel	–	\$2,480	
Vendor Material	–	\$98	
Subcontractor Labor	–	\$8,400	
Subcontractor Travel	–	\$420	
Subcontractor Material	–	\$588	
Engineering Total	–	\$16,520	4.5%
<i>Installation Cost</i>			
Vendor Labor	–	\$7,920	
Vendor Travel	–	\$3,800	
Subcontractor Mechanical	–	\$39,985	
Subcontractor Electrical	–	\$21,890	
Subcontractor Other Labor	–	\$3,850	
Installation Total	–	\$77,445	21.1%
Total Capital Investment	–	\$367,838	100%

The engineering cost included the cost for the preparation and submission of an engineering submittal package, including process flow diagram of the treatment system, mechanical drawings of the treatment equipment, and a schematic of the equipment footprint as discussed in Section 4.3.1, and the attainment of the required state permit for the implementation of the system. The engineering cost was \$16,520, which was 4.5% of the total capital investment.

The installation cost included the equipment and labor to unload and install the AERALATER[®] and skid-mounted APU-300 systems, perform piping tie-ins and electrical work, and load and backwash the media in both AERALATER[®] filter and AD-33 adsorption vessels (see Section 4.3.3). The installation was performed by AdEdge and a local subcontractor. The installation cost was \$77,445, or 21.1% of the total capital investment.

The capital cost of \$367,838 was normalized to \$1,471/gpm (\$1.02 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 \$34,720/yr using a capital recovery factor (CRF) of 0.09439 based on a 7% interest rate and a 20-yr return period. Assuming that the system operated 24 hr/day, 7 day/wk at the design flowrate of 250 gpm to produce 131,400,000 gal/yr, the unit capital cost would be \$0.26/1,000 gal. During the first six months, the system produced 10,039,000 gal of water (see Table 4-4). At this reduced rate of usage, the unit capital cost increased to \$1.73/1,000 gal.

4.6.2 Operation and Maintenance Cost. The O&M cost included items such as media replacement and disposal, electricity, and labor (see Table 4-11). There was no associated chemical cost after NaMnO₄ addition was discontinued. Although the adsorptive media was not replaced during the first six months of system operation, the media replacement cost would represent the majority of the O&M cost. The vendor estimate was \$41,370 for replacement of 128 ft³ media in the two APU-300 vessels. Because media replacement did not take place, the cost per 1,000 gal of water treated was calculated as a function of projected media run length using the vendor cost estimate (see Figure 4-18). This cost includes new media, gravel underbedding, labor, travel, equipment rental, and freight. The O&M cost will be further refined once the actual breakthrough occurs and the media replacement costs are incurred. A comparison of the electrical bills before and after system installation will be conducted for the one-year study period. Routine labor activities for O&M consumed 10 min/day for operational readings and 31 min/wk for one manual backwash event. This is equivalent to 1.7 hr/wk on a seven day per week basis. The estimated labor cost is \$0.07/1,000 gal of water treated.

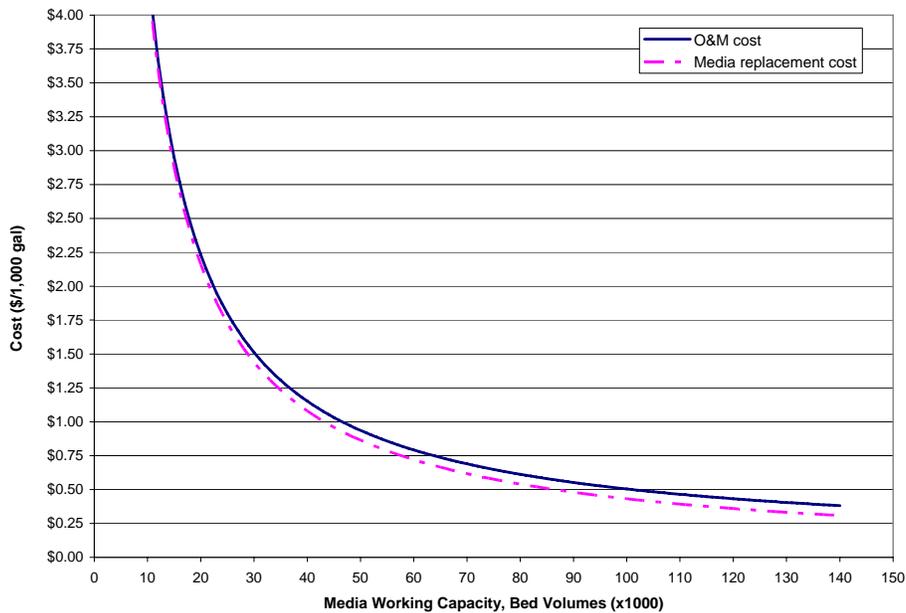


Figure 4-18. Media Replacement and O&M Cost for AERALATER[®] and APU-300 Systems at Stewart, MN

Table 4-11. O&M Cost for City of Stewart, MN Treatment System

Cost Category	Value	Assumptions
Volume Processed (Kgal)	10,039	Through August 1, 2006
Media Replacement and Disposal		
Media Cost (\$/ft ³)	\$250	Vendor quote
Total Media Volume (ft ³)	128	Two vessels
Media Replacement Cost (\$)	\$32,000	Vendor quote
Gravel Underbedding Cost (\$)	\$1,650	Vendor quote
Labor, Travel, and Equipment Cost (\$)	\$6,940	Vendor quote
Freight (\$)	\$780	Vendor quote
<i>Subtotal</i>	\$41,370	Vendor quote
Media Replacement and Disposal Cost (\$/1,000 gal)	See Figure 4-18	Based upon media run length at 10 µg/L arsenic breakthrough
Chemical Usage		
Chemical cost (\$)	–	No chemicals required after KMnO ₄ oxidation discontinued.
Electricity		
Incremental cost (\$/1,000 gal)	–	To be determined on annual basis.
Labor		
Average weekly labor (hrs)	1.7	10 min/day, plus 31 min manual backwash
Labor cost (\$/1,000 gal)	\$0.07	Average labor rate = \$16.33/hr
Total O&M Cost/1,000 gallons	See Figure 4-18	–

5.0 REFERENCES

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APPENDIX A
OPERATIONAL DATA

US EPA Arsenic Demonstration Project AT Stewart, MN – Daily System Operation Log Sheet

Week No.	Day of Week	Date	Well 3			Well 4			AER/LATER	APU-300 Unit						
			Daily Op Hours	Gallon Usage	Average Flowrate	Daily Op Hours	Gallon Usage	Average Flowrate	Backwash	Vessel A Flow Rate	Vessel A Service Totalizer	Cumulative Bed Volumes	Vessel B Flow Rate	Vessel B Service Totalizer	Cumulative Bed Volumes	Combined Backwash Totalizer
			hrs/day	gpd	gpm	hrs/day	gpd	gpm	Yes/No	gpm	gal	BV	gpm	gal	BV	gal
1	Mon	01/30/06 7:35 AM	NA	NA	NA	NA	NA	NA	No	92	282,600	590	91	275,090	575	0
	Tue	01/31/06 7:00 AM	1.13	NA	194	0.00	NA	NA	No	92	288,114	602	91	280,488	586	0
	Wed	02/01/06 7:30 AM	3.82	43,494	190	2.06	23,412	190	No	92	318,183	665	91	309,822	647	0
	Thu	02/02/06 6:30 AM	2.09	24,000	192	1.77	20,661	194	Yes	NA	337,773	705	NA	328,931	687	0
	Fri	02/03/06 8:10 AM	2.99	36,468	203	2.62	11,782	NA	No	NA	365,977	764	NA	355,460	742	7,647
	Sat	02/04/06 8:15 AM	1.79	21,625	201	1.49	37,171	NA	No	92	384,714	804	91	372,554	778	7,647
	Sun	02/05/06 8:50 AM	1.95	22,161	189	1.85	20,990	189	No	92	406,021	848	91	391,931	819	7,647
2	Mon	02/06/06 8:15 AM	2.05	24,290	198	1.84	21,011	190	No	NA	426,860	892	NA	410,436	857	7,647
	Tue	02/07/06 7:10 AM	1.15	12,358	179	1.78	20,212	189	No	NA	442,802	925	NA	424,496	887	7,647
	Wed	02/08/06 8:35 AM	1.79	21,624	201	1.61	18,885	196	No	NA	463,684	968	NA	443,020	925	7,647
	Thu	02/09/06 8:00 AM	2.05	23,675	193	1.33	15,681	196	No	NA	480,412	1,003	NA	457,596	956	7,647
	Fri	02/10/06 9:10 AM	1.62	19,359	199	2.48	26,988	181	No	NA	502,250	1,049	NA	476,125	994	7,647
	Sat	02/11/06 8:10 AM	1.98	22,957	193	1.04	18,157	NA	No	88	532,156	1,111	70	492,894	1,029	7,647
	Sun	02/12/06 8:15 AM	0.90	10,962	204	2.59	20,927	NA	No	NA	541,319	1,131	NA	507,614	1,060	7,647
3	Mon	02/13/06 7:15 AM	1.88	23,374	207	1.98	23,165	195	No	NA	563,172	1,176	NA	525,767	1,098	7,647
	Tue	02/14/06 7:30 AM	1.88	21,674	192	1.98	22,070	186	No	NA	585,122	1,222	NA	544,109	1,136	7,647
	Wed	02/15/06 7:30 AM	1.70	20,800	204	1.10	12,200	185	No	NA	601,420	1,256	NA	557,855	1,165	7,647
	Thu	02/16/06 7:35 AM	1.89	22,522	198	2.09	22,721	181	No	NA	623,167	1,302	NA	576,526	1,204	7,647
	Fri	02/17/06 8:00 AM	0.88	11,304	213	2.56	21,231	NA	Yes	NA	639,994	1,337	NA	591,015	1,234	7,647
	Sat	02/18/06 9:00 AM	1.73	20,640	199	1.63	25,632	NA	No	NA	661,073	1,381	NA	609,618	1,273	7,647
	Sun	02/19/06 8:30 AM	2.04	23,489	192	2.04	22,570	184	No	NA	682,816	1,426	NA	628,969	1,314	7,647
4	Mon	02/20/06 9:00 AM	1.96	23,608	201	1.96	21,159	180	No	NA	704,779	1,472	NA	648,622	1,355	7,647
	Tue	02/21/06 8:00 AM	1.88	23,270	206	2.30	24,939	181	No	NA	726,872	1,518	NA	668,540	1,396	7,647
	Wed	02/22/06 8:45 AM	1.75	20,461	195	1.16	13,770	197	No	NA	742,579	1,551	NA	682,802	1,426	7,647
	Thu	02/23/06 7:30 AM	1.90	22,259	195	2.53	28,905	190	No	NA	763,415	1,594	NA	702,735	1,468	13,472
	Fri	02/24/06 7:50 AM	0.89	11,441	215	1.87	20,614	183	Yes	NA	778,326	1,626	NA	717,060	1,498	13,472
	Sat	02/25/06 8:15 AM	2.75	33,420	202	1.97	21,919	186	No	82	797,262	1,665	78	735,356	1,536	13,472
	Sun	02/26/06 9:30 AM	1.62	19,675	203	1.43	15,778	184	No	NA	814,936	1,702	NA	752,279	1,571	13,472
5	Mon	02/27/06 6:30 AM	1.94	23,429	201	2.06	21,943	178	No	NA	835,831	1,746	NA	772,329	1,613	13,472
	Tue	02/28/06 10:15 AM	1.73	20,670	199	1.64	19,114	194	No	NA	856,567	1,789	NA	792,207	1,655	13,472
	Wed	03/01/06 7:15 AM	2.17	25,600	196	1.03	11,886	193	Yes	NA	872,014	1,821	NA	806,985	1,685	13,472
	Thu	03/02/06 8:15 AM	1.82	20,928	191	2.59	30,144	194	No	NA	971,158	2,028	NA	924,367	1,931	13,472
	Fri	03/03/06 7:45 AM	1.94	22,672	195	1.84	20,528	186	No	NA	992,853	2,074	NA	945,645	1,975	13,472
	Sat	03/04/06 8:30 AM	1.36	16,291	200	1.65	18,618	188	No	NA	1,000,897	2,090	NA	961,433	2,008	13,472
	Sun	03/05/06 8:30 AM	1.70	10,480	NA	1.80	14,480	134	No	NA	1,031,633	2,155	NA	983,608	2,054	13,472
6	Mon	03/06/06 6:40 AM	2.38	36,401	NA	1.84	28,497	NA	No	NA	1,054,674	2,203	NA	1,006,104	2,101	13,472
	Tue	03/07/06 7:00 AM	2.07	24,559	198	1.87	21,008	187	No	NA	1,007,817	2,105	NA	1,029,016	2,149	13,472
	Wed	03/08/06 8:00 AM	1.92	22,272	193	1.73	20,256	195	No	NA	1,100,817	2,299	NA	1,051,005	2,195	13,472
	Thu	03/09/06 7:50 AM	2.01	23,564	195	1.71	19,536	190	No	NA	1,119,988	2,339	NA	1,069,653	2,234	13,472
	Fri	03/10/06 7:30 AM	1.93	22,208	192	1.12	12,879	192	Yes	NA	1,140,465	2,382	NA	1,089,401	2,275	13,472
	Sat	03/11/06 10:00 AM	1.63	20,015	205	2.63	30,521	194	No	NA	1,163,976	2,431	NA	1,112,105	2,323	13,472
	Sun	03/12/06 9:15 AM	1.45	17,342	200	2.17	23,226	179	No	NA	1,181,234	2,467	NA	1,128,707	2,357	13,472
7	Mon	03/13/06 7:10 AM	1.53	18,068	196	2.08	23,544	189	No	NA	1,203,680	2,514	NA	1,150,212	2,402	13,472
	Tue	03/14/06 6:30 AM	1.85	22,320	201	2.06	22,731	184	No	103	1,226,174	2,561	98	1,171,717	2,447	13,472
	Wed	03/15/06 7:45 AM	1.62	19,485	201	0.95	10,646	187	No	NA	1,242,433	2,595	NA	1,187,240	2,480	13,472
	Thu	03/16/06 7:15 AM	1.33	16,545	208	2.04	22,877	187	Yes	NA	1,259,485	2,631	NA	1,203,462	2,514	13,472
	Fri	03/17/06 7:50 AM	3.51	42,956	204	1.95	20,990	179	No	NA	1,291,047	2,697	NA	1,233,215	2,576	13,472
	Sat	03/18/06 6:45 AM	1.89	21,679	192	1.05	11,834	188	No	NA	1,307,759	2,731	NA	1,248,624	2,608	13,472
	Sun	03/19/06 7:30 AM	1.55	19,685	211	2.04	22,885	187	No	NA	1,330,633	2,779	NA	1,269,754	2,652	13,472
8	Mon	03/20/06 7:30 AM	1.90	22,300	196	2.10	23,000	183	No	NA	1,350,435	2,821	NA	1,291,692	2,698	13,472
	Tue	03/21/06 7:00 AM	0.92	11,030	200	1.94	21,957	189	No	104	16,886	2,856	103	16,535	2,732	0
	Wed	03/22/06 10:00 AM	1.60	19,289	201	1.87	20,267	181	Yes	NA	40,391	2,905	NA	39,553	2,780	0
	Thu	03/23/06 7:30 AM	1.45	17,972	206	2.68	30,698	191	No	NA	56,671	2,939	NA	55,448	2,814	0
	Fri	03/24/06 7:30 AM	1.80	19,700	182	1.80	20,000	185	No	NA	79,796	2,987	NA	77,927	2,861	0
	Sat	03/25/06 7:30 AM	2.00	23,500	196	1.60	18,400	192	No	101	99,025	3,027	98	96,604	2,900	0
	Sun	03/26/06 9:30 AM	1.85	21,138	191	1.94	21,323	183	No	NA	123,300	3,078	NA	120,078	2,949	0
9	Mon	03/27/06 7:30 AM	2.18	25,091	192	1.20	13,855	192	No	NA	144,965	3,123	NA	140,960	2,992	0
	Tue	03/28/06 6:15 AM	2.11	25,002	198	1.90	21,943	193	No	104	168,523	3,173	103	163,674	3,040	0
	Wed	03/29/06 6:55 AM	1.07	11,968	186	1.65	18,876	190	No	NA	185,370	3,208	NA	179,924	3,074	0
	Thu	03/30/06 8:30 AM	1.88	21,952	195	1.69	18,762	185	No	NA	208,268	3,256	NA	201,978	3,120	0
	Fri	03/31/06 6:55 AM	2.14	24,732	193	1.07	12,205	190	Yes	NA	226,074	3,293	NA	219,063	3,155	0
	Sat	04/01/06 11:30 AM	2.18	25,777	197	2.27	26,365	194	No	NA	254,724	3,353	NA	246,480	3,213	0
	Sun	04/02/06 9:40 AM	2.17	24,577	189	0.97	11,044	189	No	NA	272,088	3,389	NA	263,018	3,247	0

US EPA Arsenic Demonstration Project AT Stewart, MN – Daily System Operation Log Sheet (Continued)

Week No.	Day of Week	Date	Well 3			Well 4			AERALATER	APU-300 Unit						
			Daily Op Hours	Gallon Usage	Average Flowrate	Daily Op Hours	Gallon Usage	Average Flowrate	Backwash	Vessel A	Vessel A Service	Cumulative Bed	Vessel B	Vessel B Service	Cumulative Bed	Combined Backwash
			hrs/day	gpd	gpm	hrs/day	gpd	gpm	Yes/No	Flow Rate	gal	BV	Flow Rate	gal	BV	gal
10	Mon	04/03/06 7:30 AM	2.31	26,162	189	2.09	23,414	187	No	NA	295,966	3,439	NA	285,813	3,295	0
	Tue	04/04/06 7:30 AM	2.00	23,700	198	1.90	21,400	188	No	91	316,719	3,482	86	305,684	3,336	0
	Wed	04/05/06 7:30 AM	2.30	25,600	186	1.80	21,000	194	No	NA	344,520	3,540	NA	332,196	3,392	0
	Thu	04/06/06 7:10 AM	1.12	12,473	186	1.83	19,876	181	Yes	NA	361,684	3,576	NA	348,582	3,426	0
	Fri	04/07/06 7:30 AM	1.87	22,290	198	2.86	32,647	190	No	NA	385,893	3,627	NA	371,649	3,474	0
	Sat	04/08/06 7:00 AM	1.74	21,447	206	1.02	11,643	190	No	NA	403,723	3,664	NA	388,618	3,510	0
	Sun	04/09/06 7:30 AM	1.67	19,494	195	2.25	24,784	183	No	NA	427,592	3,714	NA	411,311	3,557	0
11	Mon	04/10/06 8:00 AM	1.67	19,984	200	2.16	23,216	190	No	NA	450,987	3,762	NA	433,564	3,603	0
	Tue	04/11/06 7:30 AM	1.84	23,183	210	2.25	24,511	182	No	86	474,931	3,813	83	456,451	3,651	0
	Wed	04/12/06 7:30 AM	1.00	11,200	187	2.00	22,200	185	Yes	NA	493,225	3,851	NA	473,753	3,687	0
	Thu	04/13/06 7:00 AM	2.55	31,353	205	1.94	22,264	191	No	NA	517,323	3,901	NA	496,698	3,735	0
	Fri	04/14/06 7:00 AM	1.50	18,400	204	1.90	17,500	154	No	NA	523,009	3,913	NA	528,566	3,802	0
	Sat	04/15/06 7:50 AM	2.22	26,770	201	1.93	18,942	163	No	NA	542,452	3,954	NA	559,093	3,866	0
	Sun	04/16/06 10:30 AM	1.71	19,890	194	1.98	22,140	186	No	NA	567,273	4,005	NA	581,256	3,912	0
12	Mon	04/17/06 7:15 AM	1.04	13,301	213	2.43	26,140	179	No	NA	585,508	4,043	NA	598,270	3,947	0
	Tue	04/18/06 6:45 AM	2.66	31,353	197	2.55	29,413	192	No	99	611,098	4,097	95	622,415	3,998	0
	Wed	04/19/06 8:00 AM	2.38	26,044	183	2.09	23,477	187	No	94	639,417	4,156	90	649,110	4,054	0
	Thu	04/20/06 7:30 AM	2.14	25,123	195	1.43	16,647	194	No	NA	660,342	4,200	NA	668,800	4,095	0
	Fri	04/21/06 7:30 AM	2.00	22,400	187	1.50	16,600	184	No	NA	683,851	4,249	NA	691,123	4,141	0
	Sat	04/22/06 8:00 AM	2.16	24,196	187	1.86	20,963	188	No	81	706,158	4,295	98	712,438	4,186	0
	Sun	04/23/06 8:00 AM	1.10	12,400	188	1.80	20,900	194	No	NA	725,593	4,336	NA	730,996	4,225	0
13	Mon	04/24/06 7:30 AM	2.35	26,349	187	1.84	20,528	186	No	NA	749,547	4,386	NA	753,989	4,273	0
	Tue	04/25/06 9:30 AM	2.95	32,031	181	1.66	19,477	195	No	89	778,661	4,447	85	782,073	4,331	0
	Wed	04/26/06 7:30 AM	2.51	27,709	184	1.96	22,800	194	No	NA	802,861	4,497	NA	804,962	4,379	0
	Thu	04/27/06 7:30 AM	2.20	25,100	190	2.00	22,300	186	Yes	NA	824,698	4,543	NA	825,800	4,423	0
	Fri	04/28/06 6:50 AM	1.85	22,320	201	2.57	28,594	185	No	NA	847,633	4,591	NA	847,801	4,469	0
	Sat	04/29/06 8:50 AM	1.66	19,662	197	2.03	21,969	180	No	NA	871,240	4,640	NA	870,491	4,516	0
	Sun	04/30/06 10:00 AM	1.72	20,217	196	2.19	24,127	183	No	NA	895,354	4,691	NA	893,704	4,564	0
14	Mon	05/01/06 7:30 AM	2.12	3,014	NA	2.46	27,684	188	No	95	917,086	4,736	92	914,659	4,608	0
	Tue	05/02/06 8:30 AM	1.54	37,248	NA	2.11	22,752	180	No	99	939,085	4,782	96	935,859	4,653	0
	Wed	05/03/06 7:30 AM	1.46	17,635	201	2.09	23,791	190	No	NA	962,737	4,831	NA	958,668	4,700	0
	Thu	05/04/06 7:30 AM	2.00	23,800	198	2.10	22,900	182	Yes	NA	986,918	4,882	NA	982,085	4,749	0
	Fri	05/05/06 7:10 AM	3.04	36,710	201	2.23	24,034	180	No	NA	1,012,484	4,935	NA	1,006,893	4,801	0
	Sat	05/06/06 9:00 AM	1.95	22,390	191	1.86	21,368	192	No	NA	1,036,423	4,985	NA	1,029,783	4,849	0
	Sun	05/07/06 7:30 AM	2.13	25,600	200	2.35	25,280	180	No	NA	1,061,862	5,038	NA	1,054,119	4,900	0
15	Mon	05/08/06 7:30 AM	2.40	28,500	198	2.10	23,500	187	No	NA	1,086,995	5,091	NA	1,078,116	4,950	0
	Tue	05/09/06 8:35 AM	1.53	18,658	203	1.82	21,720	199	No	97	1,112,269	5,144	94	1,102,292	5,000	0
	Wed	05/10/06 7:30 AM	2.09	24,716	197	2.30	23,354	169	No	NA	1,134,854	5,191	NA	1,123,876	5,045	0
	Thu	05/11/06 7:10 AM	2.03	24,237	199	2.13	23,527	184	Yes	NA	1,159,259	5,242	NA	1,147,312	5,094	0
	Fri	05/12/06 7:00 AM	2.92	34,540	197	1.11	12,185	183	No	NA	1,178,114	5,281	NA	1,165,472	5,132	0
	Sat	05/13/06 6:00 AM	1.88	21,183	188	1.98	23,583	198	No	NA	1,197,538	5,322	NA	1,184,169	5,171	0
	Sun	05/14/06 7:50 AM	1.67	18,395	183	1.58	17,094	180	No	NA	1,220,387	5,369	NA	1,206,143	5,217	0
16	Mon	05/15/06 8:10 AM	1.97	22,685	192	1.97	23,770	201	No	NA	1,244,073	5,419	NA	1,229,005	5,265	0
	Tue	05/16/06 7:30 AM	2.16	24,171	187	1.95	21,600	184	No	91	1,267,795	5,468	90	1,251,991	5,313	0
	Wed	05/17/06 7:30 AM	2.10	22,800	181	2.00	22,700	189	No	NA	1,291,456	5,518	NA	1,274,925	5,361	0
	Thu	05/18/06 7:30 AM	2.00	22,700	189	2.10	23,700	188	No	NA	1,315,427	5,568	NA	1,298,223	5,409	0
	Fri	05/19/06 7:30 AM	2.00	22,400	187	2.00	23,000	192	Yes	NA	1,338,976	5,617	NA	1,321,122	5,457	0
	Sat	05/20/06 7:45 AM	0.99	11,480	193	3.66	41,567	189	No	NA	1,361,859	5,665	NA	1,343,381	5,504	0
	Sun	05/21/06 7:15 AM	1.94	23,591	203	2.25	23,694	176	No	NA	1,386,140	5,716	NA	1,367,029	5,553	0
17	Mon	05/22/06 7:45 AM	2.55	29,388	192	3.04	34,384	189	No	NA	1,419,448	5,785	NA	1,399,559	5,621	0
	Tue	05/23/06 7:30 AM	2.32	25,971	186	1.82	21,423	196	No	NA	1,443,607	5,836	NA	1,423,099	5,670	0
	Wed	05/24/06 8:00 AM	2.94	32,620	185	1.86	20,571	184	No	88	1,468,540	5,888	86	1,447,450	5,721	0
	Thu	05/25/06 7:00 AM	2.19	24,104	183	2.09	23,374	187	Yes	NA	1,482,626	5,917	NA	1,470,959	5,770	0
	Fri	05/26/06 7:00 AM	3.10	35,500	191	1.70	19,600	192	No	NA	1,517,547	5,990	NA	1,495,225	5,821	0
	Sat	05/27/06 7:30 AM	3.23	35,755	184	1.96	21,845	186	No	NA	1,545,234	6,048	NA	1,522,268	5,877	0
	Sun	05/28/06 9:00 AM	2.35	26,447	187	3.01	34,541	191	No	NA	1,578,619	6,118	NA	1,554,878	5,945	0
18	Mon	05/29/06 9:30 AM	2.74	30,563	186	1.96	22,237	189	No	NA	1,608,016	6,179	NA	1,583,589	6,005	0
	Tue	05/30/06 7:00 AM	4.24	45,321	178	2.46	28,800	195	No	82	1,640,353	6,247	81	1,615,279	6,072	0
	Wed	05/31/06 10:00 AM	2.84	31,822	186	3.11	34,667	186	Yes	NA	NA	NA	NA	NA	NA	0
	Thu	06/01/06 7:30 AM	3.80	43,981	193	2.57	NA	NA	No	NA	1,710,216	6,393	NA	1,683,814	6,215	0
	Fri	06/02/06 7:00 AM	3.17	37,072	195	2.76	NA	NA	No	NA	1,743,905	6,463	NA	1,716,927	6,284	0
	Sat	06/03/06 7:30 AM	3.13	37,812	201	3.72	39,967	179	No	NA	1,781,981	6,542	NA	1,754,425	6,362	0
	Sun	06/04/06 8:30 AM	3.46	40,896	197	5.57	59,520	178	No	NA	1,838,375	6,660	NA	1,810,012	6,478	0

US EPA Arsenic Demonstration Project AT Stewart, MN – Daily System Operation Log Sheet (Continued)

Week No.	Day of Week	Date	Well 3			Well 4			AERALATER	APU-300 Unit						
			Daily Op Hours	Gallon Usage	Average Flowrate	Daily Op Hours	Gallon Usage	Average Flowrate	Backwash	Vessel A Flow Rate	Vessel A Service Totalizer	Cumulative Bed Volumes	Vessel B Flow Rate	Vessel B Service Totalizer	Cumulative Bed Volumes	Combined Backwash Totalizer
			hrs/day	gpd	gpm	hrs/day	gpd	gpm	Yes/No	gpm	gal	BV	gpm	gal	BV	gal
19	Mon	06/05/06 7:15 AM	2.32	26,796	192	1.69	17,196	170	No	NA	1,859,633	6,705	NA	1,831,041	6,522	0
	Tue	06/06/06 7:15 AM	2.70	32,000	198	3.70	40,100	181	No	NA	1,896,516	6,782	NA	1,867,421	6,598	0
	Wed	06/07/06 7:30 AM	2.08	23,852	191	2.08	22,466	180	No	NA	1,920,563	6,832	NA	1,891,195	6,648	0
	Thu	06/08/06 8:00 AM	3.04	36,343	199	3.43	37,518	182	No	NA	1,956,062	6,906	NA	1,926,446	6,721	0
	Fri	06/09/06 8:00 AM	3.30	39,000	197	3.30	34,400	174	Yes	95	1,993,408	6,984	95	1,963,490	6,799	0
	Sat	06/10/06 9:00 AM	2.69	32,064	199	2.02	22,560	187	No	NA	2,018,564	7,037	NA	1,988,497	6,851	0
	Sun	06/11/06 9:00 AM	2.00	23,500	196	2.10	23,600	187	No	NA	2,042,466	7,086	NA	2,012,255	6,901	0
20	Mon	06/12/06 7:30 AM	2.13	25,387	198	2.35	25,387	180	No	NA	2,066,750	7,137	NA	2,036,415	6,951	0
	Tue	06/13/06 7:00 AM	2.45	30,128	205	2.35	25,430	180	No	95	2,092,388	7,191	96	2,061,868	7,004	0
	Wed	06/14/06 7:10 AM	2.88	32,772	190	4.07	43,399	178	No	NA	2,133,607	7,277	NA	2,102,710	7,090	0
	Thu	06/15/06 7:20 AM	1.89	23,338	206	2.09	23,239	186	Yes	NA	2,157,420	7,327	NA	2,126,215	7,139	0
	Fri	06/16/06 7:00 AM	2.23	24,034	180	2.64	31,132	197	No	NA	2,180,588	7,375	NA	2,149,056	7,186	0
	Sat	06/17/06 7:30 AM	1.37	15,673	190	2.84	31,543	185	No	NA	2,205,255	7,427	NA	2,173,412	7,237	0
	Sun	06/18/06 7:45 AM	3.56	39,390	184	2.28	25,633	188	No	NA	2,238,756	7,496	NA	2,206,522	7,306	0
21	Mon	06/19/06 7:30 AM	1.21	13,642	188	1.92	19,806	172	No	NA	2,256,658	7,534	NA	2,224,265	7,344	0
	Tue	06/20/06 9:30 AM	3.23	35,815	185	1.85	23,262	210	No	95	2,287,962	7,599	95	2,255,247	7,408	0
	Wed	06/21/06 7:00 AM	2.68	29,693	185	2.12	23,219	182	No	NA	2,312,303	7,650	NA	2,279,162	7,458	0
	Thu	06/22/06 7:00 AM	2.80	29,700	177	3.00	33,700	187	Yes	NA	2,344,847	7,718	NA	2,311,172	7,525	0
	Fri	06/23/06 7:30 AM	3.23	37,910	195	3.23	36,049	186	No	NA	2,378,811	7,789	NA	2,344,822	7,595	0
	Sat	06/24/06 9:30 AM	4.89	35,538	121	4.15	44,862	180	No	NA	2,423,121	7,882	NA	2,388,127	7,686	0
	Sun	06/25/06 8:40 AM	0.21	26,832	NA	2.18	23,413	179	No	NA	2,448,429	7,934	NA	2,412,780	7,737	0
22	Mon	06/26/06 7:00 AM	2.36	28,048	198	2.47	26,006	175	No	NA	2,474,481	7,989	NA	2,438,009	7,790	0
	Tue	06/27/06 7:30 AM	2.84	34,188	201	2.16	23,510	182	No	94	2,501,625	8,046	92	2,464,389	7,845	0
	Wed	06/28/06 7:30 AM	2.20	25,000	189	2.60	27,800	178	Yes	NA	2,531,793	8,109	NA	2,493,682	7,906	0
	Thu	06/29/06 7:00 AM	1.84	22,570	205	3.68	41,055	186	No	NA	2,557,220	8,162	NA	2,518,338	7,958	0
	Fri	06/30/06 7:00 AM	2.10	25,000	198	7.90	87,300	184	No	NA	2,616,173	8,285	NA	2,575,296	8,077	0
	Sat	07/01/06 8:00 AM	2.02	23,712	196	3.84	41,280	179	No	NA	2,651,423	8,358	NA	2,609,067	8,147	0
	Sun	07/02/06 8:00 AM	3.30	40,000	202	2.40	25,400	176	No	94	2,681,050	8,420	92	2,637,568	8,207	0
23	Mon	07/03/06 7:00 AM	2.19	24,522	187	3.23	34,017	175	No	NA	2,714,077	8,489	NA	2,669,270	8,273	0
	Tue	07/04/06 7:00 AM	2.80	32,200	192	3.70	39,400	177	No	NA	2,750,262	8,565	NA	2,703,977	8,345	0
	Wed	07/05/06 7:00 AM	3.10	36,400	196	3.40	36,100	177	No	NA	2,786,863	8,641	NA	2,739,016	8,419	0
	Thu	07/06/06 7:00 AM	2.70	31,300	193	3.40	36,600	179	Yes	NA	2,823,623	8,718	NA	2,774,146	8,492	0
	Fri	07/07/06 7:30 AM	4.31	50,841	197	4.31	44,865	173	No	85	2,865,948	8,806	81	2,814,596	8,576	0
	Sat	07/08/06 7:00 AM	3.57	42,791	200	3.47	36,153	174	No	NA	2,908,966	8,896	NA	2,855,521	8,662	0
	Sun	07/09/06 8:30 AM	2.26	25,506	188	5.27	54,306	172	No	NA	2,953,202	8,989	NA	2,897,540	8,750	0
24	Mon	07/10/06 7:30 AM	5.53	64,383	194	2.71	28,800	177	No	NA	2,998,101	9,082	NA	2,940,264	8,839	0
	Tue	07/11/06 7:30 AM	2.60	29,400	188	4.40	46,900	178	No	NA	3,038,652	9,167	NA	2,978,660	8,919	0
	Wed	07/12/06 7:45 AM	4.35	50,177	192	7.62	76,602	168	Yes	NA	3,105,202	9,306	NA	3,041,629	9,051	0
	Thu	07/13/06 7:00 AM	6.50	68,542	176	4.65	53,574	192	No	NA	3,117,350	9,332	NA	3,091,457	9,155	0
	Fri	07/14/06 7:30 AM	3.23	35,363	182	3.33	36,049	180	No	NA	3,156,849	9,414	NA	3,128,875	9,233	0
	Sat	07/15/06 7:30 AM	2.80	30,900	184	2.90	31,800	183	No	80	3,186,370	9,476	78	3,140,070	9,256	0
	Sun	07/16/06 8:00 AM	4.21	48,980	194	4.90	50,155	171	No	NA	3,241,639	9,591	NA	3,192,592	9,366	0
25	Mon	07/17/06 7:30 AM	3.06	34,315	187	2.14	24,919	194	No	93	3,268,449	9,647	91	3,218,007	9,419	0
	Tue	07/18/06 7:30 AM	3.60	38,100	176	5.80	63,500	182	No	NA	3,320,042	9,755	NA	3,266,629	9,521	0
	Wed	07/19/06 7:00 AM	5.31	56,272	177	3.37	37,481	185	No	73	3,366,506	9,852	71	3,310,241	9,612	0
	Thu	07/20/06 7:00 AM	2.00	22,000	183	2.10	23,400	186	No	83	3,388,565	9,898	77	3,330,963	9,655	0
	Fri	07/21/06 7:00 AM	3.50	36,400	173	4.80	50,800	176	Yes	81	3,433,666	9,992	74	3,373,384	9,744	0
	Sat	07/22/06 9:10 AM	3.67	41,732	190	3.49	36,504	175	No	NA	3,473,299	10,075	NA	3,410,821	9,822	0
	Sun	07/23/06 10:10 AM	3.07	35,040	190	3.07	31,200	169	No	NA	3,506,408	10,144	NA	3,442,266	9,887	0
26	Mon	07/24/06 7:15 AM	3.19	35,744	187	3.30	32,670	165	No	81	3,537,286	10,209	87	3,471,541	9,949	0
	Tue	07/25/06 7:00 AM	3.33	36,783	184	5.96	59,318	166	No	NA	3,589,635	10,318	NA	3,520,970	10,052	0
	Wed	07/26/06 6:20 AM	2.88	34,354	199	4.11	43,611	177	Yes	NA	3,626,432	10,395	NA	3,560,844	10,135	0
	Thu	07/27/06 7:00 AM	3.50	42,032	200	6.42	71,805	186	No	NA	3,678,340	10,503	NA	3,616,274	10,251	0
	Fri	07/28/06 7:00 AM	4.30	49,700	193	6.70	70,800	176	No	82	3,734,103	10,620	89	3,675,770	10,375	0
	Sat	07/29/06 8:15 AM	3.99	47,810	200	5.42	56,840	175	No	NA	3,789,942	10,736	NA	3,735,249	10,499	0
	Sun	07/30/06 8:45 AM	7.25	85,224	196	2.84	29,976	176	No	NA	3,847,814	10,857	NA	3,796,925	10,628	0
27	Mon	07/31/06 6:30 AM	2.87	35,972	209	5.08	53,517	176	Yes	NA	3,887,370	10,940	NA	3,838,985	10,716	0
	Tue	08/01/06 9:30 AM	3.82	42,667	186	4.80	51,200	178	No	82	3,931,228	11,031	88	3,885,665	10,814	0

APPENDIX B
ANALYTICAL DATA TABLES

Analytical Results from Long-Term Sampling at Stewart, MN

Sampling Date		02/02/06 ^(c)				02/14/06					02/21/06					02/27/06 ^(c)				03/06/06				
Parameter	Unit	IN	AC	AF	TB	IN	AC	AF	TA	TB	IN	AC	AF	TA	TB	IN	AC	AF	TA	IN	AC	AF	TA	TB
Bed Volume (10 ³)	BV	-	-	-	0.7	-	-	-	1.2	1.1	-	-	-	1.5	1.4	-	-	-	1.7	-	-	-	2.2	2.1
Alkalinity (as CaCO ₃)	mg/L	423	432	427	432	421	442	417	438	421	419	419	419	419	414	422	413	434	418	419	410	427	419	419
Ammonia (as N)	mg/L	1.7	1.9	1.7	1.7	-	-	-	-	-	-	-	-	-	-	1.0	1.1	1.1	1.1	-	-	-	-	-
Fluoride	mg/L	0.3	0.3	0.3	0.3	-	-	-	-	-	-	-	-	-	-	0.4	0.4	0.4	0.4	-	-	-	-	-
Sulfate	mg/L	<1	<1	<1	<1	-	-	-	-	-	-	-	-	-	-	<1	<1	<1	<1	-	-	-	-	-
Nitrate (as N)	mg/L	<0.05	<0.05	<0.05	<0.05	-	-	-	-	-	-	-	-	-	-	<0.05	<0.05	<0.05	<0.05	-	-	-	-	-
Total P (as PO ₄)	mg/L	1.0	0.9	0.3	<0.03	0.9	0.8	0.3	<0.03	<0.03	0.9	0.9	0.3	<0.03	<0.03	0.9	0.9	0.3	<0.03	0.9	0.9	0.3	<0.01	<0.01
Silica (as SiO ₂)	mg/L	27.6	25.6	24.9	24.1	25.6	26.9	25.7	24.4	25.4	26.3	25.7	25.0	25.3	24.8	26.5	24.6	23.0	23.8	24.6	24.6	24.2	23.7	24.1
Turbidity	NTU	7.3	4.3	0.9	2.0	7.9	15	1.4	1.7	1.8	6.5	15	1.1	0.8	0.9	9.2	9.6	0.7	1.0	7.1	8.9	1.5	1.6	3.5
TOC	mg/L	6.7	7.1	6.8	NA ^(a)	-	-	-	-	-	-	-	-	-	-	6.3	6.7	6.3	NA ^(a)	-	-	-	-	-
pH	S.U.	8.2	8.2	8.4	8.2	7.6	7.9	7.9	7.9	7.9	7.6	8.3	8.3	8.2	8.4	7.4	7.9	7.7	7.8	7.7	8.3	8.0	8.0	8.1
Temperature	°C	11.4	11.8	12.4	10.9	11.4	11.4	12.4	13.1	13.4	12.9	10.5	11.7	12.1	12.2	10.6	11.5	11.9	12.5	10.5	10.1	11.6	11.8	11.4
DO	mg/L	1.1	7.9	5.0	4.8	1.1	NA ^(b)	1.3	6.0	4.0	3.4	1.8	6.3	3.2	3.6	3.4								
ORP	mV	-36.6	250	203	256	35.2	128	166	175	179	294	341	333	323	321	271	273	176	177	300	288	281	289	307
Total Hardness (as CaCO ₃)	mg/L	211	209	206	214	-	-	-	-	-	-	-	-	-	-	226	224	212	210	-	-	-	-	-
Ca Hardness (as CaCO ₃)	mg/L	112	113	113	113	-	-	-	-	-	-	-	-	-	-	109	110	105	103	-	-	-	-	-
Mg Hardness (as CaCO ₃)	mg/L	98.9	95.4	93.6	101	-	-	-	-	-	-	-	-	-	-	117	114	107	106	-	-	-	-	-
As (total)	µg/L	52.3	52.4	21.2	0.3	36.9	33.5	22.6	0.4	0.3	42.7	43.8	27.1	0.6	0.5	38.7	41.4	24.0	0.7	39.7	41.8	24.8	0.7	0.6
As (soluble)	µg/L	43.8	21.3	18.5	0.2	-	-	-	-	-	-	-	-	-	-	35.6	32.5	24.4	0.4	-	-	-	-	-
As (particulate)	µg/L	8.5	31.1	2.7	<0.1	-	-	-	-	-	-	-	-	-	-	3.2	8.9	<0.1	0.3	-	-	-	-	-
As (III)	µg/L	39.8	4.2	1.3	0.9	-	-	-	-	-	-	-	-	-	-	34.2	26.4	2.0	1.7	-	-	-	-	-
As (V)	µg/L	4.0	17.0	17.2	<0.1	-	-	-	-	-	-	-	-	-	-	1.4	6.1	22.4	<0.1	-	-	-	-	-
Fe (total)	µg/L	1240	1202	<25	<25	1144	1044	<25	<25	<25	1238	1205	<25	<25	<25	1193	1192	<25	<25	120	1185	<25	<25	<25
Fe (soluble)	µg/L	1159	<25	<25	<25	-	-	-	-	-	-	-	-	-	-	855	<25	<25	<25	-	-	-	-	-
Mn (total)	µg/L	29.4	541	127	3.7	21.3	21.0	47.4	10.7	7.2	24.5	25.4	47.8	14.2	11.2	24.3	26.5	40.5	17.1	24.3	31.4	37.2	18.2	20.1
Mn (soluble)	µg/L	29.7	118	138	3.6	-	-	-	-	-	-	-	-	-	-	24.7	24.8	41.3	17.5	-	-	-	-	-

- (a) TOC sample bottle broke during transit.
- (b) Operator recorded DO readings as percentage therefore no reading available.
- (c) TT sample tap is not present. Sample taken from individual vessel for speciation week.

Analytical Results from Long-Term Sampling at Stewart, MN (Continued)

Sampling Date		03/14/06					03/21/06					03/28/06 ^(a)				04/04/06					
Sampling Location	Parameter	IN	AC	AF	TA	TB	IN	AC	AF	TA	TB	IN	AC	AF	TA	IN	AC	AF	TA	TB	
	Bed Volume (10 ³)	BV	-	-	-	2.6	2.4	-	-	-	2.9	2.7	-	-	-	3.2	-	-	-	3.5	3.3
	Alkalinity (as CaCO ₃)	mg/L	422	422	422	426	426	419	419	423	423	423	408	416	412	416	414	410	410	414	414
	Ammonia (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	1.7	1.7	1.6	1.4	-	-	-	-	-
	Fluoride	mg/L	-	-	-	-	-	-	-	-	-	-	0.4	0.4	0.4	0.4	-	-	-	-	-
	Sulfate	mg/L	-	-	-	-	-	-	-	-	-	-	<1	<1	<1	<1	-	-	-	-	-
	Nitrate (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	<0.05	<0.05	<0.05	<0.05	-	-	-	-	-
	Total P (as PO ₄)	mg/L	0.9	0.9	0.3	<0.01	<0.01	1.0	1.0	0.4	<0.01	<0.01	0.2	0.9	0.4	<0.01	0.9	0.9	0.3	<0.01	<0.01
	Silica (as SiO ₂)	mg/L	23.3	23.1	23	23.3	23.5	24.5	24.5	25.1	25.1	25.2	24.8	25	-	24.3	25.1	24.5	25.5	25.2	25.6
	Turbidity	NTU	6.1	8.6	0.9	0.8	1.2	11	9.3	0.9	0.7	0.6	5.9	9.9	1	0.6	6.3	8.7	0.7	0.8	1.1
	TOC	mg/L	-	-	-	-	-	-	-	-	-	-	6.2	6.2	6.2	6.1	-	-	-	-	-
	pH	S.U.	7.9	8.2	8.1	8.1	8.1	7.9	8.3	8.1	8.2	8.2	8.1	8.3	8.3	8.3	8.0	8.4	8.2	8.2	8.2
	Temperature	°C	12.5	10.9	11.3	10.8	11.8	16.6	11.0	12.6	11.5	11.5	12.7	11.0	11.1	11.1	12.2	13.1	13.6	14.3	15.4
	DO	mg/L	1.1	6.2	3.1	3.9	3.4	0.8	5.7	2.2	2.4	2.7	0.6	5.5	4.9	4.7	0.5	5.2	1.6	2.4	1.9
	ORP	mV	284	291	268	212	188	216	237	249	168	154	281	266	195	158	8.9	146	148	140	146
	Total Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	229	213	206	209	-	-	-	-	-
	Ca Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	117	107	102	104	-	-	-	-	-
	Mg Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	112	106	103	105	-	-	-	-	-
	As (total)	µg/L	49.3	48.4	30.3	0.6	0.7	37.2	38.9	25.0	0.5	0.5	36.5	41.4	30.2	0.5	37.1	37.6	25.2	0.5	0.5
	As (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	36.0	33.3	29.2	0.5	-	-	-	-	-
	As (particulate)	µg/L	-	-	-	-	-	-	-	-	-	-	0.5	8.1	1.0	<0.1	-	-	-	-	-
	As (III)	µg/L	-	-	-	-	-	-	-	-	-	-	33.4	24.4	2.9	0.6	-	-	-	-	-
	As (V)	µg/L	-	-	-	-	-	-	-	-	-	-	2.5	8.9	26.4	<0.1	-	-	-	-	-
	Fe (total)	µg/L	1157	1168	<25	<25	<25	1155	1139	<25	<25	<25	1096	1176	<25	<25	1077	1059	<25	<25	<25
	Fe (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	412	<25	<25	<25	-	-	-	-	-
	Mn (total)	µg/L	23.0	24.1	33.4	21.2	23.4	44.3	25.0	31.5	23.6	25.8	19.8	23.2	28.0	25.3	21.5	22.9	29.5	26.4	28.3
	Mn (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	22.8	23.2	28.8	26.0	-	-	-	-	-

(a) TT sample tap is not present. Sample taken from individual vessel for speciation week.

IN = Influent, AC = after gravity filtration; TA = after tank A; TB = after tank B; TT = after combined effluent
 NA = not available.

Analytical Results from Long-Term Sampling at Stewart, MN (Continued)

Sampling Date		04/11/06 ^(a)					04/18/06					04/25/06				05/02/06				
Sampling Location	Unit	IN	AC	AF	TA	TB	IN	AC	AF	TA	TB	IN	AC	AF	TT	IN	AC	AF	TA	TB
Bed Volume (10 ³)	BV	-	-	-	3.8	3.7	-	-	-	4.1	4.0	-	-	-	4.4	-	-	-	4.8	4.7
Alkalinity (as CaCO ₃)	mg/L	440	440	448	440	435	435	444	440	444	431	423	415	431	427	421	420	432	412	412
Ammonia (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	1.6	1.4	1.3	1.0	-	-	-	-	-
Fluoride	mg/L	-	-	-	-	-	-	-	-	-	-	0.5	0.5	0.4	0.4	-	-	-	-	-
Sulfate	mg/L	-	-	-	-	-	-	-	-	-	-	<1	<1	<1	<1	-	-	-	-	-
Nitrate (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	<0.05	<0.05	0.2	0.3	-	-	-	-	-
Total P (as PO ₄)	mg/L	0.9	0.8	0.3	<0.01	<0.01	0.9	0.9	0.3	0.0	<0.03	0.9	0.9	0.3	<0.01	0.8	0.8	0.3	<0.01	<0.01
Silica (as SiO ₂)	mg/L	24.1	24.4	25.1	25.1	25.2	24.6	25.1	23.3	25.1	24.2	25.9	24.6	25.1	24.8	25.9	25.7	25.5	26.2	26.2
Turbidity	NTU	9.4	8.9	0.9	1.0	0.7	5.0	8.8	0.7	0.5	0.4	4.3	7.6	0.5	0.6	4.6	8.3	0.6	0.4	0.8
TOC	mg/L	-	-	-	-	-	-	-	-	-	-	6.2	6.2	6.3	6.1	-	-	-	-	-
pH	S.U.	7.8	8.1	8.1	8.1	8.1	8.0	8.4	8.2	8.2	8.2	8.1	8.4	8.2	8.2	8.0	8.3	8.2	8.2	8.2
Temperature	°C	13.0	11.5	12.9	14.0	14.1	14.2	12.7	13.3	13.8	13.3	12.6	12.1	13.8	11.7	10.2	10.3	10.5	10.8	10.8
DO	mg/L	0.6	4.2	1.8	1.9	2.3	0.7	5.0	2.2	2.9	2.9	0.6	5.1	1.8	2.4	0.5	5.0	1.9	2.5	2.1
ORP	mV	21.4	210	186	168	118	89.7	213	216	164	160	119	161	229	152	16.8	349	251	198	195
Total Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	205	214	218	221	-	-	-	-	-
Ca Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	111	118	120	122	-	-	-	-	-
Mg Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	94.0	96.4	99.0	99.8	-	-	-	-	-
As (total)	µg/L	41.8	39.7	30.3	0.9	0.9	39.0	39.1	22.5	0.6	0.7	39.5	43.6	23.1	<0.1	36.6	36.1	30.8	0.7	0.9
As (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	34.1	44.9	21.9	<0.1	-	-	-	-	-
As (particulate)	µg/L	-	-	-	-	-	-	-	-	-	-	5.4	<0.1	1.2	<0.1	-	-	-	-	-
As (III)	µg/L	-	-	-	-	-	-	-	-	-	-	27.9	21.7	<0.1	<0.1	-	-	-	-	-
As (V)	µg/L	-	-	-	-	-	-	-	-	-	-	6.2	23.2	21.8	<0.1	-	-	-	-	-
Fe (total)	µg/L	1175	1179	<25	<25	<25	1197	1163	<25	<25	<25	1181	1277	<25	<25	1088	1063	<25	<25	<25
Fe (soluble)	µg/L	-	-	-	-	-	1200	1156	<25	<25	<25	-	-	-	-	-	-	-	-	-
Mn (total)	µg/L	23.1	24.2	31.9	30.5	33.2	23.3	23.8	28.5	27.9	30.2	24.0	27.7	30.4	34.2	22.2	22.6	29.6	28.2	32.3
Mn (soluble)	µg/L	-	-	-	-	-	23.6	23.8	28.2	28.5	30.6	-	-	-	-	-	-	-	-	-
Mn (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	24.6	25.6	30.9	35.1	-	-	-	-	-

(a) Water quality measurements taken on 04/10/06.

IN = Influent, AC = after gravity filtration; TA = after tank A; TB = after tank B; TT = after combined effluent
 NA = not available.

Analytical Results from Long-Term Sampling at Stewart, MN (Continued)

Sampling Date		05/09/06 ^(a)					05/16/06					05/24/06				05/30/06					
Sampling Location	Parameter	IN	AC	AF	TA	TB	IN	AC	AF	TA	TB	IN	AC	AF	TT	IN	AC	AF	TA	TB	
	Unit																				
Bed Volume (10 ³)	BV	-	-	-	5.1	5.0	-	-	-	5.5	5.3	-	-	-	5.8	-	-	-	6.2	6.1	
Alkalinity (as CaCO ₃)	mg/L	410	419	423	423	410	422	434	426	409	422	414	423	423	419	424	420	420	400	367	
Ammonia (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	1.6	1.6	1.5	1.2	-	-	-	-	-	
Fluoride	mg/L	-	-	-	-	-	-	-	-	-	-	0.5	0.5	0.5	0.5	-	-	-	-	-	
Sulfate	mg/L	-	-	-	-	-	-	-	-	-	-	<1	<1	<1	<1	-	-	-	-	-	
Nitrate (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	<0.05	<0.05	0.1	0.3	-	-	-	-	-	
Total P (as PO ₄)	mg/L	0.8	0.8	0.3	<0.01	<0.01	0.9	0.9	0.3	<0.01	<0.01	0.9	0.9	0.4	<0.01	0.9	0.9	0.4	0.1	0.1	
Silica (as SiO ₂)	mg/L	25.5	26	25.9	26.3	26.3	26.3	26.8	25.2	26	26.2	25.2	24.5	24.9	25.2	24.5	24.4	24.2	24.5	24.1	
Turbidity	NTU	4.1	8.3	0.7	0.6	0.7	5.5	8.1	0.6	0.4	0.7	4.9	9.1	0.7	0.7	4.3	9.7	0.6	0.4	1.0	
TOC	mg/L	-	-	-	-	-	-	-	-	-	-	6.3	6.3	6.5	6.6	-	-	-	-	-	
pH	S.U.	8.0	8.3	8.2	8.2	8.2	8.0	8.2	8.9	8.1	8.1	7.5	7.8	7.7	7.7	8.2	8.5	8.4	8.4	8.4	
Temperature	°C	11.8	11.0	11.0	10.6	10.5	11.0	10.8	11.1	10.9	11.5	12.6	11.6	19.3	11.7	10.9	11.5	11.2	11.4	11.5	
DO	mg/L	1.5	4.8	2.5	2.6	2.7	0.8	5.3	2.2	2.0	2.2	1.1	5.0	2.5	2.5	1.9	4.9	3.8	3.6	3.7	
ORP	mV	78.1	140	170	168	165	-1.4	140	119	112	117	71.3	248	386	150	265	340	308	300	297	
Total Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	200	189	217	222	-	-	-	-	-	
Ca Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	101	95.0	109	110	-	-	-	-	-	
Mg Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	98.8	93.9	108	111	-	-	-	-	-	
As (total)	µg/L	35.5	35.9	21.5	0.7	0.8	40.3	40.1	21.2	0.5	0.7	45.2	47.2	38.7	1.1	35.7	33.6	19.8	0.7	0.9	
As (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	41.8	33.7	26.7	1.0	-	-	-	-	-	
As (particulate)	µg/L	-	-	-	-	-	-	-	-	-	-	3.3	13.6	12.0	<0.1	-	-	-	-	-	
As (III)	µg/L	-	-	-	-	-	-	-	-	-	-	35.7	25.5	0.5	0.6	-	-	-	-	-	
As (V)	µg/L	-	-	-	-	-	-	-	-	-	-	6.2	8.2	26.2	0.3	-	-	-	-	-	
Fe (total)	µg/L	1027	1081	<25	<25	<25	1311	1235	<25	<25	<25	1057	1019	<25	<25	1063	983	<25	<25	<25	
Fe (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	784	<25	<25	<25	-	-	-	-	-	
Mn (total)	µg/L	21.0	24.5	29.7	31.2	32.9	25.1	25.7	28.5	30.7	32.0	20.3	21.8	25.1	29.4	20.3	20.3	21.9	24.6	26.4	
Mn (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	20.7	20.3	22.0	28.7	-	-	-	-	-	

(a) Operator turned off potassium permanganate pump after sampling event on 05/09/06.

B-4

IN = Influent, AC = after gravity filtration; TA = after tank A; TB = after tank B; TT = after combined effluent
 NA = not available.

Analytical Results from Long-Term Sampling at Stewart, MN (Continued)

Sampling Date		06/06/06					06/13/06					06/20/06				06/27/06				
Sampling Location	Unit	IN	AC	AF	TA	TB	IN	AC	AF	TA	TB	IN	AC	AF	TT	IN	AC	AF	TA	TB
Bed Volume (10 ³)	BV	-	-	-	6.8	6.6	-	-	-	7.2	7.0	-	-	-	7.5	-	-	-	8.0	7.8
Alkalinity (as CaCO ₃)	mg/L	422	435	431	435	422	429	416	433	454	441	454	416	425	421	421	417	417	417	417
Ammonia (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	1.8	1.6	1.2	1.2	1.6	1.3	1.5	1.0	1.1
Fluoride	mg/L	-	-	-	-	-	-	-	-	-	-	0.6	0.5	0.6	0.6	-	-	-	-	-
Sulfate	mg/L	-	-	-	-	-	-	-	-	-	-	<1	<1	<1	<1	-	-	-	-	-
Nitrate (as N)	mg/L	-	-	-	-	-	-	-	-	-	-	<0.05	<0.05	0.3	0.5	<0.05	<0.05	0.1	0.2	0.2
Total P (as PO ₄)	mg/L	1.1	0.8	0.4	0.04	0.1	1.1	1.0	0.4	<0.03	0.04	1.0	1.0	0.4	0.05	0.9	0.9	0.4	0.04	0.1
Silica (as SiO ₂)	mg/L	25.7	25.5	25.4	26.1	26.1	27.0	26.8	26.9	27.1	27.0	28.3	26.1	26.6	27.0	26.8	26.1	26.2	26.7	26.5
Turbidity	NTU	15.0	9.9	0.7	1.2	1.1	6.2	8.5	0.6	0.5	1.0	7.6	8.5	0.9	0.9	4.6	8.8	0.7	0.6	0.8
TOC	mg/L	-	-	-	-	-	-	-	-	-	-	NA ^(a)	NA ^(a)	NA ^(a)	NA ^(a)	-	-	-	-	-
pH	S.U.	8.0	8.2	8.2	8.2	8.2	8.0	8.3	8.1	8.1	8.1	7.9	8.3	8.3	8.1	8.0	8.3	8.2	8.2	8.2
Temperature	°C	10.9	12.1	11.4	11.3	11.2	11.4	10.6	11.2	11.6	12.6	11.2	11.0	11.2	11.4	10.1	10.4	11.0	11.6	11.5
DO	mg/L	1.9	3.8	4.2	3.1	3.1	0.7	5.6	2.1	2.5	3.0	1.1	4.3	2.4	2.7	0.7	4.7	1.7	2.7	2.6
ORP	mV	316	222	203	137	139	337	319	269	273	259	378	256	190	195	404	209	154	156	154
Total Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	237	236	235	240	-	-	-	-	-
Ca Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	119	118	118	120	-	-	-	-	-
Mg Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	117	118	117	119	-	-	-	-	-
As (total)	µg/L	42.2	37.4	28.6	1.1	1.5	51.1	50.3	30.4	1.1	1.9	50.9	45.5	29.0	1.4	40.6	39.2	27.9	1.7	1.7
As (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	44.6	37.3	25.8	1.2	-	-	-	-	-
As (particulate)	µg/L	-	-	-	-	-	-	-	-	-	-	6.3	8.2	3.2	0.2	-	-	-	-	-
As (III)	µg/L	-	-	-	-	-	-	-	-	-	-	40.7	27.3	1.3	0.4	-	-	-	-	-
As (V)	µg/L	-	-	-	-	-	-	-	-	-	-	3.9	10.0	24.5	0.9	-	-	-	-	-
Fe (total)	µg/L	1491	1037	27.4	<25	<25	1104	1111	<25	<25	<25	1351	1276	<25	<25	1090	1061	<25	<25	<25
Fe (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	1335	68.5	<25	<25	-	-	-	-	-
Mn (total)	µg/L	23.0	21.6	27.6	27.2	30.6	23.5	24.1	26.5	28.2	29.2	25.5	25.3	25.5	28.3	23.8	24.2	26.5	29.0	30.4
Mn (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	26.1	25.2	24.7	27.6	-	-	-	-	-

(a) Sample analysis failed laboratory QA/QC check.

IN = Influent, AC = after gravity filtration; TA = after tank A; TB = after tank B; TT = after combined effluent
 NA = not available.

Analytical Results from Long-Term Sampling at Stewart, MN (Continued)

Sampling Date		07/05/06					07/11/06					07/18/06				07/25/06				
Sampling Location	Parameter	IN	AC	AF	TA	TB	IN	AC	AF	TA	TB	IN	AC	AF	TT	IN	AC	AF	TA ^(b)	TB ^(b)
Unit																				
Bed Volume (10 ³)	BV	-	-	-	8.6	8.4	-	-	-	9.2	8.9	-	-	-	9.6	-	-	-	10.3	10.1
Alkalinity (as CaCO ₃)	mg/L	431	419	419	410	406	427	423	423	419	423	439	447	439	416	421	421	425	421	417
Ammonia (as N)	mg/L	1.2	1.2	0.9	0.7	0.9	NA	NA	NA	NA	NA	1.6	1.9	1.3	1.2	1.7	1.9	1.4	0.6	0.4
Fluoride	mg/L	-	-	-	-	-	-	-	-	-	-	0.5	0.5	0.5	0.5	-	-	-	-	-
Sulfate	mg/L	-	-	-	-	-	-	-	-	-	-	<1	<1	<1	<1	-	-	-	-	-
Nitrate (as N)	mg/L	<0.05	<0.05	0.4	0.5	0.6	NA	NA	NA	NA	NA	<0.05	<0.05	0.2	0.4	<0.05	<0.05	<0.05	0.7	1.6
Total P (as PO ₄)	mg/L	0.9	0.9	0.3	<0.03	0.05	0.8	0.9	0.3	0.1	0.1	1.1	0.9	0.4	0.1	1.1	1.1	0.4	0.8	1.0
Silica (as SiO ₂)	mg/L	24.9	24.4	25.5	25.2	24.3	25.0	24.6	24.6	25.8	25.5	25.0	24.7	25.0	24.8	25.0	25.7	24.9	25.8	25.6
		-	-	-	-	-	25.3	24.1	25.8	25.2	25.4	-	-	-	-	-	-	-	-	-
Turbidity	NTU	5.3	8.4	1.1	0.8	0.6	4.2	8.6	0.5	0.5	0.3	6.9	10.0	1.0	0.4	8.0	12.0	1.0	2.2	3.2
TOC	mg/L	-	-	-	-	-	5.5	8.6	0.5	0.6	0.5	-	-	-	-	-	-	-	-	-
TOC	mg/L	-	-	-	-	-	-	-	-	-	-	6.4	6.6	6.5	6.5	-	-	-	-	-
pH	S.U.	8.1	8.2	8.2	8.2	8.2	8.0	8.3	8.2	8.1	8.1	8.0	8.2	8.2	8.2	8.0	8.3	8.2	8.2 ^(a)	8.2
Temperature	°C	11.0	10.8	11.0	11.1	11.7	10.9	11.0	11.6	12.1	12.1	10.8	11.5	11.0	10.8	10.2	10.8	10.6	11.7 ^(a)	11.5
DO	mg/L	1.7	5.0	3.8	2.6	2.9	1.0	7.2	3.2	3.3	3.8	1.6	5.2	2.7	2.5	0.5	5.0	1.9	6.2 ^(a)	5.7
ORP	mV	311	170	166	140	134	163	172	236	229	179	343	288	261	264	371	267	156	137 ^(a)	175
Total Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	210	195	224	206	-	-	-	-	-
Ca Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	116	96.6	113	104	-	-	-	-	-
Mg Hardness (as CaCO ₃)	mg/L	-	-	-	-	-	-	-	-	-	-	94.3	98.0	110	102	-	-	-	-	-
As (total)	µg/L	46.1	45.5	26.5	2.7	2.1	36.7	38.2	26.2	2.1	2.6	43.4	43.0	38.4	2.3	56.4	56.9	32.9	7.4	9.2
As (soluble)	µg/L	-	-	-	-	-	38.7	39.1	28.7	2.1	2.1	-	-	-	-	-	-	-	-	-
As (particulate)	µg/L	-	-	-	-	-	-	-	-	-	-	39.4	33.9	26.1	3.0	-	-	-	-	-
As (III)	µg/L	-	-	-	-	-	-	-	-	-	-	4.0	9.1	12.3	<0.1	-	-	-	-	-
As (V)	µg/L	-	-	-	-	-	-	-	-	-	-	7.0	8.3	25.6	2.5	-	-	-	-	-
Fe (total)	µg/L	1321	1305	<25	<25	<25	993	1056	<25	<25	<25	1197	1230	<25	<25	1312	1309	<25	337	524
Fe (soluble)	µg/L	-	-	-	-	-	1075	1076	<25	<25	<25	-	-	-	-	-	-	-	-	-
Mn (total)	µg/L	25.8	26.1	26.1	27.7	27.5	20.9	21.5	23.1	25.1	26.0	23.2	24.7	23.6	26.4	23.9	25.0	26.1	26.9	27.5
Mn (soluble)	µg/L	-	-	-	-	-	-	-	-	-	-	23.4	24.3	23.5	26.7	-	-	-	-	-

(a) Water quality measurements taken at sampling location TT.
 (b) 07/25/06 TA and TB samples rerun with similar results for As, Fe, and Mn

IN = Influent, AC = after gravity filtration; TA = after tank A; TB = after tank B; TT = after combined effluent
 NA = not available.

Analytical Results from Long-Term Sampling at Stewart, MN (Continued)

Sampling Date		08/01/06				
Sampling Location		IN	AC	AF	TA	TB
Parameter	Unit					
Bed Volume (10 ³)	BV	-	-	-	11.0	10.8
Alkalinity (as CaCO ₃)	mg/L	416	416	412	407	412
Ammonia (as N)	mg/L	-	-	-	-	-
Ammonia (as N)	mg/L	1.9	1.6	1.2	1.0	1.0
Fluoride	mg/L	-	-	-	-	-
Sulfate	mg/L	-	-	-	-	-
Nitrate (as N)	mg/L	<0.05	<0.05	0.4	1.7 ^(a)	0.3
Total P (as PO ₄)	mg/L	1.0	0.9	0.3	0.1	0.1
Silica (as SiO ₂)	mg/L	-	-	-	-	-
		27.8	28.2	28.1	28.3	28.6
Turbidity	NTU	5.3	7.5	0.4	0.4	0.3
		-	-	-	-	-
TOC	mg/L	-	-	-	-	-
pH	S.U.	8.1	8.3	8.2	8.2	8.2
Temperature	°C	10.7	12.0	11.9	11.5	11.7
DO	mg/L	0.6	4.4	3.1	2.1	2.2
ORP	mV	111	95.9	108	88.7	83.9
Total Hardness (as CaCO ₃)	mg/L	-	-	-	-	-
Ca Hardness (as CaCO ₃)	mg/L	-	-	-	-	-
Mg Hardness (as CaCO ₃)	mg/L	-	-	-	-	-
As (total)	µg/L	52.3	44.1	27.3	2.8	3.3
		-	-	-	-	-
As (soluble)	µg/L	-	-	-	-	-
As (particulate)	µg/L	-	-	-	-	-
As (III)	µg/L	-	-	-	-	-
As (V)	µg/L	-	-	-	-	-
Fe (total)	µg/L	1121	1070	<25	<25	<25
		-	-	-	-	-
Fe (soluble)	µg/L	-	-	-	-	-
Mn (total)	µg/L	22.3	22.9	24.9	25.2	26.2
		-	-	-	-	-
Mn (soluble)	µg/L	-	-	-	-	-

- (a) 08/01/06 TA sample was rerun with similar result for nitrate
 (b) Low effluent TOC levels. Results confirmed with laboratory.

B-7

IN = Influent, AC = after gravity filtration; TA = after tank A; TB = after tank B; TT = after combined effluent
 NA = not available.