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COSTS OF ARSENIC REMOVAL TECHNOLOGIES FOR SMALL WATER SYSTEMS: U.S. EPA ARSENIC REMOVAL TECHNOLOGY DEMONSTRATION PROGRAM

by

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Sally Gutierrez, Director
National Risk Management Research Laboratory

EXECUTIVE SUMMARY

As part of the Arsenic Rule Implementation Research Program, between July 2003 and July 2011, the U.S. Environmental Protection Agency (EPA) conducted 50 full-scale demonstration projects on treatment systems removing arsenic from drinking water in 26 states throughout the U.S. The projects were conducted to evaluate the performance, reliability, and cost of arsenic removal technologies selected for demonstration and to determine their effects on water quality in distribution systems. A key objective was to collect cost and performance data that might be used by small water systems, engineering firms, and state agencies to make informed decisions on selecting appropriate arsenic treatment technologies to achieve the revised arsenic maximum contaminant level (MCL) of 10 μg/L. While results from each demonstration are documented in individual technology performance evaluation reports, this report summarizes cost data across all demonstrations grouped by the technology type. For each type of technologies, a brief overview of demonstration sites, demonstration technologies, system designs and configurations, and system operations was provided to assist in understanding relevant cost data.

The arsenic demonstration program was divided into three rounds of projects: Round 1 (12 projects), Round 2 (28 projects), and Round 2a (10 projects). Treatment systems selected for demonstration included 28 adsorptive media (AM) systems, 18 iron removal (IR) and coagulation/filtration (CF) systems (including four using IR pretreatment followed by AM), two ion exchange (IX) systems, and one each reverse osmosis (RO), point-of-use (POU) RO, POU AM, and system/process modification. Among the 50 locations, 42 were community water systems (CWS) and eight were non-transient non-community water systems (NTNCWS).

The capital cost of each treatment system was broken down into three components − equipment, site engineering, and installation, and was divided by its design capacity in gallons per minute (gpm) or gallons per day (gpd) for comparison among systems. The unit capital cost expressed per 1,000 gal of water treated was also compared based on a 7% interest rate, a 20-year return period, and the system's maximum (assuming 100 % utilization rate) and average annual production rates. Factors affecting the capital cost included system flowrate, vessel design, material of construction, media type and quantity, pre- and/or post-treatment requirements, and level of instrumentation and controls.

The operation and maintenance (O&M) cost for each treatment system was categorized into media replacement (AM systems only), chemical consumption, electricity, and labor. O&M costs might be affected by source water quality and other technology-specific factors, such as arsenic adsorptive capacities for AM technologies. Building construction and residual handling and disposal were outside of the scope of this program so their costs are not included in this report (except for spent media disposal cost).

Costs of AM Technology

Nine different AM products were used by 28 systems: three iron-based media, either ferric oxide (ARM 200 and E33) or ferric hydroxide (GFH®); four iron-modified media, either alumina-based (A/I Complex 2000 and AAFS50), silica-based (G2®), or resin-based (ArsenX^{np}); one titanium oxide-based media (Adsorbsia™ GTO™); and one zirconium oxide-based media (Isolux™). All of the media have NSF Standard 61 certification for use in drinking water applications.

Design flowrates of the AM systems ranged from 10 to 640 gpm. Total capital investment costs for the systems ranged from $14,000 to $305,000 and varied by flowrate, system design, material of construction, monitoring equipment, and specific site conditions. Normalized costs ranged from $477 to $6,171 per gpm or from $0.33 to $4.29 per gpd of design capacity. Unit costs of total capital investments

ranged from \$0.09 to \$1.11 per 1,000 gal of water treated (assuming a 100% utilization rate). Generally, the unit cost decreased as the size of the treatment system increased. Equipment costs for the treatment systems ranged from \$8,640 to \$218,000, representing an average of 70% of the total capital investment cost. Site engineering costs for the treatment systems ranged from \$1,800 to \$50,659, accounting for 14% of the total capital investment (on average). Installation costs for the treatment systems ranged from \$2,610 to \$61,209, which accounted for 12 to 34% of the total capital investment (or 16% on average).

System performance was evaluated for a period of 14 to 45 months with more extensive sampling and analysis conducted during the first 12 to 18 months and less thereafter. Spent media were replaced for 15 systems (or 54% of the AM systems), thus providing ample data for the O&M cost. The remaining 46% systems did not replace media because they had not reached 10-μg/L arsenic breakthrough. The media replacement cost was the majority (79%) of the O&M cost. Media replacement costs varied widely from \$0.30 to \$22.05 per 1,000 gal of water treated due to large variations in media cost and media life. Media costs ranged from \$40/ft^3 to \$678/ft^3, depending on the media type and quantity. Affected by media type, raw water quality, and process condition, lengths of media life to 10-μg/L arsenic breakthrough varied from 3,100 to 80,000 bed volumes (BV).

Chemicals required for system operation at some of the AM sites included carbon dioxide (CO_2) and/or acid/base for pH adjustment and chlorine for pre-oxidation and disinfection. Their costs varied from negligible to \$0.61 per 1,000 gal of water treated. Five sites used CO_2 for pH adjustment and their costs ranged from \$0.11 to \$0.41 per 1,000 gal of water. Electricity costs for the treatment systems (not including pumping from wells to treatment plants or re-pumping to distribution systems) ranged from zero to \$0.16 (or \$0.03 on average) per 1,000 gal of water treated. Routine, non-demonstration related labor activities consumed only 10 to 30 min a day, one or several days a week at most of the sites. At a labor rate of \$18.2 to \$37.5/hr (averaging \$22.4/hr), labor costs per 1,000 gal of water treated varied significantly from \$0.45 to \$3.10 for NTNCWS and from \$0.03 to \$2.36 for CWS, due largely to variations in annual water production rates at the AM sites. A NTNCWS often had a lower demand and a lower utilization rate than a CWS. Therefore, the labor cost (per 1,000 gal of water treated) of a small NTNCWS tended to be higher than that of a large CWS.

Costs of IR/CF Technology

The 18 IR/CF systems demonstrated include 10 IR systems (two requiring supplemental iron addition), four IR/AM systems, and four CF systems. Each demonstration study was conducted for a period of 12 to 15 months, except at two sites where more extensive studies were performed to troubleshoot system performance issues. Filter media used included silica sand/anthracite, GreensandPlus™, Birm®, Filox™, AD26 (AdEdge), AD GS$^+$ (AdEdge), Macrolite® (Kinetico), and Electromedia® I (Filtronics). All media have NSF Standard 61 certification for use in drinking water applications.

Design flowrates of the IR/CF systems ranged from 20 to 770 gpm. Total capital investment costs ranged from \$55,423 to \$427,407, and varied by flowrate, system design (e.g., use contact tank or not), material of construction, monitoring equipment, and specific site conditions. Normalized costs ranged from \$555 to \$3,177 per gpm or \$0.39 to \$2.21 per gpd. Unit costs of the total capital investment ranged from \$0.10 to \$0.57 per 1,000 gal of water treated (assuming 100% utilization rate). Similar to the AM systems, the unit costs of the IR/CF systems generally decreased with increasing sizes of the treatment systems. Equipment costs for the treatment systems ranged from \$19,790 to \$296,430, representing an average of 60% of the total capital investment. Site engineering costs ranged from \$3,850 to \$53,435, accounting for 15% of the total capital investment (on average). Installation costs ranged from \$12,410 to \$132,039, which accounted for 14 to 36% of the total capital investment (or 25% on average).

Total O&M costs, including the costs for chemical supplies, electricity consumption, and labor, ranged from $0.07 to $2.90 per 1,000 gal of water treated. Chemicals used for IR/CF system operation included chlorine, $KMnO_4$, or $NaMnO_4$ for oxidation and disinfection and an iron salt for coagulation. Overall chemical costs ranged from zero to $0.37 per 1,000 gal of water treated, equivalent to zero to 57% (19% on average) of the total O&M cost. Iron addition was used at six sites at a dosage of 0.5 to 2.2 mg/L (as Fe), either as a coagulant or to augment the natural iron for arsenic removal. Costs of iron addition ranged from $0.01 to $0.07 per 1,000 gal of water treated.

Incremental electricity costs ranged from zero to $0.39 and averaged $0.07 per 1,000 gal of water treated. Electricity accounted for an average of 19% of the total O&M cost. The routine, non-demonstration related labor activities consumed only 10 to 30 min per day and 3.4 hr per week (on average). At an average labor rate of $22.6/hr, labor costs per 1,000 gal of water treated varied from $0.04 to $2.57, accounting for 18 to 95% (61% on average) of the total O&M cost. A small NTNCWS often had a higher labor cost (per 1,000 gal of water treated) than a large CWS due to its lower production rate.

Costs of Other Technologies

Other arsenic removal technologies in the demonstration program included IX, RO, POU, and system/process modification, each being demonstrated at one or two sites. Two IX systems, each at a design flowrate of 250 and 540 gpm, used a strong base anionic (SBA) exchange resin to remove both arsenic and nitrate from source water. The capital investment cost of the 250-gpm system was $286,388, which included $173,195 for equipment, $35,619 for site engineering, and $77,574 for installation, equivalent to 61%, 12%, and 27% of the total capital cost, respectively. The capital investment cost of the 540-gpm system was $395,434, which included $260,194 for equipment, $49,840 for site engineering, and $85,400 for installation, equivalent to 66%, 13%, and 22% of the total capital cost, respectively. The normalized capital cost was $1,146/gpm ($0.80/gpd) for the 250-gpm system and $732/gpm ($0.51/gpd) for the 540-gpm system. Unit costs were $0.21 and $0.13 per 1,000 gal of treated water (100 % utilization rate), respectively. Total O&M costs were $0.62 and $0.35 per 1,000 gal of water treated, respectively. Salt was a major operating cost for the IX systems, accounting for 80% of the total O&M cost. Optimizing salt loading for system regeneration and adding more salt storage capacities to allow for full truckload delivery could reduce the salt cost. Electricity costs were $0.08 and $0.03/1,000 gal of water treated, respectively. Labor costs were $0.05 and $0.03/1,000 gal of water treated, respectively. The electricity and labor costs accounted for 20% of the total O&M cost.

An innovative approach using POE RO coupled with a dual plumbing distribution system was demonstrated at one NTNCWS as a low cost alternative to achieve simultaneous compliance with the arsenic and antimony MCLs. With installation of a dual distribution system, only a portion of raw water needed to be treated for potable use (i.e., kitchen sinks, water fountains, etc.). Therefore, a smaller RO system could be used to meet the potable water demand, thus reducing the capital and O&M costs. The capital investment for the system was $20,452, including $8,600 for the dual plumbing system and $11,942 for a 1,200-gpd RO system. The normalized cost was $17.12/gpd or $4.43/1,000 gal of water treated. The total annual O&M cost was $1,404, including $351 for repairs, $376 for electricity consumption, and $666 for labor cost. The annual cost was $12.89/1,000 gal of permeate water produced.

Nine POU RO units were demonstrated at a CWS with nine participating residences to remove arsenic, nitrate, and uranium from source water. Water softeners were used for pre-treatment. The cost of each RO unit was $1,220, including $1,025 for equipment and $195 for installation. The cost of each water softener was $2,395, including $1,585 for equipment and $810 for installation. The one-year O&M cost included $115 for the salt supply and $86.50 for pre- and post-filter replacement, totaling $201.50 or $17 per month.

Eight POU cartridges containing ARM 200 media were evaluated either under a sink or inside a drinking water fountain in different buildings at a university. Upon completion of initial testing, 48 POU E33 cartridges were installed by the school. The cost of each POU ARM 200 and E33 cartridge was $152 and $215, respectively. Although the cost of the E33 cartridge was 40% higher than that of the ARM 200 cartridge, E33 media was capable of producing up to 3,000 gal of permeate, almost three times higher than that by ARM 200 media.

Cost Comparison

Capital investment costs for smaller AM and IR/CF systems (with a design flowrate of <100 gpm) varied extensively but mean values of the investment for these two technology types were comparable. Capital investment costs for large AM systems (i.e., >100 gpm) generally were higher than those for IR/CF systems with similar sizes. For example, average normalized and unit costs for the large AM systems were 25% and 26%, respectively, lower than those for the large IR/CF systems. IX capital investment costs were comparable to the IR/CF costs. The large IR/CF and IX systems were more expensive than the large AM systems because of the use of ancillary equipment and controls, such as contact tanks and iron addition systems for IR/CF and salt saturators and salt supply systems for IX.

The AM systems had a higher O&M cost than the IR/CF and IX systems, due mainly to media replacement, which accounted for 79% of the total O&M cost. The lower O&M cost is a significant advantage of IR/CF over AM as long as the facility can handle IR/CF and IX residuals at a low cost. Because the O&M cost did not include residuals disposal cost, a key factor in selecting a treatment technology for arsenic removal, direction comparisons among different technologies would be less accurate.

The cost for salt constituted a large portion of the O&M cost for IX. Chemical costs for pH adjustment, (supplemental) iron addition, and pre-oxidation/disinfection was insignificant. The cost for incremental electricity to overcome headloss across filter beds and to power system controls and/or chemical feed pumps was also insignificant for any of the three technologies. Based on the average weekly labor hours reported by operators, the AM systems required the least amount of time to operate and maintain. Although subject to individual operators' opinions, the AM systems required less operator attention and were easier to operate than the IR/CF and IX systems.

CONTENTS

FIGURES

TABLES

ABBREVIATIONS AND ACRONYMS

AM	adsorptive media (process)
As	arsenic
ASME	American Society of Mechanical Engineers
ATS	Aquatic Treatment Systems
BV	bed volume
CF	coagulation/filtration (process)
CO_2	carbon dioxide
CRF	capital recovery factor
CS	carbon steel
CWS	community water system
EBCT	empty bed contact time
EPA	Environmental Protection Agency
Fe	iron
FRP	fiberglass reinforced plastic
gpd	gallons per day
gpm	gallons per minute
HDPE	high-density polyethylene
hp	horsepower
IR	iron removal (process)
IX	ion exchange (process)
$KMnO_4$	potassium permanganate
MCL	maximum contaminant level
MEI	Magnesium Elektron, Inc.
MG	million gallons
N/A	not available
NTNCWS	non-transient non-community water system
NSF	NSF International
O&M	operations and maintenance
OIP	operator’s interface panel
ORD	Office of Research and Development
PE	Professional Engineer
PLC	programmable logic controller
POE	point of entry
POU	point of use
PVC	polyvinyl chloride

RO	reverse osmosis
SBA	strong based anionic
SDWA	Safe Drinking Water Act
SMCL	secondary maximum contaminant level
SS	stainless steel
STMGID	South Truckee Meadows General Improvement District
STS	Severn Trent Services
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solid
THM	trihalomethane
TOC	total organic carbon

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1.0 INTRODUCTION

1.1 Purpose and Scope

Between July 2003 and July 2011, the U. S. Environmental Protection Agency (EPA) conducted 50 full-scale demonstration projects on treatment systems removing arsenic from drinking water in 26 states throughout the U.S. These demonstration projects evaluated the efficiency and effectiveness of the treatment systems in meeting the new arsenic maximum contaminant level (MCL) of 0.010 mg/L (10 µg/L). One of the major objectives of the demonstration program was to determine the cost-effectiveness of the technologies by collecting cost data associated with the 50 systems, including capital investment costs for equipment, site engineering, and installation, and operation and maintenance (O&M) costs.

This report summarizes the capital investment and O&M costs associated with the demonstration systems. Background information on demonstration sites, demonstration technologies, system designs and configurations is also provided to support the cost data. Building construction and residuals disposal were outside the scope of the program so their costs were not included. However, residuals disposal options and costs could affect the technology selection (EPA, 2000; Cornwell and Roth, 2011). Detailed information on the system performance and cost data can be found in individual final reports posted on the EPA Web site at http://www.epa.gov/ORD/NRMRL/wswrd/dw/arsenic/index.html.

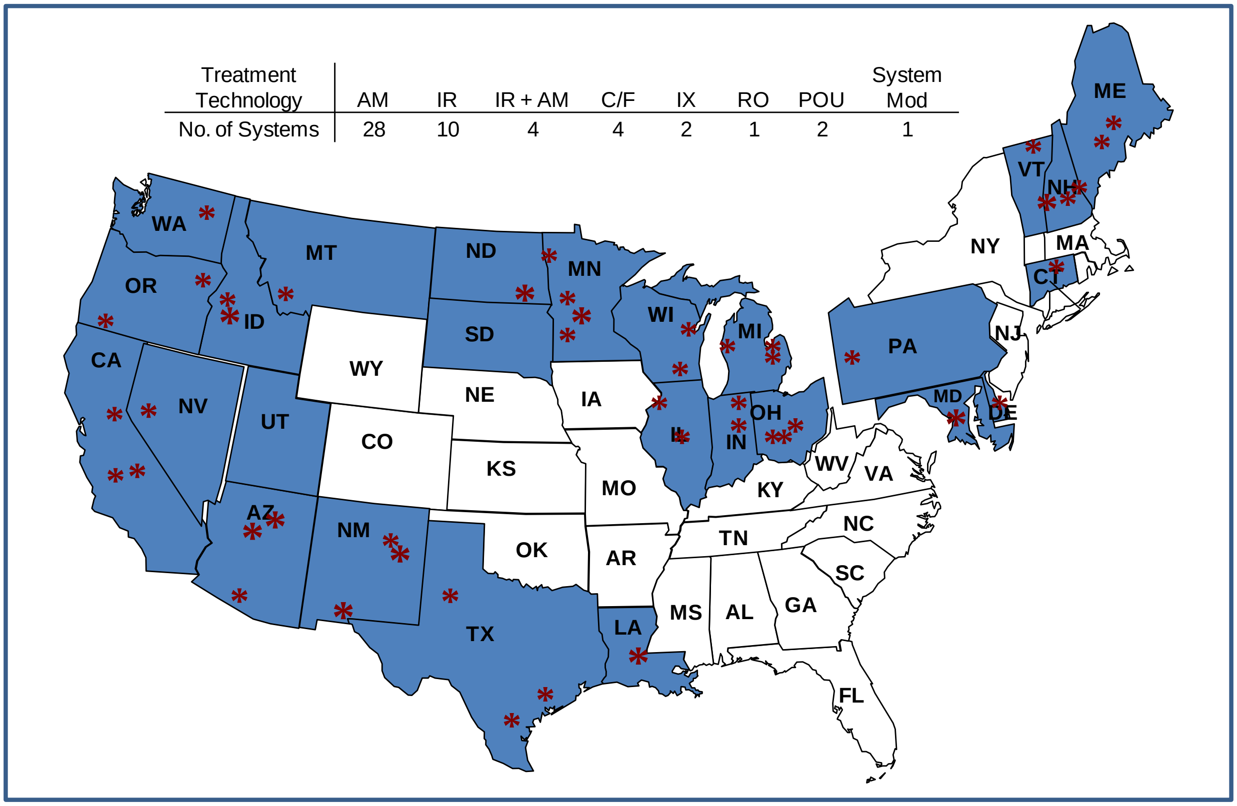
1.2 Background

The Safe Drinking Water Act (SDWA) mandates that 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 MCL for arsenic (As) 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 text on March 25, 2003, to express the MCL as 0.010 mg/L (10 µg/L) (EPA, 2003). The final rule required all community and non-transient, non-community water systems to comply with the new standard by January 23, 2006.

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

With EPA program funds and additional funding from Congress during fiscal years 2005, 2006 and 2007, EPA conducted three rounds of demonstration projects: Round 1 (12 projects), Round 2 (28 projects) and Round 2a (10 projects). The selections of the treatment technologies were made from solicited proposal through a joint effort of EPA, respective state regulators, and host sites. Figure 1-1 is a map showing the locations of the 50 demonstration projects.

Technologies selected for the 50 projects included adsorptive media (AM), iron removal (IR), coagulation/filtration (CF), ion exchange (IX), reverse osmosis (RO), point-of-use (POU), and system/process modification. Table 1-1 summarizes the locations, technologies, vendors, system flowrates, and key source water quality parameters (including As, iron [Fe], and pH). The table is



Treatment Technology	AM	IR	IR + AM	C/F	IX	RO	POU	System Mod
No. of Systems	28	10	4	4	2	1	2	1

Figure 1-1. Locations of 50 Arsenic Demonstration Projects

organized by four sections of the country: Northeast/Ohio, Great Lakes/Interior Plains, Midwest/Southwest, and Far West. Each demonstration location was assigned to a two-letter identification (ID) code, which was used throughout this report for system identification. Table 1-2 presents the number of systems for each type of technologies and the section of this report where the cost information is presented.

This report consists of six sections. Section 1 is a brief introduction. Section 2 presents the cost information of 28 AM systems demonstrated at 26 sites (one site had three AM systems). Section 3 presents the cost information of 18 IR/CF systems demonstrated at 18 sites, including 10 IR systems (including two requiring supplemental iron addition), four IR/AM systems, and four CF systems. Section 4 presents the cost information of other technologies each demonstrated at one or two sites using IX, RO, POU, or system/process modification. Section 5 summarizes and compares the costs for AM, IR/CF, and IX systems. Section 6 contains a list of references cited in this report.

Table 1-1. Summary of 50 Arsenic Removal Demonstration Locations, Technologies, and Source Water Quality

State	Demonstration Location (Two-Letter ID)	Site Name	Technology (Media)	Vendor	Design Flowrate (gpm)	Source Water Quality		
						As (µg/L)	Fe (µg/L)	pH (S.U.)
Northeast/Ohio								
ME	Carmel (CE)	Carmel Elementary School	RO	Norlen's Water	1,200 gpd	18.2	<25	7.9
ME	Wales (WA)	Springbrook Mobile Home Park	AM (A/I Complex)	ATS	14	39.1(a)	<25	8.5
NH	Bow (BW)	White Rock Water Company	AM (G2)	ADI	40(b)	46.4	<25	7.3
NH	Goffstown (GF)	Orchard Highlands Subdivision	AM (E33)	AdEdge	10	29.7	<25	7.1
NH	Rollinsford (RF)	Rollinsford Water/Sewer District	AM (E33)	AdEdge	100	37.7	297	7.7
VT	Dummerston (DM)	Charette Mobile Home Park	AM (A/I Complex)	ATS	22	42.2	<25	7.7
NY	Houghton (HT)(c)	Town of Caneadea	IR (Macrolite®)	Kinetico	550	27(a)	1,806(d)	7.6
CT	Woodstock (WS)	Woodstock Middle School	AM (Adsorbia™)	Siemens	17	24.7	27	7.1
CT	Pomfret (PF)	Seely-Brown Village	AM (ArsenX^{np})	SolmeteX	15	25	<25	7.3
DE	Felton (FE)	Town of Felton	CF (Macrolite®)	Kinetico	375	34.4(a)	26	8.3
MD	Stevensville (ST)	Queen Anne's County	AM (E33)	STS	300	20.1(a)	269(d)	7.8
PA	Conneaut Lake (CL)	Conneaut Lake Park	CF (AD GS^{+})	AdEdge	250	29(a)	188(d)	7.8
OH	Buckeye Lake (BL)	Buckeye Lake Head Start Building	AM (ARM 200)	Kinetico	10	15.4(a)	2,290(d)	7.4
OH	Springfield (SF)	Chateau Estates Mobile Home Park	IR & AM (E33)	AdEdge	250(e)	22.7(a)	1,102(d)	7.2
Great Lakes/Interior Plains								
MI	Brown City (BC)	City of Brown City	AM (E33)	STS	640	15.3(a)	177(d)	7.9
MI	Pentwater (PW)	Village of Pentwater	IR/IA (Macrolite®)	Kinetico	400	17.7(a)	426(d)	7.9
MI	Sandusky (SD)	City of Sandusky	IR (Aeralater®)	Siemens	340(e)	11.4(a)	896(d)	7.2
WI	Delavan (DV)	Vintage on the Ponds	IR (Macrolite®)	Kinetico	45	18.9(a)	1,392(d)	7.5
IN	Goshen (GS)	Clinton Christian School	IR & AM (E33)	AdEdge	25	28.6(a)	741(d)	7.3
IN	Fountain City (FC)	Northeaster Elementary School	IR (G2)	US Water	60	29.4(a)	1,865(d)	7.6
IL	Waynesville (WV)	Village of Waynesville	IR (GreensandPlus™)	Peerless	96	32(a)	2,543(d)	7.1
IL	Geneseo Hills (GE)	Geneseo Hills Subdivision	AM (E33)	AdEdge	200	19.6(a)	554(d)	7.2
WI	Greenville (GV)	Town of Greenville	IR (Macrolite®)	Kinetico	375	5.6(a)	2,068(d)	7.3
MN	Climax (CM)	City of Climax	IR/IA (Macrolite®)	Kinetico	140	36.5(a)	540(d)	7.5
MN	Sabin (SA)	City of Sabin	IR (Macrolite®)	Kinetico	250	41.8	1,350(d)	7.3
MN	Sauk Centre (SC)	Big Sauk Lake Mobile Home Park	IR (Macrolite®)	Kinetico	20	27.5(a)	2,385(d)	7.3
MN	Stewart (ST)	City of Stewart	IR &AM (E33)	AdEdge	250	44.8(a)	1,188(d)	7.9
ND	Lidgerwood (LW)	City of Lidgerwood	Process Modification	Kinetico	250	146(a)	1,325(d)	7.2
SD	Lead (LD)	Terry Trojan Water District	AM (ArsenX^{np})	SolmeteX	75	22.2	<25	7.2
Midwest/Southwest								
UT	Willard (WL)	Hot Springs Mobile Home Park	IR & AM (Adsorbia™)	Filter Tech	30	13.2	276(d)	7.6
LA	Arnaudville (AR)	United Water Systems	IR (Macrolite®)	Kinetico	770(e)	32.7(a)	2,059(d)	6.8

Table 1-1. Summary of 50 Arsenic Removal Demonstration Locations, Technologies, and Source Water Quality (Continued)

State	Demonstration Location (Two-Letter ID)	Site Name	Technology (Media)	Vendor	Design Flowrate (gpm)	Source Water Quality		
						As (µg/L)	Fe (µg/L)	pH (S.U.)
TX	Alvin (AV)	Oak Manor Municipal Utility District	AM (E33)	STS	150	40.2(a)	63	7.8
TX	Bruni (BR)	Webb Consolidated Independent School District	AM (E33)	AdEdge	40	57.6(a)	32	8.2
TX	Wellman (WM)	City of Wellman	AM (E33)	AdEdge	100	36	<25	7.8
NM	Anthony (AN)	Desert Sands Mutual Domestic Water Consumers Association	AM (E33)	STS	320	23.5(a)	80	7.8
NM	Nambe Pueblo (NP)	Nambe Pueblo Tribe	AM (E33)	AdEdge	145	32.2	<25	9.0
NM	Taos (TA)	Town of Taos	AM (E33)	STS	450	16.9	31	9.6
AZ	Rimrock (RR)	Arizona Water Company	AM (E33)	AdEdge	45(b)	59.7	<25	6.9
AZ	Tohono O'odham Nation (TN)	Tohono O'odham Utility Authority	AM (E33)	AdEdge	50	34.9	<25	8.0
AZ	Valley Vista (VV)	Arizona Water Company	AM (AAFS50/ARM 200)	Kinetico	37	39.4	<25	7.7
			Far West					
MT	Three Forks (TF)	City of Three Forks	CF (Macrolite®)	Kinetico	250	84	<25	7.5
ID	Fruitland (FL)	City of Fruitland	IX (A300E)	Kinetico	250	42.5	<25	7.6
ID	Homedale (HD)	Sunset Ranch Development	POU RO(f)	Kinetico	9 unit	57.8	112	7.3
WA	Okanogan (OK)	City of Okanogan	CF (Electromedia-I®)	Filtronics	550	17.9	78(d)	7.6
OR	Klamath Falls (KF)	Oregon Institute of Technology (OIT)	AM (Adsorbsia™/ ARM 200/ArsenX^{np}) and POU AM (ARM 200)(g)	Kinetico	60/60/30	29.8	<25	8.0
OR	Vale (VA)	City of Vale	IX (Arsenex II)	Kinetico	540	22.6	<25	7.4
NV	Reno (RN)	South Truckee Meadows General Improvement District	AM (GFH)	Siemens	350	67.2	<25	7.1
CA	Susanville (SU)	Richmond School District	AM (A/I Complex)	ATS	12	31.7	37	8.4
CA	Lake Isabella (LI)	Upper Bodfish Well CH2-A	AM (ArsenX^{np})	VEETech	50	41.7	<25	6.9
CA	Tehachapi (TE)	Golden Hills Community Service District	AM (Isolux)	MEI	150	12.7	<25	7.6

AM = adsorptive media process; CF = coagulation/filtration; IR = iron removal; IR/IA = iron removal with iron addition; 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) Selected originally to replace Village of Lyman, NE site, which withdrew in June 2006; withdrew in 2007 and later replaced by residential systems in Lewisburg, OH.
(d) Iron existing mostly as Fe(II).
(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 under-the-sink units.
(g) Including eight under-the-sink or inside-a-drinking-fountain cartridges.

Table 1-2. Number of Demonstration Systems for Each Type of Arsenic Removal Technology

Technology Type	Number of Systems	Report Section
Adsorptive Media	28(a)	2
Iron Removal (Oxidation/Filtration)	10(b)	3
Iron Removal and Adsorptive Media Combined	4	
Coagulation/Filtration	4	
Ion Exchange	2	4
Reverse Osmosis	1	
Point-of-Use Reverse Osmosis	1(c)	
Point-of-Use Adsorptive Media	1(d)	
System/Process Modifications	1	Not included

(a) 28 AM systems demonstrated at 26 sites with one having three AM systems.
(b) Two IR systems used supplemental iron addition.
(c) Including nine under-the-sink units.
(d) Including eight under-the-sink or inside-a-drinking-fountain cartridges.

2.0 ADSORPTIVE MEDIA SYSTEMS

AM systems were selected at 26 of the 50 demonstration project locations as the main treatment process for arsenic removal. The 26 water systems consisted of five non-transient non-community water systems (NTNCWS) and 21 community water systems (CWS). Table 2-1 lists AM demonstration locations, technologies and vendors, and study durations in the order of design flowrates. Because the Klamath Falls (KF) site had three POE AM systems, labeled as 4a, 4b, and 4c in Table 2-1, a total of 28 AM systems were demonstrated at the 26 sites. Performance of each system was evaluated for 14 to 45 months with more extensive sampling and analysis conducted in the first 12 to 18 months and less thereafter. Detailed information about the performance and capital and O&M costs on each system can be found in individual performance evaluation reports provided on the EPA Arsenic Demonstration Program Web site at http://www.epa.gov/ORD/NRMRL/wswrd/dw/arsenic/index.html.

Table 2-1. Summary of AM Demonstration Locations, Technologies, and Study Durations

No.	Site ID	Demonstration Location	Technology (Media)	Vendor	Design Flowrate (gpm)	Study Duration	Length of Study (mon)
Non-Transient Non-Community Water Systems							
1	BL	Buckeye Lake, OH	ARM 200	Kinetico	10	06/06–02/10	44
2	SU	Susanville, CA	A/I Complex 2000	ATS	12	09/05–06/07	21
3	WS	Woodstock, CT	Adsorbsia™ GTO™	Siemens	17	02/09–09/10	19
4a	KF	Klamath Falls, OR	ArsenX^{np}	Kinetico	30	12/05–08/09	45
4b			ARM 200		60	12/05–08/09	45
4c			Adsorbsia™ GTO™		60	02/06–08/09	43
5	BR	Bruni, TX	E33	AdEdge	40	12/05–05/08	30
Community Water Systems							
6	GF	Goffstown, NH	E33	AdEdge	10	04/05–08/07	28
7	WA	Wales, ME	A/I Complex 2000	ATS	14	03/05–08/07	29
8	PF	Pomfret, CT	ArsenX^{np}	SolmeteX	15	02/09–09/10	20
9	DM	Dummerston, VT	A/I Complex 2000	ATS	22	06/05–10/06	16
10	VV	Valley Vista, AZ	AAFS50	Kinetico	37	06/04–08/06	14
11	BW	Bow, NH	G2®	ADI	40$^{(a)}$	10/04–09/06	23
12	RR	Rimrock, AZ	E33	AdEdge	45$^{(a)}$	06/04–03/07	33
13	LI	Lake Isabella, CA	ArsenX^{np}	VEETech	50	10/05–03/07	17
14	TN	Tohono O'odham Nation, AZ	E33	AdEdge	50	02/08–03/10	25
15	LD	Lead, SD	ArsenX^{np}	SolmeteX	75	04/08–05/10	25
16	WM	Wellman, TX	E33	AdEdge	100	08/06–04/08	20
17	RF	Rollinsford, NH	E33	AdEdge	100	02/04–05/06	27
18	TE	Tehachapi, CA	Isolux™	MEI	150	10/05–03/07	17
19	AL	Alvin, TX	E33	STS	150	04/06–04/08	24
20	NP	Nambe Pueblo, NM	E33	AdEdge	145	05/07–09/09	28
21	GE	Geneseo Hills, IL	E33	AdEdge	200	05/08–07/10	26
22	SV	Stevensville, MD	E33	STS	300	06/04–04/07	34
23	AN	Anthony, NM	E33	STS	320	01/04–08/06	31
24	RN	Reno, NV	GFH®	Siemens	350	09/05–07/07	22
25	TA	Taos, NM	E33	STS	450	02/06–10/07	20
26	BC	Brown City, MI	E33	STS	640	05/04–05/07	36

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

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

2.1 Overview of AM Demonstration Sites

Table 2-2 summarizes the AM demonstration site information. All five NTNCWS were schools, including one university having three point-of-entry (POE) systems loaded with different types of media. Most of these facilities were classified as very small (serving 25 to 500 of people) and small (serving 501 to 3,300 of people) water systems. The wells supplying the demonstration systems were operated less than 10 hr/day at most of the sites. Five systems were operated on demand, with varying flowrates corresponding to momentary water demands in the distribution systems. Average daily demands varied from 450 to 17,562 gal for NTNCWS and from 1,565 to 152,280 gal for CWS. Annual productions ranged from 0.1 to 6 million gallons (MG) for NTNCWS and from 0.6 to 51 MG for CWS. The ratio of the annual production to the system maximum capacity represents a hydraulic utilization rate, varying from 2 to 19% for NTNCWS and 5 to 96% for CWS.

Source water quality plays an important role in technology selection and design and operation of a treatment system because it can affect the performance of a technology and treatment cost. Table 2-3 provides average values of several key water quality parameters of source waters treated by the AM systems. Arsenic concentrations in source waters ranged from 12.7 to 67.2 µg/L across all 26 demonstration locations. At nine of 26 sites, soluble As(III) was the most prevalent form of arsenic in the source waters. Among these nine sites, two sites (BL and GE) had total iron levels (primarily as soluble Fe[II]) above its secondary MCL (SMCL) of 300 µg/L and three sites (BL, RF, and AL) had total manganese levels above its SMCL of 50 µg/L. The BL site had a pre-existing softener that removed iron and manganese from source water before adsorption. In general, if a source water contains Fe(II) and/or Mn(II) above the respective MCL, an iron removal (IR) or an IR/AM process mostly likely would be selected for arsenic and iron removal.

The arsenic removal capacity of an AM is strongly dependent on solution pH. Most AMs adsorb arsenic more effectively at a pH value of 5.5 to 7.5, and their adsorptive capacities increase with decreasing pH. Adjusting the pH of raw water can increase the media capacity and lower the operating cost; however, the pH control equipment increases the system cost and the complexity of operation. Source water pH values ranged from 6.9 to 9.6 across all 26 demonstration locations. At 17 locations, source water pH values were higher than 7.5, which led to the use of pH adjustment to lower the pH at seven of these 17 locations (see Section 2.3.4).

2.2 Overview of AM Demonstration Technologies

Nine different types of media were evaluated, including three iron-based media, either granular ferric oxide (ARM 200 and E33) or granular ferric hydroxide (GFH®); four iron-modified media, either alumina-based (A/I Complex 2000 and AAFS50), silica-based (G2), or resin-based (ArsenX^{np}); one titanium oxide media (Adsorbsia™ GTO™); and one zirconium oxide media (Isolux™). All of these media have NSF Standard 61 certification for use in drinking water applications. Over the course of the study, some newer versions of the media were developed with slight modifications to the older versions. For example, ARM 300 is a newer version of ARM 200 with a slightly different mesh size and density. E33-P is a pelletized media, which is 25% denser than its granular counterpart, E33-G (thus, its cost per cubic foot is higher than E33-G). Both media have a similar arsenic adsorptive capacity on a weight basis. E33-P was designed for more robust applications such as frequent backwashes, but because of lack of apparent benefits, the manufacturer had stopped recommending the use of this type of media for arsenic removal in 2010. LayneRT, a newer version of hybrid adsorbent manufactured by Dow Chemical, was used to replace the original ArsenX^{np} during the media change-out at two demonstration sites. Table 2-4 summarizes the major characteristics of these nine media.

Table 2-2. Summary of AM Demonstration Sites

No.	Site ID	Design Flow rate (gpm)	Average Flow rate (gpm)	Daily Op Time (hr/day)	Average Daily Demand (gpd)	Annual Production (kgal)	Utilization Rate(a) (%)	Pre-existing Treatment
Non-Transient Non-Community Water Systems								
1	BL	10	On demand		450	83	2	Softener, Cl_2
2	SU	12	9.3	1.1	730	181	3	None
3	WS	20	16.4	1.0	984	349	3	Softener
4a	KF	30	On demand		1,341	489	3	Gas Cl_2
4b	KF	60	On demand		17,562	6,022	19	
4c	KF	60	On demand		4,580	1,672	5	
5	BR	40	40	4.2	10,080	3,679	17	Cl_2
Community Water Systems								
6	GF	10	13	5.4	4,212	1,509	29	Aeration for radon
7	WA	14	10.4	3.7	2,618	955	13	None
8	PF	15	9.6	3.6	2,074	706	9	Birm®
9	DM	22	6.1	7.6	1,565	571	5	Cl_2
10	VV	37	36	24(b)	51,840	18,750	96(a)	Cl_2
11	BW	40	41	9.5	23,370	8,530	41	Cl_2, AA, caustic
12	RR	45	31	12 or 24(b)	NA	8,508	36	Cl_2
13	LI	50	23	18.5	25,783	9,318	35	Air, Cl_2, poly-PO_4
14	TN	63	60.1	4.4	15,276	5,755	17	Cl_2
15	LD	75	71.5	12	46,866	18,790	48	Cl_2
16	WM	100	91	5.9	32,214	11,758	22	Cl_2
17	RF	120	82	9.7	48,977	21,243	34	Cl_2
18	TE	150	79.3	19.6	93,257	34,039	43	Cl_2
19	AL	150	129	6.7	51,393	18,928	24	Gas Cl_2, poly-PO_4
20	NP	160	114	12.3	84,132	30,709	37	Cl_2
21	GE	200	32.0(c)	2.6	NA	14,868	14	Cl_2, F
22	SV	300	207	6.2	77,004	28,106	18	Gas Cl_2, poly-PO_4
23	AN	320	260	7.0	109,200	40,395	24	Cl_2
24	RN	350	275	3.8	62,700	22,885	12	Cl_2
25	TA	450	503	3.9	117,702	42,961	18	Cl_2
26	BC	640	564	4.5	152,280	51,334	15	Cl_2

(a) Ratio of a system’s average annual production to its maximum capacity at design flowrate.
(b) Wells at VV and RR operated for 12 or 24 hr daily for study purposes.
(c) On demand.
AA = activated alumina; Air = aeration; NA = not available

2.3 AM System Design and Configuration

Because of varying site conditions and source water quality, the design and basic components of the AM systems varied among the demonstration sites. Table 2-5 summarizes the design and basic components of the 28 AM systems. The system flowrate, media vessel design, media type and quantity, and any pre- and/or post-treatment requirement affected the system performance and cost. In addition, the system instrumentation and controls also affected the system cost. These parameters and cost factors are discussed as follows.

Table 2-3. Summary of AM Site Source Water Quality

No.	Site ID	Total As (µg/L)	As (III) (µg/L)	Total Fe (µg/L)	Total Mn (µg/L)	Total P (µg/L)	Silica(a) (mg/L)	TOC (mg/L)	pH (S.U.)
Non-Transient Non-Community Water Systems									
1	BL	15.4	11.3	2,290	85.7	<10	15.3	2.0	7.4
2	SU	31.7	12.1	37	5.4	<10	14.1	1.0	8.4
3	WS	24.7	5.8	27	17.5	<10	15.8	1.0	7.1
4	KF	29.8	0.3	<25	0.4	<10	30.0	<0.7	8.0
5	BR	57.6	37.5	32	5.1	<10	41.8	0.9	8.2
Community Water Systems									
6	GF	29.7	0.5	<25	3.3	71	25.4	<0.7	7.1
7	WA	39.1	38.7	<25	21.9	33	10.5	<0.7	8.5
8	PF	25.2	3.2	97	56.8	180	15.1	<1.0	7.9
9	DM	42.2	1.8	<25	9.0	<10	12.6	<0.7	7.7
10	VV	39.4	0.6	<25	1.0	11	19.0	<0.5	7.7
11	BW	46.4	0.5	<25	2.3	<10	19.7	<0.7	7.3
12	RR	59.7	2.2	<25	0.3	10	25.6	NA	6.9
13	LI(b)	41.7	0.4	<25	0.2	<10	43.4	<0.7	6.9
14	TN	34.9	0.5	<25	0.7	<10	26.2	<0.7	8.0
15	LD	22.2	0.4	<25	0.6	6	16.4	<1	7.2
16	WM	36.0	1.3	<25	0.6	<10	46.8	1.3	7.8
17	RF	37.7	16.8	297	106.0	81.5	15.3	<1.0	7.7
18	TE	12.7	2.5	<25	4.0	<10	27.7	<0.7	7.6
19	AL	40.2	31.5	63	55.1	40.7	15.3	0.7	7.8
20	NP(b)	32.2	0.7	<25	0.8	<10	14.1	<1.0	9.0
21	GE	19.6	14.3	554	8.0	49.8	23.3	1.9	7.2
22	SV	20.1	19.1	269	2.9	17.3	14.6	<0.5	7.8
23	AN	23.5	21.7	80	9.6	<10	38.0	1.6	7.8
24	RN(c)	67.2	0.3	<25	0.1	115	72.6	<1.0	7.1
25	TA	16.9	0.3	31	1.3	<10	32.8	<0.7	9.6
26	BC	15.3	13.1	177	16.2	<10	9.0	<0.5	7.9

(a) as SiO_2.

(b) Source water also contained elevated uranium.

(c) Source water also contained elevated antimony.

2.3.1 System Flowrate. As shown in Table 2-5, system design flowrates varied from 10 to 60 gpm for NTNCWS and from 10 to 640 gpm for CWS. The design flowrate of an AM system was determined by the well capacity or peak flowrate. It was used to size the treatment system, thus affecting the system capital investment cost (Section 2.4). Average system flowrates as measured during the performance evaluation studies often were lower than the respective design flowrates. The average flowrate of an AM system affected media performance and O&M cost, as discussed in Section 2.5.

2.3.2 Tank Design. Most of the AM systems evaluated used two or more media tanks arranged either in series or in parallel. Since a lead/lag system requires extra media and media tanks than a parallel system, it often costs more than the parallel system treating the same flow. Smaller systems tend to use a lead/lag configuration. For example, all seven NTNCWS and eight out of 10 CWS with flowrates below 100 gpm were configured in series; whereas 10 out of 11 CWS equal to or greater than 100 gpm were configured in parallel. Systems in lead/lag configuration often had one or two treatment trains, each with a pair of tanks. Exceptions were the ATS systems demonstrated at SU, WA, and DM where one treatment train consisted of three adsorption vessels in series. Systems in parallel configuration had at least two treatment trains with one tank in each train. The RN and TA sites each had three vessels in

Table 2-4. Properties of AM Used for EPA Demonstration Projects

Parameter	**A/I Complex 2000(a)**	**AAFS50**	**Adsorbsia™ GTO™**
Matrix/Active Ingredient	91% Al_2O_3 and iron complex	83% Al_2O_3 and proprietary additive	Nanocrystalline titanium oxide
Physical Form	Dry granular solid	Dry granular solid	Dry granular solid
Color	Light brown/orange	Light amber	White
Bulk Density (g/cm^3 [lb/ft^3])	0.82 (51)	0.91 (57)	0.71 (44)
Moisture Content (%)	<5	NA	<15
BET Area (m^2/g)	320	220	200–300
Particle Size Distribution/ Effective Size	28 × 48 Tyler mesh (0.42 mm)	28 × 48 Tyler mesh	10 × 60 US Standard mesh
Manufacturer	ATS	Alcan Chemical	Dow Chemical
No. of EPA Demo Sites	3	1	2(b)
Parameter	**ARM 200(c)**	**ArsenX^{np}**	**E33**
Matrix/Active Ingredient	Iron oxide/hydroxide	Iron hydroxide nanoparticles impregnated into resin beads (36% of Fe_2O_3)	Iron oxide composite (90% FeOOH)
Physical Form	Dry granular solid	Moist resin	Dry granular solid
Color	Dark brown	Reddish brown	Amber
Bulk Density (g/cm^3[lb/ft^3])	0.80 (50)	0.79–0.84 (49–52)	0.45 (28)
Moisture Content (%)	NA	NA	<15
BET Area (m^2/g)	225	NA	142
Particle Size Distribution/ Effective Size	12 × 40 USS mesh	0.3–1.2 mm	10 × 35 USS mesh
Manufacturer	Engelhard	Purolite	Bayer
No. of EPA Demo Sites	2	4	13
Parameter	**G2®**	**GFH®**	**Isolux™-302M**
Matrix/Active Ingredient	Diatomaceous earth (Si-based) coated with ferric hydroxide	52–57% $Fe(OH)_3$ and β-FeOOH	Hydrous zirconium oxide
Physical Form	Dry powder	Moist granular solid	Amorphous powder
Color	Dark brown	Dark brown	White, bulky powder
Bulk Density (g/cm^3[lb/ft^3])	0.75 (47)	1.22–1.29 (76–80)	0.96 (60)
Moisture Content (%)	NA	47	NA
BET Area (m^2/g)	27	127	300–350
Particle Size Distribution/ Effective Size	0.32 mm	0.32–2 mm	1–3 to 40–50 µm
Manufacturer	ADI International	GEH Wasserchemie GmbH	MEI
No. of EPA Demo Sites	1	1	1

(a) Media supply discontinued in 2009 due to company closeout.
(b) Including one site using IR as pre-treatment.
(c) No longer available on marketplace.
NA = not available

parallel and the BC site had four vessels in parallel. Figures 2-1A through 2-1F show photographs of selected AM systems with different tank designs and configurations.

Lead/lag and parallel systems can be interchangeable with minor modifications. For example, the BW and RR systems were originally designed for parallel operation, but were re-configured to lead/lag to treat about half of the flow or less. The GE system was originally designed as a lead/lag system, but changed to parallel to treat twice the flow. In theory, when a parallel system is changed to lead/lag, the flow-normalized cost would double due to a 50% reduction in flowrate.

Tank size and material also affected the system cost. An adsorption tank was sized to hold an appropriate amount of media required for treatment. Tank sizes varied from 10-in × 54-in (smallest) to 72-in × 72-in (largest) with a diameter of 10, 12, 18, 20, 24, 36, 42, 48, 54, 63, 66, or 72 in and a height of 48, 52, 54, 60, 65, 72, 80, or 86 in. Adsorption tanks were constructed of fiberglass reinforced plastic (FRP), polyglass, carbon steel (CS), or stainless steel (SS). The steel tanks were American Society of Mechanical Engineers (ASME)-coded for a pressure rating of at least 100 psi. The FRP tanks were rated for 100 to 150 psi. 17 out of 26 sites used FRP tanks and five used CS tanks. The three ATS sites used small polyglass tanks. Only one site used 72-in ×72-in SS tanks, the largest tanks used for the demonstration program. Both FRP and CS tanks could be used for treatment, but the cost of smaller FRP tanks often was lower than that of smaller CS tanks. The cost of larger FRP tanks converged with that of larger CS tanks.

Tank openings and internal arrangements such as upper and bottom distributors and laterals varied among different types of tanks. For example, smaller tanks often have only one opening on the top with a riser tube. Larger tanks had top and bottom openings; some even had side openings for viewing and/or media loading. The internal distributors and laterals were constructed mostly of polyvinyl chloride (PVC) or SS.

2.3.3 Media Type and Volume. The media volume was determined by the design flowrate and empty bed contact time (EBCT) required. Table 2-6 presents design and average EBCTs for the 28 systems sorted by the media type and tank configuration.

Of the nine media, Isolux™ had the shortest design EBCT of 0.6 min because it is a powder material with much finer particle sizes (<50 µm) and, therefore, much faster adsorption kinetics than those of granular media. Isolux™ was filled into cartridges, each with an annular space sandwiched between two thin layers of tubular membrane made of porous polyethylene (PE) material. The cartridges were then loaded into adsorption modules and operated in cross-flow, unlike the downflow used by granular media. A/I Complex 2000 had a short design EBCT, i.e., 0.9 to 1.6 min per tank. But the EBCT for the entire system was tripled due to the use of three vessels in series. G2® had the longest EBCT of 15.9 min (per tank). The G2® system was originally designed for a different site to treat 75 gpm of flow using two tanks in parallel at an EBCT of 17 min. Because the site withdrew from the demonstration program and was replaced by the BW site to treat a smaller flowrate of 40 gpm, the two G2® tanks were reconfigured to lead/lag. For E33 media, the design EBCT ranged from 3.3 to 5.7 min for the parallel systems, slightly longer than that for the lead/lag systems, i.e., 3.1 to 4.1 min. For ArsenX^{np}, the design EBCT was 4.0 min for a parallel system and 1.1 to 2.8 min for lead/lag systems.

Table 2-5. Summary of AM System Design and Components

No.	Site ID	Flowrate (gpm)		Tank Design						Adsorptive Media				Pre-treatment	Post-treatment
		D	A	Configu-ration	No. of Trains	Tanks per Train	Total Tanks	Tank Size (in)	Tank Materials	Media Type	Volume per Vessel (ft^3)	Total Volume (ft^3)	EBCT(a) (D/A) (min)		
Non-Transient Non-Community Water Systems															
1	BL	10	Vary	Series	1	2	2	18 × 65	FRP	ARM 200	4.5	9	3.4 (D) Varying (A)	NaOCl, softening	None
2	SU	12	9.3	Series	1	3	3	10 × 54	Polyglass	A/I Complex 2000	1.5	4.5	1.0 (D) 1.2 (A)	Oxidation Columns	None
3	WS	20	16.4	Series	1	2	2	24 × 72	FRP	Adsorbsia™ GTO™	7.5	15	2.8 (D) 3.4 (A)	None	None
4a	KF	30	Vary	Series	2	2	4	18 × 65	FRP	ArsenX^{np}	5	20	2.5 (D) Vary (A)	Cl$_2$	None
4b	KF	60	Vary	Series	1	2	2	36 × 72	FRP	ARM 200	20	40	2.5 (D) Vary (A)	Cl$_2$	None
4c	KF	60	Vary	Series	1	2	2	36 × 72	FRP	Adsorbsia™ GTO™	20	40	2.5 (D) Vary (A)	Cl$_2$	None
5	BR	40	40	Series	1	2	2	42 × 72	CS	E33	22	44	4.1 (D) 4.1 (A)	NaOCl, pH (CO$_2$)	None
Community Water Systems															
6	GF	10	13	Series	1	2	2	18 × 65	FRP	E33	5	10	3.7 (D) 2.9 (A)	None	Aeration to remove Radon
7	WA	14	10.4	Series	2	3	6	10 × 54	Polyglass	A/I Complex 2000	1.5	9	1.6 (D) 2.2 (A)	Oxidation Columns	None
8	PF	15	9.6	Series	1	2	2	12 × 52	FRP	ArsenX^{np}	2.3	4.6	1.1 (D) 1.8 (A)	None	Birm® (old)
9	DM	22	6.1	Series	2	3	6	10 × 54	Polyglass	A/I Complex 2000	1.5	9	1.0 (D) 3.7 (A)	NaOCl	None
10	VV	37	36	Series	1	2	2	36 × 72	FRP	AAFS50 ARM 200	16.7, 22	33.4, 44	3.5 (A) 4.6 (A)	NaOCl, pH (acid)	None
11	BW	40(b)	41	Series	1	2	2	72 × 72	SS	G2®	85	170	16 (D) 16 (A)	NaOCl, pH (acid)	pH (NaOH)
12	RR	45(b)	31	Series	1	2	2	36 × 72	FRP	E33	22	44	3.7 (D) 5.3 (A)	NaOCl	None
13	LI	50	23	Parallel	1	1	2(c)	42 × 60	FRP	ArsenX^{np}	27	54	4.0 (D) 8.8 (A)	None	NaOCl, Poly-PO$_4$, Aeration
14	TN	63	60.1	Parallel	2	1	2	36 × 72	FRP	E33	19	38	4.5 (D) 4.7 (A)	NaOCl, pH (CO$_2$)	None

Table 2-5. Summary of AM System Design and Components (Continued)

		Flowrate (gpm)		Tank Design						Adsorptive Media					
No.	**Site ID**	**D**	**A**	**Configu-ration**	**No. of Trains**	**Tanks per Train**	**Total Tanks**	**Tank Size (in)**	**Tank Materials**	**Media Type**	**Volume per Vessel (ft^3)**	**Total Volume (ft^3)**	**EBCT[(a)] (D/A) (min)**	**Pre-treatment**	**Post-treatment**
15	LD	75	71.5	Series	1	2	2	42 × 72	FRP	ArsenX^{np}	28	56	2.8 (D) 2.9 (A)	None	NaOCl
16	WM	100	90	Parallel	2	1	2	48 × 72	CS	E33	38	76	5.7 (D) 6.3 (A)	NaOCl, pH (acid)	None
17	RF	120	82	Parallel	2	1	2	48 × 72	FRP	E33	30	60	3.7 (D) 5.5 (A)	NaOCl, pH (CO_2)	None
18	TE	150	79.3	Parallel	4	1	4	20 × 48	CS	Isolux™	2.9	11.6	0.6 (D) 1.1 (A)	NaOCl	None
19	AL	150	129	Series	1	2	2	63 × 86	FRP	E33	53.6, 70.3	124	3.1 (D) 3.6 (A)	Gas Cl_2	None
20	NP	160	114	Parallel	2	1	2	48 × 72	FRP	E33	35.6	71.2	3.3 (D) 4.7 (A)	NaOCl, pH (CO_2)	None
21	GE	200	32	Parallel	2	1	2	54 × 60	CS	E33	49	98	3.7 (D) 22.9 (A)	NaOCl	None
22	SV	300	207	Parallel	2	1	2	63 × 86	FRP	E33	80	160	4.0 (D) 5.8 (A)	NaOCl	Poly-PO_4
23	AN	320	260	Parallel	2	1	2	63 × 80	FRP	E33	76	152	3.6 (D) 4.4 (A)	NaOCl	None
24	RN	350	275	Parallel	3	1	3	66 × 72	CS	GFH®	80	240	5.2 (D) 6.5 (A)	NaOCl	NaOCl
25	TA	450	503	Parallel	3	1	3	63 × 86	FRP	E33	71-73	215	3.6 (D) 3.2 (A)	pH (CO_2)	Cl_2, HOCl (MIOX)
26	BC	640	564	Parallel	4	1	4	63 × 80	FRP	E33	80	320	3.7 (D) 4.2 (A)	NaOCl	NaOCl

(a) EBCT for one vessel only.
(b) System flowrate reduced to 50% after being reconfigured to lead/lag.
(c) One vessel in service and one in standby.
A = average; CS = carbon steel; D = design; EBCT = empty bed contact time; FRP = fiberglass reinforced plastic; SS = stainless steel

Figure 2-1A. 20-gpm Adsorbsia™ GTO™ Media System by Siemens (Two FRP Vessels in Series)

Figure 2-1B. 14-gpm As/I Complex 2000 Media System by ATS (Two Trains of Three Polyglass Vessels in Series)

Figure 2-1C. 40-gpm G2® Media Arsenic Adsorption System by ADI (Two Stainless Steel Vessels in Series)

Figure 2-1D. 150-gpm Isolux™-302M Media Arsenic Adsorption System by MEI (Nine Replaceable Media Cartridges in Each Carbon Steel Vessel)

Figure 2-1E. 160-gpm E33 Media Arsenic Adsorption System by AdEdge (Two FRP Vessels in Parallel)

Figure 2-1F. 450-gpm E33 Media Arsenic Adsorption System by Severn Trent Services (Three FRP Vessels in Parallel)

Table 2-6. EBCT vs. Media Type and Tank Configuration

Media Type	Design EBCT		Average EBCT	
	Lead/Lag[(a)]	Parallel	Lead/Lag[(a)]	Parallel
A/I Complex 2000	0.9–1.6 (3)	NA	1.2–3.7 (3)	NA
AAFS50	4.4 (1)	NA	3.5 (1)	NA
Adsorbsia™ GTO™	2.5, 2.8 (2)	NA	3.4 (1)	NA
ARM 200	2.5, 3.4 (2)	NA	Varying	NA
ArsenX^{np}	1.1–2.8 (3)	4.0 (1)	2.9 (1)	8.8 (1)
E33	3.1–4.1 (4)	3.3–5.7 (9)	2.9–5.3 (4)	3.4–6.3 (9)
G2®	15.9 (1)	NA	15.5 (1)	NA
GFH®	NA	5.1 (1)	NA	6.5 (1)
Isolux™	NA	0.6 (1)	NA	1.9 (1)

(a) EBCT calculated for one tank.
Numbers in parentheses indicate number of systems.
EBCT = empty bed contact time

2.3.4 Pre- and Post-Treatment. The most common pre-treatments for AM systems are pH adjustment and pre-oxidation. Any new pre- and/or post-treatment for AM systems will have an impact on the total capital investment cost and must be taken into consideration when attempting to compare the costs of different systems.

Because the adsorptive capacity of a media increases with decreasing pH, lowering the water pH can extend media life and improve media performance. As shown in Table 2-5, eight out of 28 AM systems were equipped with pH adjustment/control systems, although one site decided not to use it after its installation. Among these seven systems, five used CO_2 gas and two used mineral acid to lower raw water pH. Figure 2-2 shows a composite of photographs of a CO_2 pH adjustment/control system, which consisted of a liquid CO_2 supply assembly, an automatic pH control panel, a CO_2 membrane assembly, and a pH probe located downstream of the membrane module. Only one site used NaOH to bring the effluent pH back to near neutral.

When source water contained soluble As(III), a pre-oxidation step was included to oxidize it to As(V). If a site already disinfected water with NaClO or gas Cl_2, the chlorination point was moved to ahead of the AM system to oxide As(III). Out of the 26 sites, 18 sites used pre-chlorination, two used oxidation columns, and the remaining six did not use any pre-oxidation. However, not all 18 sites using pre-chlorination had soluble As(III) in raw water. For example, raw water at the VV site did not have soluble As(III), but was pre-chlorinated to prevent algae growth in the adsorption tanks. If raw water contained high concentrations of Fe(II) and/or Mn(II), then a more elaborate pre-treatment, such as iron removal, would be used to protect AM from being clogged and/or fouled by iron and manganese coatings.

Other pre-existing treatment processes, such as softening, aeration, Birm®, and phosphate addition, remained on site as long as they did not interfere with the arsenic treatment.

2.3.5 Instrumentation and Controls. System instrumentation and controls varied among different systems in terms of quality, material, level of complexity/automation, and functionality. Such variations had an impact on the total capital investment cost and must be taken into consideration when attempting to compare costs of different systems.

Figure 2-2. Carbon Dioxide Gas Flow Control System for pH Adjustment
(Clockwise from Top Left: Liquid CO_2 Supply Assembly; Automatic pH Control Panel; CO_2 Membrane Module; Port for pH Probe)

A fully automatic instrumentation and control system included a programmable logic controller (PLC) and operator's interface panel (OIP), software, automatic instrumentation (sensors, transmitters, controllers, alarms, electrical conductors, pneumatic tubing, etc.), and automatically controlled equipment (valves, pumps, chemical feed pumps, air compressors, etc.). The instrument could monitor pH, flow, level, pressure, and temperature. Some even had a remote dial-in capability for troubleshooting. Automatic operations reduced operator's efforts, but increased the cost for instrumentation and control equipment as well as the skill level required of the operator to maintain more sophisticated equipment.

Some systems only had a controller box on top of a media tank. The AM systems were suitable for semi-automatic or manual operation because there were not many "moving parts". The three AM systems at KF were designed for complete manual operations. There was no electrical connection for each of the three systems; all flow meters and pressure gauges were mechanical and all valves were manual. Pressure was the driving force to push water through the treatment systems. During system backwash, manual valves were physically opened and closed to change flow paths and adjust flowrates.

2.4 AM System Capital Investment Costs

This section begins with a review of total capital investment costs, and then breaks down the discussion into three cost categories: equipment, site engineering, and installation.

2.4.1 Total Capital Investment Costs. Capital investment costs for the 28 AM demonstration systems are categorized into three groups: NTNCWS, small CWS (<100 gpm), and large CWS (≥100 gpm), as shown in Table 2-7. The KF site had three separate POE systems, which were counted as three NTNCWS. One system located in the Resident Hall (Site 4b) supplied water to students living in the dorms year around, including breaks. Therefore, it was not a typical NTNCWS.

Total capital investment costs ranged from $14,000 for the 22-gpm DM system to $305,000 for the 640-gpm BC system. Figures 2-3 and 2-4 present the total capital investment costs as a function of design flowrates for smaller (<100 gpm) and larger systems (≥100 gpm), respectively. Because tank configuration could affect system costs, lead/lag and parallel systems were plotted separately in each figure. All seven NTNCWS and eight out of 10 small CWS were lead/lag systems, whereas all but one large CWS were parallel systems. Thus, the effect of tank configuration on costs could not be separated from that of system flowrates. Even though there were insufficient data to compare costs of systems with similar sizes but different configurations, lead/lag systems are generally more expensive than their parallel counterparts.

Among the seven NTNCWS, the BR system had the highest total capital investment cost of $138,642 due largely to three contributing factors: a CO_2 pH control system, two large CS vessels, and a more advanced system control. Among the smaller CWS (<100 gpm), the VV system had the highest total capital investment cost at $228,309, partly because it was equipped with a mineral acid pH control system, a backwash recycle system, and extra monitoring and control devices (see Figures 2-5 and 2-6). The BW system cost ranked the second highest at $166,050, due mainly to the use of two large (72-in × 72-in) SS tanks and two pH control systems for raw and treated water (see Figure 2-1C). The three A/I Complex 2000 systems at SU, WA, and DM had the lowest costs because they used small, inexpensive polyglass tanks (10-in × 54-in) without the backwash capability or automatic controls (see Figure 2-1B).

The data for the larger CWS systems, as shown in Figure 2-4, indicate a stronger correlation between capital investment costs and system design flowrates. Curve fittings were performed on the data set for 12 parallel systems, yielding an R^2 of 0.817 for linear regression. This result might be attributed to the fact that most of these systems used E33 and similar iron-based media for arsenic removal.

To further compare system capital investment costs, the capital cost of each system was divided by its design capacity in gpm and gpd and the results are presented in Table 2-7 and plotted against system design flowrates in Figures 2-7 and 2-8. Normalize costs for NTNCWS ranged from $992 to $3,466/gpm (or $0.69 to $2.41/gpd) and averaged $2,039/gpm (or $1.42/gpd). Normalized costs for smaller CWS (<100 gpm) ranged from $636 to $6,171/gpm (or $0.44 to $4.29/gpd) and averaged $2,395(or $1.66/gpd). These normalized costs scattered widely and did not show a clear trend. Normalized costs for larger CWS (≥100 gpm) ranged from $477 to $1,492/gpm (or $0.33 to 1.04/gpd) and averaged $806 (or $0.56/gpd). As shown in Figure 2-8, these normalized costs clearly showed a decreasing trend with system flowrates due to the economy of scale.

Unit costs of the 28 AM systems expressed as 1,000 gal of water treated are also shown in Table 2-7. To calculate the unit cost, the capital investment cost of an AM system was first converted to an annualized cost using a capital recovery factor (CRF) of 0.09439 based on a 7% interest rate and a 20-year return period and then divided by the design or average annual water production rate. The design annual production is the maximum amount of water that can be produced by a system assuming that it is operated

Table 2-7. Total Capital Investment Costs for AM Systems

No.	Site ID	Media Type	Design Flow Rate (gpm)	Total Capital Cost ($)	Normalized Capital Cost ($/gpm)	Normalized Capital Cost ($/gpd)	Annualized Cost ($/yr)	Unit Cost (/kgal of water)		Utilization Rate[b] (%)
								D[a]	A	
Non-Transient Non- Community Water Systems										
1	BL	ARM 200	10 (S)	$27,255	$2,726	$1.89	$2,573	$0.49	$31.36	2
2	SU	A/I Complex	12 (S)	$16,930	$1,411	$0.98	$1,598	$0.25	$8.90	3
3	WS	Adsorbsia™	20 (S)	$51,895	$2,595	$1.80	$4,898	$0.47	$14.03	3
4a	KF	ArsenX^{np}	30 (S)	$55,847	$1,862	$1.29	$5,271	$0.33	$10.77	3
4b	KF	ARM 200	60 (S)	$59,516	$992	$0.69	$5,618	$0.18	$0.93	19
4c	KF	Adsorbsia™	60 (S)	$73,258	$1,221	$0.85	$6,915	$0.22	$4.14	5
5	BR	E33	40 (S)	$138,642	$3,466	$2.41	$13,086	$0.62	$3.56	17
Minimum			*10*	*$16,930*	*$992*	*$0.69*	*$1,598*	*$0.18*	*$0.93*	*2*
Maximum			60	*$138,642*	*$3,466*	*$2.41*	*$13,086*	*$0.62*	*$31.36*	*19*
Average					*$2,039*	*$1.42*		*$0.37*	*$10.53*	*8*
Community Water Systems (<100 gpm)										
6	GF	E33	10 (S)	$34,201	$3,420	$2.38	$3,228	$0.61	$2.13	29
7	WA	A/I Complex	14 (S)	$16,475	$1,177	$0.82	$1,555	$0.21	$1.63	13
8	PF	ArsenX^{np}	15 (S)	$17,255	$1,150	$0.80	$1,629	$0.21	$2.31	9
9	DM	A/I Complex	22 (S)	$14,000	$636	$0.44	$1,321	$0.11	$2.31	5
10	VV	AAFS50	37 (S)	$228,309	$6,171	$4.29	$21,550	$1.11	$1.15	96[c]
11	BW	G2®	40 (S)	$166,050	$4,151	$2.88	$15,673	$0.75	$1.84	41
12	RR	E33	45 (S)	$88,307	$1,962	$1.36	$8,335	$0.35	$0.98	36
13	LI	ArsenX^{np}	50 (P)	$114,070	$2,281	$1.58	$10,767	$0.41	$1.16	35
14	TN	E33	63 (P)	$115,306	$1,830	$1.27	$10,884	$0.33	$1.89	17
15	LD	ArsenX^{np}	75 (S)	$87,892	$1,172	$0.81	$8,296	$0.21	$0.44	48
Minimum			*10*	*$14,000*	*$636*	*$0.44*	*$1,321*	*$0.11*	*$0.44*	5
Maximum			*75*	*$228,309*	*$6,171*	*$4.29*	*$21,550*	*$1.11*	*$3.56*	48
Average					*$2,395*	*$1.66*		*$0.43*	*$1.58*	*26*
Community Water Systems (>100 gpm)										
16	WM	E33	100 (P)	$149,221	$1,492	$1.04	$14,085	$0.27	$1.20	22
17	RF	E33	120 (P)	$131,692	$1,097	$0.76	$12,430	$0.20	$0.59	34
18	TE	Isolux™	150 (P)	$76,840	$512	$0.36	$7,253	$0.09	$0.21	43
19	AL	E33	150 (S)	$179,750	$1,198	$0.83	$16,967	$0.22	$0.90	24
20	NP	E33	160 (P)	$143,113	$894	$0.62	$13,508	$0.16	$0.44	37
21	GE	E33	200 (P)	$139,149	$696	$0.48	$13,134	$0.12	$0.88	14
22	SV	E33	300 (P)	$211,000	$703	$0.49	$19,916	$0.13	$0.70	18
23	AN	E33	320 (P)	$153,000	$478	$0.33	$14,442	$0.09	$0.37	24
24	RN	GFH®	350 (P)	$232,147	$663	$0.46	$21,912	$0.12	$0.96	12
25	TA	E33	450 (P)	$296,644	$659	$0.46	$28,000	$0.12	$0.65	18
26	BC	E33	640 (P)	$305,000	$477	$0.33	$28,789	$0.09	$0.56	15
Minimum			*100*	*$76,840*	*$477*	*$0.33*	*$7,253*	*$0.09*	*$0.21*	*12*
Maximum			*640*	*$305,000*	*$1,492*	*$1.04*	*$28,789*	*$0.27*	*$1.20*	*43*
Average					*$806*	*$0.56*		*$0.14*	*$0.68*	*24*

(a) System's maximum capacity at design flowrate, operating 24 hr a day, 365 days a year.
(b) Ratio of a system's average annual production rate to its maximum capacity at design flowrate.
(c) VV system operated full time for testing purposes. Data not included in statistics.
A = Average; D = Design; P = parallel configuration; S = series configuration

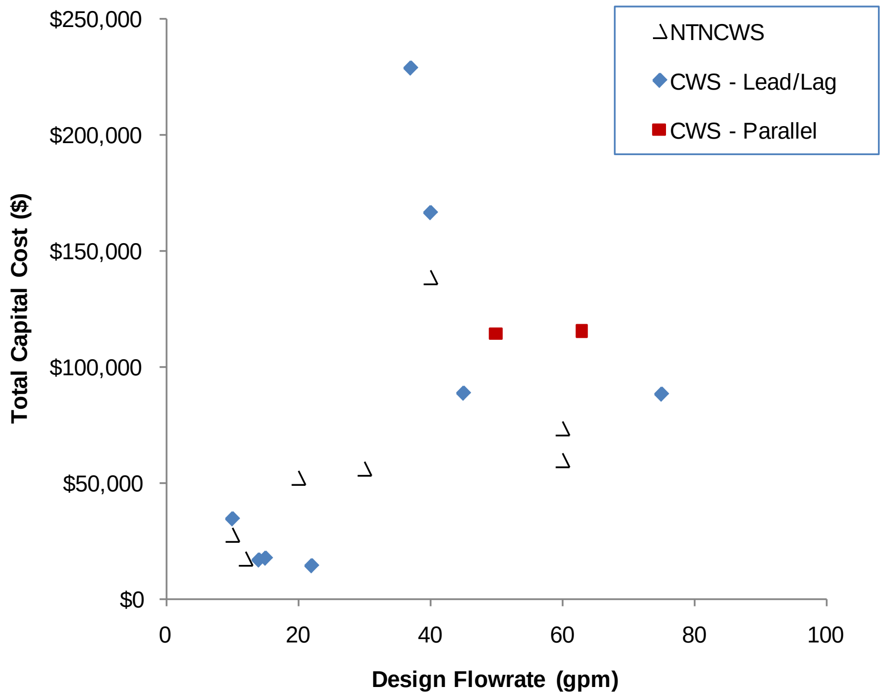


Figure 2-3. Total Capital Investment Costs of Smaller AM Systems (<100 gpm)

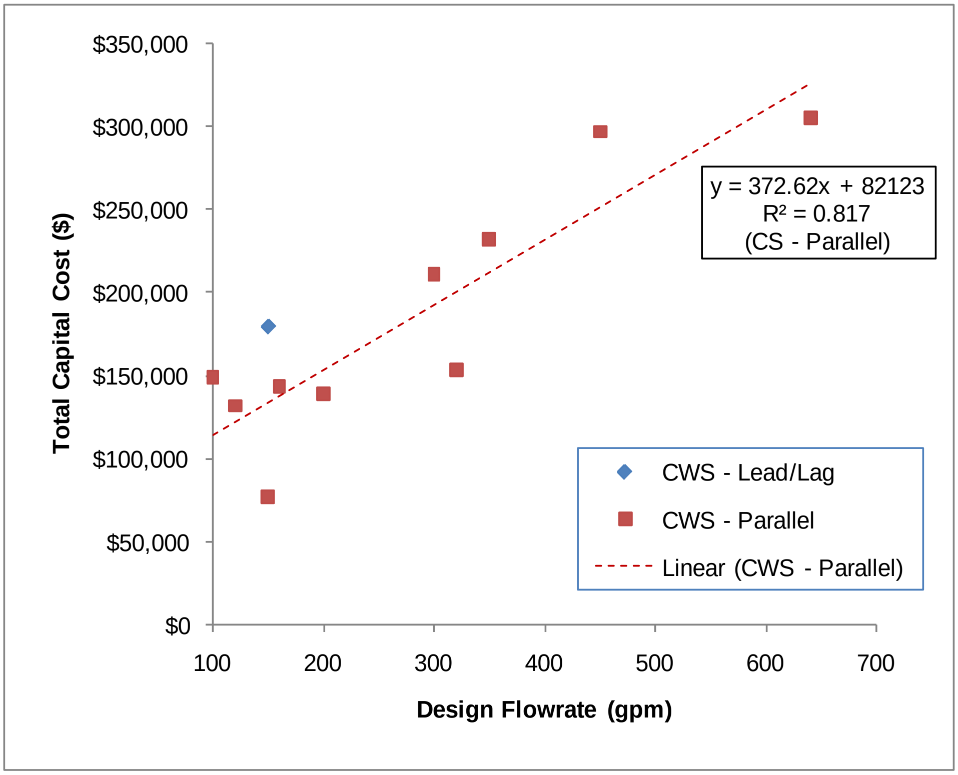


Figure 2-4. Total Capital Investment Costs of Larger AM Systems (≥100 gpm)

Figure 2-5. AM Treatment System Components at VV by Kinetico
(Clockwise from Top: POE Well No. 2 and Bypass Piping; Acid Addition Setup; In-Line pH Transmitter; Adsorption Tanks and Lower Distributor; and Main Control Panel)

Figure 2-6. Backwash Recycling System at VV
(Clockwise from Left: 1,800-gal Holding Tank; Recycle Pump and Bag Filter; and Backwash Flowrate Indicator and Pump Box)

at the design flowrate, 24 hours a day, 365 days a year. In reality, most systems, particularly small ones, do not operate at the design flowrate or 24 hours a day, 365 days a year. Therefore, the unit cost based on the average production rate is always higher than that based on the maximum possible production capacity.

The ratio of the average production to the maximum capacity, or utilization rate, affected the unit capital cost. In general, the lower the utilization rate, the higher the unit cost. Figure 2-9 presents average unit costs verses utilization rates for three groups: NTNCWS, small CWS (<100 gpm), and large CWS (≥100 gpm).

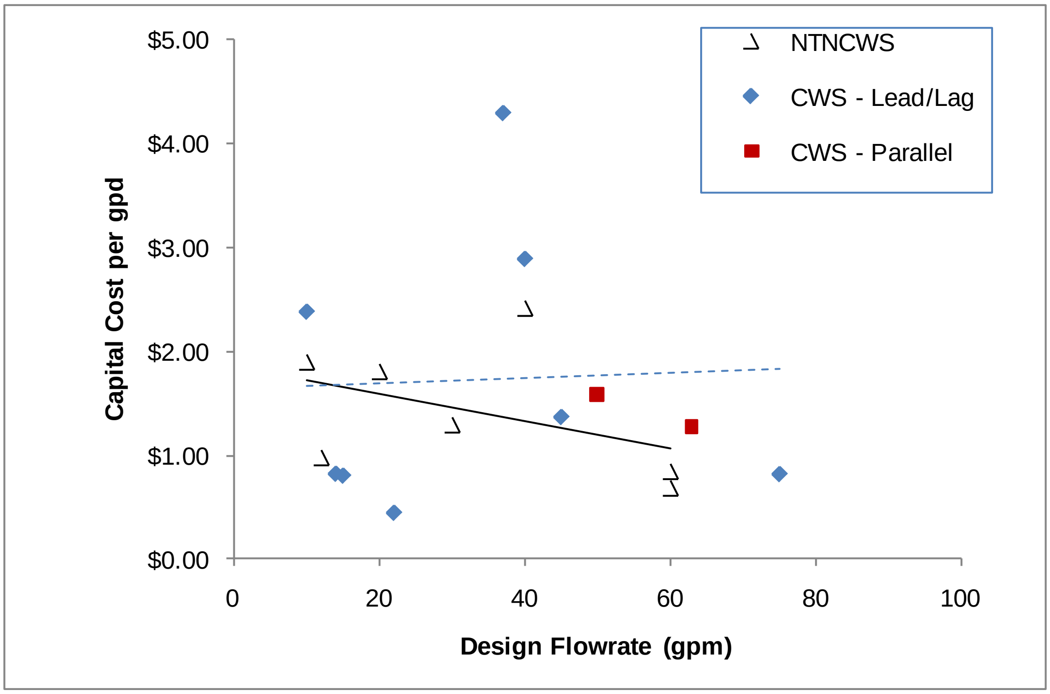


Figure 2-7. Smaller AM System Capital Investment Costs per gpd of Design Capacity (<100 gpm)

Comparison of the data in the three groups revealed some interesting observations. For example, the systems in the NTNCWS and small CWS groups had comparable flow ranges. However, because the systems in the NTNCWS group had a significantly lower utilization rate than those in the small CWS group, i.e., 8% vs. 26% (on average), their unit costs per 1,000 gal of water treated were significantly higher than those for the systems in the small CWS group, i.e., $10.53 vs. $1.58 (on average). On the other hand, the systems in the small and large CWS groups had comparable utilization rates, i.e., 26% vs. 24% (on average), and the system unit costs of the small CWS group were more than twice the costs for the large CWS group, i.e., $1.58 vs. $0.68 (on average). Therefore, the systems in the NTNCWS group had the highest unit costs due to small sizes and low utilization rates. An NTNCWS could consider using a smaller system with a larger storage capacity to achieve a higher utilization rate, thus a lower unit cost.

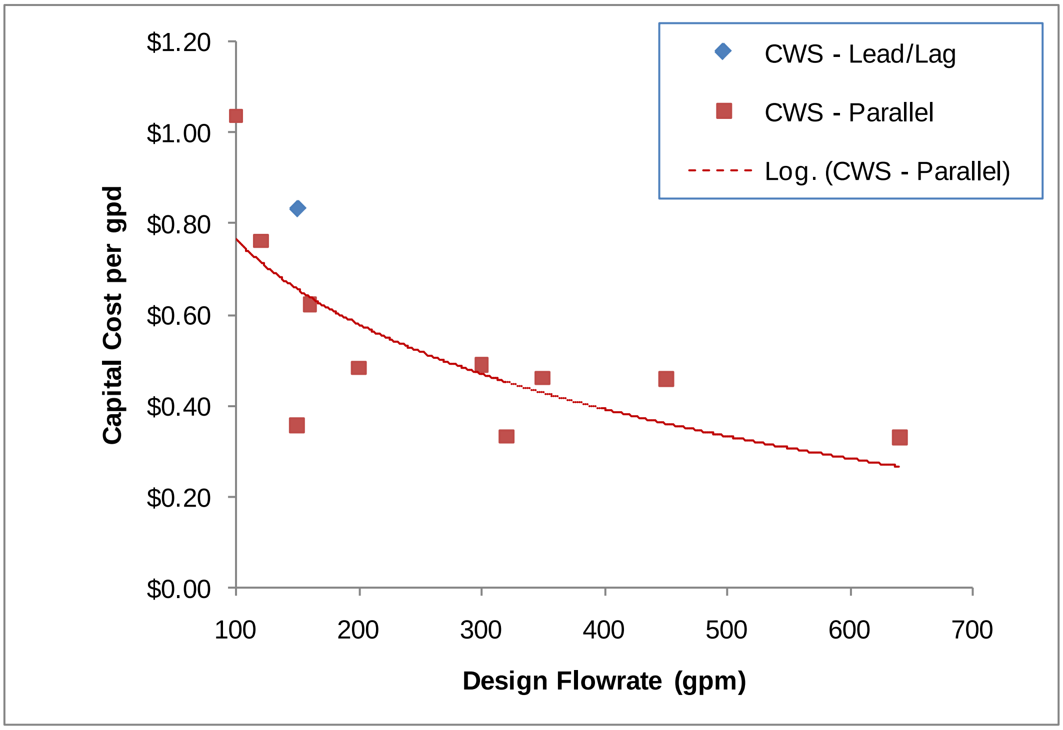


Figure 2-8. Larger AM System Capital Investment Costs per gpd of Design Capacity (≥100 gpm)

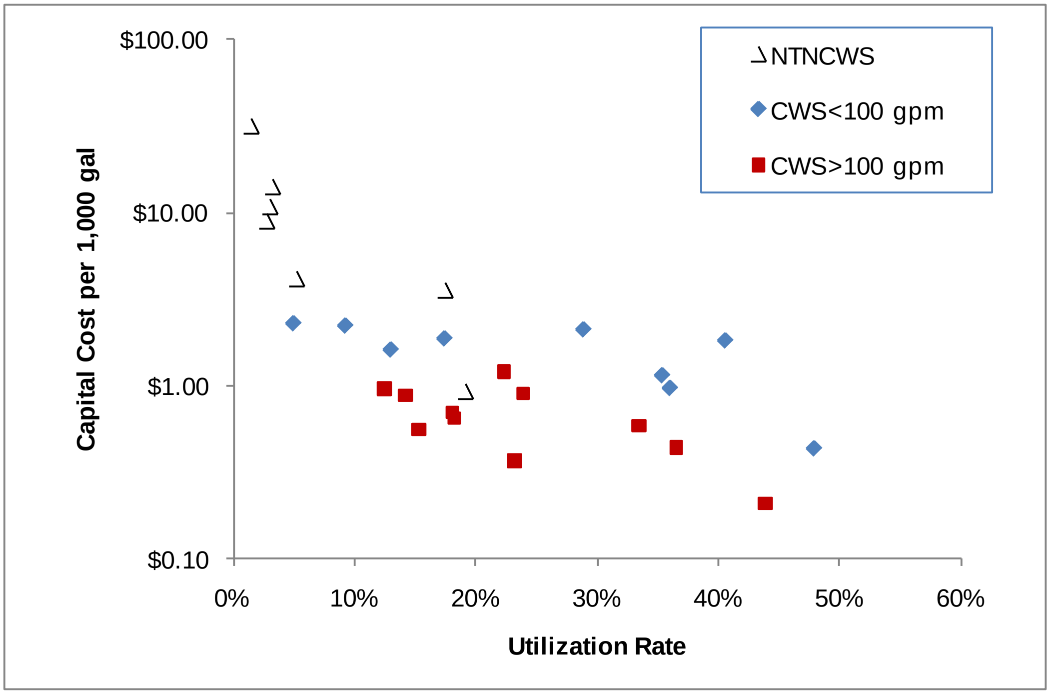


Figure 2-9. AM System Unit Costs per 1,000 gal of Water Treated as a Function of Utilization Rates

2.4.2 Equipment Cost. Treatment equipment including filtration vessels, piping and valves, and instrument and controls was mostly skid-mounted on a steel frame. The equipment cost for an AM system included the cost for the skid-mounted system, AM and under-bedding media, miscellaneous materials and supplies, freight, user's manual, and vendor's labor. It also included the cost for pH adjustment and/or pre-oxidation equipment. In one or two cases, the cost of backwash recycle equipment, such as backwash storage tank(s) and recycle pump, was also included in the equipment cost if it was part of the original proposal selected for the demonstration study.

Equipment costs for the AM systems ranged from \$8,640 for the 12-gpm SU system to \$218,000 for the 640-gpm BC system, as shown in Table 2-8. On average, the equipment costs accounted for 61%, 67%, and 72% of the total capital investment costs for NTNCWS, smaller CWS (<100 gpm), and larger CWS (≥100 gpm), respectively. Equipment cost data were plotted as a function of flowrates in Figure 2-10 for smaller systems (<100 gpm) and in Figure 2-11 for larger systems (≥100 gpm). Because the equipment costs made up the highest percentage of the total capital investment costs, equipment cost curves were similar, as expected, to the total capital investment cost curves shown in Figures 2-3 and 2-4. Factors contributing to the highest or the lowest equipment cost for the BR, VV, BW, and three A/I Complex 2000 systems were discussed in Section 2.4.1. Curve fittings were performed on the data set for 12 parallel systems (≥100 gpm), yielding an R^2 of 0.8002 for linear regression.

2.4.3 Site Engineering Cost. The site engineering cost for an AM system included the cost for the development of a system layout within the treatment building, design of piping connections to the inlet and distribution tie-in points in the building, and design of electrical connections. The site engineering cost also included the cost for the submission of engineering plans to relevant state agencies for permit review and approval.

Engineering costs for the AM treatment systems ranged from \$1,800 for the 14-gpm WA system to \$50,659 for the 37-gpm VV system. These costs represent, on average, 20%, 14%, and 12% of the total capital investment costs for NTNCWS, smaller CWS (<100 gpm), and larger CWS (≥100 gpm), respectively (see Table 2-8). As expected, the percentage decreased as the size of the system increased.

2.4.4 Installation Cost. The installation cost for an AM system included equipment and labor to unload and install the system, perform piping tie-ins and electrical connections, load and backwash AM, perform system shakedown and startup, and conduct operator's training. Piping tie-ins were completed using ductile iron or polyvinyl chloride (PVC) pipe, valves, and fittings. Figure 2-12 is a photograph showing media loading at the VV site. Installation costs for the treatment systems ranged from \$2,610 for the 22-gpm DM system to \$61,209 for the 450-gpm TA system. These installation costs represented 20%, 19%, and 16% of the total capital investment costs for NTNCWS, smaller CWS (<100 gpm), and larger CWS (≥100 gpm), respectively (see Table 2-8). Again, the percentage decreased as the size of the system increased, as expected.

2.5 AM System O&M Costs

O&M costs evaluated included the cost for media replacement and disposal, chemical supply, electricity consumption, and labor to operate the treatment systems. Of the 28 AM systems, 15 systems had spent media replaced during the study period and therefore more complete O&M costs were available. Table 2-9 summarizes the O&M costs with cost breakdowns for the 15 systems with media replacement. Two of the systems, i.e., WA and VV, experienced multiple change-outs with different media types. For the 13 systems without media replacement, estimated replacement costs were provided in individual final performance evaluation reports. Because costs were not actually incurred, the estimates were not used in the cost analysis herein. Each cost component is discussed below.

Table 2-8. Summary of Equipment, Site Engineering, and Installation Costs of AM Systems

No.	Site ID	Media Type	Design Flow Rate (gpm)	Total Capital Cost ($)	Equipment		Site Engineering		Installation &Startup	
					Cost	% of Total	Cost	% of Total	Cost	% of Total
Non-Transient Non-Community Water Systems										
1	BL	ARM 200	10	$27,255	$10,435	38	$11,000	40	$5,820	21
2	SU	A/I Complex	12	$16,930	$8,640	51	$3,400	20	$4,890	29
3	WS	Adsorbsia™	20	$51,895	$30,215	58	$10,110	19	$11,570	22
4a	KF	ArsenX^{np}	30	$55,847	$39,108	70	$9,941	18	$6,798	12
4b	KF	ARM 200	60	$59,516	$41,689	70	$10,587	18	$7,240	12
4c	KF	Adsorbsia™	60	$73,258	$51,314	70	$13,032	18	$8,912	12
5	BR	E33	40	$138,642	$94,662	68	$24,300	18	$19,680	14
		Minimum	*10*	*$16,930*	*$8,640*	*38*	*$3,400*	*18*	*$4,890*	*12*
		Maximum	*60*	*$73,258*	*$51,314*	*70*	*$13,032*	*40*	*$11,570*	*34*
		Average				*61*		*20*		*20*
Community Water Systems (<100 gpm)										
6	GF	E33	10	$34,201	$22,431	66	$4,860	14	$6,910	20
7	WA	A/I Complex	14	$16,475	$10,790	65	$1,800	11	$3,885	24
8	PF	ArsenX^{np}	15	$17,255	$11,345	66	-(a)	-(a)	$5,910	34
9	DM	A/I Complex	22	$14,000	$8,990	64	$2,400	17	$2,610	19
10	VV	AAFS50	37	$228,309	$122,544	54	$50,659	22	$55,106	24
11	BW	G2®	40	$166,050	$105,350	63	$17,200	10	$43,500	26
12	RR	E33	45	$88,307	$63,785	72	$11,372	13	$13,150	15
13	LI	ArsenX^{np}	50	$114,070	$82,470	72	$12,800	11	$18,800	16
14	TN	E33	63	$115,306	$86,018	75	$12,897	11	$16,391	14
15	LD	ArsenX^{np}	75	$87,892	$60,678	69	$14,214	16	$13,000	15
		Minimum	*10*	*$14,000*	*$8,990*	*54*	*$1,800*	*10*	*$2,610*	*14*
		Maximum	*75*	*$228,309*	*$122,544*	*75*	*$50,659*	*22*	*$55,106*	*26*
		Average				*67*		*14*		*19*
Community Water Systems (>100 gpm)										
16	WM	E33	100	$149,221	$103,897	70	$25,310	17	$20,014	13
17	RF	E33	120	$131,692	$105,805	80	$4,672	4	$21,215	16
18	TE	Isolux™	150	$76,840	$58,500	76	$8,500	11	$9,840	13
19	AL	E33	150	$179,750	$124,103	69	$14,000	8	$41,647	23
20	NP	E33	160	$143,113	$116,645	82	$11,638	8	$14,830	10
21	GE	E33	200	$139,149	$101,290	73	$19,545	14	$18,314	13
22	SV	E33	300	$211,000	$129,500	61	$36,700	17	$44,800	21
23	AN	E33	320	$153,000	$112,000	73	$23,000	15	$18,000	12
24	RN	GFH®	350	$232,147	$157,647	68	$16,000	7	$58,500	25
25	TA	E33	450	$296,644	$202,685	68	$32,750	11	$61,209	21
26	BC	E33	640	$305,000	$218,000	71	$35,500	12	$51,500	17
		Minimum	*100*	*$76,840*	*$58,500*	*61*	*$4,672*	*4*	*$9,840*	*13*
		Maximum	*640*	*$305,000*	*$218,000*	*82*	*$35,500*	*17*	*$61,209*	*25*
		Average				*72*		*12*		*16*

(a) Included in equipment cost.

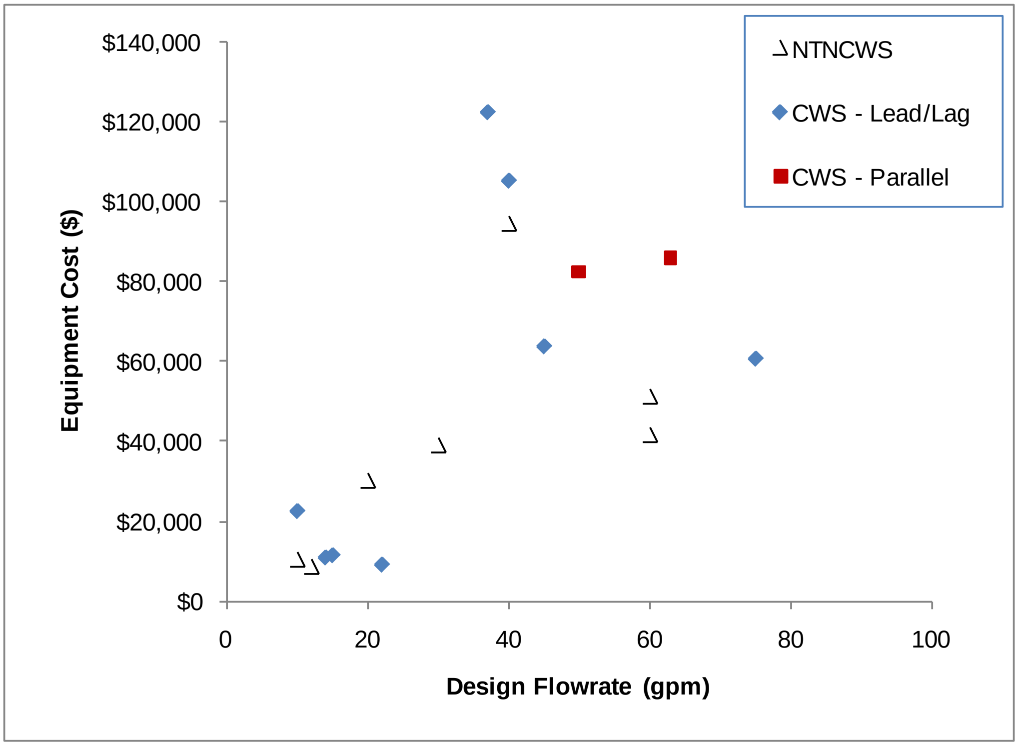


Figure 2-10. Equipment Costs of Smaller AM Systems (<100 gpm)

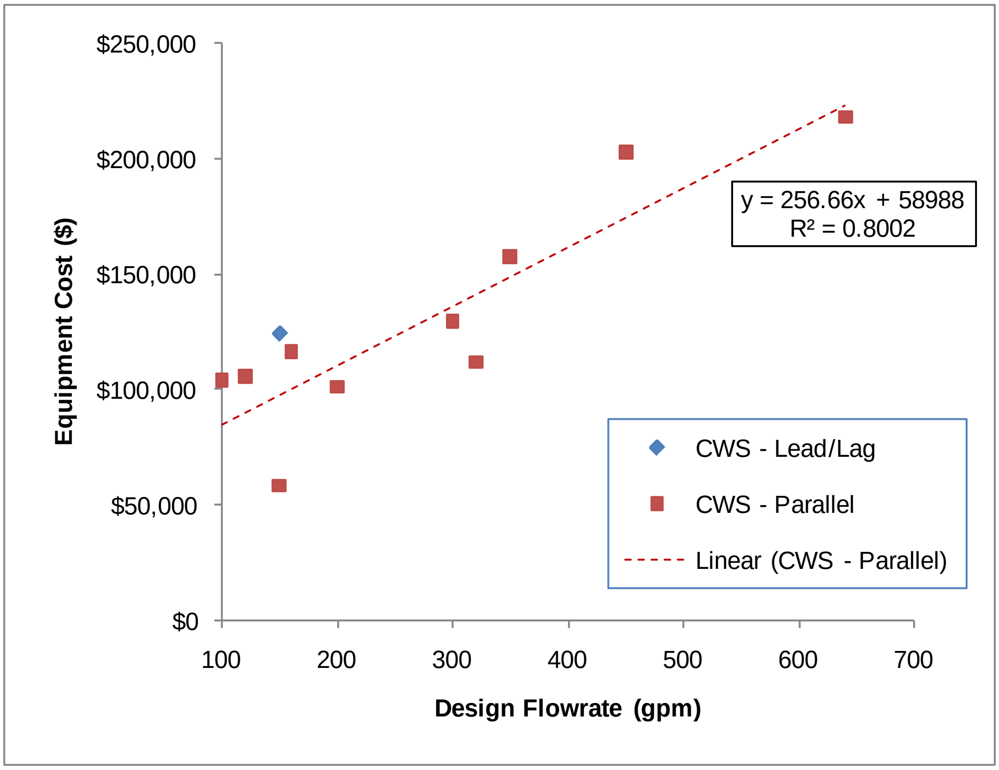


Figure 2-11. Equipment Costs of Larger AM Systems (≥100 gpm)

Figure 2-12. E33 Media Loading

2.5.1 Media Replacement Cost. As shown in Table 2-9, media replacement costs represented the majority of O&M costs, accounting for 39% to 97% of O&M costs (averaging 79%). The media replacement cost included the cost for replacement media, labor (for replacement services), spent media analysis (i.e., Toxicity Characteristic Leaching Procedure [TCLP]), spent media disposal, and freight. All spent media passed the TCLP test and were disposed off as non-hazardous wastes (the exact disposal facilities were not tracked by the study). Table 2-10 presents breakdowns of actual media replacement costs for the 15 systems, including multiple replacements for the WA and VV systems. To help understand the costs, the table also summarizes data that affected media replacement, including replacement media type, media life (at the time of replacement), volume throughput (in gallons and bed volumes [BV]), and quantity replaced.

The cost analysis also included unit media replacement costs (in $\$/\text{ft}^3$ or \$/1,000 gal of water treated) obtained by dividing lump-sum media replacement costs by either respective media quantities or volume throughputs (gallons of water treated to reach 10-µg/L arsenic in system effluent). The results of these calculations are also shown in Table 2-10 for comparisons among different media across different sites.

Table 2-11 summarizes media replacement costs of different media types occurred at one or multiple demonstration sites, i.e., five for E33, three for A/I complex 2000, two each for ARM 200, LayneRT, and GFH®, and one each for AAFS50, G2®, and Isolux™. Adsorbsia™ GTO™ was not replaced at either of the two sites during the study period; therefore, the estimated cost was presented instead.

Table 2-9. O&M Costs for AM Systems with Media Replacement

				Media Replacement			Electricity	Chemicals		Labor		
No.	**Site ID**	**Design Flowrate (gpm)**	**Total O&M Costs ($/kgal)**	**Replacement Media Type**	**Cost ($/kgal)**	**% of Total O&M**	**Cost ($/kgal)**	**Type**	**Cost ($/kgal)**	**Average Weekly Hours**	**Labor Rate ($/hr)**	**Cost ($/kgal)**
Non-Transient Non-Community Water Systems												
2	SU	12	$12.06	A/I Complex	$8.96	74	$0.000	No	$0.00	0.33	$30.0	$3.10
4b	KF	60	$5.82	ARM 200	$5.37	92	$0.000	No	$0.00	2.5	$21.0	$0.45
Community Water Systems												
6	GF	10	$2.34	E33	$2.01	86	$0.000	No	$0.00	0.5	$21.0	$0.33
7	WA	14	$22.88	A/I Complex	$22.05	96	$0.000	No	$0.00	0.75	$20.0	$0.83
			$10.44	GFH	$9.44	90	$0.000	No	$0.00	0.75	$20.0	$1.00
			$5.52	CFH	$4.76	86	$0.000	No	$0.00	0.75	$20.0	$0.76
8	PF	15	$7.67	LayneRT	$5.31	69	$0.000	No	$0.00	1.6	$20.0	$2.36
9	DM	22	$10.86	A/I Complex	$9.99	92	$0.000	No	$0.00	0.5	$20.0	$0.87
10	VV	37	$2.74	AAFS50	$2.56	93	$0.157	No	$0.00	0.4	$21.0	$0.03
			$1.48	AAFS50	$0.58	39	$0.157	Acid	$0.61	2.4	$21.0	$0.14
			$1.79	ARM 200	$1.61	90	$0.157	No	$0.00	0.4	$21.0	$0.03
11	BW	40	$5.11	G2®	$4.30	84	$0.001	Acid/Base	$0.11/0.36	2.33	$20.0	$0.34
12	RR	45	$0.86	E33	$0.64	74	$0.008	No	$0.00	1.67	$21.0	$0.22
15	LD	75	$0.98	ArsenX^{np}	$0.58	59	$0.000	No	$0.00	7.0	$21.0	$0.40
18	TE	150	$1.16	Isolux™	$1.02	88	$0.001	No	$0.00	2.5	$37.5	$0.14
19	AL	150	$0.61	E33	$0.36	59	$0.000	No	$0.00	4.67	$19.5	$0.25
22	SV	300	$0.61	E33	$0.30	49	$0.050	Replacement parts	$0.03	1.75	$21.8	$0.23
23	AN	320	$0.75	E33	$0.66	89	$0.001	Replacement parts	$0.03	1.75	$18.2	$0.05
24	RN	350	$5.69	GFH®	$5.51	97	$0.001	No	$0.00	2.5	$35.0	$0.18
Minimum			*$0.61*		*$0.30*	*39*	*$0.00*		*$0.00*	*0.4*	*$18.2*	*$0.03*
Maximum			*$22.88*		*$22.05*	*97*	*$0.16*		*$0.61*	*7.0*	*$37.5*	*$2.36*
Average			*$4.61*		*$4.15*	*79*	*$0.03*		*$0.07*	*1.9*	*$22.4*	*$0.36*

Table 2-10. Breakdowns of Media Replacement Costs

No.	Site ID	Design Flow Rate (gpm)	Media Type, Run Length, and Quantity Replaced					Media Replacement Costs						
			Replace-ment Media Type	Media Life (mon)	Volume of Water Treated[(a)] (gal)	Volume of Water Treated[(b)] (BV)	Media Volume (ft^3)	Media Unit Cost ($/$ft^3$)	Total Media Cost ($)	Labor Cost ($)	Other Costs[(c)] ($)	Total MR Cost ($)	Unit MR Cost ($/$ft^3$)	Unit MR Cost ($/kgal)
7	WA1	14 (S)	A/P & A/I[(d)]	6	342,000	5,100	3/9	$517	$6,204	$520	$845	$7,569	$631	$22.05
9	DM	22 (S)	A/I Complex	8	391,400	5,814	6	$517	$3,102	$260	$548	$3,910	$652	$9.99
2	SU	12 (S)	A/I Complex	18	257,832	7,660	3	$450	$1,350	$0	$960	$2,310	$770	$8.96
10	VV1	37 (S)	AAFS50	2	3,411,000	10,364	44	$99	$4,350	$4,375		$8,725	$198	$2.56
10	VV2	37 (S)	AAFS50	5	7,580,000	23,031	22	$99	$2,175	$2,188		$4,363	$198	$0.58
10	VV3	37 (S)	ARM 200	5.5	8,464,000	25,717	22	$500	$11,000	$2,610		$13,610	$619	$1.61
4b	KF	60 (S)	ARM 200	13.5	2,085,424	13,940	20	$385	$7,700	$3,500		$11,200	$560	$5.37
6	GF	10 (S)	E33-G	17	2,085,000	27,874	5	$300	$1,500	$1,850	$849	$4,199	$840	$2.01
19	AL	150 (S)	E33-P	24	35,375,613	38,140	48	$165	$7,920	$1,000	$3,760	$12,680	$264	$0.36
23	AN	320 (P)	E33-P	18	46,553,000	50,191	124	$202	$25,048	$4,130	$1,722	$30,900	$249	$0.66
12	RR	45 (S)	E33-G	25	17,164,000	52,151	22	$265	$5,830	$4,240	$838	$10,908	$496	$0.64
22	SV	300 (P)	E33-G	~42	93,820,742	78,393	160	$156	$24,928	$2,120	$680	$27,728	$173	$0.30
11	BW	40 (S)	G2®	13	3,896,000	3,064	170	$40	$6,800	$8,272	$1,680	$16,752	$99	$4.30
24	RN	350 (P)	GFH®	7	12,925,440	7,200	240	$240	$57,600	$12,950	$608	$71,158	$296	$5.51
7	WA2	14 (S)	Filox™/GFH®	12	391,000	11,600	1.5/4.5	$595	$2,993	$500	$201	$3,693	$616	$9.44
7	WA3	14 (S)	Filox™/CFH[(e)]	12	516,000	15,300	1.5/4.5	$320	$1,755	$500	$200	$2,455	$409	$4.76
18	TE	150 (P)	Isolux™	~4	6,941,440	80,000	11.6	$559	$6,484	Facility[(g)]	$596	$7,080	$610	$1.02
8	PF	15 (S)	LayneRT	10.5	516,120	15,000	2.3	$852[(f)]	$1,960	$360	$420	$2,740	$1,191	$5.31
15	LD	75 (S)	LayneRT	20	27,978,780	66,794	28	$480	$13,440	Facility[(g)]	$2,693	$16,133	$576	$0.58

(a) System throughput at time of reaching 10-µg/L arsenic in system effluent.
(b) For lead/lag system, BV calculated based on media in both lead and lag vessels.
(c) Other costs including spent media analysis, spent media disposal, and freight.
(d) A/P Complex 2002 oxidizing media and A/I Complex 200 adsorptive media manufactured by ATS.
(e) CFH-12 adsorptive media manufactured by Kemira Water Solutions.
(f) Including cost of media vessel.
(g) Provided by facility.
BV = bed volumes; G = granular; MR = media replacement; P = parallel or pelletized; S = series

Table 2-11. Replacement Costs of Various Types of AM

Media Type	No. of Systems	Media Cost Only ($/$ft^3$)	Media Replacement Unit Cost ($/$ft^3$)	Media Run Length (BV)	Normalized Replacement Cost ($/kgal of Water)
A/I Complex 2000	3	450–517	631–770	5,100–7,700	8.96–22.05
AAFS50	1	99	198	23,000[a], 10,400	0.58[a]; 2.56
Adsorbsia™ GTO™	2	449[b], 678[b]	774[b, d]	>5,240[c]; >21,900[c]	<10.66[c]; <2.30[c]
ARM 200	2	385; 500	560; 619	13,900; 25,700	1.61; 5.37
ArsenX^{np}/LayneRT	2	480; 852[d]	576; 1,191[d]	15,000; 66,800	0.58; 5.31[d]
E33	5	165–300	173–840	27,900–78,400	0.30–2.01
G2®	1	40	99	3,100[a]	4.30
GFH®	2	240; 595	296; 616	7,200; 11,600	5.51; 9.44
Isolux™	1	559	610	80,000	1.02

(a) With pH adjustment.
(b) Estimates provided by vendor.
(c) Based on data at end of study when arsenic had not reached 10 µg/L breakthrough in system effluent.
(d) Including cost of media vessel.

Figure 2-13 plots media replacement costs against media run lengths for eight different media. As shown in Table 2-11 and Figure 2-13, media performance and costs varied from site to site, even for the same media type. Different water quality, such as concentrations of arsenic, phosphate, and silica and water pH, and different system designs in terms of EBCT and series/parallel configuration, could affect media performance. For example, ArsenX^{np} achieved 66,800 BV at the LD site but only 15,000 BV at the PF site. The PF source water had a higher pH (7.9 vs. 7.2) and contained more phosphorus (180 vs. <10 µg/L as total P) than the LD source water. The PF system also had a shorter EBCT than the LD system (1.8 vs. 2.9 min per vessel). There are 13 systems using E33 with five having media replacement. Run lengths of E33 media ranged from 27,900 to 78,400 BV. The shortest run length of 27,900 BV occurred at the GF site where source water contained 71 µg/L (on average) of total phosphorus. In general, ferric oxide or hydroxide media outperformed the iron-modified, alumina- or silica-based media. The poor performance of GFH® observed at the RN site was caused by high phosphorus (115 µg/L as total P) and very high silica (i.e., 72.6 mg/L as SiO_2) in source water.

Figure 2-14 plots media replacement unit costs (including replacement media, labor, and spent media disposal costs) of 13 E33 systems against system design flowrates. Estimated costs were used in the plot for the systems without media replacement. The data clearly showed that unit media replacement costs decreased as system sizes increased, due primarily to the scale of economy.

The media replacement cost per 1,000 gal of water treated is a function of the unit media replacement cost per ft^3 and the media run length, as shown by the following equation:

Replacement Cost ($/1,000 gal) = Media Replacement Unit Cost ($/$ft^3$*)/(Run Length [BV] x 7.48/1,000)*

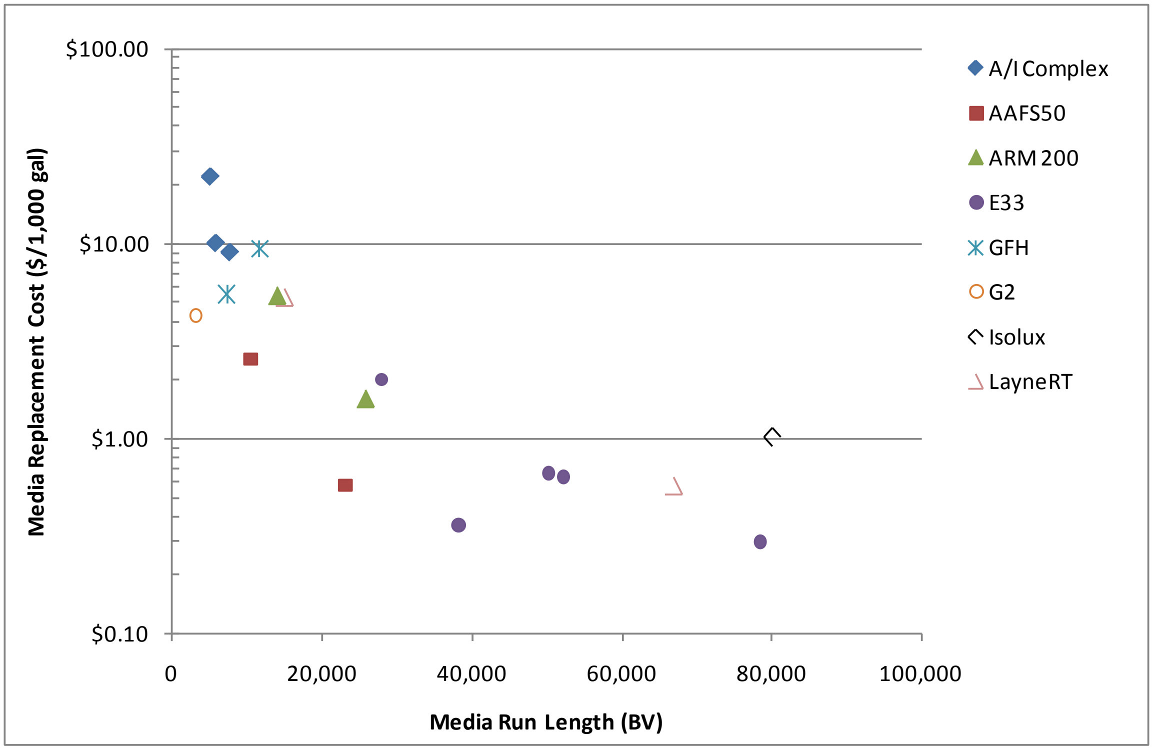


Figure 2-13. Media Replacement Costs of Various AM

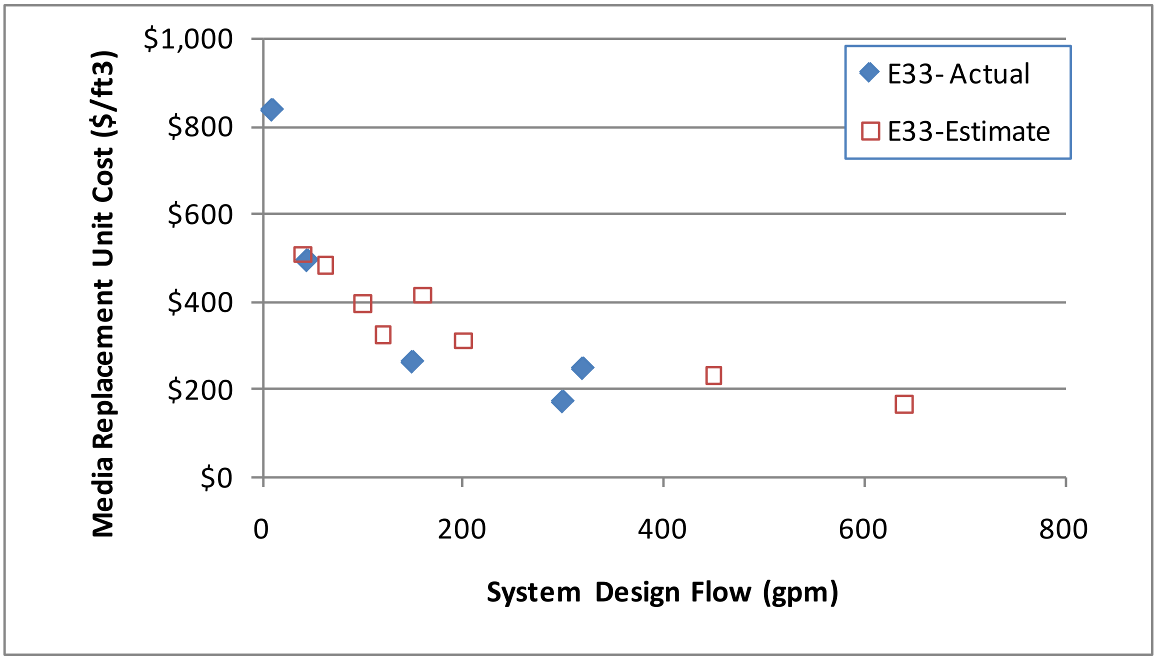


Figure 2-14. Media Replacement Costs of 13 E33 Systems

Figure 2-15 presents a series of hypothetic cost curves with each representing one media with a certain unit media replacement cost. The cost curves clearly show that the longer the run lengths are, the lower the replacement costs (per 1,000 gal of water treated) would be. These cost curves can be used as a general guideline to compare different media and help select the most cost-effective media. An example is given below to show how to use these cost curves step by step.

Assumptions:

- Media A costs \$200/ft^3 and is replaced at 25,000 BV
- Media B costs \$400/ft^3 and is replaced at 60,000 BV

Solutions:

- Step 1: Find the curve representing Media A with a unit cost of \$200/ft^3.
- Step 2: On the x-axis, draw a vertical line across 25,000 BV and intercept the \$200/ft^3 curve at Point A, find the y value of Point A, which is approximately \$1.1/1,000 gal.
- Step 3: Find the curve representing Media B with a unit cost of \$400/ft^3.
- Step 4: On the x-axis, draw a vertical line across 60,000 BV and intercept the \$400/ ft^3 curve at Point B, find the y value of Point B, which is approximately \$0.90/1,000 gal.

In this example, Media B's cost is twice as much as Media A's, but its life is more than twice as long as Media A's. Assuming all other costs, i.e., labor and media disposal, are equal, Media B has a lower replacement cost (per 1,000 gal of water treated).

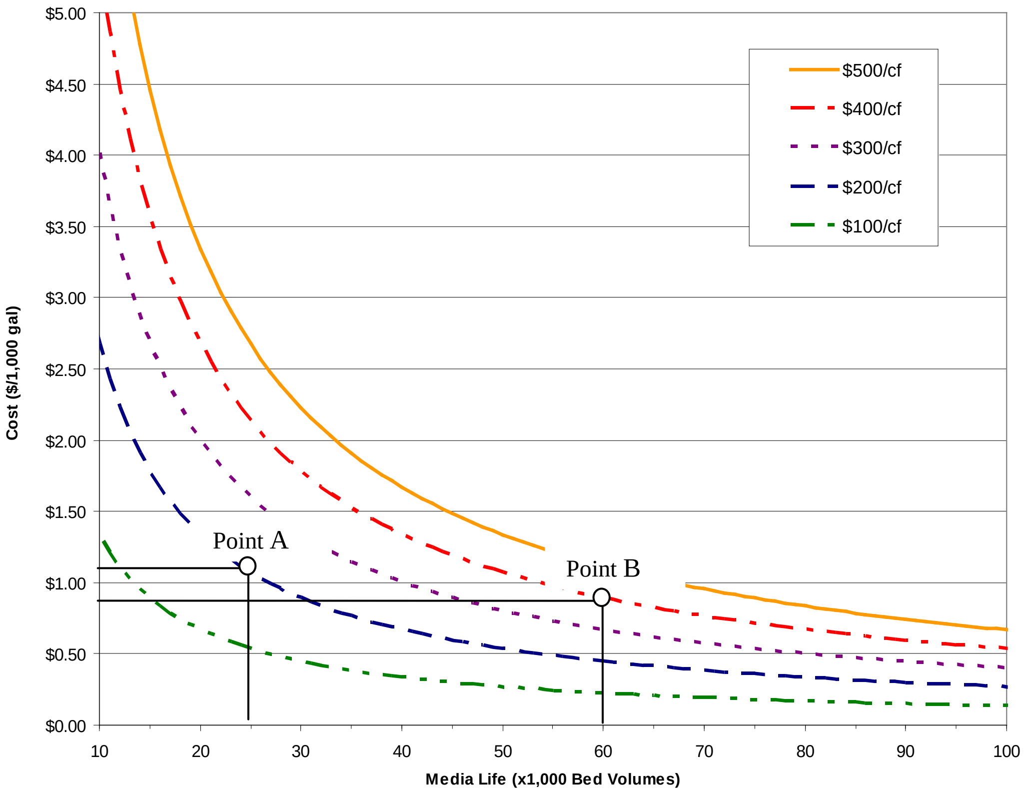


Figure 2-15. Hypothetic Media Replacement Cost Curves

2.5.2 Chemical Cost. Chemicals used during AM system operations included CO_2 and H_2SO_4/NaOH for pH adjustments and sodium hypochlorite (NaOCl) and gas chlorine for pre-oxidation and disinfection. Table 2-12 presents chemical costs for the pH control systems used at seven sites (note: the pH control system installed at the WM site was not used).

Table 2-12. Costs of pH Controls for AM Systems

Site ID	Flow Rate (gpm)	Media Type	Chemical(s)	Raw Water pH	Target pH	Usage (lb/kgal of Water)	Cost ($/kgal of Water)
VV	37	AAFS50	H_2SO_4	7.7	6.8	0.58	0.61
BW	40	G2®	H_2SO_4, NaOH	7.3(a)	6.5	0.27, 0.57	0.11, 0.36
BR	40	E33	CO_2	8.2	7.0	0.65	0.41
TN	63	E33	CO_2	8.0	7.0	0.39	0.30
RF(b)	120	E33	CO_2	7.7	7.4	0.12	0.11
NP	160	E33	CO_2	9.0	7.0	0.30	0.20
TA	450	E33	CO_2	9.6	7.2	0.36	0.29

(a) Lower than historical value of 7.7.
(b) CO_2 pH control system installed at RF site used for Phase 1, but not for Phase 2.

H_2SO_4 was available in a 37%, 50%, or 93% solution in 15- or 55-gal drums. NaOH was available in a 25% solution in 15-gal drums and used only at one site to raise pH after treatment. CO_2 was supplied with 50-lb gas cylinders for smaller systems and 380-lb dewars for larger systems. CO_2 supply costs ranged from $0.11 to $0.41 per 1,000 gal of water treated.

Some facilities had pre-existing chlorination for disinfection, which was switched to pre-chlorination if these facilities required pre-oxidation for soluble As(III) conversion. Because oxidation of soluble As(III) did not consume a significant amount of chlorine and the chlorine usage did not show any noticeable increase, the incremental chemical cost was negligible.

2.5.3 Electricity Cost. The electricity cost was tracked by comparing monthly electrical bills before and after installation of an AM treatment system. If the site did not have a separate meter for the arsenic treatment system, then the cost was estimated based on power requirements of the major equipment such as compressor, pump, etc., average operational hours, and local electricity unit price. Local electricity unit prices ranged from $0.08 to $0.14/kwh provided by the facilities.

The incremental electrical consumption was negligible for most of the sites because the AM systems have very few “moving” parts and operate mostly intermittently. Electricity costs per 1,000 gal of water treated ranged from zero to $0.16 and averaged $0.03, as shown in Table 2-9. The highest electricity cost incurred at the VV site because the VV system was equipped with a number of energy-consuming components such as a compressor (to supply air to pneumatic valves), an acid metering pump, a backwash recycling pump, and a heat lamp (during winter time), and operated around the clock for the demonstration study.

2.5.4 Labor Cost. Each demonstration site was provided with an Operator Labor Log Sheet to track labor hours used for routine O&M, EPA demonstration study-related activities, repairs, and miscellaneous activities. The routine O&M included activities such as filling field logs, performing system inspection, ordering inventory, and others as recommended by vendors. EPA study-related activities such as performing field measurements, collecting and shipping samples, and communicating with the Battelle Study Lead, were tracked, but not used for cost analysis.

The routine, non-demonstration related labor activities consumed only 10 to 30 min a day, one or several days a week at most of the AM sites. Average weekly hours ranged from 20 min to 7 hr, averaging 1.9 hr. As shown in Table 2-9, labor rates ranged from $18.2 to $37.5/hr and averaged $22.4/hr (note: these labor rates might be lower than those in certain regions of the country, such as California, but were actual numbers provided by the operators). Labor costs per 1,000 gal of water treated varied significantly from $0.45 to $3.10 for NTNCWS and from $0.03 to $2.39 for CWS due to varying annual water production rates among the AM demonstration sites. NTNCWS often had a lower demand and a lower utilization rate than CWS. Therefore, the labor cost (per 1,000 gal of water treated) of a small NTNCWS was higher than that of a large CWS.

3.0 IRON REMOVAL/COAGULATION/FILTRATION SYSTEMS

Of the 50 demonstration sites, 18 sites used IR or CF as the main treatment process, including two NTNCWS and 16 CWS. Among the 18 systems, four systems had IR followed by AM to remove iron and arsenic. At these four sites, the main purpose of the IR was to provide protection to the AM systems against iron fouling although at one site (SF), the AM system was actually used to polish the IR system effluent because the IR system had already reduced arsenic concentrations to below the MCL.

Table 3-1 lists IR/CF demonstration locations, technologies, and study durations in order of system design flowrates. The performance evaluation studies for the IR and CF systems were conducted for a period of 12 to 15 months, except for two systems for which more extensive studies were performed. Detailed information on system performance and costs can be found in individual final performance evaluation reports provided on the EPA Arsenic Demonstration Program Web site.

Table 3-1. Summary of IR/CF Demonstration Locations, Technologies, and Study Durations

No.	Site ID	Demonstration Location	Technology	Vendor	Design Flowrate (gpm)	Study Duration	Length of Study (mon)
Non-Transient Non-Community Water Systems							
1	GS	Goshen, IN	IR (AD26)+AM (E33)	AdEdge	25	06/08–06/09	12
2	FC	Fountain City, IN	IR (G2®)	US Water	60	09/08–10/09	13
Community Water Systems							
3	SC	Sauk Centre, MN	IR (Macrolite®)	Kinetico	20	07/05–10/06	15
4	WL	Willard, UT	IR (Birm®/Filox™) + AM (Adsorbsia™ GTO™)	Filter Tech	30	12/08–10/10	22
5	DV	Delavan, WI	IR (Macrolite®)	Kinetico	45	07/05–09/06	14
6	WV	Waynesville, IL	IR (GreensandPlus™)	Peerless	96	07/09–09/10	14
7	CM	Climax, MN	IR/IA (Macrolite®)	Kinetico	140	08/04–08/05	12
8	CL	Conneaut Lake, PA	CF (AD GS$^+$)	AdEdge	250	12/09–12/10	12
9	TF	Three Forks, MT	CF (Macrolite®)	Kinetico	250	11/06–02/08	15
10	SA	Sabin, MN	IR (Macrolite®)	Kinetico	250	01/06–04/07	15
11	SF	Springfield, OH	IR (AD26) +AM (E33)	AdEdge	250	09/05–09/06	12
12	ST	Stewart, MN	IR (AERALATER®)+AM (E33)	AdEdge	250	02/06–02/07	12
13	SD	Sandusky, MI	IR (AERALATER®)	Siemens	340	06/06–06/07	12
14	GV	Greenville, WI	IR (Macrolite®)	Kinetico	375	08/07–12/07; 05/09–04/10	4; 11
15	FE	Felton, DE	CF (Macrolite®)	Kinetico	375	09/06–11/07	14
16	PW	Pentwater, MI	IR/IA (Macrolite®)	Kinetico	400	11/05–12/06	13
17	OK	Okanogan, WA	CF (Electromedia® I)	Filtronics	550	08/08–08/09	12
18	AR	Arnaudville, LA	IR (Macrolite®)	Kinetico	770	06/06–09/10	51

AM = adsorptive media; CF = coagulation/filtration; IA = supplemental iron addition; IR = iron removal

3.1 Overview of IR/CF Demonstration Sites

Table 3-2 summarizes the IR/CF demonstration site information. Most of the facilities evaluated were classified as very small (serving 25 to 500 of people) and small (serving 501 to 3,300 of people) water systems. The two NTNCWS systems, both schools, were operated fewer than 2 hr/day, whereas most CWS were operated less than 10 hr/day. Average daily demand was less than 4,000 gal for NTNCWS and varied from 4,500 to 414,000 gal for CWS. Annual productions were less than 1 MG for NTNCWS and ranged from 1.6 to 139 MG for CWS. Utilization rates were 3 or 4% for NTNCWS and 9 to 48% for CWS.

Table 3-2. Summary of IR/CF Demonstration Sites

No.	Site ID	Design Flow rate (gpm)	Average Flow rate (gpm)	Daily Op Time (hr/day)	Average Daily Demand (gpd)	Annual Production (kgal)	Utilization Rate[(a)] (%)	Pre-existing Treatment
Non-Transient Non-Community Water Systems								
1	GS	25	15.2	1.9	1,733	517	4	None
2	FC	60	47	1.4	3,956	845	3	Cl_2, softener
Community Water Systems								
3	SC	20	4.0	4.6	4,523	1,650	16	None
4	WL	30	9.3	23.4	8,354	3,049	19	None
5	DV	45	20 (max)	2.6	5,981	2,200	9	Softener
6	WV	96	84	11.8/5.8	29,400	10,731	21	Cl_2, poly-PO_4
7	CM	140	132	5.6	38,560	13,800	19	Gas Cl_2
8	CL	250	153	11.9/4.3	109,242	20,114	15	Gas Cl_2, poly-PO_4
9	TF	250	206	8.9	107,400	27,200	21	Cl_2
10	SA	250	231	3.1	32,858	12,200	9	Aeration, gravity filtration, Cl_2
11	SF	250	89	9.5	45,700	16,700	13	Cl_2, poly-PO_4
12	ST	250	190	4.7	52,418	19,133	15	Gas Cl_2, poly-PO_4
13	SD	340	163	NA	166,000	60,300	34	Cl_2, poly-PO_4
14	GV	375	285	3.8	66,037	24,051	12	Gas Cl_2
15	FE	375	263	6.5	107,300	38,200	19	Cl_2
16	PW	400	350	5.1	102,800	38,300	18	Cl_2, poly-PO_4
17	OK	550	538	13.6	414,000	139,400	48	None
18	AR	770	335	14	277,128	101,152	25	Aeralator, Cl_2, softener

(a) Ratio of a system's average annual production to its maximum capacity at the design flowrate.
NA = not available

Table 3-3 presents source water quality of the 18 IR/CF sites using average values measured during the performance evaluation studies. Arsenic concentrations in source waters varied from 11.4 to 84.0 μg/L (excluding the GV water, which contained only 5.6 μg/L of total arsenic). Soluble As(III) was the predominating arsenic species at all but three sites (i.e., WL, TF, and SA). Iron, existing predominantly as soluble Fe(II), exceeded its SMCL of 300 μg/L at 13 sites, with the highest concentration measured at 2,385 μg/L at the SC site. Half of the sites had manganese levels above its SMCL of 50 μg/L. Four of the five low-iron sites, i.e., CL, TF, FE, and OK, added an iron salt to source waters as a coagulant to remove arsenic. At these sites, the treatment system was considered a CF process. The fifth site, WL, used dual Birm®/Filox™ media as a pretreatment to AM. The CM and PW sites contained moderate levels of iron in raw waters, which were insufficient to remove arsenic to below 10 μg/L in treated water. Therefore, supplemental iron was added to the waters at both sites to improve the arsenic removal rates.

During the studies, high phosphate and silica levels were found to affect system performance and reduce treatment efficiencies. At four sites (i.e., SC, WL, ST, and AR), total phosphate concentrations were over 100 μg/L. Significantly elevated silica concentrations were measured at the TF and AR sites at 48.5 and 42.5 mg/L, respectively. The presence of high total organic carbon (TOC) and ammonia had some effects

Table 3-3. Summary of IR/CF Site Source Water Quality

No.	Site ID	Total As (μg/L)	As (III) (μg/L)	% As(III)	Total Fe (μg/L)	Total Mn (μg/L)	Total P (μg/L)	Silica(a) (mg/L)	TOC (mg/L)	pH (S.U.)	NH_3(b) (mg/L)
Non-Transient Non-Community Water Systems											
1	GS	28.6	20.2	71	741	82	11	20.1	<1.0	7.3	0.1
2	FC	29.4	17.7	60	1,865	51	11	15.2	1.8	7.6	1.0
Community Water Systems											
3	SC	27.5	21.9	80	2,385	130	135	24.2	3.3	7.3	1.2
4	WL	13.2	6.0	45	276	116	112	15.4	<1.0	7.6	0.1
5	DV	18.9	16.3	86	1,392	19	70	14.5	1.8	7.5	2.9
6	WV	33.1	24.1	73	2,298	33	91	22.1	7.9	7.5	3.8
7	CM	36.5	35.8	98	540	136	<30	28.7	<1.0	7.5	0.7
8	CL	29.0	26.2	90	188	64	<10	14.1	<1.0	7.8	0.1
9	TF	84.0	0.7	1	<25	<0.1	33	48.5	1.7	7.5	<0.05
10	SA	41.8	11.6	28	1,350	341	30	29.9	1.7	7.3	0.2
11	SF	22.7	16.9	74	1,102	36	<10	18.4	<1.0	7.2	0.2
12	ST	44.8	35.3	79	1,188	24	301	25.1	6.4	7.9	1.6
13	SD	11.4	8.7	76	896	25	<10	12.0	<1.0	7.2	0.3
14	GV(c)	5.6	4.1	73	2,068	31	33	13.0	NA	7.3	NA
15	FE	34.4	29.1	85	26	1	45	9.5	0.8	8.3	0.3
16	PW	17.7	14.9	84	426	27	57	11.2	2.0	7.9	0.3
17	OK	17.9	13.4	75	78	63	51	25.9	<0.7	7.6	0.1
18	AR	32.7	24.4	75	2,059	133	648	42.5	1.3	6.8	1.9

(a) as SiO_2.
(b) as N.
(c) Source water contained elevated radium.
NA = not analyzed

on the choice of oxidants because of concerns over the trihalomethanes (THMs) formation. For example, at the SC, WV, ST, and AR sites, $KMnO_4$ was used instead of chlorine to oxidize waters due to elevated levels of TOC and ammonia. Source water pH values ranged from 6.8 to 8.3. Similar to the AM processes, the pH had some impact on the performance of the IR/CF processes.

3.2 Overview of IR/CF Demonstration Technologies

Most IR/CF technologies involved a two-step process: (1) oxidation of soluble iron and manganese to form iron and manganese solids (oxidation of soluble manganese with chlorine had slow reaction kinetics) and (2) filtration of the solids formed. Arsenic in source waters can be removed by taking advantage of adsorptive capacities of natural iron particles. The ability of a given IR process to remove arsenic to meet the arsenic MCL depends largely on the amount of arsenic and natural iron in source waters (Sorg and Logsdon, 1978; Sorg, 1993; Hering et al., 1996; Gulledge and O'Conner, 1973). As a rule of thumb, source waters having a soluble iron to soluble arsenic mass ratio of 20:1 or greater can achieve removal to below the arsenic MCL (Sorg, 2002). If source water has an insufficient amount of natural iron, arsenic removal can be enhanced with supplemental iron addition.

Some IR/CF system designs had a contact tank following chemical addition(s) but prior to pressure filtration. The extended contact time may result in an increase in arsenic adsorption/removal. A contact tank can also help reduce the filter loading rate, thereby increasing filter performance and run time. However, adding a contact tank would increase the system cost and require additional space.

After the oxidation step (with or without a contact tank), water was filtered through a filtration media in either a pressure or a gravity filter to remove arsenic-laden particles. Filter media included silica sand/anthracite, GreensandPlus™, and proprietary products, such as Macrolite® by Kinetico (currently marketed by Fairmont Minerals in Chardon, OH), AD26 by AdEdge (Buford, GA), and Electromedia® I by Filtronics (Anaheim, CA). An anthracite cap of 12 to 18 in was used to prevent excessive head loss buildup, thus reducing backwash frequency. Effective removal of iron particles was critical to good arsenic removal because any iron particles present in filter effluent would likely contain (adsorbed) arsenic.

Table 3-4 summarizes characteristics of different filtration media used in the IR/CF demonstration systems. Macrolite® is a low-density, spherical, chemically inert ceramic media, designed for higher filtration rates (i.e., up to 10 gpm/ft^2) than those commonly used for conventional filtration processes. AD26 is a manganese dioxide-based (MnO_2) granular media with physical and chemical properties similar to Pyrolusite (also known as Pyrolox™) and Filox™. Electromedia® I is processed from naturally occurring minerals and can also handle a high filtration rate of up to 10 gpm/ft^2. GreensandPlus™, branded as AD GS$^+$ by AdEdge, consists of a silica sand core with a thermally bonded MnO_2 coating, designed to withstand greater pressure drops and is less prone to stripping of the coating than standard manganese greensand. Birm® and Filox™ are MnO_2-based media commonly used for iron and manganese removal. An innovative approach using dual Birm®/Filox™ media as an alternative to chemical oxidation was demonstrated at the WL site as a pre-treatment to AM. Silica sand and anthracite were used in gravity filters at the ST and SD sites as part of the AERALATER® systems. All of the media have NSF Standard 61 certification for use in drinking water applications.

3.3 IR/CF System Design and Configuration

Because of varying site conditions and source water qualities, the design and basic components of the IR/CF systems varied among the demonstration sites. Table 3-5 summarizes the design and basic components of the 18 IR/CF systems demonstrated. Figures 3-1A through 3-1F show photographs of different types of IR/CF systems and Figure 3-2 shows photographs of chemical feed systems. System flowrate, use of contact tank(s), filter vessel design, and level of system instrumentation and controls affected the system performance and cost, and are discussed in the following subsections.

3.3.1 System Flowrate. As shown in Table 3-5, IR/CF system design flowrates were 25 and 60 gpm for the two NTNCWS systems and ranged from 20 to 770 gpm for CWS. The design flowrate of a system was determined by the capacity of supply well(s) or the peak flow rate. The design flowrate was used to size the treatment system, thus affecting the system capital cost (Section 3.4). Average flowrates measured during the performance evaluation studies often were lower than the corresponding design flowrates. The average flowrates affected the media performance and operational costs, as discussed in Section 3.5.

3.3.2 Contact/Detention Tank. As shown in Table 3-5, 12 of the 18 systems were equipped with one or two contact tanks. The AERALATER® systems at the ST and SD sites consisted of an 11- and 12-ft-diameter aluminum detention tank, providing 34 and 40 min of residence time, respectively. The detention tank was equipped with an air diffuser grid to further oxidize and mix the chlorinated water. For the other 10 pressure filtration systems, contact tank sizes varied from 12-in × 62-in to 96-in × 96-in, providing a contact time of 1.8 to 20 min. These contact tanks were constructed of FRP or CS with a pressure rating of at least 100 psi.

Table 3-4. Characteristics of Filtration Media Used in EPA Demonstration Projects

Parameter	Macrolite®	AD26(a)	AD GS+(a)
Matrix/Active Ingredient	Ceramic, chemically inert	MnO_2 (>80%)	Silica sand core coated with MnO_2
Physical Form	Dry nodular granules	Dry nodular granules	Dry nodular granules
Color	Taupe, Brown to Grey	Black	Black
Bulk Density (g/cm^3[lb/ft^3])	0.86 (54)	2.0 (125)	1.4 (85)
Specific Gravity	2.1	3.8	2.4
Mesh Size (U.S. Standard)	40 × 60	20 × 40	18 × 60
Effective Size (mm)	0.25–0.35	0.40	0.30–0.35
Uniformity Coefficient	1.1–1.2	1.54	<1.6
pH Range	Inert	6.5–9.0	6.2–8.5
Filter Rate (gpm/ft^2)	8–10	8–12	2–12
Backwash Rate (gpm/ft^2)	8–10	18–20	10–12
Manufacturer	Kinetico	Unknown	Unknown
No. of EPA Demo Sites	9	2	1

Parameter	Birm®	Filox™	GreensandPlus™
Matrix/Active Ingredient	<0.01% MnO_2	75–85% MnO_2	Silica sand core coated with MnO_2
Physical Form	Dry nodular granules	Dry nodular granules	Dry nodular granules
Color	Black	Black	Black
Bulk Density (g/cm^3[lb/ft^3])	0.64–0.72 (40–45)	1.83 (114)	1.4 (85)
Specific Gravity	2.0	3.8–4.0	2.4
Mesh Size (U.S. Standard)	10 × 40	20 × 40	18 × 60
Effective Size	0.48	0.51	0.30–0.35
Uniformity Coefficient	2.7	1.45	<1.6
pH Range	6.8–9.0	6.5–9.0	6.2–8.5
Filter Rate (gpm/ft^2)	3.5–5	5	3–5
Backwash Rate (gpm/ft^2)	10–12	25–30	10–12
Manufacturer	Clack Corporation	Matt-Son, Inc.	Inversand
No. of EPA Demo Sites	1		1

Parameter	Anthracite #1	Silica Sand	Electromedia® I (b)
Matrix/Active Ingredient	Coal	Silica	Unknown
Physical Form	Dry, crushed	Dry	Dry nodular granules
Color	Black	Light brown to light red	White
Bulk Density (g/cm^3[lb/ft^3])	0.8 (50)	1.6–1.92 (100–120)	NA
Specific Gravity	1.6	2.6	NA
Mesh Size (U.S. Standard)	14 × 30	16 × 50	NA
Effective Size (mm)	0.6–0.8	0.45–0.55	NA
Uniformity Coefficient	<1.7	≤1.6	NA
pH Range	Inert	Inert	NA
Filter Rate (gpm/ft^2)	5	3–5	Up to 10
Backwash Rate (gpm/ft^2)	12–18	10–20	NA
Manufacturer	Clack Corporation	Many	Filtronics
No. of EPA Demo Sites	2		1

(a) Marketed and supplied by AdEdge.
(b) Not disclosed by vendor.
NA = not available
Note: Characteristics of G2 media for FC site shown in Table 2-4.

Table 3-5. Summary of IR/CF System Design and Components

		Flowrate		Chemical Addition		Contact				Filtration						
					Iron Dose (mg/L as Fe)	No. of Tanks	Tank Size (in)	Contact Time (min)		No. of Filters	Filter Size (in)	Filter Media	Media Volume (ft^3)		Filtration Rate (gpm/ft^2)	
No.	Site ID	D (gpm)	A (gpm)	Oxidant				D	A				Per Filter	Total	D	A
1	GS	25	15.2	NaClO	No	None	-	-	-	3	13 × 54	AD26	2.3	6.9	9	5.6
2	FC	60	47.1	NaClO	No	None	-	-	-	4	36 × 72	G2®	17.7	70.8	2.1	1.7
3	SC	20	1-15	$KMnO_4$	No	2	36 × 57	20	103	4	13 × 54	Macrolite®	1.5	6	5.4	1.1
4	WL	30	9.3	None	No	None	-	-	-	2	24 × 72	Birm®/Filox™	5/5	10/10	4.8	1.4
5	DV	45	20 (max)	NaClO	No	1	12 × 62	1.8	4.1	2	21 × 62	Macrolite®	2.4	4.8	9.4	4.2
6	WV	96	84	$NaMnO_4$	No	None	-	-	-	4	36 × 72	GreensandPlus™	14.1	56.4	3.4	3.0
7	CM	140	132	NaClO	0.5	2	42 × 72	5	5.5	2	36 × 72	Macrolite®	14	28	10	9.1
8	CL	250	153	NaClO	1.8	None	-	-	-	3	54 × 60	AD GS^{+}	40	120	5.2	3.2
9	TF	250	206	NaClO	2.1	2	63 × 86	5	6.2	2	48 × 72	Macrolite®	25	50	10	8.0
10	SA	250	231	NaClO	No	2	63 × 86	6.8	7.4	2	48 × 72	Macrolite®	25	50	10	9.2
11	SF	250	89	NaClO	No	None	-	-	-	3	36 × 60	AD26	19	57	6.1	4.2
12	ST	250	188	NaClO	No	1	132 × 138	34	46	4 cells	132 dia	anthracite/ silica sand	24/24	95/95	2.6	2.0
13	SD	340	163	NaClO	No	1	144 × 130	40	69	3 cells	144 dia	silica sand	75.3	226	2.5	1.4
14	GV	375	285	NaClO	No	2	63 × 86	4.5	5.9	3	48 × 72	Macrolite®	25	75	10	7.6
15	FE	375	263	NaClO	2.2	2	48 × 72	3	4.3	3	48 × 72	Macrolite®	25	75	10	7.0
16	PW	400	350	NaClO	0.5	1	96 × 96	6	6.8	2	60 × 96	Macrolite®	40	80	10	8.9
17	OK	550	538	NaClO	0.9	2	48 × 96	2	2.8	1	84 × 112	Electromedia® I	174	174	10	7.0
18	AR	770	335	$KMnO_4$	No	1	132 × 84	6.5	14.9	2	84 × 96	Macrolite®	75	150	10	4.4

A = average; D = design

Figure 3-1A. 20-gpm Macrolite® Pressure Filtration System by Kinetico
(1. Duplex Units, 2. Contact Tanks, 3. Pressure Filters,
4. Chemical Day Tank, and 5. Totalizer on Raw Water Line)

Figure 3-1B. 35-gpm Birm®/Filox™ and Adsorbsia™ GTO™ System by Filter Tech

Figure 3-1C. 140-gpm Macrolite® Pressure Filtration System by Kinetico
(Clockwise from Left: Control Panel, Macrolite® Filters, and Contact Tanks)

Figure 3-1D. 250-gpm AD26/E33 Filtration System by AdEdge

Figure 3-1E. 340-gpm AERALATER® Filtration System by Siemens
(Clockwise from Left: Inlet Piping from Wells; Air Diffuser Grid within Detention Tank; Prechlorination Equipment; AERALATER® Unit with Detention Tank and Gravity Cell Influent; and Discharge Piping)

Figure 3-1F. 550-gpm Electromedia® I Filtration System by Filtronics

Figure 3-2. Chlorine and Iron Addition Systems

3.3.3 Filter Design.

As shown in Table 3-5, the pressure filtration systems demonstrated used two or more filter tanks in parallel for treatment, except for the Electromedia-I® system at the OK site which used a single horizontal filter tank. The AERALATER® systems consisted of three- or four-cell gravity filters. The filter cross-sectional area was determined by the design flowrate and the hydraulic loading rate. Table 3-6 summarizes design and average filtration rates used by different filter media.

The filter size and material affected the system cost. Pressure filter sizes varied from 13-in × 54-in (smallest) to 84-in × 112-in (largest) with various diameters and heights. The pressure filters were constructed of FRP, CS, or SS, whereas the AERALATER® chamber was constructed of either aluminum or CS. The CS or SS filter tanks were ASME-coded for a pressure rating of at least 100 psi. The FRP tanks were rated for 100 to 150 psi. The costs of FRP tanks were often lower than those of CS tanks for smaller tanks, but the costs of the two vessel types converged for larger tanks.

Table 3-6. Filtration Rates of Different Filter Media

Filter Media	No. of Systems	Design Filtration Rate (gpm/ft^2)	Average Filtration Rate (gpm/ft^2)
Macrolite®	9	5.4–10	1.1–9.2
Electromedia® I	1	10.0	7.0
AD26	2	6.1, 9.0	4.2, 5.6
GreensandPlus™	1	3.4	3.0
AD GS$^+$	1	5.2	3.2
Birm®/Filox™	1	4.8	1.4
G2®	1	2.1	1.7
Anthracite/Silica sand	2	2.5, 2.6	1.4, 2.0

3.3.4 Instrumentation and Controls.

System instrumentation and controls varied among different IR/CF systems in terms of material, quality, level of complexity/automation, and functionality. Such variations had an impact on the total capital investment cost and must be taken into consideration when attempting to compare the costs of different systems. For example, each Kinetico Macrolite® system was equipped with a turbidimeter to control the backwash operation, which added cost to the overall system.

3.4 IR/CF System Capital Investment Costs

This section begins with a review of the total capital investment cost, and then follows with a discussion of three cost categories: equipment, engineering, and installation.

3.4.1 Total Capital Investment Costs.

Capital investment costs for all 18 IR/CF demonstration systems are presented in Table 3-7 in three categories: NTNCWS, small CWS (<100 gpm), and large CWS (>100 gpm). Capital investment costs ranged from $55,423 for the 25-gpm GS system to $427,407 for the 770-gpm AR system. Figure 3-3 presents capital investment costs of six smaller IR and IR/AM systems (<100 gpm) (including two NTNCWS and four small CWS systems) as a function of design flowrates. Figure 3-4 presents similar data for the larger CWS systems (>100 gpm). The IR, IR/AM, and/or CF systems were plotted using different legends for easy identification. The data for the IR systems indicated a stronger correlation between the costs and flowrates on both figures. Curve fitting using linear regression was performed on the data set for the IR systems, yielding an R^2 of 0.8342 and 0.8808 for smaller and larger systems, respectively. Curve fitting was not performed on IR/AM or CF data due to insufficient data points.

Table 3-7. Capital Investment Costs for IR/CF Systems

No.	Site ID	Technology (Media)	Design Flow Rate (gpm)	Total Capital Cost ($)	Normalized Capital ($/gpm)	Normalized Capital ($/gpd)	Annualized Cost ($/yr)	Unit Cost ($/kgal of water)		Utilization Rate[b] (%)
								Design[a]	Average	
Non-Transient Non-Community Water Systems										
1	GS	IR (AD26)+AM (E33)	25	$55,423	$2,217	$1.54	$5,231	$0.40	$10.12	4
2	FC	IR (G2®)	60	$128,118	$2,135	$1.48	$12,093	$0.38	$14.32	3
Average					*$2,176*	*$1.51*		*$0.39*	*$12.22*	*3.5*
Community Water Systems (<100 gpm)										
3	SC	IR (Macrolite®)	20	$63,547	$3,177	$2.21	$5,998	$0.57	$3.75	15
4	WL	IR (Birm®/Filox™) + AM (Adsorbsia™ GTO™)	30	$66,362	$2,212	$1.54	$6,264	$0.40	$2.05	19
5	DV	IR (Macrolite®)	45	$60,500	$1,344	$0.93	$5,711	$0.24	$2.61	9
6	WV	IR (GreensandPlus™)	96	$161,560	$1,683	$1.17	$15,250	$0.30	$1.33	23
Minimum			*20*	*$55,423*	*$1,344*	*$0.93*	*$5,711*	*$0.24*	*$1.33*	*9*
Maximum			*96*	*$161,560*	*$3,177*	*$2.21*	*$15,250*	*$0.57*	$3.75	*23*
Average					*$2,104*	*$1.46*		*$0.38*	*$2.44*	*17*
Community Water Systems (>100 gpm)										
7	CM	IR/IA (Macrolite®)	140	$270,530	$1,932	$1.34	$25,535	$0.35	$1.85	19
8	CL	CF (AD GS$^+$)	250	$216,876	$868	$0.60	$20,471	$0.16	$1.02	15
9	TF	CF (Macrolite®)	250	$305,447	$1,222	$0.85	$28,831	$0.22	$1.06	21
10	SA	IR (Macrolite®)	250	$287,159	$1,149	$0.80	$27,105	$0.21	$2.22	9
11	SF	IR (AD26) + AM (E33)	250	$292,252	$1,169	$0.81	$27,586	$0.21	$1.64	13
12	ST	IR (AERALATER®) + AM (E33)	250	$367,838	$1,471	$1.02	$34,720	$0.26	$1.80	15
13	SD	IR (AERALATER®)	340	$364,916	$1,073	$0.75	$34,444	$0.19	$0.57	34
14	GV	IR (Macrolite®)	375	$332,584	$887	$0.62	$31,393	$0.16	$1.31	12
15	FE	CF (Macrolite®)	375	$334,297	$891	$0.62	$31,554	$0.16	$0.83	19
16	PW	IR/IA (Macrolite®)	400	$334,573	$836	$0.58	$31,580	$0.15	$0.82	18
17	OK	CF (Electromedia® I)	550	$424,817	$772	$0.54	$40,098	$0.14	$0.29	48
18	AR	IR (Macrolite®)	770	$427,407	$555	$0.39	$40,343	$0.10	$0.40	25
Minimum			*140*	*$216,876*	*$555*	*$0.39*	*$20,471*	*$0.10*	*$0.29*	*9*
Maximum			*770*	*$427,407*	*$1,932*	*$1.34*	*$40,343*	*$0.35*	*$2.22*	*48*
Average					*$1,069*	*$0.74*		*$0.19*	*$1.15*	*21*

(a) System's maximum capacity at design flowrate, operating 24 hr a day, 365 days a year.
(b) Ratio of a system's average annual production to its maximum capacity at design flowrate.
AM = adsorptive media; CF = coagulation/filtration; IA = supplemental iron addition; IR = iron removal

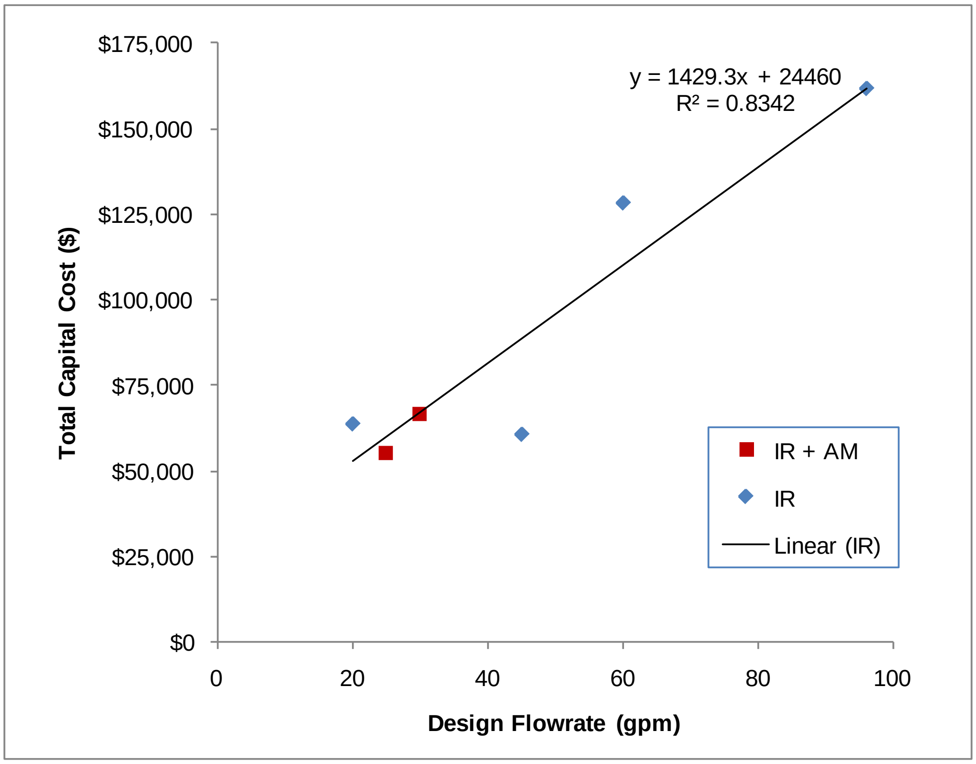


Figure 3-3. Total Capital Investment Costs of Smaller IR/CF Systems (<100 gpm)

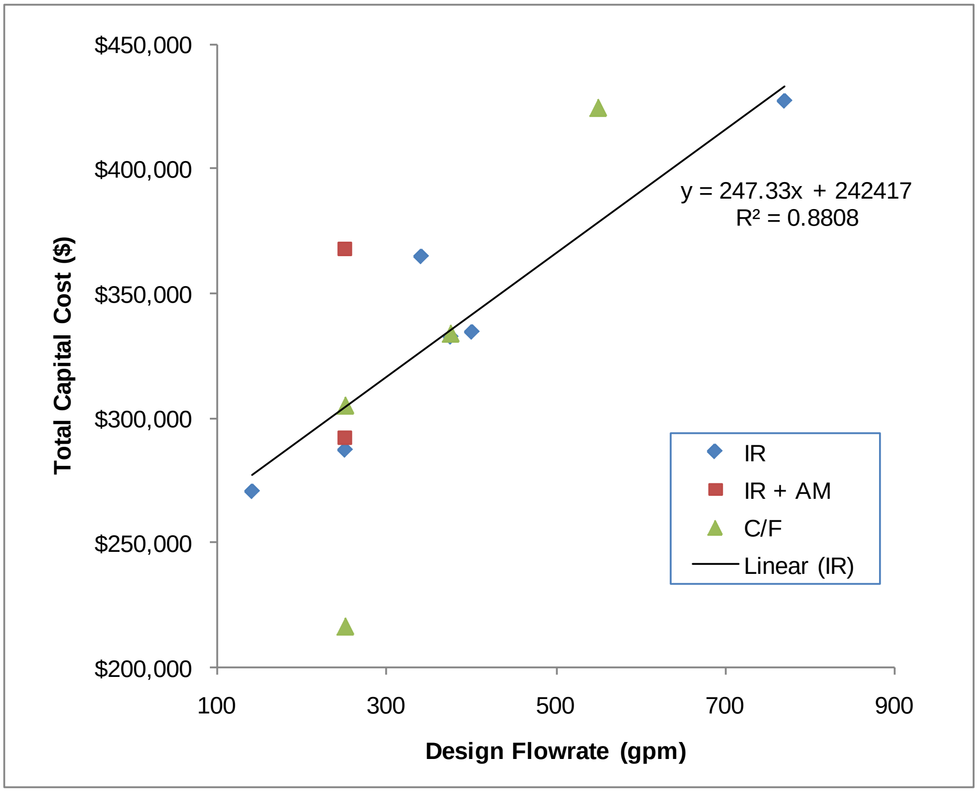


Figure 3-4. Total Capital Investment Costs of Larger IR/CF Systems (>100 gpm)

Similar to the AM systems, the capital investment cost of each IR/CF system was divided by its design capacity in gpm and gpd and the results are shown in Table 3-7 and Figures 3-5 and 3-6. Normalized costs for smaller CWS systems (<100 gpm) ranged from $1,344 to $3,177/gpm (or $0.93 to $2.21/gpd) and averaged $2,104/gpm (or $1.46/gpd). Normalized costs for the larger CWS ranged from $555 to $1,932/gpm (or $0.39 to $1.34/gpd) and averaged $1,069/gpm (or $0.74/gpd). As expected, the larger systems had lower average costs per gpm (or gpd) of the design capacity than the smaller ones. Both Figures 3-5 and 3-6 clearly show a decreasing trend with increasing flowrates, reflecting the economy of scale.

As stated in Section 3.3, in addition to flowrate, several other design parameters also affected system costs. A good way of demonstrating the effects of these parameters is to compare the costs and design features of the five 250-gpm systems, including two CF (at CL and TF), one IR (at SA), and two IR/AM systems (at SF and ST). Total capital investment costs of these five systems ranged from $216,876 for the AD GS$^+$ system at CL to $367,838 for the AERALATER®/E33 system at ST (or $868 to $1,471/gpm or $0.60 to $1.02/gpd). Comparing the two 250-gpm CF systems, the TF system cost was 40% higher than that of the CL system. The difference could be attributed to at least three factors, i.e., filter media, contact tank, and instrumentation and control. The TF system used Macrolite®, a more expensive media than AD GS$^+$ used by the CL system. The TF system included two 63-in × 86-in contact tanks while the CL system did not use any contact tank. Also, the TF system had more advanced and sophisticated instrumentation than the CL system. Because Macrolite® had a higher design filtration rate than AD GS$^+$ (8.0 vs. 3.2 gpm/ft^2), the TF system used fewer and smaller filter vessels (i.e., two 48-in × 72-in FRP tanks) than the CL system (i.e., three 54-in × 60-in CS tanks). However, the higher filtration rate did not result in a lower total system cost because of the other design features as discussed.

Other factors were iron addition and AM systems included in the system design. For example, the TF and SA sites had identical Macrolite® systems, but the TF system was equipped with iron addition while the SA system was not. The cost of the TF system (with iron addition) was $18,288, or 6.6% higher than that of the SA system (without iron addition). Using an AM system for post-treatment also increased the system cost. The IR/AM systems at the SF and SD sites cost 8 to 36% more than the average of the other cost of three IR and CF systems without AM.

Unit costs (total capital investment) of the 18 systems expressed as 1,000 gal of water treated are also shown in Table 3-7. These unit costs were calculated based on the average and maximum annual production rates similar to those for the AM systems (Section 2.4.1). The ratio of a system's average annual production to its maximum capacity at the design flowrate is the utilization rate, which affected the unit capital investment cost. In Figure 3-7, unit costs are plotted against utilization rates for three groups of systems: NTNCWS, smaller CWS (<100 gpm), and larger CWS (>100 gpm). The systems in the NTNCWS and smaller CWS groups had comparable flow ranges. However, because the NTNCWS systems had significantly lower utilization rates than those in the smaller CWS group, i.e., 3.5% vs. 17% (on average), their unit costs per 1,000 gal were significantly higher than those for the smaller CWS group (i.e., $12.22 vs. $2.44 on average). On the other hand, because the systems in the smaller and larger CWS groups had rather comparable utilization rates, i.e., 17% vs. 21% (on average), unit costs of the systems in the smaller CWS group were about twice of those in the larger CWS group, i.e., $2.44 vs. $1.15 (on average). Therefore, the NTNCWS systems had the highest unit costs due to small sizes and low utilization rates.

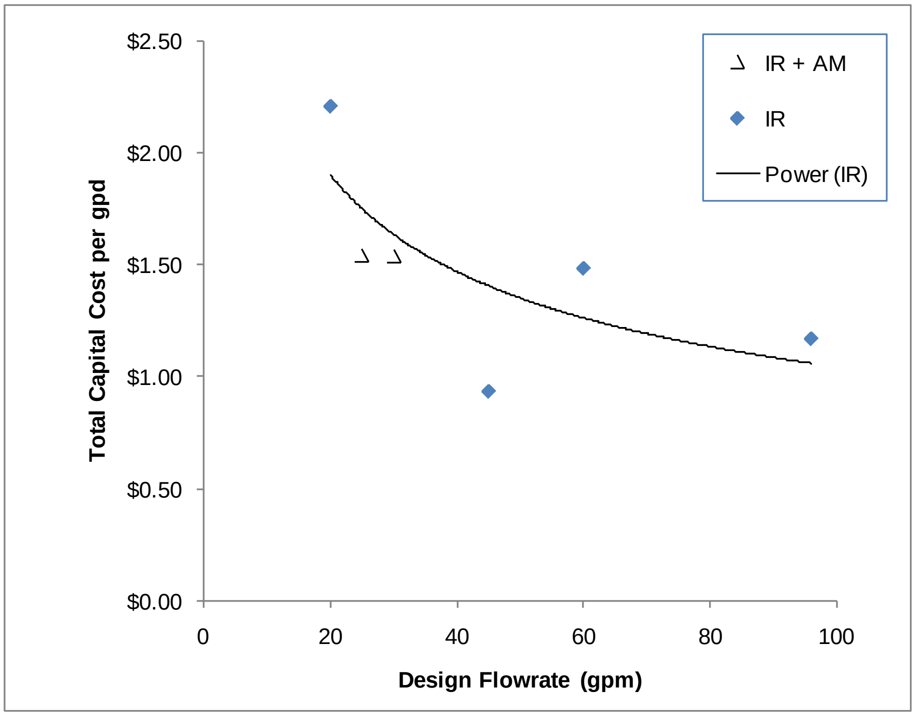


Figure 3-5. Smaller IR/CF System Capital Investment Costs per gpd of Design Capacity (<100 gpm)

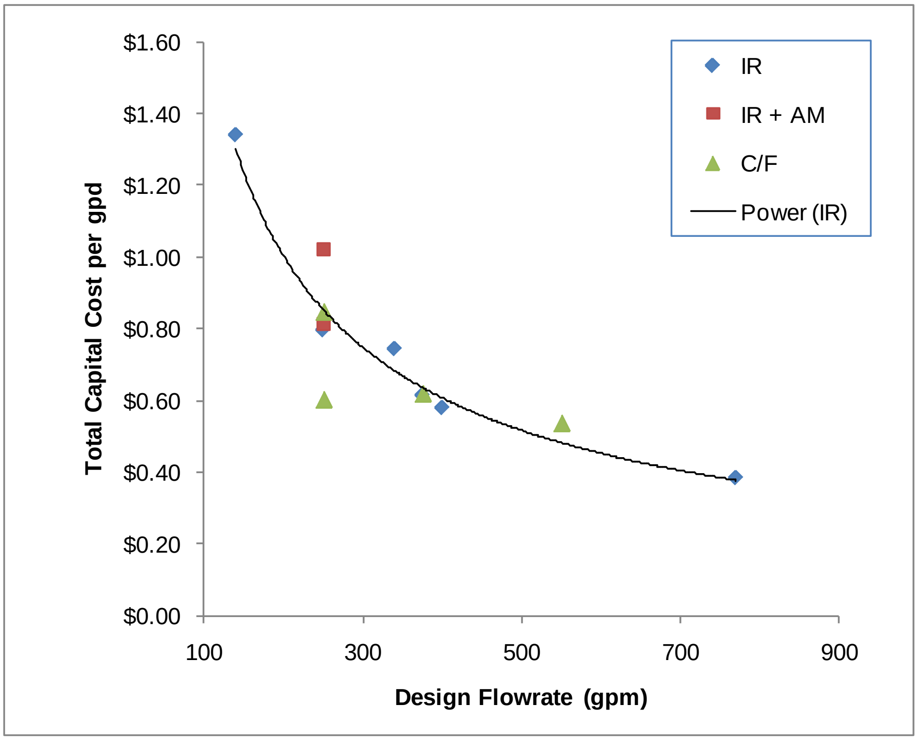


Figure 3-6. Larger IR/CF System Capital Investment Costs per gpd of Design Capacity (>100 gpm)

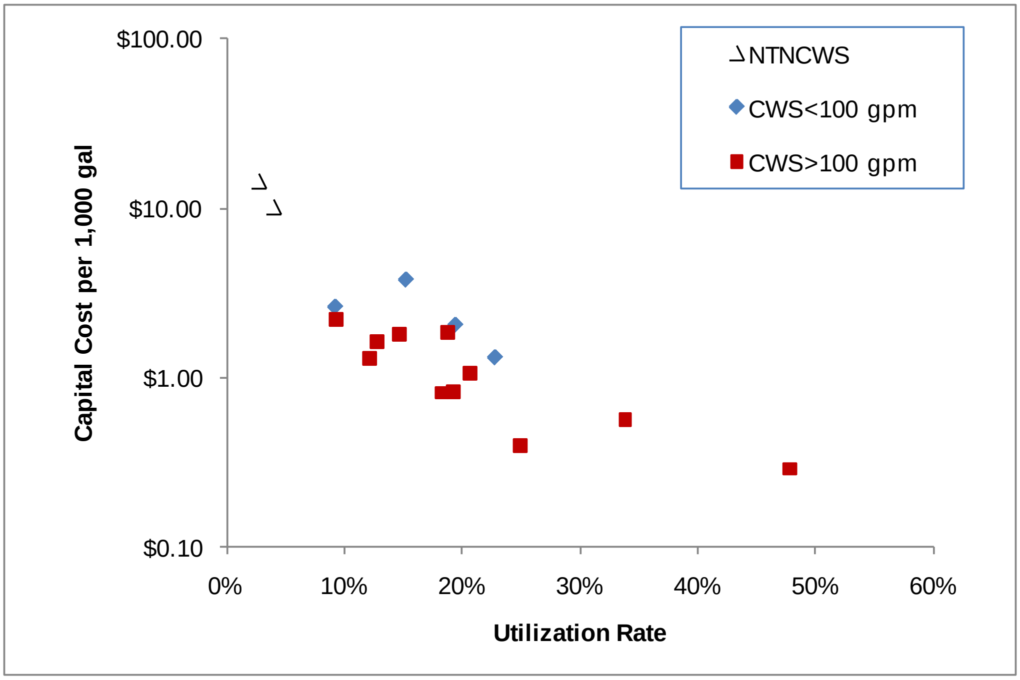


Figure 3-7. IR/CF System Unit Capital Investment Costs as a Function of Utilization Rates

3.4.2 Equipment Cost. Except for the GreensandPlus™ system at WV and the two AERALATER® package units at ST and SD, all other IR/CF treatment systems were skid-mounted with filtration vessels, piping and valves, and instrument and controls all mounted on individual steel frames. The equipment cost of a system generally included the cost for the skid-mounted system, filter media, miscellaneous materials and supplies, freight, user's manual, and vendor's labor. It also included the cost for a chemical feed system, if any. In some cases (like at WL, CL, and TF), the cost of backwash recycle equipment, such as backwash storage tank(s) and recycle pump, was also included in the equipment cost.

Equipment costs for the treatment system ranged from $19,790 for the 45-gpm DV system to $296,430 for the 550-gpm OK system, as shown in Table 3-8. On average, equipment costs accounted for 48% and 64% of total capital investment costs for the smaller CWS (<100 gpm) and larger CWS (>100 gpm), respectively. Figures 3-8 and 3-9 plot equipment costs against flowrates for the smaller (<100 gpm) and larger systems (>100 gpm). Because equipment costs made up the highest percentage of the total capital investment costs, equipment cost curves generally were similar to total capital investment cost curves shown in Figures 3-3 and 3-4. Curve fittings were performed on the data for the IR systems, yielding an R^2 of 0.5776 and 0.9297 for the smaller and larger systems, respectively.

3.4.3 Site Engineering Cost. Site engineering costs for the IR/CF systems ranged from $3,850 for the 30-gpm WL system to $53,435 for the 250-gpm TF system. These costs represented, on average, 21% and 12% of total capital investment costs for the smaller (<100 gpm) and larger CWS (>100 gpm), respectively (see Table 3-8). The percentage decreased as the size of the system increased, as expected.

Table 3-8. Summary of Equipment, Site Engineering, and Installation Costs of IR/CF Systems

No.	Site	Technology	Design Flow Rate (gpm)	Total Capital Cost ($)	Equipment		Site Engineering		Installation &Startup	
					Cost	% of Total	Cost	% of Total	Cost	% of Total
Non-Transient Non-Community Water Systems										
1	GS	IR (AD26) + AM (E33)	25	$55,423	$31,735	57	$11,278	20	$12,410	22
2	FC	IR (G2®)	60	$128,118	$103,118	80	$7,500	6	$17,500	14
		Average		*$91,771*	*67,426*	*69*	*$9,389*	*13*	*$14,955*	*18*
Community Water Systems (<100 gpm)										
3	SC	IR (Macrolite®)	20	$63,547	$22,422	35	$20,227	32	$20,898	33
4	WL	IR (Birm®/Filox™) + AM (Adsorbsia™ GTO™)	30	$66,362	$46,267	70	$3,850	6	$16,245	24
5	DV	IR (Macrolite®)	45	$60,500	$19,790	33	$20,580	34	$20,130	33
6	WV	IR (GreensandPlus™)	96	$161,560	$90,750	56	$22,460	14	$48,350	30
		Minimum	*20*	*$60,500*	*$19,790*	*33*	*$3,850*	*6*	*$16,245*	*24*
		Maximum	*96*	*$161,560*	*$90,750*	*70*	*$22,460*	*34*	*$48,350*	*33*
		Average		*$87,992*	*$44,807*	*48*	*$16,779*	*21*	*$26,406*	*30*
Community Water Systems (>100 gpm)										
7	CM	IR/IA (Macrolite®)	140	$270,530	$159,419	59	$39,344	15	$71,767	27
8	CL	CF (AD GS+)	250	$216,876	$161,650	75	$21,726	10	$33,500	15
9	TF	CF (Macrolite®)	250	$305,447	$168,142	55	$53,435	17	$83,870	27
10	SA	IR (Macrolite®)	250	$287,159	$160,875	56	$49,164	17	$77,120	27
11	SF	IR (AD26) + AM (E33)	250	$292,252	$212,826	73	$27,527	9	$51,899	18
12	ST	IR (AERALATER®) +AM (E33)	250	$367,838	$273,873	74	$16,520	4	$77,445	21
13	SD	IR (AERALATER®)	340	$364,916	$205,800	56	$27,077	7	$132,039	36
14	GV	IR (Macrolite®)	375	$332,584	$196,542	59	$48,057	14	$87,985	26
15	FE	CF (Macrolite®)	375	$334,297	$201,292	60	$44,520	13	$88,485	26
16	PW	IR/IA (Macrolite®)	400	$334,573	$224,994	67	$30,929	9	$78,650	24
17	OK	CF (Electromedia-I®)	550	$424,817	$296,430	70	$48,332	11	$80,055	19
18	AR	IR (Macrolite®)	770	$427,407	281,048	66	$50,770	12	$95,589	22
		Minimum	*140*	*$216,876*	*$159,419*	*55*	*$16,520*	*4*	*$33,500*	*15*
		Maximum	*770*	*$427,407*	*$296,430*	*75*	*$53,435*	*17*	*$132,039*	*36*
		Average		*$329,891*	*$211,908*	*64*	*$38,117*	*12*	*$79,867*	*24*

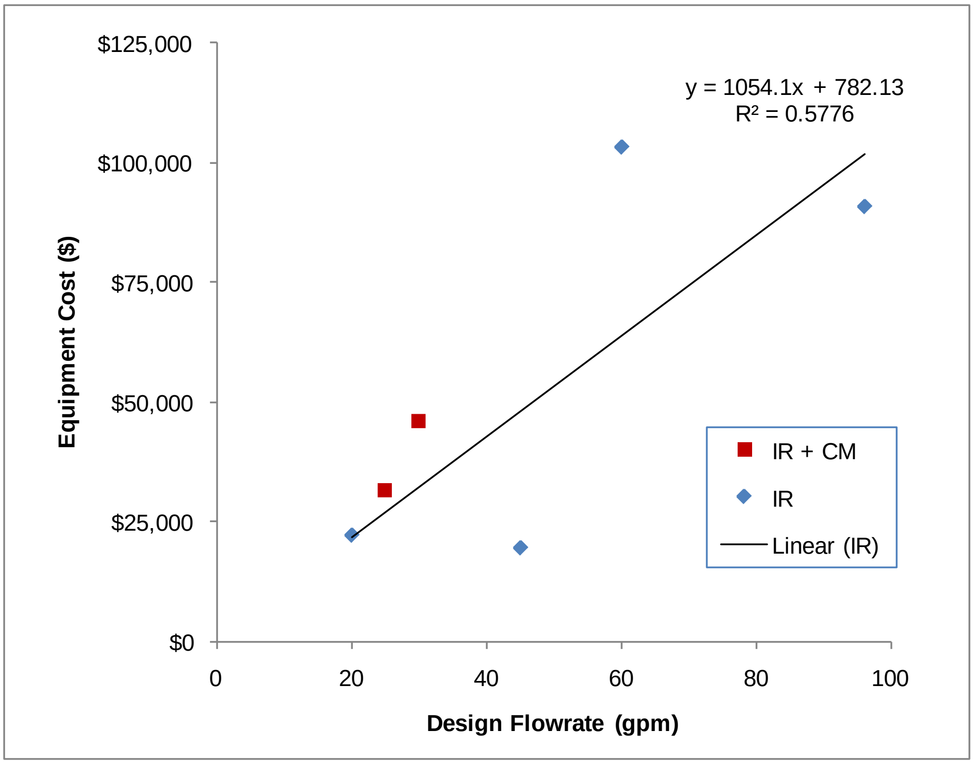


Figure 3-8. Equipment Costs of Smaller IR/CF Systems (<100 gpm)

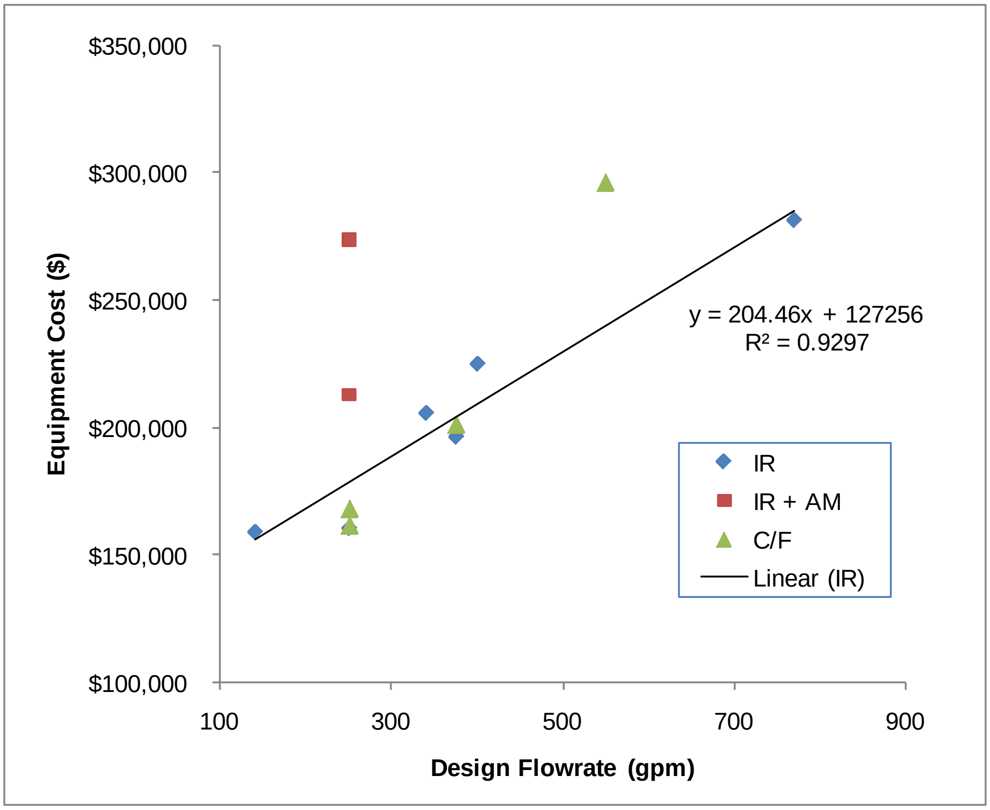


Figure 3-9. Equipment Costs of Larger IR/CF Systems (>100 gpm)

3.4.4 Installation Cost. Installation costs for the IR/CF systems ranged from $16,245 for the 30-gpm WL system to $132,039 for the 340-gpm SD system. The installation cost of the 12-ft diameter AERALATER® at the SD site was 70% higher than that of the 11-ft diameter AERALATER® and E33 system at the ST site. These installation costs represented 30% and 24% of total capital investment costs for the smaller (<100 gpm) and larger CWS (>100 gpm), respectively (see Table 3-8). The percentage decreased as the size of the system increased, as expected.

3.5 IR/CF System O&M Cost

O&M costs for the IR/CF systems included the cost of chemical supplies, electricity consumption, and labor to operate the arsenic treatment system. The backwash residual disposal cost was not included. Table 3-9 is a summary of O&M cost breakdowns for the 18 systems. Total O&M costs ranged from $0.07 to $1.93 per 1,000 gal of water treated. These costs were obtained from the first year system operations, when the systems were under warranty and required few repairs. Each cost component is discussed below.

3.5.1 Chemical Cost. Chemicals used for IR/CF system operations included NaClO, gas Cl_2, $KMnO_4$, and/or $NaMnO_4$ for oxidation/disinfection and/or an iron salt for coagulation. Where chlorination already existed at the facility for disinfection purposes, it was switched to pre-chlorination to oxidize soluble As(III), Fe(II), and/or Mn(II) before treatment. At sites where source water contained elevated TOC and ammonia, $KMnO_4$ or $NaMnO_4$ was used instead of chlorine. Incremental costs for chlorination/oxidation were negligible at three sites (e.g., FC, ST, and GV) and ranged from $0.01 to $0.37 per 1,000 gal of water treated for the other nine sites.

Iron addition was implemented at six sites, including four CF sites where iron was used as a coagulant and two IR sites where iron was added to supplement natural iron for better arsenic removal. Table 3-10 presents chemical costs for iron addition at these six sites. A 40% $FeCl_3$ solution in 15- or 55-gal drums was used at all sites. Iron dose rates ranged from 0.5 to 2.2 mg/L (as Fe). The costs of iron addition ranged from $0.01 to $0.07 per 1,000 gal of water treated.

Total chemical costs ranged from zero to $0.37 per 1,000 gal of water treated, accounting for zero to 57% (19% on average) of the total O&M costs.

3.5.2 Electricity Cost. The electricity cost was tracked by comparing the monthly electrical bills before and after the installation of the arsenic treatment system. If the site did not have a separate meter for the arsenic treatment system, then the cost was estimated based on the power requirements of the major equipment such as compressors, pumps, control panels, etc., the average operational hours, and the local electricity unit price. Local electricity unit prices ranged from $0.06 to $0.14 per kwh provided by the facilities.

The incremental electrical consumption was negligible for most of the systems. Electricity costs per 1,000 gal of water treated ranged from zero to $0.39 averaged $0.07, as shown in Table 3-9. It accounted for zero to 59% (19% on average) of the total O&M costs. The highest cost was incurred at the WL site because the well(s) ran almost around the clock.

3.5.3 Labor Cost. Labor costs accounted for 18 to 95% (61% on average) of the total O&M costs. Routine, non-demonstration related labor activities consumed only 10 to 30 min a day, one or several days a week at most of the sites. Average weekly hours ranged from 25 min to 10 hr and averaged 3.4 hr. As shown in Table 3-9, labor rates ranged from $10.8 to $30/hr and averaged $22.6/hr; these rates might be lower than those in certain regions of the country, such as California, but were actual numbers provided by the operators. Labor cost per 1,000 gal of water treated averaged $2.41 for the two

Table 3-9. O&M Costs for IR/CF Systems

					Chemicals			Electricity		Labor			
No.	**Site ID**	**Technology**	**Design Flow Rate (gpm)**	**Total O&M Costs ($/kgal)**	**Type**	**Cost ($/kgal)**	**% of Total O&M**	**Cost ($/kgal)**	**% of Total O&M**	**Average Weekly Hours (hr)**	**Labor Rate ($/hr)**	**Cost ($/kgal)**	**% of Total O&M**
Non-Transient Non-Community Water Systems													
1	GS	IR (AD26)+AM (E33)	25	$2.90(a)	NaClO	$0.33	11	$0.00	0	1.6	$16.0	$2.57	89
2	FC	IR (G2®)	60	$2.26	NaClO	$0.00	0	$0.00	0	1.67	$22.0	$2.26	100
Community Water Systems													
3	SC	IR (Macrolite®)	20	$0.36	$KMnO_4$	$0.07	19	$0.01	3	0.42	$21.0	$0.28	78
4	WL	IR (Birm®/Filox™) + AM Adsorbsia™ GTO™)	30	$1.93(a)	None	$0.00	0	$0.39	20	3	$30.0	$1.54	80
5	DV	IR (Macrolite®)	45	$0.26	NaClO	$0.09	34	$0.06	24	0.42	$10.8	$0.11	42
6	WV	IR (GreensandPlus™)	96	$0.65	$NaMnO_4$	$0.37	57	$0.16	25	1.75	$15.0	$0.12	18
7	CM	IR/IA (Macrolite®)	140	$0.29	$FeCl_3$	$0.03	10	$0.04	14	2.5	$21.0	$0.22	76
8	CL	CF (AD GS$^+$)	250	$0.46	$FeCl_3$	$0.07	15	$0.06	13	6	$22.0	$0.33	72
9	TF	CF (Macrolite®)	250	$0.18	$FeCl_3$	$0.02	9	$0.01	3	4.7	$19.6	$0.16	88
10	SA	IR (Macrolite®)	250	$0.43	NaClO	$0.05	12	$0.01	2	1.75	$10.0	$0.37	86
11	SF	IR (AD26)+AM (E33)	250	$0.33(a)	NaClO	$0.17	51	$0.00	0	2.33	$21.0	$0.16	48
12	ST	IR (AERALATER®) + AM (E33)	250	$0.16(a)	NaClO	$0.00	0	$0.08	50	1.7	$16.3	$0.08	50
13	SD	IR (AERALATER®)	340	$0.27	NaClO	$0.04	15	$0.16	59	4.5	$18.0	$0.07	26
14	GV	IR (Macrolite®)	375	$0.55	NaClO	$0.00	0	$0.03	5	10	$24.0	$0.52	95
15	FE	CF (Macrolite®)	375	$0.31	$FeCl_3$	$0.05	16	$0.05	15	5.25	$30.0	$0.21	69
16	PW	IR/IA (Macrolite®)	400	$0.17	$FeCl_3$	$0.01	8	$0.05	29	2.5	$30.0	$0.11	64
17	OK	CF (Electromedia® I)	550	$0.18	$FeCl_3$, NaClO	$0.03, $0.01	17	$0.08	44	5.25	$30.0	$0.06	33
18	AR	IR (Macrolite®)	770	$0.07	$KMnO_4$	$0.03	43	$0.00	0	2.5	$30.0	$0.04	57
		Minimum	*20*	*$0.07*		*0*	*0*	*0*	*0*	*0.4*	*10.8*	*$0.04*	*18*
		Maximum	*770*	*$1.93*		*$0.37*	*57*	*$0.39*	*59*	*10.0*	*30.0*	*$1.54*	*95*
		Average		*$0.40*		*$0.06*	*19*	*$0.07*	*19*	*3.4*	*22.6*	*$0.27*	*61*

(a) Media replacement cost not incurred during the study period; thus, not included in the total O&M cost.

Table 3-10. Cost of Iron Addition for IR/CF Systems

Site ID	Technology	Flow rate (gpm)	Raw Water As Levels µg/L)	Raw Water Fe Levels (µg/L)	Raw Water Fe/As Ratio	Fe Dosage (mg/L as Fe)	Cost ($/kgal of water)
CM	IR/IA (Macrolite®)	140	36.5	540	15	0.5	$0.03
CL	CF (AD GS$^+$)	250	29.0	188	6	1.8	$0.07
TF	CF (Macrolite®)	250	84.0	<25	<1	2.1	$0.02
FE	CF (Macrolite®)	375	34.4	26	<1	2.2	$0.05
PW	IR/IA (Macrolite®)	400	17.7	426	24	0.5	$0.01
OK	CF (Electromedia® I)	550	17.9	78	4	0.9	$0.03

(a) All sites used a 40% $FeCl_3$ solution.

and varied from $0.04 to $1.54 for the 16 CWS because annual water production rates of the treatment systems varied significantly. A NTNCWS often had a lower demand and a lower utilization rate than a CWS. Therefore, the labor cost (per 1,000 gal of water treated) of a smaller NTNCWS tended to be higher than that of a larger CWS.

4.0 OTHER ARSENIC TREATMENT TECHNOLOGIES

This section presents the cost information on two IX, one RO, and two POU arsenic demonstration systems. Table 4-1 presents demonstration locations, technologies, and study durations. The performance evaluation study on each IX system lasted much longer than 12 months to address issues of resin fouling which occurred at both sites. The demonstration of the RO system was conducted for 10 months because RO is a relatively mature technology and because a four-month pilot system had been previously conducted by EPA at the CE site. Capital investment and O&M cost data collected from these systems are presented in this section. An overview of the demonstration sites, system design and configurations is also provided to support the cost data. Detailed information on the performance and capital investment and O&M costs on the systems can be found in individual performance evaluation study reports provided on the EPA Arsenic Demonstration Program Web site.

Table 4-1. Summary of IX, RO, and POU Demonstration Locations, Technologies, and Study Durations

No.	Site ID	Demonstration Location	Technology	Vendor	Design Flowrate (gpm)	Study Duration	Length of Study (mon)
Non-Transient Non-Community Water Systems							
1	CE	Carmel, ME	RO (Dual Plumbing Distribution)	Norlen's Water	1,200 gpd	02/09–12/09	10
2	KF-POU	Klamath Falls, OR	POU ARM 200	Kinetico	8 units	12/05–11/06	11
Community Water Systems							
3	HD	Homedale, ID	POU RO	Kinetico	9 units	07/05–06/06	12
4	FL	Fruitland, ID	IX (A300E)	Kinetico	250	06/05–02/08	32
5	VA	Vale, OR	IX (Arsenex II/ PFA300E)	Kinetico	540	09/06–03/10	42

AM = adsorptive media; IX = ion exchange; POU = point of use; RO = reverse osmosis

4.1 Overview of Demonstration Sites

Table 4-2 summarizes the IX, RO, and POU demonstration site information, including two NTNCWS and three CWS. At the CE site, an innovative approach using a POE RO unit coupled with dual plumbing in the distribution system was demonstrated as a low cost alternative to achieve compliance with arsenic and antimony MCLs, compared to conventional RO treatment. At the KF site, eight POU ARM 200 cartridges were installed either under a sink or inside a drinking water fountain in eight college buildings. The HD site consisted of nine residences where a POU RO unit was installed at each residence. FL and VA are municipal facilities where IX was used to remove both arsenic and nitrate.

Table 4-3 presents average values of several source water quality parameters measured at the five sites during the performance evaluation studies. Arsenic concentrations in source waters varied from 18.2 to 57.8 µg/L with soluble As(V) being the predominant arsenic species at all five sites. The source waters also contained several co-contaminants, including antimony (Sb) at the CE site, nitrate (NO_3) at the HD, FL, and VA sites, and uranium (U) at the HD sites. The presence of these co-contaminants in source waters was the main reason for selecting RO as the treatment technology at the CE and HD sites and IX at the FL and VA sites.

Table 4-2. Summary of IX, RO, and POU Demonstration Sites

No.	Site ID	Design Flow Rate (gpm)	Average Flow Rate (gpm)	Daily Op Time (hr/day)	Average Daily Demand (gpd)	Annual Production (Kgal)	Utilization Rate (%)	Pre-existing Treatment
Non-Transient Non-Community Water Systems								
1	CE	1,200 gpd	0.8 (permeate); 1.2 (reject)	11.7	1,486(a)	108,912	25%	Cl_2
2	KF-POU	NA	NA	NA	NA	NA	NA	Cl_2
Community Water Systems								
3	HD	NA	NA	NA	NA	NA	NA	None except for softeners at 3 homes
4	FL	250	157	17.4	166,895	65,400	51%	None
5	VA	540	534	9.5	274,473	111,100	39%	Cl_2

(a) Including 562 gpd potable and 924 gpd non-potable demand.
NA = not applicable

Table 4-3. Summary of IX, RO and POU Site Source Water Quality

Site ID		CE	KF-POU	HD	FL	VA
Parameter	**Unit**	**Average Values**				
Total As	µg/L	18.2	29.8	57.8	42.5	22.6
As(III)	µg/L	0.2	0.3	1.5	1.2	1.0
NO_3 (as N)	mg/L	0.2	0.7	10.2	10.0	5.4
Total Sb	µg/L	10.8	NA	NA	<0.1	NA
Total U	µg/L	NA	0.3	27.4	19.4	6.1
Total V	µg/L	0.5	35.0	32.4	39.3	54.1
Total Fe	µg/L	<25	<25	112	<25	<25
Total Mn	µg/L	2.2	0.4	0.6	22.1	0.4
Total P	µg/L	<10	<10	<10	320	278
SO_4	mg/L	9.8	24	167	59	82
TDS	mg/L	255	200	685	580	514
TOC	mg/L	NA	<0.7	1.8	1.6	2.0
Silica	mg/L	11.2	30	66.5	57	55.6
Total Hardness	mg/L(a)	217	83	238	249	165
Total Alkalinity	mg/L(a)	206	116	295	387	329
pH	S.U.	7.9	8.0	7.3	7.6	7.4

(a) as $CaCO_3$.
NA = not available; TDS = total dissolved solids;
TOC = total organic carbon

The presence of total dissolved solids (TDS) and sulfate in source waters could affect the IX system performance and therefore the treatment cost, but the levels measured at the FL and VA sites were not high enough to cause adverse effects. However, the presence of TOC and silica in source waters was found to cause resin fouling at both the FL and VA sites. Water pH values ranged from 7.4 to 8.0. Water pH does not impact the IX or RO process as it would to the AM process.

4.2 IX Demonstration Systems

Four strong based anionic (SBA) IX resins manufactured by Purolite® were evaluated at the FL and VA sites. At FL, A300E was used to remove arsenic and nitrate. At VA where two studies were conducted, Arsenex II was used initially in Study Period I. Because of organic fouling, Arsenex II was replaced during Study Period II with PFA300E top-dressed with A850END. PFA300E was very similar to the A300E used at FL. All of these resins have NSF Standard 61 certification for use in drinking water applications. Their physical and chemical properties are presented in Table 4-4.

Table 4-4. Properties of IX Resins Used for EPA Demonstration Projects

Parameters	Arsenex II	A850END(a)	PFA300	A300E
Polymer Structure	Gel polystyrene crosslinked with DVB	Gel polyacrylic crosslinked with DVB	Gel polystyrene crosslinked with DVB	Gel polystyrene crosslinked with DVB
Functional Group	Dimethyl ethanol amine	Trimethylamine	Dimethyl ethanol amine	Dimethyl ethanol amine
Physical Form and Appearance	Opaque spherical beads	Clear spherical beads	Amber spherical beads	Clear spherical beads
Whole Bead Count	95% minimum	-	95% minimum	-
Resin Type	SBA Type II	SBA Type I	SBA Type II	SBA Type II
Ionic Form, as Shipped	Cl^-	Cl^-	Cl^-	Cl^-
Shipping Weight (g/L or [lb/ft^3])	0.69 (43)	0.68–0.73 (42.5–45.6)	0.69 (43)	0.69–0.72 (43–45)
Specific Gravity (g/mL)	-	1.09	1.10	1.09
Mesh Size(b) (Wet)	16 × 50	-	25 × 40	16 × 50
Bead Size Range (mm)	0.3–1.2	0.60–0.85	+0.710 mm <1%; -0.425 mm <1%	0.3–1.2
Uniformity Coefficient	-	1.70	1.20	1.70
Moisture Retention (%)	42–54	57–62	40–45	40–45
Reversible Swelling	Cl^- to SO_4^{2-}/NO_3^- Negligible	Cl^- to OH^- 15% (max)	Cl^- to OH^- 10% (max)	Cl^- to OH^- 10% (max)
Total Exchange Capacity, Cl^- Form (eq/L) (wet, volumetric)	1.0	1.25	1.4	1.4
pH Range	0–14	1–10	No limit	No limit
Maximum Temperature Limit (°C/°F)	100/212	85/185	85/185	85/185

Source: Purolite.

(a) Specially produced from A850 with a narrow size grading of 300 to 600 µm; some properties, such as bead size range and uniformity coefficient, expected to vary from those of A850.

(b) U.S. Standard mesh.

DVB = divinylbenzene; SBA = strong base anionic

4.2.1 IX System Design and Configuration. Because of similar site conditions and source water quality, the design and basic components of the two IX systems were very similar (see Table 4-5), except that the VA system was more than twice the size of the FL system. Both systems consisted of a sediment filter assembly, two parallel pressure tanks each containing a packed bed of resin, one or two salt saturators, brine day tanks, and brine pumps, and associated instrumentation and controls. Figure 4-1 presents a photograph of the IX system at FL.

Table 4-5. Summary of IX System Design and Components

Site ID	FL	VA	
Design Flowrate (gpm)	250	540	
Average Flowrate (gpm)	157	536	
No. of Tanks	2	2	
Tank Size (in)	48 D × 72 H	63 D × 86 H	
Resin Type	A300E	Arsenex II	A850END/PFA300E
Resin Volume/Tank (ft^3)	50	93	16.7/81.7
Total Resin Volume (ft^3)	100	186	33.4/163.4
Average Hydraulic Loading (gpm/ft^2)	6.2	12.3	12.4
Design EBCT (min)	3.0	3.0	3.0
Average EBCT (min)	4.8	2.6	2.8
Design Salt Loading (lb/ft^3)	10	12	10
Average Salt Loading (lb/ft^3)	9.5	12.8	9.3
Salt Saturator (in)	One, 96 D × 148 H (15-ton capacity)	Two, 96 D × 120 H (11-ton capacity)	
Brine Day Tank (in)	One, 61 D × 64 H (685 gal)	Two, 61 D × 97 H (1,050 gal)	
Pre-treatment	Five 20-µm bag filters in parallel	Two banks of five 5- or 20-µm bag filters	

Figure 4-1. Photograph of IX-248-As/N System at Fruitland, ID

The IX systems were regenerated in a downflow, co-current mode using brine. Triggered automatically by a throughput setpoint in a PLC, the two IX tanks were regenerated sequentially, each cycling through the steps of brine draw, slow rinse, and fast rinse before returning to service. The regeneration waste stream was discharged to the sewer at FL and an evaporation pond outside of the plant at VA.

The IX systems were fully automatic and controlled by the PLC in the central control panel. The control panel also contained a touch screen OIP that allowed the operator to monitor system flowrate and throughput since last regeneration. The OIP also allowed the operator to change system setpoints, as needed, and check status of alarms. Setpoint screens were password-protected so that changes could only be made by authorized personnel. Typical alarms were for no flow, storage tank high/low, and regeneration failure.

4.2.2 IX System Capital Investment Costs. Table 4-6 presents total capital investment costs for the two IX systems. The total capital investment costs included the cost for equipment, site engineering, and installation as shown in Table 4-7. The cost associated with the new building, sanitary sewer connection (at FL), construction of an evaporation pond and ancillary equipment (at VA), and other infrastructure improvement was not included in the capital investment costs.

Table 4-6. Total Capital Investment Costs for IX Systems

Site	Design Flow rate (gpm)	Total Capital Cost ($)	Normalized Capital Cost ($/gpm)	Normalized Capital Cost ($/gpd)	Annualized Capital Cost[(a)] ($/yr)	Unit Cost (/$kgal of water)		Utilization Rate[(c)] (%)
						Design[(b)]	Average	
FL	250	$286,388	$1,146	$0.80	$27,032	$0.21	$0.47	44
VA	540	$395,434	$732	$0.51	$37,325	$0.13	0.34	39

(a) Obtained by applying a CRF of 0.09439 (based on a 7% interest rate and a 20-year return period) to total capital cost.
(b) System's maximum capacity at design flowrate, operating 24 hr a day, 365 days a year.
(c) Ratio of a system's average annual production to its maximum capacity at design flowrate.

Table 4-7. Summary of Equipment, Site Engineering, and Installation Costs of IX Systems

Site ID	Design Flow Rate (gpm)	Total Capital Cost ($)	Equipment		Site Engineering		Installation &Startup	
			Cost	% of Total	Cost	% of Total	Cost	% of Total
FL	250	$286,388	$173,195	61	$35,619	12	$77,574	27
VA	540	$395,434	$260,194	66	$49,840	13	$85,400	22

The total capital investment cost of the VA system was 38% higher than that of the FL system, but its capacity was more than double the FL system. Therefore, in terms of the capital cost per gpm or gpd of the design capacity, the VA system is 36% lower than the FL system. Annualized and unit capital costs per 1,000 gal of water treated are also presented in Table 4-6. As expected, the unit cost based on the average production was higher than that based on the maximum capacity. The ratio of the average production to the maximum capacity, expressed as utilization rate, was comparable for both IX systems, i.e., 44% for FL and 39% for VA.

Equipment Cost. Both IX treatment systems were skid-mounted on a steel frame. Similar to an AM and a IR/CF system, the equipment cost of an IX system included the cost for the skid-mounted system, resin media, miscellaneous materials and supplies, freight, user's manual, and vendor's labor. It also included the cost for the salt delivery system, which consisted of one or two salt saturators, brine day tanks, and brine pumps. The equipment cost of the VA system was about 50% more than that of the FL system. The equipment cost accounted for 61% and 66% of the respective total capital investment costs for the FL and VA systems, making up the highest percentage of the total capital investment costs.

Site Engineering Cost. Site engineering costs included the cost for the necessary design work and engineering plans preparation. The equipment cost of the VA system was 40% more than that of the FL system. The engineering cost represented 12 or 13% of the total capital investment costs for both systems.

Installation Cost. The installation cost of the VA system was about 10% more than that of the FL system. The equipment cost accounted for 27% and 22% of the total capital cost for the FL and VA systems, respectively.

4.2.3 IX System O&M Costs. The O&M cost evaluated for the IX systems included the incremental cost associated with the salt supply, electricity consumption, and labor. The disposal cost of regeneration residual was not included. Table 4-8 is a summary of the cost breakdowns of the O&M costs for the two IX systems. The total O&M cost was $0.62 and $0.35 per 1,000 gal of water treated for the FL and VA systems, respectively. These costs were obtained from the first year system operations, when any system repairs were covered by the warranties. Each cost component is discussed below.

Table 4-8. O&M Costs for IX Systems

Site ID	Design Flow Rate (gpm)	Total O&M Costs ($/kgal)	Salt Supply			Electricity		Labor			
			Type	Cost ($/kgal)	% of Total O&M	Cost ($/kgal)	% of Total O&M	Average Wkly Hours	Labor Rate ($/hr)	Cost ($/kgal)	% of Total O&M
FL	250	$0.62	Salt	$0.49	79%	$0.08	13%	2.5	$21.0	$0.05	8%
VA[(a)]	540	$0.35	Salt, caustic	$0.29	83%	$0.03	8%	3.3	$21.0	$0.03	10%

(a) Resin replacement cost not included in total O&M cost.

Salt Supply Cost. The IX system used salt for resin regeneration. Caustic soda was mixed with brine to help remove organic foulants from the resin periodically. The average salt use rate per 1,000 gal of water treated was 3.6 lb at VA and 4.4 lb at FL. The unit salt price was cheaper at VA ($0.076 verse $0.11/lb) because VA purchased salt in bulk quantities (i.e., half truck load). The salt costs per 1,000 gal of water treated were $0.29 at VA and $0.49 at FL, accounting for 83% and 79% of the total O&M costs, respectively. Optimizing the salt loading during resin regeneration and providing more salt storage capacities to allow delivery of full truck loads can significantly reduce the overall salt cost.

Electricity Cost. The electricity cost was tracked by comparing the monthly electrical bills before and after IX system installation. For example, electricity bills at VA were approximately $850/month in 2006 and increased by 29% to $1,100/month in 2007. Thus, the annual increase was $3,000, or $0.028/1,000 gal. The electricity cost per 1,000 gal of water treated was $0.08 at FL. Electricity costs represented 13% and 8% of the total O&M costs for the FL and VA systems, respectively.

Labor Cost. The routine, non-demonstration related labor activities consumed only 10 to 30 min a day, five days a week. The average weekly hours were 2.5 hr at FL and 3.3 hr at VA. The labor rate was $21/hr for both sites. Labor costs per 1,000 gal of water treated were $0.03 and $0.05, accounting for 8 to 10% of the total O&M costs.

4.3 RO Demonstration System

A POE RO unit coupled with dual plumbing in the distribution system was demonstrated at the CE site. This approach involved installing a parallel plumbing system dedicated to the potable water distribution only. Because most water consumed at the school was for non-potable use (i.e., lavatory), only a portion of raw water would need to be treated for potable use (i.e., kitchen sinks, drinking fountains, etc). As a result, a smaller RO system with a separate distribution system was installed to meet the potable water demand, thus reducing the capital investment and O&M costs.

4.3.1 RO System Design and Configuration. The RO system selected was a Crane Environmental EPRO-1,200 system consisting of an RO unit, a calcite filter for pH adjustment, two 300-gal atmospheric storage tanks, a re-pressurization system, and a post-chlorination system. Major components of the RO unit included a 5-µm sediment filter, a ½-horsepower (hp) booster pump, and two 2.5-in × 40-in thin-film composite RO membrane modules, as shown on Figure 4-2. The RO permeate passed through the calcite filter to raise its pH levels to near neutral and then was stored in two 300-gal

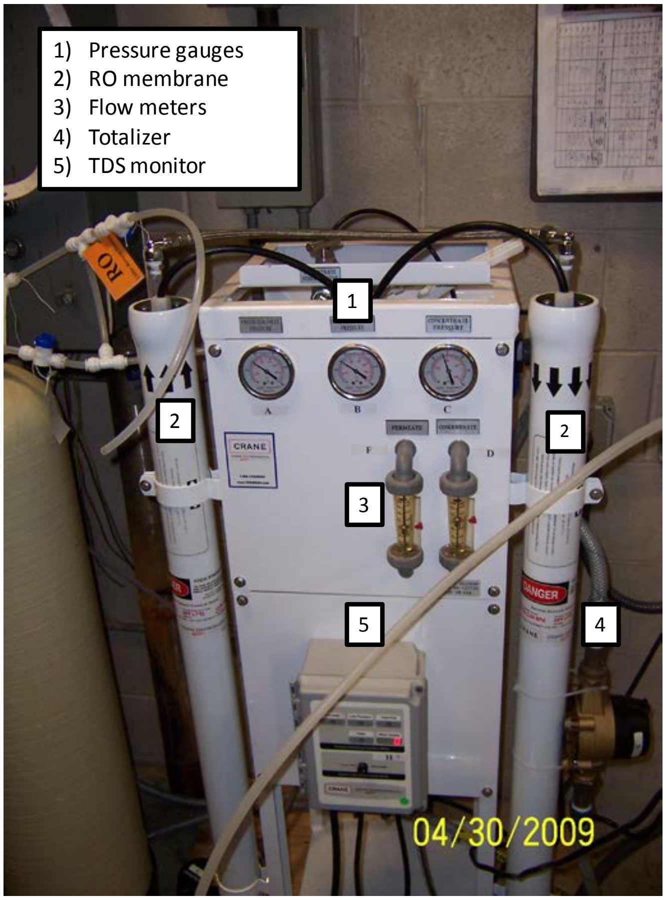


Figure 4-2. EPRO-1,200 RO Unit

atmospheric storage tanks. The water from the storage tanks was re-pressurized by a 1-hp booster pump before entering the potable distribution line. All major functions of the EPRO-1,200 RO unit were automated and required only minimal operator oversight and intervention. Table 4-9 summarizes key system design parameters of the treatment system.

Table 4-9. Design Specifications of EPRO-1,200 RO System

Parameter	Value
System Components	
No. of Pre-filters	1
Pre-filter Nominal Pore Size (µm)	5
No. of RO Membrane Elements	2
RO Membrane Construction	Thin film composite
Size of Membrane Elements	2.5-in D × 40-in H
Operating Specifications	
Feed Flowrate (gpd)	3,000
Daily Permeate Production Rate (gpd)	1,200
Recovery (%)	40
Min. Rejection (%)	98

The RO system was rated for 1,200 gpd of permeate production with a 40% recovery (or 2.5:1, that is, for every 2.5 gal of feed water, 1 gal of permeate water and 1.5 gal of reject water were produced). The reject water was discharged into the existing septic system. Both permeate and reject water lines were equipped with flow meters and totalizers, pressure gauges, and sample taps for monitoring purposes.

4.3.2 RO System Capital Investment Cost. The capital investment cost for the RO system was $20,542, including $8,600 for the dual plumbing and $11,942 for the EPRO-1,200 RO unit. The dual plumbing installation cost included $2,650 for plumbing materials and $5,950 for the labor to convert the existing plumbing into a duplex distribution system. The cost of the EPRO-1,200 RO unit included $8,471 for equipment and parts, $300 for shipping, and $3,171 for installation.

The capital investment cost of $20,542 was normalized to the system's rated capacity of 1,200 gpd of permeate, which results in $17.12/gpd of design capacity (see Table 4-10). The unit capital cost based on the average production rate was higher than that based on the maximum capacity. The ratio of the average production to the maximum capacity, expressed as utilization rate, was 25%.

Table 4-10. RO System Capital Investment Cost

Site ID	Design Flow rate (gpd)	Total Capital Costs ($)	Normalized Capital Cost ($/gpd)	Annualized Capital Cost(a) ($/yr)	Unit Cost ($1,000 gal of water)		Utilization Rate(c) (%)
					Design(b)	Average	
CE	1,200	$20,542	$17.12	$1,939	$4.43	17.80	25%

(a) Obtained by applying a CRF of 0.09439 (based on 7% interest rate and 20-year return period) to total capital cost.
(b) System's maximum capacity at design flowrate, operating 24 hr a day, 365 days a year.
(c) Ratio of system's average annual production rate to its maximum capacity at design flowrate.

4.3.3 RO System O&M Cost. The O&M cost included system repairs, electricity consumption, and labor to operate the system. Regularly scheduled maintenance activities involved replacing sediment filters on a monthly basis or when the differential pressure was greater than 10% and replenishing calcite in the calcite filter as it became depleted. Neither was required during the performance evaluation study.

The cost to diagnose and install a faulty RO motor and pump assembly was $351. Annual electricity consumption was estimated to be 5,078 kwh and cost $376. Routine labor activities consumed 10 min per day to visually inspect the system and record operational parameters, which translated into $666/yr. The total annual O&M cost was estimated to be $1,404, or $12.89/1,000 gal of permeate water produced.

4.4 POU RO Demonstration Units

4.4.1 POU RO Unit Design and Configuration. One POU RO unit was demonstrated at each of nine participating residences for arsenic, nitrate, and uranium removal from source water. Softening of source water was performed as pretreatment to meet feed water quality requirements for the RO units. Six POE softeners (three homes had existing softeners) and nine POU RO units were provided by Kinetico. Each POU RO unit consisted of a 20-µm pre-filter, an RO module with a 1.7-in × 11-in thin film composite, semi-permeable membrane element, a 3-gal storage tank, and a MACguard post-filter. The RO units were capable of producing up to 35.5 gpd of permeate water and had a feed water to permeate water ratio of 2.7 to 1, a 37% recovery rating. The RO units automatically shut down production after 500 gal of permeate water had been processed and resumed operation only after replacement of spent pre- and post-filters.

Each system was equipped with a PureMometer Filter Life Indicator to alert users for the remaining capacity of the filter cartridge. Further, a TDS monitor installed at the kitchen tap measured TDS levels in treated water. A green light on the monitor indicated that a proper amount of permeate water was generated and a yellow light indicated that it was not. The RO Plus Deluxe unit has been tested and listed under NSF Standard 58. Table 4-11 summarizes key performance specifications for the RO Plus Deluxe unit. Figure 4-3 shows a photograph of the under-the-sink RO unit.

4.4.2 POU RO Costs. The capital investment cost for purchasing and installing six water softeners and nine RO units was $31,877.50. The equipment cost was $21,732.50 (or 68% of the total capital investment costs), which included the cost for nine RO units, six water softeners, initial salt fill, additional sample tap and a water meter, and freight. The installation cost was $10,145 (or 32% of the total capital investment costs). The lump-sum cost was broken down for individual units. Each water softener cost $2,395, including $1,585 for equipment and $810 for installation. Each RO unit cost $1,220, including $1,025 for equipment and $195 for installation.

The O&M cost consisted of salt usage, pre- and post-filter replacement, RO element replacement, and maintenance. The yearly service contract with the vendor for salt supply was $115 per year. Pre- and post-cartridge filter replacement at 500 gal of treated water was $86.50. Five out of the nine residences used 500 gal of treated water during the performance evaluation period. For these five residences, the one-year O&M cost included $115 for salt supply and $86.50 for filter replacement, totaling $201.50 or $17 per month. The systems were under warranty for one year; therefore, no maintenance cost was incurred during the study period. Neither electricity nor labor cost was incurred because the water softener and the RO unit did not consume electricity and did not require a certified operator.

Table 4-11. Kinetico RO Plus Deluxe Unit Performance Specifications

Parameter	Value
System Components	
Pre-treatment	One, 20-µm pre-filter
No. of RO Membrane Elements	1
RO Membrane Construction	Thin film composite
Membrane Element Size (in)	1.7-in D x 11-in H
No. of Post-filters	1
Permeate Flush	Internal Permeate Reservoir
Element Configuration	Single
System Shutoff Control	Hydraulic
System Shutdown Volume (gal)	500
System Controller	Hydraulic
Storage Tank	One, 8-in D × 17-in H (3 gal)
Operating Specifications	
Maximum Daily Production (gpd)	75
Daily Production (gpd)	35.5
Discharge Water (or Feed Water)/ Product Water Ratio	2.7 to 1
Normal Operating Pressure (psi)	60

Source: Kinetico.

Figure 4-3. Under-the-Sink RO Plus Deluxe Unit

4.5 POU AM Demonstration Units

4.5.1 POU AM Cartridge Design and Configuration. Eight Kinetico POU AM units were installed either under a sink or inside a drinking water fountain in eight different school buildings at the KF site, but only three were monitored for their performance. Each POU unit used a single cartridge to house 600 mL of ARM 200 media for arsenic removal. A shut-off assembly and an indicator on the outside of the filter head were used to measure and show the relative remaining cartridge capacity, based on a maximum capacity of 500 gal. When 500 gal of water was processed, the shut-off assembly was completely closed, preventing any more water from passing through the cartridge. About 11 months into the performance evaluation study, the school began to install 40 new AdEdge E33 POU units and to replace the eight Kinetico units with AdEdge units. Each AdEdge POU unit consisted of E33 media in a polypropylene housing. The approximate flowrate with a system inlet pressure of 60 psi was 1 gpm. The working pressure ranged from 20 to 125 psi. The unit had a height of 13 in and a diameter of 6.75 in. Table 4-12 presents the design specifications of Kinetico and AdEdge POU units. Figure 4-4 shows photographs of the POU units installed under a sink and inside a drinking fountain.

Table 4-12. Design Specifications of Kinetico and AdEdge POU AM Cartridges

Parameter	Kinetico POU Unit	AdEdge POU Unit
Housing Material	Polypropylene	Polypropylene
Cartridge Dimensions (mm)	54 × 265 (Slightly tapered)	–
Housing Dimensions	–	–
Height	425 mm	13 in
Width	150 mm	–
Diameter	100 mm	6.75 in
Unit Weight (lb)	11	4
Media Type	ARM 200	E33
Media Volume (mL)	600	–
Inlet Connection	¼-in Female NPT	⅜ in
Outlet Connection	¼-in Female NPT	¼ in
Particulate Retention (µm)	5.0	0.5
Water Pressure (psi)	20–120	30–125
Flowrate (gpm)	0.7–1.0	1.0 @ 60 psi
Treatment Capacity (gal)	490	–

4.5.2 POU AM Cartridge Costs. The cost of purchasing eight Kinetico POU ARM 200 cartridges was \$1,216, or \$152 per unit. The cost of purchasing 48 AdEdge POU E33 cartridges was \$9,120, or \$215 per unit (these replacement cartridges were purchased by the school). Although the E33 cartridge is 40% higher than the ARM 200 cartridge, the E33 media life was almost three times as long as ARM 200. For example, one E33 cartridge treated up to 3,000 gal of water to reach 8 μg/L of arsenic in the effluent while the ARM 200 cartridge treated up to 1,000 gal of water to reach 6 μg/L of arsenic in the effluent.

The O&M cost of the POU AM unit consisted of replacing pre- and post-filter as well as AM media. Neither electricity nor labor cost was incurred because the cartridge did not consume electricity and did not require a certified operator.

Figure 4-4. POU AM Units Installed Under a Sink (top) and Inside a Drinking Water Fountain (bottom)

5.0 COST SUMMARY

This section summarizes capital investment and O&M costs of the AM, IR/CF, and IX systems. The cost data were divided into two groups with one for systems having design flowrates smaller than 100 gpm (including both NTNCWS and CWS) and the other for systems equal to or larger than 100 gpm. The group of smaller systems (<100 gpm) comprised 17 AM and six IR/CF (including two IR/AM) systems. The group of larger systems (≥100 gpm) comprised 11 AM, 12 IR/CF (including two IR/AM), and two IX systems. The range and average of cost data for the same technology in each group were calculated to allow for comparison of those within and between the groups. Because many factors can affect the costs of technologies and the number of systems in each group varies, the results of this cost analysis are valid only for the specific cost data collected from this study; any conclusions drawn from the cost comparisons should only be used as a reference.

5.1 Total Capital Investment Costs of Treatment Technologies

Capital investment costs of the full-scale arsenic removal systems/POU units demonstrated under EPA Rounds 1, 2, and 2a demonstration projects totaled $8,552,428. Table 5-1 summarizes total capital investment costs for the AM, IR/CF, and IX systems demonstrated. The cost data are plotted in Figures 5-1 and 5-2 for smaller systems (<100 gpm) and in Figures 5-3 and 5-4 for larger (≥100 gpm) systems. The four IR/AM systems were plotted separately on these figures, but were considered as IR systems in the cost analysis in Table 5-1.

Total capital investment costs of the 17 smaller AM systems scattered widely, ranging from $14,000 to $228,300. The variations observed were caused by the factors discussed in Section 2. The costs of the six smaller IR/CF systems also varied, but to a lesser extent, from $55,423 to $161,560. Normalized costs ranged from $636 to $6,171 per gpm (or $0.44 to $4.29 per gpd) for the smaller AM systems and $1,344 to $3,177 per gpm (or $0.93 to $2.21 per gpd) for the smaller IR/CF systems. Unit capital costs per 1,000 gal of water treated ranged from $0.11 to $1.11 for the smaller AM systems and $0.24 to $0.57 for the smaller IR/CF systems. Average values of the normalized and unit costs for the AM systems were 6% and 8%, respectively, higher than those for the IR/CF systems. However, individual data points in Figures 5-1 and 5-3 do not exhibit any clear trend whether AM or IR/CF is more expensive. If the highest cost associated with the 37-gpm AM system (that was equipped with a pH control system, a backwash wastewater recycling system, and excessive instrumentation and controls) was removed from the data set, average values of the normalized and unit costs for the AM technology would be lower than those of the IR/CF technology. Therefore, the capital investment costs of the smaller AM and IR/CF systems did not differ significantly from each other.

For larger treatment systems (≥100 gpm), total capital investment costs ranged from $74,840 to $305,000 for the 11 AM systems, $216,876 to 427,407 for the 12 IR/CF systems, and $286,388 to $395,434 for the two IX systems. Normalized costs ranged from $477 to $1,492 per gpm (or $0.33 to $1.04 per gpd) for the AM systems, $555 to $1,932 per gpm (or $0.39 to $1.34 per gpd) for the IR/CF systems, and $732 to $1,146 per gpm (or $0.51 to $0.80 per gpd) for the IX systems. Unit capital costs per 1,000 gal of water treated ranged from $0.09 to $0.27 for the AM systems, $0.10 to $0.35 for the IR/CF systems, and $0.13 to $0.21 for the IX systems. As shown in Figure 5-4, capital investment costs per gpd generally decreased with increasing system sizes for all technology types. Average values of the normalized and unit costs for the AM systems were 25% and 26%, respectively, lower than those for the IR/CF systems. The trendlines in Figures 5-2 and 5-4 also clearly indicate that the cost of IR/CF is higher than that of AM. The costs of the two IX systems appear to fit well with those for IR/CF. Therefore, IR/CF and IX are generally more expensive than AM for systems larger than 100 gpm. Because seven out of the 12 IR/CF systems and both IX systems were supplied by one vendor, it is possible that the cost data were skewed by this vendor's pricing structure. The larger systems have lower normalized and unit costs than the smaller systems, reflecting the scale of economy.

Table 5-1. Summary of Total Capital Investment Costs

Treatment Technology	No. of Systems	Range/ Average	Design Flow rate (gpm)	Total Capital Cost ($)	Normalized Capital Cost ($/gpm)	Normalized Capital Cost ($/gpd)	Unit Cost ($/kgal)	Equipment	Site Engineering	Installation
								(% of Total Capital Invest Costs)		
Systems < 100 gpm										
AM	17	Range	10–75	14,000–228,309	636–6,171	0.44–4.29	0.11–1.11	38–75	10–40	12–34
		Average			2,248	1.56	0.41	65	16	19
IR/CF	6[(a)]	Range	20–96	55,423–161,560	1,344–3,177	0.93–2.21	0.24–0.57	33–80	6–34	14–33
		Average			2,128	1.48	0.38	55	18	26
Systems ≥ 100 gpm										
AM	11	Range	100–640	74,840–305,000	477–1,492	0.33–1.04	0.09–0.27	61–82	4–17	13–25
		Average			806	0.56	0.14	72	12	16
IR/CF	12[(a)]	Range	140–770	216,876–427,407	555–1,932	0.39–1.34	0.10–0.35	55–75	4–17	15–36
		Average			1,069	0.74	0.19	64	12	24
IX	2	Range	250–540	286,388–395,434	732–1,146	0.51–0.80	0.13–0.21	61–66	12–13	22–27
		Average			939	0.66	0.17	63	12	24

(a) Including two AM systems with IR pretreatment.

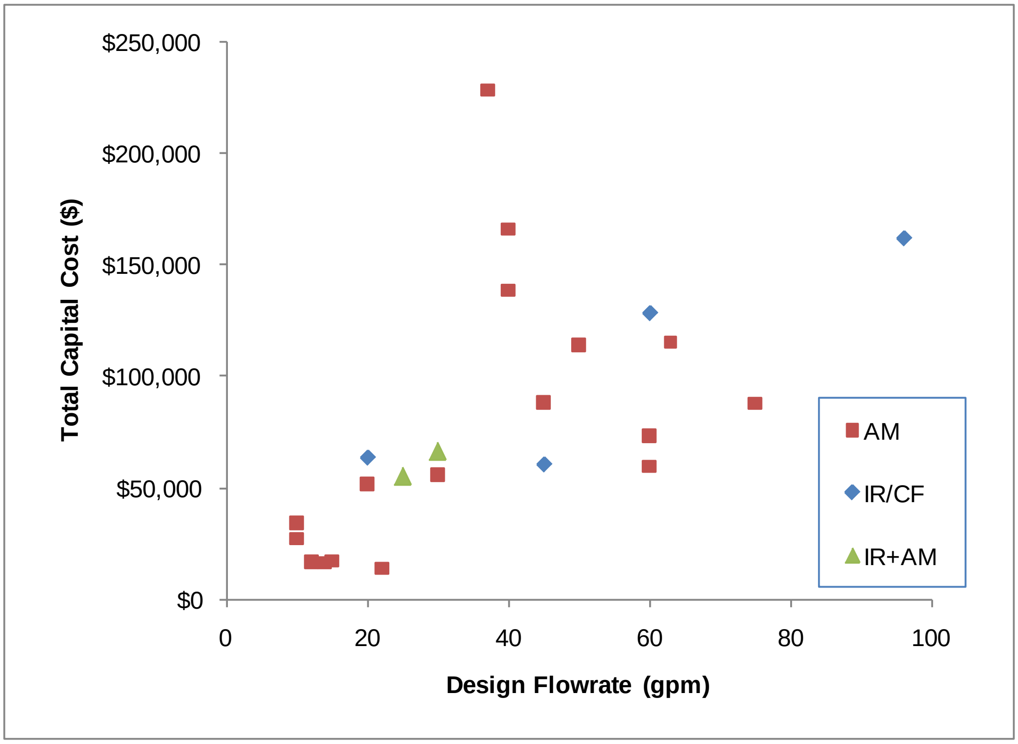


Figure 5-1. Total Capital Investment Costs of Smaller AM and IR/CF Systems (<100 gpm)

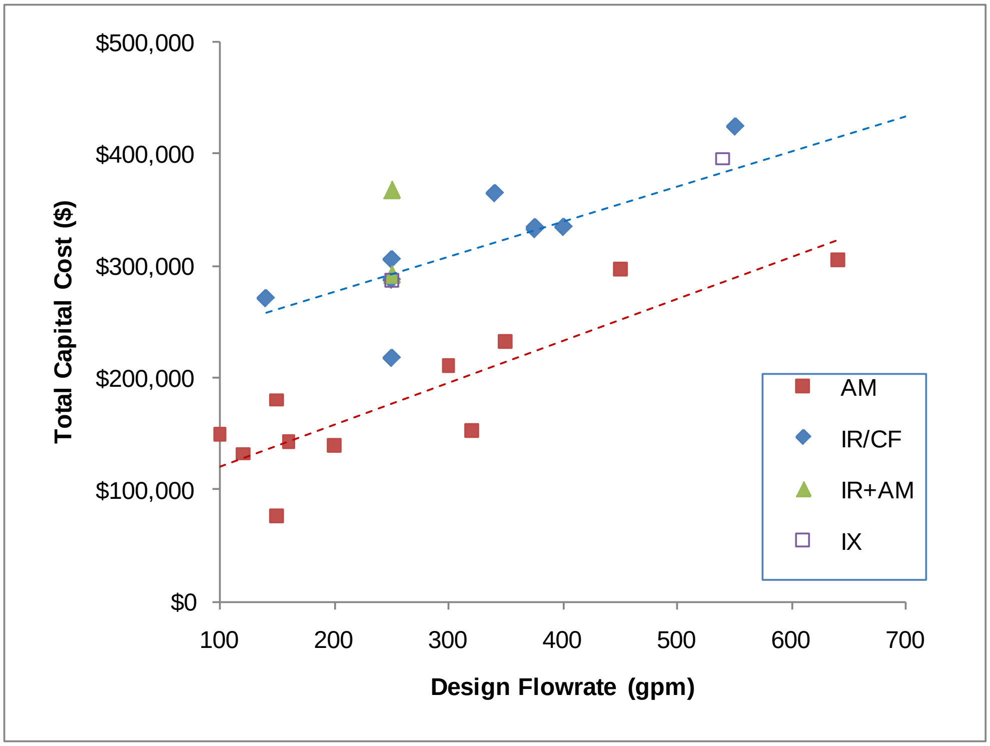


Figure 5-2. Total Capital Investment Costs of Larger AM, IR/CF, and IX Systems (≥100 gpm)

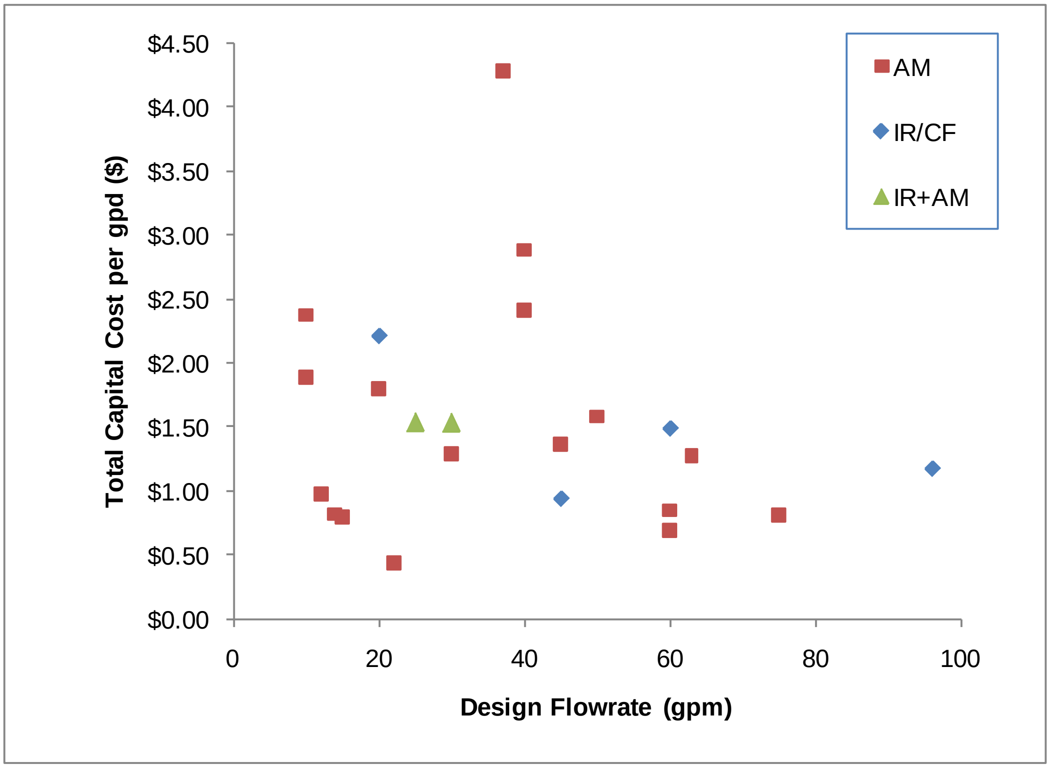


Figure 5-3. Total Capital Investment Costs per gpd of Design Capacity (<100 gpm)

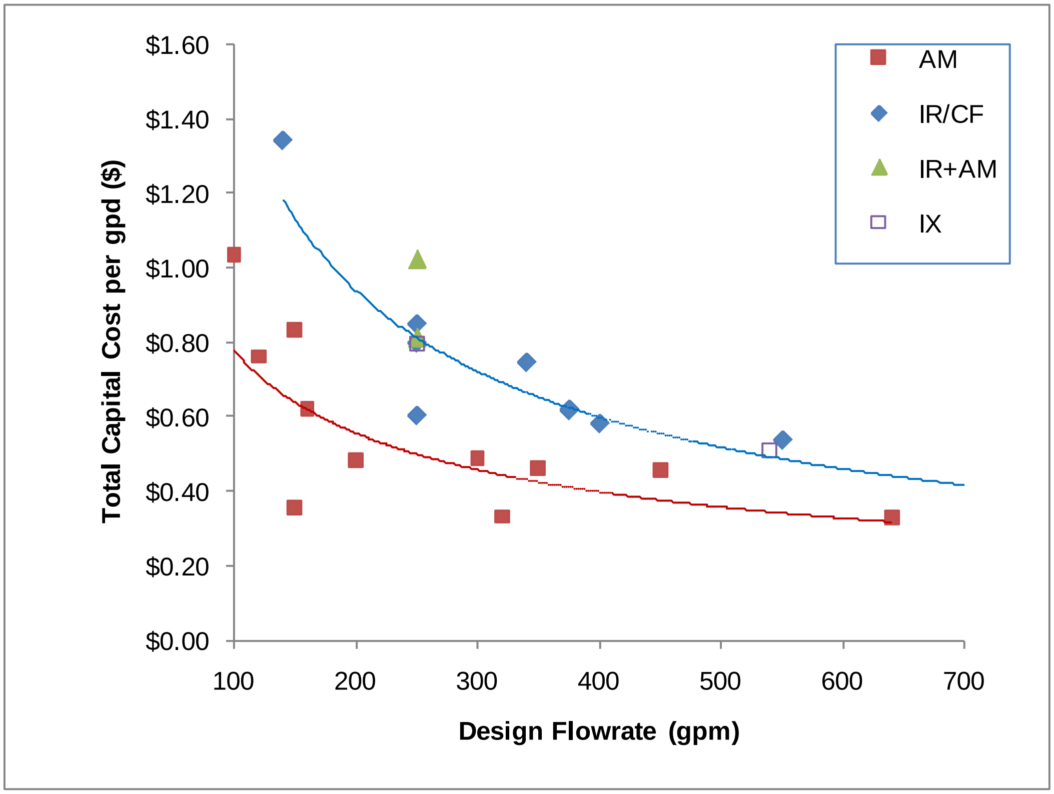


Figure 5-4. Total Capital Investment Cost per gpd of Design Capacity (≥100 gpm)

Equipment, site engineering, and installation and startup costs are plotted as a percentage of the respective total capital investment cost in Figure 5-5 through 5-7. In general, equipment costs accounted for higher percentages of total capital investment costs for larger systems than for smaller systems. For example, larger AM and IR/CF system equipment costs accounted for 72% and 64% (on average) of respective total capital investment costs, whereas smaller system equipment costs accounted for 65% and 55% of respective total capital investment costs. Regardless of system sizes, AM system equipment costs accounted for higher percentages of total cost than IR/CF system equipment costs.

Site engineering and installation/startup costs were primarily labor costs. Smaller system site engineering costs accounted for, on average, 16% and 18% of total capital investment costs for AM and IR/CF, respectively. These percentage points were higher than the 12% found for larger systems for all three technology types. Installation and startup costs of IR/CF and IX accounted for higher percentage points than those of AM, regardless of system sizes. For example, IR/CF system installation/startup costs accounted for 26% (for smaller systems) and 24% (for larger systems) of total capital investment costs, whereas AM system installation/startup costs accounted for only 19% and 16% for smaller and larger AM systems, respectively. The data suggest that the AM systems took less time and were easier to install than the IR/CF systems. The IR/CF systems frequently include contact tanks, iron addition systems, and ancillary equipment and controls that require more efforts to install and be field-tested and adjusted. The same vendor who provided seven of the 12 larger IR/CF systems also might be a factor for the higher costs observed. Because the larger IR/CF systems had higher total capital investment costs than the AM systems, the higher percentages of the installation/startup costs also indicated higher costs.

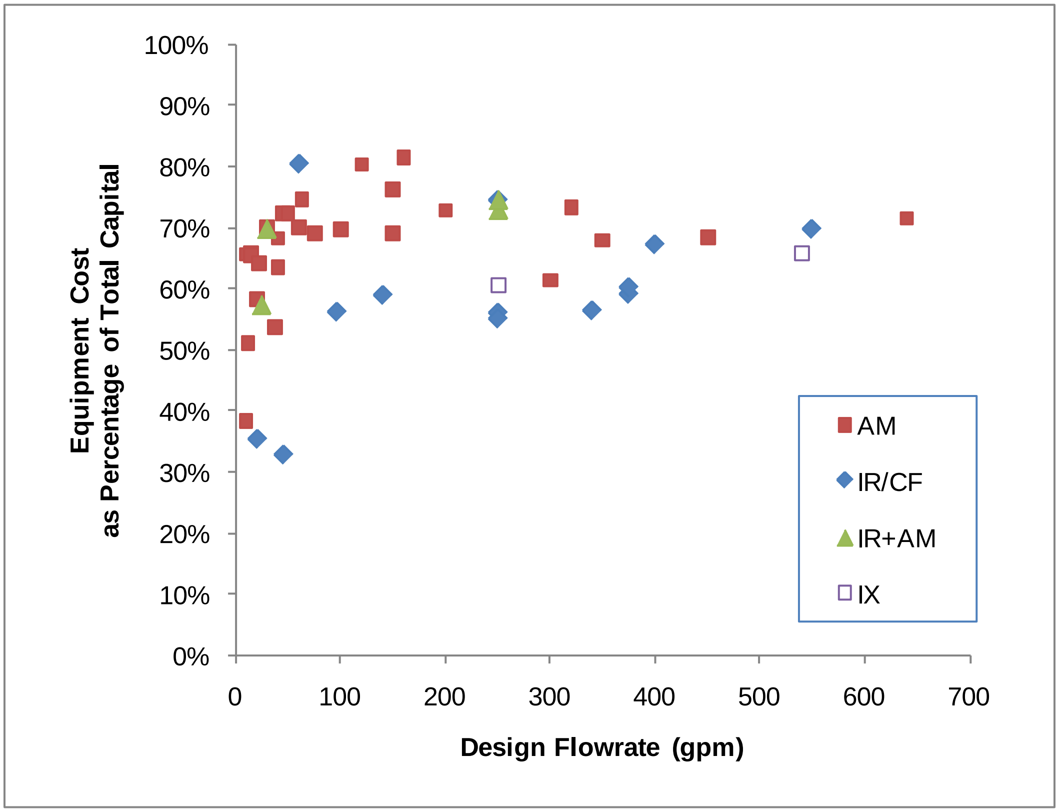


Figure 5-5. Equipment Costs as a Percentage of Total Capital Investment Costs

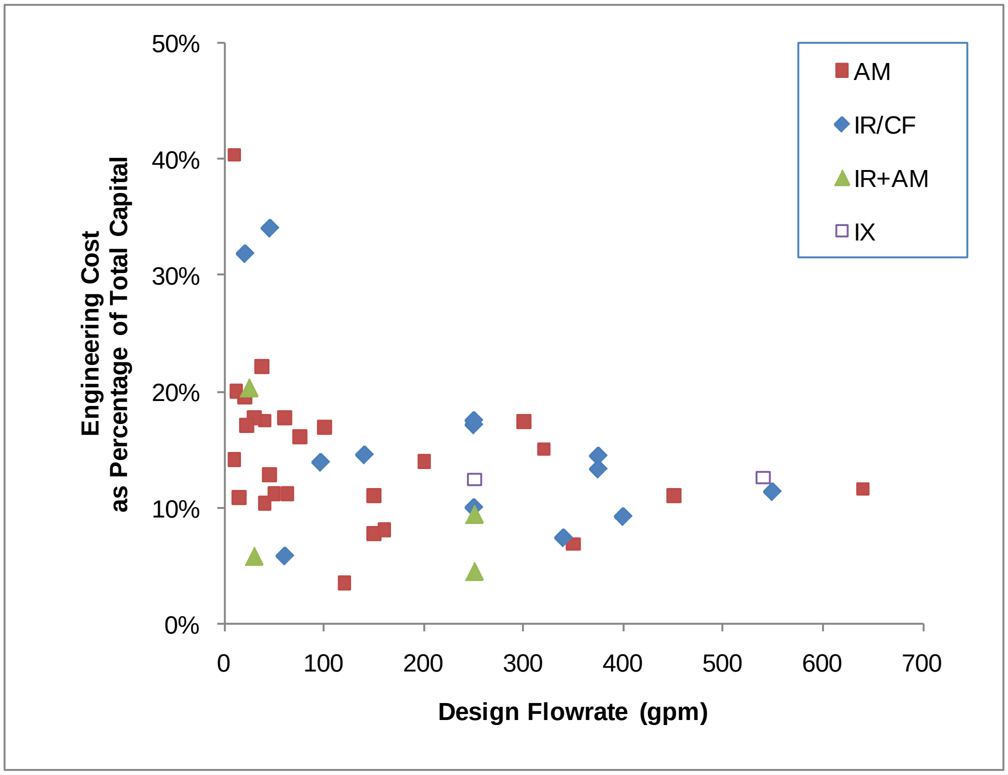


Figure 5-6. Engineering Costs as a Percentage of Total Capital Investment Costs

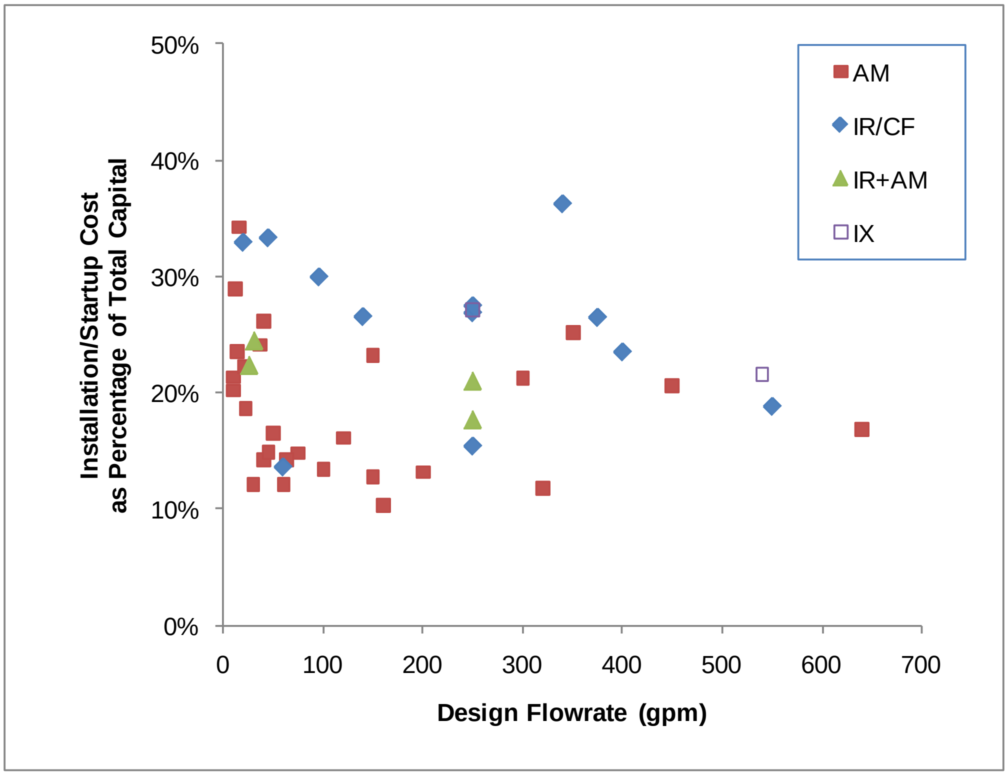


Figure 5-7. Installation/Startup Costs as a Percentage of Total Capital Investment Costs

5.2 O&M Cost of Treatment Technologies

Table 5-2 summarizes the O&M costs associated with AM, IR/CF, and IX along with cost breakdowns. The cost data also are plotted in Figures 5-8 and 5-9 for smaller (<100 gpm) and larger (≥100 gpm) systems, respectively. The four IR/AM systems were plotted separately on these figures, but were considered as IR systems in the cost analysis in Table 5-2 because media replacement did not occur during the study period.

Table 5-2. Summary of O&M Costs

Treatment Technology	No. of Systems	Range/ Average	Design Flow rate (gpm)	Total O&M Costs	Media Replacement Cost	Chemical Cost	Electricity Cost	Labor Cost
				($/1,000 gal of Water Treated)				
Systems with < 100 gpm Design Flowrates								
AM	14(a)	Range	10–75	0.86–22.88	0.58–22.05	0.00–0.61	0.00–0.16	0.03–3.1
		Average		6.47	5.58	0.08	0.03	0.78
IR/CF	6(b)	Range	20–96	0.26–2.90	NA	0.00–0.37	0.00–0.39	0.11–2.57
		Average		1.39	NA	0.14	0.10	1.15
Systems with ≥ 100 gpm Design Flowrates								
AM	5	Range	150–350	0.61–5.69	0.3-5.51	0.00–0.03	0.00–0.05	0.05–0.25
		Average		1.76	1.57	0.01	0.01	0.17
IR/CF	12(b)	Range	140–770	0.07–0.55	NA	0.00–0.17	0.00–0.16	0.04–0.52
		Average		0.28	NA	0.04	0.05	0.19
IX	2	Range	250–540	0.35–0.62	NA	0.29–0.49	0.03–0.08	0.03–0.05
		Average		0.49	NA	0.39	0.06	0.04

(a) Two systems experienced multiple media change-outs.
(b) Including two AM systems with IR pretreatment.
NA = not applicable

The data in Table 5-2 and Figures 5-8 and 5-9 indicate that the AM systems had higher O&M costs than the IR/CF and IX systems, regardless of system sizes. The higher costs observed were attributed primarily to media replacement costs, which accounted for 86% and 89% of total O&M costs for the smaller and larger systems, respectively, based on the average values presented in Table 5-2. Media replacement costs were affected by the media performance and media unit prices as discussed in Section 2.5.1. For the four E33 systems achieving a media life of 38,000 BV and higher, media replacement costs ranged from $0.30 to $0.66 per 1,000 gal of water treated and the total O&M costs ranged from $0.61 to $0.86 per 1,000 gal of water treated. Methods to extend the media life through caustic regeneration have shown promises to reduce the O&M cost of E33 systems (Chen and Wang, 2008; 2009; Sorg et al., 2010).

The O&M costs for the IR/CF and IX systems reported in this study did not include treatment and/or disposal costs of residuals generated such as backwash wastewater and spent brine/rinse water. Residual disposal costs could be a significant part of the O&M costs and play an important role in the technology selection.

Chemical cost was a major O&M cost for the IX process that used salt for resin regeneration. Chemical costs associated with pH control for AM, iron salts for IR/CF, and/or pre-oxidation of raw water for AM and IR/CF was insignificant.

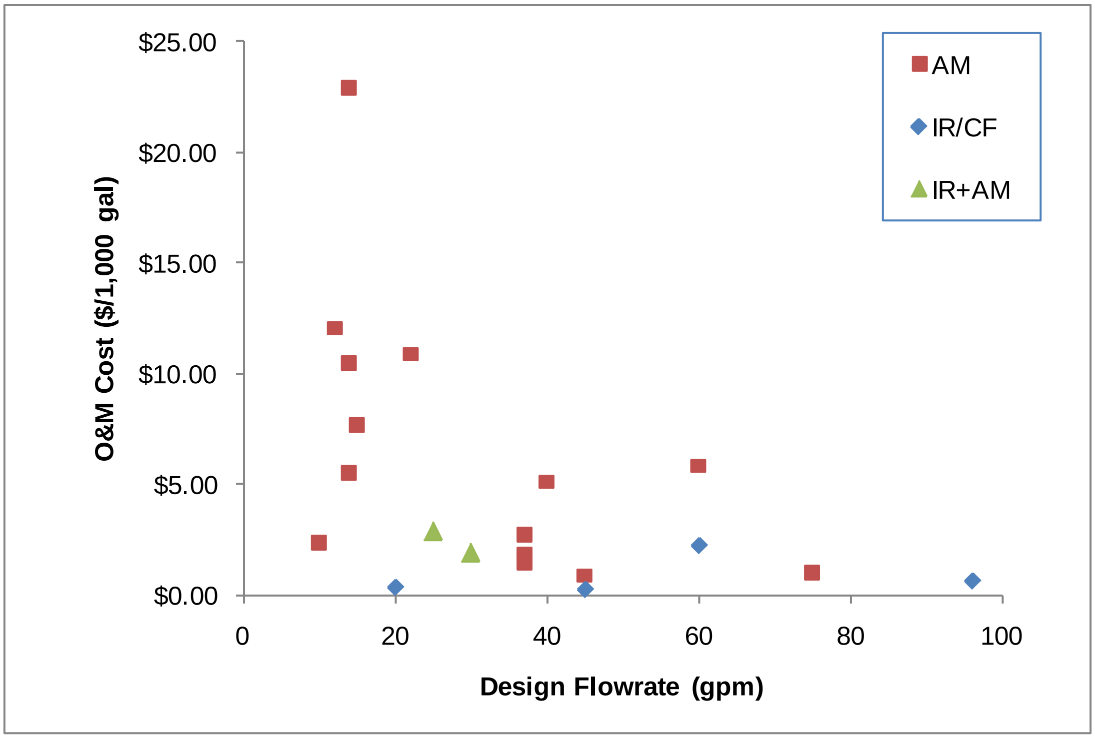


Figure 5-8. Smaller System (<100 gpm) Total O&M Costs per 1,000 gal of Water Treated

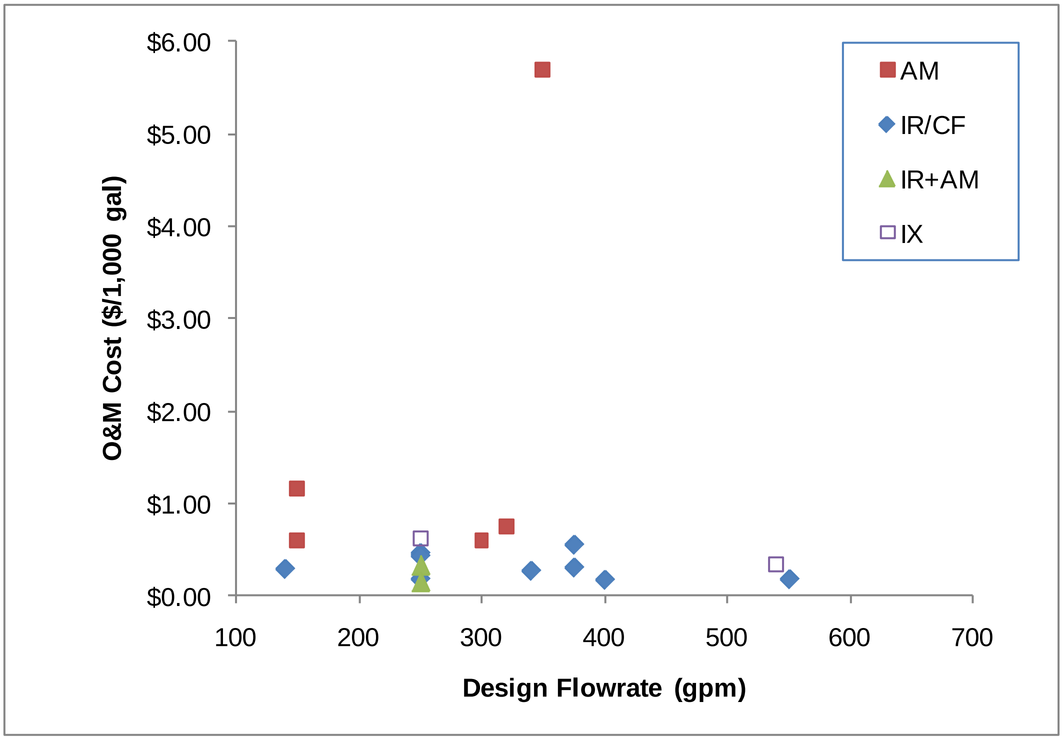


Figure 5-9. Larger System (≥100 gpm) Total O&M Costs per 1,000 gal of Water Treated

Incremental electricity cost was insignificant for AM, IR/CF, and IX technologies because these technologies did not require electricity to push water through treatment systems like membrane technologies. Electricity was consumed to overcome any headloss across treatment vessels and to power system controls and/or chemical feed pumps.

It was difficult to quantify and compare labor cost among different technologies because labor rates varied geographically and labor hours were subject to specific circumstances at different sites. Average labor rates were similar for all three technologies, i.e., \$22.4/hr for AM (Section 2.4.4), \$22.6/hr for IR/CF (Section 3.5.3), and \$21/hr for IX (Section 4.2.3). These labor rates might be lower than those in certain regions of the country, such as California. Average weekly labor hours required to operate and maintain the treatment systems were 1.8 hr for AM (Section 2.4.4), 3.4 hr for IR/CF (Section 3.5.3), and 2.5 hr for IX (Section 4.2.3). The data supported the general notion that an AM system was easier to operate and maintain compared to an IR/CF and an IX system. As shown in Table 5-2, average labor costs per 1,000 gal of water treated were \$0.78 and \$1.15 for smaller AM and IR/CF systems, respectively, and \$0.17, \$0.19, and \$0.04 for larger AM, IR/CF, and IX systems respectively. The higher labor costs for smaller systems were attributed to the lower water production rates associated with smaller systems.

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