The background of the page features a large, semi-transparent watermark of the United States Environmental Protection Agency (EPA) logo. The logo consists of a circular emblem with a stylized flower or sunburst in the center, surrounded by the words "UNITED STATES ENVIRONMENTAL PROTECTION AGENCY". Overlaid on this background is a close-up photograph of a water tap with water being poured into a clear glass filled with ice cubes. The water is captured in motion, creating a dynamic and refreshing visual.

# Treatment Technologies for Arsenic Removal

On January 18, 2001, the United States Environmental Protection Agency (EPA) finalized the maximum contaminant level (MCL) for arsenic at 0.01 mg/L. The EPA subsequently revised the rule text to express the MCL as 0.010 mg/L (10 µg/L). The final rule requires all community and non-transient, non-community water systems to comply with the new standard by February 2006. Motivation to reduce the arsenic MCL was driven by the findings of health effects research. Over the past several years, numerous toxicological and epidemiological studies have been conducted to ascertain the health risks associated with low-level exposure to arsenic ingestion.

Fundamental knowledge of arsenic chemistry and processes is important when a community is either looking to install a new treatment system or modify an old system to comply with the new arsenic rule. The purpose of this booklet is to provide engineering firms, utilities, and communities with information about treatment technologies for arsenic removal and design considerations for choosing treatment technologies.

Any opinions expressed in this document are those of the author(s) and do not, necessarily, reflect the official positions and policies of the EPA. Any mention of products or trade names does not constitute recommendation for use by the EPA.

# Importance of Arsenic

The EPA has classified arsenic as a Class A human carcinogen. Ingestion of inorganic arsenic can result in both cancer and non-cancer health effects (NRC, 1999). Chronic exposure to low arsenic levels (less than 0.050 mg/L) has been linked to health complications, including cancer of the skin, kidney, lung, and bladder, as well as skin diseases and neurological and cardiovascular system conditions (US EPA, 2000). Common sources of contamination include the erosion of natural deposits, pesticide runoff from orchards, and runoff from glass & electronics production wastes.

Based on the aforementioned research, the US EPA recently reduced the arsenic maximum contaminant level (MCL) from 0.050 mg/L to 0.010 mg/L (10 µg/L). Over 4,000 water systems are expected to be in violation of the revised MCL for arsenic.

## Best Available Treatments for Arsenic Removal

The EPA reviewed potential best available technologies (BATs) as candidates for arsenic removal, and in 2001 published a list of the determined BATs and their removal rates (US EPA, 2001). However, before summarizing those BATs, it is important to draw attention to certain system processes that can optimize arsenic removal: pre-oxidation and pH adjustment.

**Pre-Oxidation.** In water, arsenic typically occurs in one of two inorganic forms: the pentavalent arsenate, As(V), and the trivalent arsenite, As(III). In the pH range of 4 to 10, As(V) species are negatively charged, and the predominant As(III) compound is neutral in charge. Removal efficiency for As(V) is much better than removal for As(III). Therefore, in most cases, reduced inorganic As(III) should be converted to As(V) to facilitate removal. This step is often necessary to achieve optimal performance of the unit processes described below. Chlorine, permanganate, ozone, and manganese dioxide media are effective oxidizing agents for this process. Aeration (i.e. oxygen) is not an effective method for oxidizing As(III).

In addition, research has shown the point of oxidant application influences removal optimization. For instance, arsenic removal is also optimized, in the case of iron removal, when iron and arsenic are oxidized at the same time.

**pH Adjustment.** Removal performance for many media products is pH dependent. Therefore,

it is sometimes necessary to make adjustments to pH in order to optimize arsenic removal. Certain technologies are more impacted than others, particularly iron-based treatment technologies that have a higher removal capacity at a lower pH (<8).



The selection of the most appropriate treatment technology should be based on water quality, disposal options for residuals, and costs, which will be discussed in subsequent sections. An overview of various treatment processes and technologies is included below as well as the hazardous\* and non-hazardous residual waste (R).

**Ion Exchange.** Ion exchange is a physical-chemical ion exchange process in which ions are exchanged between a solution phase and solid resin phase. Ionizable groups are exchanged for ions of similar charge in solution that have a stronger exchange affinity (i.e. selectivity) for the resin. In drinking water treatment, this technology is commonly used for household water softening (cation exchange) and nitrate removal (anion exchange). It is important to note that ion exchange is not effective for As(III) removal.

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\* California defines a waste as hazardous if the total concentration of arsenic in the waste water is greater than 500 mg/kg, as per the Total Threshold Limit Concentration (TTLC).

**R** Liquid. The liquid residual consists of a composite of backwash water, regenerant solution (brine), and rinse water. The liquid waste water will likely contain high levels of arsenic that render it a hazardous waste that must be treated before disposal or sent to a sanitary sewer.

**Activated Alumina (AA).** Activated alumina is a sorption process that uses porous, granular material with ion exchange properties. In drinking water treatment, packed-bed AA adsorption is commonly used for removal of natural organic matter and fluoride. The removal of As(V) by adsorption can be accomplished by continuously passing water under pressure through one or more beds. AA media can either be regenerated or disposed and replaced with fresh media. The efficiency and economics of the system are contingent upon several factors: pre-oxidation of As (III) to As(V), constituent(s) interference with the adsorption process, and the need for pH adjustment to <6.5.

**R** Regenerated system - liquid. Liquid residual consists of a composite of backwash water, caustic regenerant solution, neutralization (low pH) water, and rinse water. The liquid waste water will likely contain high levels of arsenic that render it a hazardous waste that must be treated before disposal or sent to a sanitary sewer.

Throw-a-way media system - solid. The spent solid media contains arsenic and other constituents removed from the source water. Exhausted media will likely pass the Toxic Characteristic Leaching Procedure (TCLP) test and be classified as non-hazardous.

**Reverse Osmosis (RO).** Membrane separation technologies are attractive arsenic treatment processes for small water systems. They can address numerous water quality problems while maintaining simplicity and ease of operation. RO is a pressure-driven membrane separation process capable of removing arsenic from water by means of particle size, dielectric characteristics, and hydrophilicity/hydrophobicity. RO also effectively removes other constituents from water, including organic carbon, salts, dissolved minerals, and color. This treatment process is relatively insensitive to pH, although pH adjustment may be required to protect the membrane from fouling.

**R** Liquid. Liquid residual consists of membrane reject water, generally high in total dissolved solids. The liquid waste water likely contains high levels of arsenic and other constituents rejected from the source's water that render it a hazardous waste that must be treated before disposal or sent to a sanitary sewer.

**Enhanced Lime Softening.** Lime softening is a precipitative process commonly used to remove calcium and magnesium cations from solution. To remove arsenic, lime is added to increase the pH above 10.5 to form magnesium hydroxide. In this pH range, magnesium hydroxide and As(V) is removed by co-precipitation. Current lime softening treatment processes can be enhanced for arsenic removal.

**R** Sludge. The semi-liquid residual consists of sludge from the settling basin and filter backwash water. The residual will contain the arsenic and other constituents removed by the lime softening process and could be a hazardous waste that must be treated before disposal or sent to a sanitary sewer.

## References

National Research Council (NRC), 1999. Arsenic in Drinking Water. Washington, DC. National Academy Press.

US EPA, 2000. Technologies and Costs for Removal of Arsenic from Drinking Water, EPA 815R00028, Prepared by Malcolm Pirnie, Inc. under contract 68C60039 for EPA ORD, December 2000.

US EPA, 2001. National Primary Drinking Water Regulations; Arsenic and Clarifications to Compliance and New Source Contaminants Monitoring; Final Rule. Federal Register. Vol. 66. No. 14. January 22, 2001. Page 6981.



VALLEY VISTA (AZ) DEMO SITE - KINETICO ACTIVATED ALUMINA



## Enhanced Coagulation/Filtration.

Coagulation/filtration is a precipitative process. This process can be optimized to remove dissolved inorganic As(V) from water. The mechanism involves adsorption and co-precipitation of As(V) to an aluminum or ferric hydroxide precipitate. As(III) is not effectively removed because of its overall neutral charge under natural pH. Because As(III) is more difficult to remove than As(V), pre-oxidation is typically necessary. The efficiency and economics of the system are contingent upon several factors, including the type and dosage of coagulant, mixing intensity, and pH. Optimized coagulation-filtration systems are capable of achieving over 90% removal of As(V). Although both aluminum and iron coagulants can remove arsenic, iron coagulants (ferric chloride or ferric sulfate) are more effective.

- R** Sludge. The semi-liquid residual consists of the sludge from the settling basin and the filter backwash water. The residual will contain the arsenic and other constituents removed by the coagulation process and could be a hazardous waste that must be treated before disposal or sent to a sanitary sewer. The solids will likely pass the TCLP tests.



WHITE ROCK WATER CO. (BOW, NH) DEMO SITE - ADI IRON ADSORPTION MEDIA SYSTEM

## Oxidation/Filtration (Iron Removal).

Oxidation/filtration refers to precipitative processes that are designed to remove naturally occurring iron and manganese from water. Most systems include a contact basin. The process involves the oxidation of the soluble forms of iron and manganese to their insoluble forms that are then removed by filtration. Arsenic can be removed via two primary mechanisms: adsorption and

coprecipitation. First, soluble iron and As(III) are oxidized. The As(V) then adsorbs onto the iron hydroxide precipitates that are ultimately filtered out of solution. The arsenic removal efficiency is strongly dependent on the initial iron and arsenic concentrations. In general, the Fe:As mass ratio should be at least 20:1, which assumes 1 mg/Fe removes 50 µg/As. These conditions customarily result in an arsenic removal efficiency of 80-90%. Arsenic removals decrease with increasing pH. In addition, high levels of natural organic matter (NOM), orthophosphates, and silicates weaken arsenic removal efficiency by competing for sorption sites on iron hydroxide precipitates.

- R** Sludge. The semi-liquid residual consists of the sludge from the settling basin and the filter backwash water. The residual will contain the arsenic and other constituents removed by the coagulation process and could be a hazardous waste that must be treated before disposal or sent to a sanitary sewer. The solids will likely pass the TCLP tests.

## Non-Treatment Options

Problematic arsenic levels in drinking water can also be mitigated by using non-treatment options, including blending, connecting to a neighboring water source, and drilling a new well. These options are defined briefly below.

### Blending

Combine multiple water sources (e.g. wells) to produce a water stream with an arsenic concentration below the MCL.

### Connecting to a neighboring water source\*

Purchase water that is below the MCL from a nearby system if an interconnection exists.

### Drilling a new well\*

Abandon old well, and locate and install a new source. Drilling a new source may not be the best option if the aquifer has consistently high levels of arsenic.

\* New source installations may or may not be more costly than treatment. Assessments must be made on a case by case basis.

## Other Available Technologies for Arsenic Removal

Although not originally accepted as best available technologies (BATs) under the new rule, research and pilot testing have increased the acceptance of these technologies as effective methods for removing arsenic.

**Alternative Adsorption Media.** There are currently several adsorption media available: titanium based media, zirconium based media, and iron based media. Adsorption on Iron Based Sorbents (IBS) is an emerging treatment for arsenic. Studies have shown that this media has a strong affinity for arsenic under natural pH conditions, relative to activated Alumina. This feature allows IBS to treat much higher bed volumes without the need for pH adjustment, unless the pH is >8.

- R** Regenerated system - liquid. Liquid residual consists of a composite of backwash water, caustic regenerant solution, and rinse water. The liquid waste water will likely contain high levels of arsenic that render it a hazardous waste that must be treated before disposal or sent to a sanitary sewer.

Throw-a-way media system - solid. Spent solid media contains arsenic and other constituents removed from the source water. Media will likely pass the TCLP test and be classified as non-hazardous.

Throw-a-way system - liquid. Liquid residual consists of the media backwash water that is usually low in arsenic.

**Coagulation-Assisted Micro-Filtration.** Coagulation-assisted micro-filtration (CMF) uses the same precipitative process described for oxidation/filtration. The use of pre-engineered CMF package plants is a realistic possibility for new installations where water quality precludes the use of sorption treatment. The filter membrane retains the As(V) laden floc formed in the coagulation step and must be periodically backwashed to dislodge solids and restore hydraulic capacity. Backwash water is typically a high-volume, low solids (less than 1.0%) waste stream. The specific amount of solids will depend on several factors, including coagulant type, dosage, filter run length, and ambient solids concentration.

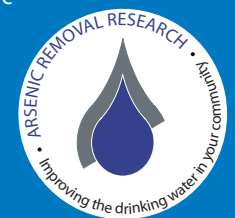
- R** Sludge. A semi-liquid residual consists of the membrane-filtered liquid waste. The residual will contain the arsenic and other constituents removed by the coagulation process and could be a hazardous waste that must be treated before disposal or sent to a sanitary sewer. The solids will likely pass the TCLP tests.

**Point-Of-Use (POU) Treatment.** POU devices can be used to treat arsenic; however, the Safe Drinking Water Act requires that devices be owned, controlled, and maintained by the public water utility or by an agency under contract with the water utility. POU devices are particularly attractive for removing contaminants that pose only an ingestion risk, e.g. arsenic. The primary advantage of using POU treatment in a small system is the potential for reduced capital and treatment costs, relative to centralized treatment, making it a more economically viable alternative for smaller systems. However, not all states accept this treatment process as a suitable method for removing arsenic. Systems interested in POU treatment should first check with their state regarding its acceptance as a small system compliance technology.

### Treatment Technology Training Workshops

Both the Water Supply and Water Resource Division (WSWRD) of the National Risk Management Research Laboratory (NRMRL) and the Office of Ground Water and Drinking Water (OGWDW) sponsor treatment technology training workshops. These workshops focus on training geared toward state drinking water staff, design engineers, systems owners, and certified operators and provide participants with in-depth training on the technologies for removing arsenic from drinking water.

For more information about past and future workshops, visit [www.epa.gov/ORD/NRMRL/arsenic](http://www.epa.gov/ORD/NRMRL/arsenic) or [www.epa.gov/OGWDW/arsenic](http://www.epa.gov/OGWDW/arsenic)



# Treatment Technology Selection Considerations

Nearly 97 percent of the water systems affected by the revised rule are small systems that serve less than 10,000 people each. In October 2001, EPA announced an initiative for additional research and development of cost-effective technologies to help small community water systems (<10,000 customers) meet the new arsenic standard and to provide technical assistance to operators of small systems in order to reduce compliance costs. The main considerations when selecting a treatment technology include water quality attributes (including pH levels and initial concentrations of iron, As(III), and As(V) present in the water), ease of implementation with current system, residual management, and cost. The information that follows provides a simplified overview of the considerations that should be made when selecting a treatment technology.

**Water Quality Considerations.** Arsenic occurs in natural waters in both inorganic and organic forms. However, inorganic forms such as arsenite [As(III)] and arsenate [As(V)] are predominant in natural waters. The valence and species of inorganic arsenic are dependent on the oxidation-reduction conditions and the pH of the water. Studies have shown that As(V) is more effectively removed from source waters than As(III) by iron coagulants, by precipitation of natural iron, and by adsorptive media. In addition, As(III) is not removed by anion exchange resins because of its uncharged nature. Consequently, if the arsenic in the source water is predominately As(III), then **oxidizing As(III) to As(V)** will result in a higher arsenic removal efficiency. In summary, research has shown that arsenic removal capacity is improved when (1) As(III) is converted to As(V) using a strong oxidant and (2) increasing levels of iron concentration are present.

The **concentration of iron** in source water can be one of the main drivers in technology selection, as it is often less expensive than other arsenic removal technologies. Therefore, given various regional water quality parameters, the presence of iron will likely play a prominent role in technology selection and the treatability of a given water source. Many of the most effective arsenic removal processes available are iron-based treatment technologies such as

chemical coagulation/filtration with iron salts and adsorptive media with iron-based products. These processes are particularly effective at removing arsenic from aqueous systems because iron surfaces have a strong affinity to adsorb arsenic. Because of the unique role that iron plays in facilitating arsenic removal, the level of iron in the source water is a primary consideration in the selection of an optimal treatment technology. Below is a more detailed description of the range of iron concentrations relative to arsenic concentrations and how the Fe:As ratio could influence the treatment technology chosen (see Figure 1).

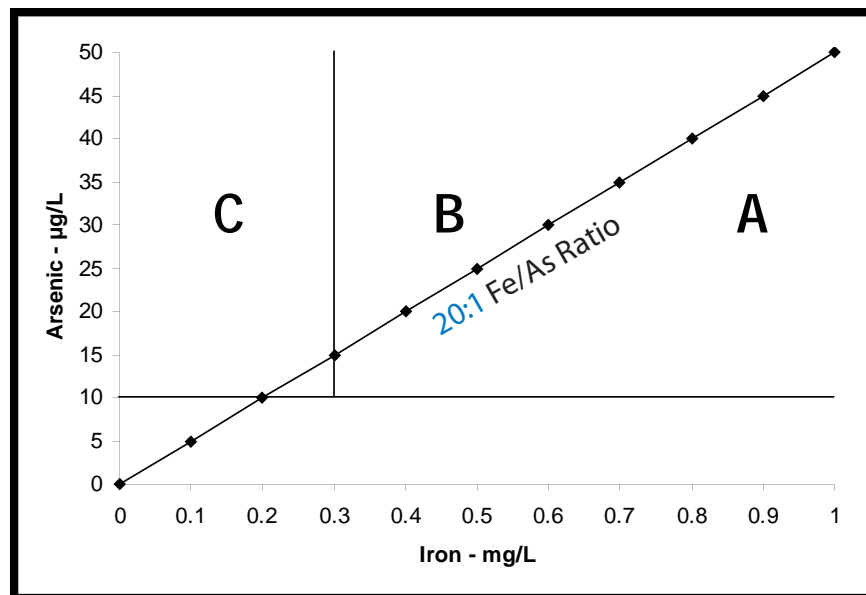
- **HIGH iron levels (> 0.3 mg/L). HIGH Fe:As ratio (>20:1).** Iron removal processes can be used to promote arsenic removal from drinking water via adsorption and co-precipitation. Source waters with this ratio are potential candidates for arsenic removal by iron removal. **(A)**
- **MODERATE iron levels (> 0.3 mg/L). LOW Fe:As ratio (< 20:1).** If the iron to arsenic ratio in the source water is less than 20:1, then a modified treatment process such as coagulation/filtration with the addition of iron salts should be considered. **(B)**
- **LOW iron levels (< 0.3 mg/L).** Technologies such as adsorptive media, coagulation/filtration, and ion exchange are best suited for sites with relatively low iron levels in their source waters at less than 300 µg/L, the secondary MCL for iron. **(C)**

This guidance is further illustrated in Figure 1, which provides selection of an optimal treatment technology based on initial concentrations of iron and arsenic in the source water. This process selection guide is very basic, and the removal capacities depicted are meant to be used as a general “rule of thumb.” These removal capacities will only be achieved under optimum adsorptive and process operational conditions with As(V).

The **adjustment of pH** is sometimes required to increase the arsenic removal capacity of adsorptive media in terms of the percent of As(III) versus As(V) removed. In general, a pH of

FIGURE 1.

Arsenic treatment - basic process selection guide.



less than 7.0 is optimal (but pH 7-8 is acceptable) for iron-based media adsorption, and a pH of 5.5 is optimal for alumina-based media adsorption. The pH range for arsenic removal with iron oxides via coagulation/filtration related processes is 5.5 to 8. As(V) removal by ion exchange is not significantly impacted by changes in pH.

**Treatment Process and Residuals Management.** The task of navigating through the alternative arsenic treatment technologies involves several technical considerations as well. Some unit processes are more economically viable under specific circumstances than others. Optimizing arsenic removal using existing processes is an ideal option for some utilities. Water systems can get a general idea of the treatment technology that would work best for their systems based on the concentrations of arsenic and iron in the water, as illustrated in Figure 1. As with other treatment processes, arsenic treatment systems produce a residual for disposal. Arsenic discharge options may be limited. Handling and disposal methods must be considered prior to selecting a technology. For instance, some liquid waste residuals are high in arsenic and are usually hazardous and need to either be treated on-site or taken to a disposal facility. However, most solid wastes associated with spent media are not hazardous and can be disposed of in landfills. State regulations vary from state to state for the discharge of residuals

to water bodies and onto land. It is important to be aware of not only the federal regulatory requirements regarding residuals management, but also applicable state requirements in order to better evaluate compliance of existing practices and to plan for needed changes in treatment plant operations.

**Testing and Monitoring.** Piloting the potential mitigation strategies is a normal procedure to optimize treatment variables and avoid implementing a strategy that may not work for unforeseen reasons. Pilot testing for adsorptive media and other treatment options, however, is a very time-intensive and expensive process. For many small systems, piloting may be performed by the vendor. Piloting, particularly with the adsorptive media selected, might be required by the state. Lab and jar tests can also be used to monitor system performance for iron removal and coagulation.

**Capital and Operating Costs.** The EPA has published several documents on the capital costs of implementing a treatment system, which include discussions of equipment, engineering, installation, operation and maintenance, and replacement media costs. These costs should certainly be considered before selecting a treatment system. (See page 10.)

# Arsenic Treatment Research Demonstration Program

The EPA is conducting full-scale demonstration studies on arsenic removal technologies. Site visits are encouraged and welcomed to help utilities with treatment selection. (Demonstration site locations and their respective treatment technologies, water quality measures, and system flow are included in Figure 2 and Table 1.) The purpose of these demonstration studies is (1) to evaluate the efficiency and effectiveness of the systems and (2) to determine the cost-effectiveness of the treatment technologies.

For additional information about each site (including costs for equipment, site engineering, installation, operation, and maintenance) visit our website at [www.epa.gov/ORD/NRMRL/arsenic](http://www.epa.gov/ORD/NRMRL/arsenic) or schedule a visit to a demonstration site near you.

FIGURE 2.

Map depicting the locations of the 2003 (Round 1) and 2004 (Round 2) demonstration sites across the country.

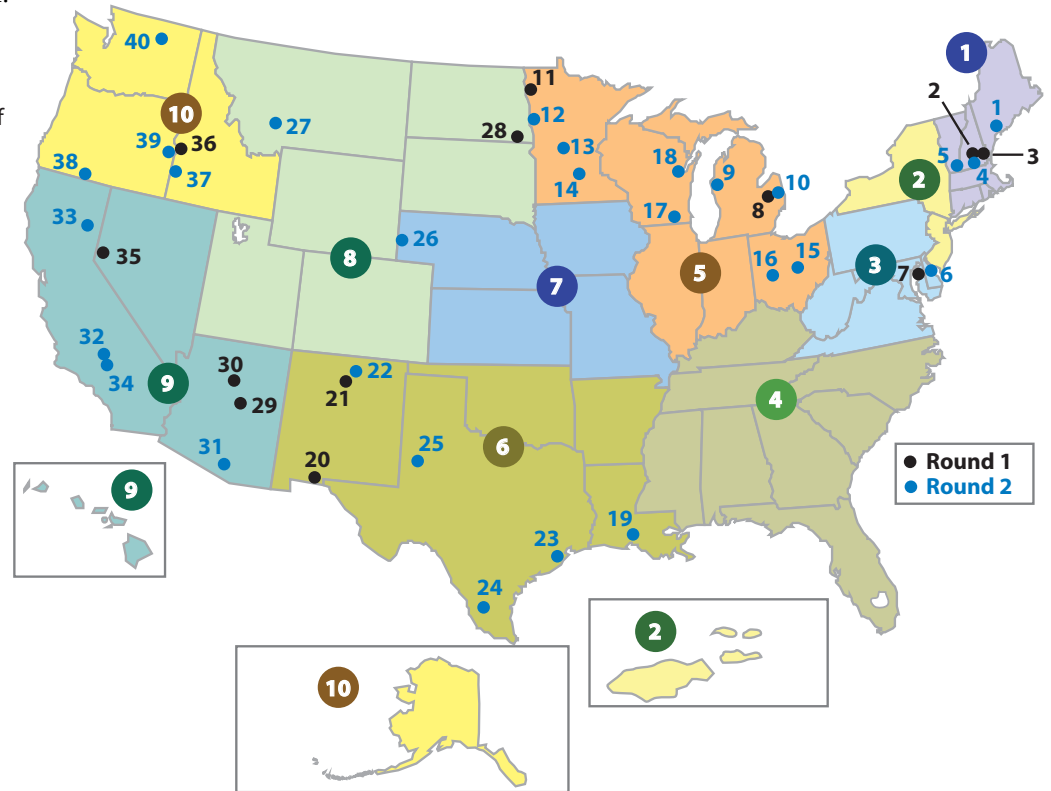


TABLE 1. Key data on arsenic treatment demonstration sites.

Demo Site	Technology Demonstrated	Water Quality				Size (flow)
		As (µg/L)	Fe (mg/L)	Mn (µg/L)	pH	
1 Spring Brook Wales, ME	ATS/A/I Complex2000	37.7	<.025	0.0	8.6	14
2 White Rock Water Co. Bow, NH	ADI/G2	29.26	0.118	0.1	7.3	70
3 Water & Sewer District Rollinsford, NH	AdEdge/AD33	36.2	<.030	0.1	7.4	100
4 Orchard Highland Goffstown, NH	AdEdge/AD33	32.7	<.025	<0.03	6.9	20
5 Dummerston, VT	ATS/A/I Complex2000	30.0	<.025	ND	7.9	7
6 Felton, DE	Kinetico/Macrolite	30.0	0.048	<0.02	8.2	375
7 Queen Anne’s County, MD	Severn Trent/Sorb33	18.8	0.270	0.0	7.3	300



TABLE 1 (CONT'D). Key data on arsenic treatment demonstration sites.

	Demo Site	Technology Demonstrated	Water Quality				Size (flow)
			As (µg/L)	Fe (mg/L)	Mn (µg/L)	pH	
8	Brown City, MI	Severn Trent/Sorb33	14.2	0.127	NA	7.3	640
9	Pentwater, MI	Kinetico/Macrolite	13.4	0.466	NA	6.9	400
10	Sandusky, MI	US Filter/Aeralater	15.8	1.387	0.0	6.9/7.2	210
11	Climax, MN	Kinetico/Macrolite	38.7	0.546	0.1	7.4	140
12	Sabin, MN	Kinetico/Macrolite	13.9	0.854	0.3	7.3	250
13	Trailer Park Sauk Centre, MN	Kinetico/Macrolite	25.0	3.078	0.1	7.1	20
14	Stewart, MN	AdEdge/AD33	42.0	1.344	0.0	7.7	250
15	Buckeye Lake HS Newark, OH	Kinetico/ARM200	17.4	2.477	<0.01	7.6	8
16	Chateau Estates Springfield, OH	AdEdge/AD33	24.6	1.615	0.0	7.3	150
17	Village of the Pond Delavan, WI	Kinetico/Macrolite	20.1	1.499	NA	7.5	50
18	Greenville, WI	Kinetico/Macrolite	34.0	14.518	0.0	7.3	350
19	United Water Systems Arnaudville, LA	Kinetico/Macrolite	33.6/35.9	.214/.199	0.11/0.10	7.0/7.0	292/292
20	Desert Sands MDWCA, NM	US Filter/GFH	26.1	0.045	9.1	7.8	250
21	Nambe Pueblo, NM	AdEdge/AD33	33.2	<.030	0.05	8.5	145
22	Taos, NM	STS/Sorb33	14.1	0.059	<0.01	9.5	400
23	Oak Manor MUD Alvin, TX	Severn Trent/Sorb33	18.8	0.095	0.1	7.8	212
24	Webb Con Schools Bruni, TX	AdEdge/AD33	55.6	<.025	0.008	8.0	100
25	Wellman, TX	AdEdge/AD33	62.0/45.4	.019/.004	0.006	8.2/7.7	NA
26	Lyman, NE	Kinetico/MetSorb	20.1	<.025	0.19	7.5	400
27	Three Forks, MT	Kinetico/Macrolite	64.3	<.025	NA	7.5	(250)
28	Lidgerwood, ND	Kinetico/Treatment Modification	146.2	1.325	0.544	7.2	250
29	Rimrock, AZ	AdEdge/AD33	50	0.170	ND	7.2	90
30	Valley Vista, AZ	Kinetico/AASF50	40.96	<.030	ND	7.7	37
31	Tohono O'odham Nation, AZ	AdEdge/AD33	33.1	<.025	0.004	8.2	100
32	California Water Service Co. Lake Isabella, CA	VEETech/HIX	35.4	<.025	0.0	6.4	(38)
33	Richmond School District Susanville, CA	ATS/A/I Compex 2000	36.7	0.125	<0.02	7.5	(7.3)
34	Goldenhills Service District Tehachapi, CA	MEI/Zirconium-based media	14.7	<.025	<0.01	6.9	100
35	STMGID Reno, NV	US Filter/GFH	87.9	<.030	0.0	7.4	350
36	Fruitland, ID	Kinetico/IX	43.5	<.030	0.1	7.4	250
37	Sunset Ranch Homedale, ID	Kinetico/POU	NA	NA	ND	NA	NA
38	Oregon Institute of Technology Klamath Falls, OR	Kinetico/POEs/POU	32.8	<.025	ND	7.9	NA
39	Vale, OR	Kinetico/IX	16.7	<.025	NA	7.5	(525)
40	Okanogan, WA	Filtronic/Electromedia	18.4	0.069	0.1	8.0	(550)

NA = not available, ND = not detectable

## Research Articles & Additional Reference Materials

Below is a list of several of the reference materials that are available. Additional resources and information relevant to arsenic treatment (e.g. design manuals, research publications, demonstration fact sheets, decision trees, etc.) are available on the following websites:

Office of Research and Development, National Risk Management Research Laboratory

[www.epa.gov/ORD/NRMRL/arsenic/resource.htm](http://www.epa.gov/ORD/NRMRL/arsenic/resource.htm)

Office of Ground Water and Drinking Water

[www.epa.gov/OGWDW/arsenic.html](http://www.epa.gov/OGWDW/arsenic.html)

### Design Manuals/Treatment Handbooks

Technology Selection and System Design USEPA Arsenic Demonstration Program Round 1 (EPA 600-R-05-001)

This report provides source water quality characteristics at each of the 12 demonstration sites and the general rationale used to select the technologies for demonstration at each site. Information on the design and operation of each treatment system also is presented. The selection of the adsorptive media and pretreatment methods depend on a number of factors that affect the system performance, including arsenic concentration and speciation, pH, and the presence of competing anions, as well as media-specific characteristics such as costs, media life, and empty-bed contact time (EBCT) requirements.

Design Manual: Removal of Arsenic from Drinking Water by Adsorptive Media (EPA 600-R-03-019)

This design manual is an in-depth presentation of the steps required to design and operate a water treatment plant for removal of excess arsenic from drinking water using the adsorptive media process.

Design Manual: Removal of Arsenic from Drinking Water by Ion Exchange (EPA 600-R-03-080)

This design manual is an in-depth presentation of the steps required to design and operate a water treatment plant for removing arsenic in the As(V) form from drinking water using the anion exchange process. The treatment process removes arsenic using a strong base anion exchange resin in either the chloride or hydroxide form; chloride is the preferred form because salt can be used as the regenerant.

### Cost Analysis Reports

Technologies and Costs for Removal of Arsenic from Drinking Water (EPA 815-R-00-028)

Provides an introduction to the arsenic statutory requirements, and defines technology categories. Also presents the organization of the document. In addition, it presents discussions on available arsenic removal technologies and associated capital and operation and maintenance costs.

Capital Costs of Arsenic Removal Technologies Demonstration Program Round 1 (EPA 600-R-04-201)

This report provides a brief description of each of the twelve, Round 1 demonstration sites and the respective technologies being evaluated. Capital costs were organized into three categories— equipment, engineering, and installation—and then summed to arrive at a total capital investment cost for each system. Operations and maintenance (O&M) costs associated with the treatment systems were not available at the time of this publication; however, vendor-supplied estimates on media replacement costs are also provided in this report.

### Residuals

Regulations on the Disposal of Arsenic Residuals from Drinking Water Treatment Plants (EPA 600-R-00-025)

With the passage of the various federal statutes, restrictions have been placed on the discharge of residuals to water bodies and onto land. This report summarizes federal regulations and selected state regulations that govern the management of residuals produced by small drinking water treatment systems removing arsenic from drinking water.

Treatment of Arsenic Residuals from Drinking Water Removal Processes (EPA 600-R-01-033)

This document provides a short-list of arsenic removal options for residuals produced by ion exchange (Ion Ex), reverse osmosis (RO), nanofiltration (NF), activated alumina (AA), and iron removal processes. Both precipitation and adsorption processes were evaluated to remove arsenic.

## Research

### Laboratory Study on the Oxidation of Arsenic III to Arsenic V (EPA 600-R-01-021)

A one-year laboratory study was performed to determine the ability of seven oxidants to oxidize As(III) to As(V). These included chlorine, permanganate, ozone, chlorine dioxide, monochloramine, a solid-phase oxidizing media, and 254 nm ultraviolet light. Chlorine and permanganate rapidly oxidized As(III) to As(V) in the pH range of 6.3 to 8.3. Dissolved manganese, dissolved iron, sulfide and TOC slowed the rate of oxidation slightly, but essentially complete oxidation was obtained in less than one minute with chlorine and permanganate under all conditions studied.

### Oxidation of As(III) by Aeration and Storage (EPA 600-R-01-102)

A study of the effects of aeration and storage on the oxidation of arsenic(III) was undertaken at three utilities in the U.S. to establish the engineering significance of aeration as a potential pre-treatment method for arsenic removal.

The following three reports document treatment plant information as well as results of sampling and analysis. The objective of sampling and analysis for each respective technology was to evaluate the effectiveness of the water treatment plants to consistently remove arsenic (As) from source water.

Arsenic Removal from Drinking Water by Coagulation/Filtration and Lime Softening Plants (EPA 600-R-00-063)

Arsenic Removal from Drinking Water by Ion Exchange and Activated Alumina Plants (EPA 600-R-00-088)

Arsenic Removal from Drinking Water by Iron Removal Plants (EPA 600-R-00-086)

## Regulations

### Small System Compliance Technology List for the Surface Water Treatment Rule and Total Coliform Rule (EPA 815-R-98-001)

This listing provides greater detail than earlier listings, on the capabilities, applicability ranges, water quality concerns, and operational and maintenance requirements for the identified compliance technologies. This listing also provides, in summary format, issues identified by EPA and its stakeholders in their review of draft materials.

### Small System Compliance Technology List for the Non-Microbial Contaminants Regulated Before 1996 (EPA 815-R-98-002)

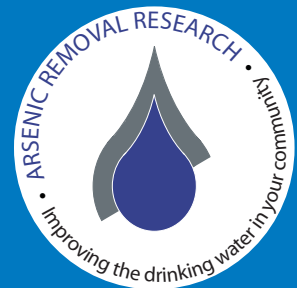
This document covers both an update of the Surface Water Treatment Rule (SWTR) list and the compliance technologies identified for the Total Coliform Rule (TCR). These have been grouped into one publication as they both address microbial contaminants and their indicators in drinking water.

### Variance Technology Findings for Contaminants Regulated Before 1996 (EPA 815-R-98-003)

This document describes the variance technology findings for the contaminants regulated before 1996, including the requirements of the 1996 SDWA; the two-stage screening process that was used to identify those contaminants that would have technology costs compared against the national-level affordability criteria; and the derivation of the national-level affordability criteria; the affordable technology determinations and how treatment costs are compared against the national level affordability criteria.

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