Proven Alternatives for Aboveground Treatment of Arsenic in Groundwater

ENGINEERING FORUM ISSUE PAPER

In January 2001, EPA published a revised maximum contaminant level (MCL) for arsenic in drinking water that requires public water suppliers to maintain arsenic concentrations at or below 0.010 milligrams per liter (mg/L) by 2006 (Ref. 1.1, 1.9). The revised standard may affect arsenic cleanup goals for groundwater.

The information contained in this issue paper can help managers at sites with arsenic-contaminated groundwater to:

- Identify proven and effective treatment technologies
- Screen those technologies based on effectiveness, treatment goals, site characteristics, and cost
- Apply technology and experience from sites with similar remediation challenges
- Find more detailed arsenic treatment information using this issue paper as a reference

Arsenic is a component of many industrial raw materials, products, and wastes, and is a contaminant of concern in groundwater at many remediation sites. Because arsenic readily changes valence state and reacts to form species with varying toxicity and mobility, effective treatment of arsenic can be challenging. Treatment can result in residuals that, under some environmental conditions, have unstable toxicity and mobility. In addition, the revised MCL for arsenic in drinking water could result in lower treatment goals for aboveground treatment systems. A lower treatment goal may significantly affect the selection, design, and operation of arsenic treatment systems.

1.0 SUMMARY

1.1 Abstract

This issue paper identifies and summarizes experiences with proven aboveground treatment alternatives for arsenic in groundwater, and provides information on their relative effectiveness and cost. The information contained in this paper can also be found in the report *"Arsenic Treatment Technologies for Soil, Waste, and Water"*, EPA542-R-02-004 (Ref. 1.12), which provides cost and performance data for additional technologies that can treat arsenic in soil, waste, and water. This paper has been developed jointly by EPA's Engineering Forum and Technology Innovation Office. EPA's Engineering Forum is a group of professionals, representing EPA Regional Offices, who are committed to identifying and resolving the engineering issues related to remediation of Superfund and hazardous waste sites. The Forum is sponsored by the Technical Support Project.

This paper is a revision of the June 2002 version, and contains additional data identified for the related report *"Arsenic Treatment Technologies for Soil, Waste, and Water"* (EPA-542-R-02-004), which can be downloaded from http://clu-in.org/arsenic.

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1.2 Background

Arsenic Occurrence

Arsenic occurs naturally in rocks, soil, water, air, plants, and animals. Natural activities such as volcanic action, erosion of rocks, and forest fires can release arsenic into the environment. Industrial products containing arsenic include wood preservatives, paints, dyes, metals, pharmaceuticals, pesticides, herbicides, soaps, and semiconductors. Man-made sources of arsenic in the environment include mining and smelting operations; agricultural applications; and the use of industrial products and disposal of wastes containing arsenic (Ref. 1.1).
Source: (Ref. 1.3)

Figure 1.1
The Five Most Common Contaminants of Concern at Superfund Sites
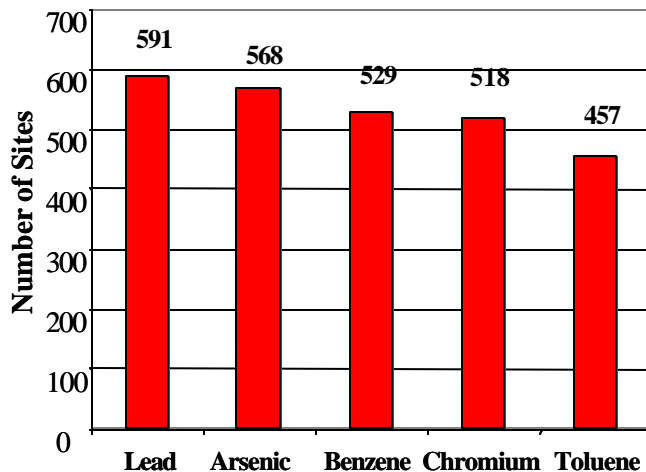
Based on information from EPA's CERCLIS 3 database through fiscal year (FY) 1999 (Ref. 1.3), arsenic is the second most common contaminant of concern (COC) cited in Records of Decision (RODs) for sites on the Superfund National Priorities List (NPL) (Figure 1.1). Arsenic is a COC at 568 sites or 47% of the 1,209 sites on the NPL for which a ROD has been signed (Ref. 1.3, 1.8). Table 1.1 lists by media the number of Superfund sites with arsenic as a COC. Arsenic is a COC for groundwater at 380 sites, or 31% of the 1,209 sites on the NPL for which a ROD has been signed.

Arsenic Chemistry

Arsenic is a metalloid or inorganic semiconductor. It occurs with valence states of -3, 0, +3 (arsenite,

As[III]), and +5 (arsenate, As[V]). Because the valence states -3 and 0 occur rarely, this discussion of arsenic chemistry focuses on As(III) and As(V). Arsenic forms inorganic and organic compounds. Inorganic compounds of arsenic include hydrides (e.g., arsine), halides, oxides, acids, and sulfides (Ref. 1.4).

The toxicity and mobility of arsenic varies with its valence state and chemical form. As(III) is generally more toxic to humans and four to ten times more soluble in water than As(V) (Ref. 1.2, 1.6). However, different chemical compounds containing arsenic exhibit varying degrees of toxicity and solubility.

Table 1.1
Superfund Sites with Arsenic as a Contaminant of Concern by Media[a]

Media	Number of Sites
Groundwater	380
Soil	372
Sediment	154
Surface Water	86
Debris	77
Sludge	45
Solid Waste	30
Leachate	24
Liquid Waste	12
Air	8
Residuals	1
Other	21

[a] The total number of sites in Table 1.1 exceeds the total number of sites with arsenic contamination (568, Figure 1.1) because some sites have more than one type of media contaminated with arsenic.
Source: (Ref. 1.3)

Arsenic can change its valence state and chemical form in the environment. Some conditions that could affect arsenic valence and speciation include (Ref. 1.7):

- pH
- Oxidation-reduction potential
- The presence of complexing ions, such as ions of sulfur, iron, and calcium
- Microbial activity

Adsorption-desorption reactions can also affect the mobility of arsenic in the environment. Clays, carbonaceous materials, and oxides of iron, aluminum, and manganese are soil components that can participate in adsorptive reactions with arsenic (Ref. 1.7).

Revised MCL for Arsenic

In January 2001, EPA published a revised MCL for arsenic in drinking water that requires public water suppliers to maintain arsenic concentrations at or below 0.010 mg/L by 2006 (Ref. 1.1, 1.9). The former MCL was 0.050 mg/L. Treatment goals for arsenic at groundwater remediation sites can be based on MCLs, background contaminant levels, or risk.

Lower treatment goals for arsenic present multiple technical challenges for the aboveground treatment of groundwater, and will likely result in higher treatment costs. Some sites that might not have needed groundwater treatment to remove arsenic under the former MCL of 0.050 mg/L may need to treat groundwater for arsenic to meet the revised MCL of 0.010 mg/L. At some sites, the plume of groundwater containing arsenic at concentrations greater than 0.010 mg/L could be significantly larger in volume and areal extent than the plume containing arsenic at greater than 0.050 mg/L. Site-specific conditions will determine if new arsenic treatment systems need to be designed, or if existing systems need to be retrofitted to treat the larger volumes. In addition, treatment of groundwater to lower arsenic concentrations can sometimes require the use of multiple technologies in sequence. For example, a site with an existing metals precipitation/ coprecipitation system may need to add another technology such as ion exchange to achieve a lower treatment goal.

In some cases, a lower treatment goal might be met by changing the operating parameters of existing systems. For example, changing the type or amount of treatment chemicals used, replacing spent treatment media more frequently, or changing treatment system flow rates can reduce arsenic concentrations in the treatment system effluent. However, such changes may increase operating costs from use of additional treatment chemicals or media, use of more expensive treatment chemicals or media, and from disposal of increased volumes of treatment residuals. Technology-specific factors that might affect costs for retrofitted systems are discussed in the individual technology summary

sections (see Sections 2.0 through 5.0) of this issue paper.

Additional information and guidance on retrofitting and optimizing the performance of aboveground treatment systems for groundwater is available from the Federal Remediation Technologies Roundtable Remedial Process Optimization/Remedial System Evaluation web page at *http://www.frtr.gov/remedopt.htm*. This website contains technology-specific guidance on optimization of aboveground treatment systems for groundwater.

Technologies and Media Addressed

This issue paper focuses on the application of treatment technologies to the aboveground removal of arsenic from groundwater. Information on the below-ground (in situ) treatment of arsenic-contaminated groundwater is not presented; for more information on in situ treatment of groundwater, refer to the related report *"Arsenic Treatment Technologies for Soil, Waste, and Water"* (Ref. 1.12), and EPA's web site, including http://clu-in.org. The following ex situ technologies are addressed in this issue paper:

- Precipitation/coprecipitation (Section 2.0)
- Adsorption (Section 3.0)
- Ion exchange (Section 4.0)
- Membrane filtration (Section 5.0)

These technologies are included because they have been used at full scale to remove arsenic from water. Each of these technologies can include more than one type of treatment system. For example, membrane filtration includes nanofiltration and reverse osmosis treatment systems, both of which have been used to treat arsenic. Although nanofiltration and reverse osmosis are sometimes discussed as distinct technologies in technical literature, this issue paper discusses them as a single technology because of their similarity in design, operation, and application to arsenic treatment. The specific treatment types included under each technology are described in the technology-specific discussions in Sections 2.0 through 5.0.

Oxidation of As(III) to As(V) can improve the performance of the technologies this issue paper focuses on. Chlorine, potassium permanganate, aeration, peroxide, ozone, and photo-oxidation have been used to convert As(III) to As(V) (Ref. 1.12). Many arsenic treatment systems use oxidation as a pretreatment step to improve performance. In addition, some of the technologies include oxidation as an intrinsic part of their application. For example, greensand filtration, which is listed as an adsorption technology in this issue paper, includes oxidation and adsorption of arsenic in one unit operation. Although oxidation can either be a pretreatment step or an intrinsic part of another technology, it is not typically used alone as an arsenic treatment. Therefore, this issue paper does not contain a separate section on oxidation.

This issue paper does not address three technologies that have been used to treat water containing arsenic:

• Biological treatment
• Phytoremediation
• Electrokinetics

Biological treatment is not addressed because it does not appear to be used for the aboveground treatment of groundwater containing arsenic. The information sources used for this issue paper contained only a limited number of bench- or pilot-scale projects on biological treatment of arsenic in water, and no aboveground treatments of groundwater conducted at full scale were found. Phytoremediation and electrokinetics are not addressed because these technologies are applied in situ. Data available on these three technologies are discussed in the related report *"Arsenic Treatment Technologies for Soil, Waste, and Water"* (Ref. 1.12).

This issue paper presents and analyzes information about the aboveground removal of arsenic from groundwater, drinking water, industrial wastewater, surface water, mine drainage, and leachate collectively referred to as "water" throughout the remainder of this paper. In some cases, the technologies used to treat one type of water are not applicable to another type of water due to different wastewater characteristics or post-treatment water use. For example, the technology used to treat industrial wastewater containing high arsenic concentrations that is discharged after treatment may not be appropriate to treat drinking water.

However, arsenic in drinking water, industrial wastewater, surface water, mine drainage, and leachate is often removed using the same technologies as those used to treat groundwater. Information about such treatment technologies can help remedial project managers (RPMs) make an informed decision about the selection, design, and operation of aboveground treatment of arsenic-contaminated groundwater.

Treatment Trains

Treatment trains consist of two or more technologies used together, either integrated into a single process or operated as a series of treatment technologies. The technologies in a treatment train may treat the same contaminant. For example, at one site a treatment train of reverse osmosis followed by ion exchange was used to remove arsenic from surface water (Ref. 1.16). A common treatment train used for arsenic-contaminated water includes an oxidation step to change arsenic from As(III) to its less soluble As(V) state, followed by precipitation/coprecipitation and filtration to remove the precipitate.

Some treatment trains are used when no single technology is capable of treating all contaminants in a particular medium. For example, at the Saunders Supply Company Superfund Site in Virginia (Appendix A, Project 18), an aboveground system consisting of metals precipitation, filtration, and activated carbon adsorption was used to treat groundwater contaminated with arsenic and pentachlorophenol (PCP). In this treatment train the precipitation and filtration processes were used for treating arsenic and the activated carbon adsorption process was used to treat PCP.

In many cases, the available information on the use of treatment trains did not specify the technologies within the train that were intended to treat arsenic. Where influent and effluent arsenic concentrations were available, often they were available only for the entire treatment train, and not the individual components. In such cases, engineering judgement was used to identify the technology for treating arsenic. For example, at the Higgins Farm Superfund Site in New Jersey (Appendix A, Project 17), a treatment train consisting of air stripping, metals precipitation, filtration, and ion exchange was used to treat groundwater contaminated with arsenic, nonhalogenated volatile organic compounds (VOCs) and halogenated VOCs. The precipitation, filtration, and ion exchange processes

were assumed to remove arsenic from the wastewater, while the air stripping process was assumed to treat the VOCs but have only a negligible effect on the arsenic concentration.

Where treatment trains included more than one potential arsenic treatment technology, all arsenic treatment technologies were assumed to contribute to arsenic treatment, unless available information indicated otherwise. For example, at the Higgins Farm Superfund site, arsenic-contaminated groundwater was treated with precipitation and ion exchange. It was assumed that both technologies contributed to the reduction in concentration of the arsenic. Information about this treatment is presented in both the precipitation/ coprecipitation (Section 2.0) and ion exchange (Section 4.0) technology sections.

Information Sources

This issue paper was prepared in conjunction with the report "*Arsenic Treatment Technologies for Soil, Waste, and Water*" (Ref. 1.12). That report contains detailed treatment information for 13 treatment technologies applicable to aqueous or nonaqueous media. This issue paper is based on information contained in that report.

The report "*Arsenic Treatment Technologies for Soil, Waste, and Water*" (Ref. 1.12) contains information gathered from the following sources:

- A comprehensive literature search
- Documents and databases prepared by EPA, the U.S. Department of Defense (DoD), and the U.S. Department of Energy (DOE)
- Information supplied by users (for example, RPMs) and vendors of treatment technologies
- Internet sites

The report "*Arsenic Treatment Technologies for Soil, Waste, and Water*" (Ref. 1.12) contains a detailed discussion of the data collection process and the data collected.

1.3 Summary of Key Findings

Arsenic Treatment Technology Performance

Based on the information gathered for this paper, precipitation/coprecipitation is frequently used to treat

arsenic-contaminated water, and is capable of treating a wide range of influent concentrations to the revised MCL for arsenic. The effectiveness of this technology is less likely to be reduced by characteristics and contaminants other than arsenic, compared to other water treatment technologies. It is also capable of treating water characteristics or contaminants other than arsenic, such as hardness or heavy metals. Systems using this technology generally require skilled operators; therefore, precipitation/coprecipitation is more cost effective at a large scale where labor costs can be spread over a larger amount of treated water produced.

The effectiveness of adsorption and ion exchange for arsenic treatment is more likely than precipitation/ coprecipitation to be affected by characteristics and contaminants other than arsenic. However, these technologies are capable of treating arsenic to the revised MCL. Small capacity systems using these technologies tend to have lower operating and maintenance costs, and require less operator expertise. Adsorption and ion exchange tend to be used more often when arsenic is the only contaminant to be treated, for relatively smaller systems, and as a polishing technology for the effluent from larger systems. Membrane filtration is used less frequently because it tends to have higher costs and produce a larger volume of residuals than other arsenic treatment technologies.

The revised MCL may require that existing membrane filtration, adsorption, and ion exchange systems be modified to help reduce arsenic concentrations in the effluent. Examples of such modifications include addition of an adsorption media bed, more frequent regeneration or replacement of ion exchange media, or use of a membrane with a smaller molecular weight cut-off. However, these modifications could increase the treatment costs. Membrane filtration, adsorption, and ion exchange can also be added as part of a treatment train to increase the effectiveness of treatment. This also would result in an increase in the overall treatment costs.

Point-of-use systems most commonly used for drinking water include adsorption (activated alumina) and membrane filtration (reverse osmosis) (Ref. 1.13). In addition, some simple, low-cost precipitation/ coprecipitation point-of-use systems have been

developed for use in developing countries to remove arsenic from drinking water (Ref. 1.22).

Table 1.2 summarizes the number of full-scale treatment processes identified for this paper. Data are available on applications used to treat groundwater and other aqueous media such as surface water, industrial wastewater, and leachate. Full-scale projects include those used to:

- Remediate an entire area of contamination; for example, a technology used to treat an entire groundwater plume,
- Remove arsenic from drinking water by a publicly-owned or commercial facility
- Commercially treat as-generated wastewaters

Table 1.2
Full-Scale, Aboveground Treatments of Arsenic
Identified for this Paper

	Media	
Technology	**Groundwater**	**Other Aqueous Media**
Precipitation/ coprecipitation	16	29
Adsorption	7	8
Ion Exchange	3	4
Membrane Filtration	1	1

Source: (Ref. 1.12)

Table 1.3 summarizes the performance data gathered on the treatment of arsenic in water (Tables 1.3 through 1.6 are provided after the list of references). The table also provides information on the number of projects that achieved less than 0.050 or 0.010 mg/L of arsenic in treatment effluent. The table is limited to technology applications for which both pretreatment and post-treatment data are available.

Table 1.3 and the sections summarizing performance data discuss the number of projects identified in the data sources that reduced arsenic concentrations to below 0.050 mg/L and 0.010 mg/L respectively. Data on projects that did not meet these treatment goals do not necessarily indicate that the technology is not capable

of meeting these goals. In many cases, the remediation project goal may have been to meet the former arsenic MCL of 0.050 mg/L, or a goal based on background levels or risk. Treatment goals for industrial wastewaters may vary depending on the particular industrial wastewater effluent guidelines or other regulations applicable to that industry. Information on site-specific treatment goals generally was not available in the references used to prepare this issue paper. Table 1.4 at the end of this section is a screening matrix for arsenic treatment technologies. It can assist decision makers in evaluating candidate cleanup technologies by providing information on each technology's relative availability, cost, and other factors. The matrix is based on the Federal Remediation Technologies Roundtable Technology (FRTR) Treatment Technologies Screening Matrix (Ref. 1.23), but has been tailored to aboveground treatment technologies for arsenic in water, based on information in this issue paper. Table 1.4 differs from the FRTR matrix by:

- Limiting the scope of the table to the technologies discussed in this issue paper.
- Changing the information based on the narrow scope of this issue paper. For example, the FRTR screening matrix lists the overall cost of precipitation as "average" (circle symbol) in comparison to other treatment technologies for surface water, groundwater, and leachate. However, in comparison to the other technologies discussed in this issue paper, precipitation/coprecipitation costs are typically lower.
- Adding information about specific water characteristics that can affect technology performance.

Table 1.4 includes the following information:

- *Development Status* - The scale at which the technology has been applied. "F" indicates that the technology has been applied to a site at full scale. All of the technologies have been applied at full scale.
- *Typically Requires Pretreatment* - Whether the technology is typically preceded by another technology. Adsorption, ion exchange, and membrane filtration typically require pretreatment because the equipment is susceptible to fouling from suspended solids and organics.

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- *Residuals Produced* - The residuals typically produced that require additional management. "S" indicates that a solid residual is produced while "L" indicates that a liquid residual is produced. Precipitation/coprecipitation typically generates a sludge, which is considered a solid residual. Although this sludge may be dewatered, generating a liquid, the liquid is typically fed back to the precipitation/coprecipitation process rather than being disposed. Adsorption and ion exchange generate spent regenerating solution and solid spent media. Membrane filtration generates a liquid reject stream.
- *O&M or Capital Intensive* - This indicates the main cost-intensive parts of the system. Operation and maintenance ("O&M") indicates that the operation and maintenance costs tend to be high in comparison to other technologies. "Cap" indicates that capital costs tend to be high in comparison to other technologies. Because of the limited cost information available for arsenic treatment, the cost ratings from the FRTR Screening Matrix were used without tailoring them to arsenic treatment.
- *Availability* - The relative number of vendors that can design, construct, or maintain the technology. A square indicates more than four vendors. All technologies are available from more than four vendors.
- *Reliability/Maintainability* - The expected reliability/maintainability of the technology. A square indicates high reliability and low maintenance and a circle, average reliability and maintenance. Precipitation/coprecipitation is rated as more reliable and maintainable because it is less susceptible to upset or interference from varying influent water characteristics such as organics and suspended solids.
- *Overall Cost* - Design, construction, and O&M costs of the core process that defines each technology, plus the treatment of residuals. It does not include mobilization, demobilization, and pre- and post-treatment costs. A square indicates lower overall cost, a circle average overall cost, and a triangle higher overall cost. Reverse osmosis (membrane filtration) is considered higher cost because it generally is more expensive and generates larger volumes of treatment residuals than other arsenic treatment technologies (Ref. 1.13).
- *Untreated Water Characteristics That May Require Pretreatment or Affect Performance and Cost* - The types of contaminants or other substances that

- generally may interfere with arsenic treatment for each technology. A "T" indicates that the presence of the characteristic may significantly interfere with technology effectiveness. Although these contaminants can usually be removed before arsenic treatment through pretreatment with another technology, the addition of a pretreatment technology may increase overall treatment costs and generate additional residuals requiring disposal.

The selection of a treatment technology for a particular site will depend on many site-specific factors; thus the matrix is not intended to be used as the sole basis for remediation decisions.

Arsenic Treatment Costs

This issue paper discusses two types of information on the cost of arsenic treatment technologies:

1. Information on the cost of aboveground treatment for groundwater containing arsenic or chromium at Superfund sites
2. Information on the cost of treating drinking water to remove arsenic

A limited amount of cost data on arsenic treatment was identified for this paper. In many cases, the cost information is incomplete. For example, some data are for O&M costs only, and do not specify the associated capital costs. In other cases, a cost per unit of water treated is provided, but total costs are not. For some technologies, no arsenic-specific cost data were identified.

In many cases, available cost information is for an entire treatment train that includes technologies intended to treat contaminants other than arsenic. Information was available on only two systems used to treat only arsenic. The technologies used to treat arsenic are also often used to treat other inorganic contaminants, such as chromium. The cost of eight systems used to treat only chromium was also available to supplement arsenic-specific costs. Table 1.5 lists cost information for 10 aboveground systems used to treat arsenic or chromium in groundwater at Superfund sites. The treatment systems at these sites were intended to treat only arsenic or chromium and consist of a single treatment technology with associated pre- or post-treatment technologies, such as post-treatment filtration

to remove solids from precipitation/coprecipitation processes.

The cost data were taken from a variety of sources, including EPA, DoD, other government sources, and information from technology vendors. The quality of these data varied, with some sources providing detailed information about the items included in the costs, while other sources gave little detail about their basis. In most cases, the particular year for the costs were not provided. The costs presented throughout this paper are the costs reported in the identified references, and are not adjusted for inflation. Because of the variation in type of information and quality, this paper does not provide a summary or interpretation of the costs presented.

The EPA document "*Technologies and Costs for Removal of Arsenic From Drinking Water*" (Ref. 1.13) contains more information on the cost to reduce the concentration of arsenic in drinking water from the former MCL of 0.050 mg/L to below the revised MCL of 0.010 mg/L. The document includes capital and O&M cost curves for a variety of processes, including:

- Retrofitting of existing precipitation/coprecipitation processes to improve arsenic removal (enhanced coagulation/filtration and enhanced lime softening)
- Precipitation/coprecipitation followed by membrane filtration (coagulation-assisted microfiltration)
- Ion exchange (anion exchange) with varying levels of sulfate in the influent
- Two types of adsorption (activated alumina at varying influent pH and greensand filtration)
- Oxidation pretreatment technologies (chlorination and potassium permanganate)
- Treatment and disposal costs of treatment residuals (including mechanical and non-mechanical sludge dewatering)
- Point-of-use systems using adsorption (activated alumina) and membrane filtration (reverse osmosis)

The EPA cost curves are based on computer cost models for drinking water treatment systems. Costs for full-scale reverse osmosis, a common type of membrane filtration, were not included because it generally is more expensive and generates larger volumes of treatment residuals than other arsenic treatment technologies (Ref. 1.13). Although the cost information is only for the removal of arsenic from drinking water, many of the same treatment technologies can be used for aboveground treatment of groundwater and have similar costs.

Table 1.6 presents estimated capital and annual O&M costs for four treatment technologies based on cost curves presented in "*Technologies and Costs for Removal of Arsenic From Drinking Water*":

1. Precipitation/coprecipitation followed by membrane filtration (coagulation-assisted microfiltration)
2. Adsorption (greensand filtration)
3. Adsorption (activated alumina with pH of 7 to 8 in the influent)
4. Ion exchange (anion exchange with <20 mg/L sulfate in the influent)

The table presents the estimated costs for three treatment system sizes: 0.01, 0.1, and 1 million gallons per day (mgd). The costs presented in Table 1.6 are for specific technologies listed in the table, and do not include costs for oxidation pretreatment or management of treatment residuals. Detailed descriptions of the assumptions used to generate the arsenic treatment technology cost curves are available (Ref. 1.13).

Table 1.7 presents the capital and O&M costs for activated alumina and reverse osmosis point-of-use treatment systems serving a single household, based on available cost curves (Ref. 1.13). The costs presented assume that only water used for drinking and cooking will be treated, at a rate of 3 gallons per day (gpd).

Table 1.7
Estimated Cost[a] of Point-of-Use Drinking Water Treatment Systems (3 Gallons per Day)

Technology	Capital Cost ($)	O&M Cost ($/year)
Adsorption (activated alumina)	297	413
Membrane filtration (reverse osmosis)	865	267

[a] Costs are rounded to three significant figures.
O&M = operation and maintenance
Source: (Ref. 1.13)

Organization of Paper

Sections 2.0 through 5.0 of this issue paper contain additional details on each of the four arsenic treatment technologies used for aboveground treatment:

- A brief summary
- Technology description and principles
- A figure depicting a model of the technology
- Type, number, and scale of identified projects for aboveground treatment
- Summary of performance data
- Advantages and potential limitations
- Summary of cost data
- Considerations for retrofitting existing systems

Appendices A through D contain tables showing more information on the arsenic treatment projects found in the sources used for this issue paper.

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Table 1.3
Summary of Performance Data for Treatment of Arsenic in Water

Technology	Number of Applications Identified[a] (Number with Performance Data)			Total Number of Applications Identified (Number with Performance Data)	Number of Applications Achieving <0.050 mg/L Arsenic	Number of Applications Achieving <0.010 mg/L Arsenic
	Bench Scale	Pilot Scale	Full Scale			
Precipitation/Coprecipitation	NC	24 (22)	45 (30)	69 (52)	35	19
Adsorption	NC	8 (5)	15 (9)	23 (14)	12	7
Ion Exchange	NC	0	7 (4)	7 (4)	3	2
Membrane Filtration	6 (0)	25 (2)	2 (2)	33 (4)	4	2

[a] Applications were identified through a search of available technical literature. The number of applications include only those identified during the preparation of this paper, and are not comprehensive.

NC = Data not collected

Source: Adapted from data in Sections 2.0 to 5.0 of this issue paper

Table 1.4
Arsenic Treatment Technologies Screening Matrix

Rating Codes — - Better; - Average; - Worse; Y - Yes; N - No. F - Full; P - Pilot. S - Solid; L - Liquid; V - Vapor. Cap - Capital; N - Neither; O&M - Operation & Maintenance. T - May require pretreatment or affect cost and performance.	Development Status	Treatment Train (excludes off-gas treatment)	Residuals Produced	O&M or Capital Intensive	Availability	System Reliability/Maintainability	Overall Cost [a]	Characteristics That May Require Pretreatment or Affect Performance or Cost			
								High Arsenic Concentration	Arsenic Chemical Form	pH	Other Characteristics
Technology											
Precipitation/Coprecipitation	F	Y	S	Cap & O&M	■	■	●		T	T	• Presence of other compounds • Type of chemical addition • Chemical dosage • Treatment goal • Sludge disposal
Adsorption	F	Y	S, L	Cap & O&M	■	●	●	T	T	T	• Flow rate • pH • Fouling • Contamination concentration • Spent media

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Rating Codes	Development Status	Treatment Train (excludes off-gas treatment)	Residuals Produced	O&M or Capital Intensive	Availability	System Reliability/Maintainability	Overall Cost [a]	Characteristics That May Require Pretreatment or Affect Performance or Cost			
								High Arsenic Concentration	Arsenic Chemical Form	pH	Other Characteristics
■ - Better; ● - Average; ▲ - Worse; Y - Yes; N - No. F - Full; P - Pilot. S - Solid; L - Liquid; V - Vapor. Cap - Capital; N - Neither; O&M - Operation & Maintenance. T - May require pretreatment or affect cost and performance.											
Ion Exchange	F	Y	S, L	Cap & O&M	■ (Better)	● (Average)	● (Average)	T	T	T	• Presence of competing ions • Presence of organics • Presence of trivalent ion • Project scale • Bed regeneration • Sulfate
Membrane Filtration	F	Y	L	Cap & O&M	■ (Better)	● (Average)	▲ (Worse)	T	T	T	• Suspended solids, high molecular weight, dissolved solids, organic compounds and colloids • Temperature • Type of membrane filtration • Initial waste stream • Rejected waste stream

Source: Adapted from the Federal Remediation Technologies Roundtable Technology Screening Matrix. http://www.frtr.gov. September 2001. (Ref. 1.23)

[a] Relative costs for precipitation/coprecipitation, adsorption, and ion exchange are sensitive to treatment system capacity, untreated water characteristics, and other factors.

Table 1.5
Available Data on the Cost[a] for Aboveground Treatment of Arsenic and Chromium in Groundwater at Superfund Sites

Site Name and State	Contaminant[b]	Treatment Technology[c]	Years in Operation[d]	Capital Costs ($ Million)	Annual O&M Costs ($ Million)	Average Annual O&M Costs ($) Per Thousand Gallons Treated	Estimated Treatment Rate (gpm)	Remedial Project Manager and Telephone Number	Reference
Precipitation/Coprecipitation									
Vineland Chemical Company, NJ	As	Precipitation/ coprecipitation	0.6	–	$4	–	1,400	Matthew Westgate 212-637-4422	1.18
Winthrop Landfill, NJ	As	Precipitation/ coprecipitation	6	$2	$0.25	–	65	Anni Loughlin, 617-918-1273	1.22
Better Brite Plating, WI	Cr	Precipitation/ coprecipitation	5.6	–	$0.036	–	–	John Peterson 312-353-1264	1.18
Odessa I, TX	Cr	Precipitation/ coprecipitation	4.2	$1.9	$0.22 ($0.5)[e]	$7.5	60	Ernest Franke 214-665-8521	1.17, 1.18
Odessa II, TX	Cr	Precipitation/ coprecipitation	4.1	$1.8	$0.16	$5.4	–	Ernest Franke 214-665-8521	1.17
Selma Treating Company, CA	Cr	Precipitation/ coprecipitation	3.2	–	$0.3	–	150	Michelle Lau 415-744-2227	1.18
United Chrome, OR	Cr	Precipitation/ coprecipitation	8.6	$5.1	$0.11	$15	–	Al Goodman 503-326-3685	1.17

Table 1.5

Available Data on the Cost[a] for Aboveground Treatment of Arsenic and Chromium in Groundwater at Superfund Sites (continued)

Site Name and State	Contaminant[b]	Treatment Technology[c]	Years in Operation [d]	Capital Costs ($ Million)	Annual O&M Costs ($ Million)	Average Annual O&M Costs ($) Per Thousand Gallons Treated	Estimated Treatment Rate (gpm)	Remedial Project Manager and Telephone Number	Reference
Ion Exchange									
Ace Services, KS	Cr	Ion exchange	0	–	$0.5	–	800	Bob Stewart 913-551-7364	1.18
Palmetto Wood, SC	Cr	Ion exchange	3.7	–	$0.3	–	130	Al Cherry 404-562-8807	1.18
Sprague Road Groundwater Plume, TX	Cr	Ion exchange	0	–	$1.2	–	200	Vincent Mallot 214-665-8313	1.18

[a]   The costs listed in this table include the costs for the entire groundwater treatment system at each site. Costs for United Chrome, Odessa I, and Odessa II are in 1999 dollars. Information is not available on the cost year for other sites.

[b]   The table lists only arsenic and chromium contaminants. Other contaminants may have been present and treated by the system.

[c]   The technology listed for each site is the technology that was intended to treat arsenic or chromium. Costs may include pre- or post-treatment technologies associated with the arsenic or chromium treatment technologies.

[d]   Years in operation for United Chrome, Odessa I, and Odessa II are as of early 1998. Years in operation for all other sites are as of May 2001.

[e]   For the Odessa I site, reference 1.17 reports average annual O&M costs of $0.22 million (1999 dollars), while reference 1.18 reports $0.5 million (cost year unknown).

Cr = Chromium   As = Arsenic   O&M = Operation and Maintenance   - = Information is not available   gpm = Gallons per minute

Table 1.6
Summary of Cost[a] Data for Treatment of Arsenic in Drinking Water

Technology	Design Flow Rate					
	0.01 mgd		0.1 mgd		1 mgd	
	Capital Cost ($)	Annual O&M Cost ($)	Capital Cost ($)	Annual O&M Cost ($)	Capital Cost ($)	Annual O&M Cost ($)
Precipitation/Coprecipitation (coagulation-assisted microfiltration)	142,000	22,200	463,000	35,000	2,010,000	64,300
Adsorption (greensand filtration)	12,400	7,980	85,300	13,300	588,000	66,300
Adsorption (activated alumina, influent pH 7 - 8)	15,400	6,010	52,200	23,000	430,000	201,000
Ion exchange (anion exchange, influent <20 mg/L sulfate)	23,000	5,770	54,000	12,100	350,000	52,200

Source: Derived from Ref. 1.13

[a] Costs are rounded to three significant figures and are in September 1998 dollars. Costs do not include pretreatment or management of treatment residuals.
   Costs for enhanced coagulation/filtration and enhanced lime softening are not presented because the costs curves for these technologies are for modification
   of existing drinking water treatment systems only (Ref. 1.13), and are not comparable to those presented in Table 1.5, which are for new treatment systems.

mgd = million gallons per day   O&M = operating and maintenance   mg/L = milligrams per liter   < = less than

2.0 PRECIPITATION/COPRECIPITATION FOR ARSENIC

Summary

Precipitation/coprecipitation has been the most frequently used method to treat arsenic-contaminated water, including groundwater, surface water, leachate, mine drainage, drinking water, and wastewater in numerous pilot- and full-scale applications. Based on the information collected for this paper, this technology typically can reduce arsenic concentrations to less than 0.050 mg/L and in some cases has reduced arsenic concentrations to below 0.010 mg/L.

Technology Description and Principles

For this issue paper, technologies were considered precipitation/coprecipitation if they involved the following steps:

- Mixing of treatment chemicals into the water
- Formation of a solid matrix through precipitation, coprecipitation, or a combination of these processes, and
- Separation of the solid matrix from the water

Technologies that remove arsenic by passing it through a fixed bed of media, where the arsenic may be removed through adsorption, precipitation/coprecipitation, or a combination of these processes, are discussed in the adsorption treatment section (Section 3.0).

Precipitation/coprecipitation usually involves pH adjustment and addition of a chemical precipitant or coagulant; it can also include addition of a chemical oxidant (Ref. 2.1). Oxidation of arsenic to its less soluble As(V) state can increase the effectiveness of precipitation processes, and can be done as a separate pretreatment step or as part of the precipitation process. Some pretreatment processes that oxidize As(III) to As(V) include ozonation, photo oxidation, or the addition of oxidizing chemicals such as potassium permanganate, sodium hypochlorite, or hydrogen peroxide (Ref. 2.8, 2.16, 2.22, 2.25, 2.29). Clarification or filtration are commonly used to remove the solid precipitate.

Technology Description: Precipitation uses chemicals to transform dissolved contaminants into an insoluble solid. In coprecipitation, the target contaminant may be dissolved or in a colloidal or suspended form. Dissolved contaminants do not precipitate, but are adsorbed onto another species that is precipitated. Colloidal or suspended contaminants become enmeshed with other precipitated species, or are removed through processes such as coagulation and flocculation. Many processes to remove arsenic from aqueous matrices involve a combination of precipitation and coprecipitation. The precipitated/coprecipitated solid is then removed from the liquid phase by clarification or filtration. Arsenic precipitation/coprecipitation can use combinations of the chemicals and methods listed below.

Contaminants Treated:
- Inorganics
- Colloids
- Suspended solids

Arsenic-Contaminated Media Treated:
- Drinking water
- Surface water
- Groundwater
- Leachate
- Wastewater
- Mine drainage

Chemicals and Methods Used for Arsenic Precipitation/Coprecipitation:
- Ferric salts (e.g., ferric chloride), ferric sulfate, ferric hydroxide
- Lime softening, limestone, calcium hydroxide
- Manganese sulfate
- Ammonium sulfate
- Copper sulfate
- Alum (aluminum hydroxide)
- Sulfide
- pH adjustment

Type, Number, and Scale of Identified Projects

Precipitation/coprecipitation processes for arsenic in water are commercially available. The data gathered in support of this issue paper include information on the full-scale precipitation/coprecipitation treatment of environmental media at 16 sites. Information on full-scale treatment of drinking water is available for eight facilities and on full-scale treatment of industrial wastewater for at least 21 facilities. Figure 2.1 shows

Model of a Precipitation/Coprecipitation System
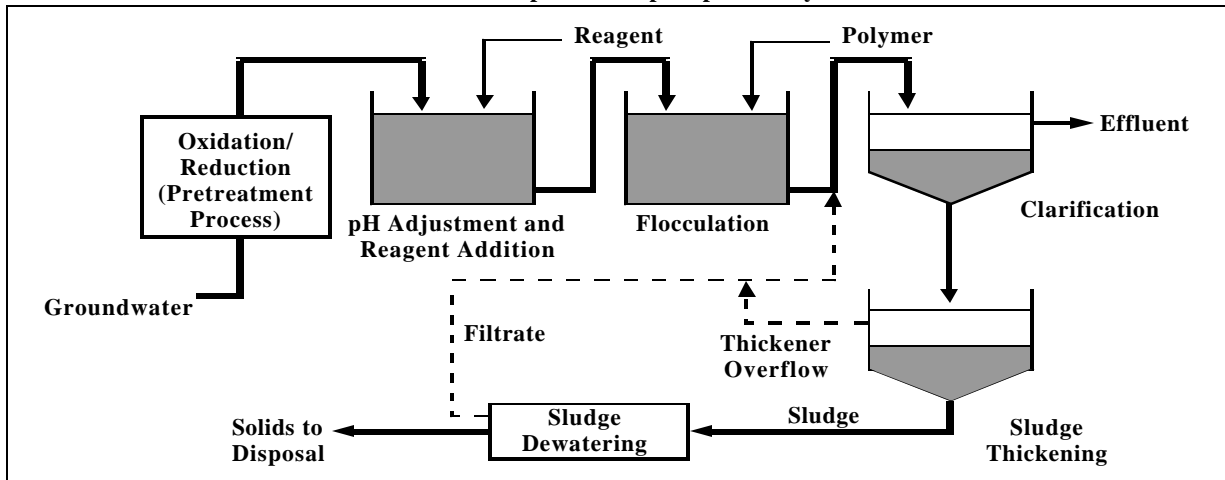
the number of pilot- and full-scale precipitation/coprecipitation projects in the sources researched.

Figure 2.1
Scale of Identified Precipitation/Coprecipitation Projects for Arsenic Treatment
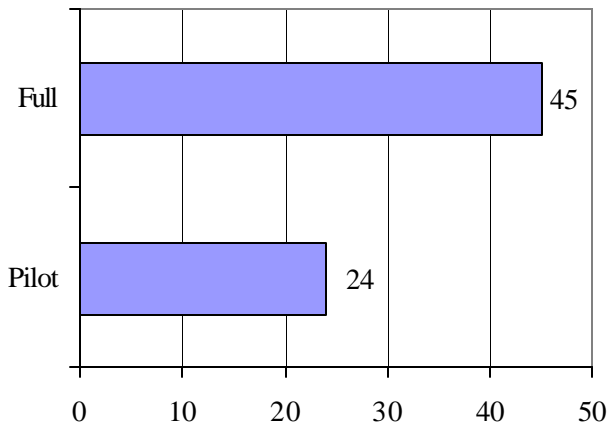
Summary of Performance Data

Appendix A presents the available performance data for pilot- and full-scale precipitation/coprecipitation treatment of wastes and environmental media. It contains information on 69 applications of precipitation/coprecipitation, including 20 environmental media, 15 drinking water, and 34 industrial wastewater applications. The information that appears in the "Precipitating Agent or Process" column of Appendix A, including the chemicals used, the descriptions of the precipitation/coprecipitation processes, and whether the process involved

Precipitation/Coprecipitation Chemistry

The chemistry of precipitation/coprecipitation is often complex, and depends upon a variety of factors, including the speciation of arsenic, the chemical precipitants used and their concentrations, the pH of the water, and the presence of other chemicals in the water be treated. As a result, the particular mechanism that results in the removal of arsenic through precipitation/coprecipitation treatment is process-specific, and in some cases is not completely understood. For example, the removal mechanism in the treatment of As(V) with Fe(III) has been debated in technical literature (Ref. 2.34).

It is beyond the scope of this issue paper to provide all possible chemical reactions and mechanisms for precipitation/coprecipitation processes that are used to remove arsenic. More detailed information on the chemistry involved in specific precipitation/coprecipitation processes can be found in the references listed at the end of this section.

precipitation or coprecipitation, is based on the cited references. This information was not independently checked for accuracy or technical feasibility. For example, in some cases, the reference used may apply the term "precipitation" to a process that is actually coprecipitation.

The effectiveness of precipitation/coprecipitation treatment can be evaluated by comparing influent and effluent contaminant concentrations. All of the 12 environmental media projects for which both influent and effluent arsenic concentration data were available had influent concentrations greater than 0.050 mg/L. The treatments achieved effluent concentrations of less than 0.050 mg/L in eight of the projects and less than 0.010 mg/L in four of the projects. Information on the leachability of arsenic from the precipitates and sludges was available for three projects. For all of these projects, the leachable concentration of arsenic as measured by the toxicity characteristic leaching procedure (TCLP) (the RCRA regulatory threshold for identifying a waste that is hazardous because it exhibits the characteristic of toxicity for arsenic) was below 5 mg/L.

Of the 12 drinking water projects having both influent and effluent concentration data, eight had influent concentrations greater than 0.050 mg/L. The treatments achieved effluent concentrations of less than 0.050 mg/L in all eight of these projects, and less than 0.010 mg/L in two projects. Information on the leachability of arsenic from the precipitates and sludges was available for six projects. For these projects the leachable concentration of arsenic was below 5 mg/L.

All of the 28 wastewater projects having both influent and effluent concentration data had influent concentrations greater than 0.050 mg/L. The treatments achieved effluent concentrations of less than 0.050 mg/L in 16 of these projects, and less than 0.010 mg/L in 11 projects. Information on the leachability of arsenic from the precipitates and sludges was available for four projects. Only one of these projects had a leachable concentration of arsenic below 5 mg/L.

Projects that did not reduce arsenic concentrations to below 0.050 or 0.010 mg/L do not necessarily indicate that precipitation/coprecipitation cannot achieve these levels. The treatment goal for some applications could have been above these concentrations, and the technology may have been designed and operated to meet a higher concentration. Information on treatment goals was not collected for this issue paper.

Some projects in Appendix A include treatment trains, the most common being precipitation followed by activated carbon adsorption or membrane filtration. In those cases, the projects are listed in all the relevant appendices. For example, Project 17 in Appendix A describes a treatment using a train consisting of air stripping, metals precipitation, filtration, and ion exchange. This project also appears as Project 2 in Appendix C, which contains performance data for ion exchange treatment.

The case study presented at the end of this section discusses in greater detail the removal of arsenic from groundwater using an aboveground treatment system at the Winthrop Landfill Superfund site. Information for this site is summarized in Appendix A, Project 1.

Advantages and Potential Limitations

Precipitation/coprecipitation is an active ex situ treatment technology designed to function with routine chemical addition and sludge removal. It usually generates a sludge residual, which typically requires treatment such as dewatering and subsequent disposal. Some sludge from the precipitation/coprecipitation of

arsenic can be a hazardous waste and require additional treatment such as solidification/stabilization prior to disposal. In the presence of other metals or contaminants, arsenic precipitation/coprecipitation processes might also cause other compounds to precipitate, which can render the resulting sludge hazardous (Ref. 2.7). The effluent may also require further treatment, such as pH adjustment, prior to discharge or reuse.

More detailed information on selection and design of arsenic treatment systems for small drinking water systems is available in the document "*Arsenic Treatment Technology Design Manual for Small Systems*" (Ref. 2.38).

Summary of Cost Data

Limited cost data are currently available for precipitation/coprecipitation treatment of arsenic. At the Winthrop Landfill Site (Appendix A, Project 1), groundwater containing arsenic, 1,1-dichloroethane, and vinyl chloride is being pumped and treated above ground through a treatment train that includes precipitation. The total capital cost of this treatment system was $2 million ($1.8 million for construction and $0.2 million for design). O&M costs were about $ 350,000 per year fro the first few years and are now approximately $250,000 per year. The treatment system has a capacity of 65 gallons per minute (gpm). However, these costs are for the entire treatment train (Ref. 2.29, cost year not provided). At the power substation in Fort Walton, Florida, (Appendix A, Project 4), the reported O&M cost was $0.006 per gallon (for the entire treatment train, Ref. 2.33, cost year not provided). Capital cost information was not provided.

Table 1.5 lists the cost of two aboveground treatment systems for arsenic and five systems for chromium using precipitation/coprecipitation. Additional information for the treatment systems is presented in Appendix A, Projects 1 and 19.

A low-cost, point-of-use precipitation/coprecipitation treatment designed for use in developing nations with arsenic-contaminated drinking water was pilot-tested in four areas of Bangladesh (Appendix A, Project 32). This simple treatment process consists of a two-bucket system that uses potassium permanganate and alum to precipitate arsenic, followed by sedimentation and filtration. The equipment cost of the project was approximately $6, and treatment of 40 liters of water daily would require a monthly chemical cost of $0.20.

The document "*Technologies and Costs for Removal of Arsenic From Drinking Water*" (Ref. 2.7) contains more information on the cost of systems to treat arsenic in drinking water to below the revised MCL of 0.010 mg/L. The document includes capital and O&M cost curves for three precipitation/coprecipitation processes:

- Enhanced coagulation/filtration
- Enhanced lime softening
- Coagulation-assisted microfiltration

Factors Affecting Precipitation/Coprecipitation Costs

- **Type of chemical addition** - The chemical added will affect costs. For example, calcium hypochlorite is a less expensive oxidant than potassium permanganate (Ref. 2.16).
- **Chemical dosage** - The cost generally increases with increased chemical addition. Larger amounts of chemicals added usually results in a larger amount of sludge requiring additional treatment or disposal (Ref. 2.7, 2.12).
- **Treatment goal** -Application could require additional treatment to meet stringent cleanup goals and/or effluent and disposal standards (Ref. 2.7).
- **Sludge disposal** - Sludge produced from the precipitation/coprecipitation process could be considered a hazardous waste and require additional treatment before disposal, or require disposal as hazardous waste (Ref. 2.7).
- **Factors affecting precipitation/coprecipitation performance** - Items in the "Factors Affecting Precipitation/Coprecipitation Performance" box will also affect costs.

These cost curves are based on computer cost models for drinking water treatment systems. Table 1.6 contains cost estimates based on these curves for coagulation assisted microfiltration. The cost information available for enhanced coagulation/ filtration and enhanced lime softening are for retrofitting existing precipitation/coprecipitation systems at drinking water treatment plants to meet the revised MCL. Therefore, the cost information could not be used to estimate the cost of a new precipitation/ coprecipitation treatment system.

Retrofitting Existing Systems

The revised MCL for arsenic in drinking water could result in lower treatment goals for aboveground treatment systems. A lower goal can significantly affect the selection, design, and operation of treatment systems. In some cases, existing systems may need to be retrofitted to achieve lower treatment goals.

Modifications to precipitation/coprecipitation treatment systems that can help reduce the effluent concentrations of arsenic include:

- Use of additional treatment chemicals
- Use of different treatment chemicals
- Addition of another technology to the treatment train, such as membrane filtration

However, these modifications might result in additional costs for purchasing additional or more expensive treatment chemicals and disposing of increased amounts of treatment residuals. For example, use of more treatment chemicals is likely to increase the amount of sludge generated.

Case Study: Winthrop Landfill Site

The Winthrop Landfill site, located in Winthrop, Maine, is a former dump site that accepted municipal and industrial wastes (Appendix A, Project 1). Groundwater at the site was contaminated with arsenic and chlorinated and nonchlorinated VOCs. A pump-and-treat system for the groundwater has been in operation at the site since 1995. Organic compounds have been remediated to below action levels, and the pump-and-treat system is currently being operated for the removal of arsenic alone. The treatment train consists of equalization/pH adjustment to pH 3, chemical oxidation with hydrogen peroxide, precipitation/coprecipitation via pH adjustment to pH 7, flocculation/clarification, and sand bed filtration. The system currently treats 65 gpm of groundwater containing average concentrations of arsenic at 0.3 mg/L to a concentration below 0.005 mg/L. Through May 2001, 359 pounds of arsenic had been removed from groundwater at the Winthrop Landfill site using this aboveground treatment system. Capital costs for the system were about $2 million, and current O&M costs are approximately $250,000 per year (Ref. 2.29).

Reference 2.7 contains cost curves for capital and O&M costs associated with retrofitting coagulation/filtration and lime softening drinking water treatment systems to meet the revised MCL of 0.010 mg/L.

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3.0 ADSORPTION TREATMENT FOR ARSENIC

Summary

Adsorption has been used to treat groundwater and drinking water containing arsenic. Based on the information collected for this paper, this technology typically can reduce arsenic concentrations to less than 0.050 mg/L and in some cases has reduced arsenic concentrations to below 0.010 mg/L. Its effectiveness is sensitive to a variety of untreated water contaminants and characteristics. It is used less frequently than precipitation/coprecipitation, and is most commonly used to treat groundwater and drinking water, or as a polishing step for other water treatment processes.

Technology Description and Principles

Technology Description: In adsorption, solutes (contaminants) concentrate at the surface of a sorbent, thereby reducing their concentration in the bulk liquid phase. The adsorption media is usually packed into a column. As contaminated water is passed through the column, contaminants are adsorbed. When adsorption sites become filled, the column must be regenerated, or disposed of and replaced with new media.

Contaminants Treated:
- Dissolved organics
- Dissolved metals

Arsenic-Contaminated Media Treated:
- Groundwater
- Drinking water

Types of Sorbent Used to Treat Arsenic:
- Activated alumina (AA)
- Activated carbon (AC)
- Copper-zinc granules
- Granular ferric hydroxide, ferric hydroxide-coated newspaper pulp, iron oxide-coated sand, iron filings mixed with sand
- Greensand filtration ($KMnO_4$ coated glauconite)
- Proprietary media
- Surfactant-modified zeolite

This section discusses arsenic removal processes that use a fixed bed of media through which water is passed. Some of the processes described in this section rely on a combination of adsorption, precipitation/coprecipitation, ion exchange, and filtration. However, the primary removal mechanism in each process is adsorption in a fixed bed of media. For example, greensand is made from glauconite, a green, iron-rich, clay-like mineral that usually occurs as small pellets mixed with other sand particles. The glauconite-containing sand is treated with potassium permanganate ($KMnO_4$), forming a layer of manganese oxides on the sand. As water passes through a greensand filtration bed, the $KMnO_4$ oxidizes As(III) to As(V), and As(V) adsorbs onto the greensand surface.

Model of an Adsorption System
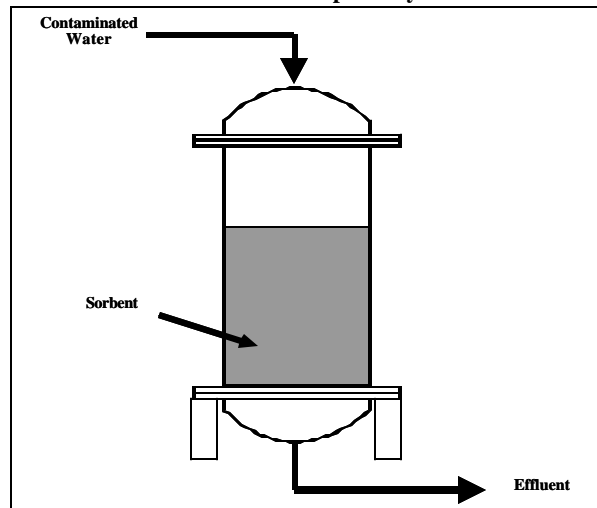
In addition, arsenic is removed by ion exchange, displacing species from the manganese oxide (presumably hydroxide ion [OH^-] and water [H_2O]). When the $KMnO_4$ is exhausted, the greensand media must be regenerated or replaced. Greensand media is regenerated with a solution of excess $KMnO_4$. Greensand filtration is also known as oxidation/filtration (Ref. 3.3).

Activated alumina (AA) is the sorbent most commonly used to remove arsenic from drinking water (Ref. 3.1) and has also been used for groundwater (Ref. 3.4). The reported adsorption capacity of AA ranges from 0.003 to 0.112 grams of arsenic per gram of AA (Ref. 3.4). AA is available in different mesh sizes, and its particle size affects contaminant removal efficiency. Up to 23,400 bed volumes of wastewater can be treated before AA

requires regeneration or disposal and replacement with new media (Ref. 3.3). AA regeneration is a four-step process:

- Backwashing
- Regeneration
- Neutralization
- Rinsing

The regeneration process desorbs the arsenic. The regeneration fluid most commonly used for AA treatment systems is a solution of sodium hydroxide. The most commonly used neutralization fluid is a solution of sulfuric acid. The regeneration and neutralization steps for AA adsorption systems might produce a sludge because the alumina can be dissolved by the strong acids and bases used in these processes, forming an aluminum hydroxide precipitate in the spent regeneration and neutralization fluids. This sludge typically contains a high concentration of arsenic (Ref. 3.1).

Activated carbon (AC) is an organic sorbent that is commonly used to remove organic and metal contaminants from drinking water, groundwater, and wastewater (Ref. 3.4). AC media are normally regenerated using thermal techniques to desorb and volatilize contaminants (Ref. 3.6). However, regeneration of AC media used for the removal of arsenic from water might not be feasible (Ref. 3.4). The arsenic might not volatilize at the temperatures typically used in AC regeneration. In addition, off-gas containing arsenic from the regeneration process might be difficult or expensive to manage.

The reported adsorption capacity of AC is 0.020 grams of As(V) per gram of AC (Ref. 3.4). As(III) is not effectively removed by AC (Ref. 3.4). AC impregnated with metals such as copper and ferrous iron has a higher reported adsorption capacity for arsenic. The reported adsorption capacity for As(III) is 0.048 grams per gram of copper-impregnated carbon and for As(V), the capacity is 0.2 grams per gram of ferrous iron-impregnated carbon (Ref. 3.4).

Iron-based adsorption media include granular ferric hydroxide, ferric hydroxide-coated newspaper pulp, iron oxide-coated sand, and iron filings mixed with sand. These media have been used primarily to remove arsenic from drinking water. Processes that use these media typically remove arsenic using adsorption in combination with oxidation, precipitation/ coprecipitation, ion exchange, or filtration. For example, iron oxide-coated sand uses adsorption and ion exchange with surface hydroxides to selectively remove arsenic from aqueous streams. The media requires periodic regeneration or disposal and replacement with new media. The regeneration process is similar to that used for AA and consists of rinsing the media with a regenerating solution containing excess sodium hydroxide, flushing with water, and neutralizing with a strong acid, such as sulfuric acid (Ref. 3.3).

The sources used for this issue paper contained information on the use of surfactant-modified zeolite (SMZ) at bench scale, but no pilot- or full-scale applications were identified. SMZ is prepared by treating zeolite with a solution of surfactant, such as hexadecyltrimethylammonium bromide (HDTMA-Br). This process forms a stable coating on the zeolite surface. The reported adsorption capacity of SMZ is 0.0055 grams of As(V) per gram of SMZ at 25^0C. SMZ must be periodically regenerated with surfactant solution or disposed and replaced with new SMZ (Ref. 3.17).

Adsorption can be operated using multiple beds in series to reduce the need for media regeneration; beds first in the series will require regeneration first, and fresh beds can be added at the end of the series. Multiple beds can also allow for continuous operation because some of the beds can be regenerated while others continue to treat water.

Type, Number, and Scale of Identified Projects

Adsorption technologies to treat arsenic-contaminated water in environmental media and drinking water are commercially available. Information is available on 23 applications of adsorption (Figure 3.1), including 12 environmental media and 11 drinking water applications. The data sources used for this report describe seven full-scale applications of adsorption to environmental media and eight full-scale applications to drinking water.

Summary of Performance Data

Adsorption treatment effectiveness can be evaluated by comparing influent and effluent contaminant concentrations. Appendix B presents the available performance data for this technology. Two of the four

Figure 3.1
Scale of Identified Adsorption Projects for Arsenic Treatment
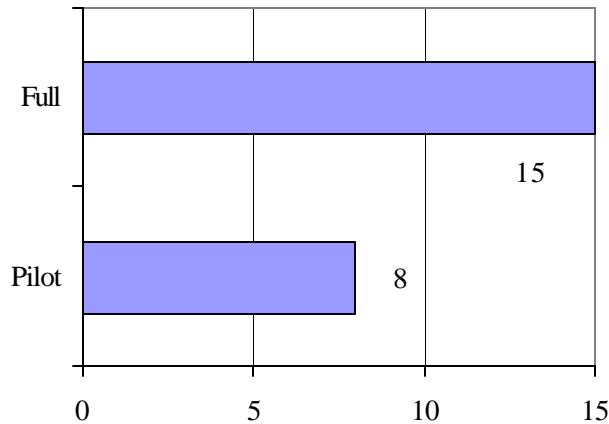
environmental media projects having both influent and effluent arsenic concentration data had influent concentrations greater than 0.050 mg/L. Effluent concentrations of 0.050 mg/L or less were achieved in both of the projects. In the other two projects, the influent concentration was between 0.010 mg/L and 0.050 mg/L, and the effluent concentration was less than 0.010 mg/L.

Factors Affecting Adsorption Performance

- **Wastewater pH** - The optimal pH to maximize adsorption of arsenic by activated alumina is acidic (pH 6). Therefore, pretreatment and post-treatment of the water could be required (Ref. 3.4).
- **Arsenic oxidation state** - Adsorption is more effective in removing As(V) than As(III) (Ref. 3.12).
- **Flow rate** - Increasing the rate of flow through the adsorption unit can decrease the adsorption of contaminants (Ref. 3.1).
- **Fouling** - The presence of suspended solids, organics, silica, or mica can cause fouling of adsorption media (Ref. 3.1, 3.4).

Of the ten drinking water projects (eight full- and two pilot-scale) having both influent and effluent arsenic concentration data, eight had influent concentrations greater than 0.050 mg/L. Effluent concentrations of less than 0.050 mg/L were achieved in seven of these

projects. For two drinking water projects the influent concentration was between 0.010 mg/L and 0.050 mg/L, and the effluent concentration was less than 0.010 mg/L.

Projects that did not reduce arsenic concentrations to below 0.050 or 0.010 mg/L do not necessarily indicate that adsorption cannot achieve these levels. The treatment goals for some applications could have been above these levels, and the technology may have been designed and operated to meet a higher arsenic concentration. Information on treatment goals was not collected for this issue paper.

Two pilot-scale studies were performed to compare the effectiveness of AA adsorption on As(III) and As(V) (Appendix B, Projects 3 and 4). For As(III), 300 bed volumes were treated before arsenic concentrations in the effluent exceeded 0.050 mg/L, whereas 23,400 bed volumes were treated for As(V) before reaching the same concentration in the effluent. The results of these studies indicate that the adsorption capacity of AA is much greater for As(V).

The case study in this section discusses in greater detail the use of AA to remove arsenic from drinking water. Information for this project is summarized in Appendix B, Project 12.

Advantages and Potential Limitations

For AA adsorption media, the spent regenerating solution might contain a high concentration of arsenic and other sorbed contaminants, and can be corrosive (Ref. 3.3). Spent AA is produced when the AA can no longer be regenerated (Ref. 3.3). The spent AA may require treatment prior to disposal (Ref. 3.4). Because regeneration of AA requires the use of strong acids and bases, some of the AA media becomes dissolved during the regeneration process. This can reduce the adsorptive capacity of the AA and cause the AA packing to become "cemented."

Regeneration of AC media normally involves the use of thermal energy, which could release volatile arsenic compounds. Use of air pollution control equipment may be necessary to remove arsenic from the off-gas produced (Ref. 3.6).

Competition for adsorption sites could reduce the effectiveness of adsorption because other constituents

might be preferentially adsorbed, resulting in a need for more frequent bed regeneration or replacement. The presence of sulfate, chloride, and organic compounds has reportedly reduced the adsorption capacity of AA for arsenic (Ref. 3.3). The order for adsorption preference for AA is provided below, with constituent having the greatest adsorption preference appearing at the top left (Ref. 3.3):

$$OH^- > H_2AsO_4^- > Si(OH)_3O^- > F^- > HSeO_3^- > SO_4^{2-} > H_3AsO_3$$
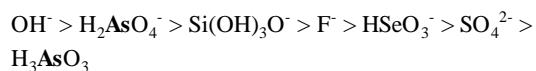
This technology's effectiveness is also sensitive to a variety of contaminants and characteristics in the untreated water, and suspended solids, organics, silica, or mica can cause fouling. Therefore, it is typically applied to groundwater and drinking water, which are less likely to contain fouling contaminants. It may also be used as a polishing step for other water treatment technologies.

More detailed information on selection and design of arsenic treatment systems for small drinking water systems is available in the document "*Arsenic Treatment Technology Design Manual for Small Systems*" (Ref. 3.21).

Summary of Cost Data

One source reported that the cost of removing arsenic from drinking water using AA ranged from $0.003 to $0.76 per 1,000 gallons (Ref. 3.4, cost year not provided). The document "*Technologies and Costs for Removal of Arsenic From Drinking Water*" (Ref. 3.3) contains more detailed information on the cost of adsorption systems to treat arsenic in drinking water to below the revised MCL of 0.010 mg/L. The document includes capital and O&M cost curves for four adsorption processes:

- AA (at various influent pH levels)
- Granular ferric hydroxide
- Greensand filtration ($KMNO_4$ - coated sand)
- AA point-of-use systems

These cost curves are based on computer cost models for drinking water treatment systems. The curves show the costs for adsorption treatment systems with different design flow rates. The document also contains information on the disposal cost of residuals from adsorption. Although this issue paper focuses on

the aboveground treatment of arsenic-contaminated groundwater, many of the same treatment technologies used to treat drinking water are also applicable to aboveground treatment of groundwater and may have similar costs.

Factors Affecting Adsorption Costs

- **Contaminant concentration** - Very high concentrations of competing contaminants may require frequent replacement or regeneration of adsorbent (Ref. 3.2). The capacity of the adsorption media increases with increasing contaminant concentration (Ref. 3.1, 3.4). High arsenic concentrations can exhaust the adsorption media quickly, resulting in the need for frequent regeneration or replacement.
- **Spent media** - Spent media that can no longer be regenerated might require treatment or disposal (Ref. 3.4).
- **Factors affecting adsorption performance -** Items in the "Factors Affecting Adsorption Performance" box will also affect costs.

Retrofitting Existing Systems

Modifications to adsorption treatment systems that could reduce the effluent concentrations of arsenic to meet the revised MCL of 0.010 mg/L include:

- Addition of an adsorption media bed
- Use of a different adsorption media
- More frequent replacement or regeneration of adsorption media
- Decrease in the flow rate of water treated
- Addition of another treatment technology to the treatment train, such as membrane filtration

However, these modifications could result in additional costs for purchasing additional or more expensive adsorption media, more frequent regeneration of adsorption media, and increased amounts of treatment.residuals. For example, more frequent regeneration of adsorption media is likely to generate greater volumes of spent regeneration fluid, and result in higher disposal costs.

Case Study: Treatment of Drinking Water By An Activated Alumina Plant

A drinking water treatment plant using AA (Appendix B, Project 1) installed in February 1996, has an average flow rate of 3,000 gpd. The arsenic treatment system consists of two parallel treatment trains, with two AA columns in series in each train. For each of the trains, the AA media in one column is exhausted and replaced every 1 to 1.5 years after treating approximately 5,260 bed volumes.

Water samples for a long-term evaluation were collected weekly for a year. Pretreatment arsenic concentrations at the inlet ranged from 0.053 to 0.087 mg/L, with an average of 0.063 mg/L. The untreated water contained primarily As(V), with only minor concentrations of As(III) and particulate arsenic. During the entire evaluation, the arsenic concentration in the treated drinking water was below 0.003 mg/L. Spent AA from the system had leachable arsenic concentrations of less than 0.05 mg/L, as measured by the TCLP, and therefore, could be disposed of as nonhazardous waste.

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4.0 ION EXCHANGE FOR ARSENIC

Summary

Ion exchange has been used to treat groundwater and drinking water containing arsenic. Based on the information collected to prepare this paper, this technology typically can reduce arsenic concentrations to less than 0.050 mg/L and in some cases has reduced arsenic concentrations to below 0.010 mg/L. Its effectiveness is sensitive to a variety of untreated water contaminants and characteristics. It is used less frequently than precipitation/coprecipitation, and is most commonly used to treat groundwater and drinking water, or as a polishing step for other water treatment processes.

Technology Description and Principles

Technology Description: Ion exchange is a physical/chemical process in which ions held electrostatically on the surface of a solid are exchanged for ions of similar charge in a solution. It removes ions from the aqueous phase by the exchange of cations or anions between the contaminants and the exchange medium (Ref. 4.1, 4.4, 4.8).

Contaminants Treated:
- Dissolved inorganic ions

Arsenic-Contaminated Media Treated:
- Groundwater
- Surface water
- Drinking water

Ion Exchange Media Used to Treat Arsenic:
- Strong base anion exchange resins

The medium used for ion exchange is typically a resin made from synthetic organic materials, inorganic materials, or natural polymeric materials that contain ionic functional groups to which exchangeable ions are attached (Ref. 4.3). Four types of ion exchange media have been used (Ref. 4.1):

- Strong acid
- Weak acid
- Strong base
- Weak base

Strong and weak acid resins exchange cations while strong and weak base resins exchange anions. Because dissolved arsenic is usually in an anionic form, and weak base resins tend to be effective over a smaller pH range, strong base resins are typically used for arsenic treatment (Ref. 4.1).

Model of an Ion Exchange System
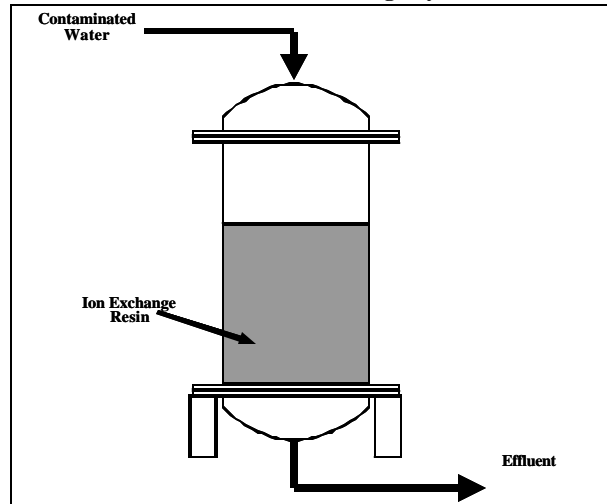
Resins may also be categorized by the ion that is exchanged with the one in solution. For example, resins that exchange a chloride ion are referred to as chloride-form resins. Another way of categorizing resins is by the type of ion in solution that the resin preferentially exchanges. For example, resins that preferentially exchange sulfate ions are referred to as sulfate-selective. Both sulfate-selective and nitrate-selective resins have been used for arsenic removal (Ref. 4.1). The resin is usually packed into a column, and as contaminated water is passed through the column, contaminant ions are exchanged for other ions such as chloride or hydroxide in the resin (Ref. 4.4). Ion exchange is often preceded by treatments such as filtration and oil-water separation to remove organics, suspended solids, and other contaminants that can foul the resins and reduce their effectiveness.

Ion exchange resins must be periodically regenerated to remove the adsorbed contaminants and replenish the

exchanged ions (Ref. 4.4). Regeneration of a resin occurs in three steps:

- Backwashing
- Regeneration with a solution of ions
- Final rinsing to remove the regenerating solution

The regeneration process results in a backwash solution, a waste regenerating solution, and a waste rinse water. The volume of spent regeneration solution ranges from 1.5 to 10 percent of the treated water volume depending on the feed water quality and type of ion exchange unit (Ref. 4.4). The number of ion exchange bed volumes that can be treated before regeneration is needed can range from 300 to 60,000 (Ref. 4.1). The regenerating solution can be used up to 25 times before treatment or disposal is required. The final rinsing step usually requires only a few bed volumes of water (Ref. 4.4).

Ion exchange can be operated using multiple beds in series to reduce the need for bed regeneration; beds first in the series will require regeneration first, and fresh beds can be added at the end of the series. Multiple beds can also allow for continuous operation because some of the beds can be regenerated while others continue to treat water. Ion exchange beds are typically operated as a fixed bed, in which the water to be treated is passed over an immobile ion exchange resin. One variation on this approach is to operate the bed in a non-fixed, countercurrent fashion in which water is applied in one direction, usually downward, while spent ion exchange resin is removed from the top of the bed. Regenerated resin is added to the bottom of the bed. This method can reduce the frequency of resin regeneration (Ref. 4.4).

Type, Number, and Scale of Identified Projects

Ion exchange technology for arsenic in environmental media and drinking water is commercially available. Information is available on seven full-scale applications (Figure 4.1), including three applications to environmental media and four applications to drinking water. No pilot-scale applications or applications to industrial wastewater were found in the sources researched.

**Figure 4.1
Scale of Identified Ion Exchange Projects for Arsenic Treatment**
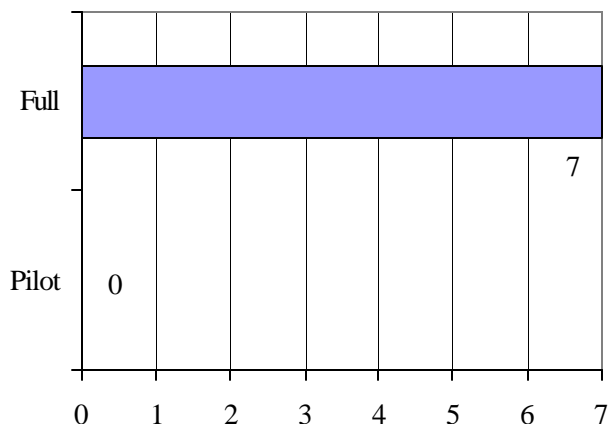
Summary of Performance Data

Appendix C presents the available performance data for this technology. Ion exchange treatment effectiveness can be evaluated by comparing influent and effluent contaminant concentrations. The single environmental media project with both influent and effluent arsenic concentration data had an influent concentration of

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Factors Affecting Ion Exchange Performance

- **Valence state** - As(III) is generally not removed by ion exchange (Ref. 4.4).
- **Presence of competing ions** - Competition for the exchange ion can reduce the effectiveness of ion exchange if ions in the resin are replaced by ions other than arsenic, resulting in a need for more frequent bed regeneration (Ref. 4.1, 4.9).
- **Fouling** - The presence of organics, suspended solids, calcium, or iron, can cause fouling of ion exchange resins (Ref. 4.4).
- **Presence of trivalent iron** - The presence of Fe(III) could cause arsenic to form complexes with the iron that are not removed by ion exchange (Ref. 4.1).
- **pH** - For chloride-form, strong-base resins, a pH in the range of 6.5 to 9 is optimal. Outside of this range, arsenic removal effectiveness decreases quickly (Ref. 4.1).

0.0394 mg/L, and an effluent concentration of 0.0229 mg/L.

Of the three drinking water projects with both influent and effluent concentration data, all had influent concentrations greater than 0.010 mg/L. Effluent concentrations of less than 0.010 mg/L were consistently achieved for only one of these projects. Projects that did not reduce arsenic concentrations to below 0.050 or 0.010 mg/L do not necessarily indicate that ion exchange cannot achieve these levels. The treatment goal for some applications could have been above these levels and the technology may have been designed and operated to meet a higher arsenic concentration. Information on treatment goals was not collected for this issue paper.

The case study at the end of this section further discusses the use of ion exchange to remove arsenic from drinking water. Information for this project is summarized in Appendix C, Project 6.

Advantages and Potential Limitations

For ion exchange systems using chloride-form resins, the treated water could contain increased levels of chloride ions and as a result be corrosive. Chlorides can also increase the redox potential of iron, thus increasing the potential for water discoloration if the iron is oxidized. The ion exchange process can also lower the pH of treated waters (Ref. 4.4).

For ion exchange resins used to remove arsenic from water, the spent regenerating solution might contain a high concentration of arsenic and other sorbed contaminants, and could be corrosive. Spent resin is produced when the resin can no longer be regenerated. The spent resin may require treatment prior to reuse or disposal.

The order for exchange for most strong-base resins is provided below, with the constituent with the greatest adsorption preference appearing at the top left (Ref. 4.4).

$$HCrO_4^- > CrO_4^{2-} > ClO_4^- > SeO_4^{2-} > SO_4^{2-} > NO_3^- > Br^- >$$
$$(HPO_4^{2-}, HAsO_4^{2-}, SeO_3^{2-}, CO_3^{2-}) > CN^- > NO_2^- > Cl^-$$
$$> (H_2PO_4^-, H_2AsO_4^-, HCO_3^-) > OH^- > CH_3COO^- > F^-$$

The effectiveness of ion exchange is also sensitive to a variety of contaminants and characteristics in the untreated water, and organics, suspended solids, calcium, or iron can cause fouling. Therefore, it is typically applied to groundwater and drinking water, which are less likely to contain fouling contaminants. It may also be used as a polishing step for other water treatment technologies.

More detailed information on selection and design of arsenic treatment systems for small drinking water systems is available in the document "*Arsenic Treatment Technology Design Manual for Small Systems*" (Ref. 4.10).

Summary of Cost Data

One project reported a capital cost for an ion exchange system of $6,886 with an additional $2,000 installation fee (Ref. 4.9, cost year not provided). The capacity of the system and O&M costs were not reported. Cost data for other projects using ion exchange were not available.

The document "*Technologies and Costs for Removal of Arsenic From Drinking Water*" (Ref. 4.1) contains additional information on the cost of ion exchange systems for treating arsenic in drinking water to levels below the revised MCL of 0.010 mg/L. The document includes capital and O&M cost curves for ion exchange at various influent sulfate (SO_4) concentrations. These cost curves are based on computer cost models for drinking water treatment systems.

Factors Affecting Ion Exchange Costs

- **Bed regeneration** - Regenerating ion exchange beds reduces the amount of waste for disposal and the cost of operation (Ref. 4.8).
- **Sulfate** - Sulfate (SO_4) can compete with arsenic for ion exchange sites, thus reducing the exchange capacity of the ion exchange media for arsenic. This can result in a need for more frequent media regeneration or replacement, and associated higher costs (Ref. 4.1).
- **Factors affecting ion exchange performance -** Items in the "Factors Affecting Ion Exchange Performance" box will also affect costs.

The curves estimate the costs for ion exchange treatment systems with different design flow rates. The document also contains information on the disposal cost for residuals from ion exchange. Although this issue paper focuses on the aboveground treatment of arsenic-contaminated groundwater, many of the technologies used to treat drinking water are applicable to aboveground treatment of groundwater and may have similar costs.

Retrofitting Existing Systems

Modifications to ion exchange treatment systems that can help reduce the effluent concentrations of arsenic to meet the revised MCL of 0.010 mg/L include:

- Addition of an ion exchange bed
- Use of a different ion exchange resin
- More frequent regeneration or replacement of ion exchange media
- Decrease in the flow rate of water treated
- Addition of another technology to the treatment train, such as membrane filtration

However, these modifications could increase costs for purchasing additional or more expensive resin, more frequent regeneration of resin, and increased amounts of treatment residuals. For example, more frequent regeneration of resin is likely to generate greater volumes of spent regeneration fluid.

Case Study: National Risk Management Research Laboratory Study

A study by EPA ORD's National Risk Management Research Laboratory tested an ion exchange system at a drinking water treatment plant. Weekly sampling for 1 year showed that the plant achieved an average of 97 percent arsenic removal. The resin columns were frequently regenerated (every 6 days). Influent arsenic concentrations ranged from 0.045 to 0.065 mg/L and effluent concentrations ranged from 0.0008 to 0.0045 mg/L (Ref. 4.9) (Appendix C, Project 6).

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5.0 MEMBRANE FILTRATION FOR ARSENIC

Summary

Membrane filtration can remove a wide range of contaminants from water. Based on the information collected to prepare this paper, this technology typically can reduce arsenic concentrations to less than 0.050 mg/L and in some cases has reduced arsenic concentrations to below 0.010 mg/L. However, its effectiveness is sensitive to a variety of untreated water contaminants and characteristics. It also produces a larger volume of residuals and tends to be more expensive than other arsenic treatment technologies. Therefore, it is used less frequently than precipitation/coprecipitation, adsorption, and ion exchange. It is most commonly used to treat groundwater and drinking water, or as a polishing step for precipitation processes. Only two full-scale projects using membrane filtration to treat arsenic were identified in the sources researched for this paper.

Technology Description and Principles

Technology Description: Membrane filtration separates contaminants from water by passing it through a semipermeable barrier or membrane. The membrane allows some constituents to pass through, while blocking others (Ref. 5.2, 5.3).

Contaminants Treated:
- Dissolved inorganics
- Suspended solids
- Dissolved organics
- Colloids

Arsenic-Contaminated Media Treated:
- Drinking water
- Groundwater
- Surface water
- Industrial wastewater

Types of Membrane Processes:
- Microfiltration (MF)
- Ultrafiltration (UF)
- Nanofiltration (NF)
- Reverse osmosis (RO)

There are four types of membrane processes: reverse osmosis (RO), nanofiltration (NF), microfiltration (MF), and ultrafiltration (UF). All four are pressure-driven and are categorized by the size of the particles that can pass through the membranes or by the molecular weight limit (i.e., pore size) of the membrane (Ref. 5.2). The force required to drive fluids across the membranes depends on the pore size; NF and RO require a relatively high pressure (50 to 150 pounds per square inch [psi]), while MF and UF require a relatively low pressure (5 to 100 psi). The low-pressure processes primarily remove contaminants through physical sieving and the high-pressure processes primarily remove contaminants through chemical diffusion across the permeable membrane (Ref. 5.4).

Because arsenic species dissolved in water tend to have relatively low molecular weights, only NF and RO membrane processes are likely to effectively treat dissolved arsenic (Ref. 5.4). MF has been used in conjunction with precipitation/coprecipitation to remove solids containing arsenic. The sources used for this issue paper did not contain any information on the use of UF to remove arsenic; therefore, UF is not discussed in this technology summary. Membrane filtration processes generate two treatment residuals from the influent waste stream: a treated effluent (permeate) and a rejected waste stream of concentrated contaminants (reject).

Model of a Membrane Filtration System
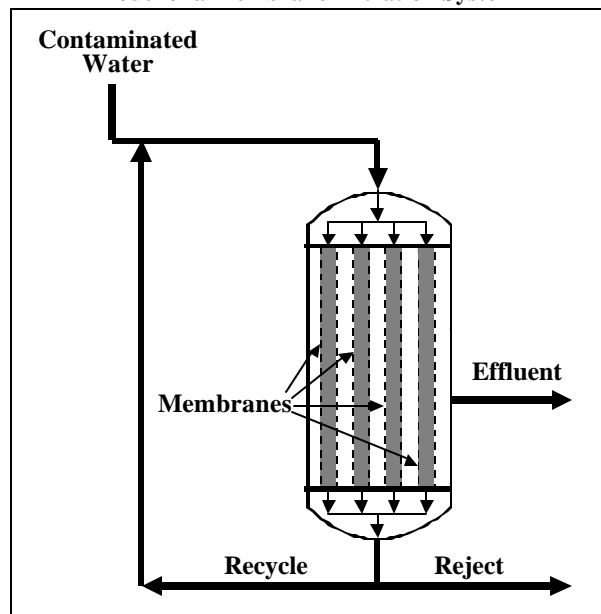
RO is a high-pressure process that primarily removes smaller ions typically associated with total dissolved solids. The molecular weight cutoff for RO membranes ranges from 1 to 20,000, which is a significantly lower limit than for NF membranes (Ref. 5.4). The molecular weight cutoff for NF membranes ranges from approximately 150 to 20,000. NF is a high-pressure process that primarily removes larger divalent ions associated with hardness (for example, calcium [Ca], and magnesium [Mg]) but not monovalent salts (for example, sodium [Na] and chlorine [Cl]). NF is slightly less efficient than RO in removing dissolved arsenic from water (Ref. 5.4).

MF is a low-pressure process that primarily removes particles with a molecular weight above 50,000 or a particle size greater than 0.050 micrometers. The pore size of MF membranes is too large to effectively remove dissolved arsenic species, but MF can remove particulates containing arsenic and solids produced by precipitation/coprecipitation processes (Ref. 5.4).

Type, Number, and Scale of Identified Projects

The data gathered for this paper identified one full-scale RO and one full-scale MF treatment of arsenic in groundwater and surface water (Figure 5.1). The MF application is a treatment train consisting of precipitaiton/coprecipitation followed by MF to remove solids. In addition, 16 pilot-scale and three bench-scale applications of RO and eight pilot-scale and three bench-scale applications of NF have been identified. One pilot-scale application of MF to remove solids from precipitation/coprecipitation processes has also been identified.

Figure 5.1
Scale of Identified Membrane Filtration Projects for Arsenic Treatment
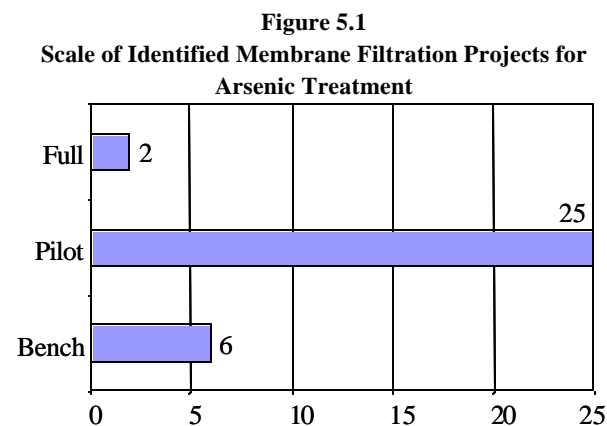
Summary of Performance Data

Appendix D presents the available performance data for this technology. Performance results for membrane filtration are typically reported as percent removal, (i.e., the percentage of arsenic, by mass, in the influent that is removed or rejected from the influent wastewater stream). A higher percentage indicates greater removal of arsenic, and therefore, more efficient treatment. Although many of the projects listed in Appendix D may have reduced arsenic concentrations to levels below 0.050 mg/L or 0.010 mg/L, data on the arsenic concentrations in the effluent and reject streams were not available for most projects.

Factors Affecting Membrane Filtration Performance

- **Suspended solids, high molecular weight, dissolved solids, organic compounds, and colloids -** The presence of these constituents in the feed stream could cause membrane fouling (Ref. 5.2).
- **Oxidation state of arsenic** - Prior oxidation of the influent stream to convert As(III) to As(V) will increase arsenic removal; As(III) is smaller and diffuses more easily through the membrane than As(V) (Ref. 5.2).
- **pH -** pH might affect the adsorption of arsenic on the membrane by creating an electrostatic charge on the membrane surface (Ref. 5.4).
- **Temperature** - Low influent stream temperatures decrease membrane flux. Increasing system pressure or increasing the membrane surface area can compensate for low influent stream temperature (Ref. 5.4).

For two RO projects, the arsenic concentration in the reject stream was available, allowing the concentration in the permeate to be calculated. For both projects, the concentration of arsenic prior to treatment was greater than 0.050 mg/L, and was reduced to less than 0.010 mg/L in the treated water.

For two projects involving removal of solids from precipitation/coprecipitation treatment of arsenic with MF, the arsenic concentration in the permeate was available. The concentration prior to precipitation/coprecipitation treatment was greater than 0.050 mg/L

for one project, and ranged from 0.005 to 3.8 mg/L for the other. For both projects, the concentrations in the treated water were less than 0.005 mg/L.

The case study at the end of this section further discusses the use of membrane filtration to remove arsenic from groundwater used as a drinking water source. Information for this site is summarized in Appendix D, Project 31.

Advantages and Potential Limitations

Membrane technologies are capable of removing a wide range of dissolved contaminants and suspended solids from water (Ref. 5.12). RO and NF technologies require no chemical addition to ensure adequate separation. This type of treatment can be run in either batch or continuous mode. This technology's effectiveness is sensitive to a variety of contaminants and characteristics in the untreated water. Suspended solids, organics, colloids, and other contaminants can cause membrane fouling. Therefore, it is typically applied to groundwater and drinking water, which are less likely to contain fouling contaminants. It is also applied to remove solids from precipitation processes and as a polishing step for other water treatment technologies when lower concentrations must be achieved.

More detailed information on selection and design of arsenic treatment systems for small drinking water systems is available in the document "*Arsenic Treatment Technology Design Manual for Small Systems*" (Ref. 5.16).

Summary of Cost Data

The research conducted for support of this issue paper did not document any cost data for specific membrane filtration projects to treat arsenic. However, the document "*Technologies and Costs for Removal of Arsenic From Drinking Water*" (Ref. 5.4) contains additional information on the cost of point-of-use reverse osmosis systems to treat arsenic in drinking water to levels below the revised MCL of 0.010 mg/L. The document includes capital and O&M cost curves for this technology. These cost curves are based on computer cost models for drinking water treatment systems.

Factors Affecting Membrane Filtration Costs

- **Type of membrane filtration** - The type of membrane selected could affect the cost of the treatment (Ref. 5.1, 5.2).
- **Initial waste stream** - Certain waste streams may require pretreatment, which would increase costs (Ref. 5.4).
- **Rejected waste stream** - Based on concentrations of the removed contaminant, further treatment might be required prior to disposal or discharge (Ref. 5.4).
- **Factors affecting membrane filtration performance -** Items in the "Factors Affecting Membrane Filtration Performance" box will also affect costs.

Retrofitting Existing Systems

Modifications to membrane filtration treatment systems that could help reduce the effluent concentrations of arsenic to meet the revised MCL of 0.010 mg/L include:

1. Increasing the volume of reject generated per volume of water treated
2. Using a membrane with a smaller molecular weight cutoff
3. Decreasing the flow rate of water treated
4. Adding another treatment technology to the treatment train, such as ion exchange

However, these modifications can result in additional costs for more expensive membranes and increased amounts of treatment residuals requiring disposal. For example, increasing the volume of reject generated per volume of water treated will produce greater volumes of reject that require treatment or disposal.

Case Study: Park City Spiro Tunnel Water Filtration Plant

The Park City Spiro Tunnel Water Filtration Plant in Park City, Utah treats groundwater from water-bearing fissures that collect in a tunnel of an abandoned silver mine to generate drinking water. A pilot-scale RO unit treated contaminated water at a flow rate of 0.77 gpm from the Spiro tunnel for 34 days. The total and dissolved arsenic in the feedwater averaged 0.065 and 0.042 mg/L, respectively. The total and dissolved arsenic concentrations in the permeate averaged <0.0005 and less than <0.0008 mg/L, respectively. The RO process reduced average As(V) from 0.035 to 0.0005 mg/L and average As(III) from 0.007 to 0.0005 mg/L. The membrane achieved 99% total As removal and 98% As(V) removal (Ref. 5.12) (Appendix D, Project 31).

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Appendix A
Precipitation/Coprecipitation Treatment Performance Data for Arsenic

Table A.1

Available Precipitation/Coprecipitation Treatment Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
Environmental Media - Coagulation/Filtration									
1	Landfill	Groundwater	Full	Winthrop Landfill Superfund Site, Winthrop, ME	0.300 mg/L	<0.005 mg/L	-	Treatment train consisting of pH adjustment, oxidation, flocculation/ clarification, air stripping, and sand-bed filtration	2.29
2	Metal ore mining and smelting	Surface water, 8,500,000 gallons	Full	Tex-Tin Superfund Site, OU 1, TX	-	-	-	Precipitation by pH adjustment followed by filtration	2.8
Environmental Media - Iron Coprecipitation									
3	Herbicide application	Groundwater	Full	-	0.005 - 3.8 mg/L	<0.005 - 0.05 mg/L	<5 mg/L (TCLP)	Iron coprecipitation followed by membrane filtration	2.27
4	Energized substation	Groundwater, 44 million gallons	Full	Fort. Walton Beach, FL	0.2-1.0 mg/L	<0.005 mg/L	-	Iron coprecipitation followed by ceramic membrane filtration	2.33

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
5	Chemical mixing	Groundwater	Full	Baird and McGuire Superfund Site, Holbrook, MA	-	-	-	Treatment train consisting of air stripping, precipitation (ferric chloride, lime slurry, phosphoric and sulfuric acids, and ammonium sulfate), filtration, and carbon adsorption	2.5, 2.14
6	Wood preserving wastes	Groundwater	Full	Silver Bow Creek/Butte Area Superfund Site - Rocker Timber Framing And Treatment Plant OU, MT	-	-	-	In situ treatment of contaminated groundwater by injecting a solution of ferrous iron, limestone, and potassium permanganate	2.8
7	Metal ore mining and smelting activities	Collection pond water	Pilot	Ryan Lode Mine, AK	4.6 mg/L	0.027 mg/L	-	Enhanced iron coprecipitation followed by filtration	2.18
8	Herbicide application	Groundwater	Pilot	-	1 mg/L	<0.005 mg/L	-	Iron coprecipitation followed by ceramic membrane filtration	2.11
9	Metals processing	Leachate from nickel roaster flue dust disposal area	Pilot	Susie Mine/Valley Forge site, Rimini, MT	423 - 439 mg/L	<0.32 mg/L	102,000 mg/kg (TWA) 0.547-0.658 mg/L (TCLP)	Photo-oxidation of arsenic followed by iron coprecipitation	2.16

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
10	Metal ore mining	Acid mine water	Pilot	Susie Mine/Valley Forge site, Rimini, MT	12.2 - 16.5 mg/L	0.017 - 0.053 mg/L	8,830-13,300 mg/kg (TWA) 0.0051-0.0076 mg/L (TCLP)	Photo-oxidation of arsenic followed by iron coprecipitation	2.16
Environmental Media - Other or Unspecified Precipitation Process									
11	-	Groundwater	Full	-	100 mg/L	< 0.2 mg/L	-	-	2.17
12	-	"Superfund wastewater"[e]	Full	-	0.1 - 1 mg/L	0.022 mg/L	-	Chemical precipitation	2.9
13	-	"Superfund wastewater"[e]	Full	-	0.1 - 1 mg/L	0.110 mg/L	-	Chemical precipitation	2.9
14	-	Groundwater	Full	-	100 mg/L	<0.010 mg/L	-	Reductive precipitation (additional information not available)	2.17
15	Chemical manufacturing wastes, groundwater	Groundwater	Full	Peterson/Puritan Inc. Superfund Site - OU 1, PAC Area, RI	-	-	-	In situ treatment of arsenic-contaminated groundwater by injecting oxygenated water	2.8
16	Chemical manufacturing	Groundwater, 65,000 gpd	Full	Greenwood Chemical Superfund Site, Greenwood, VA	-	-	-	Treatment train consisting of metals precipitation, filtration, UV oxidation and carbon adsorption	2.14

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
17	Waste disposal	Groundwater, 43,000 gpd	Full	Higgins Farm Superfund Site, Franklin Township, NJ	-	-	-	Treatment train consisting of air stripping, metals precipitation, filtration, and ion exchange	2.14
18	Wood preserving	Groundwater, 3,000 gpd	Full	Saunders Supply Company Superfund Site, Chuckatuck, VA	-	-	-	Treatment train consisting of metals precipitation, filtration, and carbon adsorption.	2.14
19	Herbicide manufacturing	Groundwater, RCRA waste code K031, 1 mgd	Full	Vineland Chemical Company Superfund Site, Vineland, NJ	-	-	-	Metals precipitation followed by filtration	2.14
20	Veterinary feed additives and pharmaceuticals manufacturing	Groundwater, 50-100 gpm	Full	Whitmoyer Laboratories Superfund Site, PA	100 mg/L	0.025 mg/L	-	Neutralization and flocculation by increasing pH to 9	2.36

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
Drinking Water - Iron Coprecipitation									
21	-	Drinking water, 1.6 mgd	Full	-	0.0203 mg/L	0.0030 mg/L	<5 mg/L (WET)	Ferric coprecipitation followed by zeolite softening	2.7
22	-	Drinking water, 1.4 mgd	Full	-	0.0485 mg/L	0.0113 mg/L	<5 mg/L (WET)	Ferric coprecipitation	2.7
23	-	Drinking water	Full	McGrath Road Baptist Church, AK	0.370 mg/L	<0.005 mg/L	-	Enhanced iron coprecipitation followed by filtration	2.18
24	-	Drinking water	Full	-	Plant A: 0.02 mg/L Plant B: 0.049 mg/L	Plant A: 0.003 mg/L Plant B: 0.012 mg/L	-	Adsorption and coprecipitation with iron hydroxide precipitates	2.10
25	-	Drinking water, 600 mgd	Full	-	0.0026 - 0.0121 mg/L	0.0008 - 0.006 mg/L	806-880 mg/kg (TWA) <0.05 - 0.106 mg/L (TCLP)	Ozonation followed by coagulation with iron- and aluminum-based additives and filtration	2.25
26	-	Drinking water, 62.5 mgd	Full	-	0.015 - 0.0239 mg/L	0.0015 - 0.0118 mg/L	293-493 mg/kg (TWA) 0.058 - 0.114 mg/L (TCLP)	Coagulation with iron- and aluminum-based additives, sedimentation, and filtration	2.25

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
27	-	Drinking water, 1.0-1.1 gpm	Pilot	Spiro Tunnel Water Filtration Plant, Park City, UT	0.0609 - 0.146 mg/L	0.0012 - 0.0345 mg/L	-	Precipitation with ferric chloride and sodium hypochlorite, followed by filtration	2.26
28	-	Drinking water	Pilot	-	-	<0.002 mg/L Arsenic (V)	-	Iron coagulation with direct filtration	2.24
29	–	Drinking water, 5.3 gallons	Pilot	Bhariab & Sreenagar Thana, Bangladesh	0.28 - 0.59 mg/L	<0.03 - 0.05 mg/L	1194 mg/kg	Iron co-precipitation followed by filtration	2.37
Drinking Water - Lime Softening									
30	-	Drinking water, 10 mgd	Full	-	0.0159 - 0.0849 mg/L	0.0063 - 0.0331 mg/L	17.0-35.3 mg/kg (TWA) <0.05 mg/L (TCLP)	Oxidation followed by lime softening and filtration	2.25
31	-	Drinking water	Full	Five facilities, identification unknown	-	<0.003 mg/L	<5 mg/L (TCLP)	Lime softening at pH >10.2	2.7
Drinking Water - Point-of-Use Systems									
32	-	Drinking water, 40 liters per day	Pilot	Noakhali, Bangladesh	0.12 - 0.46 mg/L	<0.05 mg/L	-	Coagulation with potassium permanganate and alum, followed by sedimentation and filtration	2.19

Table A.1
Available Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
33	-	Drinking water	Pilot	Harian Village Rajshaji District Bangladesh	0.092 - 0.120 mg/L	0.023 - 0.036 mg/L	-	Naturally-occuring iron at 9 mg/L facilitates precipitation, followed by sedimentation, filtration and acidification	2.22
34	-	Drinking water	Pilot	West Bengal, India	0.300 mg/L	0.030 mg/L	-	Precipitation with sodium hypochlorite and alum, followed by mixing, flocculation, sedimentation, and up-flow filtration	2.22
35	-	Drinking water, 20 liters per day	Pilot	West Bengal, India	-	-	-	Precipitation by ferric salt, oxidizing agent, and activated charcoal, followed by sedimentation and filtration	2.21
Wastewaters - Lime Softening									
36	-	K084, wastewater	Full	Charles City, Iowa	399 - 1,670 mg/L	Calcium arsenate, 60.5 - 500 mg/L	45,200 mg/kg (TWA) 2,200 mg/L (TCLP)	Calcium hydroxide	2.3
37	-	Wastewater	Full	-	4.2 mg/L	0.51 mg/L	-	Lime precipitation followed by sedimentation	2.4

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
38	-	Wastewater	Full	-	4.2 mg/L	0.34 mg/L	-	Lime precipitation followed by sedimentation and filtration	2.4
39	-	Wastewater	Full	BP Minerals America	-	-	Calcium arsenate and calcium arsenite, 1,900 - 6,900 mg/kg (TWA) 0.2 - 74.5 mg/L (EPT)	Lime	2.3
Wastewaters - Metal Sulfates									
40	-	K084, wastewater	Full	Charles City, Iowa	125 - 302 mg/L	Manganese arsenate, 6.02 - 22.4 mg/L	47,400 mg/kg (TWA) 984 mg/L (TCLP)	Manganese sulfate	2.3
41	Metals processing	Spent leachate from the recovery of Cu, Ag, and Sb from ores (amount not available)	Full	Equity Silver Mine, Houston, British Columbia, Canada	-	-	95 to 98% recovery of arsenic	Acid addition, chemical precipitation with copper sulfate, and filtration	2.30

Table A.1
Available Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
42	Metals processing	Leachate from filter cake from purification of zinc sulfate electro-winning solution (amount not available)	Full	Texasgulf Canada, Timmons, Ontario, Canada	-	-	98% recovery of arsenic	Acid addition, chemical precipitation with copper sulfate, and filtration	2.30
Wastewaters - Iron Coprecipitation									
43	-	K084, wastewater	Full	Charles City, Iowa	15 - 107 mg/L	Ferric arsenate, 0.163 - 0.580 mg/L	9,760 mg/kg (TWA) 0.508 mg/L (TCLP)	Ferric sulfate	2.3
44	-	Wastewater from wet scrubbing of incinerator vent gas (D004, P011)	Full	American NuKem	69.6 - 83.7 mg/L	<0.02 - 0.6 mg/L	-	Chemical oxidation followed by precipitation with ferric salts	2.3
Wastewaters - Other or Unspecified Precipitation Process									
45	-	Wastewater	Full	-	<0.1 - 3.0 mg/L	0.18 mg/L	-	Chemical reduction followed by precipitation, sedimentation, and filtration	2.4

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
46	Centralized waste treatment industry	Wastewater	Full	-	57 mg/L	0.181 mg/L	-	Primary precipitation with solids-liquid separation	2.6
47	Centralized waste treatment industry	Wastewater	Full	-	57 mg/L	0.246 mg/L	-	Primary precipitation with solids-liquid separation followed by secondary precipitation with solids-liquid separation	2.6
48	Centralized waste treatment industry	Wastewater	Full	-	57 mg/L	0.084 mg/L	-	Primary precipitation with solids-liquid separation followed by secondary precipitation with solids-liquid separation and multimedia filtration	2.6

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
49	Centralized waste treatment industry	Wastewater	Full	-	57 mg/L	0.011 mg/L	-	Selective metals precipitation, solids-liquid separation, secondary precipitation, solids-liquid separation, tertiary precipitation, and solid-liquid separation	2.6
50	Chemical and allied products	Wastewater	Full	-	0[b] - 0.1 mg/L	0.0063 mg/L	-	Chemically assisted clarification	2.9
51	-	Domestic wastewater	Full	-	0[b] - 0.1 mg/L	0.0015 mg/L	-	Chemical precipitation	2.9
52	Transportation equipment industry	Wastewater	Full	-	0.1 - 1 mg/L	<0.002 mg/L	-	Chemical precipitation and filtration	2.9
53	Chemicals and allied products	Wastewater	Full	-	0.1 - 1 mg/L	0.028 mg/L	-	Chemically assisted clarification	2.9
54	Metals processing	Spent leachate from the recovery of silver (Ag) from ores (amount not available)	Full	Sheritt Gordon Mines, LTD., Fort Saskatchewan, Alberta, Canada	-	-	-	Chemical precipitation and filtration	2.30

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
55	Metallurgie-Hoboken-Overpelt (MHO) solvent extraction process, metals processing	Spent electrolyte from copper (Cu) refining (amount not available)	Full	Olen, Belgium	-	-	99.96% recovery of arsenic	Chemical precipitation and filtration	2.31
56	WR Metals Industries (WRMI) arsenic leaching process, metals processing	Leachate from arsenical flue-dusts from non-ferrous smelters (amount not available)	Full	WR Metals Industries (location not available)	110,000 - 550,000 mg/kg	-	-	Chemical precipitation and filtration	2.31
57	Electric, gas, and sanitary	Wastewater	Pilot	-	0[b] - 0.1 mg/L	0.0028 mg/L	-	Chemically assisted clarification	2.9
58	Primary metals	Wastewater	Pilot	-	0[b] - 0.1 mg/L	<0.0015 mg/L	-	Chemical precipitation	2.9
59	-	Wastewater bearing unspecified RCRA listed waste code	Pilot	-	0[b] - 0.1 mg/L	0.001 mg/L	-	Chemical precipitation, activated carbon adsorption, and filtration	2.9
60	-	Domestic wastewater	Pilot	-	0[b] - 0.1 mg/L	0.001 mg/L	-	Chemical precipitation	2.9

Table A.1
Available Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
61	-	Wastewater bearing unspecified RCRA listed waste code	Pilot	-	0.1 - 1 mg/L	0.012 mg/L	-	Chemical precipitation, activated carbon adsorption, and filtration	2.9
62	-	Wastewater bearing unspecified RCRA listed waste code	Pilot	-	0.1 - 1 mg/L	0.012 mg/L	-	Chemical precipitation, activated carbon adsorption, and filtration	2.9
63	-	Wastewater bearing unspecified RCRA listed waste code	Pilot	-	0.1 - 1 mg/L	0.006 mg/L	-	Chemical precipitation, activated carbon adsorption, and filtration	2.9
64	-	Hazardous leachate, F039	Pilot	-	0.1 - 1 mg/L	0.008 mg/L	-	Chemical precipitation, activated carbon adsorption, and filtration	2.9
65	-	Wastewater bearing unspecified RCRA listed waste code	Pilot	-	0.1 - 1 mg/L	0.014 mg/L	-	Chemical precipitation, activated carbon adsorption, and filtration	2.9
66	Municipal landfill	Leachate	Pilot	-	1 - 10 mg/L	8 mg/L	-	Chemical precipitation, activated carbon adsorption, and filtration	2.9

Table A.1
Available Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source[d]
67	Metals processing	Scrubber water from lead smelter	Pilot	-	3,300 mg/L	0.007 mg/L	-	Mineral-like precipitation (additional information not available)	2.17
68	Metals processing	Thickener overflow from lead smelter	Pilot	-	5.8 mg/L	0.003 mg/L	-	Mineral-like precipitation (additional information not available)	2.17
69	-	Industrial wastewater	Pilot	-	5.8 mg/kg	< 0.5 mg/kg	-	-	2.17

[a] Excluding bench-scale treatments.

[b] Detection limit not provided.

[c] The information that appears in the "Precipitating Agent or Process" column of Appendix A, including the chemicals used, the descriptions of the precipitation/coprecipitation processes, and whether the process involved precipitation or coprecipitation, is based on the information reported in the cited references. This information was not independently checked for accuracy or technical feasability. In some cases the term "precipitation" may be applied to a process that is actually coprecipitation.

[d] Sources are listed in the References subsection of Section 2.0, Precipitation/Coprecipitation Treatment for Arsenic, on page 21.

[e]   Source did not further identify waste or media.

EPT = Extraction procedure toxicity test	gpd = gallons per day	mg/kg = milligrams per kilogram
mg/L = milligrams per liter	mgd = million gallons per day	- = Not available
RCRA = Resource Conservation and Recovery Act	TCLP = Toxicity characteristic leaching procedure	TWA = Total waste analysis
UV = Ultra violet	gpm = gallons per minute	WET = Waste extraction test

Appendix B
Adsorption Treatment Performance Data for Arsenic

Table B.1
Available Adsorption Treatment Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Adsorption Process Description[b]	Source [c]
Environmental Media - Activated Alumina								
1	-	Groundwater	Full	-	-	<0.05 mg/L	Activated alumina flow rate: 300 liters/hour	3.9
2	-	Groundwater	Pilot	-	-	<0.05 mg/L	Activated alumina adsorption at pH 5	3.4
3	-	Solution containing trivalent arsenic	Pilot	-	Trivalent arsenic, 0.1 mg/L	Trivalent arsenic, 0.05 mg/L	Activated alumina adsorption at pH 6.0 of solution containing trivalent arsenic; 300 bed volumes treated before effluent exceeded 0.05 mg/L arsenic	3.3
4	-	Solution containing pentavalent arsenic	Pilot	-	Pentavalent arsenic, 0.1 mg/L	Pentavalent arsenic, 0.05 mg/L	Activated alumina adsorbent at pH 6.0 of solution containing pentavalent arsenic; 23,400 bed volumes treated before effluent exceeded 0.05 mg/L arsenic	3.3

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Adsorption Process Description[b]	Source[c]
Environmental Media - Activated Carbon								
5	Wood preserving	Groundwater	Full	Mid-South Wood Product Superfund Site, Mena, AS	0.018 mg/L	<0.005 mg/L (29 of 35 monitoring wells)	Treatment train consisting of oil-water separation, filtration, and carbon adsorption; performance data are for the entire treatment train	3.5
6	Wood preserving	Groundwater, 27,000 gpd	Full	North Cavalcade Street Superfund Site Houston, TX	-	-	Treatment train consisting of filtration followed by carbon adsorption	3.7
7	Wood preserving	Groundwater, 3,000 gpd	Full	Saunders Supply Company Superfund Site, Chuckatuck, VA	-	-	Treatment train consisting of metals precipitation, filtration, and carbon adsorption	3.7
8	Wood preserving	Groundwater, 4,000 gpd	Full	McCormick and Baxter Creosoting Co. Superfund Site, Portland, OR	-	-	Treatment train consisting of filtration, ion exchange, and carbon adsorption	3.7
9	Chemical mixing and batching	Groundwater, 43,000 gpd	Full	Baird and McGuire Superfund Site, Holbrook, MA	-	-	Treatment train consisting of air stripping, metals precipitation, filtration, and carbon adsorption	3.7
10	Chemical manufacturing	Groundwater, 65,000 gpd	Full	Greenwood Chemical Superfund Site, Greenwood, VA	-	-	Treatment train consisting of metals precipitation, filtration, UV oxidation and carbon adsorption	3.7

Table B.1
Available Adsorption Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Adsorption Process Description[b]	Source[c]
Environmental Media - Iron-Based Media								
11	Landfill	Groundwater	Pilot	-	-	0.027 mg/L	Precipitation from barite addition followed by an iron filings and sand media filter	3.8, 3.13
12	–	Groundwater, 3,600 gpd	Pilot	CA	0.018 mg/L	<0.002 mg/L	Fixed-bed adsorber with sulfur-modified iron adsorbent; 13,300 bed volumes put through unit	3.19
Drinking Water - Activated Alumina								
13	-	Drinking water	Full	-	0.063 mg/L	<0.003 mg/L	Two activated alumina columns in series; media replaced in one column every 1.5 years	3.3
14	-	Drinking water	Full	-	0.034 - 0.087 mg/L	<0.05 mg/L	Activated alumina	3.12
15	-	Drinking water	Full	Project Earth Industries, Inc.	0.34 mg/L	0.01 - 0.025 mg/L	Activated alumina	3.8
16	-	Drinking water	Full	-	0.049 mg/L	<0.003 mg/L	Two activated alumina columns in series; media replaced in column tank every 1.5 years	3.3
17	-	Drinking water, 14,000 gpd	Full	Bow, NH	0.057 - 0.062 mg/L	0.050 mg/L	Activated alumina	3.3
Drinking Water - Iron-Based Media								
18	-	Drinking water	Full	Harbauer GmbH & Co., Berlin, Germany	0.3 mg/L	<0.01 mg/L	Granular ferric hydroxide	3.11

Table B.1
Available Adsorption Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name	Initial Arsenic Concentration	Final Arsenic Concentration	Adsorption Process Description[b]	Source[c]
19	-	Drinking Water	Pilot	-	0.1 - 0.18 mg/L	<0.01 mg/L	Fixed bed absorber with ferric hydroxide-coated newspaper pulp; 20,000 bed volumes treated before effluent exceeded 0.01 mg/L arsenic	3.15
20	-	Drinking water	Pilot	-	0.180 mg/L	0.010 mg/L	Granular ferric hydroxide	3.16
21	–	Drinking water	Full	–	0.02 mg/L	0.003 mg/L	Fixed bed adsorber with ferric oxide granules	3.20
Drinking Water - Other or Unknown Media								
22	-	Drinking water	Full	-	5 mg/L	0.01 mg/L	Copper-zinc granules	3.14
23	-	Drinking water	Pilot	ADI International	-	-	Adsorption in pressurized vessel containing proprietary media at pH 5.5 to 8.0	3.1

[a] Excluding bench-scale treatments.

[b] Some processes employ a combination of adsorption, ion exchange, oxidation, precipitation/coprecipitation, or filtration to remove arsenic from water.

[c] Sources are listed in the References subsection of Section 3.0, Adsorption Treatment for Arsenic, on page 28.

AA = activated alumina
EPT = Extraction procedure toxicity test
mg/L = milligrams per liter
RCRA = Resource Conservation and Recovery Act
WET = Waste extraction test

gpd = gallons per day
mgd = million gallons per day
TCLP = Toxicity characteristic leaching procedure
UV = Ultraviolet

mg/kg = milligrams per kilogram
- = Not available

Appendix C
Ion Exchange Treatment Performance Data for Arsenic

Table C.1
Available Ion Exchange Treatment Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media	Scale	Site Name	Ion Exchange Media or Process	Untreated Arsenic Concentration	Treated Arsenic Concentration	Ion Exchange Media Regeneration Information	Source[b]
Environmental Media									
1	Wood preserving, spill of chromated copper arsenate	Surface water	Full	Vancouver, Canada (site name unknown)	Anion and cation resins	0.0394 mg/L	0.0229 mg/L	-	4.2
2	Waste disposal	Groundwater, 43,000 gpd	Full	Higgins Farm Superfund Site, Franklin Township, NJ	Treatment train consisting of air stripping, metals precipitation, filtration, and ion exchange	-	-	-	4.7
3	Wood preserving	Groundwater, 4,000 gpd	Full	McCormick and Baxter Creosoting Co., Portland, OR	Treatment train consiting of filtration, ion exchange, and carbon adsorption	-	-	-	4.7
Drinking Water									
4	-	Drinking water	Full	-	Solid oxidizing media filter followed by an anion-exchange system	0.019 - 0.055 mg/L[a]	<0.005 - 0.080 mg/L[a]	-	4.1
5	-	Drinking water	Full	-	Potassium permanganate greensand oxidizing filter followed by a mixed bed ion-exchange system	0.040 - 0.065 mg/L[a]	<0.003 mg/L[a]	Bed regenerated every 6 days	4.1

Table C.1
Available Ion Exchange Treatment Performance Data (continued)

Project Number	Industry or Site Type	Waste or Media	Scale	Site Name	Ion Exchange Media or Process	Untreated Arsenic Concentration	Treated Arsenic Concentration	Ion Exchange Media Regeneration Information	Source[b]
6	-	Drinking water	Full	-	Strongly basic gel ion-exchange resin in chloride form	0.045 - 0.065 mg/L	0.0008 - 0.0045 mg/L	Resin regenerated every 4 weeks	4.9
7	-	Drinking water	Full	-	Chloride-form strong-base resin anion-exchange process	-	0.002 mg/L	Spent NaCl brine reused to regenerate exhausted ion-exchange bed	4.8

[a]   Data are for entire treatment train, including unit operations that are not ion exchange.

[b]   Sources are listed in the References subsection of Section 4.0, Ion Exchange Treatment for Arsenic, on page 33.

- = Not available   gpd = gallons per day   mg/L = milligrams per liter.

NaCl = Sodium chloride

Appendix D
Membrane Filtration Treatment Performance Data
for Arsenic

Table D.1
Available Membrane Filtration Treatment Performance Data for Arsenic

Project Number	Media or Waste	Scale	Site Name	Initial Arsenic Concentration	Percent Arsenic Removal[a] or Final Arsenic Concentration	Membrane or Treatment Process	Source[b]
Nanofiltration							
1	Groundwater	Pilot	Tarrytown, NY	0.038 - 0.154 mg/L	95%	NF70	5.4
2	Groundwater	Pilot	Tarrytown, NY	0.038 - 0.154 mg/L	95%	TFCS	5.4
3	Groundwater with low DOC (1mg/L)	Pilot	-	-	60%	Single element, negatively charged membrane	5.4
4	Groundwater with high DOC (11mg/L)	Pilot	-	-	80%	Single element, negatively charged membrane	5.4
5	Groundwater with high DOC (11mg/L)	Pilot	-	-	75% initial, 3-16% final	Single element, negatively charged membrane	5.4
6	Arsenic-spiked surface water	Pilot	-	-	Arsenic (III) 20% Arsenic (V) > 95%	Single element membrane	5.4
7	Arsenic-spiked surface water	Pilot	-	-	Arsenic (III) 30% Arsenic (V) > 95%	Single element membrane	5.4
8	Arsenic-spiked surface water	Pilot	-	-	Arsenic (III) 52% Arsenic (V) > 95%	Single element membrane	5.4
9	Arsenic-spiked DI water	Bench	-	-	Arsenic (III) 12% Arsenic (V) 85%	Single element, negatively charged membrane	5.4
10	Arsenic-spiked lake water	Bench	-	-	Arsenic (V) 89%	Single element, negatively charged membrane	5.4
11	Arsenic-spiked DI water	Bench	-	-	Arsenic (V) 90%	Flat sheet, negatively charged membrane	5.4

Table D.1
Available Membrane Filtration Treatment Performance Data for Arsenic (continued)

Project Number	Media or Waste	Scale	Site Name	Initial Arsenic Concentration	Percent Arsenic Removal[a] or Final Arsenic Concentration	Membrane or Treatment Process	Source[b]
Reverse Osmosis							
12	Surface water contaminated with wood preserving wastes	Full	-	24.4 mg/L	Arsenic removal, 99% reject stream, 57.7 mg/L treated effluent stream, 0.0394 mg/L	Treatment train consisting of RO followed by ion exchange; performance data are for RO treatment only	5.1
13	Groundwater	Pilot	Charlotte Harbor, FL	-	Arsenic (III) 46-84% Arsenic (V) 96-99%	-	5.4
14	Groundwater	Pilot	Cincinnati, OH	-	Arsenic (III) 73%	-	5.4
15	Groundwater	Pilot	Eugene, OR	-	50%	-	5.4
16	Groundwater	Pilot	Fairbanks, AL	-	50%	-	5.4
17	Groundwater	Pilot	Hudson, NH	-	40%	-	5.4
18	Groundwater with low DOC	Pilot	-	-	> 80%	Single element, negatively charged membrane	5.4
19	Groundwater with high DOC	Pilot	-	-	> 90%	Single element, negatively charged membrane	5.4
20	Arsenic-spiked surface water	Pilot	-	-	Arsenic (III) 60% Arsenic (V) > 95%	Single element membrane	5.4
21	Arsenic-spiked surface water	Pilot	-	-	Arsenic (III) 68% Arsenic (V) > 95%	Single element membrane	5.4
22	Arsenic-spiked surface water	Pilot	-	-	Arsenic (III) 75% Arsenic (V) > 95%	Single element membrane	5.4
23	Arsenic-spiked surface water	Pilot	-	-	Arsenic (III) 85% Arsenic (V) > 95%	Single element membrane	5.4
24	Groundwater	Pilot	San Ysidro, NM	-	91%	-	5.4

Project Number	Media or Waste	Scale	Site Name	Initial Arsenic Concentration	Percent Arsenic Removal[a] or Final Arsenic Concentration	Membrane or Treatment Process	Source[b]
25	Groundwater	Pilot	San Ysidro, NM	-	99%	Hollow fiber, polyamide membrane	5.4
26	Groundwater	Pilot	San Ysidro, NM	-	93-99%	Hollow fiber, cellulose acetate membrane	5.4
27	Groundwater	Pilot	Tarrytown, NY	-	86%	-	5.4
28	Arsenic-spiked lake water	Bench	-	-	Arsenic (III) 5% Arsenic (V) 96%	-	5.4
29	Arsenic-spiked DI water	Bench	-	-	Arsenic (III) 5% Arsenic (V) 96%	-	5.4
30	Arsenic-spiked DI water	Bench	-	-	Arsenic (V) 88%	-	5.4
31	Drinking water	Pilot	Park City Spiro Tunnel Water Filtration Plant, Park City, Utah	0.065 mg/L	0.0005 mg/L	-	5.12
Microfiltration							
32	Groundwater	Full	-	0.005 - 3.8 mg/L	<0.005 - 0.05 mg/L	Iron coprecipitation followed by membrane filtration	5.14
33	Groundwater	Pilot	-	0.2 - 1.0 mg/L	<0.005 mg/L	Iron coprecipitation followed by ceramic membrane filtration	5.13

[a] Percent arsenic rejection is 1 minus the mass of arsenic in the treated aqueous stream divided by the mass of arsenic in the influent times 100 [(1-(mass of arsenic influent/mass of arsenic effluent)) *100].

[b] Sources are listed in the References subsection of Section 5.0, Membrane Filtration Treatment for Arsenic, on page 38.

DI = Deionized   DOC = Dissolved organic carbon   - = Not available
NF = Nanofiltration   RO = Reverse Osmosis   > = Greater than
TFCS = Thin film composite

**Appendix E
Selected Annotated Bibliography**

SELECTED ANNOTATED BIBLIOGRAPHY

E.1 E-mail attachment sent from Doug Sutton, Geotrans, Inc., to Linda Fiedler, U.S. EPA. April 20, 2001. - The e-mail attachment discusses sites that are treating arsenic contamination with pump-and-treat technologies. In addition, the e-mail attachment includes site summaries for two sites using ion exchange. The purpose of the e-mail attachment is to provide site-specific information for sites treating arsenic contamination.

E.2 U.S. EPA. Office of Research and Development. Environmental Technology Verification Program (ETV). Reverse Osmosis Membrane Filtration Used In Packaged Drinking Water Treatment Systems. March 2001. *http://www.membranes.com* - This document discusses verification testing of a reverse osmosis unit used to treat arsenic-contaminated groundwater. In addition, the document includes test results for the reverse osmosis module. The purpose of the document is to verify the performance of the reverse osmosis technology for removing arsenic from groundwater.

E.3 Murcott, S. Appropriate Remediation Technologies for Arsenic-Contaminated Wells in Bangladesh. Massachusetts Institute of Technology. February 1999. - This presentation discusses ion exchange as one option for treating arsenic-contaminated groundwater in Bangladesh. In addition, this presentation includes information on various other technologies. The purpose of the presentation is to emphasize the use of low-cost technologies that may be implemented to treat arsenic-contaminated water in Bangladesh.

E.4 Tidwell, L.G., et al. Technologies and Potential Technologies for Removing Arsenic from Process and Mine Wastewater. Presented at "REWAS'99." San Sebastian, Spain. September 1999. - This presentation discusses technologies (including adsorption) being used or that may be used to treat arsenic in mine waters. In addition, the presentation includes descriptions of and results for demonstration studies. The purpose of the presentation is to provide information on the removal of arsenic from mine waters.

E.5 U.S. EPA. Office of Research and Development. Arsenic & Mercury - Workshop on Removal, Recovery, Treatment, and Disposal. EPA-600-R-92-105. August 1992 - These abstract proceedings discuss treatment technologies (including ion exchange, membrane filtration, and precipitation/coprecipitation) for treating arsenic-contaminated wastes. In addition, the proceedings include information on fundamentals; analytical techniques/ characterization; and removal, recovery, and reuse. The purpose of the proceedings is to highlight the technical presentations of the workshop, which provided a forum for discussing arsenic.

E.6 U.S. EPA. Office of Ground Water and Drinking Water. Arsenic in Drinking Water Rule Economic Analysis. EPA 815-R-00-026. December 2000. - This document discusses the impacts of the revised Arsenic Rule, which reduces the maximum contaminant level for arsenic in community water systems from 0.050 mg/L to 0.010 mg/L. In addition, the document also includes baseline, benefits, cost, and economic analyses. The purpose of the document is to estimate the costs and benefits associated with the revised Arsenic Rule.

E.7 U.S. EPA. Arsenic Removal from Drinking Water by Coagulation/Filtration and Lime Softening Plants. EPA/600/R-00/063. Office of Research and Development. June 2000 - This report discusses the design and operation of three treatment plants with arsenic-contaminated influent. In addition, the report includes the results of analyses performed on water and residual samples collected at each treatment facility. The purpose of the report is to evaluate the effectiveness of conventional coagulation/ flocculation and lime softening to consistently reduce arsenic concentrations in source water to low levels.

E.8 U.S. EPA. Office of Research and Development. Arsenic Removal from Drinking Water by Ion Exchange and Activated Alumina Plants. EPA 600-R-00-088. October 2000. - This report discusses design and operation of two activated alumina treatment plants and two ion exchange

treatment plants with arsenic in the source water. In addition, the report includes data on samples and residuals collected from the treatment plants. The purpose of the report is to evaluate the ability of these systems to consistently reduce arsenic concentrations in source water to low levels.

E.9   U.S. EPA. Office of Solid Waste. Best Demonstrated Available Technology (BDAT) Background Document for Wood Preserving Wastes: F032, F034, and F035; Final. April 1996 - This background document discusses technologies (including precipitation/coprecipitation) used to treat wood preserving wastes. In addition, the document discusses U.S. EPA's technical support and rationale for developing regulatory standards for such wastes. The purpose of the document is to present the development of new treatment performance standards as BDAT for wood preserving wastes.

E.10 U.S. EPA. Office of Water. Development Document for Effluent Limitations Guidelines and Standards for the Centralized Waste Treatment Industry. December 2000. - This document discusses the effluent limitations guidelines and standards for the centralized waste treatment industry. In addition, the document describes wastewater treatment technologies (including precipitation/ coprecipitation). The purpose of the document is to provide the technical bases for the final effluent limitations guidelines, pretreatment standards, and new source performance standards for the centralized waste treatment industry point source category.

E.11 U.S. EPA. Office of Solid Waste. Final Best Demonstrated Available Technology (BDAT) Background Document for K031, K084, K101, K102, Characteristic Arsenic Wastes (D004), Characteristic Selenium Wastes (D010), and P and U Wastes Containing Arsenic and Selenium Listing Constituents. May 1990 - This background document discusses technologies (including adsorption, ion exchange, and precipitation/coprecipitation) used to treat arsenic-containing wastes. In addition, the document discusses U.S. EPA's technical support and rationale for developing regulatory standards

for such wastes. The purpose of the document is to present the development of new treatment performance standards as BDAT for arsenic-containing wastes.

E.12 U.S. EPA. Office of Research and Development. Regulations on the Disposal of Arsenic Residuals from Drinking Water Treatment Plants. EPA/600/R-00/025. May 2000. - This report discusses water treatment processes (including adsorption, ion exchange, and membrane filtration) known to be effective in removing arsenic from small groundwater systems and characteristics of the residuals produced. In addition, the report includes regulations applicable to these residuals. The purpose of the report is to summarize federal regulations and selected state regulations that govern the management of residuals produced by treatment systems removing arsenic from drinking water.

E.13 U.S. EPA. Technologies and Costs for Removal of Arsenic From Drinking Water. EPA-R-00-028. Office of Groundwater and Drinking Water. December 2000. - This document discusses arsenic removal technologies (including adsorption, ion exchange, membrane filtration, and precipitation/coprecipitation) and technology costs. In addition, the document discusses residuals handling, disposal alternatives, and point-of-entry/ point-of-use treatment options. The purpose of the document is to provide cost information on removing arsenic from drinking water.

E.14 U.S. EPA. Office of Solid Waste and Emergency Response. Arsenic Treatment Technologies for Soil, Waste, and Water. EPA-542-R-02-004. Publication expected June 2002. - This report contains information on the current state of the treatment of soil, waste, and water containing arsenic, which can be difficult to treat and may cause a variety of adverse health effects in humans. By summarizing information on the treatment of arsenic, identifying sites and facilities where particular arsenic treatment technologies have been used in the past, and acting as a reference to more detailed arsenic treatment information, this report promotes the transfer of information on innovative and established technologies for arsenic treatment.