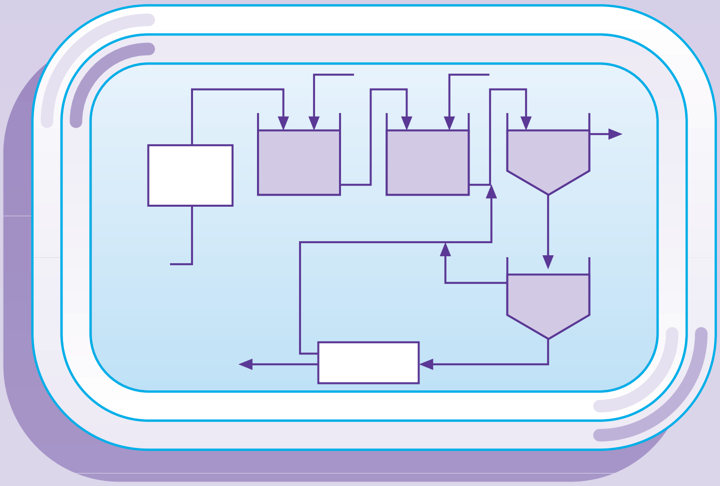
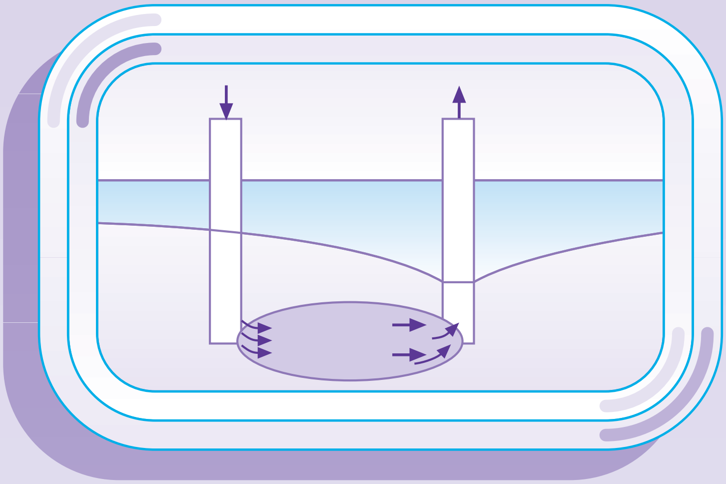
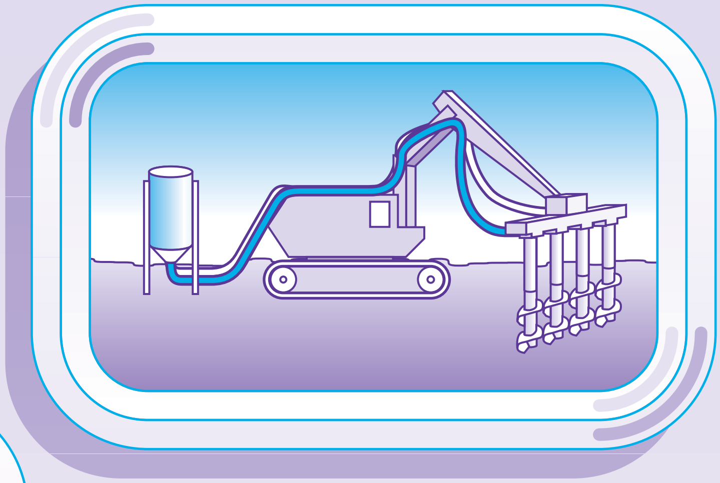
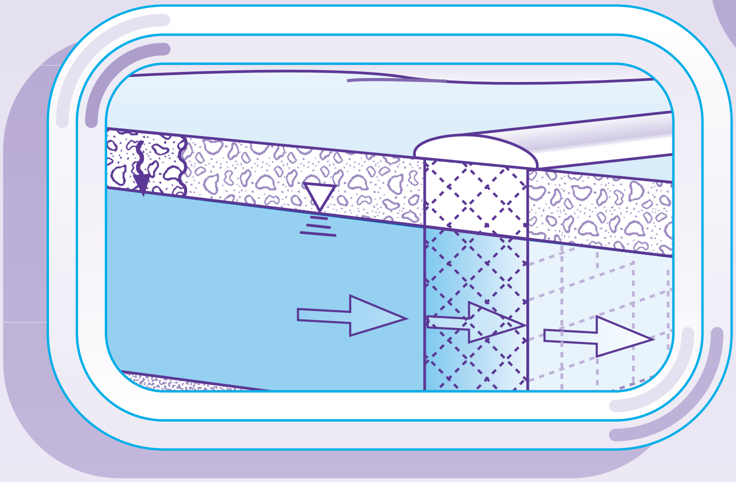
United States Environmental Protection Agency

Arsenic Treatment Technologies for Soil, Waste, and Water









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Arsenic Treatment Technologies for Soil, Waste, and Water

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LIST OF ACRONYMS AND ABBREVIATIONS

AA	Activated alumina
AC	Activated carbon
ASR	Annual Status Report
As(III)	Trivalent arsenic, common inorganic form in water is arsenite, H_3AsO_3
As(V)	Pentavalent arsenic, common inorganic form in water is arsenate, $H_2AsO_4^-$
BDAT	best demonstrated available technology
BTEX	Benzene, toluene, ethylbenzene, and xylene
CCA	Chromated copper arsenate
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CERCLIS 3	CERCLA Information System
CLU-IN	EPA's CLeanUp INformation system
CWS	Community Water System
cy	Cubic yard
DDT	Dichloro-diphenyl-trichloroethane
DI	Deionized
DOC	Dissolved organic carbon
DoD	Department of Defense
DOE	Department of Energy
EDTA	Ethylenediaminetetraacetic acid
EPA	U.S. Environmental Protection Agency
EPT	Extraction Procedure Toxicity Test
FRTR	Federal Remediation Technologies Roundtable
ft	feet
GJO	DOE's Grand Junction Office
gpd	gallons per day
gpm	gallons per minute
HTMR	High temperature metals recovery
MCL	Maximum Contaminant Level (enforceable drinking water standard)
MF	Microfiltration
MHO	Metallurgie-Hoboken-Overpelt
mgd	million gallons per day
mg/kg	milligrams per kilogram
mg/L	milligrams per Liter
NF	Nanofiltration
NPL	National Priorities List
OCLC	Online Computer Library Center
ORD	EPA Office of Research and Development
OU	Operable Unit
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
POTW	Publicly owned treatment works
PRB	Permeable reactive barrier
RCRA	Resource Conservation and Recovery Act
Redox	Reduction/oxidation
RO	Reverse osmosis
ROD	Record of Decision
SDWA	Safe Drinking Water Act
SMZ	surfactant modified zeolite
SNAP	Superfund NPL Assessment Program
S/S	Solidification/Stabilization
SVOC	Semivolatile organic compounds
TCLP	Toxicity Characteristic Leaching Procedure
TNT	2,3,6-trinitrotoluene
TWA	Total Waste Analysis
UF	Ultrafiltration
VOC	Volatile organic compounds
WET	Waste Extraction Test
ZVI	Zero valent iron

FOREWORD

The purpose of this report is to provide a synopsis of the availability, performance, and cost of 13 arsenic treatment technologies for soil, water, and waste. Its intended audience includes hazardous waste site managers; generators and treaters of arsenic-contaminated waste and wastewater; owners and operators of drinking water treatment plants; regulators; and the interested public.

There is a growing need for cost-effective arsenic treatment. The presence of arsenic in the environment can pose a risk to human health. Historical and current industrial use of arsenic has resulted in soil and groundwater contamination that may require remediation. Some industrial wastes and wastewaters currently being produced require treatment to remove or immobilize arsenic. In addition, arsenic must be removed from some sources of drinking water before they can be used.

Recently the EPA reduced the maximum contaminant level (MCL) for arsenic in drinking water from 0.050 mg/L to 0.010 mg/L, effective in 2006. Current and future drinking water and groundwater treatment systems will require better-performing technologies to achieve this lower level. EPA recently prepared an issue paper, *Proven Alternatives for Aboveground Treatment of Arsenic in Groundwater*, that describes four technologies (precipitation/coprecipitation, adsorption, ion exchange, and membrane filtration) for removing arsenic from water. The paper also discusses special considerations for retrofitting systems to meet the lower arsenic drinking water standard. This information is incorporated in this report, as well as details on emerging approaches, such as phytoremediation and electrokinetics, for addressing arsenic in groundwater.

This report is intended to be used as a screening tool for arsenic treatment technologies. It provides descriptions of the theory, design, and operation of the technologies; information on commercial availability and use; performance and cost data, where available; and a discussion of factors affecting effectiveness and cost. As a technology overview document, the information can serve as a starting point for identifying options for arsenic treatment. The feasibility of particular technologies will depend heavily on site-specific factors, and final treatment and remedy decisions will require further analysis, expertise, and possibly treatability studies.

NOTICE AND DISCLAIMER

Preparation of this report has been funded by the U.S. Environmental Protection Agency (EPA) Technology Innovation Office (TIO) under Contract Numbers 68-W-99-003 and 68-W-02-034. Information in this report is derived from numerous sources (including personal communications with experts in the field), some of which have been peer-reviewed. This study has undergone EPA and external review by subject-matter experts. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

A PDF version of *Arsenic Treatment Technologies for Soil, Waste, and Water*, is available for viewing or downloading from the Hazardous Waste Cleanup Information (CLU-IN) system web site at *http://clu-in.org/arsenic*. A limited number of printed copies are available free of charge, and may be ordered via the web site, by mail or by facsimile from:

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PART I
OVERVIEW AND FINDINGS

1.0 EXECUTIVE SUMMARY

This report contains information on the current state of the treatment of soil, waste, and water containing arsenic, a contaminant that can be difficult to treat and may cause a variety of adverse health effects in humans. This information can help managers at sites with arsenic-contaminated media, generators of arsenic-contaminated waste and wastewater, and owners and operators of drinking water treatment plants to:

- Identify proven and effective arsenic treatment technologies
- Screen those technologies based on effectiveness, treatment goals, application-specific characteristics, and cost
- Apply experience from sites with similar treatment challenges
- Find more detailed arsenic treatment information

Arsenic is in many industrial raw materials, products, and wastes, and is a contaminant of concern in soil and 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 difficult. Treatment can result in residuals that, under some environmental conditions, become more toxic and mobile. In addition, the recent reduction in the maximum contaminant level (MCL) for arsenic in drinking water from 0.050 to 0.010 mg/L will impact technology selection and application for drinking water treatment, and could result in lower treatment goals for remediation of arsenic-contaminated sites. A lower treatment goal may affect the selection, design, and operation of arsenic treatment systems.

This report identifies 13 technologies to treat arsenic in soil, waste, and water. Table 1.1 provides brief descriptions of these technologies. Part II of this report contains more detailed information about each technology.

Table 1.2 summarizes the technology applications and performance identified for this report. The table provides information on the number of projects that met certain current or revised regulatory standards, including the RCRA regulatory threshold for the toxicity characteristic of 5.0 mg/L leachable arsenic, the former MCL of 0.050 mg/L arsenic, and the revised MCL of 0.010 mg/L. The table presents information for solid-phase media (soil and waste) and aqueous media (water, including groundwater, surface water, drinking water, and wastewater). The technologies used to treat one type of media typically show similar applicability and effectiveness when applied to a similar media. For example, technologies used to treat arsenic in soil have about the same applicability and effectiveness, and are used with similar frequency, to treat solid industrial wastes. Similarly, technologies used to treat one type of water (e.g., groundwater) typically show similar applicability, effectiveness, and frequency of use when treating another type of water (e.g., surface water).

Soil and Waste Treatment Technologies

In general, soil and waste are treated by immobilizing the arsenic using solidification/stabilization (S/S). This technology is usually capable of reducing the leachability of arsenic to below 5.0 mg/L (as measured by the toxicity characteristic leaching procedure [TCLP]), which is a common treatment goal for soil and waste. S/S is generally the least expensive technology for treatment of arsenic-contaminated soil and waste.

Pyrometallurgical processes are applicable to some soil and waste from metals mining and smelting industries. However, the information gathered for this report did not indicate any current users of these technologies for arsenic in the U. S. Other soil and waste treatment technologies, including vitrification, soil washing/acid extraction, and soil flushing, have had only limited application to the treatment of arsenic. Although these technologies may be capable of effectively treating arsenic, data on performance are limited. In addition, these technologies tend to be more expensive than S/S.

Water Treatment Technologies

Based on the information gathered for this report, 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.

Innovative Technologies

Innovative technologies, such as permeable reactive barriers, biological treatment, phytoremediation, and electrokinetic treatment, are also being used to treat arsenic-contaminated soil, waste, and water. The references identified for this report contain information about only a few applications of these technologies at full scale. However, they may be used to treat arsenic more frequently in the future. Additional treatment data are needed to determine their applicability and effectiveness.

Permeable reactive barriers are used to treat groundwater in situ. This technology tends to have lower operation and maintenance costs than ex situ (pump and treat) technologies, and typically requires a treatment time of many years. This report identified three full-scale applications of this technology, but treatment data were available for only one application. In that application, a permeable reactive barrier is treating arsenic to below the revised MCL.

Biological treatment for arsenic is used primarily to treat water above-ground in processes that use microorganisms to enhance precipitation/coprecipitation. Bioleaching of arsenic from soil has also been tested on a bench scale. This technology may require pretreatment or addition of nutrients and other treatment agents to encourage the growth of key microorganisms.

Phytoremediation is an in situ technology intended to be applicable to soil, waste, and water. This technology tends to have low capital, operating, and maintenance costs relative to other arsenic treatment technologies because it relies on the activity and growth of plants. However, the effectiveness of this technology may be reduced by a variety of factors, such as the weather, soil and groundwater contaminants and characteristics, the presence of weeds or pests, and other factors. The references identified for this report contained information on one full-scale application of this technology to arsenic treatment.

Electrokinetic treatment is an in situ technology intended to be applicable to soil, waste and water. This technology is most applicable to fine-grained soils, such as clays. The references identified for this report contained information on one full-scale application of this technology to arsenic treatment.

Table 1.1
Arsenic Treatment Technology Descriptions

Technology	Description
Technologies for Soil and Waste Treatment	
Solidification/ Stabilization	Physically binds or encloses contaminants within a stabilized mass and chemically reduces the hazard potential of a waste by converting the contaminants into less soluble, mobile, or toxic forms.
Vitrification	High temperature treatment that reduces the mobility of metals by incorporating them into a chemically durable, leach resistant, vitreous mass. The process also may cause contaminants to volatilize, thereby reducing their concentration in the soil and waste.
Soil Washing/ Acid Extraction	An ex situ technology that takes advantage of the behavior of some contaminants to preferentially adsorb onto the fines fraction of soil. The soil is suspended in a wash solution and the fines are separated from the suspension, thereby reducing the contaminant concentration in the remaining soil.
Pyrometallurgical Recovery	Uses heat to convert a contaminated waste feed into a product with a high concentration of the contaminant that can be reused or sold.
In Situ Soil Flushing	Extracts organic and inorganic contaminants from soil by using water, a solution of chemicals in water, or an organic extractant, without excavating the contaminated material itself. The solution is injected into or sprayed onto the area of contamination, causing the contaminants to become mobilized by dissolution or emulsification. After passing through the contamination zone, the contaminant-bearing flushing solution is collected and pumped to the surface for treatment, discharge, or reinjection.
Technologies for Water Treatment	
Precipitation/ Coprecipitation	Uses chemicals to transform dissolved contaminants into an insoluble solid or form another insoluble solid onto which dissolved contaminants are adsorbed. The solid is then removed from the liquid phase by clarification or filtration.
Membrane Filtration	Separates contaminants from water by passing it through a semi-permeable barrier or membrane. The membrane allows some constituents to pass, while blocking others.
Adsorption	Concentrates solutes 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.
Ion Exchange	Exchanges ions held electrostatically on the surface of a solid with ions of similar charge in a solution. The ion exchange media is usually packed into a column. As contaminated water is passed through the column, contaminants are removed.
Permeable Reactive Barriers	Walls containing reactive media that are installed across the path of a contaminated groundwater plume to intercept the plume. The barrier allows water to pass through while the media remove the contaminants by precipitation, degradation, adsorption, or ion exchange.
Technologies for Soil, Waste, and Water Treatment	
Electrokinetic Treatment	Based on the theory that a low-density current applied to soil will mobilize contaminants in the form of charged species. A current passed between electrodes inserted into the subsurface is intended to cause water, ions, and particulates to move through the soil. Contaminants arriving at the electrodes can be removed by means of electroplating or electrodeposition, precipitation or coprecipitation, adsorption, complexing with ion exchange resins, or by pumping of water (or other fluid) near the electrode.
Phytoremediation	Involves the use of plants to degrade, extract, contain, or immobilize contaminants in soil, sediment, and groundwater.
Biological Treatment	Involves the use of microorganisms that act directly on contaminant species or create ambient conditions that cause the contaminant to leach from soil or precipitate/coprecipitate from water.

Table 1.2
Summary of Key Data and Findings

Technology	Media Treated		Number of Applications Identified[a] (Number with Performance Data)				Soil and Waste	Water	
	Soil and Waste	Water	Bench Scale	Pilot Scale	Full Scale	Total	Number of Applications Achieving <5.0 mg/L Leachable Arsenic	Number of Applications Achieving <0.050 mg/L Arsenic	Number of Applications Achieving <0.010 mg/L Arsenic
Solidification/Stabilization	g	-	NC	10 (10)	34 (32)	44 (42)	37	-	-
Vitrification	g	-	NC	10 (5)	6 (2)	16 (7)	7	-	-
Soil Washing/Acid Extraction	g	-	2 (0)	3 (0)	4 (0)	9 (0)	-	-	-
Pyrometallurgical Recovery	g	-	0	0	4 (2)	4 (2)	2	-	-
In Situ Soil Flushing	g	-	0	2 (0)	2 (0)	4 (0)	-	-	-
Precipitation/Coprecipitation	-	g	NC	24 (22)	45 (30)	68 (51)	-	36	19
Membrane Filtration	-	g	6 (0)	25 (2)	2 (2)	33 (4)	-	4	2
Adsorption	-	g	NC	7 (4)	14 (8)	21 (12)	-	12	7
Ion Exchange	-	g	NC	0	7 (4)	7 (4)	-	3	2
Permeable Reactive Barriers	-	g	5 (4)	2 (1)	3 (1)	10 (6)	-	6	4
Electrokinetics	g	g	3 (0)	3 (1)	1 (0)	7 (1)	-	1	0
Phytoremediation	g	g	4 (0)	2 (0)	1 (0)	7 (0)	-	-	-
Biological Treatment	g	g	1	3 (2)	1 (0)	5 (2)	-	1	0

[a] Applications were identified through a search of available technical literature (See Sections 2.9 and 2.10). The number of applications include only those identified during the preparation of this report, and are not comprehensive. Limited information on treatment of industrial wastes and wastewaters was identified, therefore the table may not be representative of these types of applications.

NC = Data not collected ! = Not applicable

Source: Adapted from data in Sections 4.0 to 16.0 of this report

2.0 INTRODUCTION

2.1 Who Needs to Know about Arsenic Treatment Technologies?

This report was prepared to provide information on the current state of arsenic treatment for soil, waste, and water. The report may be used to:

- Identify proven and effective arsenic treatment technologies
- Screen those technologies based on effectiveness, treatment goals, application-specific characteristics, and cost
- Apply experience from sites with similar treatment challenges
- Find more detailed arsenic treatment information

The report may be used by remediation site managers, hazardous waste generators (for example, wood treaters, herbicide manufacturers, mine and landfill operators), drinking water treatment plant designers and operators, and the general public to help screen arsenic treatment options.

Arsenic is a common inorganic element found widely in the environment. It is in many industrial products, wastes, and wastewaters, and is a contaminant of concern at many remediation sites. Arsenic-contaminated soil, waste, and water must be treated by removing the arsenic or immobilizing it. Because arsenic readily changes valence states and reacts to form species with varying toxicity and mobility, effective, long-term treatment of arsenic can be difficult. In some disposal environments arsenic has leached from arsenic-bearing wastes at high concentrations (Ref. 2.11).

Recently, the EPA reduced the maximum contaminant level (MCL) for arsenic in drinking water from 0.050 mg/L to 0.010 mg/L, effective in 2006 (Ref. 2.9). Drinking water suppliers may need to add new treatment processes or retrofit existing treatment systems to meet the revised MCL. In addition, it may affect Superfund remediation sites and other sites that base cleanup goals on the arsenic drinking water MCL. This report provides information needed to help meet the challenges of arsenic treatment.

2.2 Background

Where Does Arsenic Come From?

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, pharmaceuticals, herbicides, and semi-conductors. The man-made sources of arsenic in the environment include mining and smelting operations; agricultural applications; burning of fossil fuels and wastes; pulp and paper production; cement manufacturing; and former agricultural uses of arsenic (Ref. 2.1).

What Are the Health Effects of Arsenic?

Many studies document the adverse health effects in humans exposed to inorganic arsenic compounds. A discussion of those effects is available in the following documents:

- National Primary Drinking Water Regulations; Arsenic and Clarifications to Compliance and New Source Contaminants Monitoring (66 FR 6976 / January 22, 2001) (Ref. 2.1)
- The Agency for Toxic Substances and Disease Registry (ATSDR) ToxFAQs^{TM} for Arsenic (Ref. 2.13).

How Does Arsenic Chemistry Affect Treatment?

Arsenic is a metalloid or inorganic semiconductor that can form inorganic and organic compounds. It occurs with valence states of -3, 0, +3 (arsenite), and +5 (arsenate). However, the valence states of -3 and 0 occur only rarely in nature. This discussion of arsenic chemistry focuses on inorganic species of As(III) and As(V). Inorganic compounds of arsenic include hydrides (e.g., arsine), halides, oxides, acids, and sulfides (Ref. 2.4).

The toxicity and mobility of arsenic varies with its valence state and chemical form. Arsenite and arsenate are the dominant species in surface water and sea water, and organic arsenic species can be found in natural gas and shale oil (Ref. 2.12). Different chemical compounds containing arsenic exhibit varying degrees of toxicity and solubility.

Arsenic readily changes its valence state and chemical form in the environment. Some conditions that may affect arsenic valence and speciation include (Ref. 2.7):

- pH - in the pH range of 4 to 10, As(V) species are negatively charged in water, and the predominant As(III) species is neutral in charge
- redox 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 may participate in adsorptive reactions with arsenic (Ref. 2.7).

The unstable nature of arsenic species may make it difficult to treat or result in treated wastes whose toxicity and mobility can change under some environmental conditions. Therefore, the successful treatment and long-term disposal of arsenic requires an understanding of arsenic chemistry and the disposal environment.

2.3 How Often Does Arsenic Occur in Drinking Water?

Arsenic is a fairly common environmental contaminant. Both groundwater (e.g., aquifers) and surface water (e.g., lakes and rivers) sources of drinking water can contain arsenic. The levels of arsenic are typically higher in groundwater sources. Arsenic levels in groundwater tend to vary geographically. In the U.S., Western states (AK, AZ, CA, ID, NV, OR, UT, and WA) tend to have the highest concentrations (>0.010 mg/L), while states in the North Central (MT, ND, SD, WY), Midwest Central (IL, IN, IA, MI, MN, OH, and WI), and New England (CT, MA, ME, NH, NJ, NY, RI, and VT) regions tend to have low to moderate concentrations (0.002 to 0.010 mg/L). However, some portions of these areas may have no detected arsenic in drinking water. Other regions of the U.S. may have isolated areas of high concentration. EPA estimates that 4,000 drinking water treatment systems may require additional treatment technologies, a retrofit of existing treatment technologies, or other measures to achieve the revised MCL for arsenic. An estimated 5.4% of community water systems (CWSs) using groundwater as a drinking water source and 0.7% of CWSs using surface water have average arsenic levels above 0.010 mg/L. (Ref. 2.1)

2.4 How Often Does Arsenic Occur at Hazardous Waste Sites?

Hazardous waste sites fall under several clean-up programs, such as Superfund, Resource Conservation and Recovery Act (RCRA) corrective actions, and state cleanup programs. This section contains information on the occurrence and treatment of arsenic at National Priorities List (NPL) sites, known as Superfund sites. Information on arsenic occurrence and treatment at Superfund sites was complied from the CERCLIS 3 database (Ref. 2.3), the Superfund NPL Assessment Program (SNAP) database, and the database supporting the document "*Treatment Technologies for Site Cleanup: Annual Status Report (Tenth Edition)*" (Ref. 2.8). The information sources identified for this report did not contain information on arsenic occurrence and treatment at RCRA corrective action and state cleanup program sites.

Table 2.1 lists the number of Superfund sites with arsenic as a contaminant of concern by media. Groundwater and soil were the most common media contaminated with arsenic at 380 and 372 sites, respectively. The number of sites in Table 2.1 exceeds the number of total sites with arsenic contamination (568) because each site may have more than one type of media contaminated with arsenic.

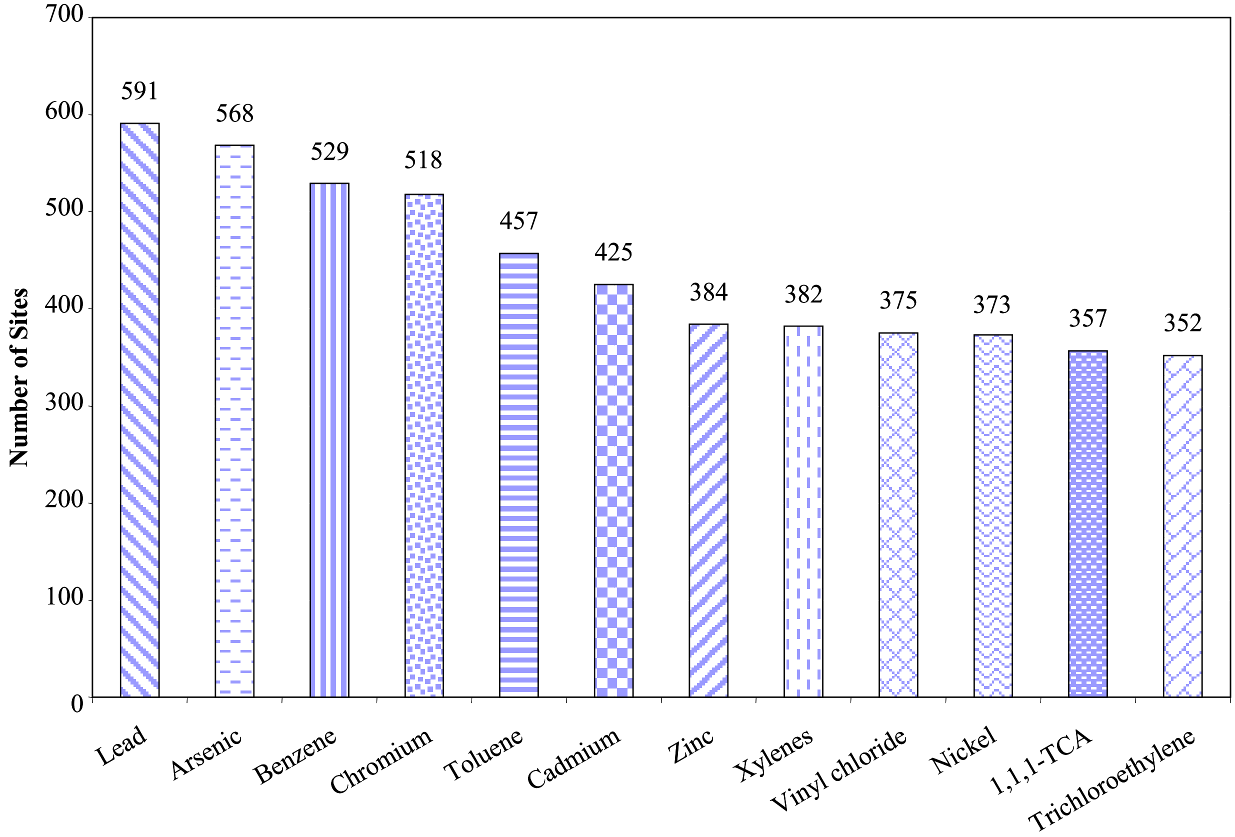
Table 2.1
Number of Superfund Sites with Arsenic as a Contaminant of Concern by Media

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

Source: Ref. 2.3

Arsenic occurs frequently at NPL sites. Figure 2.1 shows the most common contaminants of concern present at Superfund sites for which a Record of Decision (ROD) has been signed, through FY 1999, the most recent year for which such information is available. Arsenic is the second most common contaminant of concern (after lead), occurring at 568 sites (47% of all sites on the NPL with RODs).

Figure 2.1
Top Twelve Contaminants of Concern at Superfund Sites



Source: Ref. 2.3

Table 2.2 lists the number of Superfund sites with arsenic as a contaminant of concern by site type. The most common site types were landfills and other disposal facilities, chemicals and allied products, and lumber and wood products. Some sites may have more than one site type.

Figure 2.2 shows the use of treatment technologies to address arsenic at Superfund sites. These projects may be planned, ongoing, or completed. Solidification/ stabilization was the most common treatment technology for soil and waste, used in 45 projects to treat arsenic. The most common treatment technology for water was precipitation/coprecipitation, which is known to have been used in nine projects. More detail on these applications is provided in the technology-specific sections (Sections 4.0 through 16.0). Information in Figure 2.2 on the treatment of contaminant sources (i.e., contaminated soil, sludge, sediment, or other environmental media excluding groundwater) and in situ groundwater treatment is based on a detailed review of RODs and contacts with RPMs. A similar information source for pump and treat technologies (precipitation/coprecipitation, membrane filtration, adsorption, ion exchange) for groundwater containing arsenic at Superfund Sites was not available.

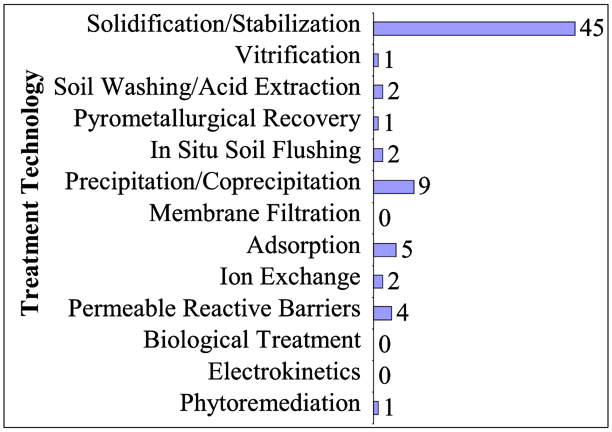
Table 2.2
Number of Superfund Sites with Arsenic as a Contaminant of Concern by Site Type

Site Type	Number of Sites[b]
Landfills and Other Disposal	209
Chemicals and Allied Products	42
Lumber and Wood Products	33
Groundwater Plume Site	26
Metal Fabrication and Finishing	20
Batteries and Scrap Metal	18
Military and Other Ordnance	18
Transportation Equipment	15
Primary Metals Processing	14
Chemicals and Chemical Waste	12
Ordnance Production	12
Electrical Equipment	11
Radioactive Products	9
Product Storage and Distribution	8
Waste Oil and Used Oil	8
Metals	6
Drums and Tanks	6
Transportation	5
Research and Development	5
Other[a]	104

Sources: Ref. 2.3, 2.15

a Includes site types with fewer than 5 sites, sites whose site types were identified as "other"or "multiple", and unspecified industrial waste facilities.
b Some sites have more than one site type.

Figure 2.2
Number of Applications of Arsenic Treatment Technologies at Superfund Sites[a]



a Information on the application of groundwater pump and treat technologies, including precipitation/coprecipitation, membrane filtration, adsorption, and ion exchange, is based on available data and is not comprehensive.

2.5 What Are the Structure and Contents of the Report?

Part I of this report, the Overview and Findings, contains an Executive Summary, an Introduction, and a Comparison of Arsenic Treatment Technologies. This Introduction describes the purpose of the report, presents background information, and summarizes the methodology used to gather and analyze data. The "Comparison of Technologies" Section (3.0) analyzes and compares the data gathered.

Part II of this report contains 13 sections, each summarizing the available information for an arsenic treatment technology. Each summary includes a brief description of the technology, information about how it is used to treat arsenic, its status and scale, and available cost and performance data, including the amount and type of soil, waste, and water treated and a summary of the results of analyses of untreated soil, waste, and water and treatment residuals for total and leachable arsenic concentrations. The technology summaries are organized as follows: the technologies typically used to treat soil and waste appear first, in the order of their frequency of full-scale applications, followed by those typically used for water in the same order, and then by those used to treat soil, waste, and water.

2.6 What Technologies and Media Are Addressed in the Report?

This report provides information on the 13 technologies listed in Table 1.1. These technologies have been used at full scale for the treatment of arsenic in soil, waste, and water. For the purposes of this report, the term "soil" includes soil, debris, sludge, sediments, and other solid-phase environmental media. Waste includes non-hazardous and hazardous solid waste generated by industry. Water includes groundwater, drinking water, non-hazardous and hazardous industrial wastewater, surface water, mine drainage, and leachate.

2.7 How Is Technology Scale Defined?

This report includes available information on bench-, pilot- and full-scale applications for the 13 technologies. Full-scale projects include those used commercially to treat industrial wastes and those used to remediate an entire area of contamination. Pilot-scale projects are usually conducted in the field to test the effectiveness of the technology on a specific soil, waste, and water or to obtain information for scaling a treatment system up to full scale. Bench-scale projects are conducted on a small scale, usually in a laboratory to evaluate the technology's ability to treat soil, waste, and water. These often occur during the early phases of technology development.

The report focuses on full- and pilot-scale data. Bench-scale data are presented only when less than 5 full-scale applications of a technology were identified. For the technologies with at least 5 identified full-scale applications (solidification/stabilization, vitrification, precipitation/coprecipitation, adsorption, and ion exchange), the report does not include bench-scale data.

2.8 How Are Treatment Trains Addressed?

Treatment trains consist of two or more technologies used together, either integrated into a single process or operated as a series of treatments in sequence. The technologies in a train may treat the same contaminant. The information gathered for this report included many projects that used treatment trains. A common treatment train used for arsenic in 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 trains are employed when one technology alone is not capable of treating all of the contaminants. For example, at the Baird and McGuire Superfund Site (Table 9.1), an above-ground system consisting of air stripping, metals precipitation, and activated carbon adsorption was used to treat groundwater contaminated with volatile organic compounds (VOCs), arsenic, and semivolatile organic compounds (SVOCs). In this treatment train the air stripping was intended to treat VOCs, the precipitation, arsenic, and the activated carbon adsorption, SVOCs and any remaining VOCs.

In many cases, the available information does not specify the technologies within the train that are intended to treat arsenic. Influent and effluent concentrations, where available, often were provided for the entire train, and not the individual components. In such cases, engineering judgement was used to identify the technology that treated arsenic. For example, at the Greenwood Chemical Superfund site (Table 9.1), a treatment train consisting of metals precipitation, filtration, UV oxidation and carbon adsorption was used to treat groundwater contaminated with arsenic, VOCs, halogenated VOCs, and SVOCs. The precipitation and filtration were assumed to remove arsenic, and the UV oxidation and carbon adsorption were assumed to have only a negligible effect on the arsenic concentration.

Where a train 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 (Tables 9.1 and 12.1). Information about this treatment is presented in both the precipitation/coprecipitation (Section 9.0) and ion exchange (Section 12.0) sections.

Activated carbon adsorption is most commonly used to treat organic contaminants. This technology is generally ineffective on As(III) (Ref. 2.14). Where treatment trains included activated carbon adsorption and another arsenic treatment technology, it was assumed that activated carbon adsorption did not contribute to the arsenic treatment, unless the available information indicated otherwise.

2.9 What Are the Sources of Information for This Report?

This report is based on an electronic literature search and information gathered from readily-available data sources, including:

- Documents and databases prepared by EPA, DOD, and DOE
- Technical literature
- Information supplied by vendors of treatment technologies
- Internet sites
- Information from technology experts

Most of the information sources used for this report contained information about treatments of environmental media and drinking water. Only limited information was identified about the treatment of industrial waste and wastewater containing arsenic. This does not necessarily indicate that treatment industrial wastes and wastewater containing arsenic occurs less frequently, because data on industrial treatments may be published less frequently.

The authors and reviewers of this report identified these information sources based on their experience with arsenic treatment. In addition, a draft version of this report was presented at the U.S. EPA Workshop on Managing Arsenic Risks to the Environment, which was held in Denver, Colorado in May of 2001. Information gathered from this workshop and sources identified by workshop attendees were also reviewed and incorporated where appropriate. Proceedings for this workshop may be available from EPA in 2002.

2.10 What Other Types of Literature Were Searched and Referenced for This Report?

To identify recent and relevant documents containing information on the application of arsenic treatment technologies in addition to the sources listed in Section 2.9, a literature search was conducted using the Dialog® and Online Computer Library Center (OCLC) services. The search was limited to articles published between January 1, 1998 and May 30, 2001 in order to ensure that the information gathered was current. The search identified documents that included in their title the words "arsenic," "treatment," and one of a list of key words intended to encompass the types of soil, waste, and water containing arsenic that might be subject to treatment. Those key words were:

- Waste
- Sludge
- Mining
- Groundwater
- Hazardous
- Sediment
- Water
- Mine
- Debris
- Soil
- Toxic
- Slag

The Dialog® search identified 463 references, and the OCLC search found 45 references. Appendix A lists the title, author, and publication source for each of the 508 references identified through the literature search. The search results were reviewed to identify the references (in English) that provided information on the treatment of waste that contains arsenic using one of the technologies listed in Table 1.1. Using this methodology, a total of 44 documents identified through the literature search were obtained and reviewed in detail to gather information for this report. These documents are identified in Appendix A with an asterisk (*).

2.11 References

2.1 U.S. EPA. National Primary Drinking Water Regulations; Arsenic and Clarifications to Compliance and New Source Contaminants Monitoring; Proposed Rule. Federal Register, Vol 65, Number 121, p. 38888. June 22, 2000. http://www.epa.gov/safewater/ars/arsenic.pdf.

2.2 U.S. Occupational Safety and Health Administration. Occupational Safety and Health Guidelines for Arsenic, Organic Compounds (as As). November, 2001. http://www.osha-slc.gov/SLTC/healthguidelines/arsenic/recognition.html.

2.3 U.S. EPA Office of Emergency and Remedial Response. Comprehensive Environmental Response Compensation and Liability Information System database (CERCLIS 3). October 2001.

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2.5 Kirk-Othmer. "Arsenic Compounds" The Kirk-Othemer Encyclopedia of Chemical Technology, Volume 3. John Wiley and Sons, New York. 1992.

2.6 EPA. Treatment Technology Performance and Cost Data for Remediation of Wood Preserving Sites. Office of Research and Development. EPA-625-R-97-009. October 1997. http://epa.gov/ncepihom.

2.7 Vance, David B. "Arsenic - Chemical Behavior and Treatment". October, 2001. http://2the4.net/arsenicart.htm.

2.8 EPA. Treatment Technologies for Site Cleanup: Annual Status Report (Tenth Edition). Office of Solid Waste and Emergency Response. EPA-542-R-01-004. February 2001. http://clu-in.org.

2.9 U.S. EPA. National Primary Drinking Water Regulations; Arsenic and Clarifications to Compliance and New Source Contaminants Monitoring; Final Rule. Federal Register, Volume 66, Number 14, p. 6975-7066. January 22, 2001. http://www.epa.gov/sbrefa/documents/pnl14f.pdf

2.10 U.S. EPA Office of Water. Fact Sheet: EPA to Implement 10ppb Standard for Arsenic in Drinking Water. EPA 815-F-01-010. October, 2001. http://www.epa.gov/safewater/ars/ars-oct-factsheet.html.

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2.12 National Research Council. Arsenic in Drinking Water. Washington, D.C. National Academy Press. 1999. http://www.nap.edu/catalog/6444.html

2.13 The Agency for Toxic Substances and Disease Registry (ATSDR): ToxFAQs^{TM} for Arsenic (12). July, 2001. http://www.atsdr.cdc.gov/tfacts2.html.

2.14 U.S. EPA. Cost Analyses for Selected Groundwater Cleanup Projects: Pump and Treat Systems and Permeable Reactive Barriers, EPA-542-R-00-013, February 2001. http://clu-in.org

2.15 U.S. EPA Office of Emergency and Remedial Response. Superfund NPL Assessment Program (SNAP) database. April 11, 2002.

3.0 COMPARISON OF ARSENIC TREATMENT TECHNOLOGIES

3.1 What Technologies Are Used to Treat Arsenic?

This report identifies 13 technologies applicable to arsenic-contaminated soil, waste, and water. Technologies are considered applicable if they have been used at full scale to treat arsenic.

Arsenic Treatment Technologies

Soil and Waste Treatment Technologies

- Solidification/ Stabilization
- Vitrification
- Soil Washing/Acid Extraction
- Pyrometallurgical Recovery
- In Situ Soil Flushing

Water Treatment Technologies

- Precipitation/ Coprecipitation
- Membrane Filtration
- Adsorption
- Ion Exchange
- Permeable Reactive Barriers

Soil, Waste, and Water Treatment Technologies

- Electrokinetics
- Phytoremediation
- Biological Treatment

Table 3.1 summarizes their applicability to arsenic-contaminated media. The media treated by these technologies can be grouped into two general categories: soil and waste; and water.

Technologies applicable to one type of soil and waste are typically applicable to other types. For example, solidification/stabilization has been used to effectively treat industrial waste, soil, sludge, and sediment. Similarly, technologies applicable to one type of water are generally applicable to other types. For example, precipitation/coprecipitation has been used to effectively treat industrial wastewaters, groundwater, and drinking water.

3.2 What Technologies Are Used Most Often to Treat Arsenic?

This section provides information on the number of treatment projects identified for each technology and estimates of the relative frequency of their application. Figures 3.1 to 3.3 show the number of treatment projects identified for each technology. Figure 3.1 shows the number for technologies applicable to soil and waste based on available data. The most frequently used technology for soil and waste containing arsenic is solidification/stabilization. The available data show that this technology can effectively meet regulatory cleanup levels, is commercially available to treat both soil and waste, is usually less expensive, and generates a residual that typically does not require further treatment prior to disposal.

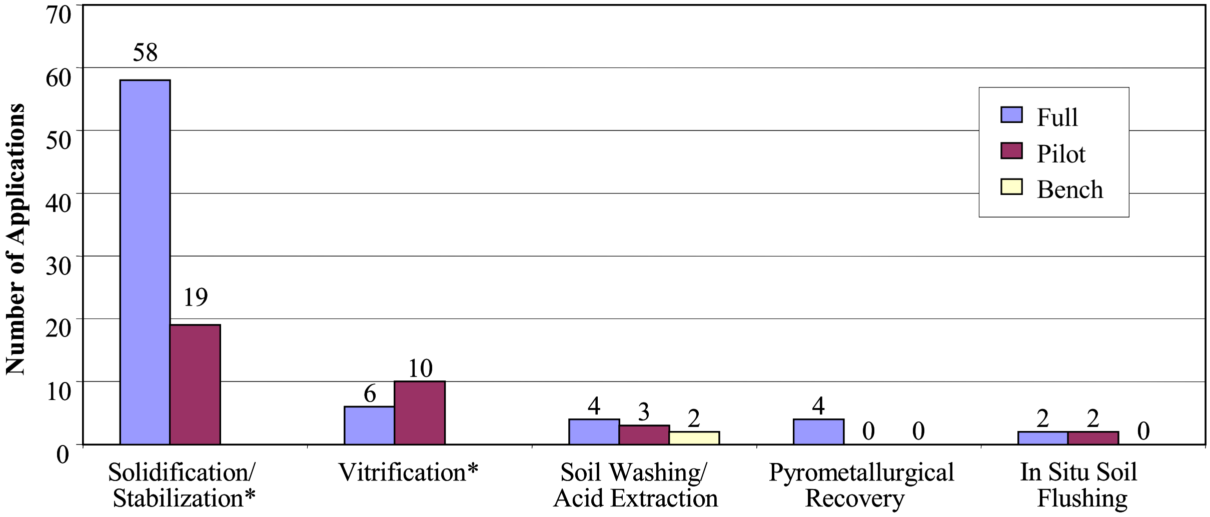
Other arsenic treatment technologies for soil and waste are typically used for specific applications. Vitrification may be used when a combination of contaminants are present that cannot be effectively treated using solidification/stabilization. It has also been used when the vitrification residual could be sold as a commercial product. However, vitrification typically requires large amounts of energy, can be more expensive than S/S, and may generate off-gasses containing arsenic.

Soil washing/acid extraction is used to treat soil primarily. However, it is not applicable to all types of soil or to waste. Pyrometallurgical treatment has been used primarily to recycle arsenic from industrial wastes containing high concentrations of arsenic from metals refining and smelting operations. These technologies may not be applicable to soil and waste containing low concentrations of arsenic. In situ soil flushing treats soil in place, eliminating the need to excavate soil. However, no performance data were identified for the limited number of full-scale applications of this technology to arsenic.

Figure 3.2 shows the number of treatment projects identified for technologies applicable to water. For water containing arsenic, the most frequently used technology is precipitation/coprecipitation. Based on the information gathered for this report, 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.

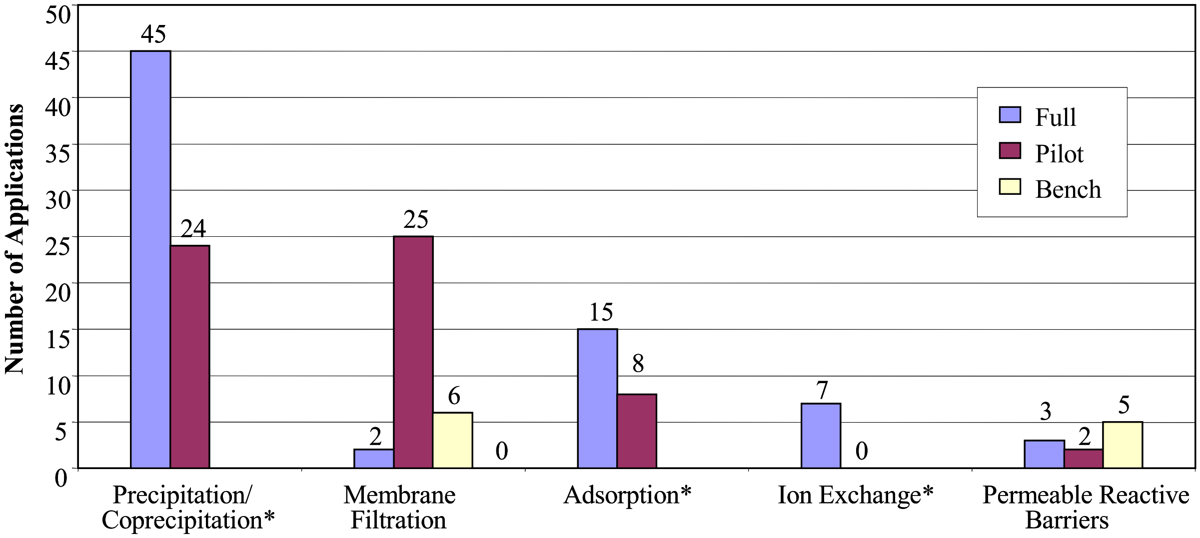
The effectiveness of adsorption and ion exchange for arsenic treatment is more likely than precipitation/ coprecipitation to be affected by characteristics and contaminants other than arsenic. However, these technologies are capable of treating arsenic to the

Figure 3.1
Number of Identified Applications of Arsenic Treatment Technologies for Soil and Waste



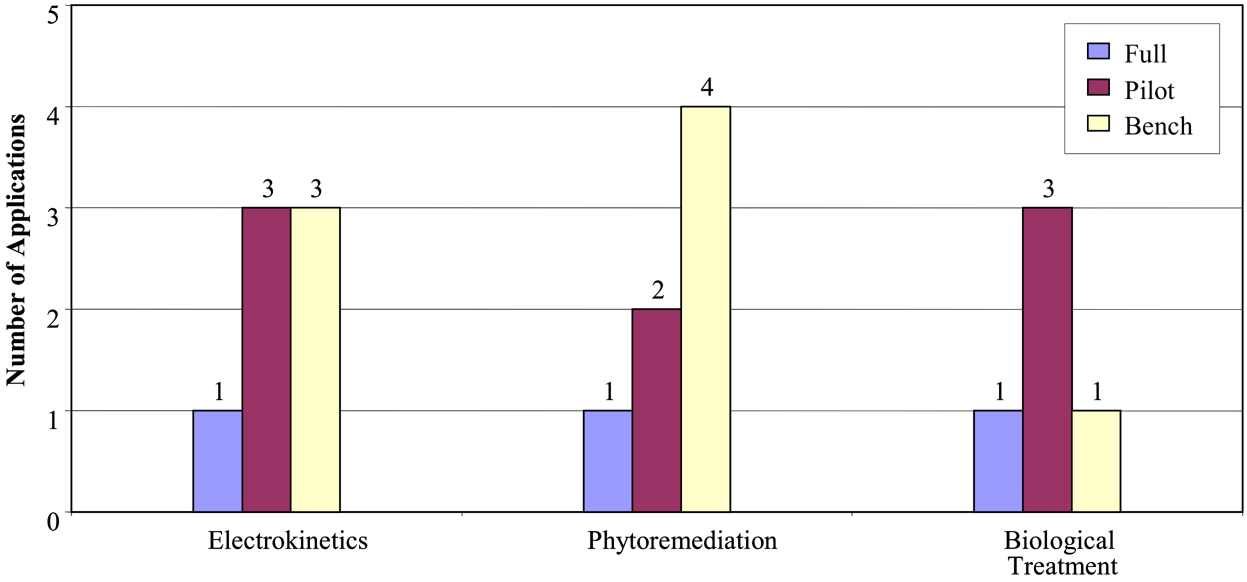
* Bench-scale data not collected for this technology.

Figure 3.2
Number of Identified Applications of Arsenic Treatment Technologies for Water



* Bench-scale data not collected for this technology.

Figure 3.3
Number of Identified Applications of Arsenic Treatment Technologies for Soil, Waste, and Water



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.

Permeable reactive barriers are used to treat groundwater in situ. This technology tends to have lower operation and maintenance costs than ex situ (pump and treat) technologies, and typically requires a treatment time of many years. This report identified three full-scale applications of this technology, but treatment data were available for only one application. In that application, a permeable reactive barrier is treating arsenic to below the revised MCL.

Figure 3.3 shows the number of treatment projects identified for technologies applicable to soil, waste, and water. Three arsenic treatment technologies are generally applicable to soil, waste, and water: electrokinetics, phytoremediation, and biological treatment. These technologies have been applied in only a limited number of applications.

Electrokinetic treatment is an in situ technology intended to be applicable to soil, waste and water. This technology is most applicable to fine-grained soils, such as clays. The references identified for this report contained information on one full-scale application of this technology to arsenic treatment.

Phytoremediation is an in situ technology intended to be applicable to soil, waste, and water. This technology tends to have low capital, operating, and maintenance costs relative to other arsenic treatment technologies because it relies on the activity and growth of plants. However, this technology tends to be less robust. The references identified for this report contained information on one full-scale application of this technology to arsenic treatment.

Biological treatment for arsenic is used primarily to treat water above-ground in processes that use microorganisms to enhance precipitation/ coprecipitation. Bioleaching of arsenic from soil has also been tested on a bench scale. This technology may require pretreatment or addition of nutrients and other treatment agents to encourage the growth of key microorganisms.

3.3 What Factors Affect Technology Selection for Drinking Water Treatment?

For the treatment of drinking water, technology selection depends on several of factors, such as existing systems, the need to treat for other contaminants, and the size of the treatment system. Although the data collected for this report indicate that precipitation/coprecipitation is the technology most commonly used to remove arsenic from drinking water, in the future other technologies may become more common as drinking water treatment facilities modify their operations to meet the revised arsenic MCL.

Precipitation/coprecipitation is often used to remove contaminants other than arsenic from drinking water, such as hardness or suspended solids. However, the precipitation/coprecipitation processes applied to drinking water usually also remove arsenic, or can be easily modified to do so. Where precipitation/coprecipitation processes are already in place, or are needed to remove other contaminants, these processes are commonly used to remove arsenic. Where precipitation/coprecipitation is not needed to treat drinking water for other contaminants, treaters may be more likely to choose another technology, such as adsorption, ion exchange, or reverse osmosis.

In addition, the size of a drinking water treatment system may affect the choice of technology. Precipitation/coprecipitation processes tend to be more complex, requiring more unit operations and greater operational expertise and monitoring, while adsorption and ion exchange units are usually less complex and require less operator expertise and monitoring. Therefore, operators of smaller drinking water treatment systems are more likely to select adsorption or ion exchange to treat arsenic instead of precipitation/coprecipitation.

3.4 How Effective Are Arsenic Treatment Technologies?

Applications are considered to have performance data when analytical data for arsenic are available both before and after treatment. For the technologies applicable to soil and waste, Table 1.2 (presented in the Executive Summary) includes performance data only for those projects with leachable arsenic concentration data for the treated soil and waste, and either leachable or total arsenic concentrations for the untreated soil and waste. Performance data were compared to the RCRA TCLP regulatory threshold of 5.0 mg/L (Ref. 3.1). For this table, projects that measured leachability with other procedures, such as the EPT and the WET, were also compared directly to this level. The tables in the technology-specific sections (Sections 4.0 to 16.0) identify the leaching procedures used to measure performance. The text box to the right describes the leaching procedures most frequently identified in the information sources used for this report.

For the technologies applicable to water, the performance was compared to the former MCL of 0.050 mg/L, and the revised MCL of 0.010 mg/L (Ref. 3.2). Information was available on relatively few projects that have treated arsenic to below 0.010 mg/L. However, this does not necessarily indicate that these treatment technologies cannot achieve 0.010 mg/L arsenic. In many cases, the treatment goal in the projects was greater than 0.010 mg/L, and in most cases was the previous arsenic MCL of 0.050 mg/L. In such cases, the treatment technology may be capable of meeting 0.010 mg/L arsenic with modifications to the treatment technology design or operating parameters.

Leaching Procedure Descriptions

Toxicity Characteristic Leaching Procedure (TCLP): The TCLP is used in identifying RCRA hazardous wastes that exhibit the characteristic of toxicity. In this procedure, liquids are separated from the solid phase of the waste, and the solid phase is then reduced in particle size until it is capable of passing through a 9.5 mm sieve. The solids are then extracted for 18 hours with a solution of acetic acid equal to 20 times the weight of the solid phase. The pH of the extraction fluid is a function of the alkalinity of the waste. Following extraction, the liquid extract is separated from the solid phase by filtration. If compatible, the initial liquid phase of the waste is added to the liquid extract and analyzed, otherwise they are analyzed separately. The RCRA TCLP regulatory threshold for arsenic is 5.0 mg/L in the extraction fluid (Ref. 3.22).

Extraction Procedure Toxicity Test (EPT): This procedure is similar to the TCLP test, with the following differences:
- The extraction period is 24 hours
- The extraction fluid is a pH 5 solution of acetic acid.

The EPT was replaced by the TCLP test in March, 1990 for purposes of hazardous waste identification, and is therefore no longer widely used (Ref. 3.23)

Waste Extraction Test (WET): The WET is used in identifying hazardous wastes in California. This procedure is similar to the TCLP, with the following differences
- The solid phase is reduced in particle size until it is capable of passing through a 2 mm sieve.,
- The waste is extracted for 48 hours
- The extraction fluid is a pH 5 solution of sodium citrate equal to 10 times the weight of the solid phase. The WET regulatory threshold for arsenic is 5.0 mg/L (Ref. 3.24).

3.5 What Are Special Considerations for Retrofitting Existing Water Treatment Systems?

On January 22, 2001, EPA published a revised MCL for arsenic in drinking water that would require public water suppliers to maintain arsenic concentrations at or below 0.010 mg/L by 2006 (Ref. 2.9). Some 4,000 drinking water treatment systems may require additional treatment technologies, a retrofit of existing treatment technologies, or other measures to achieve this level (Ref. 2.10). In addition, this revised MCL may affect Superfund remediation sites and other sites that base cleanup goals on the arsenic drinking water MCL. A lower goal could affect the selection, design, and operation of treatment systems.

Site-specific conditions will determine the type of changes needed to meet the revised MCL. Some arsenic treatment systems may be retrofitted, while other may require new arsenic treatment systems to be designed. In addition, treatment to lower arsenic concentrations could 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.

Examples of technology-specific modifications that can help reduce effluent concentrations of arsenic include:

<u>Precipitation/Coprecipitation</u>
- Use of additional treatment chemicals
- Use of different treatment chemicals
- Addition of another technology to the treatment train, such as membrane filtration

<u>Adsorption</u>
- 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

<u>Ion Exchange</u>
- 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

<u>Membrane Filtration</u>
- Increase in the volume of reject generated per volume of water treated
- Use of membranes with a smaller molecular weight cutoff
- Decrease in the flow rate of water treated
- Addition of another treatment technology to the treatment train, such as ion exchange

3.6 How Do I Screen Arsenic Treatment Technologies?

Table 3.2 at the end of this section is a screening matrix for arsenic treatment technologies. It can assist decision makers in evaluating candidate treatment technologies by providing information on relative availability, cost, and other factors for each technology. The matrix is based on the Federal Remediation Technologies Roundtable Technology (FRTR) Treatment Technologies Screening Matrix (Ref. 3.3), but has been tailored to treatment technologies for arsenic in soil, waste, and water. Table 3.2 differs from the FRTR matrix by:

- Limiting the scope of the table to the technologies discussed in this report.

- Changing the information based on the narrow scope of this report. For example, the FRTR screening matrix lists the overall cost of adsorption as "worse" (triangle symbol) in comparison to other treatment technologies for water. However, when applied to arsenic treatment, the costs of the technologies discussed in this report may vary based on scale, water characteristics, and other factors. Therefore, adsorption costs are not necessarily higher than the costs of other technologies discussed in this report, and this technology's overall cost is rated as "average" (circle symbol) in Table 3.2.

- Adding information about characteristics that can affect technology performance or cost.

Table 3.2 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.

- *Treatment Trains* - "Y" indicates that the technology is typically used in combination with other technologies, such as pretreatment or treatment of residuals (excluding off gas). “N” indicates that the technology is typically used independently.

- *Residuals Produced* - The residuals typically produced that may require additional management. “S” indicates production of a solid residual, “L”, a liquid residual, and “V” a vapor residual. All of the technologies generate a solid residual, with the exceptions of soil flushing and membrane filtration, which generate only liquid residuals. Vitrification and pyrometallurgical recovery produce a vapor residual.

- *O&M or Capital Intensive* -This indicates the main cost-intensive parts of the system. “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. “N” indicates neither operation and maintenance nor capital costs are intensive.

- *Availability* - The relative number of vendors that can design, construct, or maintain the technology. A square indicates more than four vendors; a circle, two to three vendors; and a triangle, fewer than two vendors. All of the technologies have more than four vendors with the exception of pyrometallurgical recycling, bioremediation, electrokinetics, and phytoremediation, which have less than two.

- *System Reliability/Maintainability* - The expected reliability/maintainability of the technology. A square indicates high reliability and low maintenance; a circle, average reliability and maintenance; and a triangle, low reliability and high maintenance. Biological treatment, electrokinetics, and phytoremediation are rated low because of the limited number of applications for those technologies, and indications that some applications were not effective.

- *Overall Cost* - Design, construction, and O&M costs of the core process that defines each technology, plus the treatment of residuals. A square indicates lower overall cost; a circle, average overall cost; and a triangle, higher overall cost. Solidification/stabilization is rated a low cost technology because it typically uses standard equipment and relatively low cost chemicals and additives. Phytoremediation is low cost because of the low capital expense to purchase and plant phytoremediating species and the low cost to maintain the plants.

- *Characteristics That May Require Pretreatment or Affect Performance or 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 interfere with technology effectiveness or result in increased costs. 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. “Other characteristics” are technology-specific elements which affect technology performance, cost, or both. These characteristics are described in Sections 4.0 through 16.0.

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 treatment decisions.

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. 3.25).

3.7 What Does Arsenic Treatment Cost?

A limited amount of cost data on arsenic treatment was identified for this report. Table 3.3 summarizes this information. In many cases, the cost information was incomplete. For example, some data were for operating and maintenance (O&M) costs only, and did not specify the associated capital costs. In other cases, a cost per unit of soil, waste, and water treated was provided, but total costs were not. For some technologies, no arsenic-specific cost data were identified.

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 in Table 3.3 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 report does not provide a summary or interpretation of the costs in Table 3.3.

In general, Table 3.3 only includes costs specifically for treatment of arsenic. Because arsenic treatment is very waste- and site-specific, general technology cost estimates are unlikely to accurately predict arsenic treatment costs. However, general technology cost estimates were included for three technologies: solidification/stabilization, pyrometallurgical recovery, and phytoremediation.

One of the solidification/stabilization costs listed in Table 3.3 is a general cost for treatment of metals, and is not arsenic-specific. This cost was included because solidification/stabilization processes for arsenic are similar to those for treatment of metals. The only cost for pyrometallurgical recovery listed in Table 3.3 is a general cost for the treatment of volatile metals and is not arsenic-specific. This cost was included because arsenic is expected to behave in a manner similar to other volatile metals when treated using pryometallurgical recovery processes. For phytoremediation, costs for applications to metals and radionuclides are included due to the lack of data on arsenic.

The EPA document "Technologies and Costs for Removal of Arsenic From Drinking Water" (Ref. 3.4) 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. 3.4). Although the cost information is only for the removal of arsenic from drinking water, many of the same treatment technologies can be used for the treatment of other waters and may have similar costs.

Table 3.4 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 3.4 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. 3.4).

3.8 References

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Table 3.1.
Applicability of Arsenic Treatment Technologies

Technology	Soil[a]	Waste[b]	Water		
			Groundwater and Surface Water[c]	Drinking Water	Wastewater[d]
Solidification/Stabilization	g	g			
Vitrification	g	g			
Soil Washing/Acid Extraction	g				
Pyrometallurgical Treatment	g	g			
In Situ Soil Flushing	g				
Precipitation/Coprecipitation			g	g	g
Membrane Filtration			g	g	
Adsorption			g	g	
Ion Exchange			g	g	
Permeable Reactive Barriers			g		
Electrokinetics	g	g	g		
Phytoremediation	g		g		
Biological Treatment			g		g

g = Indicates treatment has been conducted at full scale.

[a] Soil includes soil, debris, sludge, sediments, and other solid phase environmental media.
[b] Waste includes non-hazardous and hazardous solid waste generated by industry.
[c] Groundwater and surface water also includes mine drainage.
[d] Wastewater includes nonhazardous and hazardous industrial wastewater and leachate.

Table 3.2
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**	**Characteristics That May Require Pretreatment or Affect Performance or Cost**			
								High Arsenic Concentration	**Arsenic Chemical Form**	**pH**	**Other Characteristics**
Technology											
Solidification/Stabilization	F	N	S	Cap	■	■	■		T	T	• Redox potential • Presence of organics • Fine particulate • Type of binder & reagent • Pretreatment
Vitrification	F	N	S, V	Cap & O&M	■	●	△				• Presence of halogenated organic compounds • Presence of volatile metals • Particle size • Lack of glass forming materials • Moisture content • Organic content • Volume of contaminated soil and waste • Characteristics of treated waste

Table 3.2
Arsenic Treatment Technologies Screening Matrix (continued)

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**	**Characteristics That May Require Pretreatment or Affect Performance or Cost**			
								High Arsenic Concentration	**Arsenic Chemical Form**	**pH**	**Other Characteristics**
Soil Washing/Acid Extraction	F	Y	S, L	Cap & O&M	■	●	●			T	• Soil homogeneity • Multiple contaminants • Moisture content • Temperature • Soil particle size distribution
Pyrometallurgical Recycling	F	N	S, L, V	Cap& O&M	△	●	△				• Particle size • Moisture content • Thermal conductivity • Presence of impurities
Soil Flushing	F	Y	L	O&M	■	●	●	T	T		• Number of contaminants treated • Soil characteristics • Precipitation • Temperature • Reuse of flushing solution • Contaminant recovery

Table 3.2
Arsenic Treatment Technologies Screening Matrix (continued)

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**	**Characteristics That May Require Pretreatment or Affect Performance or Cost**			
								High Arsenic Concentration	**Arsenic Chemical Form**	**pH**	**Other Characteristics**
Precipitation/Coprecipitation	F	Y	S	Cap & O&M	■	■	●[a]		T	T	• Presence of other compounds • Type of chemical addition • Chemical dosage • Treatment goal • Sludge disposal
Membrane Filtration	F	Y	L	Cap & O&M	■	●	△	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

Table 3.2
Arsenic Treatment Technologies Screening Matrix (continued)

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**	**Characteristics That May Require Pretreatment or Affect Performance or Cost**			
								High Arsenic Concentration	**Arsenic Chemical Form**	**pH**	**Other Characteristics**
Adsorption	F	Y	S, L	Cap & O&M	■	●	● [a]	T	T	T	• Flow rate • pH • Fouling • Contamination concentration • Spent media
Ion Exchange	F	Y	S, L	Cap & O&M	■	●	● [a]	T	T	T	• Presence of competing ions • Presence of organics • Presence of trivalent ion • Project scale • Bed regeneration • Sulfate
Permeable Reactive Barriers	F	N	S	Cap	■	■	●		T		• Fractured rock • Deep aquifers & contaminant plumes • High aquifer hydraulic conductivity • Stratigraphy • Barrier plugging • PRB depth

Table 3.2
Arsenic Treatment Technologies Screening Matrix (continued)

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**	**Characteristics That May Require Pretreatment or Affect Performance or Cost**			
								High Arsenic Concentration	**Arsenic Chemical Form**	**pH**	**Other Characteristics**
Biological Treatment	F	Y	S, L	Cap & O&M	△	△	🟢	T	T	T	• Iron concentration • Contaminant concentration • Available nutrients • Temperature • Pretreatment requirements
Electrokinetics	F	Y	S, L	O&M	△	△	△	T	T	T	• Salinity & cation exchange capacity • Soil moisture • Polarity & magnitude of ionic charge • Soil type • Contaminant extraction system
Phytoremediation	F	N	L, S	N	△	△	🟥	T	T	T	• Contaminant depth • Climatic or seasonal conditions

Source: Adapted from the Federal Remediation Technologies Roundtable Technology Screening Matrix. http://www.frtr.gov. September 2001. (Ref. 3.3)

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

Table 3.3
Available Arsenic Treatment Cost Data

Site	Amount Treated	Capital Cost	Annual O & M Cost	Unit Cost	Total Cost	Cost Explanation	Source
Solidification/Stabilization							
-	-	-	-	$60 - $290 per ton	-	• Cost is for S/S of metals and is not arsenic-specific • Cost year not specified	3.5
Electrical Substation in Florida	3,300 cubic yards	-	-	$85 per cubic yard	-	• Excludes Disposal Costs • Costs in 1995 Dollars	3.6, 3.7
Vitrification							
Parsons Chemical Superfund Site	3,000 cubic yards	$350,000 - $550,000	-	$375 - $425 per ton	-	• Capital cost includes pilot testing, mobilization, and demobilization • Unit cots are for operation of vitrification equipment only • Cost year nor specified	3.8
Soil Washing/Acid Extraction							
King of Prussia Superfund Site	12,800 cubic yards	-	-	$400 per ton	-	• Cost year not specified	3.9, 3.10
-	-	-	-	$100 - $300 per ton	-	• Cost year not specified	3.10
-	-	-	-	$65 per ton	-	• Cost year not specified	3.11
-	400 cubic yards	-	-	$80 per ton	-	• Cost year not specified	3.11
-	38,000 tons	-	-	$203 per ton	$7.7 million	• Cost year not specified	3.12
Pyrometallurgical Recovery							
-	-	-	-	$208 to $458 per ton	_	• Cost is not arsenic-specific • Costs in 1991 dollars	3.10
In Situ Soil Flushing - No cost data identified							
Precipitation/Coprecipitation							
Vineland Chemical Company	1,400 gpm	-	$4 million	-	-	• Cost year not specified	3.13
Winthrop Landfill	65 gpm	$2 million	$250,000	-	-	• Cost year not specified	3.14
Energized Substation in Florida	44 million gallons	-	-	$0.0006 per gallon	-	• Cost year not specified	3.15
Membrane Filtration - No cost data identified							

Table 3.3
Available Arsenic Treatment Cost Data (Continued)

Site	Amount Treated	Capital Cost	Annual O & M Cost	Unit Cost	Total Cost	Cost Explanation	Source
Adsorption							
-	-	-	-	$0.003 - $0.76 per 1,000 gallons	-	• Cost year not specified	3.16
Ion Exchange							
-	-	$9,000	-	-	-	• Cost year not specified	3.17
Permeable Reactive Barrier							
Monticello Mill Tailings	-	$1.2 million	-	-	-	• Cost year not specified	3.18
Electrokinetics							
Pederok Plant, Kwint, Loppersum, Netherlands	325 cubic yards	-	-	$70 per ton	-	• Cost year not specified	3.11
Blackwater River State Forest, FL	-	-	-	$883 per ton	-	• Cost year not specified	3.21
Phytoremediation							
-	12 acres	-	-	-	$200,000	• 1998 dollars • Cost is for phytoextraction of lead from soil	3.26
-	1 acre, 20 inches deep	-	-	-	$60,000 - $100,000	• Cost year not specified • Cost is for phytoextraction from soil • Contaminant was not specified	3.27
-	-	-	-	$2 - $6 per 1,000 gallons	-	• Cost is for ex situ treatment of water containing radionuclides • Cost year not specified	3.28
-	-	-	-	$0.02 - $.76 per cubic yard	-	• Cost year not specified • Cost is for phytostabilization of metals, and is not arsenic-specific	3.29
Biological Treatment							
-	-	-	-	$0.50 per 1,000 gallons	-	• Cost year not specified	3.19
-	-	-	-	$2 per 1,000 gallons	-	• Cost year not specified	3.20

- = Data nor provided gpm - gallons per minute

Table 3.4
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. 3.4

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. 3.4), and are not comparable to other costs presented in this table, which are for new treatment systems.

mgd = million gallons per day

O&M = operating and maintenance

mg/L = milligrams per liter

< = less than

II
ARSENIC TREATMENT TECHNOLOGY SUMMARIES

IIA
ARSENIC TREATMENT TECHNOLOGIES APPLICABLE TO SOIL AND WASTE

4.0 SOLIDIFICATION AND STABILIZATION TREATMENT FOR ARSENIC

Summary

Solidification and stabilization (S/S) is an established treatment technology often used to reduce the mobility of arsenic in soil and waste. The most frequently used binders for S/S of arsenic are pozzolanic materials such as cement and lime. S/S can generally produce a stabilized product that meets the regulatory threshold of 5 mg/L leachable arsenic as measured by the TCLP. However, leachability tests may not always be accurate indicators of arsenic leachability for some wastes under certain disposal conditions.

Technology Description and Principles

The stabilization process involves mixing a soil or waste with binders such as Portland cement, lime, fly ash, cement kiln dust, or polymers to create a slurry, paste, or other semi-liquid state, which is allowed time to cure into a solid form. When free liquids are present the S/S process may involve a pretreatment step (solidification) in which the waste is encapsulated or absorbed, forming a solid material. Pozzolanic binders such as cement and fly ash are used most frequently for the S/S of arsenic. No site-specific information is currently available on the use of organic binders to immobilize arsenic.

Technology Description: S/S reduces the mobility of hazardous substances and contaminants in the environment through both physical and chemical means. It physically binds or encloses contaminants within a stabilized mass and chemically reduces the hazard potential of a waste by converting the contaminants into less soluble, mobile, or toxic forms.

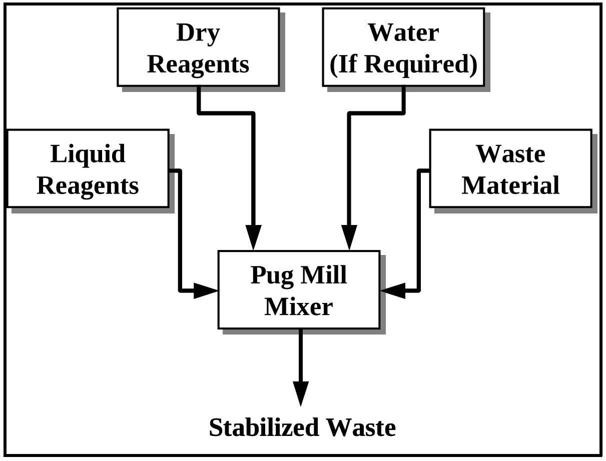
Media Treated:

- Soil
- Sludge
- Other solids
- Industrial waste

Binders and Reagents used in S/S of Arsenic:

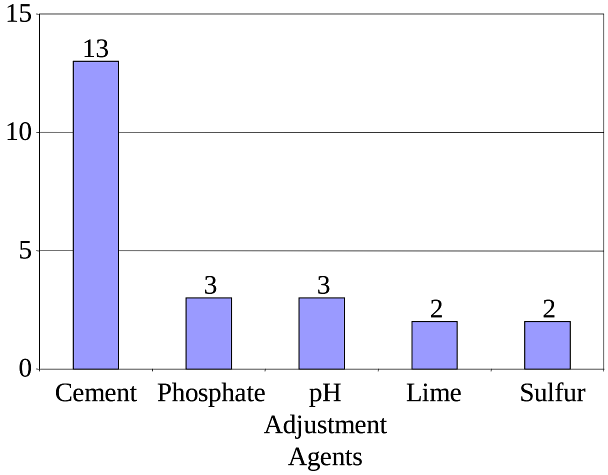
- Cement
- Fly Ash
- Lime
- Phosphate
- pH adjustment agents
- Sulfur

Model of a Solidification/Stabilization System



The process also may include the addition of pH adjustment agents, phosphates, or sulfur reagents to reduce the setting or curing time, increase the compressive strength, or reduce the leachability of contaminants (Ref. 4.8). Information gathered for this report included 45 Superfund remedial action projects treating soil or waste containing arsenic using S/S. Figure 4.1 shows the frequency of use of binders and reagents in 21 of those S/S treatments. The figure includes some projects where no performance data were available but information was available on the types of binders and reagents used. Some projects used more than one binder or reagent. Data were not available for all 46 projects.

Figure 4.1
Binders and Reagents Used for Solidification/Stabilization of Arsenic for 21 Identified Superfund Remedial Action Projects



S/S often involves the use of additives or pretreatment to convert arsenic and arsenic compounds into more stable and less soluble forms, including pH adjustment agents, ferric sulfate, persulfates, and other proprietary reagents (Ref. 4.3, 4.8). Prior to S/S, the soil or waste may be pretreated with chemical oxidation to render the arsenic less soluble by converting it to its As(V) state (Ref. 4.3). Pretreatment with incineration to convert arsenic into ferric arsenate has also been studied, but limited data are available on this process (Ref. 4.3).

This technology has also been used to immobilize arsenic in soil in situ by injecting solutions of chemical precipitants, pH adjustment agents, and chemical oxidants. In this report, such applications are referred to as in situ S/S. In one full-scale treatment, a solution of ferrous iron, limestone, and potassium permanganate was injected (Ref. 4.8). In another full-scale treatment, a solution of unspecified pH adjustment agents and phosphates was injected (Ref. 4.10).

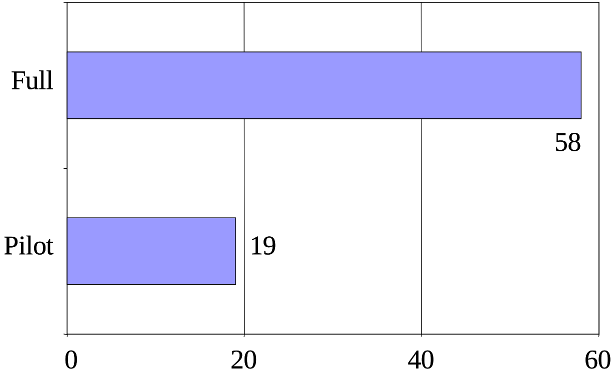
Media and Contaminants Treated

S/S is used frequently to immobilize metals and inorganics in soil and waste. It has been used to immobilize arsenic in environmental media such as soil and industrial wastes such as sludges and mine tailings.

Type, Number, and Scale of Identified Projects Treating Soil and Wastes Containing Arsenic

S/S of soil and waste containing arsenic is commercially available at full scale. Data sources used for this report included information about 58 full-scale and 19 pilot-scale applications of S/S to treat arsenic. This included 45 projects at 41 Superfund sites (Ref. 4.8). Figure 4.2 shows the number of applications at both full and pilot scale.

Figure 4.2
Scale of Identified Solidification/Stabilization Projects for Arsenic Treatment



Factors Affecting S/S Performance

- **Valence state** - The specific arsenic compound or valence state of arsenic may affect the leachability of the treated material because these factors affect the solubility of arsenic.
- **pH and redox potential** - The pH and redox potential of the waste and waste disposal environment may affect the leachability of the treated material because these factors affect the solubility of arsenic and may cause arsenic to react to form more soluble compounds or reach a more soluble valence state.
- **Presence of organics** - The presence of volatile or semivolatile organic compounds, oil and grease, phenols, or other organic contaminants may reduce the unconfined compressive strength or durability of the S/S product, or weaken the bonds between the waste particles and the binder.
- **Waste characteristics** - The presence of halides, cyanide, sulfate, calcium, or soluble salts of manganese, tin, zinc, copper, or lead may reduce the unconfined compressive strength or durability of the S/S product, or weaken the bonds between the waste particles and the binder.
- **Fine particulate** - The presence of fine particulate matter coats the waste particles and weakens the bond between the waste and the binder.
- **Mixing** - Thorough mixing is necessary to ensure waste particles are coated with the binder.

Summary of Performance Data

Table 4.1 provides performance data for 10 pilot-scale treatability studies and 34 full-scale remediation projects. Due to the large number of projects, Table 4.1 lists only those for which leachable arsenic concentrations are available for the treated soil or waste, with the exception of projects involving only in situ stabilization. In situ projects without information on the leachability of arsenic in the stabilized mass are included in the table because this type of application is more innovative and information is available for only a few applications.

The performance of S/S treatment is usually measured by leach testing a sample of the stabilized mass. For most land-disposed arsenic-bearing hazardous wastes that fall under RCRA (including both listed and characteristic wastes), the treatment standard is less than 5.0 mg/L arsenic in the extract generated by the toxicity characteristic leaching procedure (TCLP). The standard for spent potliners from primary aluminum smelting (K088) is 26.1 mg/kg total arsenic (Ref. 4.10). For listed hazardous wastes, the waste must be disposed in a Subtitle C land disposal unit after treatment to meet the standard for arsenic and any other applicable standards, unless it is specifically delisted. For hazardous wastes exhibiting the characteristic for arsenic, the waste may be disposed in a Subtitle D landfill after being treated to remove the characteristic and to meet all other applicable standards.

Of the 23 soil projects identified for this report, 22 achieved a leachable arsenic concentration of less than 5.0 mg/L in the stabilized material. Of the 19 industrial waste projects, 17 achieved a leachable arsenic concentration of less than 5.0 mg/L in the stabilized material. Leachability data are not available for the projects that involve only in situ stabilization.

Four projects (Projects 25, 26, 27, and 41, Table 4.1) included pretreatment to oxidize As(III) to As(V). In these projects, the leachability of arsenic in industrial wastes was reduced to less than 0.50 mg/L. The compound treated in Projects 24, 25, and 26 was identified as arsenous trisulfide. All three treatment processes involved pretreating a waste containing 5,000 to 40,000 mg/kg arsenous trisulfide with chemical oxidation (Ref. 4.1). The specific arsenic compound in another S/S treatment (Project 41) was identified as As_2O_3. This treatment process included pretreatment by chemical oxidation to form ferric arsenate sludge followed by S/S with lime (Ref. 4.3).

Limited data are available about the long-term stability of soil and waste containing arsenic treated using S/S. Projects 12, 13, and 16 were part of one study that tested the leachability of arsenic six years after S/S was performed (see Case Study: Long-Term Stability of S/S or Arsenic).

The case study on Whitmoyer Laboratories Superfund Site discusses in greater detail the treatment of arsenic using S/S. This information is summarized in Table 4.1, Project 20.

Applicability, Advantages, and Potential Limitations

The mobility of arsenic depends upon its valence state, the reduction-oxidation potential of the waste disposal environment, and the specific arsenic compound contained in the waste (Ref. 4.1). This mobility is usually measured by testing the leachability of arsenic under acidic conditions. In some disposal environments the leachability of arsenic may be different than that predicted by an acidic leach test, particularly when the specific form of arsenic in the waste shows increased solubility at higher pH and the waste disposal environment has a high pH. Analytical data for leachate from monofills containing wastes bearing RCRA waste code K088 (spent aluminum potliners) indicate that arsenic may leach from wastes at levels

Case Study: Long-Term Stability of S/S of Arsenic

EPA obtained leachate data from landfills accepting wastes treated using solidification/stabilization operated by Waste Management, Inc., Envirosafe, and Reynolds Metals. The Waste Management, Inc. landfills received predominantly hazardous wastes from a variety of sources, the Envirosafe landfill received primarily waste bearing RCRA waste code K061 (emission control dust and sludge from the primary production of steel in electric furnaces) and the Reynolds Metals facility was a monofill accepting waste bearing RCRA waste code K088 (spent potliners from primary aluminum reduction). Analysis of the leachate from 80 landfill cells showed 9 cells, or 11%, had dissolved arsenic concentrations higher than the TCLP level of 5.0 mg/L. The maximum dissolved arsenic concentration observed in landfill leachate was 120 mg/L. Analysis of the leachate from 152 landfill cells showed 29 cells, or 19%, had total arsenic concentrations in excess of the TCLP level of 5.0 mg/L. The maximum total arsenic concentration observed in landfill leachate was 1,610 mg/L (Ref. 4.12).

Another study reported the long-term stability of S/S technologies treating wastes from three landfills contaminated with heavy metals, including arsenic (Ref. 4.16). S/S was performed at each site using cement and a variety of chemical additives. TCLP testing showed arsenic concentrations ranging from zero to 0.017 mg/L after a 28-day cure time. Six years later, TCLP testing showed leachable arsenic concentrations that were slightly higher than those for a 28-day cure time (0.005 - 0.022 mg/L), but the levels remained below 0.5 mg/L. However, the stabilized waste was stored above ground, and therefore may not be representative of waste disposed in a landfill (see Projects 12, 13, and 16 in Table 4.1 and Table 4.2).

Case Study: Whitmoyer Laboratories Superfund Site

The Whitmoyer Laboratories Superfund Site was a former veterinary feed additives and pharmaceuticals manufacturing facility. It is located on approximately 22 acres of land in Jackson Township, Lebanon County, Pennsylvania. Production began at the site in 1934. In the mid-1950's the facility began using arsenic in the production of feed additives. Soils on most of the area covered by the facility are contaminated with organic arsenic.

Off-site stabilization began in mid-1999 and was completed by the spring of 2000. A total of 400 tons of soil were stabilized using a mixture of 10% water, 10% ferric sulfate, and 5% Portland cement. The concentration of leachabile arsenic in the treated soil was below 5.0 mg/L, as measured by the TCLP. Information on the pretreatment arsenic leachability was not available.

higher than those predicted by the TCLP (see Case Study: Long-term Stability of S/S of Arsenic).

Some S/S processes involve pretreatment of the waste to render arsenic less soluble prior to stabilization (Ref. 4.1, 4.3). Such processes may render the waste less mobile under a variety of disposal conditions (See Projects 25, 26, 27,and 41 in Table 4.1), but also may result in significantly higher waste management costs for the additional treatment steps.

In situ S/S processes may reduce the mobility of arsenic by changing it to less soluble forms, but do not remove the arsenic. Ensuring thorough mixing of the binder and the waste can also be challenging for in situ S/S processes, particularly when the subsurface contains large particle size soil and debris or subsurface obstructions. The long-term effectiveness of this type of treatment may be impacted if soil conditions cause the stabilized arsenic to change to more soluble and therefore more mobile forms.

Summary of Cost Data

The reported costs of treatment of soil containing metals using S/S range from $60 to $290 per ton (Ref. 4.5, cost year not identified). Limited site-specific cost data are currently available for S/S treatment of arsenic. At two sites, (Projects 21 and 22), total project costs, in 1995 dollars, were about $85 per cubic yard, excluding disposal costs (Ref. 4.21).

Factors Affecting S/S Costs

- **Type of binder and reagent** - The use of proprietary binders or reagents may be more expensive than the use of non-proprietary binders (Ref. 4.16).
- **Pretreatment** - The need to pretreat soil and waste prior to S/S may increase management costs (Ref. 4.18).
- **Factors affecting S/S performance** - Items in the “Factors Affecting S/S Performance” box will also affect costs.

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Table 4.1
Solidification/Stabilization Treatment Performance Data for Arsenic

Project Number	Industry and Site Type	Waste or Media	Scale[a]	Site Name, Location, and Project Completion Date[b]	Initial Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Final Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Binder or Stabilization Process	Source
Environmental Media								
1	Disposal Pit	20,000 cy sludge and soil	Full	Pab Oil Superfund Site, LA August 1998	7.5 - 25.1 mg/kg	<0.1 mg/L (TCLP)	Cement, organophilic clay, other unspecified organic, ferric sulfate, other unspecified inorganic, and sulfur	4.8
2	Fire/Crash Training Area; Federal Facility	3,000 cy sludge and soil	Full	Jacksonville Naval Air Station Superfund Site, FL October 1995	ND[c] - 61 mg/kg	<5 mg/L (TCLP)	Cement, lime, other unspecified inorganic, and kiln dust	4.8
3	Metal Ore Mining and Smelting	500,000 cy soil	Full	Anaconda Co. Smelter Superfund Site, MT January 1994	50 - 100 mg/L (EPT)	<2 mg/L (TCLP)	Unspecified inorganic	4.8
4	Munitions Manufacturing/ Storage	1,000 cy soil	Full	Fernald Environmental Management Project Superfund Site, OH September 1999	3 - 18 mg/kg	<5mg/L (TCLP)	Cement and other unspecified inorganic	4.8
5	--	Soil	Full	--	0.18 mg/L (EPT)	0.028 mg/L (EPT)	Cement	4.4
6	--	Soil	Full	--	0.19 mg/L (TCLP)	0.017 mg/L (TCLP)	Cement	4.4
7	--	Soil	Full	--	0.0086 mg/L (EPT)	0.0049 mg/L (EPT)	Proprietary binder	4.4
8	--	Soil	Full	--	0.0091 mg/L (TCLP)	<0.002 mg/L (TCLP)	Proprietary binder	4.4
9	--	Soil	Full	--	0.017 mg/L (TCLP)	0.0035 mg/L (TCLP)	Proprietary binder	4.4

Table 4.1
Solidification/Stabilization Treatment Performance Data for Arsenic (continued)

Project Number	Industry and Site Type	Waste or Media	Scale[a]	Site Name, Location, and Project Completion Date[b]	Initial Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Final Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Binder or Stabilization Process	Source
10	--	Soil	Full	--	2,430 mg/kg	0.11 - 0.26 mg/L (TCLP)	fly ash, cement, and proprietary reagent	4.3
11	--	Soil	Full	--	0.10 mg/L (TCLP)	0.04 mg/L (TCLP)	--	4.1
12	Oil Processing & Reclamation	Filter cake and oily sludge	Full	Imperial Oil Co - Champion Chemical Co Superfund Site, NJ	40 mg/kg	ND[c,d] (TCLP)	Cement and proprietary additives	4.16
13	Oil Processing & Reclamation	Soil	Full	Imperial Oil Co - Champion Chemical Co Superfund Site, NJ	92 mg/kg	0.017[d] mg/L (TCLP)	Cement and proprietary additives	4.16
14	Pesticides	Soil	Full	--	0.60 mg/L (EPT) 28.0 mg/L (WET)	0.27 mg/L (EPT) 6.5 mg/L (WET)	--	4.1
15	Pharmaceutical	3,800 tons sludge and soil	Full	--	260,000 mg/kg 4,310 - 4,390 mg/L (TCLP)	1.24 - 3.44 mg/L (TCLP)	Potassium persulfate, ferric sulfate, and cement	4.15
16	Transformer and Metal Salvage	Soil	Full	Portable Equipment Salvage Co, OR	42 mg/kg	0.004[d] mg/L (TCLP)	Proprietary binder	4.16
17	Wood Preserving	14,800 cy soil	Full	Macgillis And Gibbs/Bell Lumber And Pole Superfund Site, MN February 1998	1 - 672 mg/kg	55 mg/L (TCLP)	Cement	4.8

Table 4.1
Solidification/Stabilization Treatment Performance Data for Arsenic (continued)

Project Number	Industry and Site Type	Waste or Media	Scale[a]	Site Name, Location, and Project Completion Date[b]	Initial Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Final Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Binder or Stabilization Process	Source
18	Wood Preserving	Soil	Full	--	91 - 128 mg/kg	0.015 - 0.29 mg/L	Reduction of hexavalent chromium followed by stabilization with cement and lime	4.16
19	Wood Preserving	13,000 cy soil	Full	Palmetto Wood Preserving Superfund Site, SC 1989	6,200 mg/kg	0.02 mg/L (TCLP)	Cement and a pH adjustment agent	4.8
20	Veterinary feed additives and pharmaceutical manufacturing	400 tons	Full	Whitmoyer Laboratories Superfund Site	--	< 5 mg/L (TCLP)	Water, ferric sulfate, and Portland cement	4.23
21	Electrical substation	1,000 cy soil	Pilot	Florida 1995	<0.5 -2,000 mg/kg 1.42 - 3.7 mg/L (TCLP)	ND - 0.11 (TCLP)	Cement and ferrous sulfate	4.21, 4.22
22	Electrical substation	3,300 cy soil	Pilot	Florida 1995	<0.5 - 1,900 mg/kg 0.15 - 3.5 mg/L (TCLP)	0.22 - 0.38 (TCLP)	Cement and ferrous sulfate	4.21, 4.22
23	Wood Preserving	Soil	Pilot	Selma Pressure Treating Superfund Site, Selma, CA 1998	10 mg/L (TCLP)	< 0.1 mg/L (TCLP)	Proprietary binder	4.19

Table 4.1
Solidification/Stabilization Treatment Performance Data for Arsenic (continued)

Project Number	Industry and Site Type	Waste or Media	Scale[a]	Site Name, Location, and Project Completion Date[b]	Initial Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Final Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Binder or Stabilization Process	Source
Industrial Wastes								
24	Food-grade H_3PO_4 manufacture from phosphate rock	--	Full	--	70.0 mg/L (TCLP)	1.58 mg/L (TCLP)	--	4.1
25	Food-grade H_3PO_4 manufacture from phosphate rock	Arsenous trisulfide	Full	--	5,000 - 40,000 mg/kg	0.43 mg/L (TCLP)	Oxidation with NaOH and NaOCl followed by stabilization with bed ash	4.1
26	Food-grade H_3PO_4 manufacture from phosphate rock	Arsenous trisulfide	Full	--	5,000 - 40,000 mg/kg	<0.14 mg/L (TCLP)	Oxidation with hydrated lime and NaOCl followed by stabilization with bed ash	4.1
27	Food-grade H_3PO_4 manufacture from phosphate rock	Arsenous trisulfide	Full	--	5,000 - 40,000 mg/kg	<0.10 mg/L (TCLP)	Pretreatment with cement and CaOCl2 followed by stabilization with lime and cement	4.1
28	--	Dry waste	Full	--	0.005 mg/L (TCLP)	<0.002 mg/L (TCLP)	Cement and other unspecified additives	4.4
29	--	Dry waste	Full	--	0.01 mg/L (EPT)	0.0023 mg/L (TCLP)	Cement and other unspecified additives	4.4
30	--	Sludge	Full	--	0.011 mg/L (EPT)	0.002 mg/L (EPT)	Cement and other unspecified additives	4.4
31	--	Sludge	Full	--	0.014 mg/L (TCLP)	<0.002 mg/L (TCLP)	Cement and other unspecified additives	4.4

Table 4.1
Solidification/Stabilization Treatment Performance Data for Arsenic (continued)

Project Number	Industry and Site Type	Waste or Media	Scale[a]	Site Name, Location, and Project Completion Date[b]	Initial Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Final Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Binder or Stabilization Process	Source
32	Pesticide	Pesticide sludge	Full	--	52.0 mg/L (WET) 19.0 mg/L (EPT)	5.20 mg/L (WET) 0.14 mg/L (EPT)	--	4.1
33	Waste disposal	Hazardous waste landfill leachate	Full	--	4.20 mg/L (TCLP)	0.016 mg/L (TCLP)	--	4.1
34	Waste treatment	Hazardous waste incinerator ash	Full	--	0.07 mg/L (TCLP)	0.019 mg/L (TCLP)	--	4.1
35	Waste treatment	Hazardous waste incinerator pond sludge	Full	--	0.30 mg/L (TCLP) 0.30 mg/L (EPT)	<0.01 mg/L (TCLP) <0.01 mg/L (EPT)	--	4.1
36	Glass Manufacturing	D004/D005 Waste	Pilot	--	296 mg/L (TCLP)	66.3 mg/L (TCLP)	Cement and fly ash	4.14
37	Glass Manufacturing	D004/D005 Waste	Pilot	--	6 mg/L (TCLP)	<1 mg/L (TCLP)	Cement and fly ash and ferrous sulfate	4.14
38	Glass Manufacturing	D004/D005 Waste	Pilot	--	18 mg/L (TCLP)	<1 mg/L (TCLP)	Cement and fly ash and ferric sulfate	4.14
39	Mining	Mine Tailings	Pilot	Spring Hill Mine, Montana	6,000 mg/kg	ND[c] (TCLP)	Silica Microencapsulation	4.17
40	--	D004, spent catalyst	Pilot	--	280,000 mg/kg	0.79 mg/L (TCLP) 1.25 mg/L (alkaline leaching test at pH 9.5)	Chemical oxidation of waste to form ferric arsenate sludge, followed by stabilization with lime	4.3
41	--	P012, As_2O_3	Pilot	--	750,000 mg/kg	<0.05 - 0.59 mg/L (TCLP) 0.34 - 0.79 mg/L (alkaline leaching test at pH 9.5)	Chemical oxidation of waste to form ferric arsenate sludge, followed by stabilization with lime	4.3

Table 4.1
Solidification/Stabilization Treatment Performance Data for Arsenic (continued)

Project Number	Industry and Site Type	Waste or Media	Scale[a]	Site Name, Location, and Project Completion Date[b]	Initial Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Final Arsenic Concentration (mg/kg) or Leachability (mg/L) (Test method)	Binder or Stabilization Process	Source
42	--	Sludge	Pilot	--	6,430 mg/L	0.823 mg/L (TCLP)	Embedding calcium and ferric arsenates/arsenites in a cement matrix	4.20
In Situ Stabilization Only								
43	Agricultural application of pesticides	Soil, 5,000 cubic yards	Full	Wisconsin DNR-Orchard Soil	ND[c] - 50 mg/L (type of analysis not reported)	ND[c] - 1 mg/L (type of analysis not reported)	In situ treatment of contaminated soil by injecting pH adjustment agents and phosphates	4.6
44	Wood preserving wastes, soil, 50,000 cubic yards	Soil, 50,000 cubic yards	Full	Silver Bow Creek/Butte Area Superfund Site, MT 1998	--	--	In situ treatment of contaminated soil by injecting a solution of ferrous iron, limestone, and potassium permanganate	4.8

a Excludes all bench-scale projects. Also excludes full- and pilot-scale projects where data on the leachability of stabilized wastes are not available.
b Project completion dates provided for Superfund remedial action projects only.
c Detection limit not provided.
d Analyzed after 28 days. See Table 1.2 for long-term TCLP data.

EPT = Extraction procedure toxicity test.
-- = Not available
WET = Waste extraction test
mg/kg = Milligrams per kilogram
TCLP = Toxicity characteristic leaching procedure
OU = Operable Unit
mg/L = Milligrams per liter
TWA = Total waste analysis
cy = Cubic yard

Table 4.2
Long-Term Solidification/Stabilization Treatment Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration (Total Waste Analysis)	Final Arsenic Concentration of Leachability (28 day cure time)	Long-Term Leachable Arsenic Concentration (6 year cure time)		Binder or Stabilization Process
							Archived	Field	
1	Oil Processing & Reclamation	Filter cake and oily sludge	Full	Imperial Oil Co. - Champion Chemical Co. Superfund Site, NJ	40 mg/kg	ND[b] (TCLP)	0.009 mg/L (TCLP)	0.005 mg/L (TCLP)	Cement and proprietary additives
2	Oil Processing & Reclamation	Soil	Full	Imperial Oil Co. - Champion Chemical Co. Superfund Site, NJ	92 mg/kg	0.017 mg/L (TCLP)	0.021 mg/L (TCLP)	0.022 mg/L (TCLP)	Cement and proprietary additives
3	Transformer and Metal Salvage	Soil	Full	Portable Equipment Salvage Co., OR	42 mg/kg	0.004 mg/L (TCLP)	--	0.005 mg/L (TCLP)	Proprietary binder

Source: 4.16

a Excludes all bench-scale projects. Also excludes full- and pilot-scale projects where data on the leachability of stabilized wastes are not available.
b Detection limit not provided.

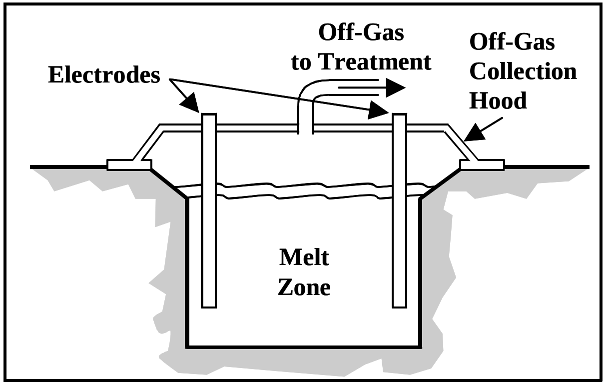
-- = Not available.
ND = Not detected.
TCLP = Toxicity characteristic leaching procedure.

5.0 VITRIFICATION FOR ARSENIC

Summary

Vitrification has been applied in a limited number of projects to treat arsenic-contaminated soil and waste. For soil treatment, the process can be applied either in situ or ex situ. This technology typically requires large amounts of energy to achieve vitrification temperatures, and therefore can be expensive to operate. Off-gases may require further treatment to remove hazardous constituents.

Model of an In Situ Vitrification System



Technology Description and Principles

During the vitrification treatment process, the metals are surrounded by a glass matrix and become chemically bonded inside the matrix. For example, arsenates can be converted into silicoarsenates during vitrification (Ref. 5.4).

Technology Description: Vitrification is a high temperature treatment aimed at reducing the mobility of metals by incorporating them into a chemically durable, leach resistant, vitreous mass (Ref. 5.6). This process also may cause contaminants to volatilize or undergo thermal destruction, thereby reducing their concentration in the soil or waste.

Media Treated
- Soil
- Waste

Energy Sources Used for Vitrification:
- Fossil fuels
- Direct joule heat

Energy Delivery Mechanisms Used for Vitrification:
- Arcs
- Plasma torches
- Microwaves
- Electrodes (in situ)

In Situ Application Depth:
- Maximum demonstrated depth is 20 feet
- Depths greater than 20 feet may require innovative techniques

Ex situ processes provide heat to a melter through a variety of sources, including combustion of fossil fuels, and input of electric energy by direct joule heating. The heat may be delivered via arcs, plasma torches, and microwaves. In situ vitrification uses resistance heating by passing an electric current through soil by means of an array of electrodes (Ref. 5.6). In situ vitrification can treat up to 1,000 tons of soil in a single melt.

Vitrification occurs at temperatures from 2,000 to 3,600^{0}F (Ref. 5.1, 5.4). These high temperatures may cause arsenic to volatilize and contaminate the off-gas of the vitrification unit. Vitrification units typically employ treatment of the off-gas using air pollution control devices such as baghouses (Ref. 5.5).

Pretreatment of the waste to be vitrified may reduce the contamination of off-gasses with arsenic. For example, in one application (Project 15), prior to vitrification of flue dust containing arsenic trioxide (As_2O_3), a mixture of the flue dust and lime was roasted at 400 ^{0}C to convert the more volatile arsenic trioxide to less volatile calcium arsenate ($Ca_3(AsO_4)_2$) (Ref. 5.5). Solid residues from off-gas treatment may be recycled into the feed to the vitrification unit (Ref. 5.6).

The maximum treatment depth for in situ vitrification has been demonstrated to be about 20 feet (Ref. 5.6). Table 5.1 describes specific vitrification processes used to treat soil and wastes containing arsenic.

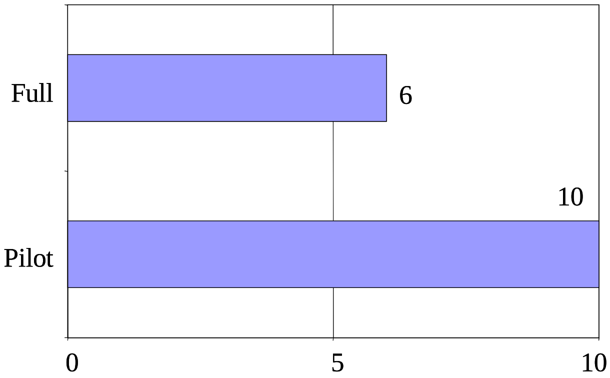
Media and Contaminants Treated

Vitrification has been applied to soil and wastes contaminated with arsenic, metals, radionuclides, and organics. This method is a RCRA best demonstrated available technology (BDAT) for various arsenic-containing hazardous wastes, including K031, K084, K101, K102, D004, and arsenic-containing P and U wastes (Ref. 5.5, 5.6).

Type, Number, and Scale of Identified Projects Treating Soil and Wastes Containing Arsenic

Vitrification of arsenic-contaminated soil and waste has been conducted at both pilot and full scale. The sources for this report contained information on ex situ vitrification of arsenic-contaminated soil at pilot scale at three sites and at full scale at one site. Information was also identified for two in situ applications for arsenic treatment at full scale. In addition, 7 pilot-scale and 3 full-scale applications to industrial waste were identified. Figure 5.1 shows the number of applications identified at each scale.

Figure 5.1
Scale of Identified Vitrification Projects for Arsenic Treatment



Summary of Performance Data

Table 5.1 lists the vitrification performance data identified in the sources used for this report. For ex situ vitrification of soil, total arsenic concentrations prior to treatment ranged from 8.7 to 540 mg/kg (Projects 2 and 4). Data on the leachability of arsenic from the vitrified product were available only for Project 4, for which the leachable arsenic concentration was reported as 0.9 mg/L. For in situ vitrification of soil, total arsenic concentrations prior to treatment ranged from 10.1 to 4,400 mg/kg (Projects 6 and 5, respectively). The leachability of arsenic in the stabilized soil and waste ranged from <0.004 to 0.91 mg/L (Projects 5 and 6).

For treatment of industrial wastes, the total arsenic concentrations prior to treatment ranged from 27 to 25,000 mg/kg (Projects 7 and 16) and leachable concentrations in the vitrified waste ranged from 0.007 mg/L to 2.5 mg/L (Projects 15 and 16). For some of the projects listed in Table 5.1, the waste treated was identified as a spent potliner from primary aluminum reduction (RCRA waste code K088) but the concentration of arsenic in the waste was not identified. Some K088 wastes contain relatively low concentrations of arsenic, and these projects may involve treatment of such wastes.

The case study in this section discusses in greater detail the in situ vitrification of arsenic-contaminated soil at the Parsons Chemical Superfund Site. This information is summarized in Table 5.1, Project 6.

Case Study: Parsons Chemical Superfund Site Vitrification

The Parsons Chemical Superfund Site in Grand Ledge, Michigan was an agricultural chemical manufacturing facility. Full-scale in situ vitrification was implemented to treat 3,000 cubic yards of arsenic-contaminated soil. Initial arsenic concentrations ranged from 8.4 to 10.1 mg/kg. Eight separate melts were performed at the site, which reduced arsenic concentrations to 0.717 to 5.49 mg/kg . The concentration of leachable arsenic in the treated soils ranged from <0.004 to 0.0305 mg/L, as measured by the TCLP. The off-gas emissions had arsenic concentrations of <0.000269 mg/m^3, <0.59 mg/hr (see Table 5.1, Project 6).

Applicability, Advantages, and Potential Limitations

Arsenic concentrations present in soil or waste may limit the performance of the vitrification treatment process. For example, if the arsenic concentration in the feed exceeds its solubility in glass, the technology's effectiveness may be limited (Ref. 5.6). Metals retained in the melt must be dissolved to minimize the formation of crystalline phases that can decrease leach resistance of the vitrified product. The approximate solubility of arsenic in silicate glass ranges from 1 - 3% by weight (Ref. 5.7).

The presence of chlorides, fluorides, sulfides, and sulfates may interfere with the process, resulting in higher mobility of arsenic in the vitrified product. Feeding additional slag-forming materials such as sand to the process may compensate for the presence of chlorides, fluorides, sulfides, and sulfates (Ref. 5.4). Chlorides, such as those found in chlorinated solvents, in excess of 0.5 weight percent in the waste will typically fume off and enter the off-gas. Chlorides in the off-gas may result in the accumulation of salts of alkali, alkaline earth, and heavy metals in the solid residues collected by off-gas treatment. If the residue is returned to the process for treatment, separation of the chloride salts from the residue may be necessary. When excess chlorides are present, dioxins and furans may also form and enter the off-gas treatment system (Ref. 5.6). The presence of these constituents may also lead to the formation of volatile metal species or corrosive acids in the off-gas (Ref. 5.7).

During vitrification, combustion of the organic content of the waste liberates heat, which will raise the temperature of the waste, thus reducing the external energy requirements. Therefore, this process may be advantageous to wastes containing a combination of arsenic and organic contaminants or for the treatment of organo-arsenic compounds. However, high concentrations of organics and moisture may result in high volumes of off-gas as organics volatilize and combust and water turns to steam. This can overwhelm emissions control systems.

Factors Affecting Vitrification Performance

- **Presence of halogenated organic compounds** - The combustion of halogenated organic compounds may result in incomplete combustion and the deposition of chlorides, which can result in higher mobility of arsenic in the vitrified product (Ref. 5.4).
- **Presence of volatile metals** - The presence of volatile metals, such as mercury and cadmium, and other volatile inorganics, such as arsenic, may require treatment of the off-gas to reduce air emissions of hazardous constituents (Ref. 5.6).
- **Particle size** - Some vitrification units require that the particle size of the feed be controlled. For wastes containing refractory compounds that melt above the unit's nominal processing temperature, such as quartz and alumina, size reduction may be required to achieve acceptable throughputs and a homogeneous melt. High-temperature processes, such as arcing and plasma processes may not require size reduction of the feed (Ref. 5.6).
- **Lack of glass-forming materials** - If insufficient glass-forming materials (SiO_2 >30% by weight) and combined alkali (Na + K > 1.4% by weight) are present in the waste the vitrified product may be less durable. The addition of frit or flux additives may compensate for the lack of glass-forming and alkali materials (Ref. 5.6).
- **Subsurface air pockets** - For in situ vitrification, subsurface air pockets, such as those that may be associated with buried drums, can cause bubbling and splattering of molten material, resulting in a safety hazard (Ref. 5.10).
- **Metals content** - For in situ vitrification, a metals content greater than 15% by weight may result in pooling of molten metals at the bottom of the melt, resulting in electrical short-circuiting (Ref. 5.10).
- **Organic content** - For in situ vitrification, an organic content of greater than 10% by weight may cause excessive heating of the melt, resulting in damage to the treatment equipment (Ref. 5.10). High organics concentrations may also cause large volumes of off-gas as the organics volatilize and combust, and may overwhelm air emissions control systems.

Vitrification can also increase the density of treated material, thereby reducing its volume. In some cases, the vitrified product can be reused or sold. Vitrified wastes containing arsenic have been reused as industrial glass (Ref. 5.5). Metals retained in the melt that do not dissolve in the glass phase can form crystalline phases upon cooling that can decrease the leach resistance of the vitrified product.

Excavation of soil is not required for in situ vitrification. This technology has been demonstrated to a depth of 20 feet. Contamination present at greater depths may require innovative application techniques. In situ vitrification may be impeded by the presence of subsurface air pockets, high metals concentrations, and high organics concentrations (Ref. 5.10).

Factors Affecting Vitrification Costs

- **Moisture content** - Greater than 5% moisture in the waste may result in greater mobility of arsenic in the final treated matrix. These wastes may require drying prior to vitrification (Ref. 5.4). Wastes containing greater than 25% moisture content may require excessive fuel consumption or dewatering before treatment (Ref. 5.6).
- **Characteristics of treated waste** - Depending upon the qualities of the vitrified waste, the treated soil and waste may be able to be reused or sold.
- **Factors affecting vitrification performance** - Items in the “Factors Affecting Vitrification Performance” box will also affect costs.

Summary of Cost Data

Cost information for ex situ vitrification of soil and wastes containing arsenic was not found in the references identified for this report. The cost for in situ vitrification of 3,000 cubic yards of soil containing arsenic, mercury, lead, DDT, dieldrin and chlordane at the Parsons Chemical Superfund site are presented below (Ref. 5.8, cost year not provided):

- Treatability/pilot testing $50,000 - $150,000
- Mobilization $150,000 - $200,000
- Vitrification operation $375 - $425/ ton
- Demobilization $150,000 - $200,000

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Table 5.1
Vitrification Treatment Performance Data for Arsenic

Project Number	Industry or Site Type	Media or Waste	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Vitrified Product and Final Arsenic Concentration	Vitrification Process Description	Source
Environmental Media								
1	Metal Ore Mining and Smelting	River and harbor sludge	Pilot	Ecotechneik B.V., Utrecht, Netherlands	117 mg/kg (TWA)	Artificial gravel	Rotary kiln vitrification at 1,150°C	5.1
2	Industrial Landfill	Mixture of solids, soil, and sludge	Pilot	Matanza-Riachuelo River, Monditech, S.A., Buenos Aires, Argentina	8.7 - 12 mg/kg (TWA)	Artificial gravel, 0.01 mg/L (TCLP)	Seizing, grinding, and milling pretreatment followed by vitrification in a rotary kiln at 1,000°C	5.1
3	--	Soil, 400 tons	Full	Chatham Dockyard, St. Mary's Island, VERT, Kent, England	--	Glass fait	Wastes are mixed with sand and limestone and fed to a furnace containing a pool of molten glass maintained at 1550°C. Glass is removed from bottom of pool and water cooled to produce fait.	5.1
4	--	Soil	Pilot	University of Pittsburgh Applied Research Center, Harmarville, PA	540 mg/kg (TWA)	Glass cullet 0.9 mg/L (TCLP)	Vortec Corporation Advanced Combustion Melting System, counter-rotating vortex combustor followed by cyclone melter and water quench	5.2
5	RCRA waste code K031 and other pesticide wastes	--	Full	--	4,400 mg/kg (TWA)	0.91 mg/L (TCLP)	In situ vitrification at 1200 degrees C with unspecified air pollution control equipment	5.5

Table 5.1
Vitrification Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Media or Waste	Scale^{a}	Site Name or Location	Initial Arsenic Concentration	Vitrified Product and Final Arsenic Concentration	Vitrification Process Description	Source
6	Agricultural chemicals manufacturing	Soil, 3,000 cubic yards	Full	Parsons Chemical Superfund Site, MI	8.4 - 10.1 mg/kg (TWA)	0.717 - 5.49 mg/kg (TWA) <0.004 - 0.0305 mg/L (TCLP)	In situ vitrification, eight separate melts. Stack gas emissions of arsenic <0.000269 milligrams per cubic meter, <0.59 milligrams per hour.	5.8
Industrial Waste								
7	Incinerator air pollution control scrubber wastewater	Incinerator ash	Pilot	University of Pittsburgh Applied Research Center, Harmarville, PA	27 mg/kg (TWA)	Glass cullet 0.05 mg/L (TCLP)	Vortec Corporation Advanced Combustion Melting System, counter-rotating vortex combustor followed by cyclone melter and water quench	5.2
8	Residues from incineration of municipal solid waste	Fly ash	Pilot	University of Pittsburgh Applied Research Center, Harmarville, PA	981 mg/kg (TWA)	Glass cullet <0.05 mg/L (TCLP)	Vortec Corporation Advanced Combustion Melting System, counter-rotating vortex combustor followed by cyclone melter and water quench	5.2
9	--	Hazardous baghouse dust	Pilot	University of Pittsburgh Applied Research Center, Harmarville, PA	--	Glass cullet <0.02 mg/L (TCLP)	Vortec Corporation Advanced Combustion Melting System, counter-rotating vortex combustor followed by cyclone melter and water quench	5.2
10	Primary aluminum reduction, RCRA hazardous waste code K088	Spent potliners, 30,000 tons per year	Full	Barnard Environmental, Richland, WA	--	Molten glass	Terra-Vit process, resistance heating using electrodes submerged in the molten mass, molten glass effluent is formed into products	5.3

Table 5.1
Vitrification Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Media or Waste	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Vitrified Product and Final Arsenic Concentration	Vitrification Process Description	Source
11	Primary aluminum reduction, RCRA hazardous waste code K088	Spent potliners, 200 - 300 kilograms per hour	Pilot	Elkem Technology, Norway	--	Slag	Slagging process with addition of iron ore and quartz	5.3
12	Primary aluminum reduction, RCRA hazardous waste code K088, and electric arc furnace dust, RCRA hazardous waste code K066	Spent potliners	Pilot	Enviroscience, Inc., Vancouver, Washington	--	Slag wool	Extractive metallurgical process conducted in a shaft furnace to produce zinc, calcium, and lead oxides in the baghouse dust, pig iron, and mineral wool	5.3
13	Primary aluminum reduction, RCRA hazardous waste code K088	Spent potliners	Pilot	Ormet Corporation	--	Industrial glass	Spent potliners and glass-forming ingredients are vitrified in an in-flight suspension combustor followed by a cyclone separation and melting chamber	5.3
14	Primary aluminum reduction, RCRA hazardous waste code K088	Spent potliners	Full	Reynolds Metals	--	Kiln residue has been delisted, disposed at non-hazardous landfill	Spent potliners, limestone, and brown sand are blended and fed to a rotary kiln vitrification unit	5.3

Table 5.1
Vitrification Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Media or Waste	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Vitrified Product and Final Arsenic Concentration	Vitrification Process Description	Source
15	--	Flue dust	Full	--	--	3,000 - 235,000 mg/kg (TWA) 0.007 - 1.8 mg/L (TCLP)	Roasting at 400 degrees C to convert arsenic trioxide to calcium arsenate followed by vitrification in an iron silicate slag at 1,290 degrees C	5.5
16	Phosphoric acid production, RCRA hazardous waste code D004	Sludge containing arsenic sulfide	Pilot	Rhone-Poulenc	20,000 - 25,000 mg/kg (TWA)	<0.5 - 0.5 mg/L (EPT) <0.5 - 2.5 mg/L (TCLP)	--	5.5

a Excluding bench-scale treatments

-- = Not available

WET = Waste extraction test

C = Celsius

TCLP = Toxicity characteristic leaching procedure

EPT = Extraction procedure toxicity test

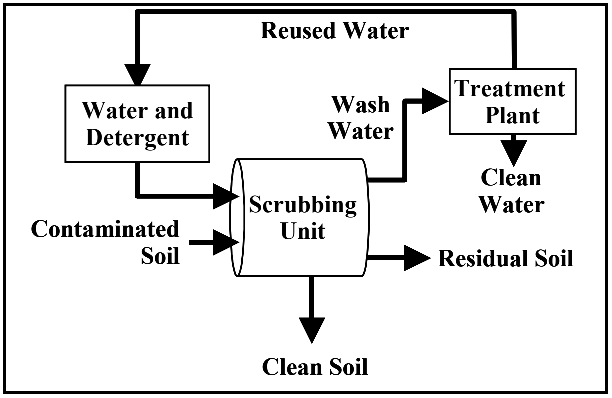
TWA = Total waste analysis

6.0 SOIL WASHING/ACID EXTRACTION FOR ARSENIC

Summary

Soil washing/acid extraction (soil washing) has been used to treat arsenic-contaminated soil in a limited number of applications. The process is limited to soils in which contaminants are preferentially adsorbed onto the fines fraction. The separated fines must be further treated to remove or immobilize arsenic.

Model of Soil Washing System



Technology Description and Principles

Soil washing uses particle size separation to reduce soil contaminant concentrations. This process is based on the concept that most contaminants tend to bind to the finer soil particles (clay, silt) rather than the larger particles (sand, gravel). Because the finer particles are attached to larger particles through physical processes (compaction and adhesion), physical methods can be used to separate the relatively clean larger particles from the finer particles, thus concentrating the contamination bound to the finer particles for further treatment (Ref. 6.7).

In this process, soil is first screened to remove oversized particles, and then homogenized. The soil is then mixed with a wash solution consisting of water or water enhanced with chemical additives such as leaching agents, surfactants, acids, or chelating agents to help remove organics and heavy metals. The particles are separated by size (cyclone and/or gravity separation depending on the type of contaminants in the soil and particle size), concentrating the contaminants with the fines. Because the soil washing process removes and concentrates the contaminants but does not destroy them, the resulting concentrated fines or sludge usually require further treatment. The coarser-grained soil is generally relatively "clean", requiring no additional treatment. Wash water from the process is treated and either reused in the process, or disposed (Ref. 6.7). Commonly used methods for treating the wastewater include ion exchange and solvent extraction.

Technology Description: Soil washing is an ex situ technology that takes advantage of the behavior of some contaminants to preferentially adsorb onto the fines fraction. The soil is suspended in a wash solution and the fines are separated from the suspension, thereby reducing the contaminant concentration in the remaining soil.

Media Treated:
- Soil (ex situ)

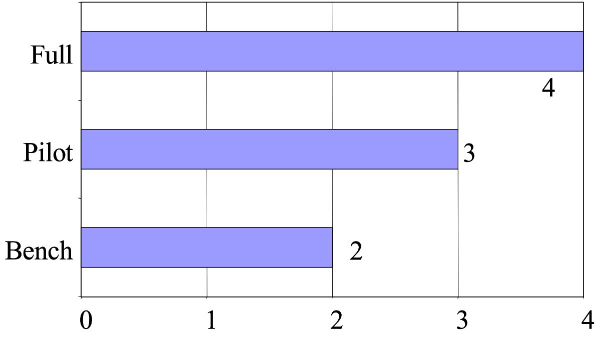
Media and Contaminants Treated

Soil washing is suitable for use on soils contaminated with SVOCs, fuels, heavy metals, pesticides, and some VOCs, and works best on homogenous, relatively simple contaminant mixtures (Ref. 6.1, 6.4, 6.7). Soil washing has been used to treat soils contaminated with arsenic.

Type, Number, and Scale of Identified Projects Treating Soil and Wastes Containing Arsenic

Nine projects were identified where soil washing was performed to treat arsenic. Of these, four were performed at full scale, including two at Superfund sites. Three projects were conducted at pilot scale, and two at bench scale (Ref. 6.4). Figure 6.1 shows the number of arsenic soil washing projects at bench, pilot, and full scale.

Figure 6.1
Scale of Identified Soil Washing/Acid Extraction Projects for Arsenic Treatment



Case Study: King of Prussia Superfund Site

The King of Prussia Superfund Site in Winslow Township, New Jersey is a former waste processing and recycling facility. Soils were contaminated with arsenic, berylllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, and zinc from the improper disposal of wastes (Project 1). Approximately 12,800 cubic yards of arsenic-contaminated soil, sludge, and sediment was treated using soil washing in 1993. The treatment reduced arsenic concentrations from 1 mg/kg to 0.31 mg/kg, a reduction of 69%.

Summary of Performance Data

Table 6.1. lists the available performance data. For soil and waste, this report focuses on performance data expressed as the leachability of arsenic in the treated material. However, arsenic leachability data are not available for any of the projects in Table 6.1. The case study in this section discusses in greater detail the soil washing to treat arsenic at the King of Prussia Superfund Site. This information is summarized in Table 6.1, Project 1.

Applicability, Advantages, and Potential Limitations

The principal advantage of soil washing is that it can be used to reduce the volume of material requiring further treatment (Ref. 6.3). However, this technology is generally limited to soils with a range of particle size distributions, and contaminants that preferentially adsorb onto the fines fraction.

Summary of Cost Data

Table 6.1. shows the reported costs for soil washing to treat arsenic. The unit costs range from $30 to $400 per ton of material treated (costs not adjusted to a consistent cost year). For one project treating 19,200 tons of soil, sludge, and sediment (Table 6.1, Project 1), the total reported treatment costs, including off-site disposal of treatment residuals, was $7.7 million, or $400/ton (Ref. 6.6, 6.8, cost year not provided).

Factors Affecting Soil Washing Costs

- **Soil particle size distribution** - Soils with a high proportion of fines may require disposal of a larger amount of treatment residual.
- **Residuals management** - Residuals from soil washing, including spent washing solution and removed fines, may require additional treatment prior to disposal.
- **Factors affecting soil washing performance** - Items in the "Factors Affecting Soil Washing Performance" box will also affect costs.

Factors Affecting Soil Washing Performance

- **Soil homogeneity** - Soils that vary widely and frequently in characteristics such as soil type, contaminant type and concentration, and where blending for homogeneity is not feasible, may not be suitable for soil washing (Ref. 6.1).
- **Multiple contaminants** - Complex, heterogeneous contaminant compositions can make it difficult to formulate a simple washing solution, requiring the use of multiple, sequential washing processes to remove contaminants (Ref. 6.1).
- **Moisture content** - The moisture content of the soil may render its handling more difficult. Moisture content may be controlled by covering the excavation, storage, and treatment areas to reduce the amount of moisture in the soil (Ref. 6.1).
- **Temperature** - Cold weather can cause the washing solution to freeze and can affect leaching rates (Ref. 6.1).

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Table 6.1
Arsenic Soil Washing Treatment Cost and Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media	Scale	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Soil Washing Agent or Process	Cost ($/ton)[a]	Source
1	Waste treatment, recycling, and disposal	Soil (12,800 cy)	Full	King of Prussia Superfund Site, Winslow Township, NJ	1 mg/kg (TWA)	0.31 mg/kg (TWA)	Screening, separation, and froth flotation	$400	6.4, 6.8
2	Pesticide manufacturing	Soil (180,000 cy)	Full	Vineland Chemical Company Superfund Site, Operable Unit 01 Vineland, NJ	--	--	--	--	6.4
3	Inorganic chemical manufacturing, wood preserving	Soil (5000 cy)	Full	Ter Apel, Moerdijk, Netherlands	15 - 455 mg/kg (TWA)	20 mg/kg (TWA)	--	--	6.5
4	--	Soil	Full	--	250 mg/kg (TWA)	20 mg/kg (TWA)	--	$100 - $300	6.6
5	Herbicide manufacturing, explosives manufacturing	Soil (130 cy)	Pilot	--	97 - 227 mg/kg (TWA)	6.6 - 142 mg/kg (TWA)	--	$65	6.5
6	Munitions Manufacturing	Soil, sediments, and other solids (400 cy)	Pilot	--	2 - 129 mg/kg (TWA)	0.61 - 3.1 (mg/kg)	--	$80	6.5
7	Munitions Manufacturing	Soil	Pilot	--	--	--	--	--	6.5
8	Pesticide manufacturing	Soil	Bench	Camp Pendleton Marine Corps Base Superfund Site, CA	4.5 mg/kg (TWA)	3 mg/kg (TWA)	--	--	6.5
9	Wood preserving	Sediment	Bench	Thunder Bay, Ontario, Canada	9.1 mg/kg (TWA)	0.015 mg/kg (TWA)	--	--	6.3

[a] Cost year not provided.

mg/kg = milligrams per kilogram -- = Not available TWA = Total waste analysis cy = Cubic yards

7.0 PYROMETALLURGICAL RECOVERY FOR ARSENIC

Summary

Information gathered for this report indicate that pyrometallurgical processes have been implemented to recover arsenic from soil and wastes in four full-scale applications. These technologies may have only limited application because of their cost ($208 - $458 per ton in 1991 dollars) and because the cost of importing arsenic is generally lower than reclaiming it using pyrometallurgical processes (Ref. 7.6). The average cost of imported arsenic metal in 1999 was $0.45 per pound (Ref. 7.6, in 1999 dollars). In order to make recovery economically feasible, the concentration of metals in the waste should be over 10,000 mg/kg (Ref. 7.2).

Technology Description and Principles

Technology Description: Pyrometallurgical recovery processes use heat to convert an arsenic-contaminated waste feed into a product with a high arsenic concentration that can be reused or sold.

Media Treated
- Soil
- Industrial wastes

Types of Pyrometallurgical Processes
- High temperature metals recovery
- Slag cleaning process

A variety of processes reportedly have been used to recover arsenic from soil and waste containing arsenic. High temperature metals recovery (HTMR) involves heating a waste feed to cause metals to volatilize or "fume". The airborne metals are then removed with the off-gas and recovered, while the residual solid materials are disposed. Other pyrometallurgical technologies typically involve modifications at metal refining facilities to recover arsenic from process residuals. The Metallurgie-Hoboken-Overpelt (MHO) slag cleaning process involves blast smelting with the addition of coke as a reducing agent of primary and secondary materials from lead, copper, and iron smelting operations (Ref. 7.9).

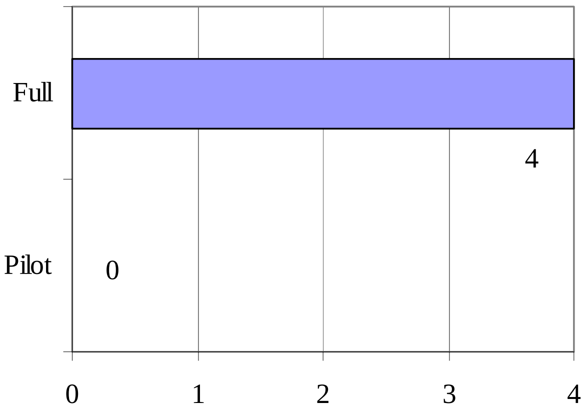
Media and Contaminants Treated

This technology has recovered heavy metals, such as arsenic and lead, from soil, sludge, and industrial wastes (Ref. 7.8). The references used for this report contained information on applications of HTMR to recover arsenic from contaminated soil (Ref. 7.3) and secondary lead smelter soda slag (Ref. 7.8). In addition, one metals refining process that was modified to recover arsenic (Ref. 7.9) was identified. The recycling and reuse of arsenic from consumer end-product scrap is not typically done (Ref. 7.6).

Type, Number, and Scale of Identified Projects Treating Soil and Wastes Containing Arsenic

This report identified application of pyrometallurgical recovery of arsenic at full scale at four facilities (Ref. 7.3, 7.8, 7.9). No pilot-scale projects for arsenic were found.

Figure 7.1
Scale of Identified Pyrometallurgical Projects for



Arsenic Treatment

Summary of Performance Data

Table 7.1 presents the available performance data. Because this technology typically generates a product that is reused instead of disposed, the performance of these processes is typically measured by the percent removal of arsenic from the waste, the concentration of arsenic in the recovered product, and the concentration of impurities in the recovered product. Other soil and waste treatment processes are usually evaluated by leach testing the treated materials.

Both of the soil projects identified have feed and treated material arsenic concentrations. One project had an arsenic feed concentration of 86 mg/kg and a treated arsenic concentration of 6.9 mg/kg (Project 1). The other project had an leachable arsenic concentration in the feed of 0.040 mg/L and 0.019 mg/L in the treated material (Project 2).

Both of the industrial waste projects identified have feed and residual arsenic data, and one has post-treatment leachability data. The feed concentrations ranged from 428 to 2,100 mg/kg (Projects 3 and 4). The residual arsenic concentrations ranged from 92.1 to 1,340 mg/kg, with less than 5 mg/L leachability (Project 3).

The case study in this section discusses in greater detail an HTMR application at the National Smelting and Refining Company Superfund Site. This information is summarized in Table 7.1, Project 3.

Case Study: National Smelting and Refining Company Superfund Site, Atlanta, Georgia

Secondary lead smelter slag from the National Smelting and Refining Company Superfund Site in Atlanta, Georgia was processed using high temperature metals recovery at a full-scale facility. The initial waste feed had an arsenic concentration range of 428 to 1,040 mg/kg. The effluent slag concentration ranged from 92.1 to 1,340 mg/kg of arsenic, but met project goals for arsenic leachability (<5 mg/L TCLP). The oxide from the baghouse fumes had an arsenic concentration of 1,010 to 1,170 mg/kg; however, the arsenic was not recovered (Ref. 7.8) (see Project 3, Table 7.1).

Applicability, Advantages, and Potential Limitations

Although recovering arsenic from soil and wastes is feasible, it has not been done in the U.S. on a large scale because it is generally less expensive to import arsenic than to obtain it through reclamation processes (Ref. 7.5-7). The cost of importing arsenic in 1999 was approximately $0.45 per pound (Ref. 7.6, in 1999 dollars). In order to make recovery economically feasible, the concentration of metals in the waste should be over 10,000 mg/kg (Ref. 7.2). In some cases, the presence of other metals in the waste, such as copper, may provide sufficient economic incentive to recover copper and arsenic together for the manufacture of arsenical wood preservatives (Ref. 7.1). However, concern over the toxicity of arsenical wood preservatives is leading to its phase-out (Ref. 7.10).

Factors Affecting Pyrometallurgical Recovery Performance

- **Particle size** - Larger particles do not allow heat transfer between the gas and solid phases during HTMR. Smaller particles may increase the particulate in the off-gas.
- **Moisture content** - A high water content generally reduces the efficiency of HTMR because it increases energy requirements.
- **Thermal conductivity** - Higher thermal conductivity of the waste results in better heat transfer into the waste matrix during HTMR (Ref. 7.2).
- **Presence of impurities** - Impurities, such as other heavy metals, may need to be removed, which increases the complexity of the treatment process.

At present, arsenic is not being recovered domestically from arsenical residues and dusts at nonferrous smelters, although some of these materials are processed for the recovery of other materials (Ref. 7.6).

This technology may produce treatment residuals such as slag, flue dust, and baghouse dust. Although some residuals may be treated using the same process that generated them, the residuals may require additional treatment or disposal.

Summary of Cost Data

The estimated cost of treatment using HTMR ranges from $208 to $458 per ton (in 1991 dollars). However, these costs are not specific to treatment of arsenic (Ref. 7.2). No cost data for pyrometallurgical recovery for arsenic was found.

Factors Affecting Pyrometallurgical Recovery Costs

- **Factors affecting pyrometallurgical recovery performance** - Items in the “Factors Affecting Pyrometallurgical Recovey Performance” box will also affect costs.

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Table 7.1
Arsenic Pyrometallurgical Recovery Performance Data for Arsenic

Project Number	Industry or Site Type	Media or Waste Reclaimed	Scale	Site Name or Location	Reclamation Process Feed Arsenic Concentration	Reclamation Process Residual Arsenic Concentration	Recovered Arsenic Concentration	Reclamation Process Used	Source
Environmental Media									
1	--	Soil (amount not available)	Full	--	86 mg/kg (TWA)	6.9 mg/kg (TWA)	--	HTMR	7.3
2	--	Soil (amount not available)	Full	--	0.040 mg/L (TCLP)	0.019 mg/L (TCLP)	--	HTMR	7.3
Industrial Wastes									
3	--	Secondary lead smelter soda slag (72 tons)	Full	National Smelting and Refining Company Superfund Site, Atlanta, GA	428 - 1,040 mg/kg (TWA)	Slag, 92.1 - 1,340 mg/kg (TWA) Slag, <5 mg/L (TCLP)	Arsenic trioxide, 1,010 - 1,170 mg/kg (TWA)	HTMR	7.8
4	--	Primary and secondary materials (additional description of materials not available)	Full	Hoboken, Belgium	2,100 mg/kg (TWA)	Slag, 100 mg/kg (TWA) zinc flue dust, 1,000 mg/kg (TWA)	Lead-copper-iron alloy, 52,000 mg/kg (TWA) lead bullion, 3,900 mg/kg (TWA) Arsenic trioxide (concentration not available)	MHO	7.9

TCLP = Toxicity Characteristic Leaching Procedure.
-- = Not available
MHO = Metallurgie-Hoboken-Overpelt process.
TWA = Total Waste Analysis.
HTMR = High Temperature Metals Recovery.

8.0 IN SITU SOIL FLUSHING FOR ARSENIC

Summary

Data gathered for this report show that in situ soil flushing has been used to treat arsenic-contaminated soils in a limited number of applications. Two projects have been identified that are currently operating at full scale, but performance results are not yet available.

Technology Description and Principles

In situ soil flushing techniques may employ water or a mixture of water and additives as the flushing solution. Additives may include acids (sulfuric, hydrochloric, nitric, phosphoric, or carbonic acid), bases (for example, sodium hydroxide), chelating or complexing agents (such as EDTA), reducing agents, or surfactant to aid in the desorption and dissolution of the target contaminants (Ref. 8.1).

Subsurface containment barriers or other hydraulic controls have sometimes been used in conjunction with soil flushing to help control the flow of flushing fluids and assist in the capture of the contaminated fluid. Impermeable membranes have also been used in some cases to limit infiltration of groundwater, which could cause dilution of flushing solutions and loss of hydraulic control (Ref. 8.1).

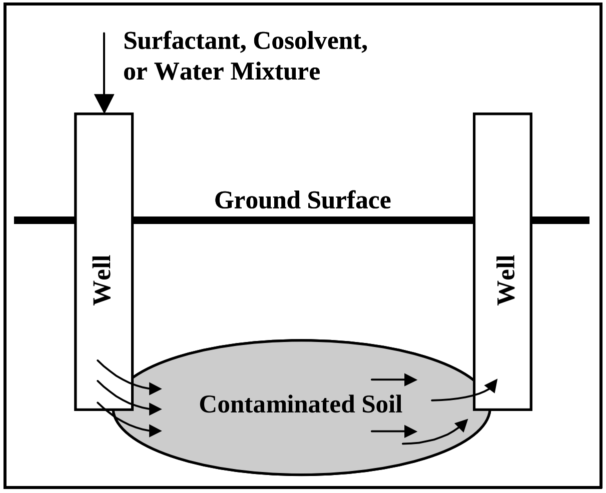
Technology Description: In situ soil flushing is a technology that extracts organic and inorganic contaminants from soil by using water, a solution of chemicals in water, or an organic extractant, without excavating the contaminated material itself. The solution is injected into or sprayed onto the area of contamination, causing the contaminants to become mobilized by dissolution or emulsification. After passing through the contamination zone, the contaminant-bearing flushing solution is collected by downgradient wells or trenches and pumped to the surface for removal, treatment, discharge, or reinjection (Ref. 8.1).

Media Treated:
- Soil (in situ)

Media and Contaminants Treated

Soil flushing has been used to treat soils in situ contaminated with organic, inorganic, and metal contaminants (Ref. 8.1), including arsenic.

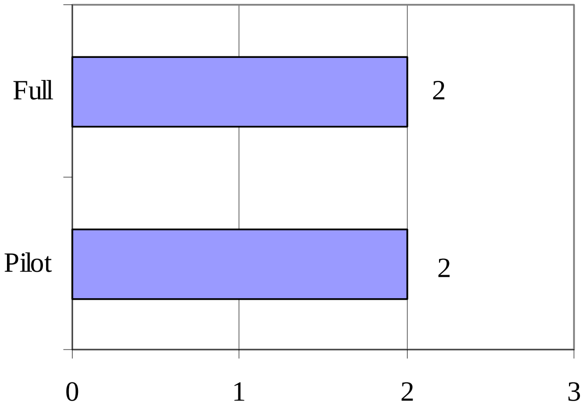
Model of an In Situ Flushing System



Type, Number, and Scale of Identified Projects Treating Soil Containing Arsenic

The references identified for this report contained information on two full-scale in situ soil flushing projects for the treatment of arsenic at two Superfund sites (Ref. 8.4), and two at pilot scale at two other sites (Ref. 8.6, 8.7). At one of the Superfund sites, 150,000 cubic yards of soil are being treated, while at the other 19,000 cubic yards of soil are being treated. Figure 8.1 shows the number of projects identified at pilot and full scale.

Figure 8.1
Scale of Identified In Situ Soil Flushing Projects for Arsenic Treatment



Summary of Performance Data

Arsenic treatment is ongoing at two Superfund sites using in situ soil flushing, and has been completed at two other sites (Ref. 8.3, 8.4, 8.6, 8.7). Performance data for the Superfund site projects are not yet available as the projects are ongoing. Performance data are also not available for the other two projects. See Table 8.1 for information on these projects. The case study in this section discusses in greater detail a soil flushing application at the Vineland Chemical Company Superfund Site. This information is summarized in Table 8.1, Project 3.

Case Study: Vineland Chemical Company Superfund Site

The Vineland Chemical Company Superfund Site in Vineland, New Jersey is a former manufacturing facility for herbicides containing arsenic. Soils were contaminated with arsenic from the improper storage and disposal of herbicide by-product salts (RCRA waste code K031). Approximately 150,000 cubic yards of soil were treated. Pretreatment arsenic concentrations were as high as 650 mg/kg. The soil was flushed with groundwater from the site, which was extracted, treated to remove arsenic, and reinjected into the contaminated soil. Because the species of arsenic contaminating the soil is highly soluble in water, the addition of surfactants and cosolvents was not necessary. No data are currently available on the treatment performance (Ref. 8.3, 8.4, 8.8) (see Project 1, Table 8.1). The remedy at this site was changed to soil washing in order to reduce treatment cost and the time needed to remediate the site.

Factors Affecting Soil Flushing Performance

- **Number of contaminants treated** - The technology works best when a single contaminant is targeted. Identifying a flushing fluid that can effectively remove multiple contaminants may be difficult (Ref. 8.1).
- **Soil characteristics** - Some soil characteristics may effect the performance of soil flushing. For example, an acidic flushing solution may have reduced effectiveness in an alkaline soil (Ref. 8.1).
- **Precipitation** - Soil flushing may cause arsenic or other chemicals in the soil to precipitate and obstruct the soil pore structure and inhibit flow through the soil (Ref. 8.1).
- **Temperature** - Low temperatures may cause the flushing solution to freeze, particularly when shallow infiltration galleries and above-ground sprays are used to apply the flushing solution (8.1).

Applicability, Advantages, and Potential Limitations

The equipment used for in situ soil flushing is relatively easy to construct and operate, and the process does not involve excavation or disposal of the soil, thereby avoiding the expense and hazards associated with these activities (Ref. 8.1). Spent flushing solutions may require treatment to remove contaminants prior to reuse or disposal. Treatment of flushing fluid results in process sludges and residual solids, such as spent carbon and spent ion exchange resin, which may require treatment before disposal. In some cases, the spent flushing solution may be discharged to a publicly-owned treatment works (POTW), or reused in the flushing process. Residual flushing additives in the soil may be a concern and should be evaluated on a site-specific basis (Ref. 8.1). In addition, soil flushing may cause contaminants to mobilize and spread to uncontaminated areas of soil or groundwater.

Factors Affecting Soil Flushing Costs

- **Reuse of flushing solution** - The ability to reuse the flushing solution may reduce the cost by reducing the amount of flushing solution required (Ref. 8.1).
- **Contaminant recovery** - Recovery of contaminants from the flushing solution and the reuse or sale of recovered contaminants may be possible in some cases (Ref. 8.3, 8.4).
- **Factors affecting soil flushing performance** - Items in the “Factors Affecting Soil Flushing Performance” box will also affect costs.

Summary of Cost Data

No data are currently available on the cost of soil flushing systems used to treat arsenic.

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Table 8.1
Arsenic In Situ Soil Flushing Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media	Scale	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Soil Flushing Agent or Process	Source
1	Pesticide manufacturing	Soil (150,000 cy)	Full	Vineland Chemical Company Superfund Site, Operable Unit 01 Vineland, NJ	20 - 650 mg/kg (TWA)	--	Flushing with groundwater followed by extraction, treatment, and reuse to flush soil. Project was changed to soil washing prior to completion.	8.3, 8.4, 8.8
2	Primary aluminum production	Soil (19,000 cy)	Full	Ormet Superfund Site, Hannibal, OH	--	0.027 mg/L	Flushing with water followed by extraction, treatment, and discharge to surface water under an NPDES permit. Project completion is expected in 2007.	8.3, 8.4
3	Power substation	Soil	Pilot	Ft. Walton Beach, FL	--	--	Flushing with 0.01 M phosphoric acid.	8.7
4	Power substation	Soil	Pilot	Florida	--	--	Treatment train consisting of flushing with citric acid followed by iron coprecipitation and ceramic membrane filtration.	8.6

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

-- = Not available

TWA = Total waste analysis

IIB
ARSENIC TREATMENT TECHNOLOGIES APPLICABLE TO WATER

9.0 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 to prepare this report, 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: 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 water 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.

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

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

Technology Description and Principles

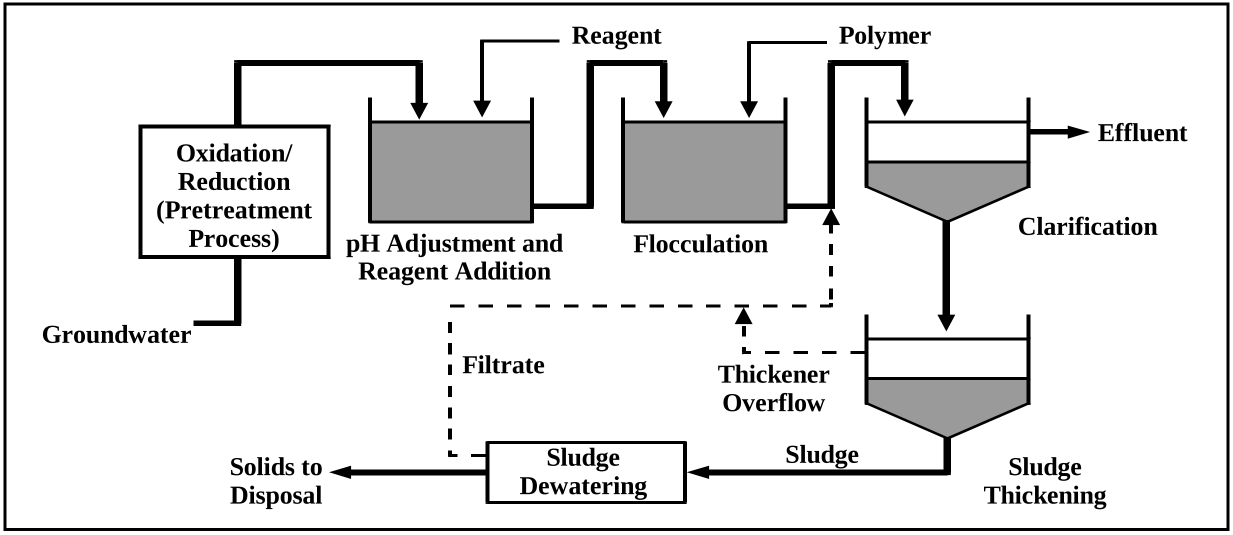
For this report, technologies were considered precipitation/coprecipitation if they involved the following steps:

- 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 11.0).

Precipitation/coprecipitation usually involves pH adjustment and addition of a chemical precipitant or coagulant; it can also include addition of a chemical oxidant (Ref. 9.1). Oxidation of arsenic to its less soluble As(V) state can increase the effectiveness of

Model of a Precipitation/Coprecipitation System



precipitation/coprecipitation 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. 9.8, 9.16, 9.22, 9.25, 9.29). Clarification or filtration are commonly used to remove the solid precipitate.

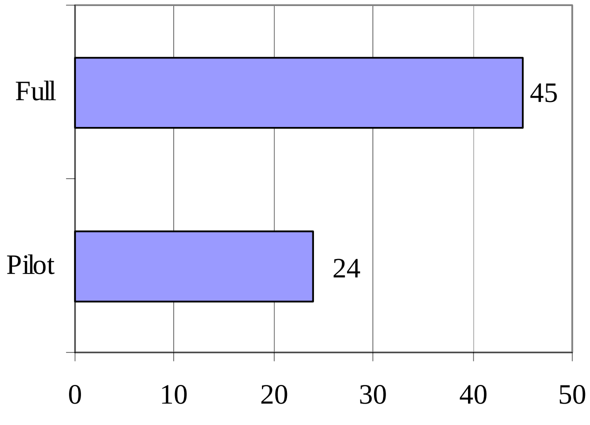
Media and Contaminants Treated

Precipitation/coprecipitation is frequently used to treat water contaminated with metals (Ref. 9.1). The references identified for this report contained information on its application to industrial wastewater, groundwater, surface water, leachate, and mine drainage.

Type, Number, and Scale of Identified Projects Treating Water Containing Arsenic

Precipitation/coprecipitation processes for arsenic in drinking water, groundwater, and industrial wastewater are commercially available. The data gathered in support of this report include information on its full-scale application at 16 sites. Information on full-scale treatment of drinking water is available for eight facilities and of industrial wastewater for 21 facilities. Information on 24 pilot-scale applications was also identified. Figure 9.1 shows the number of pilot- and full-scale precipitation/coprecipitation projects in the sources researched.

Figure 9.1
Scale of Identified Precipitation/Coprecipitation Projects for Arsenic Treatment



Summary of Performance Data

Table 9.1 presents the available performance data for pilot- and full-scale precipitation/coprecipitation treatment. It contains information on 69 applications, including 20 groundwater, surface water, and mine drainage, 15 drinking water, and 34 industrial wastewater projects. The information that appears in the "Precipitating Agent or Process" column of Table 9.1, including the chemicals used, the descriptions of the processes, and whether it involved precipitation or coprecipitation, is based on the cited references. This information was not independently checked for accuracy or technical feasability. For example, in some cases, the reference used may apply the term "precipitation" to a process that is actually coprecipitation.

The effectiveness of this technology 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 concentration of leachable 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 5.0 mg/L.

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 to 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 the technical literature (Ref. 9.33).

It is beyond the scope of this report 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 processes can be found in the references listed at the end of this section.

Factors Affecting Precipitation/Coprecipitation Performance

- **Valence state of arsenic** - The presence of the more soluble trivalent state of arsenic may reduce the removal efficiency. The solubility of arsenic depends upon its valence state, pH, the specific arsenic compound, and the presence of other chemicals with which arsenic might react (Ref. 9.12). Oxidation to As(V) could improve arsenic removal through precipitation/coprecipitation (Ref. 9.7).
- **pH** - In general, arsenic removal will be maximized at the pH at which the precipitated species is least soluble. The optimal pH range for precipitation/coprecipitation depends upon the waste treated and the specific treatment process (Ref. 9.7).
- **Presence of other compounds** - The presence of other metals or contaminants may impact the effectiveness of precipitation/coprecipitation. For example, sulfate could decrease arsenic removal in processes using ferric chloride as a coagulant, while the presence of calcium or iron may increase the removal of arsenic in these processes (Ref. 9.7).

Of the 12 drinking water projects having both influent and effluent arsenic 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 5.0 mg/L.

All of the 28 wastewater projects having both influent and effluent arsenic 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 5.0 mg/L.

Projects that did not reduce effluent 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 report.

Some projects in Table 9.1 include treatment trains, the most common being precipitation/coprecipitation followed by activated carbon adsorption or membrane filtration. In those cases, the performance data listed are for the entire treatment train, not just the precipitation/coprecipitation step.

The case study in this section discusses in greater detail the removal of arsenic from groundwater using an aboveground treatment system at the Winthrop Landfill Superfund site. This information is summarized in Table 9.1, Project 1.

Applicability, 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

Case Study: Winthrop Landfill Site

The Winthrop Landfill Site, located in Winthrop, Maine, is a former dump site that accepted municipal and industrial wastes (See Table 9.1, 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. It treats 65 gallons per minute of groundwater containing average arsenic concentrations of 0.3 mg/L to below 0.005 mg/L. Through May, 2001, 359 pounds of arsenic had been removed from groundwater at the Winthrop Landfill Site using this above ground treatment system. Capital costs for the system were about $2 million, and O&M costs are approximately $250,000 per year (Ref. 9.29, cost year not provided).

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. 9.16).
- **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. 9.7, 9.12).
- **Treatment goal** - Application could require additional treatment to meet stringent cleanup goals and/or effluent and disposal standards (Ref. 9.7)
- **Sludge disposal** - Sludge produced from the precipitation/coprecipitation process could be considered a hazardous waste and require additional treatment before disposal, or disposal as hazardous waste (Ref. 9.7).
- **Factors affecting precipitation/coprecipitation performance** - Items in the “Factors Affecting Precipitation/Coprecipitation Performance” box will also affect costs.

contaminants, arsenic precipitation/coprecipitation processes may also cause other compounds to precipitate, which can render the resulting sludge hazardous (Ref. 9.7). 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. 9.36).

Summary of Cost Data

Limited cost data are currently available for precipitation/coprecipitation treatment of arsenic. At the Winthrop Landfill Site (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 for the first few years and are now approximately $250,000 per year. The treatment system has a capacity of 65 gpm. However, these costs are for the entire treatment train (Ref. 9.29, cost year not provided). At the power substation in Fort Walton, Florida, (Table 9.1, Project 4), the reported O&M cost was $0.006 per gallon (for the entire treatment train, Ref 9.32, cost year not provided). Capital cost information was not provided.

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 (Project 31). 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 (Ref. 9.22, cost year not provided).

The document "*Technologies and Costs for Removal of Arsenic From Drinking Water*" (Ref. 9.7) 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

These cost curves are based on computer cost models for drinking water treatment systems. Table 3.4 in Section 3 of this document 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.

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Table 9.1
Arsenic Precipitation/Coprecipitation Treatment Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c.]	Source
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	9.29
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	9.8
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	9.27
4	Power substation	Groundwater, 44 million gallons	Full	Ft. Walton Beach, FL	0.2-1.0 mg/L	<0.005 mg/L	--	Iron coprecipitation followed by ceramic membrane filtration	9.32
5	Chemical mixing	Groundwater, 43,000 gpd	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.	9.5, 9.15

Table 9.1
Arsenic Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c.]	Source
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	9.8
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 co-precipitation followed by filtration	9.18
8	Herbicide application	Groundwater	Pilot	--	1 mg/L (TWA)	<0.005 mg/L (TWA)	--	Iron coprecipitation followed by ceramic membrane filtration	9.11
9	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 0.0051-0.0076 mg/L (TCLP)	Photo-oxidation of arsenic followed by iron coprecipitation	9.16
10	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 0.547-0.658 mg/L (TCLP)	Photo-oxidation of arsenic followed by iron coprecipitation	9.16
Environmental Media - Other or Unspecified Precipitation Process									
11	--	"Superfund wastewater"	Full	--	0.1 - 1 mg/L	0.022 mg/L	--	Chemical precipitation	9.9
12	--	Groundwater	Full	--	100 mg/L	< 0.2 mg/L	--	Precipitation	9.17
13	--	"Superfund wastewater"	Full	--	0.1 - 1 mg/L	0.110 mg/L	--	Chemical precipitation	9.9

Table 9.1
Arsenic Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c.]	Source
14	--	Groundwater	Full	--	100 mg/L	<0.010 mg/L	--	Reductive Precipitation (additional information not available)	9.17
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	9.8
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	9.15
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	9.15
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.	9.15
19	Herbicide manufacturing	RCRA waste code K031, 1 mgd	Full	Vineland Chemical Company Superfund Site, Vineland, NJ	--	--	--	Metals precipitation followed by filtration	9.15

Table 9.1
Arsenic Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c.]	Source
20	Veterinary feed additives and pharmaceuticals manufacturing	Groundwater, 50-100 gpm	Full	Whitmoyer Laboratories Superfund Site	100 mg/L	0.025 mg/L	--	Neutralization and flocculation by increasing pH to 9	9.34
Drinking Water - Iron Coprecipitation									
21	--	Drinking water, 1.6 mgd	Full	--	0.0203 mg/L (TWA)	0.0030 mg/L (TWA)	<5 mg/L (WET)	Ferric coprecipitation followed by zeolite softening	9.7
22	--	Drinking water, 1.4 mgd	Full	--	0.0485 mg/L (TWA)	0.0113 mg/L (TWA)	<5 mg/L (WET)	Ferric coprecipitation	9.7
23	--	Drinking water	Full	McGrath Road Baptist Church, AK	0.370 mg/L	<0.005 mg/L	--	Enhanced iron co - precipitation followed by filtration	9.18
24	--	Drinking water, 600 mgd	Full	--	0.0026 - 0.0121 mg/L	0.0008 - 0.006 mg/L	806-880 mg/kg <0.05-0.106 mg/L (TCLP)	Ozonation followed by coagulation with iron- and aluminum-based additives and filtration	9.25
25	--	Drinking water, 62.5 mgd	Full	--	0.015 - 0.0239 mg/L	0.0015 - 0.0118 mg/L	293-493 mg/kg 0.058-0.114 mg/L (TCLP)	Coagulation with iron and aluminum based additives, sedimentation, and filtration	9.25
26	--	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	9.10
27	--	Drinking water	Pilot	--	--	<0.002 mg/L Arsenic (V)	--	Iron coagulation with direct filtration	9.24

Table 9.1
Arsenic Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c.]	Source
28	–	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	9.35
Drinking Water - Lime Softening									
29	--	Drinking water	Full	5 facilities, identification unknown	--	<0.003 mg/L (TWA)	<5 mg/L (TCLP)	Lime softening at pH >10.2	9.7
30	--	Drinking water, 10 mgd	Full	--	0.0159 - 0.0849 mg/L	0.0063 - 0.0331 mg/L	17.0-35.3 mg/kg <0.05 mg/L (TCLP)	Oxidation followed by lime softening and filtration	9.25
Drinking Water - Point-of-Use Systems									
31	--	Drinking water	Pilot	Harian Village Rajshaji District Bangladesh	0.092 - 0.120 mg/L	0.023 - 0.036 mg/L	--	Naturally-occurring iron at 9 mg/L facilitates precipitation, followed by sedimentation, filtration and acidification	9.22
32	--	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	9.22
33	--	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	9.19

Table 9.1
Arsenic Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c]	Source
34	--	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	9.26
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	9.21
Wastewaters - Lime Softening									
36	Veterinary pharmaceuticals	K084, wastewater	Full	Charles City, Iowa	399 - 1,670 mg/L (TWA)	Calcium arsenate, 60.5 - 500 mg/L (TWA)	45,200 mg/kg (TWA) 2,200 mg/L (TCLP)	Calcium hydroxide	9.3
37	--	Wastewater	Full	--	4.2 mg/L (TWA)	0.51 mg/L (TWA)	--	Lime precipitation followed by sedimentation	9.4
38	--	Wastewater	Full	--	4.2 mg/L (TWA)	0.34 mg/L (TWA)	--	Lime precipitation followed by sedimentation and filtration	9.4
39	--	Wastewater	Full	BP Minerals America	--	--	Calcium arsenate and calcium arsenite, 1,900 - 6,900 mg/kg (TWA) 0.2 - 74.5 mg/L (EP Tox)	Lime	9.3

Table 9.1
Arsenic Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c.]	Source
Wastewaters - Metal Sulfates									
40	Veterinary pharmaceuticals	K084, wastewater	Full	Charles City, Iowa	125 - 302 mg/L (TWA)	Manganese arsenate, 6.02 - 22.4 mg/L (TWA)	47,400 mg/kg (TWA) 984 mg/L (TCLP)	Manganese sulfate	9.3
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	9.30
42	Metals processing	Leachate from filter cake from purification of zinc sulfate electrowinning solution (amount not available)	Full	Texasgulf Canada, Timmons, Ontario, Canada	--	--	98% recovery of arsenic	Acid addition, chemical precipitation with copper sulfate, and filtration	9.30
Wastewaters - Iron Coprecipitation									
43	--	Wastewater from wet scrubbing of incinerator vent gas (D004, P011)	Full	American NuKem	69.6 - 83.7 mg/L (TWA)	<0.02 - 0.6 mg/L (TWA)	--	Chemical oxidation followed by precipitation with ferric salts	9.3
44	Veterinary pharmaceuticals	K084, wastewater	Full	Charles City, Iowa	15 - 107 mg/L (TWA)	Ferric arsenate, 0.163 - 0.580 mg/L (TWA)	9,760 mg/kg (TWA) 0.508 mg/L (TCLP)	Ferric sulfate	9.3

Table 9.1
Arsenic Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c.]	Source
Wastewaters - Other or Unspecified Precipitation Process									
45	--	Wastewater	Full	--	<0.1 - 3.0 mg/L (TWA)	0.18 mg/L (average, TWA)	--	Chemical reduction followed by precipitation, sedimentation, and filtration	9.4
46	Centralized waste treatment industry	Wastewater	Full	--	57 mg/L (TWA)	0.181 mg/L (TWA)	--	Primary precipitation with solids-liquid separation	9.6
47	Centralized waste treatment industry	Wastewater	Full	--	57 mg/L (TWA)	0.246 mg/L (TWA)	--	Primary precipitation with solids-liquid separation followed by secondary precipitation with solids-liquid separation	9.6
48	Centralized waste treatment industry	Wastewater	Full	--	57 mg/L (TWA)	0.084 mg/L (TWA)	--	Primary precipitation with solids-liquid separation followed by secondary precipitation with solids-liquid separation and multimedia filtration	9.6
49	Centralized waste treatment industry	Wastewater	Full	--	57 mg/L (TWA)	0.011 mg/L (TWA)	--	Selective metals precipitation, solids-liquid separation, secondary precipitation, solids-liquid separation, tertiary precipitation, and solid-liquid separation	9.6

Table 9.1
Arsenic Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c.]	Source
50	Chemical and allied products	Wastewater	Full	--	0[b.] - 0.1 mg/L (TWA)	0.0063 mg/L (TWA)	--	Chemically assisted clarification	9.9
51	--	Domestic wastewater	Full	--	0[b.] - 0.1 mg/L (TWA)	0.0015 mg/L (TWA)	--	Chemical precipitation	9.9
52	Transportation equipment industry	Wastewater	Full	--	0.1 - 1 mg/L (TWA)	<0.002 mg/L (TWA)	--	Chemical precipitation and filtration	9.9
53	Chemicals and allied products	Wastewater	Full	--	0.1 - 1 mg/L (TWA)	0.028 mg/L (TWA)	--	Chemically assisted clarification	9.9
54	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 (TWA)	--	--	Chemical precipitation and filtration	9.31
55	Metals processing	Spent leachate from the recovery of Ag from ores (amount not available)	Full	Sheritt Gordon Mines, LTD., Fort Saskatchewan, Alberta, Canada	--	--	--	Chemical precipitation and filtration	9.30
56	Metallurgie-Hoboken-Overpelt (MHO) solvent extraction process Metals processing	Spent electrolyte from Cu refining (amount not available)	Full	Olen, Belgium	--	--	99.96% recovery of arsenic	Chemical precipitation and filtration	9.31
57	Electric, gas, and sanitary	Wastewater	Pilot	--	0[b.] - 0.1 mg/L (TWA)	0.0028 mg/L (TWA)	--	Chemically assisted clarification	9.9
58	Primary metals	Wastewater	Pilot	--	0[b.] - 0.1 mg/L (TWA)	<0.0015 mg/L (TWA)	--	Chemical precipitation	9.9

Table 9.1
Arsenic Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c.]	Source
59	--	Wastewater bearing unspecified RCRA listed waste code	Pilot	--	0[b.] - 0.1 mg/L (TWA)	0.001 mg/L (TWA)	--	Chemical precipitation, activated carbon adsorption, and filtration	9.9
60	--	Domestic wastewater	Pilot	--	0[b.] - 0.1 mg/L (TWA)	0.001 mg/L (TWA)	--	Chemical precipitation	9.9
61	--	Wastewater bearing unspecified RCRA listed waste code	Pilot	--	0.1 - 1 mg/L (TWA)	0.012 mg/L (TWA)	--	Chemical precipitation, activated carbon adsorption, and filtration	9.9
62	--	Wastewater bearing unspecified RCRA listed waste code	Pilot	--	0.1 - 1 mg/L (TWA)	0.012 mg/L (TWA)	--	Chemical precipitation, activated carbon adsorption, and filtration	9.9
63	--	Wastewater bearing unspecified RCRA listed waste code	Pilot	--	0.1 - 1 mg/L (TWA)	0.006 mg/L (TWA)	--	Chemical precipitation, activated carbon adsorption, and filtration	9.9
64	Landfill	Hazardous leachate, F039	Pilot	--	0.1 - 1 mg/L (TWA)	0.008 mg/L (TWA)	--	Chemical precipitation, activated carbon adsorption, and filtration	9.9
65	--	Wastewater bearing unspecified RCRA listed waste code	Pilot	--	0.1 - 1 mg/L (TWA)	0.014 mg/L (TWA)	--	Chemical precipitation, activated carbon adsorption, and filtration	9.9

Table 9.1
Arsenic Precipitation/Coprecipitation Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Precipitating Agent or Process[c.]	Source
66	Municipal landfill	Leachate	Pilot	--	1 - 10 mg/L (TWA)	8 mg/L (TWA)	--	Chemical precipitation, activated carbon adsorption, and filtration	9.9
67	Metals processing	Scrubber water from lead smelter	Pilot	--	3,300 mg/L	0.007 mg/L	--	Mineral-like precipitation (additional information not available)	9.17
68	Metals processing	Thickener overflow from lead smelter	Pilot	--	5.8 mg/L	0.003 mg/L	--	Mineral-like precipitation (additional information not available)	9.17
69	--	Industrial wastewater	Pilot	--	5.8 mg/kg	< 0.5 mg/kg	--	--	9.17

a Excluding bench-scale treatments.

b Detection limit not provided.

c The information that appears in the "Precipitating Agent or Process" column, including the chemicals used, the descriptions of the precipitation/ coprecipitation processes, and whether the process involved precipitation or coprecipitation, were prepared 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.

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

10.0 MEMBRANE FILTRATION FOR ARSENIC

Summary

Membrane filtration can remove a wide range of contaminants from water. Based on the information collected to prepare this report, 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 report.

Technology Description and Principles

There are four types of membrane processes: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). All four of these processes are pressure-driven and are categorized by the size of the particles that can pass through the membranes or by the molecular weight cut off (i.e., pore size) of the membrane (Ref. 10.2). The force required to drive fluid across the membrane 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 lower pressure (5 to 100 psi) (Ref. 10.4). The low pressure processes primarily remove contaminants through physical sieving, and the high pressure processes through chemical diffusion across the permeable membrane (Ref. 10.4).

Technology Description: Membrane filtration separates contaminants from water by passing it through a semi-permeable barrier or membrane. The membrane allows some constituents to pass through, while blocking others (Ref. 10.2, 10.3).

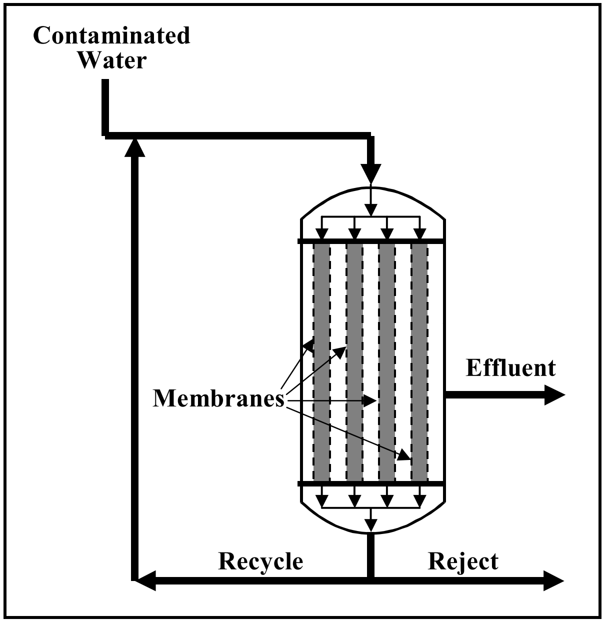
Media Treated:

- Drinking water
- Groundwater
- Surface water
- Industrial wastewater

Types of Membrane Processes:

- Microfiltration
- Ultrafiltration
- Nanofiltration
- Reverse osmosis

Model of a Membrane Filtration System



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. 10.4). MF has been used with precipitation/coprecipitation to remove solids containing arsenic. The sources used for this report did not contain any information on the use of UF to remove arsenic; therefore, UF is not discussed in this technology summary. MF generates two treatment residuals from the influent waste stream: a treated effluent (permeate) and a rejected waste stream of concentrated contaminants (reject).

RO is a high pressure process that primarily removes smaller ions typically associated with total dissolved solids. The molecular weight cut off for RO membranes ranges from 1 to 20,000, which is a significantly lower cut off than for NF membranes. The molecular weight cut off 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. 10.4).

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 (Ref. 10.4).

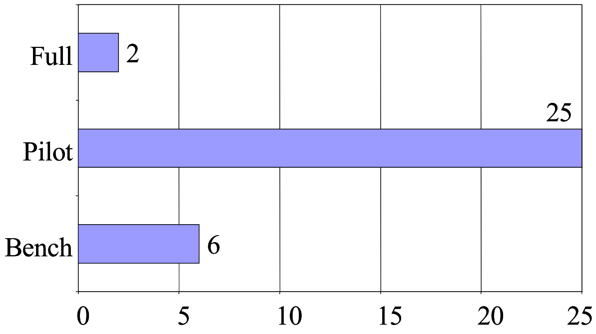
Media and Contaminants Treated

Drinking water, surface water, groundwater, and industrial wastewater can be treated with this technology. Membrane filtration can treat dissolved salts and other dissolved materials (Ref. 10.12).

Type, Number, and Scale of Identified Projects Treating Water Containing Arsenic

The data gathered for this report identified one full-scale RO and one full-scale MF treatment of arsenic in groundwater and surface water (Figure 10.1). The MF application is a treatment train consisting of precipitation/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 of arsenic has also been identified.

Figure 10.1
Scale of Identified Membrane Filtration Projects for Arsenic Treatment



Summary of Performance Data

Table 10.1 presents the performance data found 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 effective treatment.

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 may cause membrane fouling.
- **Oxidation state of arsenic** - Prior oxidation of the influent stream to convert As(III) to As(V) will increase arsenic removal; As(V) is generally larger and is captured by the membrane more effectively than As(III).
- **pH -** pH may affect the adsorption of arsenic on the membrane by creating an electrostatic charge on the membrane surface.
- **Temperature** - Low influent stream temperatures decreases membrane flux. Increasing system pressure or increasing the membrane surface area may compensate for low influent stream temperature.

Although many of the projects listed in Table 10.1 may have reduced arsenic concentrations to below 0.05 mg/L or 0.01 mg/L, data on the concentration of arsenic in the effluent and reject streams were not available for most projects.

For two RO projects, the arsenic concentration in the reject stream was available, allowing the concentration in 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 concentration in the treated water was 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 Table 10.1, Project 31.

Applicability, Advantages, and Potential Limitations

Membrane technologies are capable of removing a wide range of dissolved contaminants and suspended solids from water (Ref. 10.12). RO and NF technologies require no chemical addition to ensure adequate separation. This type of treatment may 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. 10.15).

Factors Affecting Membrane Filtration Costs

- **Type of membrane filtration** - The type of membrane selected may affect the cost of the treatment (Ref. 10.1, 10.2).
- **Initial waste stream** - Certain waste streams may require pretreatment, which would increase costs (Ref. 10.4).
- **Rejected waste stream** - Based on concentrations of the removed contaminant, further treatment may be required prior to disposal or discharge (Ref. 10.4).
- **Factors affecting membrane filtration performance** - Items in the "Factors Affecting Membrane Filtration Performance" box will also affect costs.

Summary of Cost Data

The research conducted in support of this report did not document any cost data for specific membrane filtration projects to treat of arsenic. The document "*Technologies and Costs for Removal of Arsenic From Drinking Water*" (Ref. 10.4) 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.

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 gallons per minute (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 <0.0008 mg/L, respectively. The RO process reduced As (V) from 0.035 to 0.0005 mg/L and As (III) from 0.007 to 0.0005 mg/L. The membrane achieved 99% total As removal and 98% As (V) removal (Ref. 10.12) (see Project 31, Table 10.1).

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Table 10.1
Membrane Filtration Treatment Performance Data for Arsenic

Project Number	Media or Waste	Scale	Site Name or Location	Initial Arsenic Concentration	Percent Arsenic Removal[a] or Final Arsenic Concentration	Membrane or Treatment Process	Source
Nanofiltration							
1	Groundwater	Pilot	Tarrytown, NY	0.038 - 0.154 mg/L	95%	--	10.4
2	Groundwater	Pilot	Tarrytown, NY	0.038 - 0.154 mg/L	95%	--	10.4
3	Groundwater with low DOC (1mg/L)	Pilot	--	--	60%	Single element, negatively charged membrane	10.4
4	Groundwater with high DOC (11mg/L)	Pilot	--	--	80%	Single element, negatively charged membrane	10.4
5	Groundwater with high DOC (11mg/L)	Pilot	--	--	75% initial, 3-16% final	Single element, negatively charged membrane	10.4
6	Arsenic spiked surface water	Pilot	--	--	Arsenic (III) 20% Arsenic (V) > 95%	Single element membrane	10.4
7	Arsenic spiked surface water	Pilot	--	--	Arsenic (III) 30% Arsenic (V) > 95%	Single element membrane	10.4
8	Arsenic spiked surface water	Pilot	--	--	Arsenic (III) 52% Arsenic (V) > 95%	Single element membrane	10.4
9	Arsenic spiked DI water	Bench	--	--	Arsenic (III) 12% Arsenic (V) 85%	Single element, negatively charged membrane	10.4
10	Arsenic spiked lake water	Bench	--	--	Arsenic (V) 89%	Single element, negatively charged membrane	10.4
11	Arsenic spiked DI water	Bench	--	--	Arsenic (V) 90%	Flat sheet, negatively charged membrane	10.4

Table 10.1
Membrane Filtration Treatment Performance Data for Arsenic (continued)

Project Number	Media or Waste	Scale	Site Name or Location	Initial Arsenic Concentration	Percent Arsenic Removal[a] or Final Arsenic Concentration	Membrane or Treatment Process	Source
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.	10.1
13	Groundwater	Pilot	Charlotte Harbor, FL	--	Arsenic (III) 46-84% Arsenic (V) 96-99%	--	10.4
14	Groundwater	Pilot	Cincinnati, OH	--	Arsenic (III) 73%	--	10.4
15	Groundwater	Pilot	Eugene, OR	--	50%	--	10.4
16	Groundwater	Pilot	Fairbanks, AL	--	50%	--	10.4
17	Groundwater	Pilot	Hudson, NH	--	40%	--	10.4
18	Groundwater with low DOC	Pilot	--	--	> 80%	Single element, negatively charged membrane	10.4
19	Groundwater with high DOC	Pilot	--	--	> 90%	Single element, negatively charged membrane	10.4
20	Arsenic spiked surface water	Pilot	--	--	Arsenic (III) 60% Arsenic (V) > 95%	Single element membrane	10.4
21	Arsenic spiked surface water	Pilot	--	--	Arsenic (III) 68% Arsenic (V) > 95%	Single element membrane	10.4
22	Arsenic spiked surface water	Pilot	--	--	Arsenic (III) 75% Arsenic (V) > 95%	Single element membrane	10.4
23	Arsenic spiked surface water	Pilot	--	--	Arsenic (III) 85% Arsenic (V) > 95%	Single element membrane	10.4
24	Groundwater	Pilot	San Ysidro, NM	--	91%	--	10.4
25	Groundwater	Pilot	San Ysidro, NM	--	99%	Hollow fiber, polyamide membrane	10.4
26	Groundwater	Pilot	San Ysidro, NM	--	93-99%	Hollow fiber, cellulose acetate membrane	10.4

Table 10.1
Membrane Filtration Treatment Performance Data for Arsenic (continued)

Project Number	Media or Waste	Scale	Site Name or Location	Initial Arsenic Concentration	Percent Arsenic Removal[a] or Final Arsenic Concentration	Membrane or Treatment Process	Source
27	Groundwater	Pilot	Tarrytown, NY	--	86%	--	10.4
28	Arsenic spiked lake water	Bench	--	--	Arsenic (III) 5% Arsenic (V) 96%	--	10.4
29	Arsenic spiked DI water	Bench	--	--	Arsenic (III) 5% Arsenic (V) 96%	--	10.4
30	Arsenic spiked DI water	Bench	--	--	Arsenic (V) 88%	--	10.4
31	Drinking water	Pilot	Park City Spiro Tunnel Water Filtration Plant, Park City, Utah	0.065 mg/L	0.0005 mg/L	--	10.12
Microfiltration							
32	Groundwater	Full	--	0.005 - 3.8 mg/L	<0.005 - 0.05 mg/L	Iron coprecipitation followed by membrane filtration	10.14
33	Groundwater	Pilot	--	0.2 - 1.0 mg/L	<0.005 mg/L	Iron coprecipitation followed by ceramic membrane filtration	10.13

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

DI = Deionized
DOC = Dissolved organic carbon
-- = Not available
NF = Nanofiltration
RO = Reverse Osmosis

11.0 ADSORPTION TREATMENT FOR ARSENIC

Technology Description and Principles

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. 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. 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. 11.3).

Summary

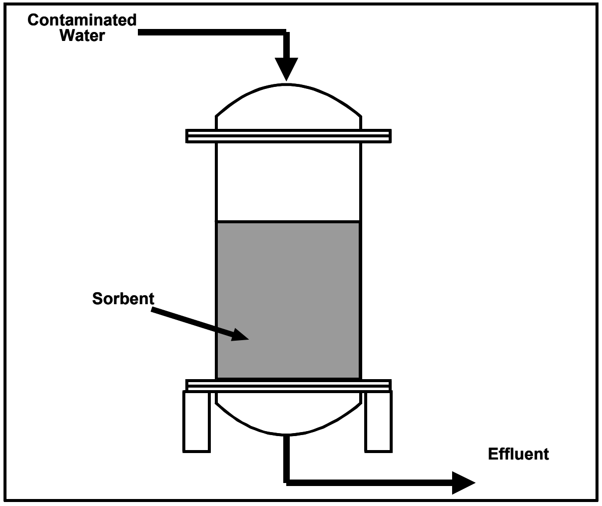
Adsorption has been used to treat groundwater and drinking water containing arsenic. Based on the information collected for this report, this technology typically can reduce arsenic concentrations to less than 0.050 mg/L and in some cases has reduced arsenic concentrations to below 0.010 mg/L. Its effectiveness 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.

Activated alumina (AA) is the sorbent most commonly used to remove arsenic from drinking water (Ref. 11.1), and has also been used for groundwater (Ref. 11.4). The reported adsorption capacity of AA ranges from 0.003 to 0.112 grams of arsenic per gram of AA (Ref. 11.4). It 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. 11.3). Regeneration is a four-step process:

- Backwashing
- Regeneration
- Neutralization
- Rinsing

Model of an Adsorption System



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.

Media Treated:
- Groundwater
- Drinking water

Types of Sorbent Used in Adsorption 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

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. 11.1).

Activated carbon (AC) is an organic sorbent that is commonly used to remove organic and metal contaminants from drinking water, groundwater, and wastewater (Ref. 11.4). AC media are normally regenerated using thermal techniques to desorb and volatilize contaminants (Ref. 11.6). However, regeneration of AC media used for the removal of arsenic from water might not be feasible (Ref. 11.4). The arsenic might not volatilize at the temperatures typically used in AC regeneration. In addition, off-gas containing arsenic from the regeneration process may be difficult or expensive to manage.

The reported adsorption capacity of AC is 0.020 grams of As(V) per gram of AC. As(III) is not effectively removed by AC. 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) is 0.2 grams per gram of ferrous iron-impregnated carbon (Ref. 11.4).

Iron-based adsorption media include granular ferric hydroxide, ferric hydroxide-coated newspaper pulp, ferric oxide, iron oxide-coated sand, sulfur-modified iron, 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 water. 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. 11.3).

The sources used for this report 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. 11.17).

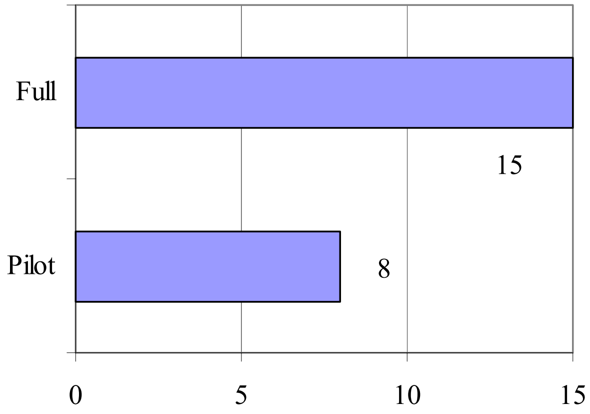
Media and Contaminants Treated

Adsorption is frequently used to remove organic contaminants and metals from industrial wastewater. It has been used to remove arsenic from groundwater and drinking water.

Type, Number, and Scale of Identified Projects Treating Water Containing Arsenic

Adsorption technologies to treat arsenic-contaminated water in water are commercially available. Information was found on 23 applications of adsorption (Figure 11.1), including 7 full- and 5 pilot-scale projects fro groundwater and surface water and 8 full- and 3 pilot-scale projects for drinking water.

Figure 11.1
Scale of Identified Adsorption Projects for Arsenic Treatment



Summary of Performance Data

Adsorption treatment effectiveness can be evaluated by comparing influent and effluent contaminant concentrations. Table 11.1 presents the available performance data for this technology. Two of the four groundwater and surface water 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

Factors Affecting Adsorption Performance

- **Fouling** - The presence of suspended solids, organics, solids, silica, or mica, can cause fouling of adsorption media (Ref. 11.1, 11.4).
- **Arsenic oxidation state** - Adsorption is more effective in removing As(V) than As(III) (Ref. 11.12).
- **Flow rate** - Increasing the rate of flow through the adsorption unit can decrease the adsorption of contaminants (Ref. 11.1).
- **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. 11.4).

achieved in both of the projects. In the other two groundwater and surface water projects the influent arsenic concentration was between 0.010 mg/L and 0.050 mg/L, and the effluent concentration was less than 0.010 mg/L.

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 arsenic 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 goal for some applications may 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 report.

Two pilot-scale studies were performed to compare the effectiveness AA adsorption on As(III) and As(V) (Projects 3 and 4 in Table 11.1). 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 at the end of this section discusses in greater detail the use of AA to remove arsenic from drinking water. Information for this project is summarized in Table 11.1, Project 13.

Applicability, 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. 11.3). Spent AA is produced when the AA can no longer be regenerated (Ref. 11.3). The spent AA may require treatment prior to disposal (Ref. 11.4). 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 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. 11.6).

Competition for adsorption sites could reduce the effectiveness of adsorption because other constituents may 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. 11.3). The order for adsorption preference for AA is provided below, with the constituents with the greatest adsorption preference appearing at the top left (Ref. 11.3):

$$OH^- > H_2\mathbf{As}O_4^- > Si(OH)_3O^- > F^- > HSeO_3^- > SO_4^{2-} > H_3\mathbf{As}O_3$$

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. 11.20).

Summary of Cost Data

One source reported that the cost of removing arsenic from drinking water using AA ranged from $0.003 to

Factors Affecting Adsorption Costs

- **Contaminant concentration** - Very high concentrations of competing contaminants may require frequent replacement or regeneration of adsorbent (Ref. 11.2). The capacity of the adsorption media increases with increasing contaminant concentration (Ref. 11.1, 11.4). 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. 11.4).
- **Factors affecting adsorption performance** - Items in the "Factors Affecting Adsorption Performance" box will also affect costs.

$0.76 per 1,000 gallons (Ref. 11.4, cost year not provided). The document "*Technologies and Costs for Removal of Arsenic From Drinking Water*" (Ref. 11.3) contains 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 operating and maintenance (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 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. Many of the technologies used to treat drinking water are applicable to treatment of other types of water, and may have similar costs. Table 3.4 in Section 3 of this document contains cost estimates based on these curves for AA and greensand filtration.

Case Study: Treatment of Drinking Water by an Activated Alumina Plant

A drinking water treatment plant using AA (see Table 11.1, Project 13) installed in February 1996 has an average flow rate of 3,000 gallons per day. 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 study, 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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Table 11.1
Adsorption Treatment Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Adsorption Process Description[b]	Source
Environmental Media - Activated Alumina								
1	--	Groundwater	Full	--	--	<0.05 mg/L	Activated alumina. Flow rate: 300 liters/hour.	11.9
2	--	Groundwater	Pilot	--	--	<0.05 mg/L	Activated alumina adsorption at pH 5	11.4
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.	11.3
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.	11.3

Table 11.1
Adsorption Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Adsorption Process Description[b]	Source
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.	11.5
6	Wood Preserving	Groundwater, 27,000 gpd	Full	North Cavalcade Street Superfund Site Houston, TX	--	--	Treatment train consisting of filtration followed by carbon adsorption	11.7
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	11.7
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	11.7
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	11.7
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	11.7

Table 11.1
Adsorption Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Adsorption Process Description[b]	Source
Environmental Media - Iron-Based Media								
11	Landfill	Groundwater	Pilot	--	--	0.027 mg/L	Treatment train consisting of precipitation from barite addition followed by an iron filings and sand media filter. Performance data are for the entire treatment train.	11.8, 11.13
12	--	Groundwater, 3,600gpd	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	11.18
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	11.3
14	--	Drinking water	Full	--	0.034 - 0.087 mg/L	<0.05 mg/L	Activated alumina	11.12
15	--	Drinking water	Full	Project Earth Industries, Inc.	0.34 mg/L	0.01 - 0.025 mg/L	Activated alumina	11.8
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	11.3
17	--	Drinking water, 14,000 gpd	Full	Bow, NH	0.057 - 0.062 mg/L	0.050 mg/L	Activated alumina	11.3
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	11.11

Table 11.1
Adsorption Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale[a]	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Adsorption Process Description[b]	Source
19	--	Drinking Water	Pilot	--	0.1 - 0.18 mg/L	<0.01 mg/L	Fixed bed adsorber with ferric hydroxide-coated newspaper pulp; 20,000 bed volumes treated before effluent exceeded 0.01 mg/L arsenic	11.15
20	--	Drinking water	Pilot	--	0.180 mg/L	0.010 mg/L	Granular ferric hydroxide	11.16
21	--	Drinking water	Full	--	0.02mg/L	0.003 mg/L	Fixed bed adsorber with ferric oxide granules	11.19
Drinking Water - Other or Unknown Media								
22	--	Drinking water	Full	--	5 mg/L	0.01 mg/L	Copper-zinc granules	11.14
23	--	Drinking water	Pilot	ADI International	--	--	Adsorption in pressurized vessel containing proprietary media at pH 5.5 to 8.0	11.1

[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.

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

gpd = gallons per day
mgd = million gallons per day

TCLP = Toxicity characteristic leaching procedure
mg/kg = milligrams per kilogram

-- = Not available
TWA = Total waste analysis
WET = Waste extraction test

12.0 ION EXCHANGE TREATMENT FOR ARSENIC

Summary

Ion exchange has been used to treat groundwater and drinking water containing arsenic. Based on the information collected to prepare this report, 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

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. 12.3). Four types of ion exchange media have been used (Ref. 12.1):

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

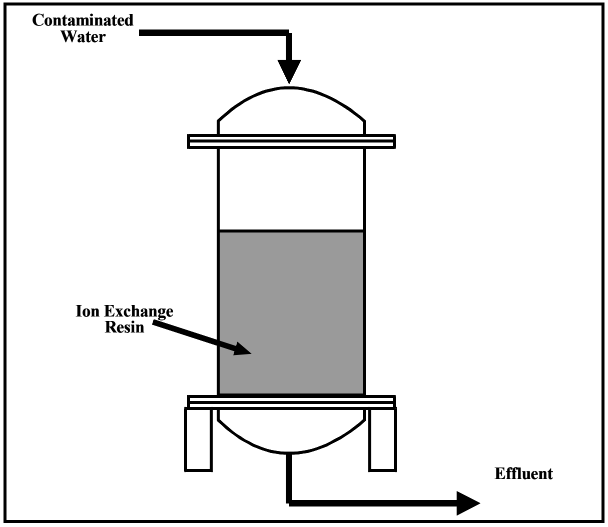
Strong and weak acid resins exchange cations while strong and weak base resins exchange anions. Because dissolved arsenic is usually in an anionic form, and weak base resins tend to be effective over a smaller pH range, strong base resins are typically used for arsenic treatment (Ref. 12.1).

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. 12.1, 12.4, 12.8).

Media Treated:
- Groundwater
- Surface water
- Drinking water

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

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. 12.1).

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. 12.4). 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. 12.4). 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. 12.4). The number of ion exchange bed volumes that can be treated before regeneration is needed can range from 300 to 60,000 (Ref. 12.1). The regenerating solution may 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. 12.4).

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 may reduce the frequency of resin regeneration (Ref. 12.4).

Media and Contaminants Treated

Anion exchange resins are used to remove soluble forms of arsenic from wastewater, groundwater, and drinking water (Ref. 12.1, 12.4). Ion exchange treatment is generally not applicable to soil and waste. It is commonly used in drinking water treatment for softening, removal of calcium, magnesium, and other cations in exchange for sodium, as well as removing nitrate, arsenate, chromate, and selenate (Ref. 12.9).

Type, Number, and Scale of Identified Projects Treating Water Containing Arsenic

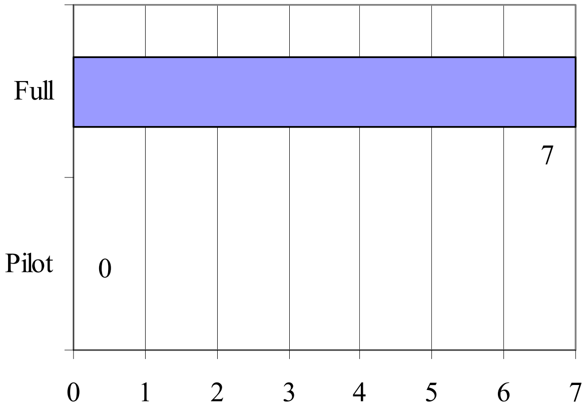
Ion exchange of arsenic and groundwater, surface water, and drinking water is commercially available. Information is available on seven full-scale applications (Figure 12.1), including three applications to groundwater and surface water, and four applications to drinking water. No pilot-scale applications or applications to industrial wastewater were found in the sources researched.

Summary of Performance Data

Table 12.1 presents the performance data found for this technology. Ion exchange treatment effectiveness can be evaluated by comparing influent and effluent contaminant concentrations. The single surface water project with both influent and effluent arsenic concentration data had an influent concentrations of 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 in 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 report.

Figure 12.1
Scale of Identified Ion Exchange Projects for Arsenic Treatment



Factors Affecting Ion Exchange Performance

- **Valence state** - As(III) is generally not removed by ion exchange (Ref. 12.4).
- **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. 12.1, 12.9).
- **Fouling** - The presence of organics, suspended solids, calcium, or iron, can cause fouling of ion exchange resins (Ref. 12.4).
- **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. 12.1).
- **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. 12.1).

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 Table 12.1, Project 1.

Applicability, 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. 12.4).

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 (Ref. 12.8).

The order for exchange for most strong-base resins is provided below, with the constituents with the greatest adsorption preference appearing at the top left (Ref. 12.4).

$HCrO_4^- > CrO_4^{2-} > ClO_4^- > SeO_4^{2-} > SO_4^{2-} > NO_3^- > Br^-$
$> (HPO_4^{2-}, H\mathbf{As}O_4^{2-}, SeO_3^{2-}, CO_3^{2-}) > CN^- > NO_2^- > Cl^- >$
$(H_2PO_4^-, H_2\mathbf{As}O_4^-, HCO_3^-) > OH^- > CH_3COO^- > F^-$

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. 12.10).

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. 12.9, 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 found.

Factors Affecting Ion Exchange Costs

- **Bed regeneration** - Regenerating ion exchange beds reduces the amount of waste for disposal and the cost of operation (Ref. 12.1).
- **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. 12.1).
- **Factors affecting ion exchange performance** - Items in the "Factors Affecting Ion Exchange Performance" box will also affect costs.

The document "*Technologies and Costs for Removal of Arsenic From Drinking Water*" (Ref. 12.1) contains additional information on the cost of ion exchange 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 ion exchange at various influent sulfate (SO_4) concentrations. These cost curves are based on computer cost models for drinking water treatment systems.

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. Table 3.4 in Section 3 of this document contains cost estimates based on these curves for ion exchange. Many of the technologies used to treat drinking water are applicable to treatment of other types of water, and may have similar costs.

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 one 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. 12.9) (see Project 1, Table 12.1).

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Table 12.1
Ion Exchange Treatment Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media	Scale	Site Name or Location	Ion Exchange Media or Process	Untreated Arsenic Concentration	Treated Arsenic Concentration	Ion Exchange Media Regeneration Information	Source
Drinking Water									
1	--	Drinking Water	Full	--	Treatment train consisting of 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	12.1
2	--	Drinking Water	Full	--	Treatment train consisting of a solid oxidizing media filter followed by an anion exchange system	0.019 - 0.055 mg/L[a]	<0.005 - 0.080 mg/L[a]	--	12.1
3	--	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 four weeks	12.9
4	--	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	12.8
Environmental Media									
5	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	--	12.2
6	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	--	--	--	12.7

Table 12.1
Ion Exchange Treatment Performance Data for Arsenic (continued)

Project Number	Industry or Site Type	Waste or Media	Scale	Site Name or Location	Ion Exchange Media or Process	Untreated Arsenic Concentration	Treated Arsenic Concentration	Ion Exchange Media Regeneration Information	Source
7	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	--	--	--	12.7

a Data are for entire treatment train, including unit operations that are not ion exchange.
-- = Not available.
TWA = Total waste analysis.
gpd = gallons per day
mg/L = milligrams per liter.

13.0 PERMEABLE REACTIVE BARRIERS FOR ARSENIC

Summary

Permeable reactive barriers (PRBs) are being used to treat arsenic in groundwater at full scale at only a few sites. Although many candidate materials for the reactive portion of the barrier have been tested at bench scale, only zero valent iron and limestone have been used at full scale. The installation techniques for PRBs are established for depths less than 30 feet, and require innovative installation techniques for deeper installations.

Technology Description: Permeable reactive barriers (PRBs) are walls containing reactive media that are installed across the path of a contaminated groundwater plume to intercept the plume. The barrier allows water to pass through while the media remove the contaminants by precipitation, degradation, adsorption, or ion exchange.

Media Treated:

- Groundwater (in situ)

Chemicals and Reactive Media Used in PRBs to Treat Arsenic:

- Zero valent iron (ZVI)
- Limestone
- Basic oxygen furnace slag
- Surfactant modified zeolite
- Ion exchange resin

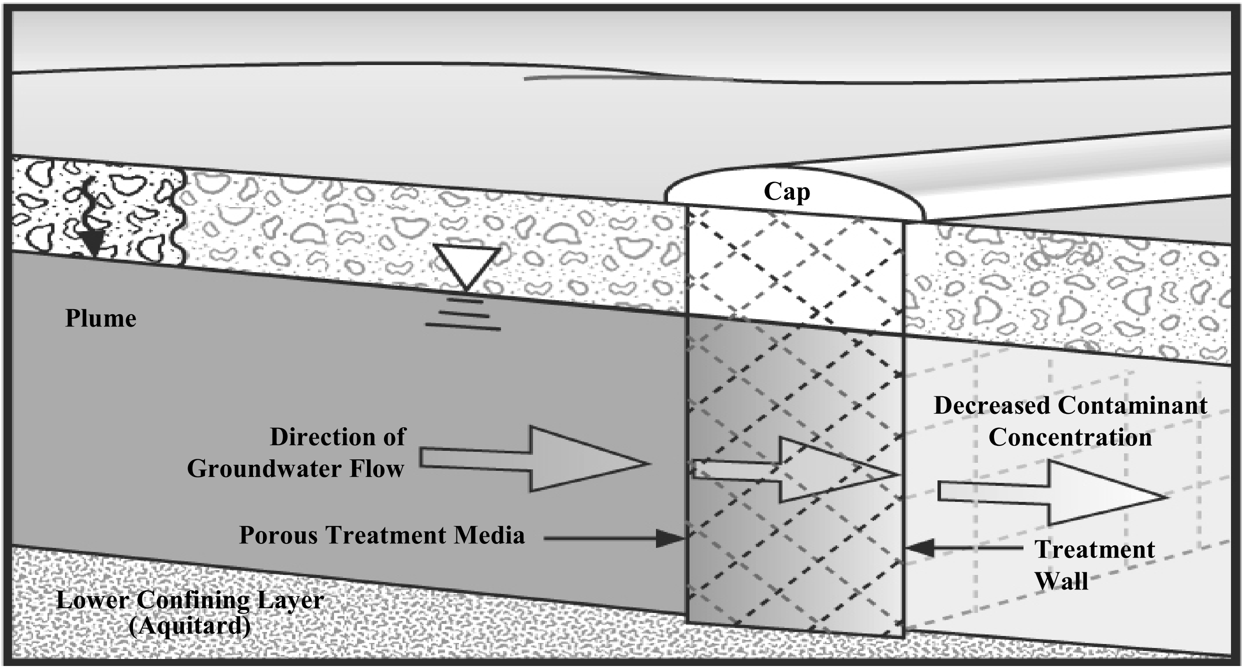
Installation Depth:

- Up to 30 feet deep using established techniques
- Innovative techniques required for depths greater than 30 feet

Technology Description and Principles

PRBs are applicable to the treatment of both organic and inorganic contaminants. The former usually are broken down into carbon dioxide and water, while the latter are converted to species that are less toxic or less mobile. The most frequent applications of PRBs is the in situ treatment of groundwater contaminated with chlorinated solvents. A number of different treatment media have been used, the most common being zero-valent iron (ZVI). Other media include hydrated lime, slag from steelmaking processes that use a basic oxygen furnace, calcium oxides, chelators (ligands selected for their specificity for a given metal), iron oxides, sorbents, substitution agents (e.g., ion exchange resins) and microbes (Ref. 13.6, 13.8, 13. 18). The cost of the reactive media will impact the overall cost of PRB remedies. The information sources used for this report included information about PRB applications using ZVI, basic oxygen furnace slag, limestone, surfactant modified zeolite, and ion exchange resin to treat arsenic.

Model of a Permeable Reactive Barrier System



For the PRB projects identified for this report, ZVI was the most commonly used reactive media. As groundwater reacts with ZVI, pH increases, Eh decreases, and the concentration of dissolved hydrogen increases. These basic chemical changes promote a variety of processes that impact contaminant concentrations. Increases in pH favor the precipitation of carbonates of calcium and iron as well as insoluble metal hydroxides. Decreases in Eh drive reduction of metals and metalloids with multiple oxidation states. Finally, an increase in the partial pressure of hydrogen in subsurface systems supports the activity of various chemotrophic organisms that use hydrogen as an energy source, especially sulfate-reducing bacteria and iron-reducing bacteria (Ref. 13.15).

Arsenate [As (V)] ions bind tightly to the iron filings, causing the ZVI to be oxidized to ferrous iron, aerobically or anaerobically in the presence of water, as shown by the following reactions:

(anaerobic) $Fe^0 + 2H_2O \rightarrow Fe^{+2} + H_2 + 2OH^-$
(aerobic) $2Fe^0 + 2H_2O + O_2 \rightarrow 2Fe^{+2} + 4OH^-$

The process results in a positively charged iron surface that sorbs the arsenate species by electrostatic interactions (Ref. 13.5, 13.17).

In systems where dissolved sulfate is reduced to sulfide by sulfate-reducing bacteria, arsenic may be removed by the precipitation of insoluble arsenic sulfide (As_2S_3) or co-precipitated with iron sulfides (FeS) (Ref. 13.15).

PRBs can be constructed by excavating a trench of the appropriate width and backfilling it with a reactive medium. Commercial PRBs are built in two basic configurations: the funnel-and-gate and the continuous wall. The funnel-and-gate uses impermeable walls, for example, sheet pilings or slurry walls, as a “funnel” to direct the contaminant plume to a “gate(s)” containing the reactive media, while the continuous wall transects the flow path of the plume with reactive media (Ref. 13.6).

Most PRBs installed to date have had depths of 50 feet (ft) or less. Those having depths of 30 ft or less can be installed with a continuous trencher, while depths between 30 and 70 ft require a more innovative installation method, such as biopolymers. Installation of PRBs at depths greater than 70 ft is more challenging (Ref. 13.13).

Media and Contaminants Treated

This technology can treat both organic and inorganic contaminants. Organic contaminants are broken down into less toxic elements and compounds, such as carbon dioxide and water. Inorganic contaminants are converted to species that are less toxic or less mobile. Inorganic contaminants that can be treated by PRBs include, but are not limited to, chromium (Cr), nickel (Ni), lead (Pb), uranium (U), technetium (Tc), iron (Fe), manganese (Mn), selenium (Se), cobalt (Co), copper (Cu), cadmium (Cd), zinc (Zn), arsenic (As), nitrate (NO_3^-), sulfate (SO_4^{2-}), and phosphate (PO_4^{3-}). The characteristics that these elements have in common is that they can undergo redox reactions and can form solid precipitates with common groundwater constituents, such as carbonate (CO_3^{2-}), sulfide (S^{2-}), and hydroxide (OH^-). Some common sources of these contaminants are mine tailings, septic systems, and battery recycling/disposal facilities (Ref. 13.5, 13.6, 13.14).

PRBs are designed to treat groundwater in situ. This technology is not applicable to other contaminated media such as soil, debris, or industrial wastes.

Type, Number, and Scale of Identified Projects Treating Water Containing Arsenic

PRBs are commercially available and are being used to treat groundwater containing arsenic at a full scale at two Superfund sites, the Monticello Mill Tailings and Tonolli Corporation sites, although arsenic is not the primary target contaminant for treatment by the technology at either site (Ref. 13.1). At a third Superfund site, the Asarco East Helena site, this technology has been tested at a bench scale, and implementation at a full scale to treat arsenic is currently planned (Ref. 13.15). In 1999, a pilot-scale treatment was conducted at Bodo Canyon Disposal Cell Mill Tailings Site, Durango, Colorado, to remediate groundwater contaminated with arsenic (Ref. 13.12). In addition, PRBs have been used in two bench-scale treatability studies by the U.S. Department of Energy’s Grand Junction Office (GJO) to evaluate their application to the Monticello Mill Tailings site and a former uranium ore processing site (Ref. 13.3). Figure 13.1 shows the number of applications found at each scale.

Additional bench-scale studies of the treatment of arsenic using PRBs that contain various reactive media are listed below (Ref. 13.8, 13.11). These studies were not conducted to evaluate the application of PRBs to specific sites. The organizations conducting the studies are listed in parentheses. However, no performance data are available for the studies, and therefore, they are not included in Figure 13.1 above, or in Table 13.1.

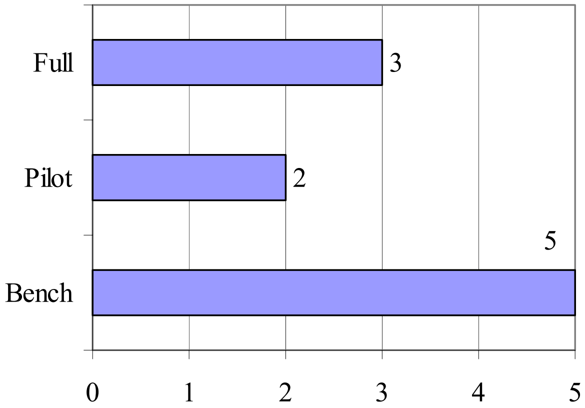
Other Bench-Scale Studies Using Adsorption or Ion Exchange Barriers

- Activated alumina (Dupont)
- Bauxite (Dupont)
- Ferric oxides and oxyhydroxides (Dupont, University of Waterloo),
- Peat, humate, lignite, coal (Dupont)
- Surfactant-modified zeolite (New Mexico Institute of Mining and Technology)

Other Bench-Scale Studies Using Precipitation Barriers

- Ferrous hydroxide, ferrous carbonate, ferrous sulfide (Dupont)
- Limestone (Dupont)
- Zero-Valent Metals (DOE GJO)

Figure 13.1
Scale of Identified Permeable Reactive Barrier Projects for Arsenic Treatment



Summary of Performance Data

Table 1 provides performance data for full-scale PRB treatment of groundwater contaminated with arsenic at three sites, two pilot-scale treatability study and five bench-scale treatability studies. PRB performance typically is measured by taking groundwater samples at points upgradient and downgradient of the wall and measuring the concentration of contaminants of concern at each point. Data on the Monticello site show a reduction in arsenic concentration from a range of 0.010 to 0.013 mg/L before installation of the PRB to <0.002 mg/L after the installation of a PRB. One pilot-scale study showed a reduction in arsenic concentrations from 0.4 mg/L to 0.02 mg/L. Four bench-scale treatability studies also show a reduction in arsenic concentrations.

Factors Affecting PRB Performance

- **Fractured rock** - The presence of fractured rock in contact with the PRB may allow groundwater to flow around, rather than through, the PRB (Ref. 13.6).
- **Deep aquifers and contaminant plumes** - PRBs may be difficult to install for deep aquifers and contaminant plumes (>70 ft deep) (Ref. 13.13).
- **High aquifer hydraulic conductivity** - The hydraulic conductivity of the barrier must be greater than that of the aquifer to prevent preferential flow around the barrier (Ref. 13.13).
- **Stratigraphy** - Site stratigraphy may affect PRB installation. For example, clay layers might be "smeared" during installation, reducing hydraulic conductivity near the PRB (Ref. 13.6).
- **Barrier plugging** - Permeability and reactivity of the barrier may be reduced by precipitation products and microbial growth (Ref. 13.6).

Applicability, Advantages, and Potential Limitations

PRBs are a passive treatment technology, designed to function for a long time with little or no energy input. They produce less waste than active remediation (for example, extraction systems like pump and treat), as the contaminants are immobilized or altered in the subsurface (Ref. 13.14). PRBs can treat groundwater with multiple contaminants and can be effective over a range of concentrations. PRBs require no aboveground equipment, except monitoring devices, allowing return of the property to economic use during remediation (Ref. 13.5, 13.14). PRBs are best applied to shallow, unconfined aquifer systems in unconsolidated deposits, as long as the reactive material is more conductive than the aquifer. (Ref. 13.13).

PRBs rely on the natural movement of groundwater; therefore, aquifers with low hydraulic conductivity can require relatively long periods of time to be remediated. In addition, PRBs do not remediate the entire plume, but only the portion of the plume that has passed through the PRB. Because cleanup of groundwater contaminated with arsenic has been conducted at only two Superfund sites and these barriers have been recently installed (Tonolli in 1998 and Monticello in 1999), the long-term effectiveness of PRBs for arsenic treatment has not been demonstrated (Ref. 13.13).

Case Study: Monticello Mill Tailings Site Permeable Reactive Barrier

The Monticello Mill Tailings in Southeastern Utah is a former uranium/vanadium processing mill and mill tailings impoundment (disposal pit). In January 1998, the U.S. Department of Energy completed an interim investigation to determine the nature and extent of contamination in the surface water and groundwater in operable unit 3 of the site. Arsenic was one among several contaminants in the groundwater, and was found at concentrations ranging from 0.010 to 0.013 mg/L. A PRB containing ZVI was constructed in June 1999 to treat heavy metal and metalloid contaminants in the groundwater. Five rounds of groundwater sampling occurred between June 1999 and April 2000, and was expected to continue on a quarterly basis until July 2001. The average concentration of arsenic entering the PRB, as measured from September to November 1999 was 0.010 mg/L, and the effluent concentration, measured in April 2000, was less than 0.0002 mg/L (Ref. 13.1, 13.2, 13.14) (see Project 2, Table 13.1).

Summary of Cost Data

EPA compared the costs of pump-and-treat systems at 32 sites to the costs of PRBs at 16 sites. Although the sites selected were not a statistically representative sample of groundwater remediation projects, the capital costs for PRBs were generally lower than those for pump and treat systems (Ref. 13.13). However, at the Monticello site, estimates showed that capital costs for a PRB were greater than those for a pump-and-treat system, but lower operations and maintenance costs would result in a lower life-cycle cost to achieve similar cleanup goals. For the PRB at the Monticello site, total capital cost was $1,196,000, comprised of $1,052,000 for construction and $144,000 for the reactive PRB media. Construction costs are assumed to include actual construction costs and not design activities or treatability studies (Ref. 13.14, cost year not provided). Cost data for the other projects described in the section are not available.

Factors Affecting PRB Costs

- **PRB depth** - PRBs at depths greater than 30 feet may be more expensive to install, requiring special excavation equipment and construction materials (Ref. 13.13).
- **Reactive media** - Reactive media vary in cost, therefore the reactive media selected can affect PRB cost.
- **Factors affecting PRB performance** - Items in the "Factors Affecting PRB Performance" box will also affect costs.

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Table 13.1
Permeable Reactive Barrier Arsenic Treatment Performance Data for Arsenic

Project Number	Scale	Site Name and Location	Initial Arsenic Concentration (mg/L)	Final Arsenic Concentration (mg/L)	Barrier Type and Media	Project Duration	Source
1	Full	Tonolli Corporation Superfund Site, Nesquehoning, PA	0.313	Not available	Trench, limestone	August 1998 - present	13.1, 13.7
2	Full	Monticello Mill Tailings - OU3, Monticello, UT	0.010 - 0.013	<0.0002	Funnel and gate, ZVI	June 1999 - present	13.1, 13.2, 13.14
3	Full	Industrial Site, Chicago, IL	--	--	Trench, basic oxygen furnace slag	June 2002 - present	13.19
4	Pilot	Industrial Site, Northwestern Ontario, Canada	0.4 mg/L	0.02 mg/L	Trench, mixture of ZVI, surfactant modified zeolite, and ion exchange resin	--	13.19
5	Pilot	Bodo Canyon Disposal Cell Mill Tailings Site, Durango, CO	--	--	ZVI	--	13.12
6	Bench	Former Uranium Ore Processing Site, Tuba City, AZ	0.52	0.010	ZVI	--	13.3
7	Bench	Monticello Mill Tailings, Monticello, UT	0.024	0.001-0.008	ZVI	--	13.3
8	Bench	Asarco East Helena Plant, East Helena, MT	11	Not available	ZVI	--	13.15
9	Bench	--	1-3 mg/L	<0.02 mg/L	--	--	13.16
10	Bench	–	4 mg/L	<0.003 mg/L	Basic oxygen furnace slag	–	13.18

ZVI = Zero valent iron
mg/L = Milligrams per liter
-- = Not available

IIC
ARSENIC TREATMENT TECHNOLOGIES APPLICABLE TO SOIL, WASTE, AND WATER

14.0 ELECTROKINETIC TREATMENT OF ARSENIC

Summary

Electrokinetic treatment is an emerging remediation technology designed to remove heavy metal contaminants from soil and groundwater. The technology is most applicable to soil with small particle sizes, such as clay. However, its effectiveness may be limited by a variety of contaminants and soil and water characteristics. Information sources researched for this report identified a limited number of applications of the technology to arsenic.

Technology Description: Electrokinetic remediation is based on the theory that a low-density current will mobilize contaminants in the form of charged species. A current passed between electrodes is intended to cause water, ions, and particulates to move through the soil, waste, and water (Ref. 14.8). Contaminants arriving at the electrodes can be removed by means of electroplating or electrodeposition, precipitation or coprecipitation, adsorption, complexing with ion exchange resins, or by pumping of water (or other fluid) near the electrode (Ref. 14.10).

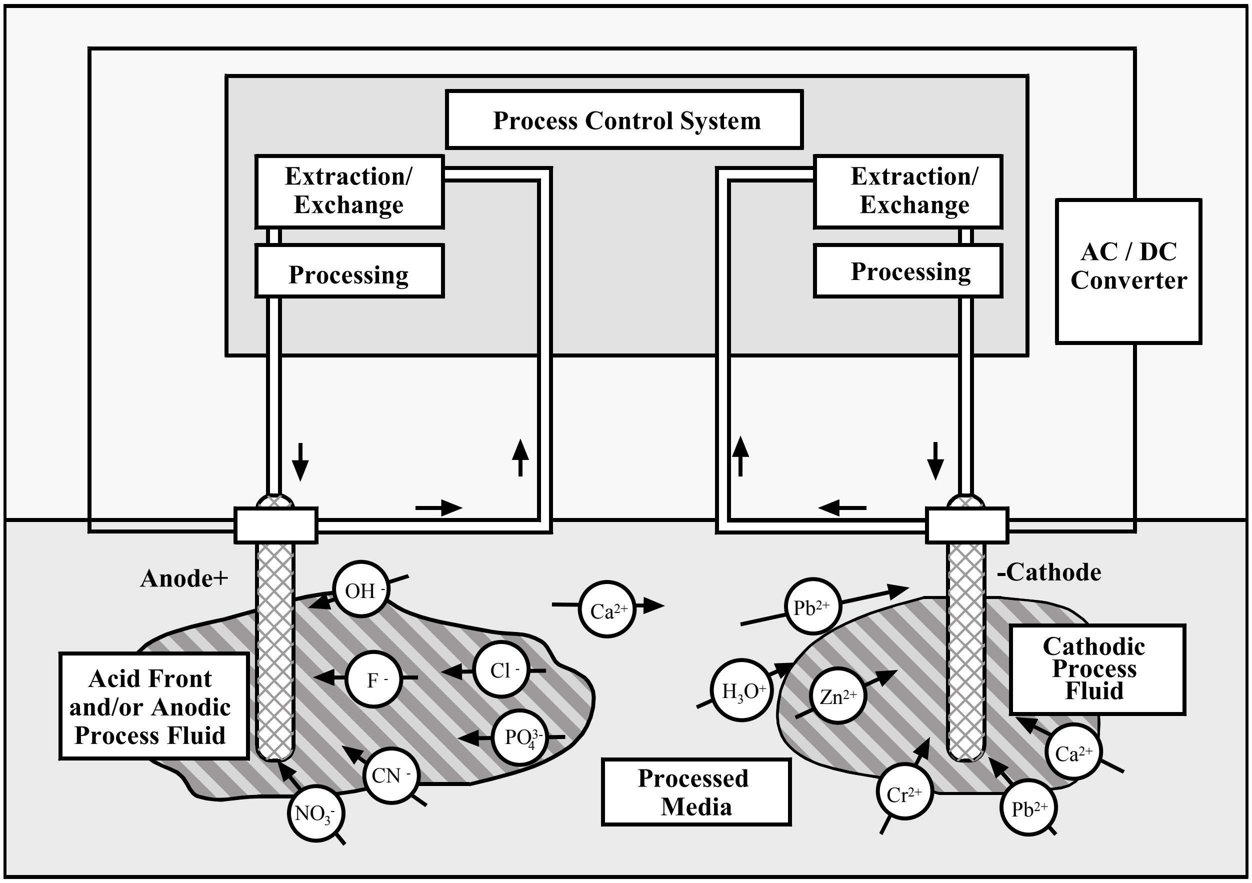
Media Treated:
- Soil
- Groundwater
- Industrial wastes

Chemicals Used in Electrokinetic Process to Treat Arsenic:
- Sulfuric Acid
- Phosphoric Acid
- Oxalic Acid

Technology Description and Principles

In situ electrokinetic treatment of arsenic uses the natural conductivity of the soil (created by pore water and dissolved salts) to affect movement of water, ions, and particulates through the soil (Ref. 14.8). Water and/or chemical solutions can also be added to enhance the recovery of metals by electrokinetics. Positively-

Model of an Electrokinetic Treatment System



charged metal or metalloid cations, such as As (V) and As (III) migrate to the negatively-charged electrode (cathode), while metal or metalloid anions migrate to the positively charged electrode (anode) (Ref. 14.9). Extraction may occur at the electrodes or in an external fluid cycling/extraction system (Ref. 14.11). Alternately, the metals can be stabilized in situ by injecting stabilizing agents that react with and immobilize the contaminants (Ref. 14.12). Arsenic has been removed from soils treated by electrokinetics using an external fluid cycling/extraction system (Ref. 14.2, 14.18).

This technology can also be applied ex situ to groundwater by passing the water between electrodes. The current causes arsenic to migrate toward the electrodes, and also alters the pH and oxidation-reduction potential of the water, causing arsenic to precipitate/coprecipitate. The solids are then removed from the water using clarification and filtration (Ref. 14.21).

Media and Contaminants Treated

Electrokinetic treatment is an in situ treatment process that has had limited use to treat soil, groundwater, and industrial wastes containing arsenic. It has also been used to treat other heavy metals such as zinc, cadmium, mercury, chromium, and copper (Ref. 14.1, 14.4, 14.20).

Electrokinetic treatment may be capable of removing contaminants from both saturated and unsaturated soil zones, and may be able to perform without the addition of chemical or biological agents to the site. This technology also may be applicable to low-permeability soils, such as clay (Ref. 14.1, 14.4, 14.9).

Type, Number, and Scale of Identified Projects Treating Soil, Waste, and Water Containing Arsenic

The sources identified for this report contained information on one full-scale, three pilot-scale, and three bench-scale applications of electrokinetic remediation to arsenic. Figure 14.1 shows the number of applications identified at each scale.

Summary of Performance Data

Table 14.1 provides a performance summary of electrokinetic treatment of arsenic. One full-scale application reduced arsenic concentrations in soil from greater than 250 mg/kg to less than 30 mg/kg. One ex situ pilot-scale application reduced arsenic in groundwater from 0.6 mg/L to 0.013 mg/L. The case study at the end of this section further discusses this project, and information in Table 14.1, Project 3 summarizes the available information about it.

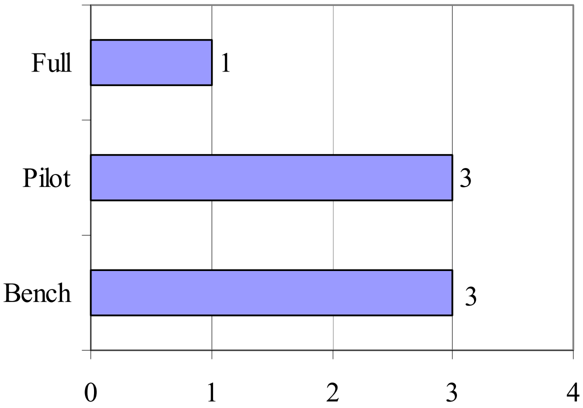
Factors Affecting Electrokinetic Treatment Performance

- **Contaminant properties** - The applicability of electrokinetics to soil and water containing arsenic depends on the solubility of the particular arsenic species. Electrokinetic treatment is applicable to acid-soluble polar compounds, but not to insoluble metals (Ref. 14.6).
- **Salinity and cation exchange capacity** - The technology is most efficient when these parameters are low (Ref. 14.14). Chemical reduction of chloride ions at the anode by the electrokinetic process may also produce chlorine gas (Ref. 14.6).
- **Soil moisture** - Electrokinetic treatment requires adequate soil moisture; therefore addition of a conducting pore fluid may be required (Ref. 14.7). Electrokinetic treatment is most applicable to saturated soils (Ref. 14.9). However, adding fluid to allow treatment of soils without sufficient moisture may flush contaminants out of the targeted treatment area.
- **Polarity and magnitude of the ionic charge** - These factors affect the direction and rate of contaminant movement (Ref. 14.11).
- **Soil type** - Electrokinetic treatment is most applicable to homogenous soils (Ref. 14.9). Fine-grained soils are more amenable to electrokinetic treatment due to their large surface area, which provides numerous sites for reactions necessary for electrokinetic processes (Ref. 14.13).
- **pH** - The pH can affect process electrochemistry and cause precipitation of contaminants or other species, reducing soil permeability and inhibiting recovery. The deposition of precipitation solids may be prevented by flushing the cathode with water or a dilute acid (Ref. 14.14).

Applicability, Advantages, and Potential Limitations

Electrokinetics is an emerging technology with relatively few applications for arsenic treatment. It is an in situ treatment technology, and therefore does not require excavation of contaminated soil or pumping of contaminated groundwater. Its effectiveness may be limited by a variety of soil and contaminant characteristics, as discussed in the box opposite. In addition, its treatment depth is limited by the depth to which the electrodes can be placed.

Figure 14.1
Scale of Electrokinetic Projects for Arsenic Treatment



Case Study: The Overpelt Project

A pilot-scale test of electrokinetic remediation of arsenic in groundwater was conducted in Belgium in 1997. This ex situ application involved pumping groundwater contaminated with zinc, arsenic, and cadmium and treating it in an electrokinetic remediation system with a capacity of 6,600 gpm. The treatment system precipitated the contaminants, and the precipitated solids were removed using clarification and filtration. The electrokinetic treatment system did not use additives or chemicals. The treatment reduced arsenic concentrations in groundwater from 0.6 mg/L to 0.013 mg/L. The reported costs of the treatment were $0.004 per gallon for total cost, and $0.002 per gallon for O&M. (Ref. 14.21) (see Project 3, Table 14.1).

Summary of Cost Data

Estimated costs of in situ electrokinetic treatment of soils containing arsenic range from $50 - $270 per cy (Ref. 14.2, 14.4, cost year not provided). The reported costs for one pilot-scale, ex situ treatment of groundwater of the treatment were $0.004 per gallon for total cost, and $0.002 per gallon for O&M. (Ref. 14.21) (see Project 3, Table 14.1).

Factors Affecting Electrokinetic Treatment Costs

- **Contaminant extraction system -** Some electrokinetic systems remove the contaminant from the subsurface using an extraction fluid. In such systems, the extraction fluid may require further treatment, which can increase the cost (Ref. 14.4).
- **Factors affecting electrokinetic treatment performance** - Items in the "Factors Affecting Electrokinetic Treatment Performance" box will also affect costs.

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Table 14.1
Electrokinetic Treatment Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media, Volume	Scale	Site Name and Location	Initial Arsenic Concentration	Final Arsenic Concentration or Treatment Results	Electrokinetic Process Description	Source
1	Wood Preserving	Soil, 325 cubic yards	Full	Pederok Plant Kwint, Loppersum, Netherlands	> 250 mg/kg	< 30 mg/kg	Contaminant removed by recirculation of electrolyte through casing around electrodes	14.2, 14.18
2	Herbicide application	Soil, 690 cubic yards	Pilot	--	450 mg/kg	--	--	14.12, 14.15, 14.16, 14.17
3	Metals refining and smelting	Groundwater	Pilot	Belgium	0.6 mg/L	0.013 mg/L	Bipolar electrolysis, without use of additional chemicals. Ex situ, pump and treat application	14.21
4	Herbicide application	Soil & Groundwater	Pilot	Florida	ND - 1,400 mg/kg <0.005 - 0.7 mg/L	--	Bipolar electrolysis, without use of additional chemicals	14.24
5	Cattle vat (pesticide)	Soil	Bench	Blackwater River State Forest, FL	113 mg/kg	4.7% of arsenic migrated to anode, 1.6% to cathode	Addition of sulfuric acid to enhance electrokinetic process	14.4
6	Cattle vat (pesticide)	Soil	Bench	Blackwater River State Forest, FL	113 mg/kg	25% of arsenic migrated to anode, none to cathode	Addition of phosphoric acid to enhance electrokinetic process	14.4
7	Wood Preserving	Sawdust from CCA-treated pole	Bench	Leiria, Portugal	811- 871 mg/kg	27-99% removal efficiency	Electrodialytic removal, enhanced by addition of oxalic acid	14.22

-- = Not available
CCA = Chromated copper arsenate
mg/L = Milligrams per liter
mg/kg = Milligrams per kilogram

15.0 PHYTOREMEDIATION TREATMENT OF ARSENIC

Summary

Phytoremediation is an emerging technology. The data sources used for this report contained information on only one applications of phytoremediation to treat arsenic at full scale and two at pilot scale. Experimental research into identifying appropriate plant species for phytoremediation is ongoing. It is generally applicable only to shallow soil or relatively shallow groundwater that can be reached by plant roots. In addition, the phytoremediating plants may accumulate high levels of arsenic during the phytoremediation process, and may require additional treatment prior to disposal.

Technology Description: Phytoremediation is designed to use plants to degrade, extract, contain, or immobilize contaminants in soil, sediment, or groundwater (Ref. 15.6). Typically, trees with deep roots are applied to groundwater and other plants are used for shallow soil contamination.

Media Treated:

- Soil
- Groundwater

Types of Plants Used in Phytoremediation to Treat Arsenic:

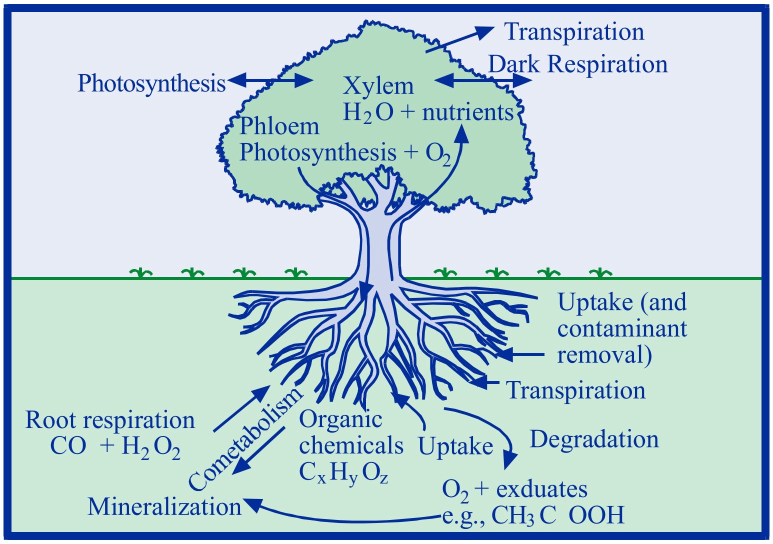
- Poplar
- Cottonwood
- Sunflower
- Indian mustard
- Corn

Technology Description and Principles

Phytoremediation is an emerging technology generally applicable only to shallow contamination that can be reached by plant roots. Phytoremediation applies to all biological, chemical, and physical processes that are influenced by plants and the rhizosphere, and that aid in cleanup of the contaminated substances. Phytoremediation may be applied in situ or ex situ, to soils, sludges, sediments, other solids, or groundwater (Ref. 15.1, 15.4, 15.5, 15.7). The mechanisms of phytoremediation include phytoextraction (also known as phytoaccumulation, the uptake of contaminants by plant roots and the translocation/accumulation of contaminants into plant shoots and leaves), enhanced rhizosphere biodegradation (takes place in soil or groundwater immediately surrounding plant roots), phytodegradation (metabolism of contaminants within plant tissues), and phytostabilization (production of chemical compounds by plants to immobilize contaminants at the interface of roots and soil). The data sources used for this report identified phytoremediation applications for arsenic using phytoextraction and phytostabilization.

The selection of the phytoremediating species depends upon the species ability to treat the contaminants and the depth of contamination. Plants with shallow roots (for example, grasses, corn) are appropriate only for contamination near the surface, typically in shallow soil. Plants with deeper roots, (for example, trees) may be capable of remediating deeper contaminants in soil or groundwater plumes.

Examples of vegetation used in phytoremediation include sunflower, Indian mustard, corn, and grasses (such as ryegrass and prairie grasses) (Ref. 15.1). Some plant species, known as hyperaccumulators, absorb and concentrate contaminants within the plant at levels greater than the concentration in the surrounding soil or groundwater. The ratio of contaminant concentration in the plant to that in the surrounding soil or groundwater is known as the bioconcentration factor. A hyperaccumulating fern (*Pteris vittata*) has been used in the remediation of arsenic-contaminated soil, waste, and water. The fern can tolerate as much as 1,500 parts per million (ppm) of arsenic in soil, and can have a bioconcentration factor up to 265. The arsenic concentration in the plant can be as high as 2 percent (dry weight) (Ref. 15.3, 15.6).



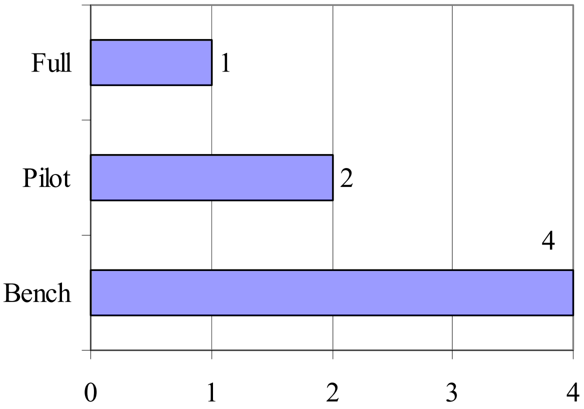
Media and Contaminants Treated

Phytoremediation has been applied to contaminants from soil, surface water, groundwater, leachate, and municipal and industrial wastewater (Ref. 15.4). In addition to arsenic, examples of pollutants it can potentially address include petroleum hydrocarbons such as benzene, toluene, ethylbenzene, and xylenes (BTEX), polycyclic aromatic hydrocarbons (PAHs), pentachlorophenol, polychlorinated biphenyls (PCBs), chlorinated aliphatics (trichloroethylene, tetrachloroethylene, and 1,1,2,2-tetrachloroethane), ammunition wastes (2,4,6-trinitrotoluene or TNT, and RDX), metals (lead, cadmium, zinc, arsenic, chromium, selenium), pesticide wastes and runoff (atrazine, cyanazine, alachlor), radionuclides (cesium-137, strontium-90, and uranium), and nutrient wastes (ammonia, phosphate, and nitrate) (Ref. 15.7).

Type, Number, and Scale of Identified Projects Treating Soil, Waste, and Water Containing Arsenic

The data sources used for this report contained information on phytoremediation of arsenic contaminated soil at full scale at one Superfund site (Ref. 15.7). Two pilot-scale applications and four bench-scale tests were also identified (Ref. 15.2, 15.3, 15.7-11). Figure 15.1 shows the number of identified applications at each scale.

Figure 15.1
Scale of Identified Phytoremediation Projects for Arsenic Treatment



Summary of Performance Data

Table 15.1 provides a performance summary of the identified phytoremediation projects. Data on the effect of phytoremediation on the leachability of arsenic from soil were not identified. Where available, Table 15.1 provides total arsenic concentrations prior to and following phytoremediation treatment. However, no projects with arsenic concentrations in the treated soil, waste, and water both prior to and after treatment were identified. Bioconcentration factors were available for one pilot- and two bench-scale studies, and ranged from 8 to 320.

Applicability, Advantages, and Potential Limitations

Phytoremediation is conducted in situ and therefore does not require soil excavation. In addition, revegetation for the purpose of phytoremediation also can enhance restoration of an ecosystem (Ref. 15.5). This technology is best applied at sites with shallow contamination. If phytostabilization is used, the vegetation and soil may require long-term maintenance to prevent re-release of the contaminants. Plant uptake and translocation of metals to the aboveground portions of the plant may introduce them into the food chain if the plants are consumed (Ref. 15.5). Products could bioaccumulate in animals that ingest the plants (Ref. 15.4). In addition, the toxicity and bioavailability of contaminants absorbed by plants and phytodegradation products is not always known.

Concentrations of contaminants in hyperaccumulating plants are limited to a maximum of about 3% of the

Factors Affecting Phytoremediation Performance

- **Contaminant depth** - The treatment depth is limited to the depth of the plant root system (Ref. 15.5).
- **Contaminant concentration** - Sites with low to medium level contamination within the root zone are the best candidates for phytoremediation processes (Ref. 15.4, 15.5). High contaminant concentrations may be toxic to the remediating flora.
- **Climatic or seasonal conditions** - Climatic conditions may interfere or inhibit plant growth, slow remediation efforts, or increase the length of the treatment period (Ref. 15.4).
- **Contaminant form** - In phytoaccumulation processes, contaminants are removed from the aqueous or dissolved phase. Phytoaccumulation is generally not effective on contaminants that are insoluble or strongly bound to soil particles.
- **Agricultural factors** - Factors that affect plant growth and health, such as the presence of weeds and pests, and ensuring that plants receive sufficient water and nutrients will affect phytoremediation processes.

plant weight on a dry weight basis. Based on this limitation, for fast-growing plants, the maximum annual contaminant removal is about 400 kg/hectare/year. However, many hyperaccumulating species do not achieve contaminant concentrations of 3%, and are slow growing. (Ref. 15.12)

The case study at the end of this section further discusses an application of phytoremediation to the treatment to arsenic-contaminated soil. Information for this project is summarized in Table 15.1, Project 1.

Summary of Cost Data

Cost data specific to phytoremediation of arsenic were not identified. The estimated 30-year costs (1998 dollars) for remediating a 12-acre lead site were $200,000 for phytoextraction (Ref. 15.15). Costs were estimated to be $60,000 to $100,000 using phytoextraction for remediation of one acre of 20-inch-thick sandy loam (Ref. 15.14). The cost of removing radionuclides from water with sun-flowers has been estimated to be $2 to $6 per thousand gallons of water (Ref. 15.16). Phytostabilization system costs have been estimated at $200 to $10,000 per hectare, equivalent to $0.02 to $1.00 per cubic meter of soil, assuming a 1-meter root depth (Ref. 15.17).

Factors Affecting Phytoremediation Costs

- **Number of crops grown** - A greater number of crops may decrease the time taken for contaminants to be remediated to specified goals, thereby decreasing costs (Ref. 15.2). However, the number of crops grown will be limited by the length of the growing season, the time needed for crops to reach maturity, the potential for multiple crops to deplete the soil of nutrients, climatic conditions, and other factors.
- **Factors affecting phytoremediation performance** - Items in the "Factors Affecting Phytoremediation Performance" box will also affect costs.

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Table 15.1
Arsenic Phytoremediation Treatment Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media	Scale	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Bioconcentration Factor	Remediating Flora	Source
1	Mining	Deep soil	Full	Whitewood Creek Superfund Site, SD	1,000 mg/kg	Performance data not available due to death of remediating flora.		Hybrid poplar (specific variety not identified)	15.7
2	Munitions Manufacturing/Storage	Surface soil	Pilot	Twin Cities Army Ammunition Plant, Site C and Site 129-3, Minneapolis-St. Paul, MN	--	--	--	Corn (specific variety not identified), white mustard (*Sinapis alba*)	15.2
3	--	Groundwater (ex situ)	Pilot	Montezuma Well, AZ	100 mg/L (Well water)	4.59 mg/kg (shoots) 8.87 mg/kg (roots)	8	*Potomogeton illinoiensis*	15.9
4	--	Surface soil	Bench	--	650	--	20 - 75 (leaves)	Moss verbena (*V. tenuisecta*)	15.10
					--	--	60 - 320 (shoots)	Saw palmetto (*S. repens*)	
5	Wood Preserving	Surface soil	Bench	FL	400	--	265	Brake fern (*Pteris vittata*)	15.3
6	--	Soil	Bench	East Palo Alto, CA	--	--	--	Tamarisk (*Tamarix ramosissima*), *Eucalyptus*	15.8
7	--	Soil	Bench	--	--	34 mg/kg (shoots) 177 mg/kg (roots)	--	Water lettuce (*Pistia stratiotes*)	15.11

16.0 BIOLOGICAL TREATMENT FOR ARSENIC

Summary

Biological treatment designed to remove arsenic from soil, waste, and water is an emerging remediation technology. The information sources used for this report identified a limited number of projects treating arsenic biologically. Arsenic was reduced to below 0.050 mg/L in one pilot-scale application. This technology promotes precipitation/coprecipitation of arsenic in water or leaching of arsenic in soil and waste. The leachate from bioleaching requires additional treatment for arsenic prior to disposal.

Technology Description and Principles

Although biological treatments have usually been applied to the degradation of organic contaminants, some innovative techniques have applied biological remediation to the treatment of arsenic. This technology involves biological activity that promotes precipitation/coprecipitation of arsenic from water and leaching of arsenic in soil and waste.

Biological precipitation/coprecipitation processesfor water create ambient conditions intended to cause arsenic to precipitate/coprecipitate or act directly on arsenic species to transform them into species that are more amenable to precipitation/coprecipitation. The microbes may be suspended in the water or attached to a submerged solid substrate. Iron or hydrogen sulfide may also be added (Ref. 16.2, 16.3, 16.4, 16.4).

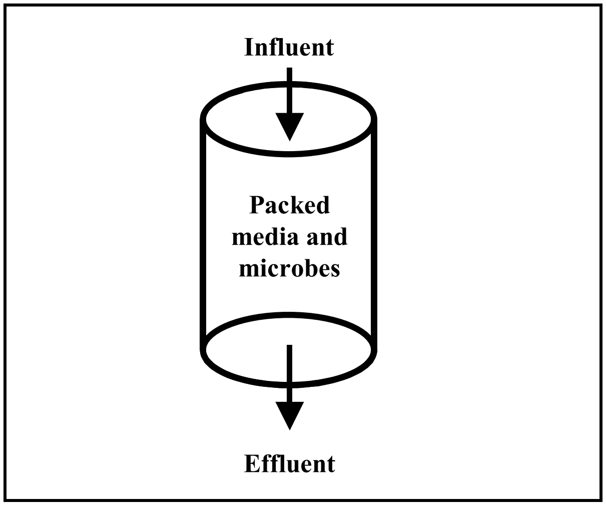
Technology Description: Biological treatment of arsenic is based on the theory that microorganisms that act directly on arsenic species or create ambient conditions that cause arsenic to precipitate/ coprecipitate from water and leach from soil and waste.

Media Treated:
- Soil
- Waste
- Water

Microbes Used:
- Sulfate-reducing bacteria
- Arsenic-reducing bacteria

One water treatment process depends upon biological activity to produce and deposit iron oxides within a filter media, which provides a large surface area over which the arsenic can contact the iron oxides. The aqueous solution is passed through the filter, where arsenic is removed from solution through coprecipitation or adsorption to the iron oxides. An arsenic sludge is continuously produced (Ref. 16.3).

Model of a Biological Treatment System



Another process uses anaerobic sulfate-reducing bacteria and other direct arsenic-reducing bacteria to precipitate arsenic from solution as insoluble arsenic-sulfide complexes (Ref. 16.2). The water containing arsenic is typically pumped through a packed-bed column reactor, where precipitates accumulate until the column becomes saturated (Ref. 16.5). The arsenic is then stripped and the column is biologically regenerated (Ref. 16.2). Hydrogen sulfide has also been used in suspended reactors to biologically precipitate arsenic out of solution (Ref. 16.2, 16.4). These reactors require conventional solid/liquid separation techniques for removing precipitates.

Removal of arsenic from soil biologically via "accelerated bioleaching" has also been tested on a bench scale. The microbes in this system produce nitric, sulfuric, and organic acids which are intended to mobilize and remove arsenic from ores and sediments (Ref. 16.4). This biological activity also produces surfactants, which can enhance metal leaching (Ref. 16.4).

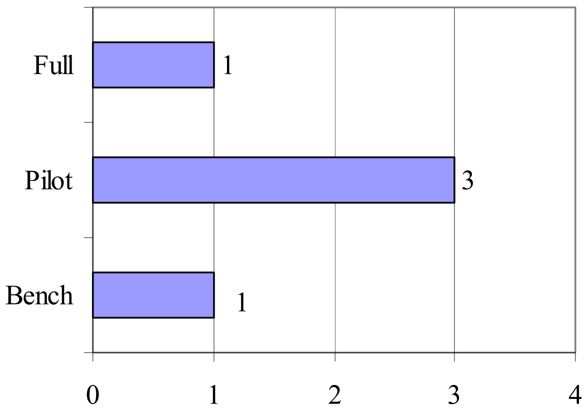
Media and Contaminants Treated

Biological treatment typically uses microorganisms to degrade organic contaminants in soil, sludge, solids groundwater, and wastewaters. Biological treatment has also been used to treat arsenic in water via precipitation/coprecipitation and in soil through leaching (Ref. 16.1, 16.3).

Type, Number, and Scale of Identified Projects Treating Soil, Waste, and Water Containing Arsenic

The data sources used for this report contained information on biological treatment of arsenic at full scale at one facility, at pilot scale at three facilities, and at bench scale for one project. Figure 16.1 shows the number of identified applications at each scale. An enhanced bioleaching system for treating soil containing arsenic has been tested at bench scale (Ref. 16.4) (Table 16.1, Project 5). In addition, a biological treatment system using hydrogen sulfide has been used in a bioslurry reactor to treat arsenic at bench and pilot scales (Ref. 16.4) (Table 16.1, Project 4).

Figure 16.1
Scale of Identified Biological Treatment Projects for Arsenic



Summary of Performance Data

Table 16.1 lists the available performance data for three projects using biological treatment for arsenic contamination in water. Of the two projects that treated wastewaters containing arsenic, only one had both influent and effluent arsenic concentration data (Project 1). The arsenic concentration was not reduced to below 0.05 mg/L in this project.

One project (Project 3) treated groundwater spiked with sodium arsenite. The groundwater had naturally-occurring iron at 8 - 12 mg/L (Ref. 16.3). The initial arsenic concentration ranged from 0.075 to 0.400 mg/L, and was reduced by treatment to less than 0.050 mg/L. No data were available for the one soil bioleaching project.

Factors Affecting Biological Treatment Performance

- **pH** - pH levels can inhibit microbial growth. For example, sulfate-reducing bacteria perform optimally in a pH range of 6.5 to 8.0 (Ref. 16.5).
- **Contaminant concentration** - High arsenic concentrations may be toxic to microorganisms used in biological treatment (Ref. 16.1).
- **Available nutrients** - An adequate nutrient supply should be available to the microbes to enhance and stimulate growth. If the initial solution is nutrient deficient, nutrient addition may be necessary.
- **Temperature** - Lower temperatures decrease biodegradation rates. Heating may be required to maintain biological activity (Ref. 16.1).
- **Iron concentration** - For biologically-enhanced iron precipitation, iron must be present in the water to be treated. The optimal iron level depends primarily on the arsenic concentration. (Ref. 16.3).

The case study at the end of this section further discusses a pilot-scale application of biological treatment to arsenic-contaminated groundwater. Information for this project is summarized in Table 16.1, Project 3.

Applicability, Advantages, and Potential Limitations

A variety of arsenic-contaminated soil, waste, and water can be treated using biological processes. Biological treatment of arsenic may produce less sludge than conventional ferric arsenic precipitation (Ref. 16.2). A high concentration of arsenic could inhibit biological activity (Ref. 16.1, 16.2).

Factors Affecting Biological Treatment Costs

- **Pretreatment requirements** - Pretreatment may be required to encourage the growth of key microorganisms. Pretreatment can include pH adjustment and removal of contaminants that may inhibit microbial growth.
- **Nutrient addition** - If nutrient addition is required, costs may increase.
- **Factors affecting biological treatment performance** - Items in the “Factors Affecting Biological Treatment Performance” box will also affect costs.

Summary of Cost Data

The reported costs for biological treatment of arsenic-contaminated soil, waste, and water range from less than \$0.50 to \$2.00 per 1,000 gallons (Ref. 16.2, 16.4, cost year not provided).

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Case Study: Sodium Arsenite Spiked Groundwater, Forest Row, Sussex, United Kingdom

Groundwater with naturally-occurring iron between 8 and 12 mg/L was extracted in Forest Row, Sussex, England and spiked with sodium arsenite. The arsenic concentration before treatment ranged from 0.075 to 0.400 mg/L in the untreated water. The spiked groundwater was passed through a pilot biological filtration unit, 3 m high with a 15 cm diameter and filled to 1 m with silica sand. The arsenic concentration was reduced to <0.04 mg/L (Ref. 16.3) (see Project 3, Table 16.1).

Table 16.1
Biological Treatment Performance Data for Arsenic

Project Number	Industry or Site Type	Waste or Media	Scale	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Precipitate Arsenic Concentration	Biological Process	Source
1	--	Wastewater	Full	--	--	<0.05 mg/L	--	Reduction and precipitation from sulfate reducing bacteria and direct arsenic-reducing bacteria	16.2
2	--	Wastewater	Pilot	--	13 mg/L	<0.5 mg/L	--	Anaerobic sulfate-reducing bacteria with a two-stage reactor, arsenic precipitation and column system	16.1
3	--	Groundwater spiked with sodium arsenite	Pilot	--	0.075 - 0.400 mg/L	0.010 - 0.040 mg/L	--	Biological filtration where microbial activity produces iron oxides for coprecipitation or adsorption of arsenic	16.3
4	–	Groundwater	Pilot	–	–	–	--	Precipitation of arsenic sulfides using hydrogen sulfide in a bioreactor system	16.4
5	–	Ores and sediments	Bench	–	–	–	--	Enhanced bioleaching system using microbial-generated acids to accelerate anion and cation removal from ores and sediments	16.4

mg/L = Milligram per liter
-- = Not available