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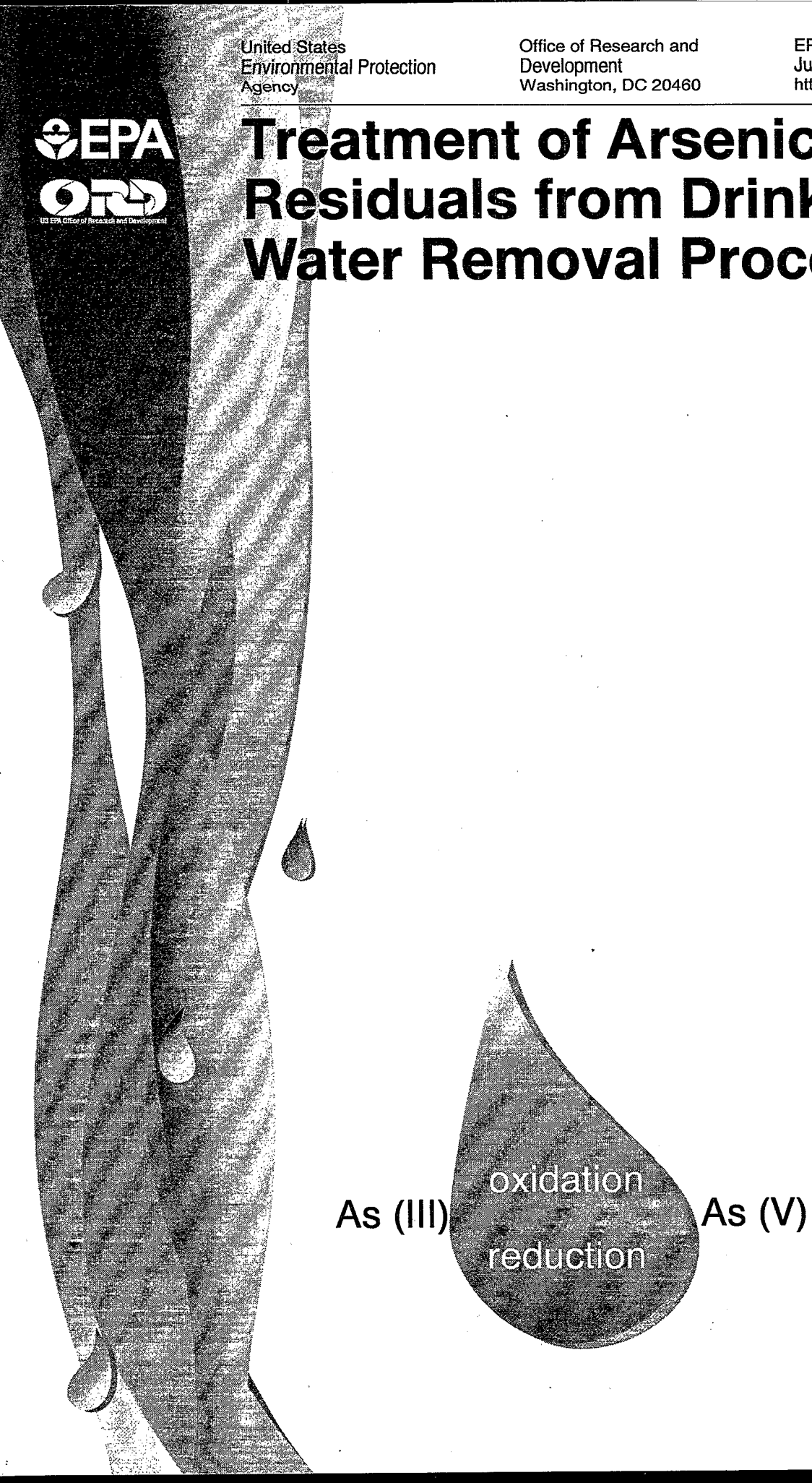
Treatment of Arsenic Residuals from Drinking Water Removal Processes



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Treatment of Arsenic Residuals from Drinking Water Removal Processes

by

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Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels. The goal of this research effort is to evaluate the effectiveness of various treatment processes for removing arsenic from residuals produced by arsenic removal drinking water treatment technologies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

The drinking water MCL was recently lowered from 0.05 mg/L to 0.01 mg/L. One concern was that a reduction in the TCLP arsenic limit in response to the drinking water MCL could be problematic with regard to disposal of solid residuals generated at arsenic removal facilities. This project focused on developing a short-list of arsenic removal options for residuals produced by ion exchange (Ion Ex), reverse osmosis (RO), nanofiltration (NF), activated alumina (AA), and iron removal processes. Both precipitation and adsorption processes were evaluated to assess their arsenic removal effectiveness.

In precipitation tests, ferric chloride outperformed alum for removal of arsenic from residuals by sedimentation, generally resulting in arsenic removals of 88 to 99 percent. Arsenic removal from the high alkalinity ion exchange samples was poorer. The required iron-to-arsenic molar ratio for best removal of arsenic in these screening tests varied widely from 4:1 to 191:1, depending on residuals type, and best arsenic removal using ferric chloride typically occurred between pH 5.0 and 6.2. Polymer addition typically did not significantly improve arsenic removal using either coagulant. Supernatant total arsenic levels of 0.08 mg/L or lower were attained with ferric chloride precipitation for membrane concentrates and residuals from iron removal facilities compared to an in-stream arsenic limit of 0.05 mg/L in place in some states. Settling alone with no coagulant also effectively removed arsenic from iron removal facility residuals. Even with ferric chloride dosages of 50 to 200 mg/L applied to ion exchange regenerants, supernatant arsenic levels after treatment were 1 to 18 mg/L. Required iron-to-arsenic molar ratios developed in precipitation work could be used by utilities as guidelines for establishing coagulant dose needs to meet in-stream standards, and to develop preliminary treatment costs.

Adsorption tests demonstrated the potential for different types of media and resins to remove arsenic from liquid residuals, but did not assess ultimate capacity. Overall, the iron-based granular ferric hydroxide media evaluated in testing outperformed the aluminum-based media and ion exchange resin for removal of arsenic. However, activated alumina and the iron-based media provided comparable arsenic removals of close to 100 percent with an empty bed contact time (EBCT) of 3-min for most of the membrane concentrates and the settled iron removal facility residuals. Removal of suspended solids was key to the success of adsorption for spent filter backwash water and clarifier flush residuals. Arsenic breakthrough occurred very rapidly for the ion exchange samples and for one RO concentrate, all of which had an alkalinity of more than 1,000 mg/L (as $CaCO_3$). This again suggests that alkalinity significantly interferes with adsorption of arsenic. Based on this work, use of adsorption media for treatment of arsenic-laden water plant residuals merits further exploration.

Of all of the residuals streams tested, Ion Ex regenerants were the most difficult to treat using precipitation or adsorption. Disposal of supernatant streams resulting from treatment of arsenic-laden residuals from ion exchange plants could pose a major challenge. TCLP arsenic levels in all residuals generated in this work and in full-scale solid media samples were far below the regulatory limit of 5 mg/L, and in fact were below 0.5 mg/L.

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Acronyms, Abbreviations, and Symbols

AA	Activated alumina
As	Arsenic
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
AWWSC	American Water Works Association Service Company
BV	Bed volumes
CA	California
CERCLA	Comprehensive Environmental Response Compensation Liability Act
CFR	Code of Federal Register
CWA	Clean Water Act
EBCT	Empty bed contact time
EE&T	Environmental Engineering & Technology, Inc.
EP	Extraction procedure
EPA	United States Environmental Protection Agency
Fe	Iron
$FeCl_3$	Ferric chloride
GFH	Granular ferric hydroxide
HMTA	Hazardous Materials Transportation Act
ID	Identification
Ion Ex	Ion exchange
MCL	Maximum contaminant level
Mn	Manganese
MSWLF	Municipal solid waste landfill
NF	Nanofiltration
NM	New Mexico
NOF	Natural occurrence factor
NPDES	National Pollutant Discharge Elimination System
NSF	National Science Foundation
QA/QC	Quality assurance/quality control
QA	Quality assurance
QAPP	Quality assurance project plan
RCRA	Resource Conservation and Recovery Act
RO	Reverse osmosis
SDWA	Safe Drinking Water Act
SFBW	Spent filter backwash water
SFBW/ACF	Spent filter backwash water/adsorption clarifier flush
TBLL	Technically based local limits
TCLP	Toxicity characteristic leaching procedure
TDS	Total dissolved solids
USDOT	United States Department of Transportation
WTP	Water treatment plant
WWTP	Wastewater treatment plant

1. Introduction

1.1 Background

On December 24, 1975, EPA issued the National Interim Primary Drinking Water Regulations. These regulations established a maximum contaminant level (MCL) for arsenic at 0.05 mg/L. Arsenic was designated as a priority for regulation under the Safe Drinking Water Act (SDWA) Amendments of 1986, and a decade later, under the SDWA Amendments of 1996, Congress required EPA to develop a revised arsenic regulation by January 2001. On June 22, 2000, the USEPA published in the Federal Register a notice of proposed rulemaking to lower the arsenic MCL to 0.005 mg/L, and on January 22, 2001, a final MCL of 0.01 mg/L was published.

With reduced drinking water limits, the arsenic-laden residuals may also become a problem. Arsenic concentrations in residuals will increase as more arsenic is removed from raw water during treatment. Enhanced coagulation is one treatment technique for increasing removal of arsenic from raw water that will increase the arsenic content and quantity of residuals. Higher concentrations of arsenic in residuals will be of particular concern if regulatory arsenic limits in residuals are lowered in response to the new drinking water limit. For example, the toxicity characteristic leaching procedure (TCLP) arsenic limit is currently set at 5.0 mg/L, or 100 times the drinking water MCL of 0.05 mg/L. A proportional reduction would mean that the TCLP limit would drop to 1.0 mg/L.

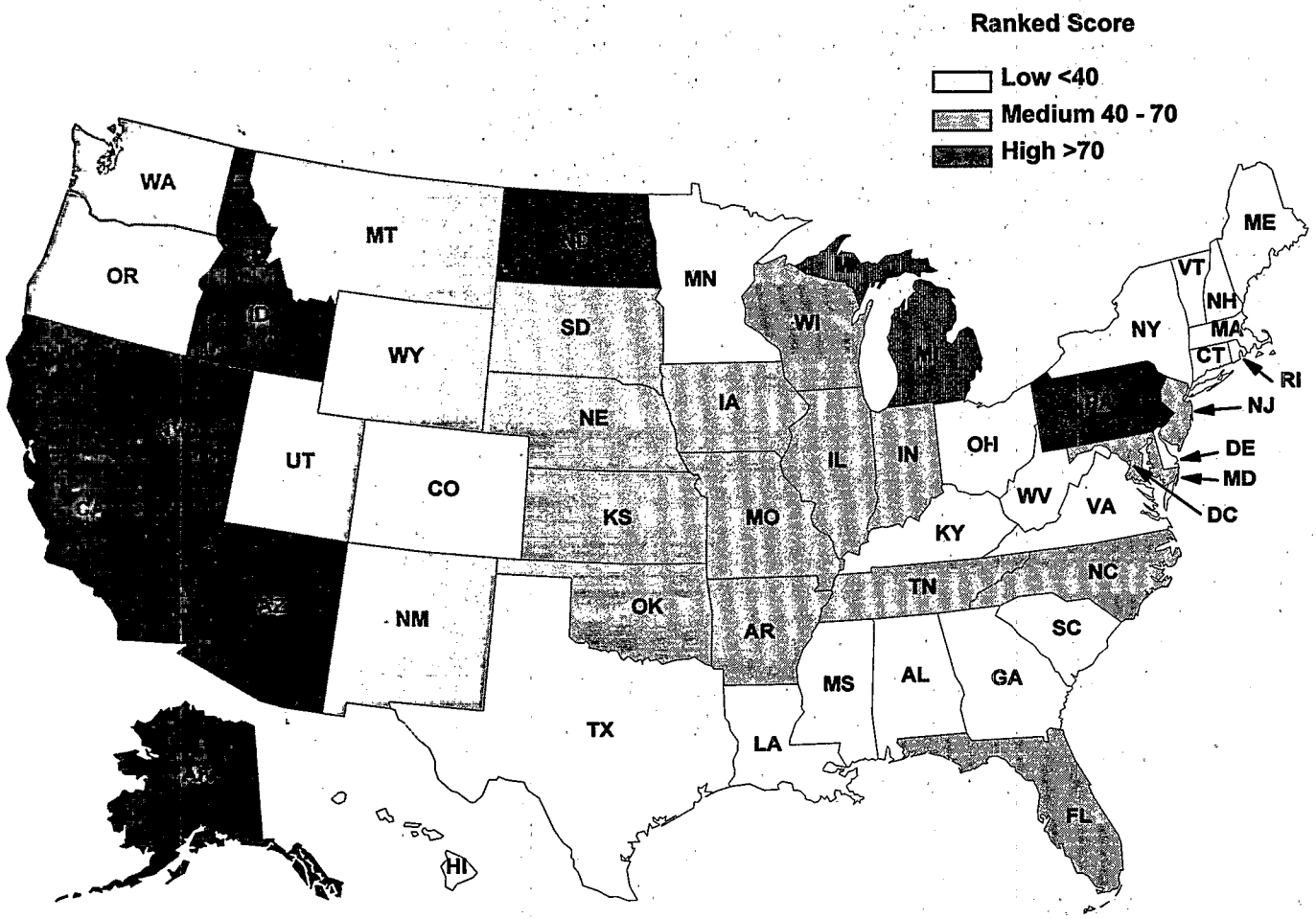
Arsenic in residuals can come from two major sources, the raw water and the treatment chemicals. Based on recent surveys by Frey and Edwards (1997), locations in the U.S. that are likely to have high raw water arsenic levels have been identified. Arsenic occurrence in groundwater systems is presented in Figure 1-1. The natural occurrence factor (NOF) is a descriptive variable used by the authors to differentiate arsenic occurrence patterns geographically. A ranking system was developed to assign qualitative NOF levels to individual states in that work. The American Water Works Service Company (AWWSC) conducted a study to evaluate the potential impact of contaminants including arsenic in treatment chemicals on sludge characteristics by analyzing treatment chemicals from several water treatment facilities (Dixon *et al.* 1988). Results showed the presence of 108 to 122 mg As/kg in a ferric chloride solution, and 214 to 270 mg As/kg in liquid alum.

The handling and disposal of arsenic-laden residuals may be a problem because various handling and disposal methods may release arsenic back to the environment. Because arsenic removal is sensitive to both the pH of precipitation and the oxidation state, any process that changes pH or results in a reducing environment may release arsenic from the solid phase. These processes, including chemical conditioning during dewatering, storage and lagooning, and ultimate disposal options such as landfilling, land application, discharge to sewer, and coagulant recycle, may all contribute arsenic back to the environment.

1.2 Literature Review

A thorough review of the literature and a search of AWWA's database, including the last ten years of American Water Works Association (AWWA) journals and conference proceedings, yielded relatively few published works that specifically address characteristics of residuals containing arsenic and removal of arsenic from those residuals. The search also included numerous AWWARF publications, three of which deal with residuals, and proceedings from the Inorganic Contaminants Workshop (February 2000) held in Albuquerque, New Mexico. Numerous publications dealing with treatment of drinking water to remove arsenic were found; however, limited information was available regarding characteristics of residuals produced by arsenic removal processes, or treatment of those residuals streams for removal of arsenic.

In one residuals characterization effort conducted by NSF, and partially sponsored by EPA, residuals quality data from an arsenic removal facility were discussed (Bartley *et al.* 1991). Cornwell *et al.* (1992) characterized water plant



Source: Frey and Edwards, 1997

Figure 1-1. Natural occurrence factors for arsenic in groundwater systems

residuals in terms of inorganic constituents such as arsenic and presented results of TCLP extractions. Those data, however, were not from plants designed to remove arsenic. Hathaway and Rubel (1987) and Clifford and Lin (1986) both reported results of Extraction Procedure (EP) toxicity tests performed on residuals containing arsenic. Three recent EPA publications (Wang *et al.*, 2000; Fields *et al.*, 2000; and Fields *et al.*, 2000) present TCLP results for residuals collected at arsenic removal treatment facilities, and four additional recent publications—Chen *et al.* (1999), Clifford *et al.* (1999), Clifford *et al.* (1998), and Chwirka (1999)—address levels of arsenic in residuals.

Bartley *et al.* (1991) characterized residuals produced at eight water treatment plants, including one arsenic removal plant, according to inorganic constituents, including arsenic. The 18-mgd arsenic-removal plant documented in that study includes an 8-mgd surface water train and a 10-mgd groundwater train that treats water from several wells, one of which is known to be contaminated with arsenic. Water from the contaminated well is treated with ferric sulfate and chlorine applied upstream of a contact tank, and water from the other wells is aerated and chlorinated. The aerated/chlorinated water is combined with the contact tank effluent and filtered. Finished water from the groundwater treatment train is combined with filtered water from the surface water treatment train.

Supernatant from the contact basin in the arsenic removal process is recycled to the head of the surface water train, and contact basin solids, spent filter backwash water, etc., are routed to a wastewater holding tank, lagoons, and a

temporary storage area. Arsenic levels in composite contact basin solids samples collected over a period of six months averaged 5,880 mg/kg. Arsenic levels in TCLP extracts averaged just 0.016 mg/L, rendering the sludge non-hazardous according to toxicity.

Hathaway and Rubel (1987) described a dried sludge generated through precipitation of aluminum hydroxide from a spent activated alumina regeneration stream that easily passed the Extraction Procedure (EP) toxicity test in a pilot study on removal of arsenic from drinking water at the Fallon, NV Naval Air Station using activated alumina and ion exchange. The EP toxicity test is essentially the precursor to the TCLP test. Under the EP toxicity test, a solid waste is adjusted to a pH of 5.0, modified if necessary to conform to particle size requirements, and placed in an extractor along with deionized water for a period of 24 hours. The extract from the waste is analyzed for a number of parameters, including arsenic. The toxicity criterion used to define a waste as hazardous under the Resource Conservation and Recovery Act (RCRA) was determined by the Extraction Procedure (EP) toxicity test prior to 1990, when that test was replaced by the TCLP test. A sludge in that study containing 1627 mg/kg of As yielded just 0.036 mg/L As in the extract. In another study, Clifford and Lin (1991) reported 0.6 mg/L As in a leachate produced by similar treatment of a spent alumina regenerant.

aluminum salts or lime contained 1.5 mg/L arsenic when subjected to the EP toxicity test. Reuse of spent regenerant was explored in the Albuquerque study, in which arsenic levels in the reused brine rose to 190 mg/L (AWWA 1999).

Wang *et al.* (2000) reported TCLP arsenic results for spent alumina ranging from <0.05 mg/L to 0.066 mg/L in a recently completed EPA research report. In another EPA research effort completed this year, Fields *et al.* (2000) reported TCLP arsenic levels of less than 0.05 mg/L at an iron removal facility. Fields *et al.* (2000) reported arsenic TCLP concentrations of 0.30 mg/L or lower for residuals collected at two coagulation/filtration plants and one lime softening plant in a third research effort sponsored by EPA. TCLP arsenic levels in more than 30 sludge samples collected from dewatered sludge lagoons at the two coagulation plants ranged from below the detection limit to 0.3 mg/L. In dewatered residuals collected from the softening plant, TCLP arsenic concentrations were all below the detection limit of 0.05 mg/L.

Chen *et al.* (1999) reported TCLP results for arsenic residuals collected at six different utilities. Data are summarized in Table 1-1. The authors noted that the As levels in the TCLP extract of all but one residuals sample were well below the existing limit of 5.0 mg/L as well as much lower limits that could result if the TCLP limit is reduced in proportion to the drinking water MCL. The

Table 1-1. Results of TCLP tests from six utilities

Sludge source	Treatment method	Total As (mg/kg dry solid)	TCLP concentration (mg/L)
Utility F	Lime softening	6.9	0.0039
	Coagulation	2.4	0.0009
Utility G	Lime softening	14.8	0.002
Utility J	Lime softening	24.6	0.028
Utility L	Alum coagulation	NA	0.0093
Utility C	Fe-Mn removal	369	0.0444
Utility O	Iron coagulation	338	1.56

Source: Chen *et al.* 1999.
NA - Not Analyzed

Three major laboratory and field studies addressing key issues surrounding arsenic removal by ion exchange have been conducted by Clifford and his colleagues at the following locations: Hanford, CA (Clifford and Lin 1986); McFarland, CA (Ghurye, Clifford, *et al.* 1999); and Albuquerque, NM (Clifford, Ghurye, *et al.* 1997). In the Hanford work, the extract from dried sludges generated by treating spent ion-exchange regenerant using ferric or exception was the iron coagulation sludge from Utility O. Further, a WET extraction performed on that sludge using citric acid increased the As level in the extract by ten-fold.

Clifford *et al.* (1998) addressed removal of arsenic from spent ion exchange brine containing 3,450 µg/L As using ferric hydroxide coagulation followed by filtration through a 0.22 µm filter. Ferric chloride dosages ranging from 1 to 50

moles Fe/mol As in the brine were evaluated in that work, and pH was varied from 5.5 to 8.5. At a pH of 5.5, a molar ratio of 20:1 was required to lower the As concentration by 99.5 percent to 20 µg/L, consistent with the removal goal. At pH 6.2, a molar ratio of 50:1 was required to attain similar results. Molar ratios of 20:1 and 50:1 are approximately equivalent to $FeCl_3$ dosages of 150 to 375 mg/L.

Table 1-2 provides a summary of example arsenic concentrations in water treatment residuals reported by Chwirka (1999). The residuals volumes and arsenic concentrations shown in the table for various types of residuals were calculated assuming a raw water arsenic content and arsenic removal for each treatment technology.

Calculated arsenic concentrations in residuals volumes generated in each process shown in Table 1-2 ranged from 0.098 mg/L for membrane technologies to approximately 10 mg/L for activated alumina and ion exchange. On a dry weight basis, theoretical arsenic concentrations ranged from 165 to more than 14,000 mg/kg. Actual arsenic concentrations would be site-specific. Based on the calculated arsenic levels, the author explored the feasibility of various disposal options.

1.3 Project Objectives

The primary objective of this project was to conduct laboratory evaluations to determine the effectiveness of various treatment options for removal of arsenic from residuals produced by arsenic removal treatment technologies. An assessment of disposal issues (e.g., hazardous, non-hazardous) associated with effective treatments was also a key part of the research effort. The approach followed to meet that objective included:

1. Collection of residuals streams and/or solid media samples from nine different water treatment plants
2. Treatment of liquid waste streams using precipitation and adsorption processes
3. Performance of TCLP arsenic analyses on solid media samples and semi-liquid residuals fractions generated in precipitation tests

Treatment performance was evaluated based on arsenic removal, and residual arsenic levels in precipitation test supernatant samples and adsorption column effluent streams.

Table1-2. Summary of example residuals characteristics

Treatment technology	Volume of residuals produced (gal/MG)	As concentration in residuals volume (mg/L)	Quantity of solids produced (lbs/MG)	As concentration in solids (mg/kg dry weight)
Conventional coagulation	4,300	9.25	180	1,850
Softening	9,600	4.2	2,000	165
Ion exchange	4,000	10	23.4	14,250
Activated alumina	4,200	9.52	23.4 (calculated)	14,250 (calculated)
Iron oxide coated sand	21,000	1.9	23.4 (calculated)	14,250 (calculated)
Nanofiltration/Reverse osmosis	664,000	0.098	NA	NA
Coagulation/Microfiltration	52,600	0.76	112.6	2,957

Source: Chwirka 1999.
NA - Not Applicable

2. Experimental Procedures

2.1 Introduction

Three different types of water treatment plant residuals were evaluated during the project: liquid, semi-liquid, and solid waste. Precipitation and adsorption removal techniques were evaluated for removal of arsenic from liquid and semi-liquid residuals collected at full-scale facilities and shipped to Environmental Engineering & Technology, Inc. (EE&T) in Newport News, VA for testing. Settled solids (semi-liquid residuals) generated from the precipitation tests were thickened to 6 to 8 percent and analyzed to determine the TCLP arsenic concentration. Only residuals from the iron removal facilities generated enough settled solids to perform TCLP analyses.

TCLP tests were conducted on solid media waste from a full-scale activated alumina plant and filter media collected at an iron-manganese removal facility. Ion exchange resin material used in this project was also evaluated with a TCLP analysis.

2.2 Treatment Plant Residuals

Residuals were collected from nine drinking water treatment plants. The water treatment plant residuals evaluated were generated by the following treatment processes:

- Ion exchange - 2
- Activated alumina adsorption - 1
- Iron-manganese removal - 2
- Nanofiltration - 2
- Reverse osmosis - 2

A total of nine (9) samples were evaluated. Eight different liquid residuals samples were collected at various locations across the U.S. (see Figure 2-1) and delivered to EE&T for testing, and one liquid (AA regenerant) residuals stream was generated at EE&T's process laboratory. A summary description of each liquid residuals stream is presented in Table 2-1 and a process schematic for each full-scale water treatment process used to generate these liquid residuals is shown in the following sections along with a brief description of each treatment process.

2.2.1 Ion Exchange

The ion exchange (Ion Ex) water treatment process is shown in Figure 2-2. Ion exchange resins are designed to selectively remove impurities from drinking water. A chloride-form strong-base anion-exchange resin is used to remove arsenate (As(V)). The resin must be regenerated periodically using a brine solution to remove impurities that accumulate on the ion exchange resin. Regeneration steps include backwashing the resin and brine regeneration followed by a final rinse to remove the brine water. All three regeneration waste streams are typically blended together for final disposal.

In testing conducted for this project, three different regenerant waste samples—backwash, brine, and rinse—were delivered to EE&T for testing in separate containers. For ion exchange (A), each stream was analyzed individually and the three waste streams were then blended together in equal portions (1:1:1) to form a composite ion exchange sample. The blend ratio was determined based on the sample volume that was supplied for testing. The composite sample was used for precipitation and adsorption testing.

Ion exchange (B) regenerant samples were also collected from a full-scale WTP during a media regeneration cycle. The regenerant wastes included backwash water, brine, and rinse water in separate containers. After analysis of each individual sample, the regenerant streams were blended into a single composite sample for testing. The blend was a 4:1:1 ratio of brine, backwash water, and rinse water, respectively. The blend ratio was determined based on the sample volume that was supplied for testing. The composite blend sample used for testing was also analyzed to characterize its quality.

2.2.2 Activated Alumina

A process schematic for a full-scale activated alumina water treatment system is also shown in Figure 2-2. The

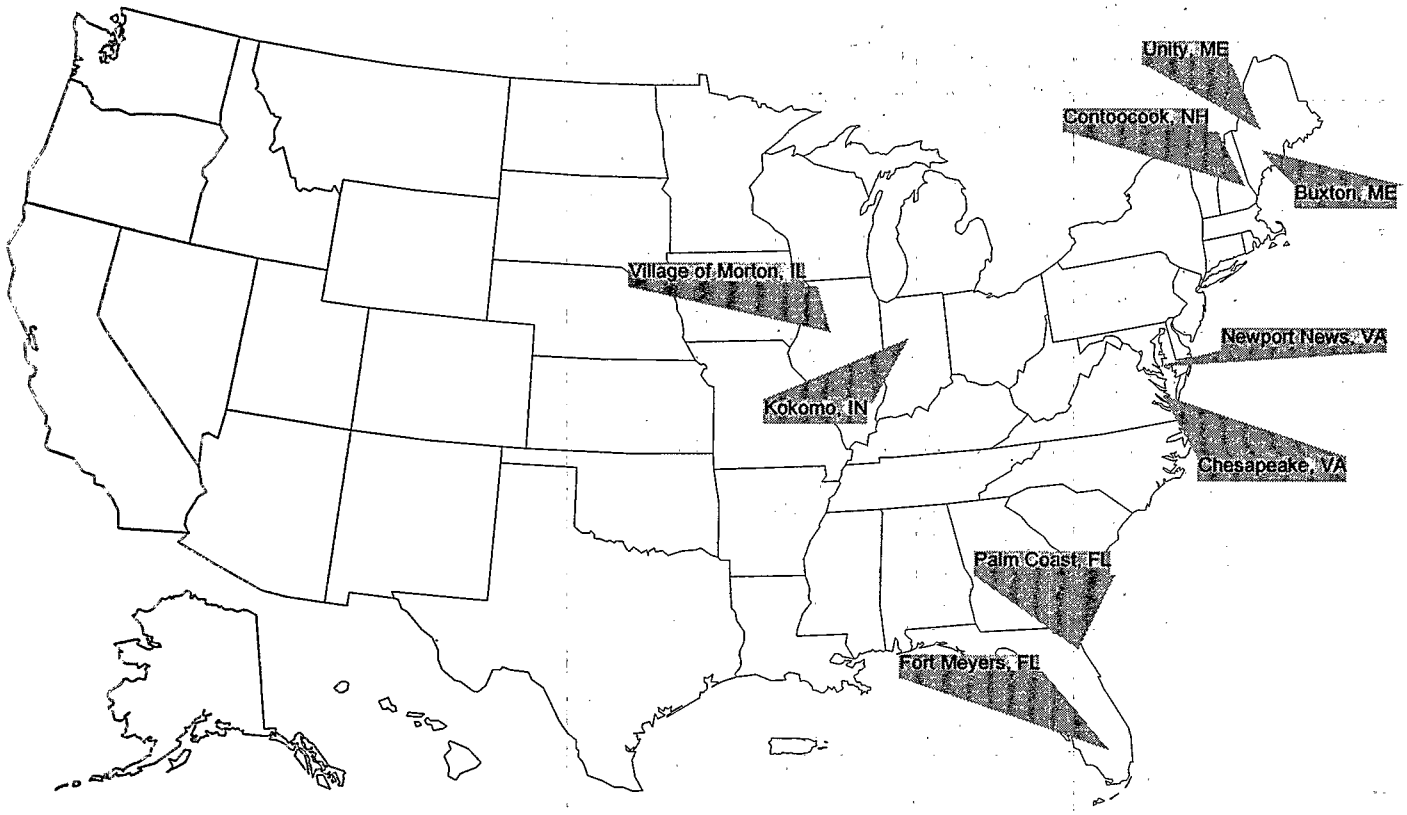


Figure 2-1. Location of full-scale treatment facilities providing residuals samples

Table 2-1. Liquid-residuals sample description

Sample ID	Process description	Liquid residuals sample description
AA regenerant*	Activated alumina adsorption	Sample of activated alumina regenerant
SFBW (A)	Fe-Mn removal system	Spent filter backwash water
SFBW/ACF (B)	Adsorption clarifier - Fe-Mn removal system	Composite sample of spent filter backwash water and adsorption clarifier flush
RO (A)	Reverse osmosis	Concentrate
RO (B)	Reverse osmosis	Concentrate
NF (A)	Nanofiltration	Concentrate
NF (B)	Nanofiltration	Concentrate
Ion Ex (A)	Ion exchange	Composite of ion exchange regenerant waste streams (brine, rinse, backwash)
Ion Ex (B)	Ion exchange	Composite of ion exchange regenerant waste streams (brine, rinse, backwash)

*Sample was generated at EE&T, all other samples were generated by full-scale WTPs.

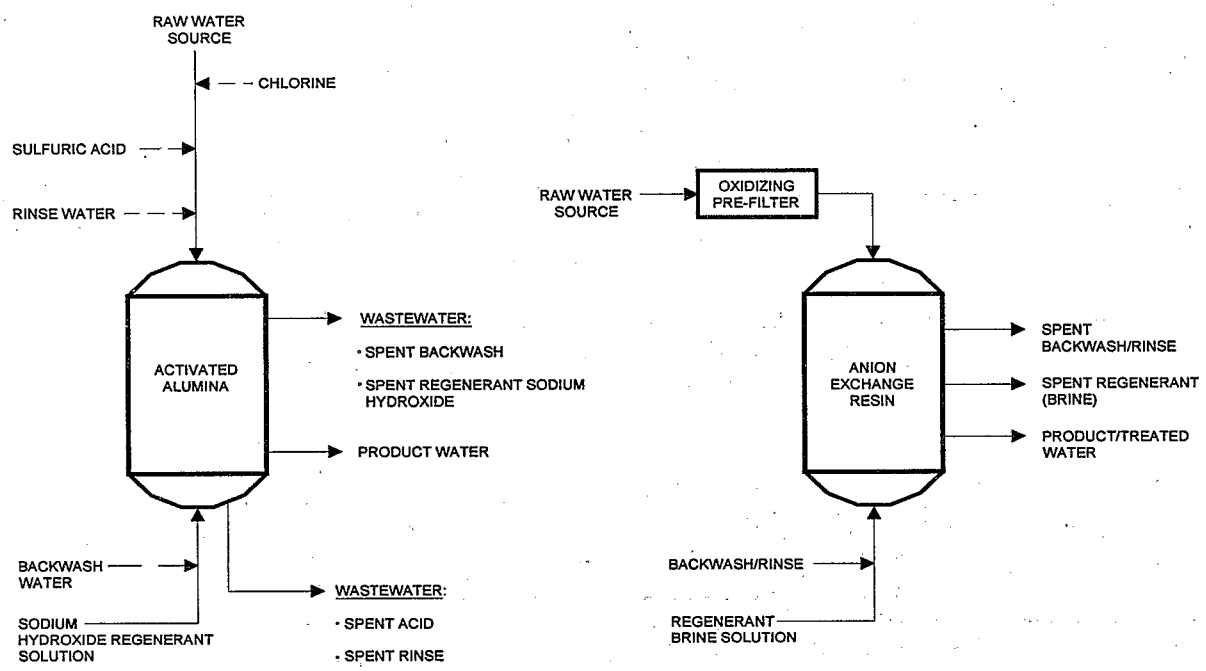


Figure 2-2. Schematic of ion exchange and activated alumina adsorption processes with regeneration

regenerant stream tested in this study was generated using the same procedure as for full-scale regeneration, but it was accomplished in the bench-scale contactor column. The procedure used for regeneration is described in the following paragraphs. Regeneration of activated alumina includes the following sequence—backwashing, caustic soda regeneration, and final rinse for removal of the caustic regenerant solution. The waste product from each regeneration step is typically combined into a common waste product for disposal.

The activated alumina (AA) regenerant used for testing was generated at EE&T's process laboratory using a spent AA media from a full-scale water treatment plant that removes arsenic from drinking water. The procedure used for the bench-scale regeneration of the AA media included the following steps:

1. Load AA media into the bench-scale test column
2. Backwash media with 2.5 bed volumes (BV) of tap water
3. Flush media with 3 BV of 4 percent caustic soda
4. Rinse media with 10 BV of tap water
5. Combine all three regenerant streams into a composite sample
6. Adjust pH of sample to 7.0 using sulfuric acid

This procedure was used to collect enough AA regenerant to perform precipitation testing.

2.2.3 *Membrane Filtration*

Membrane treatment processes generate two streams—a permeate (product water) and a concentrate (waste stream). The two membrane treatment system concentrate streams evaluated in this study were generated by reverse osmosis (RO) and nanofiltration (NF). Reverse osmosis and nanofiltration remove contaminants in the ionic and molecular size ranges from drinking water. Reverse osmosis is mainly used to remove salts from brackish water or sea water, and nanofiltration is used for softening fresh waters and for removal of disinfection byproduct precursors. Both processes, however, can be used for removal of trace inorganic contaminants. A process schematic for a typical membrane water treatment system is shown in Figure 2-3.

Concentrate streams collected from two full-scale RO plants and two full-scale nanofiltration drinking water treatment facilities were used in this study.

Membrane concentrate samples (both RO and NF) were spiked with arsenic before conducting laboratory removal tests because they contained such low concentrations of the metal. Arsenic in the NF concentrates was measured at 0.005 to 0.013 mg/L, while arsenic levels were below the detection limit in RO samples.

Actual pilot data generated by EE&T during the preliminary design phase at RO(A) were examined to determine the concentration factor (from feed water to concentrate stream) for arsenic and other constituents. That factor was 5. A more conservative factor of 10 was applied, consistent with concentration factors for different membrane system recoveries described by Mickley *et al.* (1993) and tabulated in Table 2-2. Based on a brackish RO system recovery of 85 percent (which was documented in EE&T pilot work), a concentration factor of 5 to 10 would apply. Assuming a source water arsenic concentration of 0.05 mg/L (the arsenic MCL established in 1975), and applying a concentration factor of 10, a spike dose of 0.5 mg/L was selected for both RO concentrate streams.

Table 2-2. Concentration factors for different membrane system recoveries

Recovery (percent)	Concentration factor
50	2.0
60	2.5
70	3.33
80	5.0
90	10.0

Source: Mickley *et al.* 1993.

Typical system recoveries associated with nanofiltration system range from 75 to 90 percent (Mickley *et al.* 1993). The same conservative concentration factor of 10 was therefore applied. Assuming a source water arsenic level of 0.05 mg/L, a spike dose of 0.5 mg/L was used.

Brandhuber and Amy (2000) reported comparable rejection of As (V) by RO and NF membranes (>90 percent) in short-term (~4-hr) experiments, depending on experimental condition. The authors also found that As (III) was more difficult to reject than As (V) and that rejection in RO and NF systems averaged 67 and 32 percent, respectively. The objective in this work was not to evaluate the effectiveness of membranes for arsenic removal, however, but rather to determine a reasonable concentration factor to use in spiking membrane concentrate samples with arsenic for testing. Arsenic (V) was used in spiking work for this project.

2.2.4 Iron-Manganese Removal System

A process schematic for a typical iron-manganese filtration system is shown in Figure 2-3. Feed water is passed through a greensand media bed for removal of oxidized iron and manganese following oxidant addition. Periodic backwashing of the greensand media is required to remove excess iron and manganese, as well as other particulate contaminants removed from the feed water. Backwashing is accomplished by reversing the flow of water through the filter bed to flush out particulates. The backwash waste contains elevated concentrations of Fe and Mn as well as other contaminants.

The spent filter backwash residuals stream and spent filter backwash water/adsorption clarifier flush blend (SFBW/ACF) evaluated in this project were collected at facilities that also have a clarification step for removal of solids prior to filtration. SFBW/ACF (B) was shipped from a water treatment plant in the Midwestern U.S. that removes iron, manganese, and arsenic from groundwater using aeration, chlorination, clarification using an adsorption clarifier, and granular media filtration. Two separate samples were collected at the plant—spent filter backwash water and clarifier flush water. A raw characterization was conducted for both residuals streams (Appendix A), after which the two samples were blended (1:1) to obtain a composite sample for arsenic removal testing. The adsorption clarifier flush and spent filter backwash water are blended similarly for subsequent treatment and disposal at the full-scale facility.

2.3 Experimental Design

Various precipitation and adsorption arsenic removal processes were evaluated for each of the following types of liquid and semi-liquid residuals streams:

- Activated alumina (AA) regenerant
- Ion exchange (Ion Ex) regenerant
- Nanofiltration (NF) concentrate
- Reverse osmosis (RO) concentrate
- Spent filter backwash from Fe/Mn removal plant and adsorption clarifier flush from Fe/Mn removal plant

Limited volumes of residuals shipped from remote plant sites allowed for a rough screening of all of the treatment options shown in Figure 2-4, but not a determination of optimal conditions in each case.

Precipitation tests were conducted using two different coagulants, alum and ferric chloride. Sulfuric acid, lime, and

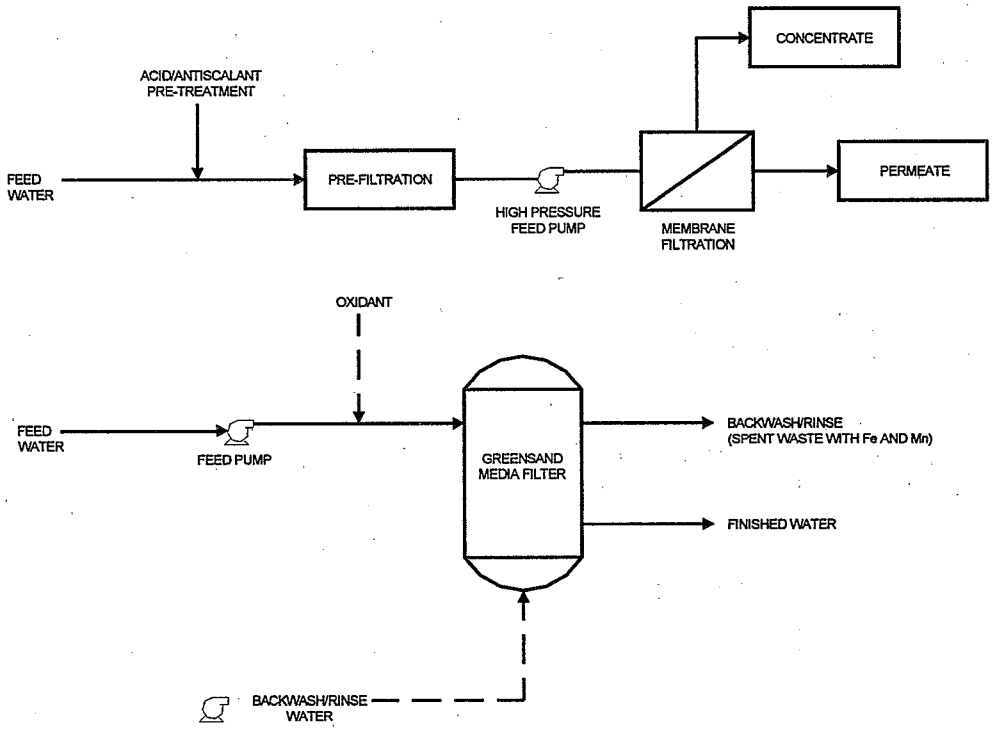


Figure 2-3. Schematic of membrane and iron-manganese removal filtration process

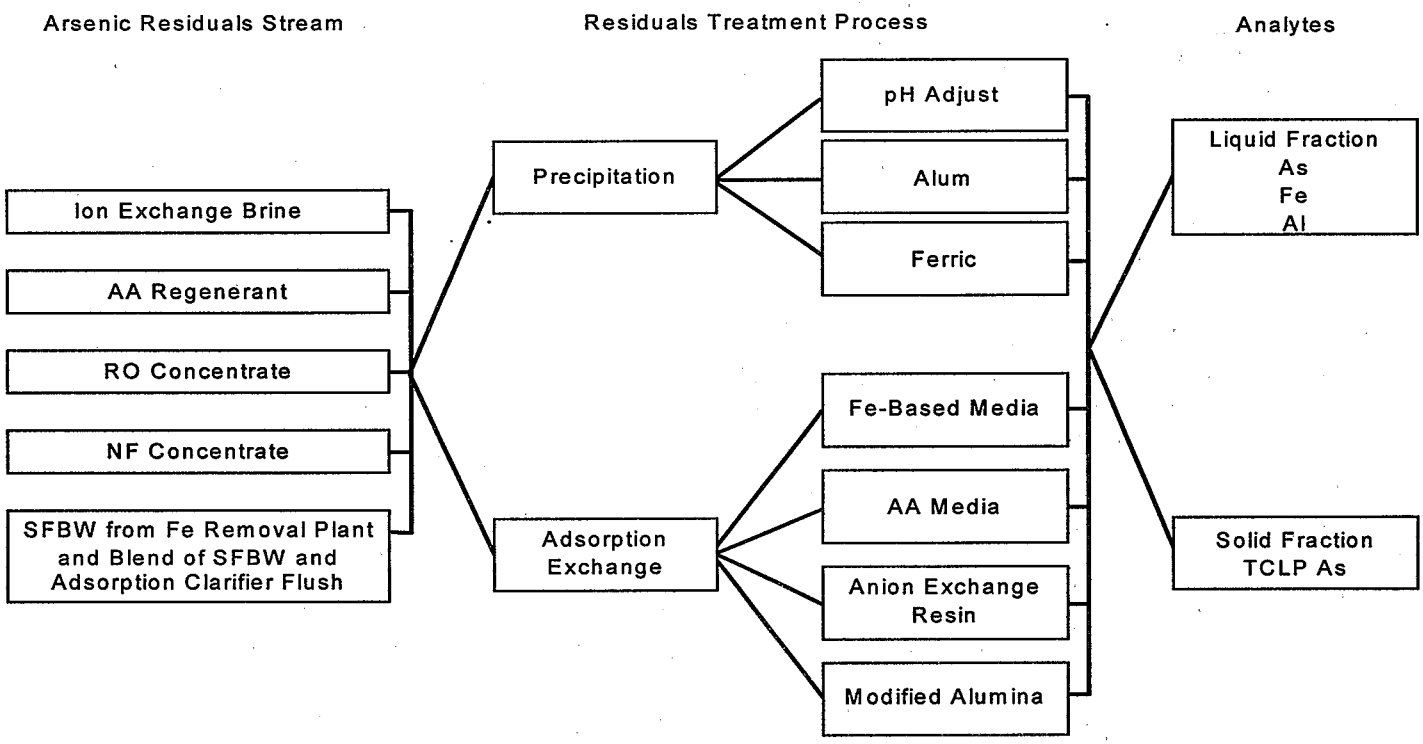


Figure 2-4. Summary of arsenic residuals treatment plan

Table 2-3. Liquid and semi-liquid residuals stream test matrix

Residuals origin	Treatment processes tested	Analyses conducted on liquid fraction following treatment
Activated alumina regenerant	$FeCl_3$ precipitation	Total As and Fe
Ion exchange regenerant	Alum precipitation	Total As and Al
	$FeCl_3$ precipitation	Total As and Fe
	pH adjustment	Total As
	Fe media adsorption	Total As
	Activated alumina adsorption	Total As
Nanofiltration concentrate	Alum precipitation	Total As and Al
	$FeCl_3$ precipitation	Total As and Fe
	Fe media adsorption	Total As
	Activated alumina adsorption	Total As
	Modified alumina adsorption	Total As
	Ion exchange	Total As
Reverse osmosis concentrate	Alum precipitation	Total As and Al
	$FeCl_3$ precipitation	Total As and Fe
	pH adjustment	Total As
	Fe media adsorption	Total As
	Activated alumina adsorption	Total As
Spent filter backwash water from Fe removal plant	Gravity settling	Total As
	Alum precipitation	Total As and Al
	$FeCl_3$ precipitation	Total As and Fe
	pH adjustment	Total As
	Fe media adsorption	Total As
	Activated alumina adsorption	Total As
	Ion exchange	Total As
Blend of spent filter backwash water and adsorption clarifier flush from Fe removal plant	Gravity settling	Total As
	Alum precipitation	Total As and Al
	$FeCl_3$ precipitation	Total As and Fe
	pH adjustment	Total As
	Fe media adsorption	Total As
	Activated alumina adsorption	Total As
	Ion exchange	Total As

sodium hydroxide were also used to adjust pH, when required. Two to four different types of adsorption media/exchange resins were evaluated for each untreated residuals stream (see Figure 2-4). The combination of treatment techniques used for individual waste samples was selected based on results of characterization tests which were used to identify potential interferences. For example, the effectiveness of ion exchange is reduced by common ions such as sulfate, which the resin sites prefer to arsenic (Ghurye *et al.* 1999).

The general testing approach shown in Figure 2-4 was modified to eliminate some treatments for some waste streams as follows:

1. Because sulfate levels were much greater than 250 mg/L and TDS levels were much greater than 500 mg/L, most wastes were not treated using ion exchange.
2. Modified alumina media was provided near the end of the test program, so it could only be evaluated using the nanofiltration wastes.
3. Only ferric chloride ($FeCl_3$) precipitation tests were conducted on the activated alumina regenerant, because of its very high starting aluminum concentration.
4. Gravity settling was added to the test matrix for the wastes containing relatively high concentrations of suspended solids.

2.4 Test Methods and Materials

All laboratory treatment tests were conducted on site at EE&T's process laboratory. The test matrix presented in Table 2-3 shows treatments tested for each residuals sample, along with samples analyzed.

2.4.1 Precipitation Tests

Precipitation tests were evaluated using a standard jar test. The jar test system consisted of a Phipps and Bird six-paddle stirrer with 2-L square Gator jars. Untreated liquid residuals samples were dosed with treatment chemicals and mixed for 1 min. The mixing intensity or velocity gradient was 300 sec^{-1}. The coagulant chemicals applied during rapid mixing included alum or ferric chloride, sometimes along with pH adjustment chemical and/or polymer to aid settling. In some cases, only a pH adjustment chemical was added. Rapid mixing was followed by 30 min of flocculation, during which the mixing intensity was tapered over the 30-min period (40-30-15 sec^{-1}).

Following flocculation, the mixer was turned off to allow for settling of particulate matter. After 10 min of settling (corresponding to an overflow rate of 0.25 gpm/ft^2), samples were collected for analysis.

Precipitation tests were performed using each of the nine liquid residuals samples collected. The chemicals used to precipitate arsenic from the liquid residuals included alum, ferric chloride, two polymers, and lime. Required pH adjustments were made with either sulfuric acid or sodium hydroxide. Lime and sodium hydroxide were applied in a single test. The coagulant dose range selected was based on preliminary screening tests for each residuals sample. Qualitative screening tests were conducted by applying various coagulant dosages to 200-mL beakers containing each liquid residuals stream, mixing for about 30 sec, and observing floc formation and settling. The coagulant dose ranges used for alum and ferric chloride precipitation tests are shown in Figure 2-5.

When sufficient quantities (approximately 100-mL) of settled solids were generated during precipitation testing conducted in 2-L Gator jars, the solids were separated from the supernatant and used for TCLP analysis. Supernatant samples were analyzed for arsenic and either iron or aluminum depending on the use of ferric chloride or alum.

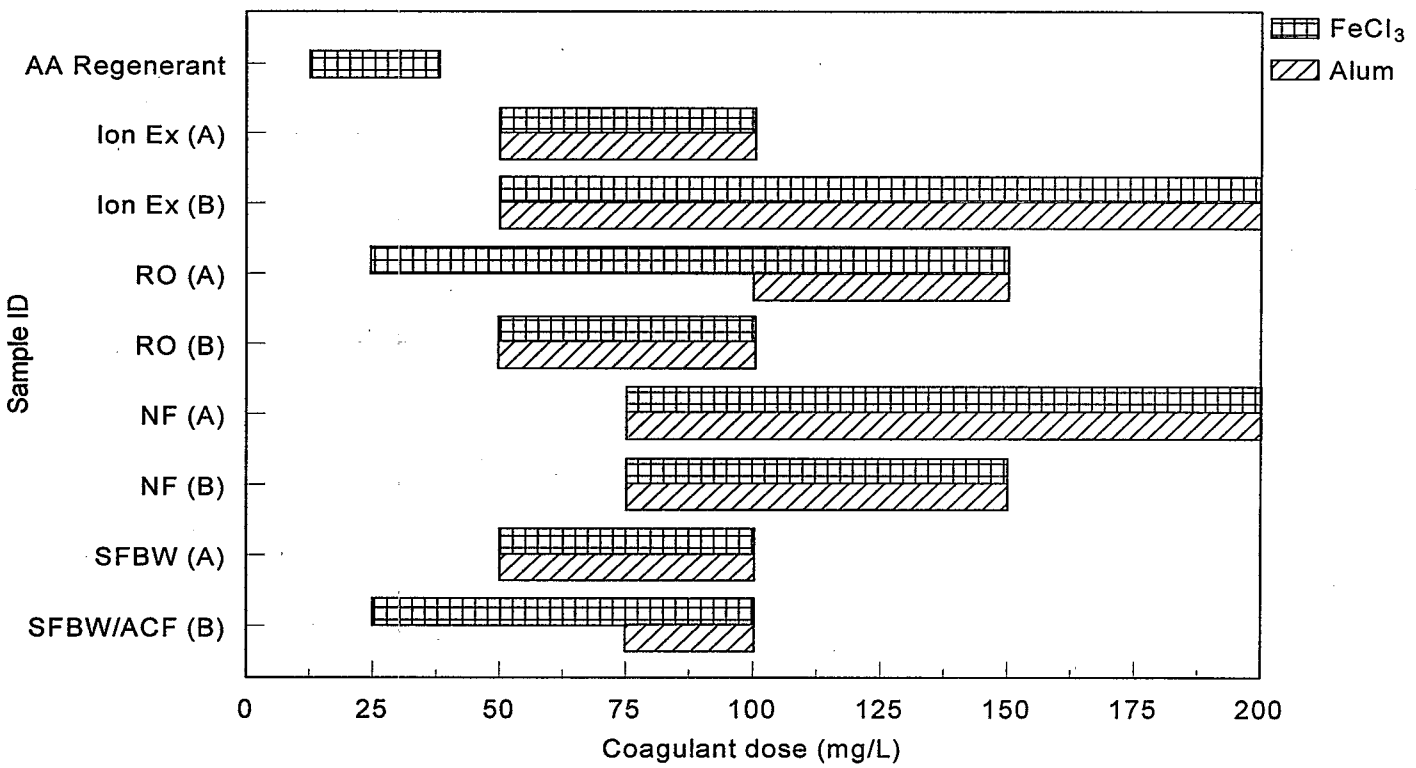


Figure 2-5. Coagulant dosage ranges used in precipitation tests

2.4.2 Adsorption Tests

Four different adsorption/exchange media were used in testing:

1. Iron-based adsorption media (Vertell 2000)
2. Activated alumina (APYRON)
3. Anion exchange resin (Ionac)
4. Modified alumina (Solmetex)

Table 2-4 shows some pertinent characteristics of the media and resins used in testing.

Table 2-4. Arsenic removal media tested

Media no.	Media type	Trade name	Media properties
1	Iron-based granular ferric hydroxide	Vertell 2000 Hawleys, UK	---
2	Activated alumina	APYRON Aqua-Bind™ Modified AA	Size = 0.3 to 1.4 mm UC <1.6 ES >0.6
3	Anion exchange resin	Ionac ASBI P	Strong base anion Chloride form Bead size = 0.3 to 1.2 mm
4	Modified alumina	Solmetex Corporation Metall:X	Size = 0.85 to 1.70 mm

The iron-based media, Vertell 2000, was an early variant of a granular ferric hydroxide media produced by Hawleys of the UK. Severn Trent Water in the UK evaluated this media and the granular ferric hydroxide media GEH, produced by GEH Wasserchemic Gmb/H&Co. of Germany. Treatment at the first UK arsenic treatment plant, commissioned in 1999, consists of adsorption onto GEH followed by disinfection. Prior to design of that facility, exhaustive pilot trials concentrated on treatment by adsorption, primarily with AA and granular ferric medias (Simms *et al.* 2000). The APYRON AA is an aluminum-based granular adsorption media designed to selectively remove both arsenic (V) and arsenic (III). The third material used in testing was a standard chloride-form anion exchange resin, while the fourth test media was a modified alumina that is used for removal of multivalent anionic metal species.

Adsorption/exchange tests were conducted using a single 2.2-cm diameter glass column filled with 90-mL of adsorption media. Liquid residuals were pumped through the column at a rate of 30 mL/min using a peristaltic pump for a period of 6 hours. The corresponding empty bed contact time (EBCT) was 3 min. Experimental set-up and EBCT times were consistent with work conducted by Ghurye and Clifford (Ghurye *et al.* 1999) on removal of arsenic and nitrate using ion exchange. The EBCT was also consistent with work conducted by Simms and Azizian (1997) on removal of arsenic by activated alumina. Those authors found that run length was linearly proportional to EBCT in the range of 3 to 12 min using a 14 x 28 mesh AA sample, but preferred to operate in the 3- to 6-min EBCT range to minimize bed size and media quantities.

In this project, EBCTs up to 6-min were evaluated for some residuals samples. Samples were collected hourly over the 6-hour test period and analyzed for total arsenic during all tests. The test set-up was the same for all media/resins. Adsorption tests in this work were not run to exhaustion because of the very limited quantities of liquid residuals provided for testing.

2.4.3 Analytical Tests

TCLP Tests

TCLP extraction tests were conducted on solid-phase residuals received from operating arsenic removal plants and on thickened SFBW/ACF residuals generated in precipitation tests. The latter were actually semi-liquid samples separated from jar test liquid supernatant by concentrating them in a separatory funnel to approximately 6 to 8 percent solids. Extractions were done in accordance with EPA Method 1311, as outlined in the Federal Register (1990), and analyses were conducted using EPA Method 6010B.

For solid residuals samples, the extraction fluid used was determined based on the pH of each sample by combining 5 g of the sample with 96.5 mL of reagent water. This solution was vigorously stirred for 5 min using a magnetic stirrer. If

the pH was less than 5.0, an extraction fluid (#1) with a pH = 4.93 ± 0.05 was used. If the pH was greater than 5.0, then 3.5 mL of 1 N hydrochloric acid (HCL) was added to the solution, it was heated to 50°C and then was held for 10 min. After the solution was cooled, if the resulting pH was less than 5.0, extraction fluid #1 was used. If the pH was greater than 5.0, an extraction fluid (#2) with a pH = 2.88 ± 0.05 was used.

The solid media samples plus a volume of extraction fluid equal to 20 times the weight of the sample were added to an extractor vessel, secured in a rotary agitation device and rotated at 30 ± 2 rpm for 18 ± 2 hrs. The extract was acidified with nitric acid to pH less than 2. An acid digestion was performed on the extract in preparation for arsenic analysis using EPA Method 6010B.

The residuals samples generated in precipitation tests were thickened to 6 to 8 percent solids and filtered through a glass fiber filter in a pressure filter device. An extraction was performed on the solids (plus filter). The extract and filtrate were subsequently combined for arsenic analysis.

Chemical Tests

Bench-scale treatment tests conducted on the liquid residuals included two different chemical precipitation treatments and four adsorption/exchange technologies. Prior to conducting those arsenic removal tests, each liquid residuals sample was analyzed to determine total and dissolved arsenic content. Several other water quality parameters were also determined to characterize the samples.

The characterization tests conducted for each liquid residuals sample included the following laboratory parameters:

- Total arsenic
- Dissolved arsenic
- pH
- Alkalinity
- Hardness
- Conductivity
- Total dissolved solids (TDS)
- Total iron
- Total manganese
- Total aluminum (AA regenerant only)
- Sulfate

Three samples—SFBW/ACF (B), Ion Ex (A), and Ion Ex (B)—included more than one waste stream. SFBW/ACF (B) was a blend of adsorption clarifier flush water and spent filter backwash water. Both ion exchange regenerant samples included water from backwash, brine, and rinse cycles from regeneration. Individual waste streams were combined into composites for testing at EE&T. These composite samples were also characterized using the same array of laboratory tests.

2.4.4 Quality Assurance/Quality Control

A Quality Assurance Project Plant (QAPP) was submitted to and approved by EPA in February 1999. The report summarized the data quality objectives for the analytical determinants for this project. The arsenic measurement was determined to be the most critical parameter because arsenic removal was used to compare treatment performance. The other parameters that were considered key measurements were total iron, total manganese, total aluminum, and sulfate. The QA objectives set for these parameters are listed in Table 2-5.

Table 2-5. Data quality objectives for key measurements

Parameter	Sample	Method	Method detection limit	Precision (percent)	Accuracy (percent)
TCLP As	Semi-liquid	EPA 6010B	0.002 mg/L	± 25	75 - 125
Total and dissolved As	Liquid	EPA 200.7	0.002 mg/L	± 25	75 - 125
Total Fe	Liquid	EPA 200.7	0.010 mg/L	± 25	75 - 125
Total Mn	Liquid	EPA 200.7	0.005 mg/L	± 25	75 - 125
Total Al	Liquid	EPA 200.7	0.050 mg/L	± 25	75 - 125
Sulfate	Liquid	EPA 300.0A	0.350 mg/L	± 25	75 - 125

Project-specific quality assurance objectives were not established for the remaining water quality parameters evaluated for characterization of the various residuals streams, however, the test procedures used for analysis were either EPA or Standard Methods for the Examination of

Water and Wastewater approved methods. The specific methods used for these water quality parameters are listed in Table 2-6.

Table 2-6. Analysis methods summary for arsenic-containing residuals

Parameter	Method
Alkalinity	SM 2320B
pH	SM 4500H$^+$B
Hardness (total)	SM 2340C
TDS	SM 2540 C
Conductivity	SM 2510 B

3. Test Results

3.1 Introduction

Residuals samples were characterized prior to conducting precipitation and adsorption tests, and before blending or spiking with arsenic, if required. Blended composite and spiked samples were also characterized using the same array of laboratory tests.

3.2 Residuals Characterization

Table 3-1 provides a summary of the key water quality results for each sample. For samples that were blended, only results for the composite samples used in testing are shown. The concentrate samples collected from the reverse osmosis and nanofiltration plants had either no arsenic or very low arsenic concentrations, and therefore had to be spiked with arsenic prior to testing. These samples were re-analyzed after spiking to determine the arsenic concentration. Complete results from all characterization analyses are tabulated in Appendix Tables A-1 and A.2.

3.2.1 Arsenic Concentrations

Total arsenic levels measured in all untreated residuals samples are plotted in Figure 3-1. For the reverse osmosis and nanofiltration samples, spiked arsenic concentrations are shown. Arsenic concentrations ranged from approximately 0.5 mg/L spiked in the membrane concentrate samples to around 10 to 25 mg/L in the ion exchange regenerant streams. The spent filter backwash water and spent filter backwash water/adsorption clarifier flush blend had total arsenic levels between the two extremes (about 1.5 mg/L), and arsenic in the AA regenerant stream was 2.6 mg/L.

Both total and dissolved arsenic levels in the untreated residuals samples are shown in Table 3-1. EPA Method 200.7, which was used in analyzing total and dissolved arsenic, includes a digestion step to dissolve all particulate matter. Nanofiltration and reverse osmosis arsenic concentrations shown in the table are the measured levels before spiking. Ninety-three to 99 percent of the arsenic in the nanofiltration and reverse osmosis concentrate streams and in the composite ion exchange regenerant samples was in the dissolved form. In contrast, almost none of the arsenic in the AA regenerant stream and the SFBW samples was dissolved.

Concentration Factors

Arsenic levels in the residuals streams were compared to corresponding source water arsenic levels to determine a "concentration factor," or the degree to which arsenic levels were concentrated in the residuals by the various treatment processes. Results of those calculations are summarized below in Table 3-2. Data are not included for the RO and NF samples because they were spiked with arsenic, assuming a concentration factor of 10.

The concentration factors for the SFBW and SFBW/ACF samples were 12 and 61, respectively. Concentration of arsenic of the AA regenerant stream was comparable, with a concentration factor of 44. The highest concentration of arsenic occurred in the ion exchange waste streams. Arsenic levels were 270 and 236 times greater than the corresponding source water arsenic concentrations for the composite waste streams (brine, backwash, and rinse waters) tested. Concentration of arsenic was greater for the brine streams, which contained higher concentrations of arsenic than the blends. Clifford *et al.* (1998) reported that arsenic was concentrated by a factor of 144 in a brine.

3.2.2 Alkalinity, pH, and Total Hardness

Alkalinity, pH, and total hardness of the nine liquid-fraction residuals samples varied significantly. Results are shown graphically in Figure 3-2. The highest alkalinity of 7,000 mg/L as ($CaCO_3$) was measured for Ion Ex (B). Ion Ex (A) and RO (A) also had high alkalinities of 950 mg/L and 2,800 mg/L, respectively. The alkalinities of the AA regenerant, the SFBW stream and SFBW/ACF blend, and the nanofiltration concentrates were comparable, in the 200 to 400 mg/L (as $CaCO_3$) range. For the two RO concentrates, alkalinities were very different, at 600 mg/L (as $CaCO_3$) for RO (B) and 2,800 mg/L (as $CaCO_3$) for RO (A).

Table 3-1. Residuals sample characterization

	Untreated residuals characteristics									
Sample ID	pH	Alk.*	Total hardness*	TDS (mg/L)	Total As (mg/L)	Dissolved As (mg/L)	Total Fe (mg/L)	Total Mn (mg/L)	Conductivity (µS/cm)	Sulfate (mg/L)
AA regenerant	7.1	268	13	10,240	2.63	0.12	0.83	0.09	22,640	16,338
SFBW (A)	7.6	430	365	460	1.41	<0.002	78.5	7.52	900	4.82
SFBW/ACF (B)†	8.1	197	400	341	1.74	0.03	45.9	3.75	680	97.3
RO (A)‡	7.9	2,800	460	14,300	<0.002	<0.002	0.65	0.23	28,500	544
RO (B)‡	7.3	600	840	11,750	<0.002	<0.002	0.86	1.11	23,800	---
NF (A)‡	7.1	325	1,560	1,765	0.013	0.007	2.16	0.14	3,515	1,075
NF (B)‡	6.6	210	1,750	1,533	0.005	0.009	0.46	0.08	3,080	1,190
Ion Ex (B)†	9.7	7,000	86	6,240	24.8	24.7	<0.01	<0.005	8,100	910
Ion Ex (A)†	9.0	950	90	4,100	10.5	10.3	0.49	---	12,440	---

*mg/L as $CaCO_3$
†After blending individual waste streams.
‡Before spiking with As

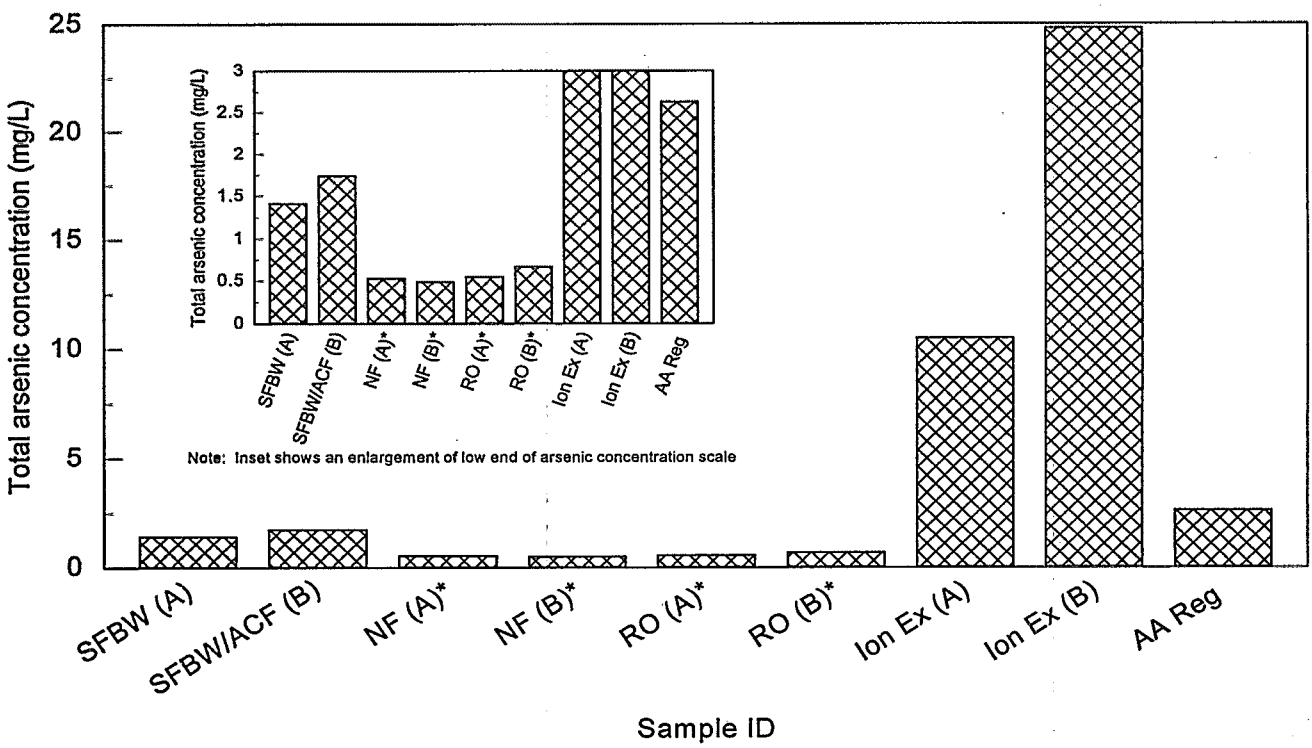


Figure 3-1. Total arsenic concentrations in the untreated liquid residuals
*NF and RO samples were spiked with arsenic in the laboratory

Table 3-2. Concentration of arsenic in residuals

Sample ID	Arsenic concentration (mg/L)		Concentration factor
	Source water	Residuals stream	
Ion Ex (A)	0.039	10.5	270
Ion Ex (B)	0.105	24.8	236
SFBW (A)	0.023	1.41	61
SFBW/ACF (B)	0.149	1.74	12
AA regenerant	0.060	2.63	44

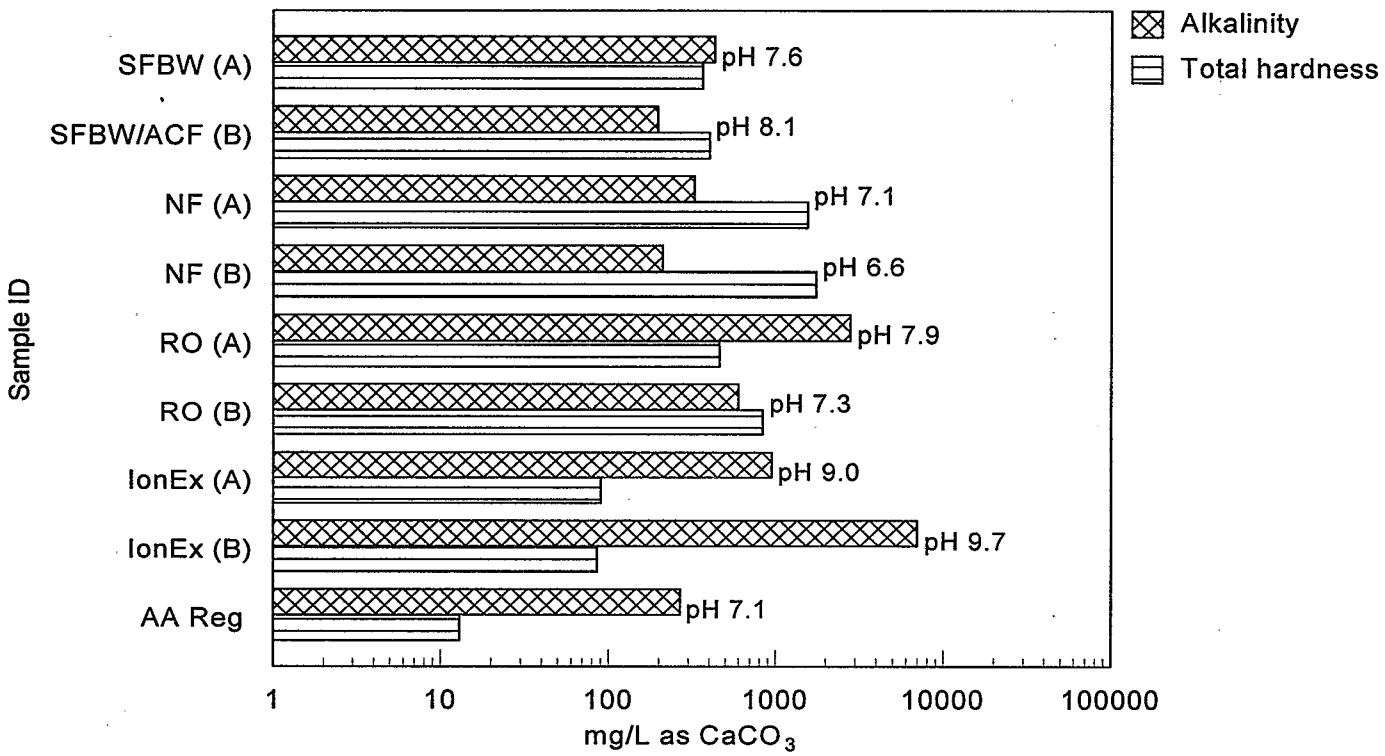


Figure 3-2. Alkalinity, total hardness, and pH of the untreated liquid residuals

The pH of most of the residuals samples was in the 6.5 to 8.0 range. Along with higher alkalinity, ion exchange regenerant samples exhibited a much higher pH range of 9.0 to 9.7.

The highest levels of total hardness were measured in the nanofiltration concentrate stream. Those levels, approximately 1,500 to 1,800 mg/L (as $CaCO_3$) were comparable to NF concentrate TDS levels. The next highest total hardness value was associated with RO (B) at 840 mg/L (as $CaCO_3$). At 840 mg/L (as $CaCO_3$), the total hardness in that sample was nearly twice the hardness measured in RO (A). Ion exchange regenerants and the AA regenerant stream exhibited much lower hardness levels, less than 100 mg/L (as $CaCO_3$), than any of the other residuals streams.

3.2.3 TDS

TDS levels of the liquid waste streams before treatment are plotted in Figure 3-3. TDS ranged from 341 mg/L in SFBW/ACF (B) to 14,300 mg/L in RO (A). Corresponding conductivity ranged from 680 µS/cm to 28,500 µS/cm. The highest levels of total dissolved solids (approximately 10,000 to 15,000 mg/L) were found in the AA regenerant and RO concentrate streams. SFBW TDS levels were at the low end of the spectrum at around 300 to 500 mg/L. NF concentrate TDS levels were also comparatively low (about 1,500 to 1,800 mg/L), and TDS levels in ion exchange regenerant streams were comparatively high (4,000 to 6,000 mg/L).

3.2.4 Total Fe and Total Mn

Total Fe and Mn concentrations were below detection limits in the Ion Ex (B) regenerant, and as expected were highest in the SFBW (A) residuals sample. Iron and manganese levels in the SFBW and SFBW/ACF blend samples were 78.5 and 45.9 mg/L and 7.5 and 3.8 mg/L, respectively. In all other samples, except NF (A), total Fe levels were in the 0.5 to 0.9 mg/L range. Similarly, Mn concentrations for the other samples were in the 0.1 to 0.2 mg/L range, except for RO (B). Iron and manganese concentrations are shown in Figure 3-4.

3.2.5 Sulfate

The liquid residuals samples had sulfate levels ranging from less than 100 mg/L in the SFBW and SFBW/ACF blend to over 16,000 mg/L in the AA regenerant and Ion Ex (A) brine. Sulfate levels were in between those extremes at around 500 to 2,000 mg/L in the NF and RO concentrates and Ion Ex (B) brine. If the source water contains <500 mg/L TDS and <150 mg/L sulfate, ion exchange may be a practical treatment method for arsenic removal (Clifford and Lin 1986; Clifford *et al.* 1997; Ghurye *et al.* 1999; Clifford *et al.* 1999). Clifford (1999) compiled data collected in field studies conducted in Hanford, CA; McFarland, CA; and Albuquerque, NM that illustrate the impact of influent sulfate concentration on ion exchange run length. Those data are tabulated below in Table 3-3.

As shown in Table 3-3, a run length of 490 BV in Clifford (1999) was achieved, even with a sulfate concentration of

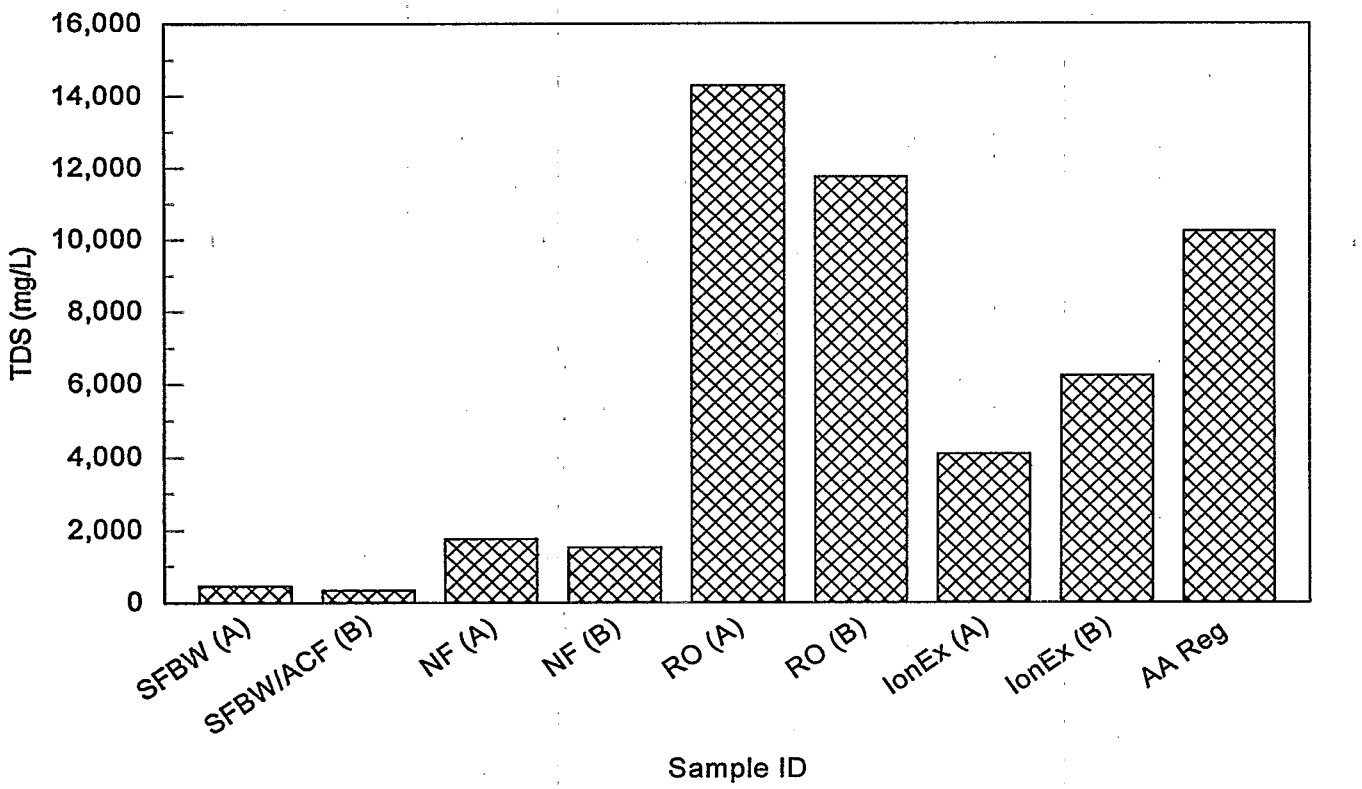


Figure 3-3. Total dissolved solids concentrations of untreated liquid residual

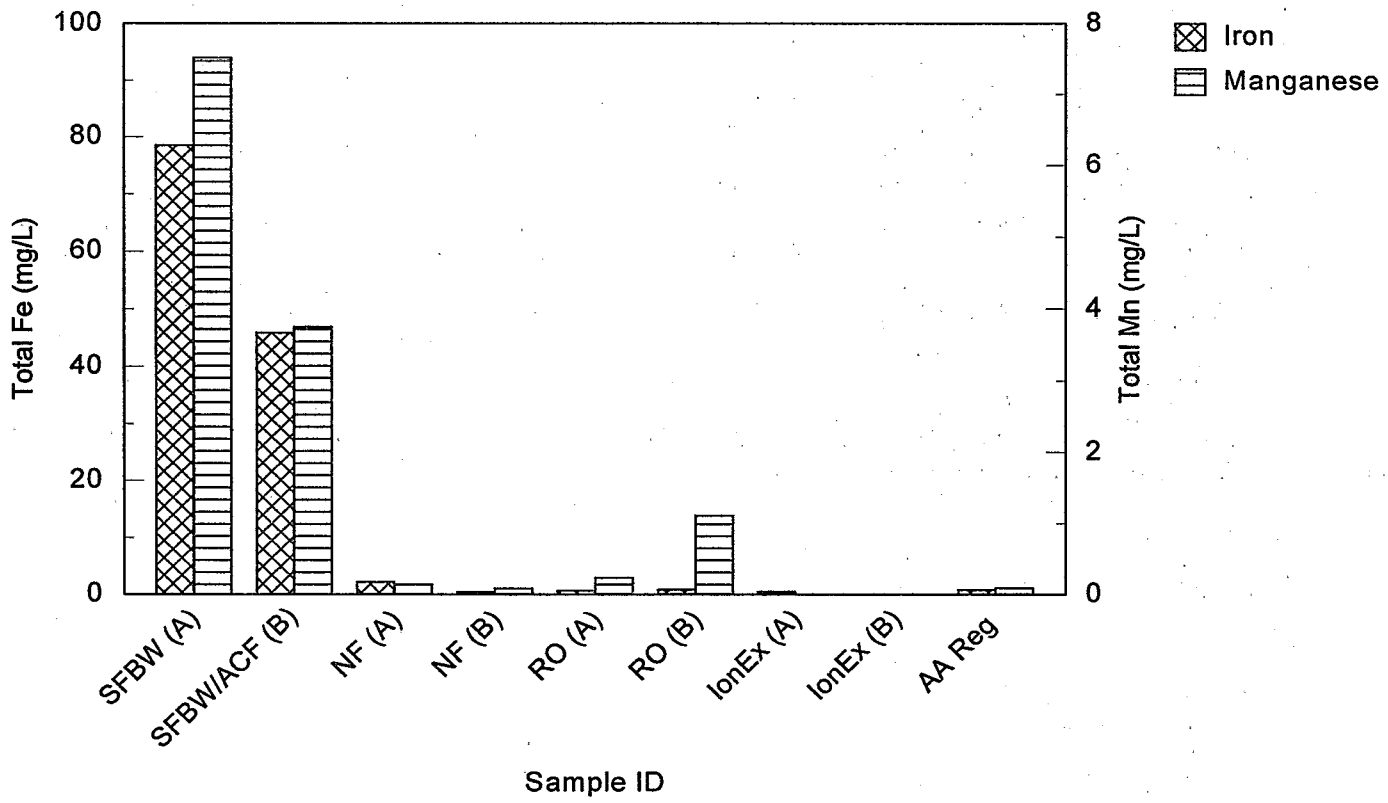


Figure 3-4. Iron and manganese concentration of untreated liquid residuals

Table 3-3. Ion exchange run length as a function of influent sulfate concentration*

Location	Source water concentration			Run length (BV)†
	As (µg/L)	TDS (mg/L)	Sulfate (mg/L)	
Hanford, CA	50	213	5	1,500
McFarland, CA (unspiked)	13	170	40	1,030‡
Albuquerque, NM	26	328	82	640
McFarland, CA (SO_4^{2-} spiked)	13	259	100	490
McFarland, CA (SO_4^{2-} spiked)	13	436	220	250

Source: Clifford (1999).

*Run lengths for ASB-2 type 2 SBA resin regenerated with 20 lbs NaCl/ft^3. When regenerated with 10 lbs NaCl/ft^3, run lengths decreased by about 25 percent.

†Based on run termination at effluent arsenic concentration of 2 µg/L.

‡Extrapolated value based on comparison with IRA 404 performance in McFarland.

100 mg/L. The 250-BV run length attained with a sulfate concentration of 220 mg/L is probably too short for economical full-scale operation, which is why <150 mg/L sulfate is suggested as one criterion for selecting ion exchange for arsenic removal (Clifford, 1999).

3.3 Precipitation Test Results

3.3.1 Overview

The precipitation test results obtained using alum and ferric chloride are summarized in the following paragraphs and tables. A comprehensive table of test results is included as Appendix Table A-3, and Appendix Figures A.1 through A.18 illustrate arsenic removal attained in precipitation work. While a benchmark of 0.05 mg/L arsenic in the supernatant was not a treatment goal at the outset of testing, it was used as a comparison point when treatment results were evaluated.

3.3.2 Activated Alumina

Table 3-4 presents test conditions including ferric chloride dosage, molar ratio of ferric chloride as Fe, applied to the untreated As concentration, and coagulation pH, along with test results of arsenic concentration remaining in the supernatant and arsenic removal. Only ferric chloride was used for precipitation testing conducted with the activated alumina regenerant, which contained 113 mg/L aluminum. Appendix Figure A.1 shows those results graphically.

With no chemical addition (gravity settling only), 84.5 percent of the total arsenic was removed from the activated alumina (AA) regenerant waste, leaving 0.386 mg/L As in the supernatant. Arsenic removal increased to about 94 percent with the addition of 25 to 50 mg/L ferric chloride (Fe:As ratio of 4.4 to 8.8). Corresponding supernatant arsenic levels in those tests were approximately 0.15 mg/L.

3.3.3 Ion Exchange Regenerants

Table 3-5 presents arsenic removal results for precipitation tests conducted using the ion exchange regenerant streams. For the Ion Ex (A) composite sample, a ferric chloride dose of 100 mg/L, equivalent to a molar ratio of Fe:As of 4.4:1, yielded an arsenic removal of approximately 79 percent at ambient pH 7.9 (pH resulting from coagulant addition alone) compared to about 88 percent at reduced pH 6.2. Alkalinity was also reduced at the reduced pH condition. Corresponding supernatant arsenic concentrations were 2.36 and 1.28 mg/L. The same ferric chloride dose applied to the brine component of the composite, however, which contained about three times as much arsenic, achieved 87 percent arsenic removal at ambient pH 8.8 compared to 57 percent removal at pH 6.4. Alum tests yielded much poorer arsenic reductions (11 to 43 percent). Appendix Figures A.2 and A.3 show total arsenic removal and total arsenic remaining in the supernatant for ferric chloride and alum precipitation tests conducted on the composite sample.

Table 3-4. Activated alumina regenerant precipitation results

Untreated regenerant							Settled regenerant (supernatant)	
Total As (mg/L)	Dissolved As (mg/L)	Total Al (mg/L)	$FeCl_3$ dose (mg/L)	Fe:As*	Coag. pH (units)	Polymer	total As (mg/L)	As removal (percent)
2.6	0.12	113.0	0	—	7.1	No	0.386	85.3
2.6	0.12	113.0	25	4.4	7.1	No	0.171	93.5
2.6	0.12	113.0	50	8.8	7.0	No	0.154	94.1

*Molar ratio of $FeCl_3$ as Fe applied to untreated regenerant As concentration.

As shown in Table 3-5, alum and ferric chloride precipitation tests for the Ion Ex (B) composite sample were conducted at ambient pH 9.9 and reduced pH 6.2, with alum and ferric chloride dosages ranging from 50 to 200 mg/L. In ferric chloride precipitation tests, increasing the ferric chloride dosage from 50 mg/L to 200 mg/L increased arsenic removal from 0 to 25 percent without polymer, and to about 30 percent with polymer at reduced pH 6.2. The corresponding improvement in arsenic reduction was less than 10 percent for ferric tests at ambient pH 9.9, and about the same for alum tests conducted at 6.2. Carbonate complexing with the iron and aluminum in these very high alkalinity samples likely interfered with arsenic removal. Appendix Figures A.4 and A.5 present arsenic levels remaining in the supernatant for ferric chloride and alum tests.

Clifford *et al.* (1998) studied removal of arsenic from spent ion exchange brine containing about 3.45 mg/L As with ferric

Table 3-5. Ion exchange regenerant precipitation results

		Ferric precipitation						Alum precipitation					
Sample ID	Untreated regenerant total As (mg/L)	$FeCl_3$ dose (mg/L)	Fe:As*	Coag. pH (units)	Polymer	Settled regenerant (supernatant) total As (mg/L)	As removal (percent)	Alum dose (mg/L)	Al:As†	Coag. pH (units)	Polymer	Settled regenerant (supernatant) total As (mg/L)	As removal (percent)
Ion Ex (A) composite	10.5	100	4.4	7.9	No	2.36	78.6	100	2.4	8.9	No	9.31	11.3
		100	4.4	6.2	No	1.28	87.8	100	2.4	5.5	No	5.98	43.1
Ion Ex (A) brine	33.2	50	0.7	6.4	No	10.9	10.2						
		100	1.4	8.8	No	4.9	86.9						
		100	1.4	6.4	No	6.0	56.6						
Ion Ex (A) backwash	0.032	75	1,082	6.5	No	<0.002	96.9						
Ion Ex (A) rinse	1.7	75	20	7.5	No	0.176	89.7						
Ion Ex (B) composite	24.8	50	0.9	9.9	No	25.8	0	50	0.5	9.9	No	26.6	0
		50	0.9	6.2	No	26.0	0	50	0.5	6.2	No	23.5	5.2
		100	1.9	9.9	No	25.3	0	100	1.0	9.9	No	24.6	0.8
		100	1.9	6.2	No	23.3	6.1	100	1.0	6.2	No	23.3	6.1
		200	3.7	9.9	No	22.7	8.5	200	2.0	9.9	No	25.5	0
		200	3.7	6.2	No	18.7	24.6	200	2.0	6.2	No	22.8	8.1
		200	3.7	9.9	Yes[1]	23.2	6.5	200	2.0	9.9	Yes[1]	26.3	0
		200	3.7	6.2	Yes[1]	17.5	29.4	200	2.0	6.2	Yes[1]	25.5	0

*Molar ratio of $FeCl_3$ as Fe applied to untreated As concentration.
†Molar ratio of alum as Al applied to untreated As concentration.
[1]0.5 mg/L cationic LT 22S

chloride precipitation. In that work, molar ratios of 20:1 and 50:1 (equivalent to ferric chloride dosages of 150 to 350 mg/L) were required to effect 99.5 percent removal of arsenic. In this project, ferric chloride doses of 460 mg/L to 3,600 mg/L would have been required to achieve equivalent molar ratios.

3.3.4 Reverse Osmosis Concentrates

Precipitation test conditions and results for RO concentrates using ferric chloride and alum are summarized in Table 3-6. In tests conducted using RO (A), increasing the ferric chloride dose from 25 to 150 mg/L resulted in a dramatic increase in arsenic removal from less than 10 percent to greater than 90 percent. Addition of polymer in those tests had little impact on arsenic removal, while depressing the coagulation pH from 7.5 to 6.0 yielded a dramatic reduction in arsenic levels remaining from nearly 0.4 mg/L to less than 0.1 mg/L (equivalent to arsenic removals of 30 and 80 percent). The significant improvement in arsenic removal may be due to the reduction in alkalinity brought about by the reduction in pH, and the associated reduction in carbonate complexing in the highly alkaline concentrate stream. For the dose and pH conditions evaluated, alum yielded no arsenic removal. This result is consistent with results of alum precipitation tests conducted with Ion Ex (B). Appendix Figures A.6 and A.7 show total arsenic remaining as a function of coagulant dose achieved using ferric chloride and alum for RO (A).

For RO (B), ferric chloride and alum dosages of 50 and 100 mg/L, or Fe:As molar ratios of 35 and 70 for ferric chloride and Al:As molar ratios of 19 and 30 for alum were evaluated. A ferric chloride dose of 100 mg/L resulted in supernatant arsenic concentrations of 0.078 at pH 6.2 and 0.132 mg/L at pH 7.2. For the alum coagulation conditions tested, the best arsenic reduction attained was about 57 percent. Appendix Figures A.8 and A.9 show precipitation results achieved using ferric chloride and alum graphically.

3.3.5 Nanofiltration Concentrates

A summary of precipitation results achieved using ferric chloride and alum for nanofiltration concentrates NF (A) and NF (B) is presented in Table 3-7. Figures A.10 through A.13 illustrate the impacts of coagulant dose, polymer, and coagulation pH graphically.

In ferric chloride precipitation tests conducted using NF (A), lowering the coagulation pH from about 6.5 to 5.0 increased arsenic reduction by 4 to 12 percent, depending on ferric chloride dose. Ferric chloride dose had little impact on arsenic removal at ambient pH 6.5, however, at pH 5.0, arsenic removal increased from 82 percent with 75 mg/L ferric chloride to 98 percent with 200 mg/L. Addition of polymer at pH 5 and 150 mg/L ferric chloride increased arsenic removal from 76 to 88 percent (corresponding to supernatant arsenic levels of 0.117 and 0.061 mg/L). The impact of polymer addition was more significant in alum tests. With 200 mg/L alum at pH 6.6, arsenic reductions with and without polymer were 94 and 69 percent, respectively. Increasing alum dose increased arsenic removal from about 60 percent at 75 mg/L to 94 percent at 200 mg/L. Reducing the coagulation pH from around 7 to 6, however, had little effect on removal of arsenic.

While a marginal improvement in arsenic reduction of 5 percent was observed when ferric chloride dose was increased from 50 mg/L to 150 mg/L, reducing the pH from 6.5 to 5.0 had no impact in tests conducted with NF (B). As shown in Table 3-7, all ferric chloride precipitation tests reduced total As to below 0.05 mg/L. The effect of pH was similar in alum tests, however, the dose effect was much more significant. Arsenic removals of 40 to 50 percent were attained with 50 mg/L alum, and a dose of 150 mg/L reduced arsenic by 93 percent.

As observed for the other types of liquid residuals, on a weight basis, ferric chloride yielded greater reductions in arsenic than equivalent dosages of alum. On the basis of moles of metal applied per mole of arsenic, however, comparable molar ratios yielded similar results using the two coagulants. For example, for NF (A), a molar ratio of Fe:As of 72:1 with polymer reduced arsenic by 86.4 percent to 0.071 mg/L, compared to an arsenic removal of 86.0 percent at an Al:As molar ratio of 78:1.

3.3.6 Iron Removal Plant Residuals

Results of precipitation tests conducted using spent filter backwash waters from iron removal plants are summarized in Table 3-8 and presented graphically in Appendix Figures A.14 through A.18. Arsenic removals of 93 percent or greater were achieved in precipitation tests conducted with SFBW (A) using both ferric chloride and alum at dosages of 25 and 50 mg/L. Neither coagulant dose nor coagulation pH impacted arsenic removal significantly. Polymer also had no impact on arsenic removal. Supernatant arsenic levels were reduced to 0.06 mg/L or less in all ferric chloride tests, and generally below 0.05 mg/L, which is the in-stream domestic water supply standard in some states including Arizona, Nebraska, New Mexico, and Nevada (EPA 2000). Supernatant arsenic levels were 0.1 mg/L or lower in all alum tests.

In tests conducted with SFBW/ACF (B), increasing the ferric chloride dose from 25 mg/L to 100 mg/L increased arsenic removal from 91 to 96 percent, and lowered the supernatant arsenic concentration from 0.152 mg/L to 0.075 mg/L.

Table 3-6. RO concentrate precipitation results

	Ferric precipitation						Alum precipitation					
Sample ID	$FeCl_3$ dose (mg/L)	Fe:As*	Coag. pH (units)	Polymer	Settled concentrate (supernatant) total As (mg/L)	As removal (percent)	Alum dose (mg/L)	Al:As†	Coag. pH (units)	Polymer	Settled concentrate (supernatant) total As (mg/L)	As removal (percent)
RO (A)	25	22	6.0	No	0.494	9.5	100	48	7.7	No	0.526	0.1
	25	22	6.0	Yes[2]	0.519	5.0	100	48	8.2	Yes[2]	0.773	0
	50	44	6.0	No	0.304	44.3	100	48	6.0	Yes[2]	0.698	0
	50	44	6.0	Yes[2]	0.364	33.3	150	72	8.2	Yes[2]	0.730	0
	100	88	7.5	Yes[1]	0.368	30.0	150	72	6.0	Yes[2]	0.644	0
	100	88	7.5	Yes[3]	0.388	26.2						
	100	88	6.3	Yes[1]	0.094	82.1						
	100	88	6.0	No	0.091	83.3						
	100	88	6.0	Yes[2]	0.097	82.2						
	150	132	6.0	No	0.047	91.4						
	150	132	6.0	Yes[2]	0.041	92.5						
RO (B)	50	35	6.7	No	0.189	71.5	50	19	7.0	No	0.286	56.9
	50	35	5.8	No	0.561	15.4	50	19	5.9	No	0.570	14.0
	100	70	7.2	No	0.132	80.1	100	38	7.6	No	0.442	33.3
	100	70	6.2	No	0.078	88.2	100	38	6.3	No	0.306	53.9

Note: Spiked As concentration = 0.526 mg/L for RO (A) and 0.663 mg/L for RO (B).
*Molar ratio of $FeCl_3$ as Fe applied to spiked As concentration in concentrate.
†Molar ratio of alum as Al applied to spiked As concentration in concentrate
[1]2 mg/L anionic A3040 LTR
[2]2 mg/L cationic LT 22s
[3]5 mg/L anionic A3040 LTR

Table 3-7. NF concentrate precipitation results

	Ferric precipitation						Alum precipitation					
Sample ID	$FeCl_3$ dose (mg/L)	Fe:As*	Coag. pH (units)	Polymer	Settled concentrate (supernatant) total As (mg/L)	As removal (percent)	Alum dose (mg/L)	Al:As†	Coag. pH (units)	Polymer	Settled concentrate (supernatant) total As (mg/L)	As removal (percent)
NF (A)	75	72	4.8	Yes[1]	0.071	86.4	75	39	7.2	Yes[1]	0.197	62.3
	75	72	6.7	No	0.085	82.4	75	39	6.1	Yes[1]	0.221	57.7
	100	96	4.9	Yes[1]	0.093	82.2	100	52	7.1	Yes[1]	0.130	75.1
	100	96	6.4	No	0.143	70.4	100	52	6.1	Yes[1]	0.162	69.0
	150	143	5.0	Yes[1]	0.061	88.3	100	52	6.8	No	0.225	53.4
	150	143	6.2	No	0.094	80.5	150	78	7.0	Yes[1]	0.060	88.5
	150	143	5.3	No	0.117	75.8	150	78	6.0	Yes[1]	0.073	86.0
	200	191	5.2	Yes[1]	0.009	98.1	200	104	6.6	No	0.148	69.4
							200	104	6.6	Yes[1]	0.029	94.0
NF (B)	50	47	5.1	Yes[2]	0.030	93.8	50	26	6.0	Yes[2]	0.235	51.7
	75	71	5.0	Yes[2]	0.036	92.6	50	26	6.9	Yes[2]	0.283	41.8
	75	71	6.5	Yes[1]	0.009	98.2	75	39	6.6	Yes[1]	0.116	76.1
	100	95	6.3	Yes[1]	0.006	98.8	75	39	6.8	Yes[2]	0.157	67.7
	100	95	4.9	Yes[2]	0.020	95.9	75	39	6.1	Yes[2]	0.129	73.5
	150	142	6.2	Yes[1]	0.005	99.0	100	52	6.5	Yes[1]	0.067	86.2
							100	52	6.8	Yes[2]	0.087	82.1
							100	52	6.0	Yes[2]	0.073	85.0
							150	78	6.4	Yes[1]	0.035	92.8

Note: Spiked As concentration = 0.483 mg/L for NF(A) and 0.486 mg/L for NF (B)
*Molar ratio of $FeCl_3$ as Fe applied to spiked As concentration in concentrate.
†Molar ratio of alum as Al applied to spiked As concentration in concentrate
[1]4 mg/L LT 22S
[2]0.5 mg/L LT 22S

Table 3-8. Iron removal plant precipitation results

Wastewater		Ferric precipitation							Alum precipitation					
Sample ID	As conc. (mg/L)	$FeCl_3$ dose (mg/L)	Fe:As*	Total Fe:As**	Coag. pH (units)	Polymer	Settled backwash§ (supernatant) total As (mg/L)	As removal (percent)	Alum dose (mg/L)	Al:As†	Coag. pH (units)	Polymer	Settled backwash§ (supernatant) total As (mg/L)	As removal (percent)
SFBW (A)	1.41	25	8.2	83.0	7.3	Yes‡	0.034	97.6	25	4.5	7.6	Yes‡	0.074	94.8
		50	16.4	90.9	7.1	No	0.022	98.4	50	9.0	7.4	No	0.048	96.6
		50	16.4	90.9	5.0	No	0.056	96.0	50	9.0	6.0	No	0.096	93.2
		50	16.4	90.9	7.1	Yes‡	0.013	99.1	50	9.0	7.4	Yes‡	0.021	98.5
		50	16.4	90.9	5.5	Yes‡	0.031	97.8						
SFBW/ACF (B)	1.74	25	6.6	42.0	6.0	No	0.152	91.3	75	10.9	7.3	No	0.194	88.9
		50	13.3	48.6	6.6	No	0.100	94.3	75	10.9	6.1	No	0.205	88.2
		75	19.9	55.2	7.2	No	0.064	96.3	100	14.5	7.1	No	0.248	85.8
		75	19.9	55.2	6.1	No	0.070	96.0	100	14.5	6.1	No	0.214	87.7
		100	26.5	61.9	6.7	No	0.110	93.7						
		100	26.5	61.9	6.1	No	0.075	95.7						
Settled SFBW/ACF (B)	0.043	25	268	††	7.3	No	0.093	0						
		50	537	††	6.9	No	0.018	58.1						
		75	805	††	6.7	No	0.013	69.8						
		100	1,073	††	6.5	No	0.011	74.4						

*Molar ratio of $FeCl_3$ as Fe applied to untreated As concentration.
†Molar ratio of alum as Al applied to untreated As concentration.
‡4 mg/L anionic A3040 LTR
§Settled backwash/adsorption clarifier flush blend for tests conducted using SFBW/ACF(B).
**Molar ratio of Fe in untreated sample plus $FeCl_3$ as Fe applied to untreated As concentration.
††Could not be calculated because Fe in settled SFBW/ACF(B) before coagulant addition not measured.

Reducing the coagulation pH from about 7 to 6 had little impact on arsenic removal. For the range of alum conditions tested (two dosages at two pH levels) arsenic removals of 86 to 89 percent were achieved.

The iron concentration of the untreated SFBW(A) was 78.5 mg/L. Therefore, as indicated in Table 3-8 the molar ratio of background iron plus iron applied as coagulant to background arsenic concentration was much higher (5 to 10 times) than the molar ratio of iron applied in the coagulant to untreated arsenic concentration. Similarly for SFBW/ACF(B) in which the background iron level was 45.9 mg/L, molar Fe:As ratios were 2 to 6 times higher when the background iron was included. Background iron concentrations were only considered in residuals collected at iron removal facilities where iron levels in residuals were 45 mg/L or greater. Iron concentrations were approximately 2 mg/L or lower in all other samples.

Gravity settling the SFBW and SFBW/ACF blend samples with no chemical addition reduced arsenic levels by 99.5 and 97.5 percent to well below 0.05 mg/L. Ferric chloride dosages of 25 to 100 mg/L were added to settled SFBW/ACF (B) to determine additional achievable arsenic reductions. Up to 75 percent more arsenic was removed beyond that achieved through gravity settling alone.

3.3.7 *Summary of Precipitation Testing*

The effectiveness of alum and ferric chloride precipitation for arsenic removal was evaluated by conducting laboratory jar tests using nine different liquid residuals streams. A summary of untreated and treated total arsenic concentrations attained for ferric chloride tests for each residuals stream is presented in Figure 3-5. A similar presentation of alum precipitation results is shown in Figure 3-6. On a weight basis, ferric chloride outperformed alum for every residuals stream treated with the exception of NF (A). Further, ferric chloride precipitation reduced the total arsenic concentration of six of the nine residuals samples to less than 0.10 mg/L but to less than 0.05 mg/L for only the SFBW and NF samples. Exceptions were the AA regenerant and the two ion exchange regenerants, where supernatant arsenic levels of 0.15 mg/L (AA), 1.28 mg/L (Ion Ex (A)), and 18.7 mg/L (Ion Ex (B)) were attained. Figure 3-7 shows a comparison of the arsenic percent removals attained with

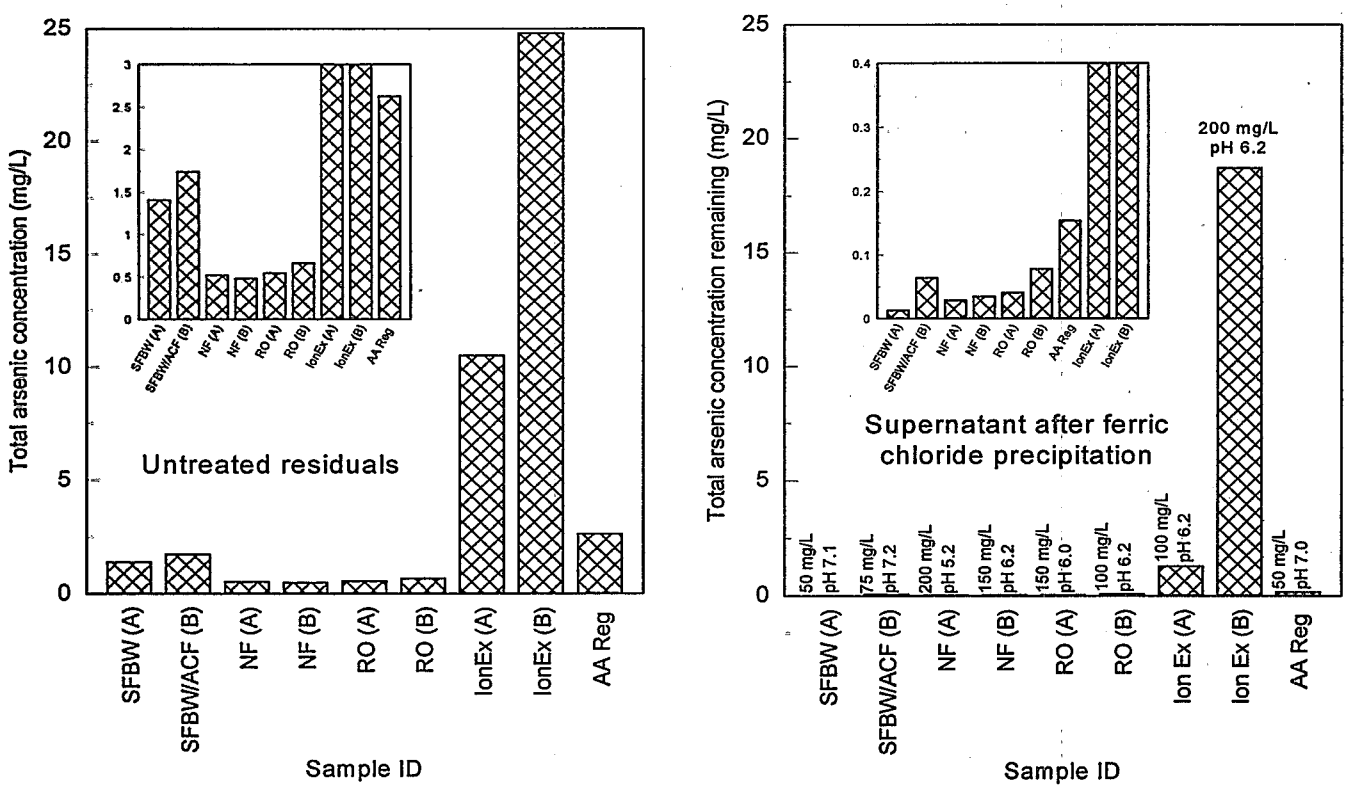


Figure 3-5. Total arsenic concentration in the untreated residuals and in the supernatant after ferric chloride precipitation

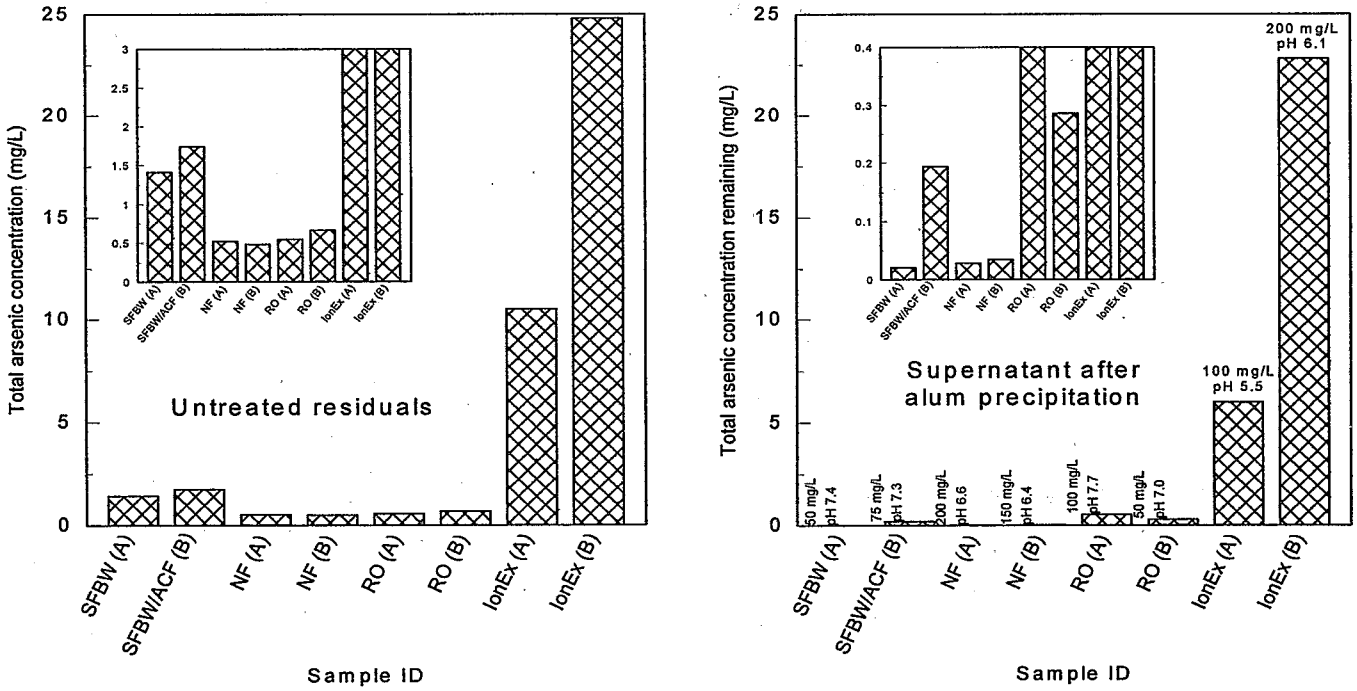


Figure 3-6. Total arsenic concentration in the untreated residuals and in the supernatant after alum precipitation

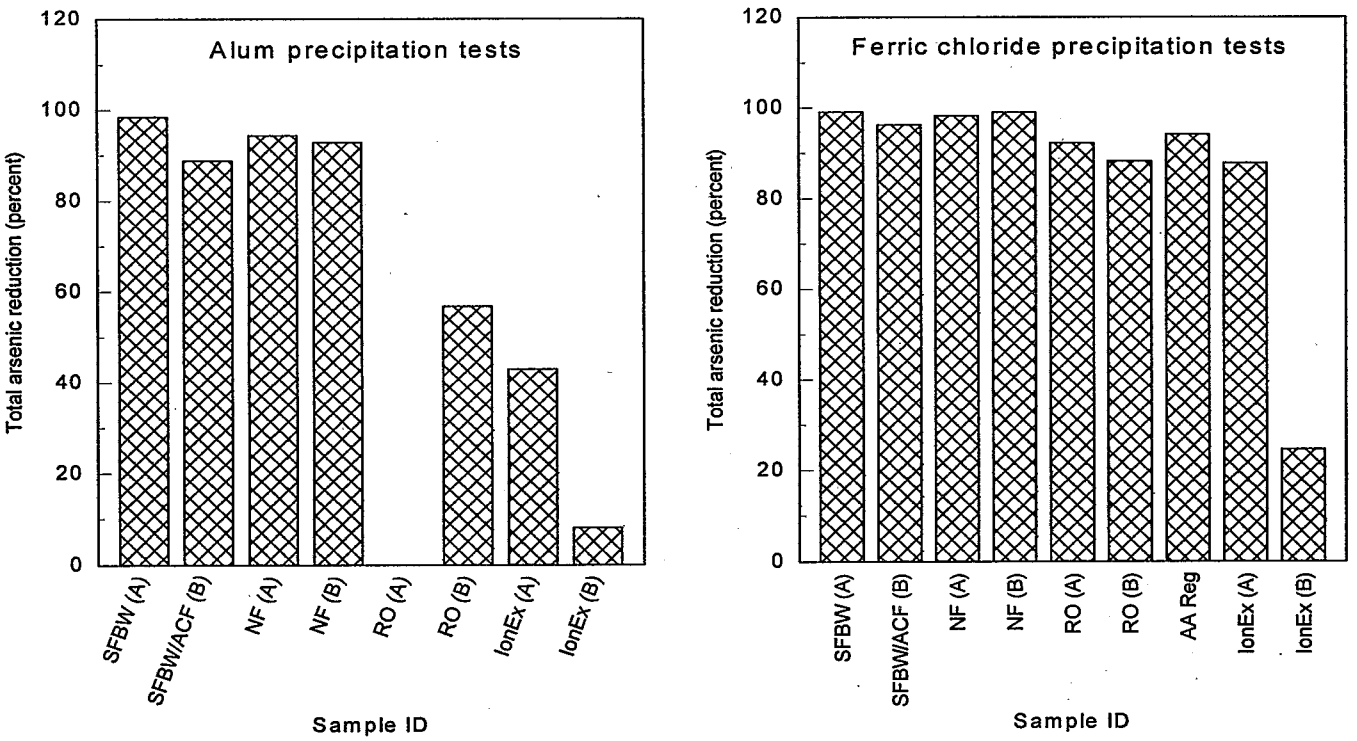


Figure 3-7. Comparison of percent total arsenic reduction after alum and ferric chloride precipitation

alum and ferric chloride precipitation. The best precipitation test results achieved for each liquid residuals sample are presented in Table 3-9. The Table lists the coagulant and coagulation conditions that yielded the greatest reduction in arsenic.

As shown in Table 3-9, ferric chloride precipitation was effective for removing 88 to more than 99 percent of arsenic from all residuals samples except Ion Ex (B). Total arsenic concentrations remaining in the supernatant ranged from 0.007 to 0.078 mg/L for all samples, except for the activated alumina regenerant and ion exchange regenerant streams. The ion exchange and activated alumina regenerants had much higher initial total arsenic concentrations, so comparable arsenic reductions of 94 and 88 percent for the activated alumina and Ion Ex (A) resulted in much higher supernatant arsenic concentrations (0.154 mg/L and 1.28 mg/L). Table 3-9 shows that for the SFBW, the SFBW/ACF blend, RO (A), and NF (B), the total arsenic concentration remaining in the supernatant water was reduced to below 0.05 mg/L, and supernatant arsenic levels less than 0.10 mg/L were attained in precipitation tests for RO (B) and NF (A).

In general, addition of polymer did not have a significant impact on arsenic removals achieved using the best ferric chloride condition alone, but did result in small improvements in some cases. The pH that resulted in best arsenic removals with ferric chloride was in the range of pH 5.0 to 6.7. Greatest benefit in depressing pH for arsenic removal was achieved with ion exchange regenerants and one reverse osmosis concentrate stream, which had much higher alkalinity (1,000 mg/L or greater) than the other residuals streams. For example, As removal was about three times higher at pH 6 to 6.3 (82 percent) compared to pH 7.5 (30 percent) for RO (A) with 100 mg/L of ferric chloride.

Table 3-9. Summary of precipitation testing

Residuals stream	Best precipitation conditions						Super-natant water arsenic conc. (mg/L)	Percent arsenic removed (%)
Sample ID	Total arsenic conc. (mg/L)	Coagulant type	Dose (mg/L)	Fe:As* molar ratio	Polymer (mg/L)	Coagulation pH (units)		
AA regenerant	2.63	$FeCl_3$	50	8.8	0	7.0	0.154	94.1
Ion Ex (A)								
Composite	10.5	$FeCl_3$	100	4.4	0	6.2	1.28	87.8
Brine	33.2	$FeCl_3$	100	1.4	0	8.8	4.35	86.9
Ion Ex (B)	24.8	$FeCl_3$	200	3.7	0.5†	6.2	18.7	29.4
RO (A)	0.546	$FeCl_3$	150	127	2†	6.0	0.041	92.5
RO (B)	0.663	$FeCl_3$	100	70	0	6.2	0.078	88.2
NF (A)	0.523	$FeCl_3$ or Alum	150	133	4†	5.0 7.0	0.060	88.4
NF (B)	0.486	$FeCl_3$	150	143	4†	6.2	0.005	98.9
SFBW (A)								
Composite	1.41	$FeCl_3$	50	16.4	4‡	7.1	0.013	99.1
Settled comp.	1.41	None	0	None	0	7.6	0.007	99.5
SFBW/ACF (B)								
Composite	1.74	$FeCl_3$	75	19.9	0	6.2	0.070	96.0
Settled comp.	0.043	$FeCl_3$	100	1,075	0	6.5	0.011	74.4

*Based on Fe added as coagulant (does not consider Fe in the untreated wastewater).
†Cationic LT 22S
‡Anionic A3040 LTR

The best ferric chloride coagulation conditions for each residuals sample tested were used to determine the total arsenic removal achieved as a function of the total amount of iron that was present in untreated residuals samples, plus the iron added by ferric chloride addition. Limited volumes of residuals allowed for a screening of treatment conditions, but not a determination of optimal conditions in each case. The parameters used for these calculations are shown in Table 3-10.

level. Observed removals ranged from approximately 0.0005 mol As/mol Fe to 0.05 mol As/mol Fe at treated arsenic concentrations ranging from 0.0001 mg/L to 0.1 mg/L. By comparison, removals in this work were similar, ranging from approximately 0.005 to 0.017 mol As/mol Fe at supernatant arsenic concentrations of 0.005 mg/L to 0.078 mg/L.

Precipitation results can also be examined using a linear adsorption isotherm relationship described by Herring *et al.*

Table 3-10. Parameters used for calculating the arsenic removal versus iron applied (best ferric chloride precipitation test data)

			Untreated residuals		Residuals plus coagulant	Treated settled water (supernatant)	
Sample ID	Coag. pH (units)	$FeCl_3$ dose (mg/L as Fe)	Fe conc. (mg/L)	As conc. (mg/L)	Total Fe* conc. (mg/L)	Fe conc. (mg/L)	As conc. (mg/L)
SFBW (A)	7.1	17	78.50	1.41	95.5	1.57	0.013
SFBW/ACF (B)	7.2	26	45.90	1.74	71.9	2.66	0.064
Ion Ex (A)	6.2	34	0.49	10.5	34.5	3.51	1.28
Ion Ex (B)	6.2	68	0.01	24.8	61.0	7.89	18.7
RO (A)	6.0	51	0.07	0.5	51.0	0.02	0.041
RO (B)	6.2	34	0.86	0.7	34.9	3.22	0.078
NF (A)	5.2	68	2.16	0.5	70.2	1.41	0.009
NF (B)	6.2	51	0.46	0.5	51.4	0.47	0.005
AA Regenerant	7.0	17	0.83	2.6	17.8	1.15	0.154

*Total iron, iron in untreated wastewater plus iron added as $FeCl_3$.

For each residuals sample, Table 3-10 shows the best ferric chloride dose expressed in mg/L as iron and the iron concentration in the untreated residuals. The untreated and treated total arsenic concentrations used for calculating arsenic removal are also shown in Table 3-10. Figure 3-8 depicts arsenic removal in terms of mg As removed per mg Fe present (total). The figure shows that the ratio of mg As removed/mg Fe ranged from 0.007 to 0.267. With the exception of the AA regenerant and Ion Ex (A and B) wastewaters, the ratio ranged from 0.007 to 0.023 mg As removed/mg Fe in solution, or 0.005 to 0.017 mol As/mol Fe. The amount of iron in solution included the background iron content of the untreated sample along with the contribution from ferric chloride added.

Edwards (1994) synthesized all previously published work on arsenic coagulation in water treatment, calculated moles of arsenate removed per mole trivalent ion added, and plotted the calculated results as a function of final treated arsenic

(1996) and McNeill and Edwards (1997). The simplified isotherm equation described by the authors suggests that the amount of arsenic adsorbed or removed is primarily a function of the amount of adsorbent available. The equation strictly applies for low concentrations of dissolved arsenic and only as long as surface sites are not saturated by adsorbed arsenic or by competing species. Table 3-11 shows amount of arsenic removed per amount of iron removed in ferric chloride precipitation tests, along with the corresponding adsorption coefficient (K) calculated using the isotherm relationship. K values in this project ranged from 13 mM^{-1} to 105 mM^{-1}, compared to 80 mM^{-1} to 120 mM^{-1} reported by McNeill and Edwards (1997). Thus, the isotherm relationship may also be useful for evaluating precipitation experiments conducted on arsenic-containing residuals samples with higher arsenic concentrations.

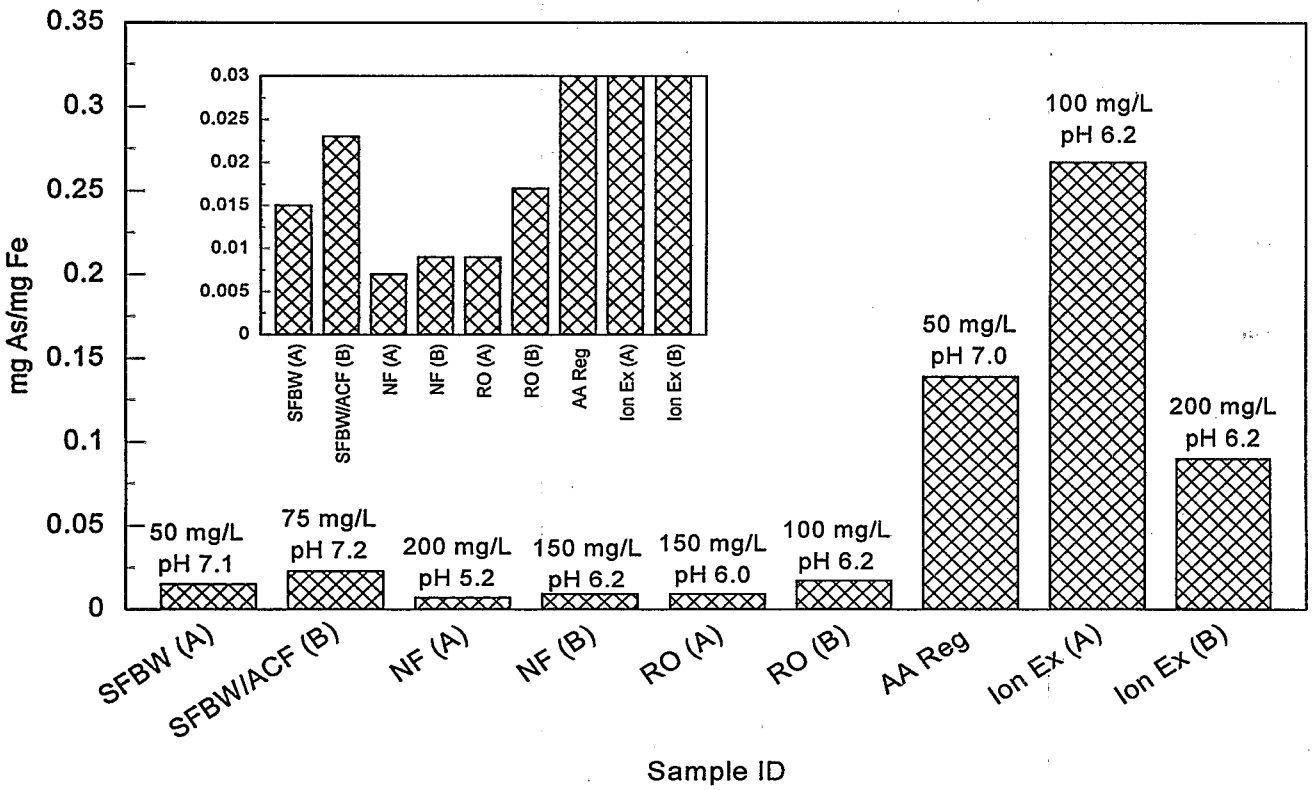


Figure 3-8. Total arsenic removal achieved per milligram of iron in solution using ferric chloride precipitation

Table 3-11. Alternative evaluation of arsenic removal by precipitation (best ferric chloride precipitation test data)

	$FeCl_3$ dose (mg/L as Fe)	As removed (mg/L)	As removed (percent)	mg/L As removed per mg/L Fe in solution	mg/L As removed per mg/L Fe removed	K* (mM^{-1})
SFBW (A)	17	1.397	99.1	0.015	0.015	63.9
SFBW/ACF (B)	26	1.676	96.3	0.023	0.024	21.1
Ion Ex (A)	34	6.990	66.6	0.267	0.298	3.6
Ion Ex (B)	68	6.100	24.6	0.090	0.102	0.3
RO (A)	51	0.485	92.2	0.009	0.010	12.9
RO (B)	34	0.585	88.2	0.017	0.018	13.2
NF (A)	68	0.514	98.3	0.007	0.008	46.4
NF (B)	51	0.461	99.0	0.009	0.009	105.4
AA Regenerant	17	2.47	94.1	0.139	0.148	53.8
AA Regenerant (accounting for Al)	17	2.47	94.1	---	0.011*	3.8*

*Accounts for aluminum.

The K values indicate possible interference in precipitating arsenic from ion exchange residuals. Interference in the high alkalinity ion exchange regenerant streams is likely due to carbonate complexing of the iron, and higher iron dosages would be required to achieve higher arsenic removals. Also, Clifford *et al.* (1999) found that much higher molar ratios of iron to arsenic were required to successfully remove arsenic from an ion exchange brine than those applied in this work, again suggesting that higher iron dosages (more adsorbent) would be needed. In this work it was not practical to apply the higher molar ratios, because corresponding coagulant dosages were approximately 500 mg/L to 3,500 mg/L.

The K value for the AA regenerant sample decreased substantially when the aluminum removed was considered in addition to the iron. The K value when aluminum was accounted for was in line with that for the ion exchange samples, even though arsenic removal from the AA regenerant was much better (94 percent compared to 25 to 67 percent). While arsenic in the ion exchange composite samples was nearly all dissolved, most of the arsenic in the AA regenerant was incorporated into the solids, suggesting that precipitation for removal of arsenic from AA is defined by more than the sorption mechanism, and should focus on suspended solids removal.

3.3.8 Residual Iron and Aluminum Concentrations

Analysis for each precipitation test conducted using alum or ferric chloride included a total metals analysis to determine the supernatant iron or aluminum concentration remaining. The iron concentration for each residuals sample was also determined during the raw characterization testing, while the aluminum concentration was only measured in the supernatant from alum precipitation tests. A comparison of the initial and final iron concentration after precipitation using the best conditions for arsenic removal is presented in Figure 3-9. The figure demonstrates that the SFBW and SFBW/ACF blend had very high initial iron concentrations that were reduced to less than 3 mg/L after ferric chloride precipitation. Iron concentrations in the other residuals increased after dosing with ferric chloride for precipitation.

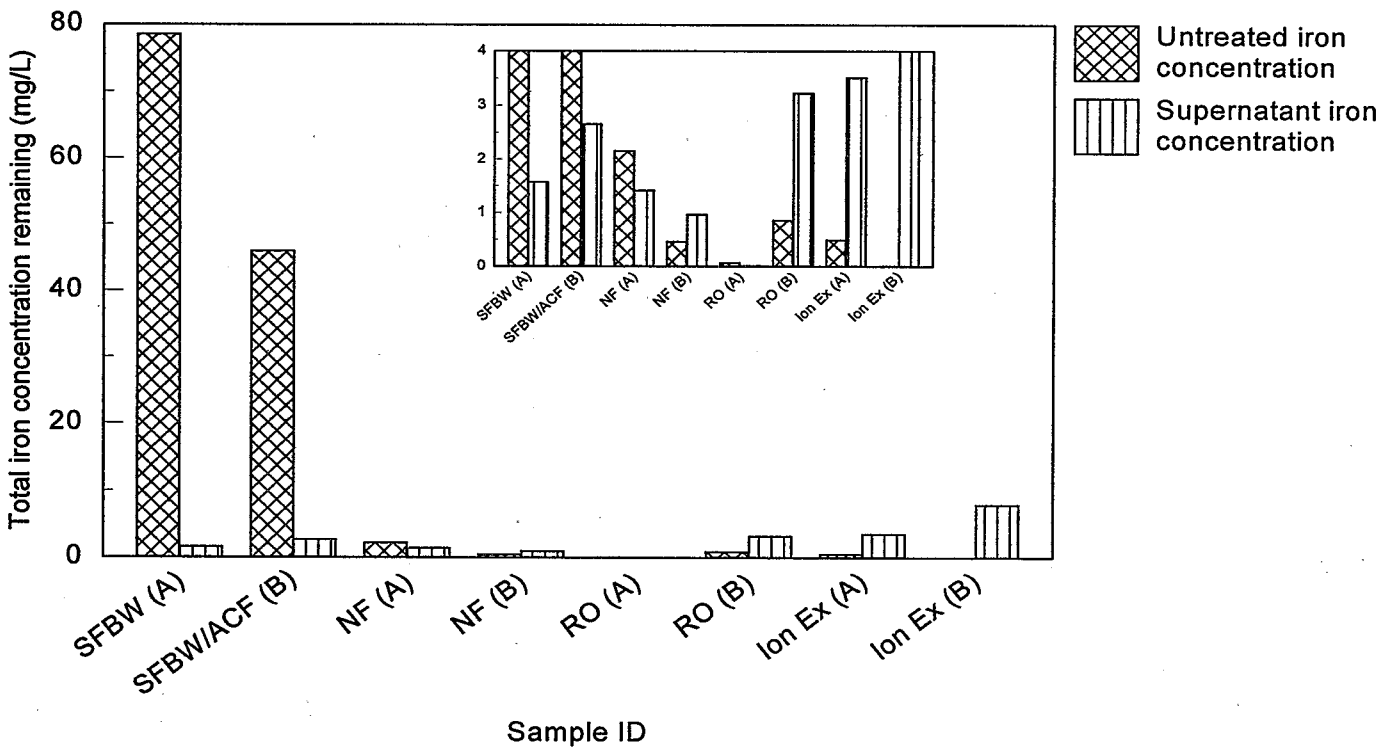


Figure 3-9. Comparison of iron concentrations in untreated residuals versus supernatant iron concentrations after precipitation using ferric chloride

For RO (B) and Ion Ex (A) and (B), at the best precipitation treatment conditions based on arsenic removal, iron levels in the supernatant were greater than 3 mg/L.

Aluminum concentrations measured in the supernatant corresponding to the best conditions for arsenic removal ranged from less than 0.5 mg/L for SFBW (A) to more than 7.0 mg/L for the AA regenerant (see Table 3-12). As would be expected, the untreated AA regenerant contained a very high level of aluminum, 113 mg/L. Supernatant aluminum levels in the ion exchange tests were 4 to 6 mg/L, and were about 3 mg/L in RO alum precipitation tests. Residual aluminum concentrations in the supernatant were lowest for the nanofiltration, SFBW, and SFBW/ACF blend samples, about 0.4 to 0.8 mg/L, in which alum precipitation yielded arsenic reductions of 85 percent or higher.

Table 3-12. Aluminum concentrations in the supernatant following alum precipitation

Sample ID	Aluminum supernatant concentration (mg/L)
AA regenerant*	7.42
Ion Ex (A)	3.73
Ion Ex (B)	5.82
RO (A)	2.76
RO (B)	3.09
NF (A)	0.673
NF (B)	0.654
SFBW (A)	0.429
SFBW/ACF (B)	0.762

*After ferric precipitation

3.3.9 TCLP Test Results

During precipitation testing using alum and ferric chloride, SFBW/ACF (B) generated a high enough volume of settled sludge to perform a TCLP analysis. Sludge solids were separated from supernatant in eight different precipitation tests conducted on SFBW/ACF (B) to perform TCLP tests. Also, two sludge samples were collected following gravity settling of the SFBW wastes without chemical addition. The test conditions, untreated residuals arsenic levels, and supernatant arsenic concentrations are shown along with TCLP results for these tests in Table 3-13. The percent solids for these thickened residuals samples was in the 6 to 8 percent range. The highest TCLP arsenic concentration was 0.021 mg/L, which is significantly lower than the existing EPA TCLP limit of 5 mg/L.

3.4 Adsorption Test Results

Because of limited quantities of residuals samples, adsorption tests could not be run to exhaustion. The purpose of these tests, therefore, was to assess the potential of various media to remove arsenic from liquid residuals streams and not to determine ultimate adsorption capacities or evaluate media exhaustion.

3.4.1 Ion Exchange Regenerants

Adsorption tests were conducted using both Ion Ex (A) brine and composite regenerant samples. The adsorption media used for testing included an iron-based media and an activated alumina media. Two adsorption tests were

Table 3-13. TCLP results from precipitation and settling tests

Sample ID	Coagulant	Dose (mg/L)	Coagulation pH (units)	Untreated residuals arsenic conc. (mg/L)	Supernatant arsenic conc. (mg/L)	TCLP arsenic conc. (mg/L)
Precipitation tests						
SFBW/ACF (B)	$FeCl_3$	75	7.2	1.74	0.064	<0.002
SFBW/ACF (B)	$FeCl_3$	100	6.7	1.74	0.110	<0.002
SFBW/ACF (B)	$FeCl_3$	75	6.2	1.74	0.070	<0.002
SFBW/ACF (B)	$FeCl_3$	100	6.1	1.74	0.075	<0.002
SFBW/ACF (B)	Alum	75	7.3	1.74	0.194	0.003
SFBW/ACF (B)	Alum	100	7.1	1.74	0.248	<0.002
SFBW/ACF (B)	Alum	75	6.1	1.74	0.205	0.018
SFBW/ACF (B)	Alum	100	6.1	1.74	0.214	0.006
Settling tests						
SFBW (A)	None	---	7.6	1.41	0.007	<0.002
SFBW/ACF (B)	None	—	8.1	1.74	0.122	0.021

conducted using the Ion Ex (A) composite regenerant sample using iron media EBCTs of 1.5 and 3 min. Ghurye *et al.* (1999) used the same EBCTs and found that decreasing the EBCT from 3.0 to 1.5 min did not greatly alter breakthrough of As into the product water. Results from adsorption tests are presented in Figure 3-10. The iron-based media removed 60 percent of the arsenic from the raw water up to 100 BV for both the 1.5 and 3 min EBCT tests. The corresponding arsenic concentration after 100 BV was 3.80 mg/L for the 3 min EBCT test. After 100 BV, the arsenic removal significantly decreased. The effluent arsenic concentration from the 1.5 min EBCT test was 7.02 mg/L after 240 BV.

The Ion Ex (A) brine sample was also treated using the iron media (1.5 min EBCT) and the activated alumina media (1.5 min EBCT). The results from these tests demonstrated that neither media was effective for removing arsenic from the Ion Ex (A) brine, perhaps because of the very high alkalinity of the sample. The total arsenic concentration remaining after 100 BV with AA adsorption was 11.5 mg/L.

Adsorption tests were conducted using only the Ion Ex (B) regenerant composite sample that had an arsenic content of 24.8 mg/L. Two adsorption tests were conducted using the iron-based media and activated alumina media at a 3-min EBCT. The iron media adsorption test was conducted for a total of six hours (120 BV), and samples were collected after each hour of operation. The arsenic concentrations in the effluent are plotted versus the total bed volumes of sample treated in Figure 3-11. The results indicate that arsenic removal from the composite sample using the iron adsorption media was poor. After only 40 BV, the arsenic removal was less than 35 percent, and 16.7 mg/L of arsenic was measured in the column effluent. Arsenic reduction declined to less than 10 percent after 120 BV. The poor arsenic removal may again be attributable to the very high alkalinity of the sample.

The activated alumina adsorption test was also conducted for 120 BV, or six hours of operation at the 3-min EBCT. The activated alumina media removed less than 10 percent of the arsenic concentration after 40 BV, while only 3 percent of the arsenic was removed after 120 BV.

3.4.2 RO Concentrates

RO (A) concentrate was treated using both the iron-based media at 1.5 and 3 min EBCTs and activated alumina media at a 3 min EBCT. The results of these tests are presented in Figure 3-12. These data indicate that the iron-based media with a 3 min EBCT provided the greatest arsenic removal from the RO (A) concentrate. In that test, the total arsenic concentration was reduced by 77 percent to 0.119 mg/L up to 80 BV. The corresponding arsenic concentration for the 1.5-min EBCT test was 0.211 mg/L after 80 BV. By comparison, activated alumina adsorption at a 3-min EBCT lowered the total arsenic concentration by just 26 percent to 0.389 mg/L after 80 BV of water was passed through the column.

The effectiveness of the iron-based media and activated alumina were also evaluated for removing arsenic from RO (B) concentrate. Adsorption tests were conducted using EBCTs of both 1.5 and 3 min for each of the two adsorption medias. The results from the four adsorption tests are presented in Figure 3-13. These data indicate that the iron-based media outperformed the activated alumina media, resulting in arsenic reductions of 95 percent or greater at 120 BV. Arsenic reduction for the 1.5-min EBCT test decreased to 84 percent after 240 BV when the arsenic level in the column effluent increased to 0.106 mg/L.

The activated alumina was also effective for arsenic removal from the RO (B) concentrate. AA adsorption at a 3-min EBCT reduced the effluent total arsenic concentration by 89 percent to 0.071 mg/L after 120 BV, compared to 56 percent at a 1.5-min EBCT. For both test media, increasing the EBCT increased arsenic removal from the RO (B) concentrate.

The greatest difference in the quality of the two untreated RO concentrate samples was alkalinity. While the alkalinity of RO (B) was 600 mg/L (as $CaCO_3$), the alkalinity of RO (A) was more than four times as high at 2,800 mg/L. The much poorer arsenic removal attained in adsorption tests with RO (A) may be due to interference from the alkalinity.

3.4.3 Nanofiltration Concentrates

Nanofiltration (A) concentrate was treated using an iron-based media, activated alumina media, ion exchange resin, and modified alumina. A total of six adsorption tests were performed; iron-based media (3 and 6 min EBCT), ion exchange (3 min EBCT), activated alumina (3 and 6 min EBCT), and modified alumina media (3 min EBCT). The spiked total arsenic concentration of the nanofiltration concentrate was 0.486 mg/L prior to treatment. The results for all six tests are presented in Figure 3-14. Both the iron media and the activated alumina media tests with 3-min EBCT provided greater than 90 percent removal of arsenic up to 120 BV treated, with corresponding effluent arsenic levels of 0.021 mg/L and 0.034 mg/L, respectively. The arsenic removal provided by the activated alumina and iron media were also very similar using a 6 min EBCT; after 60 BV the effluent total arsenic concentration was less than 0.007 mg/L for both.

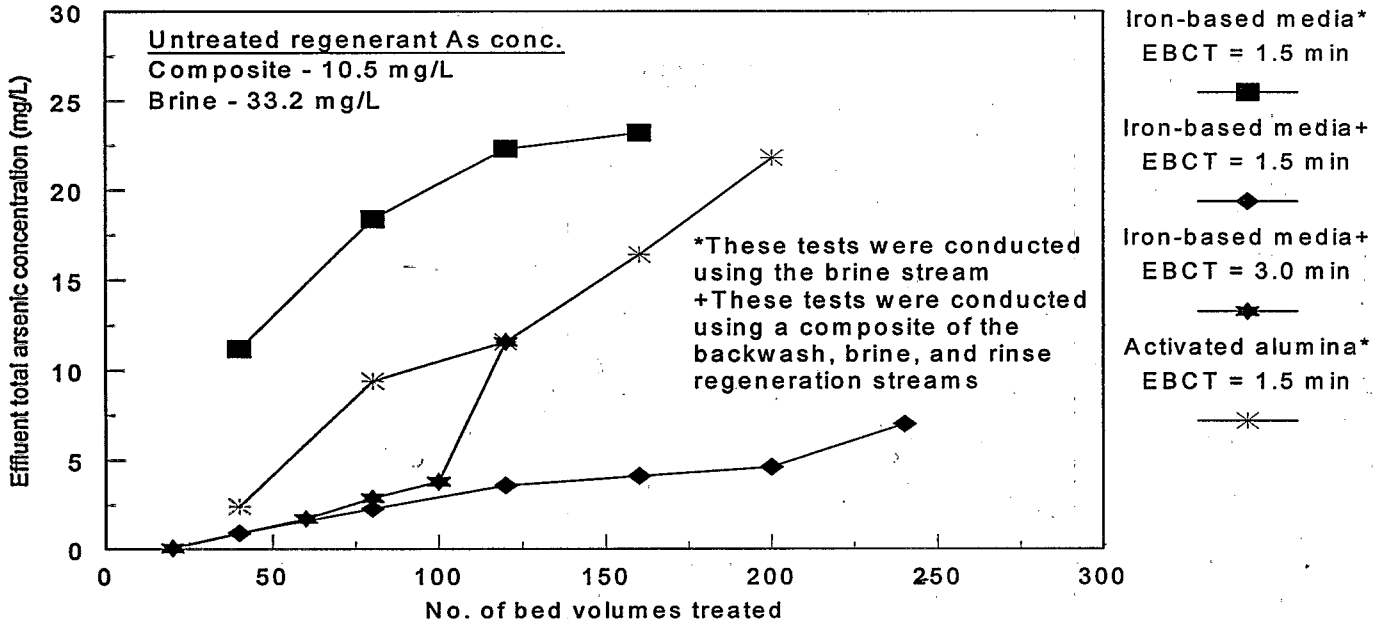


Figure 3-10. Treatment of ion exchange (A) regenerant with iron-based media and activated alumina

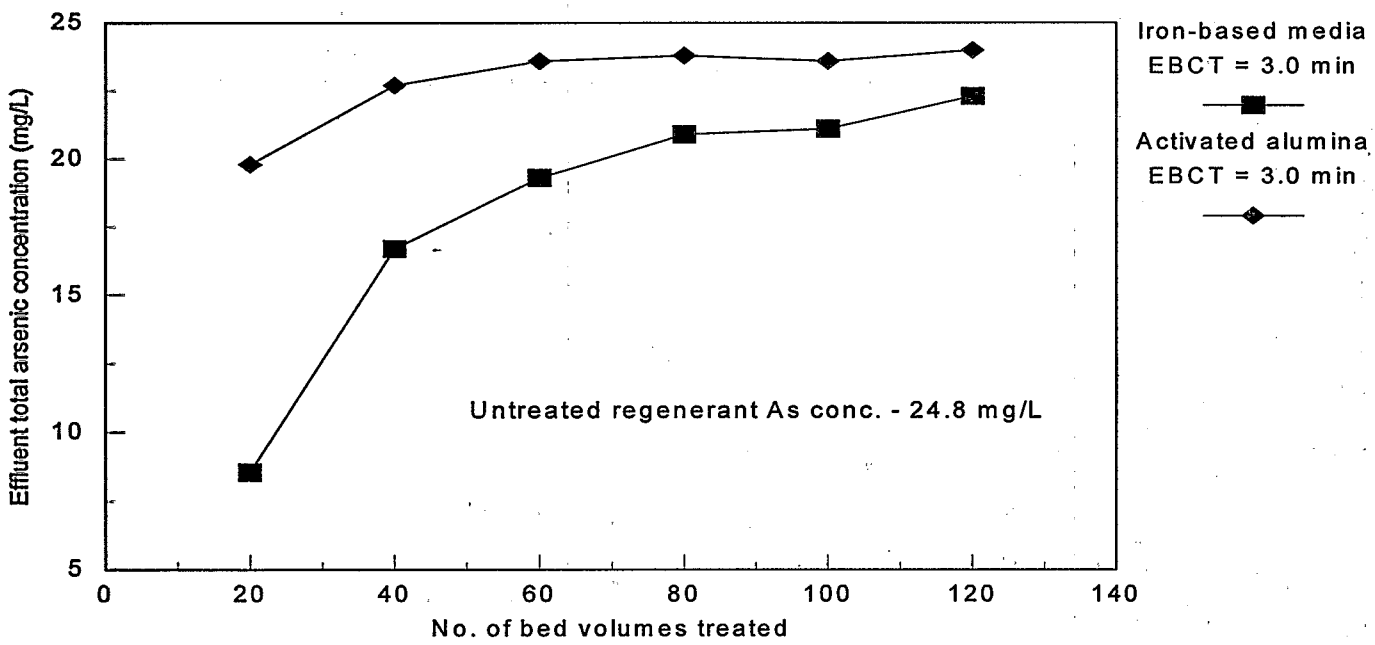


Figure 3-11. Treatment of ion exchange (B) regenerant with iron-based media and activated alumina

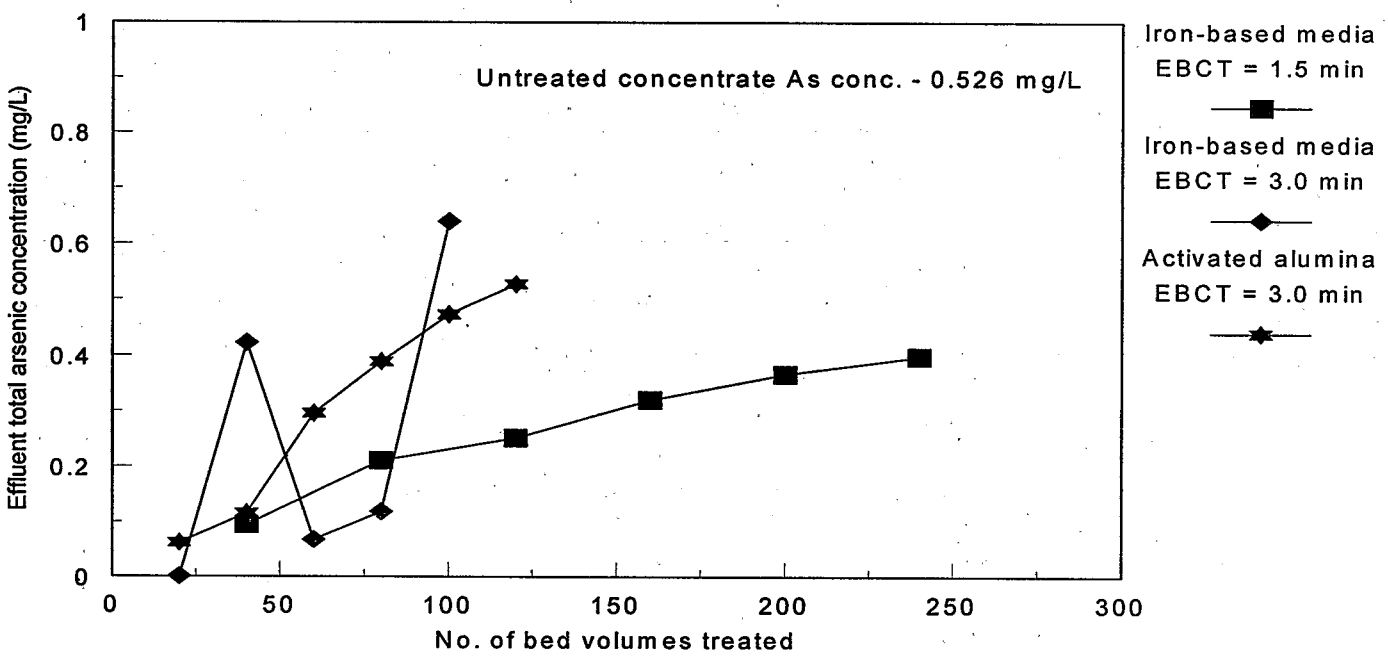


Figure 3-12. Treatment of reverse osmosis (A) concentrate with iron-based media and activated alumina

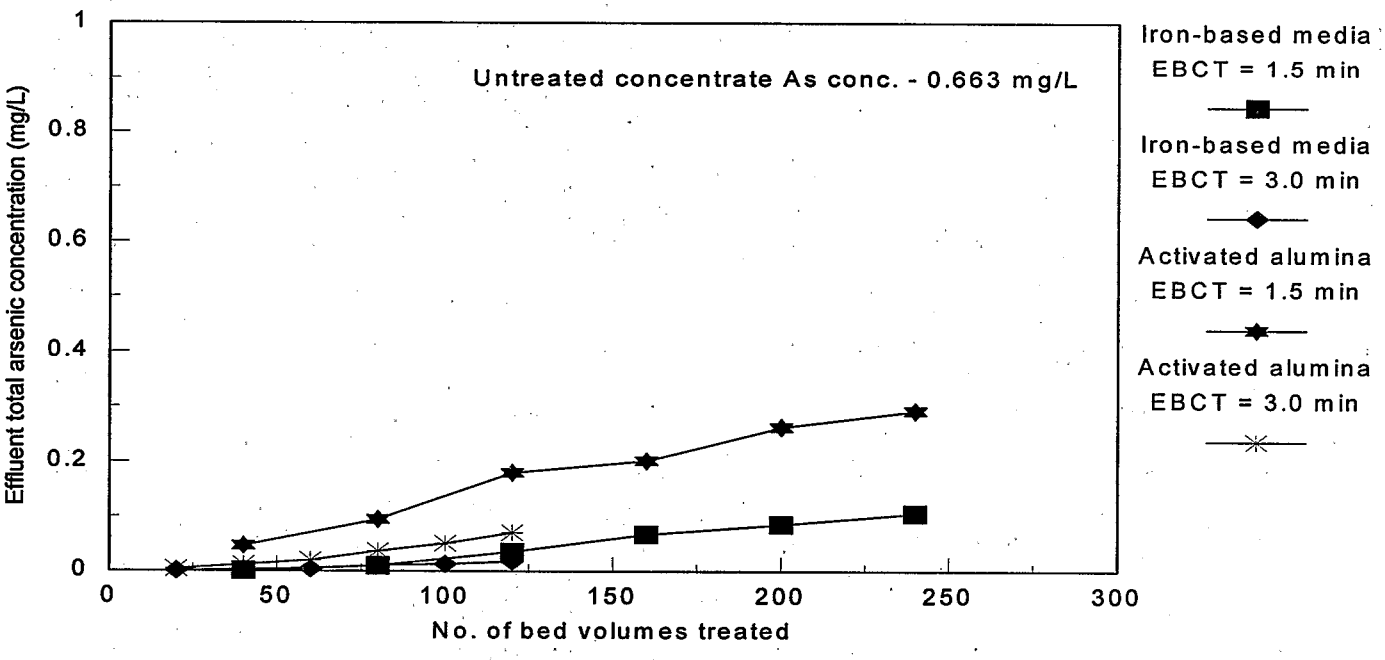


Figure 3-13. Treatment of reverse osmosis (B) concentrate with iron-based media and activated alumina

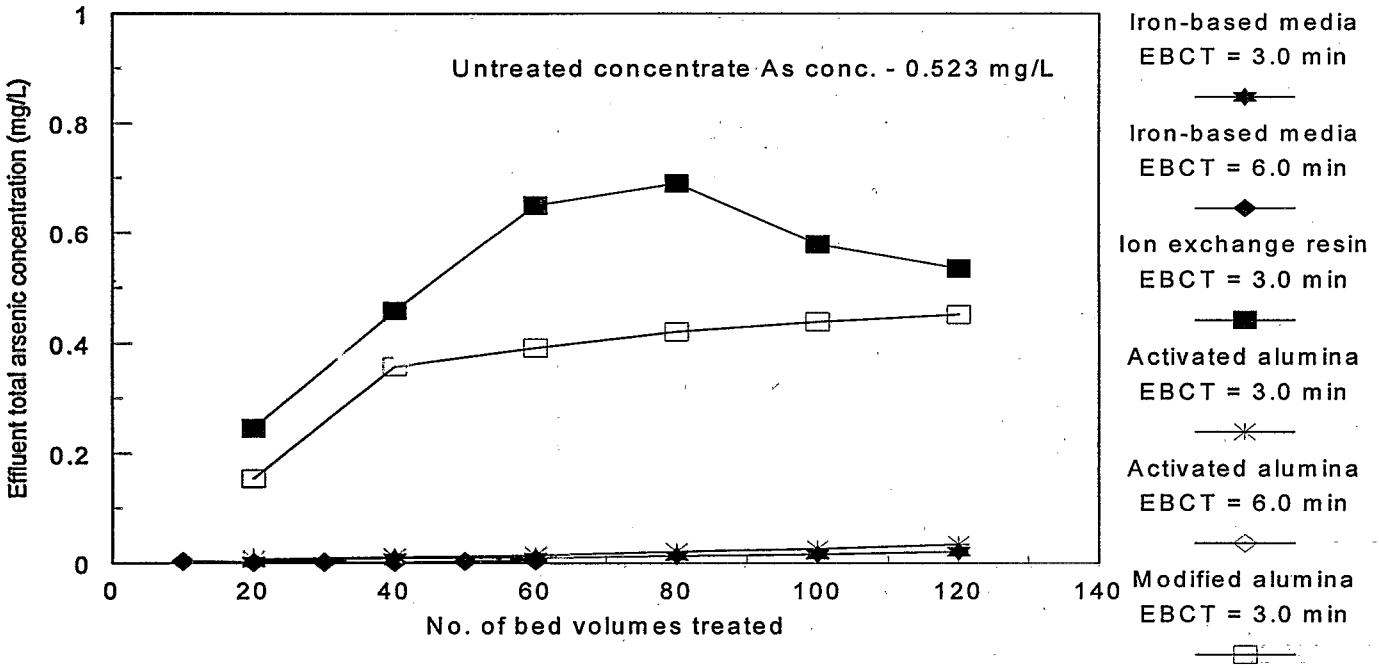


Figure 3-14. Treatment of nanofiltration (A) concentrate with iron-based media, an ion exchange resin, and activated alumina

After 40 BV passed through the column, the ion exchange resin was exhausted. The modified alumina media was also ineffective for removing arsenic from the concentrate. This media only achieved 28 percent removal after 120 BV of sample were treated.

Nanofiltration (B) concentrate was also treated using the same four test adsorption medias and EBCTs as used for the NF (A) concentrate. NF (B) concentrate had a spiked total arsenic concentration of 0.486 mg/L. The test results showed that both the iron media and activated alumina media were able to remove greater than 99 percent of the arsenic, achieving arsenic levels below the detection limit of 0.002 mg/L, using either a 3- or 6-min EBCT (see Figure 3-15). The ion exchange resin and modified alumina media removed less than 10 percent of the arsenic up to 120 BV of sample treated.

3.4.4 Iron Removal Plant Residuals

SFBW (A) (mixed/unsettled sample) was treated using both the iron-based media (1.5 and 4.5 min EBCT) and activated alumina media (1.5 min EBCT). The results from these adsorption tests are presented in Figure 3-16. These data indicate that neither media was effective for removing arsenic from SFBW (A). No removal was achieved using the activated alumina media, and only a limited amount of removal (24 percent after 80 BV) was achieved using the iron media (4.5 min EBCT). The very poor arsenic removal for these tests was attributed to the high solids loading to the adsorption column; the SFBW (A) was a mixed, non-settled sample.

Following these tests, the test procedure was modified to include settling prior to adsorption tests for high solids waste streams. The settled SFBW/ACF (B) water arsenic concentration applied to the adsorption column was less than 0.15 mg/L. Ion exchange, iron media, and activated alumina were used to treat the settled SFBW at an EBCT of 3-min. The test results show that close to 100 percent of the arsenic remaining was removed by each media tested. All measured arsenic concentrations were less than the detection limit of 0.002 mg/L, which is well below an in-stream arsenic limit of 0.05 mg/L that is in place in some states.

3.4.5. Adsorption Test Summary

A summary of the best adsorption conditions for each wastewater sample tested, along with the lowest arsenic concentration achieved, is presented in Table 3-14, while Appendix Table A-4 shows all data generated in adsorption tests. The data indicate that only four of the residuals samples were successfully treated using the various adsorption media. These were RO (B) concentrate, NF (A) and NF (B) concentrate, and settled SFBW/ACF (B).

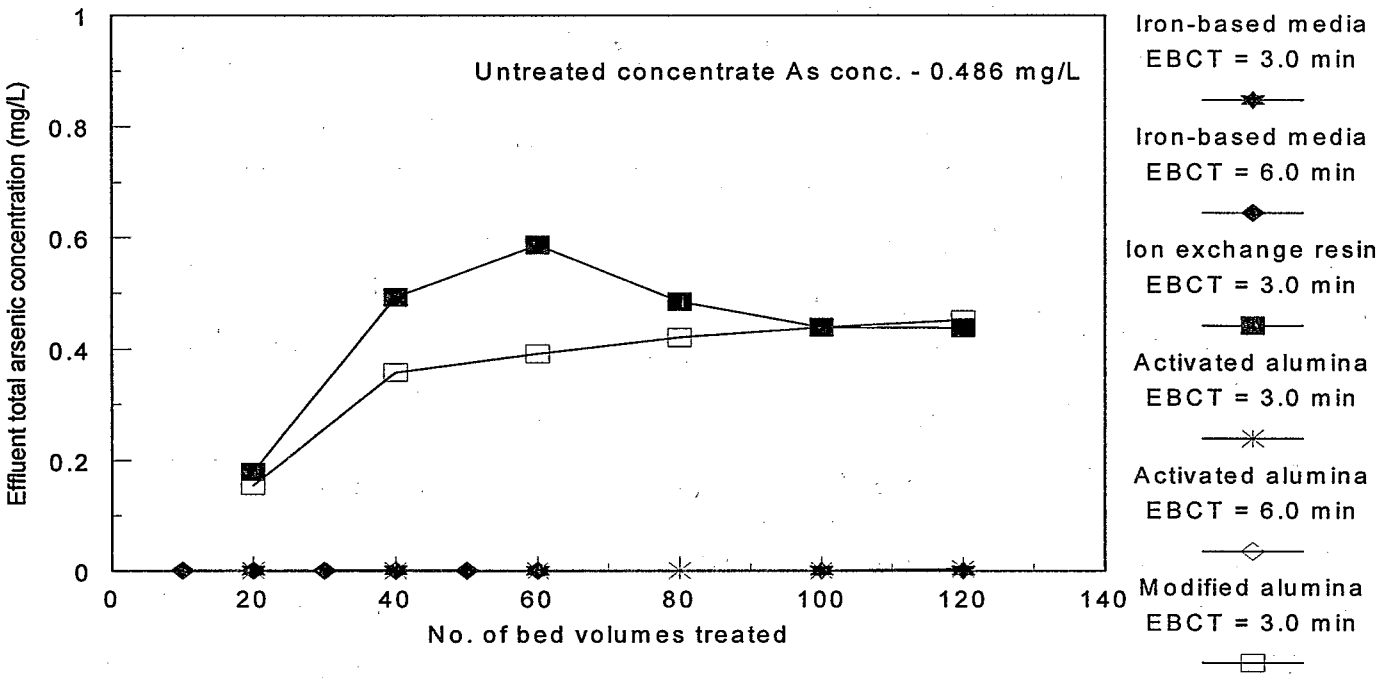


Figure 3-15. Treatment of nanofiltration (B) concentrate with iron-based media, an ion exchange resin, and activated alumina

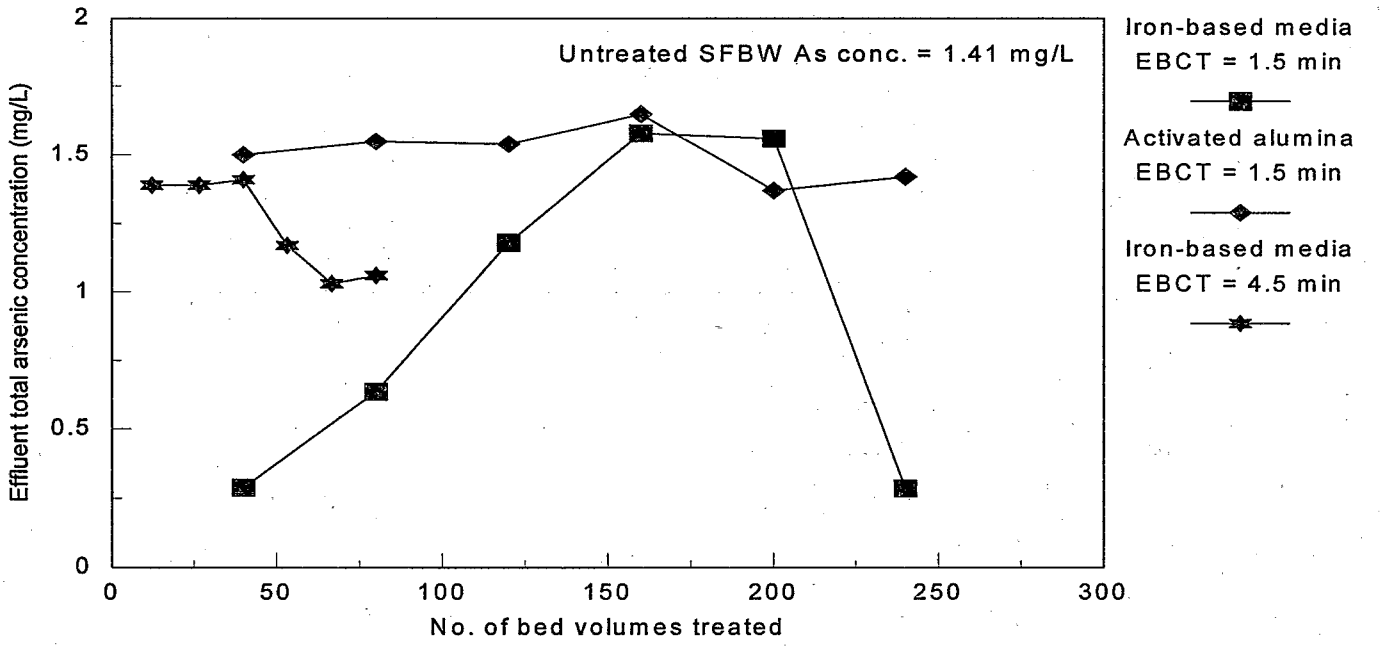


Figure 3-16. Treatment of iron removal plant spent filter backwash water A (unsettled) with iron-based media and activated alumina

Table 3-14. Summary of adsorption test results

Residuals stream		Best adsorption conditions					
Sample ID	Total arsenic concentration (mg/L)	Adsorption media	EBCT	No. of bed volumes treated	pH	Arsenic conc.* (mg/L)	Percent arsenic reduction
Ion Ex (A)	10.5	Iron-based media	3.0	100	9.0	3.81	63.7
Ion Ex (B)	24.8	Iron-based media	3.0	120	9.9	22.3	10.0
RO (A)	0.546	Iron-based media	3.0	80	7.5	0.119	77.4
RO (B)	0.663	Iron-based media	3.0	120	7.3	0.018	97.3
NF (A)	0.523	Iron-based media or activated alumina	3.0	120	7.1	0.030	94.0
NF (B)	0.486	Iron-based media or activated alumina	3.0	120	6.6	<0.002	99.8
SFBW (A)†	1.41	Iron-based media	4.5	80	7.6	1.06	24.8
SFBW/ACF (B) (settled blend)	0.043	Iron-based media, activated alumina, or ion exchange	3.0	120	8.1	<0.002	97.8

*Arsenic concentration remaining in column effluent sample collected after the number of BV listed had passed through the media.

The table shows that none of the media tested was successful at removing arsenic from either of the ion exchange regenerant waste waters. The maximum removal achieved was 64 percent for the Ion Ex (A) composite, however, the resulting effluent arsenic concentration was nearly 4 mg/L.

Adsorption worked best for removing arsenic from the two nanofiltration concentrates and one of the RO concentrate samples. Both the iron media and activated alumina were equally effective for treating the nanofiltration concentrates (NF (A) and NF (B)), while the iron-based media worked best for removing arsenic from the RO (B) concentrate. For all three of these samples, the arsenic concentration was reduced to less than 0.05 mg/L. Due to the very low arsenic concentration in the settled SFBW/ACF (B) sample, all three adsorption/exchange medias tested (iron-based media, activated alumina, and ion exchange resin) were able to remove nearly 100 percent of the arsenic. Adsorption yielded the poorest arsenic removal for the ion exchange samples and RO (A), which were the three residuals samples with the highest alkalinity, suggesting that alkalinity was an interference.

3.5 Comparison of Treatment Processes

The precipitation and adsorption test results were compared to determine which treatment technique was most effective for removing total arsenic from each residuals sample. Treatment comparison was based on the concentration of total arsenic remaining in the supernatant or column effluent water after treatment.

3.5.1 SFBW (A) and SFBW/ACF (B)

A total of six treatment processes were used to treat the SFBW and SFBW/ACF blend (settled and unsettled) samples. These tests included gravity settling, alum and ferric chloride precipitation, iron-based media adsorption, AA adsorption, and anion exchange. The results from these tests are presented in Figure 3-17. Adsorption was only effective for SFBW/ACF (B), which was settled prior to passing it through the adsorption column. Gravity settling without chemical addition for SFBW/ACF (B) reduced the total arsenic concentration by 97.5 percent to 0.043 mg/L. Ferric chloride precipitation was also effective for removing arsenic from the unsettled SFBW (A) and SFBW/ACF (B) yielding supernatant concentrations of 0.013 mg/L and 0.064 mg/L, respectively. By comparison, alum precipitation of SFBW (A) resulted in a supernatant concentration of 0.021 mg/L (98.5 percent reduction). These supernatant arsenic levels attained through precipitation were near or below the in-stream standard of 0.05 mg/L that is in effect in some states.

Overall, the optimal treatment scheme for arsenic removal from SFBW (A) and SFBW/ACF (B), depending on the treated total arsenic concentration required, would include gravity settling to lower the TSS concentration, and possibly coupling that with either ferric chloride precipitation or an adsorption process.

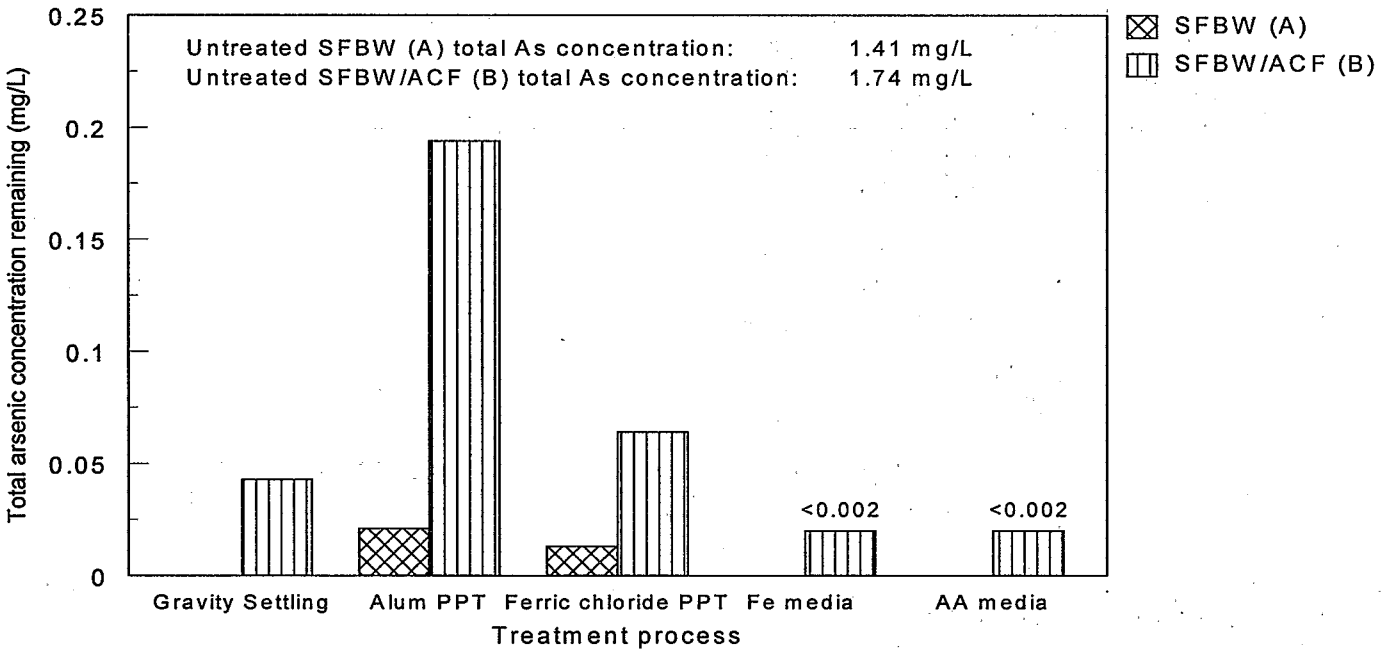


Figure 3-17. Comparison of treatment processes for removing arsenic from iron removal plant residuals-filter backwash and spent filter backwash/adsorption clarifier flush blend

3.5.2 RO (A) and (B) Concentrates

RO concentrate samples A and B were each treated using alum and ferric precipitation and adsorption using an iron-based media and AA. Treatment results are compared in Figure 3-18. As shown in the figure, ferric chloride precipitation was the best treatment for RO (A), yielding a total arsenic level in the supernatant of 0.015 mg/L, while adsorption with an iron-based media was best for RO (B). With the iron-based media, total As in the column effluent was 0.02 mg/L after 120 BV. It should be noted that while the iron-based media adsorption treatment provided the best removal arsenic from the RO (B) concentrate, the final arsenic concentration was analyzed after only 120 BV. Alum precipitation and activated alumina adsorption were not effective for removing arsenic from these two RO concentrate samples. For both RO concentrate streams, arsenic levels were reduced below an in-stream level of 0.05 mg/L.

3.5.3 Nanofiltration (A) and (B) Concentrates

Nanofiltration concentrate samples A and B were each treated using alum and ferric chloride precipitation and adsorption using all four test medias (iron media, AA, ion exchange, and modified alumina). The resulting treated water arsenic concentrations are shown graphically in Figure 3-19. Ferric chloride precipitation lowered the total arsenic concentration from NF (A) to 0.009 mg/L and from NF (B) to 0.005 mg/L. Alum precipitation was slightly less effective for arsenic removal from the NF concentrates tested, however, total arsenic was reduced to below 0.05 mg/L using alum. Only the iron-based media and activated alumina media were effective for removing arsenic from the NF concentrates in adsorption tests. The iron-based media provided the best total arsenic removal from both NF (A) and NF (B), yielding effluent As concentrations of 0.021 mg/L and <0.002 mg/L, respectively. Based on these data, either precipitation or adsorption would be viable treatment options for total arsenic removal to achieve a total arsenic concentration below 0.05 mg/L.

3.5.4 Ion Exchange Regenerant (A) and (B) Composite Streams

Due to the very high total arsenic concentrations present in the Ion Ex (A) and Ion Ex (B) wastewaters (230 to 270 times the concentrations in the corresponding source waters), the supernatant and effluent total arsenic concentrations resulting from precipitation and adsorption treatments were greater than 1.0 mg/L. A comparison of the total arsenic concentrations remaining for each treatment option is shown graphically in Figure 3-20. These data indicate that ferric chloride precipitation provided the best overall treatment, however, for the dosages tested, the total arsenic

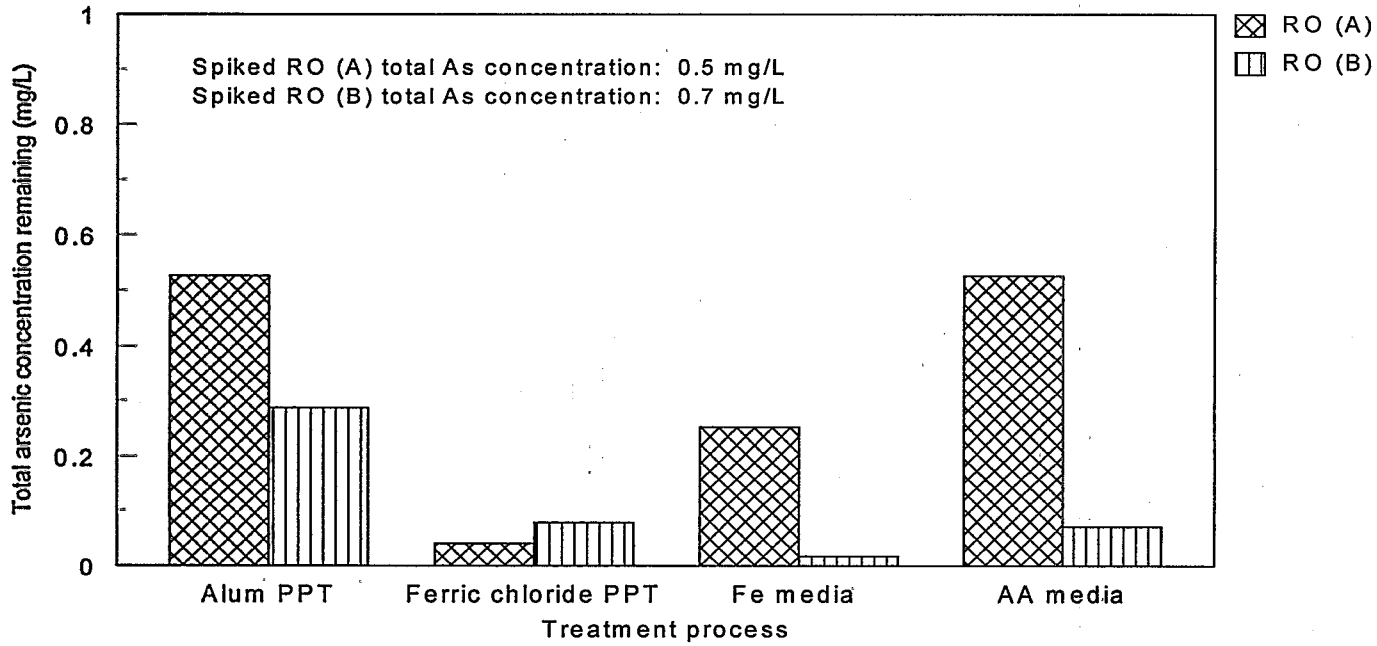


Figure 3-18. Comparison of treatment processes for removing arsenic from reverse osmosis concentrate

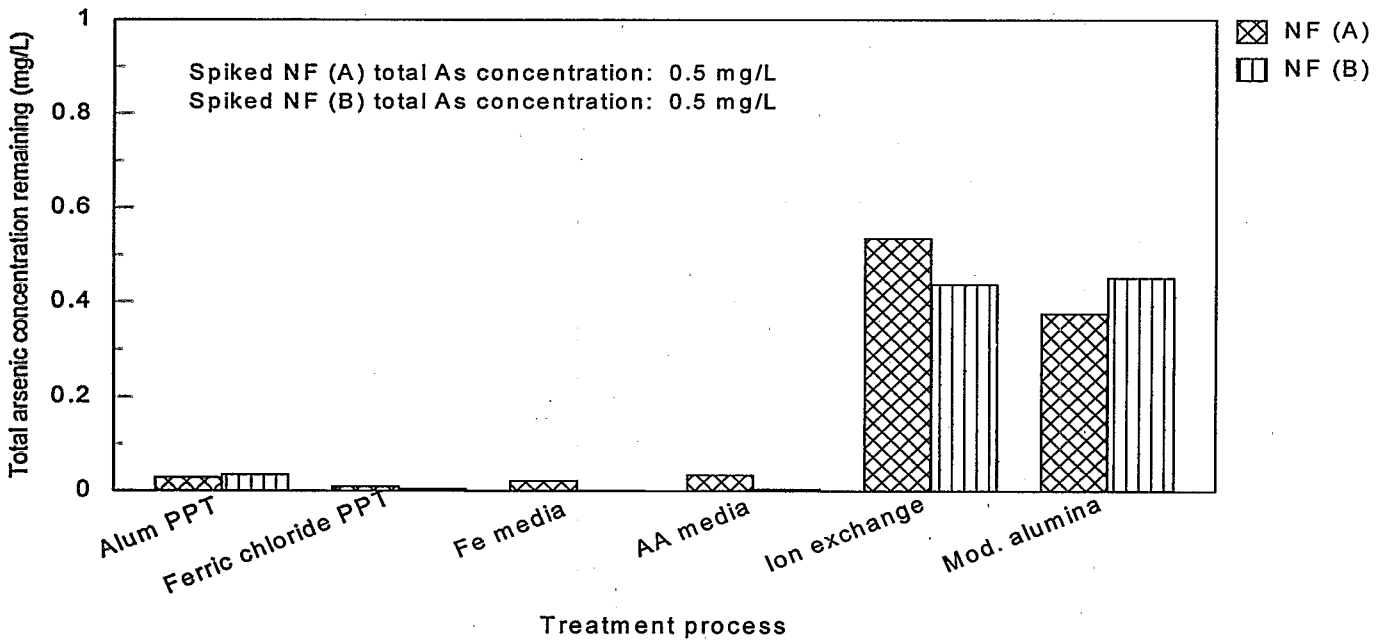


Figure 3-19. Comparison of treatment processes for removing arsenic from nanofiltration A and B concentrate

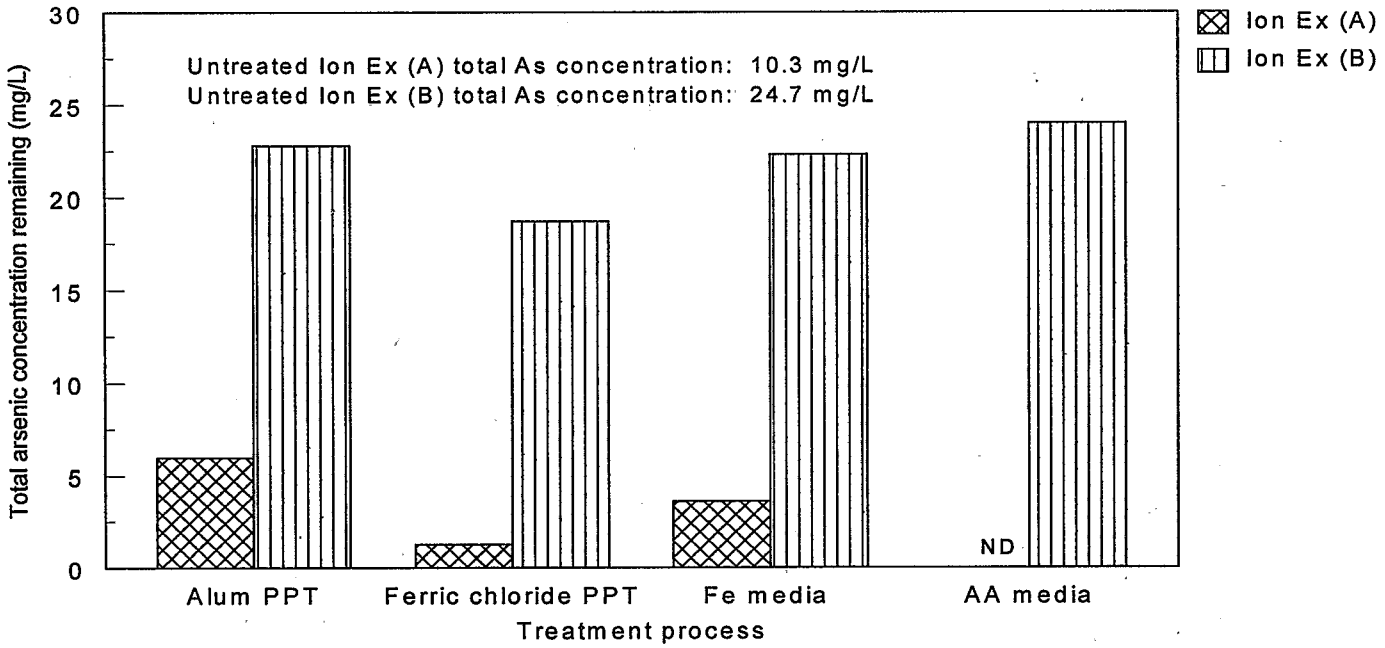


Figure 3-20. Comparison of treatment processes for removing arsenic from ion exchange A and B regenerant

concentrations remaining from the Ion Ex (A) and Ion Ex (B) wastewaters were 1.28 mg/L and 18.7 mg/L, respectively. Adsorption treatments were ineffective for removing arsenic from these regenerant streams.

3.5.5 Activated Alumina Regenerant

Only one treatment process, ferric chloride precipitation, was used to treat the activated alumina regenerant. Total arsenic in the AA regenerant was lowered by 94 percent from 2.36 mg/L to 0.154 mg/L.

3.5.6 Summary

Using the test matrix for this work, a summary of the best treatment technology determined for each residuals sample is presented in Table 3-15. Only three residuals streams (AA regenerant, Ion Ex (A), and Ion Ex (B)) had treated total arsenic concentrations that exceeded 0.05 mg/L, which is the in-stream arsenic standard in some states, in all tests. The results show that overall, the iron-based coagulants and adsorption media resulted in greater arsenic reductions than the aluminum-based coagulant and adsorption media. The adsorption tests only provided an indication for the potential of arsenic removal, since exhaustion could not be adequately assessed using the relatively low number of BVs that could be treated.

3.6 Solid Fraction Residuals

TCLP tests were conducted on four spent adsorption/filtration media. The media tested were an activated alumina media from a full-scale arsenic removal facility, a spent iron-manganese filter media from a full-scale WTP, and a spent anion exchange resin from two in-house ion exchange tests. The anion exchange resins analyzed were collected after ion exchange tests using SFBW/ACF (B) and NF (A) concentrate. The results of the TCLP arsenic analyses are included in Table 3-16.

The maximum TCLP arsenic concentration was 0.203 mg/L, which is significantly below the current TCLP arsenic limit of 5.0 mg/L. TCLP arsenic levels were in fact below 1.0 mg/L, which could be the future limit if the TCLP limit is lowered in proportion to the drinking water MCL. The other solid waste TCLP arsenic concentrations were at least an order of magnitude lower. Based on these findings, these media would not be classified as hazardous wastes.

Other researchers have reported similar TCLP results. Wang *et al.* (2000) reported TCLP arsenic concentrations of less than 0.05 mg/L and 0.07 mg/L or less in spent activated alumina samples collected from roughing filters at two full-scale activated alumina facilities. Chwirka (1999) reported no incidences of TCLP failure among eight different conventional facilities whose residuals were analyzed for TCLP arsenic. A wide range of arsenic levels in the TCLP extract was reported (0.0009 mg/L to 1.6 mg/L), however, and overall arsenic concentrations were higher than those determined in this work.

Table 3-15. Summary of treatment processes for removing arsenic

Sample ID	Best treatment conditions determined from testing	Total As remaining (mg/L)
AA regenerant	None	0.154
Ion Ex (A)	None	1.28
Ion Ex (B)	None	18.7
RO (A)	Ferric chloride precipitation	0.041
RO (B)	Iron media adsorption	0.018
NF (A)	Ferric chloride precipitation, iron-based media or AA adsorption	0.009, 0.030
NF (B)	Iron media adsorption, ferric chloride precipitation	<0.002, 0.005
SFBW (A) (settled)	Ferric chloride precipitation	0.013
SFBW/ACF (B) (unsettled)	Gravity settling (no chemical addition)	0.043
(settled)	Iron media, ion exchange, or AA adsorption	<0.002

Table 3-16. TCLP arsenic from solid fraction residuals

Solid waste ID	TCLP arsenic concentration (mg/L)
Spent activated alumina (full-scale WTP)	0.010
Spent Fe-Mn filter media (full-scale WTP)	0.004
Spent anion exchange resin (bench-scale SFBW test)	0.023
Spent anion exchange resin (bench-scale nanofiltration concentrate test)	0.203

4. Sludge Disposal Options

4.1 Sludge Production

In order to quantify the volume of settled solids that could be expected when treating various types of water treatment plant residuals streams, using alum or ferric chloride precipitation techniques, empirical sludge production equations were utilized (Cornwell 1999). The equations used were developed for estimating sludge production from the treatment of raw water for production of drinking water using chemical coagulants. Equation inputs used for this analysis include a volume of residuals treated, the total suspended solids (TSS) concentration in the residuals, and the coagulant dose used for arsenic removal. The coagulant dose range used for precipitation testing was between 25 and 200 mg/L, therefore, sludge production estimates for each coagulant type were calculated using doses of 25, 50, 75, 100, 150, and 200 mg/L. The measured TSS value for each of the residuals used for estimating sludge production along with the actual alum and ferric dose range used for each residuals stream are listed in Table 4-1. SFBW (A) had the highest TSS of 193 mg/L due to the nature of the residuals stream, while the NF (A) concentrate and Ion Ex (B) had TSS concentrations less than 10 mg/L.

The sludge production estimates (dry lb/MG of residuals treated) calculated using the empirical equations for alum and ferric chloride are shown in Figures 4-1 and 4-2, respectively. Both figures show that the SFBW (A) would generate the most sludge per volume of residuals treated. SFBW (A) was generated by backwashing filters that remove larger suspended particles from drinking water, and therefore had a higher TSS concentration than the other residuals analyzed. The RO concentrates, nanofiltration concentrate, and ion exchange regenerant were all generated by treatment processes that were designed for removing dissolved macro molecular or ionic contaminants from drinking water, meaning the TSS concentration in those residuals is low compared to the SFBW.

Figures 4-1 and 4-2 illustrate that ferric chloride generates significantly higher sludge quantities than equivalent doses of alum (on a weight basis). Results from the empirical sludge production calculations demonstrate that the amount of sludge generated using ferric chloride would be 25 to 100 percent higher than the dry weight of the alum sludge produced using similar applied doses. The minimum and maximum amounts of dry sludge per volume of residuals treated for both coagulants are shown in Table 4-2. The sludge production calculation includes the best coagulant dose for arsenic removal for both alum and ferric chloride. The table shows that due to the high doses of ferric chloride necessary for achieving optimal arsenic removal, the sludge amounts produced for the different waste steams would range between 1.0 and 2.0 dry lbs/1,000 gal of residuals treated.

Table 4-1. Parameters used for calculating residuals production estimates

Sample ID	Measured total suspended solids concentration (mg/L)	Alum dose range tested (mg/L)	Ferric chloride dose range tested (mg/L)
SFBW (A)	193.0	25 to 50	25 to 50
RO (A)	32.5	100 to 150	25 to 100
RO (B)	27.5	50 to 100	50 to 100
NF (A)	1.5	75 to 200	75 to 200
Ion Ex (B)	9.0	50 to 200	50 to 200

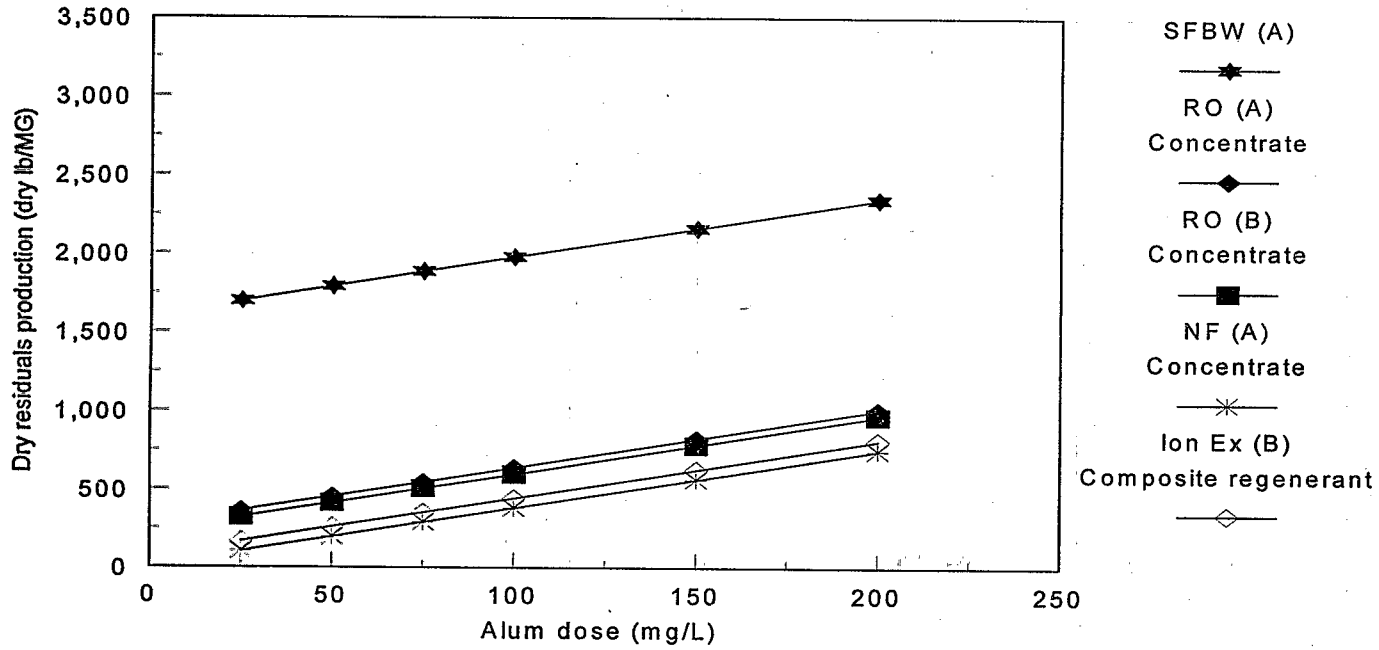


Figure 4-1. Residuals production estimates from alum precipitation of wastewaters containing arsenic

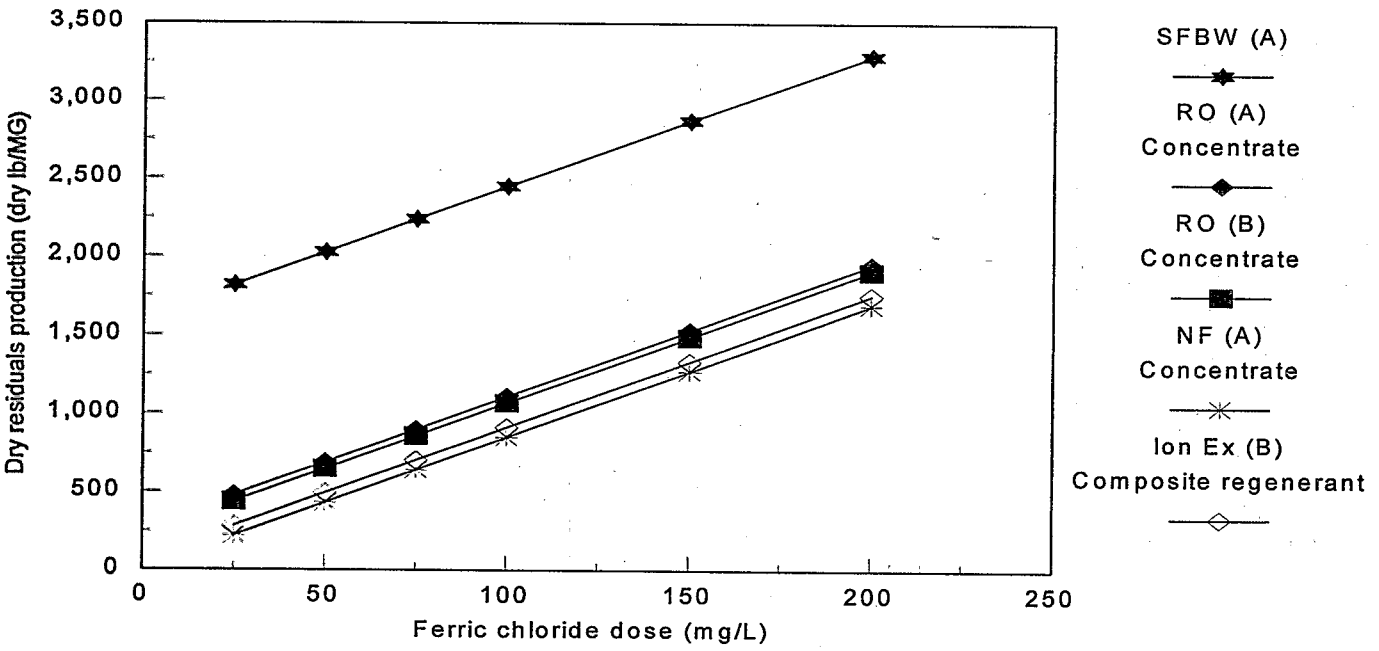


Figure 4-2. Residuals production estimates from ferric chloride precipitation of wastewater containing arsenic

Table 4-2. Estimated sludge production per 1,000 gal of residuals treated by precipitation

Sample ID		Coagulant dose range used for precipitation testing: Alum (mg/L)	Coagulant dose range used for precipitation testing: $FeCl_3$ (mg/L)	Sludge production estimate (dry weight): Alum sludge (lb/1,000 gal)	Sludge production estimate (dry weight): $FeCl_3$ sludge (lb/1,000 gal)
SFBW (A)	min.	25	25	1.70	1.82
	max.	50	50	1.79	2.03
	best dose	–	50	—	2.03
RO (A)	min.	100	25	0.64	0.48
	max.	150	150	0.82	1.53
	best dose	–	150	—	1.53
RO (B)	min.	50	50	0.41	0.65
	max.	100	100	0.60	1.07
	best dose	–	100	—	1.07
NF (A)	min.	75	75	0.29	0.64
	max.	200	200	0.75	1.69
	best dose	150	150	0.56	1.27
Ion Ex (B)	min.	50	50	0.26	0.50
	max.	200	200	0.81	1.75
	best dose	---	---	—	—

--- No optimal condition was found.

4.1.1 Normalizing Sludge Quantities According to Treatment Process Type

The calculated sludge production data (Table 4-2) provide the expected mass of sludge generated per known volume of residuals treated, however, these data do not provide a mass of sludge produced per volume of raw water treated by each of the different treatment processes. Normalizing these results provides a better understanding of how much sludge each treatment process analyzed would be expected to generate. In order to normalize these data, the following assumptions were made:

- Percentage of residuals generated by each treatment process (RO, NF, Fe/Mn removal, Ion Ex)
- Total treatment plant process (raw water) flow rate (in this case 1 mgd was used)

Each of these parameters is defined in Table 4-3.

These data show that the membrane treatment processes would generate a significantly higher volume of residuals than the Fe/Mn filtration and ion exchange systems. Both RO and NF would generate approximately 150,000 gpd per 1 mgd treated, compared to 50,000 gpd for Fe/Mn filtration and 20,000 gpd for ion exchange.

Table 4-3. Estimated volume of residuals generated per 1 MG treated

	Total plant flow rate (mgd)	Residuals generated (percent of total flow)	Volume of residuals generated (gpd)
Reverse osmosis	1	15	150,000
Nanofiltration	1	15	150,000
Fe/Mn filtration	1	5	50,000
Ion exchange	1	2	20,000

In order to determine the mass of sludge produced per 1 mgd of raw water treated, the sludge production amounts (dry lb/1,000 gal) calculated for the best coagulant dose (Table 4-2) was multiplied by the volume of residuals generated for each process (Table 4-3). These data are summarized in Table 4-4.

The table shows that the mass of sludge produced per MG of raw water treated is highest for the membrane processes due to the large volume of residuals generated. For example, the reverse osmosis facility that generated the RO

Table 4-4. Estimated sludge production for a 1-mgd treatment facility

Sample ID	Residuals volume	Best $FeCl_3$ dose* (mg/L)	Sludge production using best $FeCl_3$ dose (dry lb/1,000 gal of wastewater)	Total sludge production (dry lb/mil gal raw water treated)
SFBW (A)	50,000	50	2.03	101.5
RO (A)	150,000	150	1.53	229.5
RO (B)	150,000	150	1.07	160.5
NF (A)	150,000	150	1.27	190.5
Ion Ex (B)	20,000	200	1.75	35

*Best $FeCl_3$ dose found for removing As from each untreated residuals sample during precipitation testing.

(A) residuals would be expected to generate almost 230 dry lbs of sludge per MG treated if removal of arsenic from the concentrate was required. The ion exchange facility (Ion Ex B) would produce the least amount of sludge at 35 dry lb/MG raw water treated.

4.2 Federal Disposal Regulations

There are no existing comprehensive federal regulations that specifically apply to water treatment plant (WTP) residuals. There are, however, existing federal regulations that were developed for biosolids and solid waste disposal. Many states have adopted all or parts of these federal guidelines for regulating WTP residuals disposal.

Federal statutory and regulatory requirements for disposal of liquid and solid WTP residuals were summarized in a recent publication (Science Applications International 2000). A summary description of some of the federal regulations that are currently being adopted by states for applications involving WTP residuals are as follows:

- 40 CFR 257: Classification of Solid Waste Disposal Facilities and Practices
- 40 CFR 258: Criteria for Municipal Solid Waste Landfills (MSWLF)
- 40 CFR 261: Toxicity Characteristic Leaching Procedure (TCLP) Test
- 40 CFR 403: General Pretreatment Regulations for Existing and New Sources of Pollution
- 40 CFR 503: Standards for the Disposal of Sewage Sludge
- CERCLA: Comprehensive Environmental Response Compensation Liability Act
- HMTA: Hazardous Materials Transportation Act

The Clean Water Act (CWA), Section 405, established guidelines for the use and disposal of sewage sludge in order to protect leaching of contaminants into waterways. Leaching of metals into groundwater is the primary issue addressed by CWA Section 405. The framework defined by CWA Section 405 was also adopted for use in land applied WTP sludge. The Resource Conservation and Recovery Act (RCRA) was established primarily to determine toxicity or hazard potential of a solid waste prior to landfilling in order to protect land, water, and air from contamination. The RCRA also provides guidelines concerning the following topics:

- Classification of hazardous wastes
- Standard for treatment, storage, and final use
- Enforcement of standards
- Authorization for states to implement regulations
- Cradle to grave manifest system

Although developed for biosolids and solid waste, specific sections of RCRA have been adopted by many states for regulating WTP residuals end use applications. A summary of the 40 CFR sections that could apply to WTP residuals are listed in the following paragraphs.

4.2.1 40 CFR 257: Criteria for Classification of Solid Waste Disposal Facilities and Practices

This regulation includes provisions that deal with land application of a solid waste, including WTP residuals. In order to comply with Section 405(d) of the Clean Water Act, the owner or generator of a publicly owned treatment facility must comply with the guidelines for sludge applications outlined in 40 CFR 257. The regulation contains specific criteria governing application of sludge to land for production of human food-chain crops and limiting annual and cumulative applications of cadmium and PCBs.

4.2.2 40 CFR 258: Criteria for Municipal Solid Waste Landfills (MSWLF)

The 40 CFR 258 regulation establishes minimum national criteria for all MSWLF units and for MSWLF that are used to dispose of biosolids. Biosolids, solid wastes, and WTP residuals that are placed in a MSWLF must be nonhazardous as determined by 40 CFR 261, and must not contain free liquids as determined by the Paint Filter Liquid Tests.

4.2.3 40 CFR 261: Identification and Listing of Hazardous Wastes

The 40 CFR 261 identifies the solid waste materials which are subject to regulation as a hazardous waste. A solid is considered a hazardous waste if it exhibits any of the characteristics of ignitability, corrosivity, reactivity, or toxicity as defined in Subpart C of CFR 261 or if it is listed in Subpart D of CFR 261. This regulation is pertinent since the final use options considered for WTP residuals application require a nonhazardous designation. Since WTP residuals are not ignitable, corrosive, reactive, or considered hazardous wastes, the toxicity characteristic leaching procedure (TCLP) could be used as the primary indicator that a WTP residual is not a hazardous material. The TCLP regulatory limits established by 40 CFR 261 are listed in Table 4-5.

Table 4-5. EPA 40 CFR Part 261 TCLP limits

Contaminant	EPA Section 40 Part 261 TCLP limits (mg/L)
Metals	
Silver	5
Barium	100
Cadmium	1
Chromium	5
Lead	5
Arsenic	5
Selenium	1
Mercury	0.2
Volatiles	
Benzene	0.5
Carbon Tetrachloride	0.5
Chlorobenzene	100
Chloroform	6
1,2-Dichloroethane	0.5
1,1-Dichloroethylene	0.7
Methyl ethyl ketone	200
Tetrachloroethylene	0.07
Trichloroethylene	0.5
Vinyl Chloride	0.2
1,4-Dichlorobenzene	7.5
Semi-Volatiles	
o-cresol	200
m-cresol	200
p-cresol	200
Cresol (total)	200
2,4-Dinitrotoluene	0.13
Hexachlorobenzene	0.13
Hexachlorobutadiene	0.5
Hexachloroethane	3
Nitrobenzene	2
Pentachlorophenol	100
Pyridine	5
2,4,5-Trichlorophenol	400
2,4,6-Trichlorophenol	2
1,4-Dichlorobenzene	7.5
Herbicides/Pesticides	
2,4,-D	10
2,4,5-TP (Silvex)	1
Chlordane	0.03
Endrin	0.02
Heptachlor	0.008
Heptachlor epoxide	0.008
Lindane	0.44
Methoxychlor	10
Toxaphene	0.5

4.2.4 40 CFR 403: General Pretreatment Regulations for Existing and New Sources of Pollution

Discharges to the sanitary sewer are subject to EPA's National Pretreatment Standards and any additional pretreatment requirements mandated by the state or wastewater treatment facility. Examples of arsenic limits from seven states reviewed in a recent USEPA publication (Science Applications International 2000) range from 0.051 mg/L for Albuquerque, New Mexico to 1.07 mg/L for Farmington, New Mexico. Residual arsenic levels in this range were attained through precipitation or adsorption treatments for all wastewaters examined in this work except Ion Ex (B). The requirements imposed on a wastewater treatment facility through a permit and/or local ordinance are necessary to enable the facility to achieve compliance with their NPDES permit.

Pretreatment required prior to discharge liquid residuals into the environment is typically site-specific. Several states have a surface water quality arsenic standard of 0.05 mg/L for waters used as public water supplies (Science Applications International 2000).

4.2.5 40 CFR 503: Standards for the Use or Disposal of Sewage Sludge

This regulation describes comprehensive criteria for the management of biosolids. Under 40 CFR 503, biosolids are either land applied in bulk form, sold, or given away. Application can occur on either agricultural land, forests, public contact sites, and reclamation sites or on lawns and home gardens. In order for biosolids to be land applied, criteria for pollutant limits, pathogens, and vector attraction reduction must be met. The Part 503 pollutant limits for land application are given in Table 4-6. All biosolids that are to be land applied must meet the ceiling concentrations in *Table 1 of 503.13*. Bulk biosolids that are applied to agricultural land, forest, public contract sites, or reclamation sites must also either meet the pollutant limits in *Table 3 of 503.13* or be applied at rates so that the cumulative loading rates in *Table 2 of 503.13* are not exceeded. Bulk biosolids that are applied to lawn or home gardens must meet the pollutant limits in *Table 3 of 503.13*. Biosolids that are sold or given away must either meet the pollutant limits in *Table 3 of 503.13*, or be applied so as not to exceed the annual pollutant rates in *Table 4 of 503.13*, while still meeting the ceiling concentrations in *Table 1 of 503.13*.

4.2.6 Comprehensive Environmental Response Compensation Liability Act (CERCLA)

The CERCLA, also known as the Superfund Act, was established to deal with the numerous existing abandoned or uncontrolled hazardous waste disposal sites that pose a real threat to public health and safety as well as to the environment. Prior to the act's passage, USEPA was only authorized to regulate hazardous waste management at active and properly closed sites. The Superfund, which is essentially a pool of money derived from special taxes, forms the core of CERCLA. Establishment of this fund fulfilled the primary focus of CERCLA. An expansion of the Superfund pool that serves to continue cleanup efforts begun under CERCLA is provided by the Superfund Amendments and Reauthorization Act (SARA) of 1986. The funds thereof are used to remediate contaminated sites in accord with RCRA requirements.

The USEPA is authorized under CERCLA to take necessary short-term actions to deal with sites posing some immediate threat to human health or the environment as well as to implement long-term plans to clean up complex sites, which are selected on the basis of risk assessments. The identification of responsible parties is an important part of the remediation process. Possibly the most noteworthy aspect of these regulations, however, is that they employ a volume use basis in assessing cleanup costs, which could potentially place the liability with a utility whose sludge did not cause the problem.

4.2.7 Hazardous Materials Transportation Act (HMTA)

The Hazardous Materials Transportation Act (HMTA) applies to all beneficial uses requiring transportation of sludge. The WTP sludge must be determined to be non-hazardous by RCRA and HMTA in order to transport the material. The

Table 4-6. Part 503 pollutant limits for sewage sludge land application

	Table 1 of 503.13 Ceiling concentrations (mg/kg)	*Table 2 of 503.13* Cumulative pollutant loading rates (kg/ha)	*Table 3 of 503.13* Pollutant concentrations (mg/kg)	*Table 4 of 503.13* Annual pollutant loading rates (kg/ha/yr)
Arsenic	75	41	41	2.0
Cadmium	85	39	39	1.9
Copper	4,300	1,500	1,500	75
Lead	840	300	300	15
Mercury	57	17	17	0.85
Molybdenum	75			
Nickel	420	420	420	21
Selenium	100	100	100	5.0
Zinc	7,500	2,800	2,800	140

HMTA also outlines U.S. Department of Transportation (USDOT) packaging requirements.

4.3 Residuals Disposal Options

The effective removal of arsenic from WTP liquid residuals streams results in a supernatant or effluent streams that may meet regulatory criteria for reuse, stream discharge, or sewer disposal and a sludge or media waste that contains a concentrated amount of total arsenic. As discussed in the Federal regulatory review, final land disposal of solid residuals is dependent on the TCLP arsenic leaching (mg/L) and total arsenic concentration (mg/kg), as well as other TCLP or non-metal contaminants regulated by EPA.

Although only a limited amount of sludge solids from precipitation tests were TCLP tested to determine arsenic leaching, all samples tested had TCLP arsenic concentrations well below the 5 mg/L limit. The TCLP arsenic concentrations of the adsorption media tested were also significantly lower than the 5 mg/L maximum limit for arsenic. Based on TCLP arsenic results, these waste samples would be considered nonhazardous (unless other contaminants exist that would fail the TCLP analysis).

If a waste material is found to exceed the TCLP arsenic concentration of 5 mg/L, the liquid or solid material would be considered hazardous and would require disposal in hazardous waste handling facilities. If the material is determined to be nonhazardous, the following disposal options may apply for liquid or solid media wastes:

- Liquid/Semi-Liquid Wastes
  - Stream discharge (NPDES permit probably requires solids removal)
  - Sewer disposal to WWTP
  - Land application
  - MSWLF landfilling (requires dewatering)
- Solid Media
  - Land application
  - Landfilling
  - Regeneration/Reuse

Each of these disposal options are summarized in the following sections. It should be noted that landfill disposal, sewer disposal, land application, and stream discharge regulations vary from state to state. Some states have adopted the Federal regulations for these disposal applications, while others have developed their own specific guidelines for disposal.

4.3.1 Liquid or Semi-Liquid Waste Disposal

Stream Discharge

Discharge of WTP residuals to surface water requires a National Pollutant Discharge Elimination System (NPDES) permit. NPDES permit requirements are based on stream flow conditions and provide maximum limits for solids discharge and contaminant loadings. The limits established in the NPDES for specific contaminants are determined by the water quality criteria established for the receiving water, ambient levels of the specific contaminants, the established low flow condition of the receiving water, and the design flow of the proposed discharge from the arsenic treatment process (Chwirka 1999). Table 3-15 shows treatments successful in reducing arsenic levels to 0.05 mg/L or lower, which is the existing in-stream standard in some states. As shown, one or more treatment techniques were able to attain arsenic concentrations of 0.05 mg/L or lower in all residuals except the ion exchange and activated alumina regenerant streams.

Sewer Disposal

The quality of WTP residuals allowable for discharge to the sanitary sewer is dependent on limits imposed by the wastewater treatment plant receiving the liquid waste. Each WWTP has an Industrial Pretreatment Program to prevent unacceptable concentrations of contaminants from entering the WWTP treatment process. Those guidelines protect the operation of the WWTP from inhibition of the biological processes used to treat municipal wastewater, prevent violations of the WWTP NPDES permit, and prevent unacceptable accumulation of contaminants in the WWTP biosolids. The Industrial Pretreatment Program establishes Technically Based Local Limits (TBLL). The TBLL for arsenic will typically be limited by contamination of the wastewater treatment plant biosolids rather than discharge limitations or process inhibitions (Chwirka 1999).

Land Application

Land application of WTP residuals is dependent on the state regulatory guidelines. Some states do not allow land application of WTP residuals. The general criteria for allowing WTP residuals to be land applied are based on the following Federal regulations:

- EPA CFR 40 261 - TCLP Hazardous Determination
- EPA CFR 40 503 - Biosolids Metals Concentrations
- EPA CFR 40 257 - Solid Waste Disposal

If WTP residuals meet the criteria established by these Federal regulations, as well as any state or local regulations, then the material would be allowed for land application. EPA 503 established maximum loading limits for heavy metals including arsenic. A "clean sludge" limit of 41 mg/kg was established by EPA 503 for biosolids disposal. Clean sludge can be land applied with no limitations (Chwirka 1999). A cumulative arsenic loading limit to soils was set by EPA in the Part 503 regulations at 36.6 lbs/acre (41 kg/ha).

Landfill Disposal (MSWLF)
Municipal solid waste landfills have established a set of disposal guidelines that are similar for most landfill agencies. The basic guidelines for disposal include the following:

- No free liquids (pass paint filter test)
- TCLP nonhazardous (EPA CFR 40 Part 261)
- Non-corrosive, non-reactive, non-ignitable (EPA 261)

Liquid or semi-liquid WTP residuals would require mechanical or nonmechanical dewatering prior to acceptance. If the WTP residuals exceeds the TCLP limits established by EPA 40 CFR 261, then the material would have to be disposed of in a hazardous waste landfill.

4.3.2 Solid Media Disposal

Land Application
The same regulatory requirements used for sludge disposal would apply to disposal of adsorption medias. If the material is determined to be nonhazardous (TCLP limits from EPA 40 CFR 261) and meets the EPA 503 metals limits, then land application is an option. The ability of the solid media to blend into the natural soil environment must also be considered prior to land disposal. Iron-based media may provide an iron amendment to soils, however, aluminum-based media and ion exchange resins would most likely not provide a benefit to soils. Also, under reduced pH conditions, Fe(III) could be reduced to Fe(II), and arsenic bound to iron complexes could be released to surrounding soils.

Landfill Disposal
The same criteria discussed for landfilling WTP sludge would apply to disposal of solid adsorption media. TCLP hazard evaluation, no free liquids, and determination of corrosivity, ignitability, and reactivity are each required prior to acceptance. All solid media samples in this work met the current TCLP arsenic limit of 5.0 mg/L.

Recycling/Reuse
It is possible that adsorption media may be regenerated by the manufacturer and reused for similar or different applications. To determine reuse potential for a specific solid adsorption media, the manufacturer of the media should be contacted.

5. Summary and Conclusions

5.1 Summary

5.1.1 Project Description

Liquid and semi-liquid residuals streams were collected from eight operating full-scale treatment plants around the U.S. for evaluation of several treatment approaches to remove arsenic. Spent media samples collected from a ninth plant were used to generate another liquid stream for testing. Precipitation processes and adsorption/exchange technologies that have been demonstrated to be successful in removing arsenic from potable water treatment plants were evaluated for their effectiveness in removing arsenic from the following types of liquid and semi-liquid residuals streams.

- Activated alumina regenerant
- Ion exchange regenerant
- Nanofiltration concentrate
- Reverse osmosis concentrate
- Spent filter backwash water and spent filter backwash water/adsorption clarifier flush blend from Fe/Mn removal plants

Treatment effectiveness was compared based on reductions in arsenic and residual concentrations of arsenic following treatment. Residual iron and aluminum levels were also considered. When sufficient quantities of sludge were generated in precipitation tests, TCLP analyses were conducted on the sludge fraction of the samples. Also, TCLP analyses were conducted on three types of solid media samples: (1) filter media from an Fe/Mn removal plant, (2) spent activated alumina, and (3) an ion exchange resin.

5.1.2 Untreated Residuals Sample Characterization

Untreated liquid residuals streams were characterized according to the following parameters: total and dissolved arsenic, total iron and manganese, pH and alkalinity, total dissolved solids and conductivity, total hardness, and sulfate. Untreated residuals arsenic concentrations were determined to assess arsenic removal, and they varied widely from about 0.5 mg/L (spiked) to 1.7 mg/L for all samples except ion exchange and activated alumina regenerants (Figure 3-1). As levels in composite ion exchange regenerant samples were approximately 11 mg/L and 25 mg/L and the activated alumina regenerant sample contained 2.6 mg/L arsenic. Other characteristics including pH, sulfate, and TDS were used to select appropriate treatment options, and were also important in interpretation of treatment results.

Alkalinity and pH ranged from 197 mg/L to 7,000 mg/L as $CaCO_3$ and from 6.6 to 9.7, respectively. Both parameters were highest in ion exchange regenerant wastes. Total hardness, on the other hand, was comparatively low (less than 100 mg/L) in ion exchange regenerants and was highest at around 1,600 mg/L (as $CaCO_3$) in the nanofiltration concentrates. TDS and conductivity exceeded 10,000 mg/L and 20,000 µS/cm in the AA regenerant and RO concentrates. As expected, total iron and manganese levels were highest in spent filter backwash water and spent filter backwash water/adsorption clarifier flush blend samples (up to 78.5 mg/L and 7.5 mg/L), while sulfate levels were lowest (less than 100 mg/L for SFBW and SFBW/ACF blend compared to greater than 500 mg/L for all other residuals).

5.1.3 Precipitation and Adsorption Test Results

Table 5-1 summarizes arsenic results from treatment of all nine residuals samples. The table shows the minimum total arsenic concentration remaining in the supernatant or effluent following treatment. Unless noted otherwise, adsorption test results are for samples collected at 120 bed volumes during tests where the empty bed contact time (EBCT) was 3 min. Precipitation results show the total arsenic concentration remaining in the supernatant following precipitation using the best coagulant dose and pH combinations for each residuals sample.

As shown in Table 5-1, for all residuals samples, precipitation using ferric chloride was more effective for removing arsenic than precipitation using alum for the range of test conditions evaluated. Similarly, the iron-based media produced the

Table 5-1. Comparison of treatment processes for arsenic removal

Sample ID	Residuals arsenic conc. (mg/L)	Treated water arsenic remaining (mg/L)					
		Precipitation		Adsorption (3 min EBCT, 120 BV)			
		Alum	$FeCl_3$	Fe-based media	Activated alumina media	Ion exchange resin	Modified alumina media
AA regenerant*	2.63	---	0.154	---	---	---	---
Ion Ex (A)	10.5	5.98	1.28	3.60*	---	---	---
Ion Ex (B)	24.8	22.8	18.7	22.3	24.0	---	---
RO (A)	0.526	0.526	0.041	0.252*	0.526	---	---
RO (B)	0.663	0.286	0.078	0.018	0.071	---	---
NF (A)	0.523	0.029	0.009	0.021	0.034	0.535	0.376
NF (B)	0.486	0.035	0.005	<0.002	0.004	0.438	0.452
SFBW (A) (unsettled)	1.41	0.021	0.013	1.18*	1.41*	---	---
SFBW/ACF (B) (unsettled)	1.74	0.194	0.064	---	---	---	---
(settled)	0.043	---	0.011	<0.002	<0.002	<0.002	---

*Arsenic concentration measured after 120 BV using an EBCT of 1.5 min.

lowest effluent arsenic concentrations of the adsorption/exchange media evaluated for all of the various liquid residuals streams tested. Further, $FeCl_3$ precipitation reduced arsenic levels to 0.05 mg/L (in-stream standard for arsenic for a number of states) or lower in five of the nine samples tested, and below 0.1 mg/L in six of the nine residuals samples.

Figures 5-1 and 5-2 show total arsenic concentrations remaining along with corresponding percent removal for the best ferric chloride and alum precipitation conditions tested for each residuals sample. While percent removals indicate the potential of precipitation to remove arsenic from each specific residuals stream tested, total arsenic concentrations remaining in the supernatant (or liquid-fraction) following treatment are also very important with regard to disposal options available. As Chwirka (1999) described, the disposal of liquid residuals containing arsenic to receiving waters will be subject to compliance with National Pollution Discharge Elimination System (NPDES) limits, which are determined by water quality criteria established for the receiving water, ambient levels of the specific contaminants, the established low flow condition of the receiving water, and the design flow of the proposed discharge. Chwirka (1999) also notes that discharge of arsenic-containing residuals to a sanitary sewer (the other option for discharge of liquid residuals) is subject to the established Technically Based Local Limits (TBLL) of the current Industrial Pretreatment Program, and that the TBLL for arsenic will typically be limited by the contamination of the wastewater treatment plant biosolids as opposed to discharge limitations or process inhibition.

Arsenic removals attained in this work demonstrated that treatments shown to be effective at removing arsenic from source waters with relatively low arsenic concentrations were also successful in removing arsenic from residuals streams generated from arsenic removal processes. These residuals streams, of course, contained much higher levels of arsenic than the corresponding source water (from 12 to 270 times more arsenic in this study). Similar data covering such a broad range of liquid residuals streams have not been previously reported in the literature. Also, these data can be compared to achievable removal levels reported in the literature such as 95 percent for coagulation/filtration (USEPA 1999b).

Results of the TCLP analysis are key in dictating disposal options for solid wastes. TCLP arsenic levels determined for semi-liquid residuals generated in precipitation tests were all below the current threshold limit of 5.0 mg/L. TCLP arsenic levels in media samples from arsenic removal plants were also well below that limit (Table 5-2).

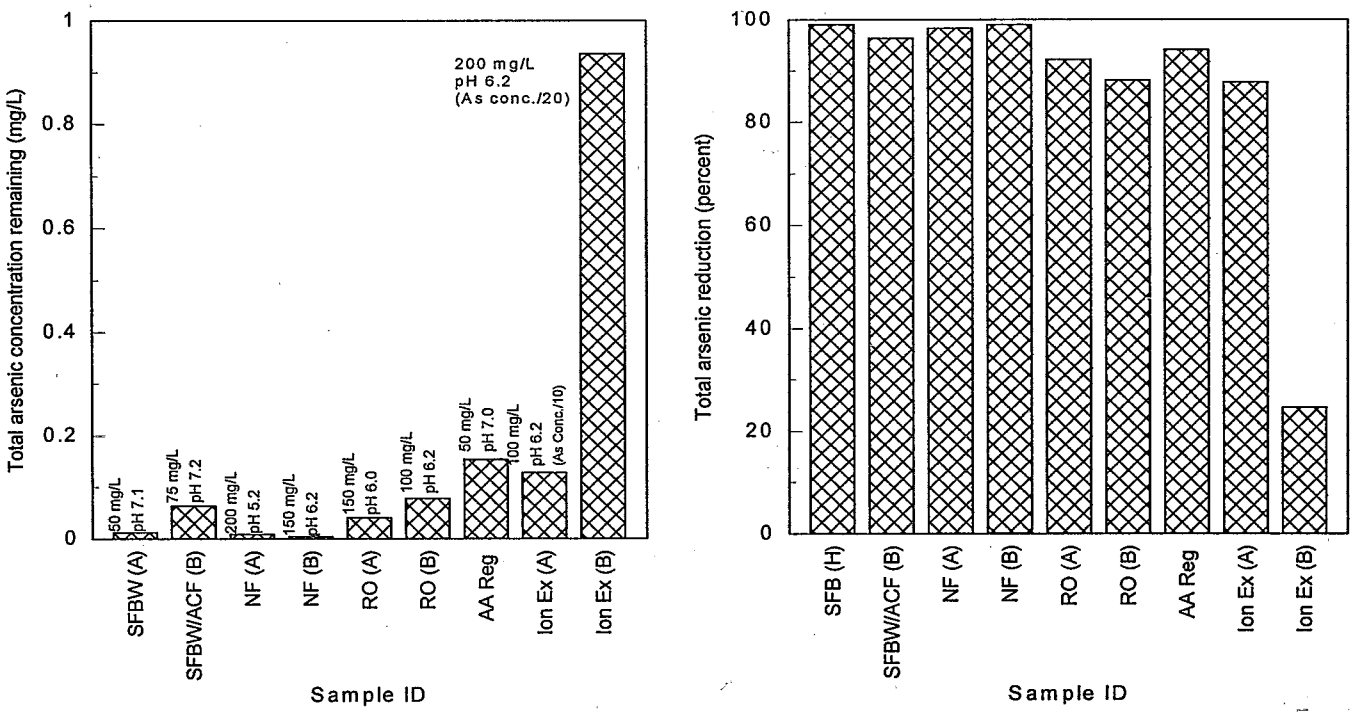


Figure 5-1. Total arsenic concentrations remaining in the supernatant and percent reduction after ferric chloride precipitation

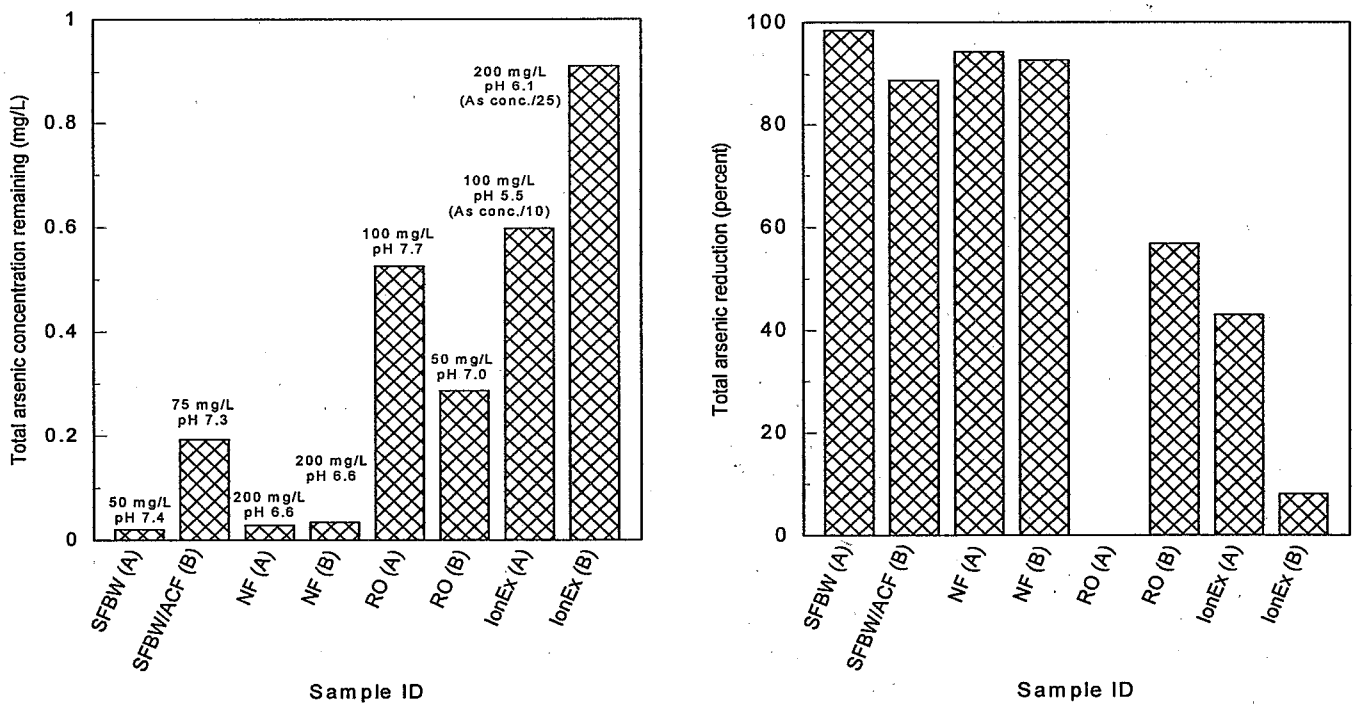


Figure 5-2. Total arsenic concentrations remaining in the supernatant and percent reduction after alum precipitation

Summaries of results from adsorption and ion exchange tests are presented for the iron-based media, activated alumina, ion exchange resin, and modified alumina in Figures 5-3 through 5-6. Results are shown both in terms of total arsenic levels detected in adsorption or ion-exchange column effluents and arsenic percent reduction. Figure 5-3 shows that the iron-based media was very effective at removing arsenic for the settled SFBW/ACF blend sample (settled first), the NF concentrate samples, and one of the RO concentrate samples over the total test duration during which 120 bed volumes of water were passed through the column. Arsenic breakthrough occurred very rapidly (at or before 60 bed volumes) for the ion exchange samples, and for one of the RO concentrates. Overall, the trends were similar for the activated alumina tests, although the iron-based media was more effective than the activated alumina (Figure 5-4). Figure 5-5 shows that ion exchange was effective only for the settled SFBW/ACF blend that had a very low arsenic concentration (0.043 mg/L). TDS and sulfate levels were too high (>500 mg/L and >250 mg/L) in the NF concentrate for ion exchange to be effective. Breakthrough also occurred very rapidly for the modified alumina tests conducted on the NF concentrate samples (see Figure 5-6).

Table 5-2. TCLP arsenic from solid fraction residuals

Solid waste ID	TCLP arsenic concentration (mg/L)
Spent activated alumina (full-scale WTP)	0.010
Spent Fe-Mn filter media (full-scale WTP)	0.004
Spent anion exchange resin (bench-scale SFBW test)	0.023
Spent anion exchange resin (bench-scale nanofiltration concentrate test)	0.203

5.2 Conclusions

This work focused on evaluation of liquid, semi-liquid, and solid waste streams from five arsenic removal plants and four membrane plants across the U.S. for removal of arsenic by precipitation and adsorption. TCLP tests were conducted on the solid wastes and semi-liquid residuals generated in precipitation tests. Precipitation and adsorption investigations were not intended to identify optimal treatment conditions due to the small quantities of residuals shipped for testing, but rather to screen treatment options for arsenic removal capability. Based on the findings, the major conclusions from this work follow.

5.2.1 Precipitation

For the array of types of residuals samples tested, precipitation using ferric chloride yielded greater reductions in arsenic than precipitation using alum. Required dosages, iron-to-arsenic molar ratios, and pH to achieve the best arsenic removal varied depending on the residuals stream. Pertinent findings that stemmed from precipitation work are as follows:

- Ferric chloride outperformed alum for removal of arsenic from residuals by sedimentation.
- The required molar iron-to-arsenic ratio for best removal of arsenic in these screening tests varied widely from 4:1 to 191:1, depending on residual type. Arsenic removals achieved were greater than 88 percent for all but one of the waste streams (Ion Ex B).
- Generally, polymer addition did not significantly improve arsenic removal.
- Best performance with ferric chloride precipitation typically occurred between pH 5.0 and 6.2.
- Supernatant residual total arsenic levels after ferric precipitation were between 0.005 mg/L and 0.078 mg/L for all waste streams, except ion exchange and activated alumina, compared to an in-stream arsenic limit of 0.05 mg/L in some states. For Ion Ex (A), Ion Ex (B), and the AA regenerant, those levels were 1.28 mg/L, 18.7 mg/L, and 0.154 mg/L, respectively.
- TCLP arsenic concentrations in semi-liquid residuals generated in ferric precipitation tests were between <0.002 mg/L and 0.018 mg/L. These values are well below the current TCLP arsenic limit of 5 mg/L.
- Alkalinity likely inhibited arsenic removal.
- Based on these findings, ion exchange regenerant wastes might be the most difficult to treat for meeting in-stream standards.

5.2.2 Adsorption

The iron-based adsorption media was the most effective of the media and resins tested for removing arsenic from the liquid residuals evaluated in this work. Adsorption tests demonstrated the potential for different types of media and resins to remove arsenic from various residuals streams, but did not assess media capacity for arsenic adsorption because tests were not run to exhaustion. Specific findings from adsorption tests are as follows:

- The iron-based media evaluated in adsorption testing typically outperformed the aluminum-based media and ion exchange media for removal of arsenic.

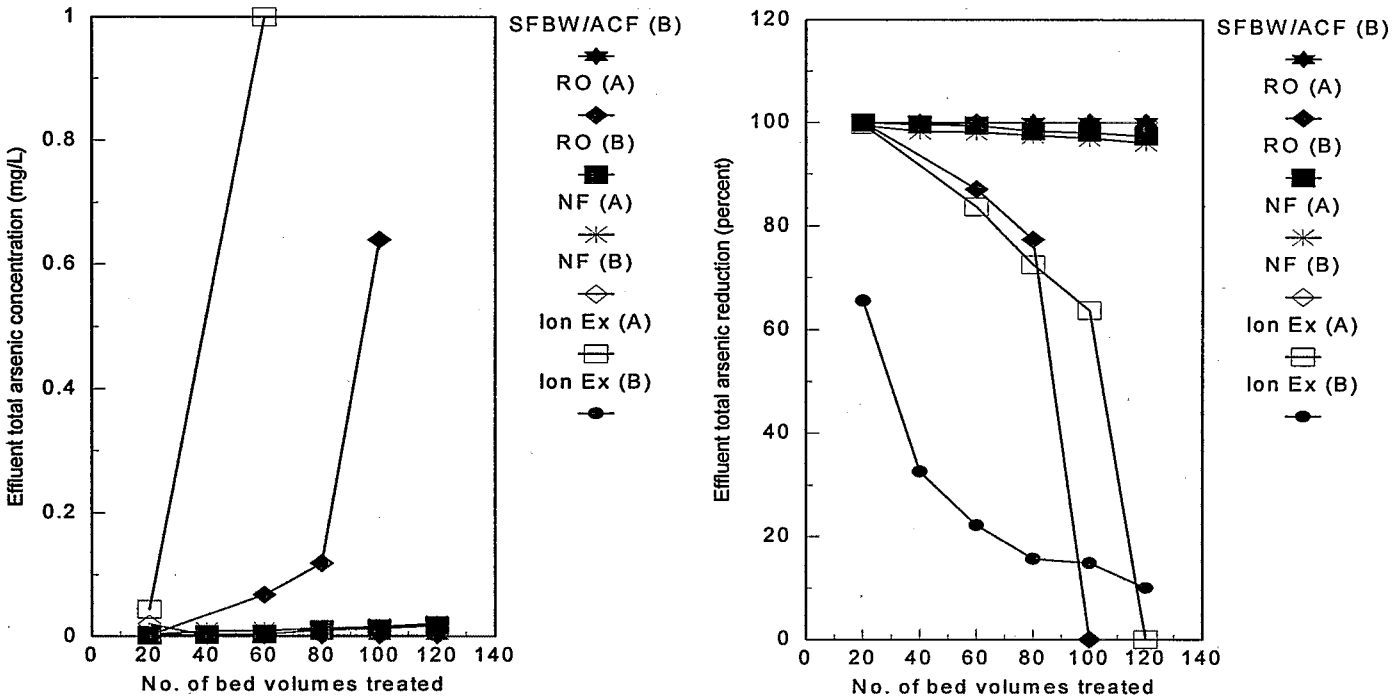


Figure 5-3. Total arsenic concentrations in the column effluent and percent reduction after iron-based media adsorption using a 3 min EBCT

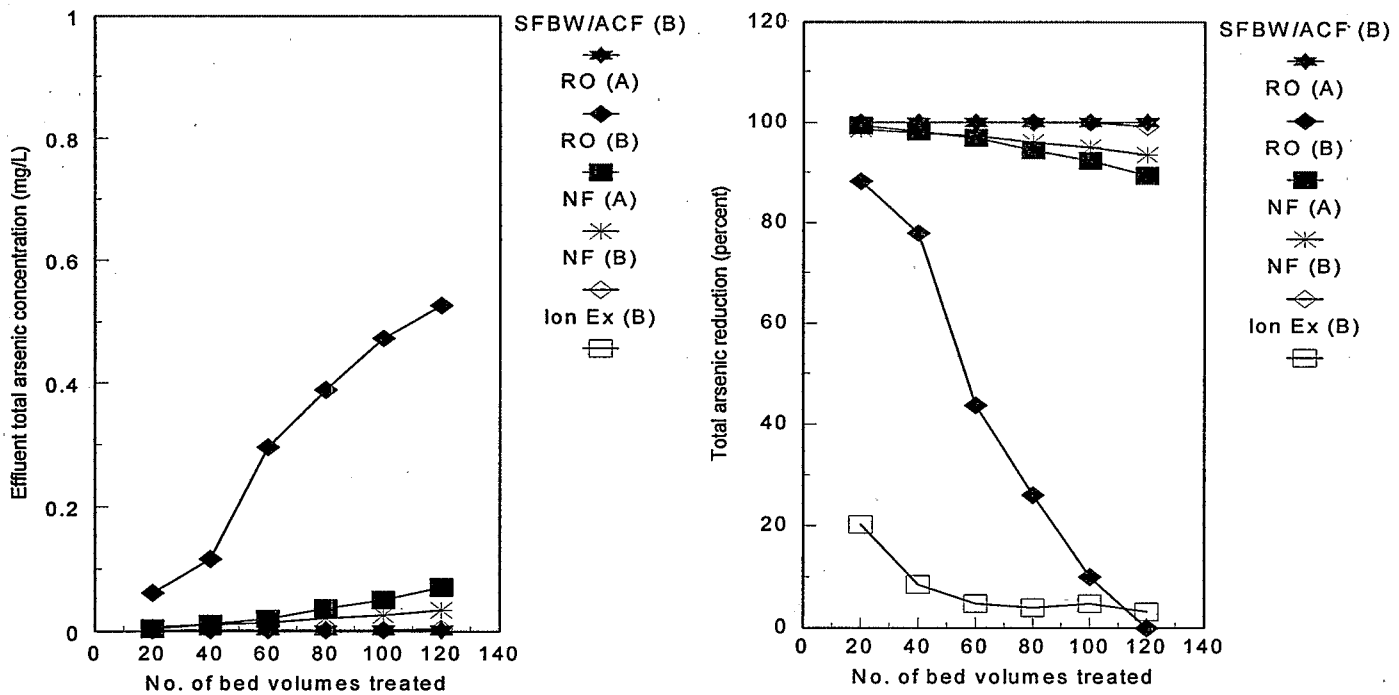


Figure 5-4. Total arsenic concentration in the column effluent and percent reduction after activated alumina adsorption using a 3 min EBCT

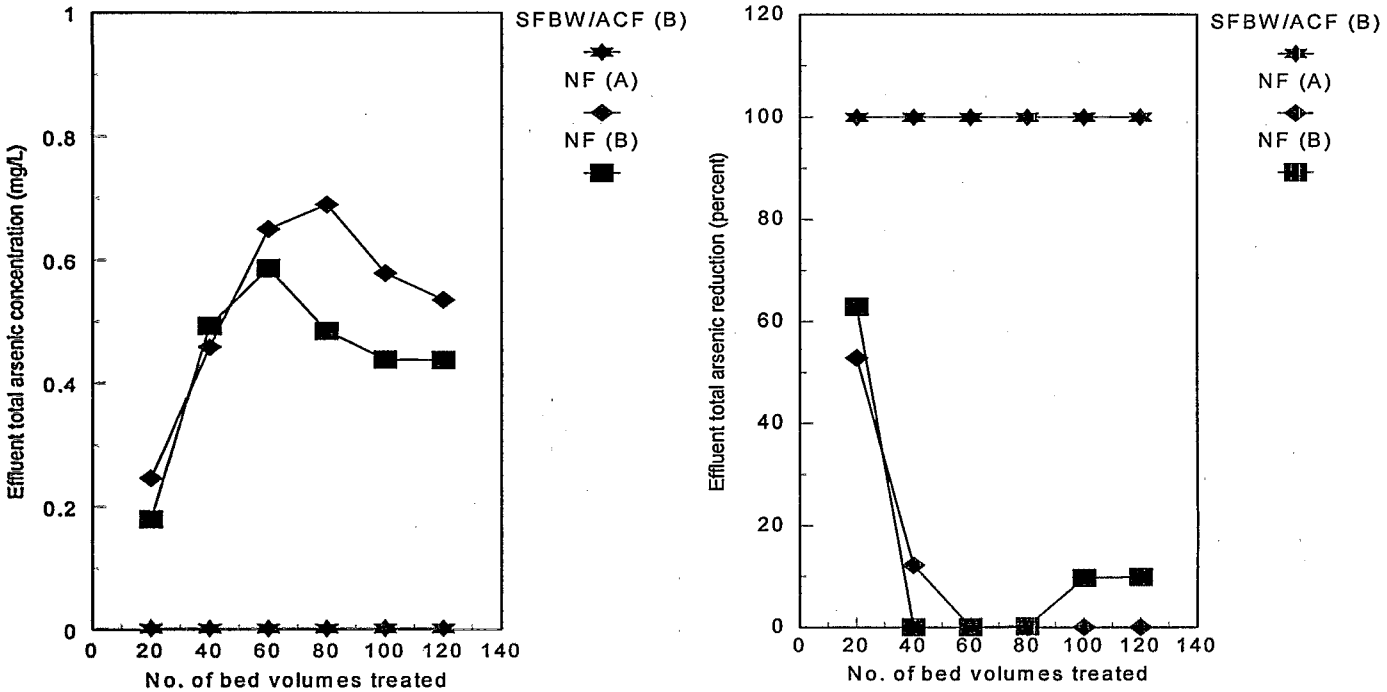


Figure 5-5. Total arsenic concentration in the column effluent and percent reduction after ion exchange using a 3 min EBCT

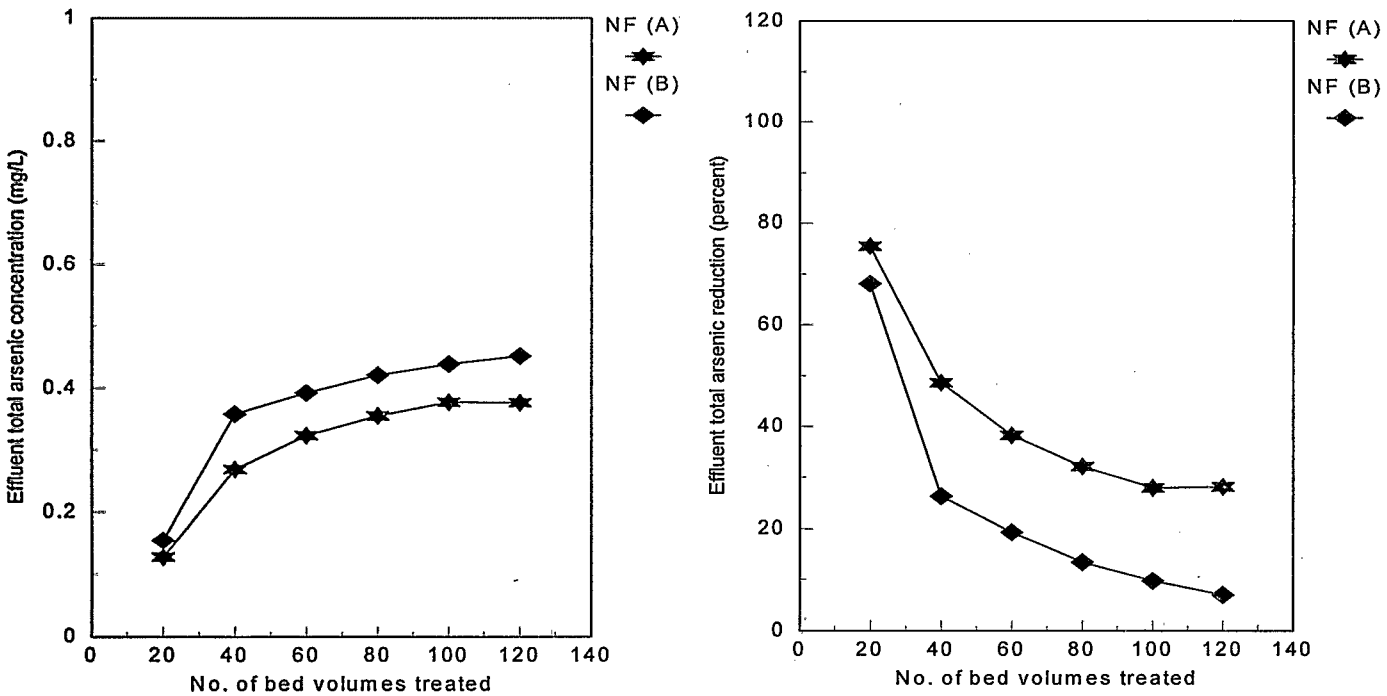


Figure 5-6. Total arsenic concentration in the column effluent and percent reduction after modified alumina media adsorption using a 3 min EBCT

- Activated alumina and the iron-based media provided comparable arsenic removal for the NF concentrates and the settled SFBW/ACF.
- Arsenic removals attained by adsorption using the iron-based media were 77 percent for RO (A) and close to 100 percent for RO (B), NF (A), NF (B), and SFBW/ACF (B) up to 120 bed volumes using an empty bed contact time of 3 min. Poorer performance resulted with the ion exchange regenerant streams, where corresponding arsenic reductions were 10 and 63.7 percent.
- Column effluent total arsenic concentrations below 0.030 mg/L were attained in adsorption tests conducted for the two NF concentrates, RO (B), and SFBW/ACF (B).
- In order to assess ultimate capacity of adsorption medias/exchange resins for removal of arsenic, tests should be run to exhaustion in future work where possible. Isotherm tests would also be instructive.
- Alkalinity may have inhibited arsenic removal.
- As for precipitation, ion exchange regenerant may be the most difficult waste to treat for meeting an in-stream arsenic standard.

5.2.3 Solids

The recent reduction in the drinking water arsenic MCL from 0.05 mg/L to 0.01 mg/L could be followed by a comparable reduction in the arsenic TCLP limit from 5.0 mg/L to 1.0 mg/L. TCLP arsenic concentrations reported in the literature indicate that solids from existing arsenic removal facilities can meet the current limits of 5.0 mg/L. While TCLP arsenic levels for solid media samples and thickened residuals samples in this work were all well below 5.0 mg/L, some facilities could have difficulty in meeting either the current or some reduced limit upon making treatment process modifications to remove more arsenic. The following findings regarding solids stemmed from this work:

- All TCLP As concentrations for solid media samples were well below the TCLP threshold limit of 5.0 mg/L (0.004 mg/L to 0.203 mg/L). Therefore, disposal of the solid medias would not be TCLP-limited based on arsenic.
- Total production of sludge after coagulant addition to treat residuals for arsenic removal was in the range of 35 to 230 dry lb sludge/MG raw water treated, and the relative order from least to greatest is ion exchange, SFBW, nanofiltration, reverse osmosis.

5.3 Recommendations for Future Work

Additional work could serve to build on the findings from this research. Some recommended areas of focus for future work are listed below:

- Determining optimal treatment conditions (chemical type, dosage, and coagulation pH) in precipitation tests for activated alumina and for ion exchange regenerants and other residuals streams with high alkalinity.
- Defining the role of alkalinity as a possible interference in arsenic removal (in precipitation and absorption tests).
- Assessing ultimate capacity for arsenic removal in adsorption tests run to exhaustion.
- Preparing isotherms to define arsenic removal.
- Determining arsenic speciation in residuals samples and the impact of speciation on removal of arsenic from residuals.
- Investigating the relationship between the TCLP and California WET test and assessing disposal implications for arsenic-laden residuals.

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Appendix A. Raw Characterization, Precipitation, and Adsorption Data and Precipitation Figures

Table A-1. Untreated residuals characterization data: General water quality parameters

Analysis date	EE&T Sample ID No.	Source name	Sample description	Sample quality characterization					
				pH	Alkalinity (mg/L)	Hardness (mg/L)	Conduct (uS/cm)	TDS (mg/L)	Sulfate (mg/L)
5/16/99	145As-FJS-RG1	Frank Jewitt School	Backwash water	7.21	71.5	68	250	130	11
5/16/99	145As-FJS-RG2	Frank Jewitt School	Brine	8.88	> 5000	260	42,570	18,660	17500
5/16/99	145As-FJS-RG3	Frank Jewitt School	Rinse	8.48	300	70	15,450	8,250	1550
7/19/99	200As-FJS	Frank Jewitt School	Backwash water no. 2	7.34	97	78	330	170	15
7/19/99	200As-FJS	Frank Jewitt School	Brine no. 2	8.97	2900	50	26,900	11,600	11589
7/26/99	200As-FJS	Frank Jewitt School	Rinse no. 2	8.43	400	80	2,500	1,250	
7/26/99	200As-FJS	Frank Jewitt School	Composite	9.00	950	90	8,100	4,100	-
6/29/99	169As-VOM	Village of Morton	Backwash water	7.60	430	365	900	460	4.82
6/29/99	169As-VOM	Village of Morton	Supernatant	-	-	-	-	-	-
7/16/99	187As-NN	Newport News, Va	RO Concentrate	7.90	2800	460	28,500	14,300	544
7/16/99	187As-NN (sp III)	Newport News, Va	RO Conc spiked (As III)	7.90	2800	460	28,500	14,300	-
01/28/00	020As-NN (sp V)	Newport News, Va	RO Conc spiked (As V)	8.03	-	-	-	-	-
7/12/99	190As-CRO	Chesapeake, Va	RO Concentrate	7.30	600	840	23,800	11,750	-
8/4/99	190As-CRO (spk)	Chesapeake, Va	RO Conc spiked w/ AsV	7.30	600	840	23,800	11,750	-
9/10/99	243As-IA	Indiana American	Backwash water	8.12	186	500	670	323	-
10/01/99	243As-IA	Indiana American	Settled BW	8.12	-	-	-	-	-
9/10/99	243As-IA	Indiana American	Clarifier flush	8.12	202	510	710	358	191.4
10/01/99	243As-IA	Indiana American	Settled CF	8.12	-	-	-	-	-
9/10/99	243As-IA	Indiana American	BW / Clarifier (50:50)	8.12	197	400	680	341	97.3
9/13/99	243As-IA	Indiana American	Settled 1 (50:50 blend)	8.12	-	-	-	-	-
9/27/99	243As-IA	Indiana American	Settled 2 (50:50 blend)	8.12	-	-	-	-	-
10/19/99	243As-IA	Indiana American	Settled 3 (50:50 blend)	8.12	-	-	-	-	-
10/12/99	281As-FM	Fort Myers, FL	Nanofiltration	6.91	360	1700	2,830	1,418	1090
10/20/99	281As-FM (spk)	Fort Myers, FL	Nanofilt. spiked w/ As V	7.06	325	1560	3,515	1,765	1075
02/10/00	041As-FM (spk)	Fort Myers, FL	Nanofilt. spiked w/ As V	6.90	-	-	-	-	-
10/14/99	285As-AA1	Act. Alum. - Battelle	AA Regenerant	7.13	268	13	22,640	10,240	16338
11/11/99	313As-PC	Palm Coast, FL	Nanofiltration	6.57	240	1,550	3,050	1,523	1220
11/15/99	313As-PC (spk)	Palm Coast, FL	Nanofilt. spiked w/ As V	6.59	210	1,750	3,080	1,533	1190
02/09/00	039As-JL	Jerry Lowry	Backwash	7.90	95	108	237	118	-
02/09/00	039As-JL	Jerry Lowry	Brine	9.80	9,800	80	15,100	7,550	1864
02/09/00	039As-JL	Jerry Lowry	Brine (Jug 8 - not mixed)	9.80	-	-	-	-	-
02/09/00	039As-JL	Jerry Lowry	Brine (Jug 9 - not mixed)	9.80	-	-	-	-	-
02/09/00	039As-JL	Jerry Lowry	Rinse	9.80	4,000	84	11,460	5,740	-
02/10/00	039As-JL	Jerry Lowry	Composite	9.70	7,000	86	12,440	6,240	910

Table A-2. Untreated residuals characterization data: Metals

Analysis date	EE&T Sample ID No.	Source name	Sample description	Sample quality characterization				
				Total As (mg/L)	Total Fe (mg/L)	Total Mn (mg/L)	Total Al (mg/L)	Disolv As (mg/L)
5/16/99	145As-FJS-RG1	Frank Jewitt School	Backwash water	0.032	0.088	< 0.005	-	0.031
5/16/99	145As-FJS-RG2	Frank Jewitt School	Brine	37.00	0.894	< 0.005	-	17.70
5/16/99	145As-FJS-RG3	Frank Jewitt School	Rinse	1.700	0.282	0.007	-	1.670
7/19/99	200As-FJS	Frank Jewitt School	Backwash water no. 2	0.069	1.780	0.060	-	0.037
7/19/99	200As-FJS	Frank Jewitt School	Brine no. 2	33.20	< 0.01	< 0.005	-	31.80
7/26/99	200As-FJS	Frank Jewitt School	Rinse no. 2	1.240	0.106	0.010	-	1.270
7/26/99	200As-FJS	Frank Jewitt School	Composite	10.50	0.490	-	-	10.30
6/29/99	169As-VOM	Village of Morton	Backwash water	1.410	78.50	7.52	-	< 0.002
6/29/99	169As-VOM	Village of Morton	Supernatant	0.007	0.381	-	-	< 0.002
7/16/99	187As-NN	Newport News, Va	RO Concentrate	< 0.002	0.067	0.232	-	< 0.002
7/16/99	187As-NN (sp III)	Newport News, Va	RO Conc spiked (As III)	0.526	0.067	0.232	-	0.501
01/28/00	020As-NN (sp V)	Newport News, Va	RO Conc spiked (As V)	0.546	-	-	-	-
7/12/99	190As-CRO	Chesapeake, Va	RO Concentrate	< 0.002	0.858	1.110	-	< 0.002
8/4/99	190As-CRO (spk)	Chesapeake, Va	RO Conc spiked w/ AsV	0.663	0.858	1.110	-	-
9/10/99	243As-IA	Indiana American	Backwash water	1.160	31.00	2.50	-	0.031
10/01/99	243As-IA	Indiana American	Settled BW	0.038	-	-	-	-
9/10/99	243As-IA	Indiana American	Clarifier flush	2.450	64.60	5.24	-	0.030
10/01/99	243As-IA	Indiana American	Settled CF	0.046	-	-	-	-
9/10/99	243As-IA	Indiana American	BW / Clarifier (50:50)	1.740	45.90	3.75	-	0.029
9/13/99	243As-IA	Indiana American	Settled 1 (50:50 blend)	0.122	-	-	-	-
9/27/99	243As-IA	Indiana American	Settled 2 (50:50 blend)	0.024	0.054	-	-	-
10/19/99	243As-IA	Indiana American	Settled 3 (50:50 blend)	0.043	-	-	-	-
10/12/99	281As-FM	Fort Myers, FL	Nanofiltration	0.013	2.620	0.12	-	0.007
10/20/99	281As-FM (spk)	Fort Myers, FL	Nanofilt. spiked w/ As V	0.523	2.160	0.140	-	0.487
02/10/00	041As-FM (spk)	Fort Myers, FL	Nanofilt. spiked w/ As V	0.483	-	-	-	-
10/14/99	285As-AA1	Act. Alum. - Battelle	AA Regenerant	2.630	0.831	0.085	113.0	0.117
11/11/99	313As-PC	Palm Coast, FL	Nanofiltration	0.005	0.450	0.084	-	0.009
11/15/99	313As-PC (spk)	Palm Coast, FL	Nanofilt. spiked w/ As V	0.486	0.458	0.081	-	0.515
02/09/00	039As-JL	Jerry Lowry	Backwash	0.089	0.084	<0.005	-	0.094
02/09/00	039As-JL	Jerry Lowry	Brine	34.3	<0.010	0.006	-	25.3
02/09/00	039As-JL	Jerry Lowry	Brine (Jug 8 - not mixed)	32.4	-	-	-	-
02/09/00	039As-JL	Jerry Lowry	Brine (Jug 9 - not mixed)	21.3	-	-	-	-
02/09/00	039As-JL	Jerry Lowry	Rinse	12.4	<0.010	<0.005	-	14.0
02/10/00	039As-JL	Jerry Lowry	Composite	24.8	<0.010	<0.005	-	24.7

Table A-3. Precipitation test data

Wastewater ID	Sample description	Treatment conditions				Treated characteristics			Arsenic removal (percent)
		Alum (mg/L)	Ferric (mg/L)	Polymer (mg/L)	Coag. pH	Total As (mg/L)	Total Fe (mg/L)	Total Al (mg/L)	
SFBW (A)	Backwash water	25	-	4	7.60	0.074	-	0.467	94.75
SFBW (A)	Backwash water	50	-	-	7.40	0.048	-	0.531	96.60
SFBW (A)	Backwash water	50	-	-	6.00	0.096	-	0.616	93.19
SFBW (A)	Backwash water	50	-	4	7.40	0.021	-	0.429	98.51
SFBW (A)	Backwash water	-	25	4	7.30	0.034	3.380	-	97.59
SFBW (A)	Backwash water	-	50	-	7.07	0.022	2.880	-	98.44
SFBW (A)	Backwash water	-	50	-	5.00	0.056	6.460	-	96.03
SFBW (A)	Backwash water	-	50	4	7.10	0.013	1.570	-	99.08
SFBW (A)	Backwash water	-	50	4	5.07	0.031	3.900	-	97.80
SFBW (A)	Backwash water	-	-	-	5.92	0.231	-	-	83.62
RO (A)	RO concentrate	-	25	-	6.00	0.494	7.100	-	9.52
RO (A)	RO concentrate	-	25	2	6.00	0.519	0.986	-	4.95
RO (A)	RO concentrate	-	50	-	6.00	0.304	8.460	-	44.32
RO (A)	RO concentrate	-	50	2	6.00	0.364	0.739	-	33.33
RO (A)	RO concentrate	-	100	2	7.45	0.368	1.750	-	30.04
RO (A)	RO concentrate	-	100	5	7.50	0.388	1.930	-	26.24
RO (A)	RO concentrate	-	100	2	6.29	0.094	5.480	-	82.13
RO (A)	RO concentrate	-	100	-	6.00	0.091	4.910	-	83.33
RO (A)	RO concentrate	-	100	2	6.00	0.097	0.877	-	82.23
RO (A)	RO concentrate	-	150	-	6.00	0.047	3.520	-	91.39
RO (A)	RO concentrate	-	150	2	6.00	0.041	0.015	-	92.49
RO (A)	RO concentrate	100	-	-	7.70	0.526	-	2.760	0.06
RO (A)	RO concentrate	100	-	2	8.20	0.773	-	5.270	0.00
RO (A)	RO concentrate	100	-	2	6.00	0.698	-	6.860	0.00
RO (A)	RO concentrate	150	-	2	8.20	0.730	-	7.490	0.00
RO (A)	RO concentrate	150	-	2	6.00	0.644	-	9.200	0.00
RO (A)	RO concentrate	-	-	-	6.14	0.575	-	-	0.00
RO (A)	RO concentrate	-	-	NaOH (pH)	10.75	0.483	-	-	11.54
RO (A)	RO concentrate	-	-	Lime (pH)	10.70	0.570	-	-	0.00
Ion Ex (A)	Backwash	-	75	-	6.50	< 0.002	0.497	-	96.88
Ion Ex (A)	Rinse	-	75	-	-	0.176	1.670	-	89.65
Ion Ex (A)	Rinse	-	100	-	-	0.387	2.510	-	77.24
Ion Ex (A)	Composite	-	100	-	7.86	2.360	5.430	-	78.60
Ion Ex (A)	Composite	-	100	-	6.19	1.280	3.510	-	87.81
Ion Ex (A)	Composite	100	-	-	8.87	9.310	-	2.990	11.33
Ion Ex (A)	Composite	100	-	-	5.48	5.980	-	3.730	43.05

Table A-3. Continued

Wastewater ID	Sample description	Treatment conditions				Treated characteristics			Arsenic removal (percent)
		Alum (mg/L)	Ferric (mg/L)	Polymer (mg/L)	Coag. pH	Total As (mg/L)	Total Fe (mg/L)	Total Al (mg/L)	
Ion Ex (A)	Composite	-	-	-	6.07	9.060	-	-	13.71
Ion Ex (A)	Brine	-	50	-	6.35	29.800	10.900	-	10.24
Ion Ex (A)	Brine	-	100	-	8.81	4.350	4.900	-	86.89
Ion Ex (A)	Brine	-	100	-	6.38	14.400	6.030	-	56.63
Ion Ex (A)	Brine	100	-	-	8.19	32.600	-	7.320	1.81
Ion Ex (A)	Brine	100	-	-	6.42	28.700	-	5.800	13.55
RO (B)	RO concentrate	-	50	-	6.70	0.189	4.420	-	71.49
RO (B)	RO concentrate	-	50	-	5.78	0.561	-	4.410	15.38
RO (B)	RO concentrate	-	100	-	7.18	0.132	0.087	-	80.09
RO (B)	RO concentrate	-	100	-	6.16	0.078	3.220	-	88.24
RO (B)	RO concentrate	50	-	-	7.01	0.286	7.800	-	56.86
RO (B)	RO concentrate	50	-	-	5.88	0.570	-	4.880	14.03
RO (B)	RO concentrate	100	-	-	7.55	0.442	-	2.500	33.33
RO (B)	RO concentrate	100	-	-	6.26	0.306	-	3.090	53.85
RO (B)	RO concentrate	-	-	-	5.99	0.719	-	-	0.00
SFBW/ACF (B)	Composite	-	25	-	6.00	0.152	4.700	-	91.26
SFBW/ACF (B)	Composite	-	50	-	5.97	0.100	3.930	-	94.25
SFBW/ACF (B)	Composite	-	75	-	7.19	0.064	2.660	-	96.32
SFBW/ACF (B)	Composite	-	75	-	6.18	0.070	2.800	-	95.98
SFBW/ACF (B)	Composite	-	100	-	6.65	0.110	4.890	-	93.68
SFBW/ACF (B)	Composite	-	100	-	6.12	0.075	3.440	-	95.69
SFBW/ACF (B)	Composite	75	-	-	7.28	0.194	-	0.762	88.85
SFBW/ACF (B)	Composite	75	-	-	6.07	0.205	-	0.720	88.22
SFBW/ACF (B)	Composite	100	-	-	7.13	0.248	-	1.150	85.75
SFBW/ACF (B)	Composite	100	-	-	6.12	0.214	-	0.974	87.70
SFBW/ACF (B)	Settled Comp.	-	25	-	7.32	0.093	3.650	-	0.00
SFBW/ACF (B)	Settled Comp.	-	50	-	6.94	0.018	2.570	-	58.14
SFBW/ACF (B)	Settled Comp.	-	75	-	6.68	0.013	1.910	-	69.77
SFBW/ACF (B)	Settled Comp.	-	100	-	6.54	0.011	2.620	-	74.42
AA Regen	AA Regenerant	-	-	-	7.13	0.386	-	11.800	85.32
AA Regen	AA Regenerant	-	25	-	7.10	0.171	0.677	7.420	93.50
AA Regen	AA Regenerant	-	50	-	6.95	0.154	1.150	7.620	94.14
NF (A)	NF concentrate	-	75	4	4.79	0.071	5.24	-	86.42
NF (A)	NF concentrate	-	75	-	6.74	0.085	0.154	-	82.40
NF (A)	NF concentrate	-	100	4	4.90	0.093	8.68	-	82.22
NF (A)	NF concentrate	-	100	-	6.35	0.143	0.152	-	70.39
NF (A)	NF concentrate	-	150	4	4.98	0.061	8.64	-	88.34

Table A-3. Continued

Wastewater ID	Sample description	Treatment conditions				Treated characteristics			Arsenic removal (percent)
		Alum (mg/L)	Ferric (mg/L)	Polymer (mg/L)	Coag. pH	Total As (mg/L)	Total Fe (mg/L)	Total Al (mg/L)	
NF (A)	NF concentrate	-	150	-	6.20	0.094	10.0	-	80.54
NF (A)	NF concentrate	-	150	-	5.30	0.117	11.9	-	75.78
NF (A)	NF concentrate	-	200	4	5.20	0.009	1.41	-	98.14
NF (A)	NF concentrate	75	-	4	7.20	0.197	-	1.220	62.33
NF (A)	NF concentrate	75	-	4	6.08	0.221	-	1.640	57.74
NF (A)	NF concentrate	100	-	4	7.11	0.130	-	1.230	75.14
NF (A)	NF concentrate	100	-	4	6.11	0.162	-	1.480	69.02
NF (A)	NF concentrate	100	-	-	6.83	0.225	-	3.810	53.42
NF (A)	NF concentrate	150	-	4	6.97	0.060	-	0.821	88.53
NF (A)	NF concentrate	150	-	4	6.04	0.073	-	1.200	86.04
NF (A)	NF concentrate	200	-	-	6.60	0.148	-	4.970	69.36
NF (A)	NF concentrate	200	-	4	6.59	0.029	-	0.673	94.00
NF (B)	NF concentrate	-	50	0.5	5.06	0.030	1.22	-	93.83
NF (B)	NF concentrate	-	75	0.5	5.04	0.036	2.23	-	92.59
NF (B)	NF concentrate	-	75	4	6.52	0.009	4.69	-	98.15
NF (B)	NF concentrate	-	100	4	6.31	0.006	0.699	-	98.77
NF (B)	NF concentrate	-	100	0.5	4.94	0.020	1.59	-	95.88
NF (B)	NF concentrate	-	150	4	6.24	0.005	0.967	-	98.97
NF (B)	NF concentrate	50	-	0.5	6.04	0.235	-	0.649	51.65
NF (B)	NF concentrate	50	-	0.5	6.90	0.283	-	0.566	41.77
NF (B)	NF concentrate	75	-	4	6.55	0.116	-	0.491	76.13
NF (B)	NF concentrate	75	-	0.5	6.79	0.157	-	0.796	67.70
NF (B)	NF concentrate	75	-	0.5	6.05	0.129	-	0.697	73.46
NF (B)	NF concentrate	100	-	4	6.51	0.067	-	0.526	86.21
NF (B)	NF concentrate	100	-	0.5	6.75	0.087	-	0.525	82.10
NF (B)	NF concentrate	100	-	0.5	6.02	0.073	-	0.626	84.98
NF (B)	NF concentrate	150	-	4	6.44	0.035	-	0.654	92.80
Ion Ex (B)	Composite	-	50	-	9.90	25.8	6.14	-	0.00
Ion Ex (B)	Composite	-	50	-	6.18	26.0	9.55	-	0.00
Ion Ex (B)	Composite	-	100	-	9.90	25.3	5.95	-	0.00
Ion Ex (B)	Composite	-	100	-	6.15	23.3	8.81	-	6.05
Ion Ex (B)	Composite	-	200	-	9.90	22.7	5.44	-	8.47
Ion Ex (B)	Composite	-	200	-	6.15	18.7	7.89	-	24.60
Ion Ex (B)	Composite	-	200	0.5	9.90	23.2	8.17	-	6.45
Ion Ex (B)	Composite	-	200	0.5	6.20	17.5	2.96	-	29.44
Ion Ex (B)	Composite	50	-	-	9.90	26.6	-	4.54	0.00
Ion Ex (B)	Composite	50	-	-	6.15	23.5	-	4.05	5.24
Ion Ex (B)	Composite	100	-	-	9.90	24.6	-	8.59	0.81

Table A-3. Continued

Wastewater ID	Sample description	Treatment conditions				Treated characteristics			Arsenic removal (percent)
		Alum (mg/L)	Ferric (mg/L)	Polymer (mg/L)	Coag. pH	Total As (mg/L)	Total Fe (mg/L)	Total Al (mg/L)	
Ion Ex (B)	Composite	100	-	-	6.14	23.3	-	5.59	6.05
Ion Ex (B)	Composite	200	-	-	9.90	25.5	-	16.2	0.00
Ion Ex (B)	Composite	200	-	-	6.12	22.8	-	5.82	8.06
Ion Ex (B)	Composite	200	-	0.5	9.90	26.3	-	16.7	0.00
Ion Ex (B)	Composite	200	-	0.5	6.12	25.5	-	1.28	0.00

Table A-4. Adsorption test data

Wastewater ID	Sample description	Media type	EBCT (min)	Sample time (hrs)	Sample bed-volumes	Test pH	Treated characteristics			As removal (percent)
							Total As (mg/L)	Total Fe (mg/L)	Total Al (mg/L)	
SFBW (A)	Backwash	Iron media	1.5	1	40	7.6	0.289	27.8	-	79.50
			-	2	80	-	0.636	59.5	-	54.89
			-	3	120	-	1.180	111.0	-	16.31
			-	4	160	-	1.580	149.0	-	0.00
			-	5	200	-	1.560	146.0	-	0.00
			-	6	240	-	0.286	28.0	-	79.70
SFBW (A)	Backwash	Iron media	4.5	1	12.2	7.6	1.390	136.0	-	1.42
			-	2	26.6	-	1.390	135.0	-	1.42
			-	3	40	-	1.410	141.0	-	0.00
			-	4	53.2	-	1.170	118.0	-	17.02
			-	5	66.6	-	1.030	102.0	-	26.95
			-	6	80	-	1.060	105.0	-	24.82
SFBW (A)	Backwash	Activated alumina	1.5	1	40	7.6	1.500	141.0	-	0.00
			-	2	80	-	1.550	146.0	-	0.00
			-	3	120	-	1.540	145.0	-	0.00
			-	4	160	-	1.650	154.0	-	0.00
			-	5	200	-	1.370	129.0	-	0.00
			-	6	240	-	1.420	136.0	-	0.00
RO (A)	Concentrate	Iron media	1.5	1	40	7.5	0.095	0.209	-	81.94
			-	2	80	-	0.211	< 0.01	-	59.89
			-	3	120	-	0.252	< 0.01	-	52.09
			-	4	160	-	0.320	< 0.01	-	39.16
			-	5	200	-	0.366	< 0.01	-	30.42
			-	6	240	-	0.398	< 0.01	-	24.33
RO (A)	Concentrate	Iron media	3	1	20	7.5	< 0.002	0.407	-	100.00
			-	2	40	-	0.423	0.078	-	19.58
			-	3	60	-	0.068	0.102	-	87.07
			-	4	80	-	0.119	< 0.01	-	77.37
			-	5	100	-	0.640	< 0.01	-	0.00
RO (A)	Concentrate	Activated alumina	3	1	20	7.5	0.062	-	2.2	88.21
			-	2	40	-	0.116	-	2.0	77.95
			-	3	60	-	0.296	-	1.0	43.72
			-	4	80	-	0.389	-	0.7	26.04
			-	5	100	-	0.473	-	0.5	10.07
			-	6	120	-	0.527	-	0.3	0.00
Ion Ex (A)	Brine	Iron media	1.5	1	40	8.9	11.20	0.813	-	69.73
			-	2	80	-	18.40	0.783	-	50.27
			-	3	120	-	22.30	0.753	-	39.73
			-	4	160	-	23.20	0.755	-	37.30
Ion Ex (A)	Brine	Activated alumina	1.5	1	40	6.0	2.410	-	-	92.74
			-	2	80	-	9.410	-	-	71.65
			-	3	120	-	11.600	-	-	65.06
			-	4	160	-	16.400	-	-	50.60
			-	5	200	-	21.800	-	-	34.33

Table A.4. Continued

Wastewater ID	Sample description	Media type	EBCT (min)	Sample time (hrs)	Sample bed-volumes	Test pH	Treated characteristics			As removal (percent)
							Total As (mg/L)	Total Fe (mg/L)	Total Al (mg/L)	
Ion Ex (A)	Composite	Iron media	1.5	1	40	9.0	0.897	< 0.01	-	91.96
			-	2	80	-	2.280	< 0.01	-	78.29
			-	3	120	-	3.600	< 0.01	-	65.71
			-	4	160	-	4.120	< 0.01	-	60.76
			-	5	200	-	4.620	< 0.01	-	56.00
			-	6	240	-	7.020	< 0.01	-	33.14
Ion Ex (A)	Composite	Iron media	3	1	20	9.0	0.044	< 0.01	-	99.58
			-	2	40	-	11.600	< 0.01	-	0.00
			-	3	60	-	1.710	0.061	-	83.71
			-	4	80	-	2.890	0.097	-	72.47
			-	5	100	-	3.810	< 0.01	-	63.71
			-	6	120	-	11.600	< 0.01	-	0.00
RO (B)	Concentrate	Activated alumina	1.5	1	40	7.3	0.047	-	0.3	92.91
			-	2	80	-	0.095	-	0.3	85.67
			-	3	120	-	0.180	-	0.4	72.85
			-	4	160	-	0.202	-	0.4	69.53
			-	5	200	-	0.263	-	0.4	60.33
			-	6	240	-	0.292	-	0.3	55.96
RO (B)	Concentrate	Activated alumina	3	1	20	7.3	0.004	-	0.2	99.40
			-	2	40	-	0.012	-	0.3	98.19
			-	3	60	-	0.020	-	0.4	96.98
			-	4	80	-	0.037	-	0.5	94.42
			-	5	100	-	0.051	-	0.5	92.31
			-	6	120	-	0.071	-	0.6	89.29
RO (B)	Concentrate	Iron media	1.5	1	40	8.0	< 0.002	< 0.01	-	100.00
			-	2	80	-	0.010	0.072	-	98.49
			-	3	120	-	0.036	0.189	-	94.57
			-	4	160	-	0.068	0.275	-	89.74
			-	5	200	-	0.086	0.317	-	87.03
			-	6	240	-	0.106	0.366	-	84.01
RO (B)	Concentrate	Iron media	3	1	20	7.3	<0.002	0.243	-	100.00
			-	2	40	-	0.003	0.565	-	99.55
			-	3	60	-	0.004	0.047	-	99.40
			-	4	80	-	0.011	0.111	-	98.34
			-	5	100	-	0.013	0.134	-	98.04
			-	6	120	-	0.018	0.218	-	97.29
SFBW/ACF (B)	Settled composite	Ion exchange	3	1	20	8.1	< 0.002	-	-	100.00
			-	2	40	-	< 0.002	-	-	100.00
			-	3	60	-	< 0.002	-	-	100.00
			-	4	80	-	< 0.002	-	-	100.00
			-	5	100	-	< 0.002	-	-	100.00
			-	6	120	-	< 0.002	-	-	100.00

Table A.4. Continued

Wastewater ID	Sample description	Media type	EBCT (min)	Sample time (hrs)	Sample bed-volumes	Test pH	Treated characteristics			As removal (percent)
							Total As (mg/L)	Total Fe (mg/L)	Total Al (mg/L)	
SFBW/ACF (B)	Settled composite	Iron media	3	1	20	8.1	< 0.002	0.039	-	100.00
			-	2	40	-	< 0.002	0.021	-	100.00
			-	3	60	-	< 0.002	0.023	-	100.00
			-	4	80	-	< 0.002	0.056	-	100.00
			-	5	100	-	< 0.002	0.017	-	100.00
			-	6	120	-	< 0.002	0.030	-	100.00
SFBW/ACF (B)	Settled 50:50 blend	Activated alumina	3	1	20	8.1	0.002	-	0.1	95.35
			-	2	40	-	< 0.002	-	0.1	100.00
			-	3	60	-	< 0.002	-	0.1	100.00
			-	4	80	-	< 0.002	-	0.1	100.00
			-	5	100	-	< 0.002	-	0.1	100.00
			-	6	120	-	< 0.002	-	0.1	100.00
NF (A)	Concentrate	Iron media	3	1	20	7.1	0.003	0.273	-	99.43
			-	2	40	-	0.009	0.483	-	98.28
			-	3	60	-	0.010	0.723	-	98.09
			-	4	80	-	0.013	0.959	-	97.51
			-	5	100	-	0.016	1.110	-	96.94
			-	6	120	-	0.021	1.210	-	95.98
NF (A)	Concentrate	Iron media	6	1	10	7.1	0.003	3.550	-	99.43
			-	2	20	-	<0.002	0.145	-	100.00
			-	3	30	-	<0.002	0.087	-	100.00
			-	4	40	-	<0.002	0.138	-	100.00
			-	5	50	-	0.003	0.191	-	99.43
			-	6	60	-	0.004	0.021	-	99.24
NF (A)	Concentrate	Ion exchange	3	1	20	7.1	0.246	-	-	52.96
			-	2	40	-	0.459	-	-	12.24
			-	3	60	-	0.650	-	-	0.00
			-	4	80	-	0.690	-	-	0.00
			-	5	100	-	0.579	-	-	0.00
			-	6	120	-	0.535	-	-	0.00
NF (A)	Concentrate	Activated alumina	3	1	20	7.1	0.007	-	0.3	98.66
			-	2	40	-	0.011	-	0.3	97.90
			-	3	60	-	0.014	-	0.3	97.32
			-	4	80	-	0.021	-	0.3	95.98
			-	5	100	-	0.026	-	0.3	95.03
			-	6	120	-	0.034	-	0.3	93.50
NF (A)	Concentrate	Activated alumina	6	1	10	7.1	0.004	-	0.2	99.24
			-	2	20	-	0.002	-	0.2	99.62
			-	3	30	-	0.003	-	0.2	99.43
			-	4	40	-	0.002	-	0.2	99.62
			-	5	50	-	0.004	-	0.1	99.24
			-	6	60	-	0.007	-	0.1	98.66

Table A.4. Continued

Wastewater ID	Sample description	Media type	EBCT (min)	Sample time (hrs)	Sample bed-volumes	Test pH	Treated characteristics			As removal (percent)
							Total As (mg/L)	Total Fe (mg/L)	Total Al (mg/L)	
NF (A)	Concentrate	Modified alumina	3	1	20	7.1	0.128	0.961	0.3	75.53
			-	2	40	-	0.269	0.998	0.2	48.57
			-	3	60	-	0.323	0.928	0.2	38.24
			-	4	80	-	0.355	0.998	0.1	32.12
			-	5	100	-	0.377	0.920	0.2	27.92
			-	6	120	-	0.376	0.856	0.2	28.11
NF (B)	Concentrate	Iron media	3	1	20	6.6	<0.002	0.152	-	100.00
			-	2	40	-	0.002	<0.010	-	99.59
			-	3	60	-	<0.002	0.269	-	100.00
			-	4	80	-	0.491	0.359	-	0.00
			-	5	100	-	<0.002	0.254	-	100.00
			-	6	120	-	<0.002	0.185	-	100.00
NF (B)	Concentrate	Iron media	6	1	10	6.6	<0.002	0.118	-	100.00
			-	2	20	-	<0.002	0.072	-	100.00
			-	3	30	-	<0.002	0.075	-	100.00
			-	4	40	-	<0.002	0.097	-	100.00
			-	5	50	-	<0.002	0.077	-	100.00
			-	6	60	-	<0.002	0.192	-	100.00
NF (B)	Concentrate	Ion Exchange	3	1	20	6.6	0.180	-	-	62.96
			-	2	40	-	0.493	-	-	0.00
			-	3	60	-	0.587	-	-	0.00
			-	4	80	-	0.485	-	-	0.21
			-	5	100	-	0.439	-	-	9.67
			-	6	120	-	0.438	-	-	9.88
NF (B)	Concentrate	Activated alumina	3	1	20	6.6	<0.002	-	0.1	100.00
			-	2	40	-	<0.002	-	0.1	100.00
			-	3	60	-	<0.002	-	0.1	100.00
			-	4	80	-	<0.002	-	0.2	100.00
			-	5	100	-	<0.002	-	0.1	100.00
			-	6	120	-	0.004	-	0.1	99.18
NF (B)	Concentrate	Activated alumina	6	1	10	6.6	<0.002	-	0.3	100.00
			-	2	20	-	<0.002	-	0.3	100.00
			-	3	30	-	<0.002	-	0.3	100.00
			-	4	40	-	<0.002	-	0.3	100.00
			-	5	50	-	<0.002	-	0.3	100.00
			-	6	60	-	<0.002	-	0.3	100.00
NF (B)	Concentrate	Modified alumina	3	1	20	6.6	0.155	0.167	0.2	68.11
			-	2	40	-	0.358	0.099	0.2	26.34
			-	3	60	-	0.392	0.179	0.2	19.34
			-	4	80	-	0.421	0.462	0.2	13.37
			-	5	100	-	0.439	0.414	0.2	9.67
			-	6	120	-	0.452	0.315	0.2	7.00

Table A.4. Continued

Wastewater ID	Sample description	Media type	EBCT (min)	Sample time (hrs)	Sample bed-volumes	Test pH	Treated characteristics			As removal (percent)
							Total As (mg/L)	Total Fe (mg/L)	Total Al (mg/L)	
Ion Ex (B)	Composite	Iron media	3	1	20	9.9	8.54	12.3	-	65.56
			-	2	40	-	16.7	1.50	-	32.66
			-	3	60	-	19.3	1.01	-	22.18
			-	4	80	-	20.9	0.252	-	15.73
			-	5	100	-	21.1	0.726	-	14.92
			-	6	120	-	22.3	0.600	-	10.08
Ion Ex (B)	Composite	Activated alumina	3	1	20	9.9	19.8	-	9.8	20.16
			-	2	40	-	22.7	-	8.2	8.47
			-	3	60	-	23.6	-	7.5	4.84
			-	4	80	-	23.8	-	6.7	4.03
			-	5	100	-	23.6	-	6.2	4.84
			-	6	120	-	24.0	-	5.4	3.23

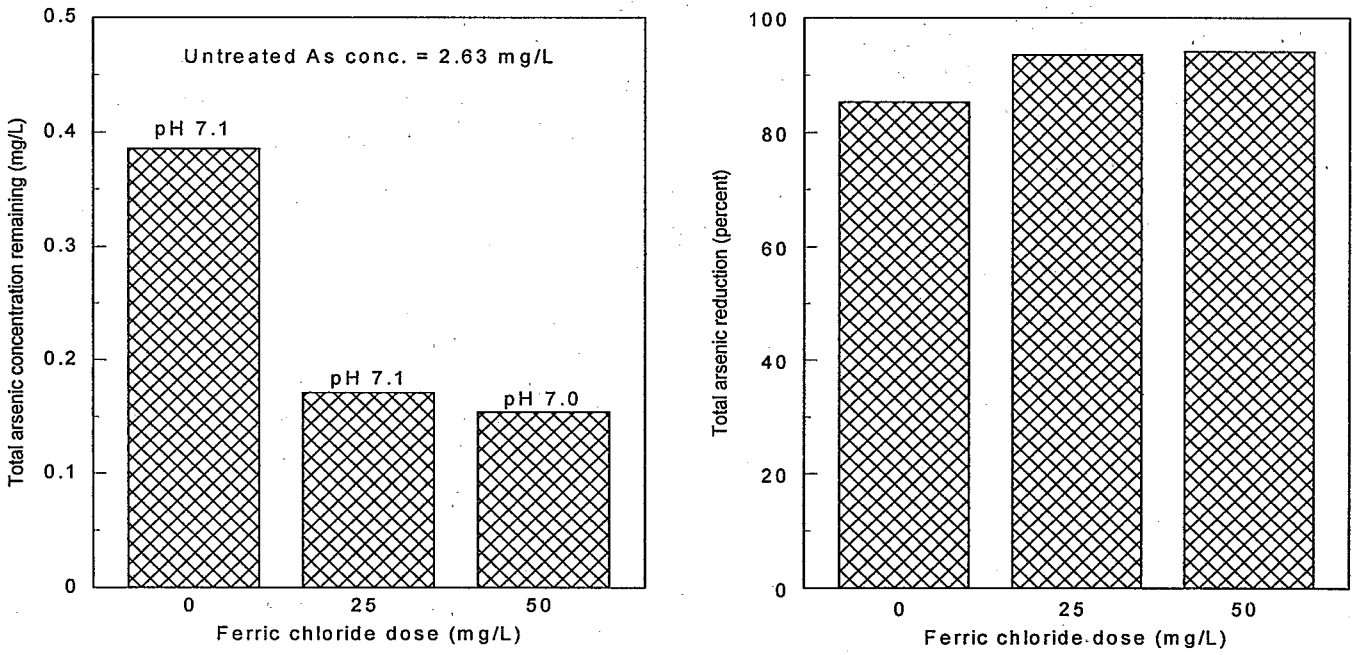

Figure A-1. Total arsenic removal and total arsenic in the supernatant after ferric chloride precipitation in activated alumina regenerant

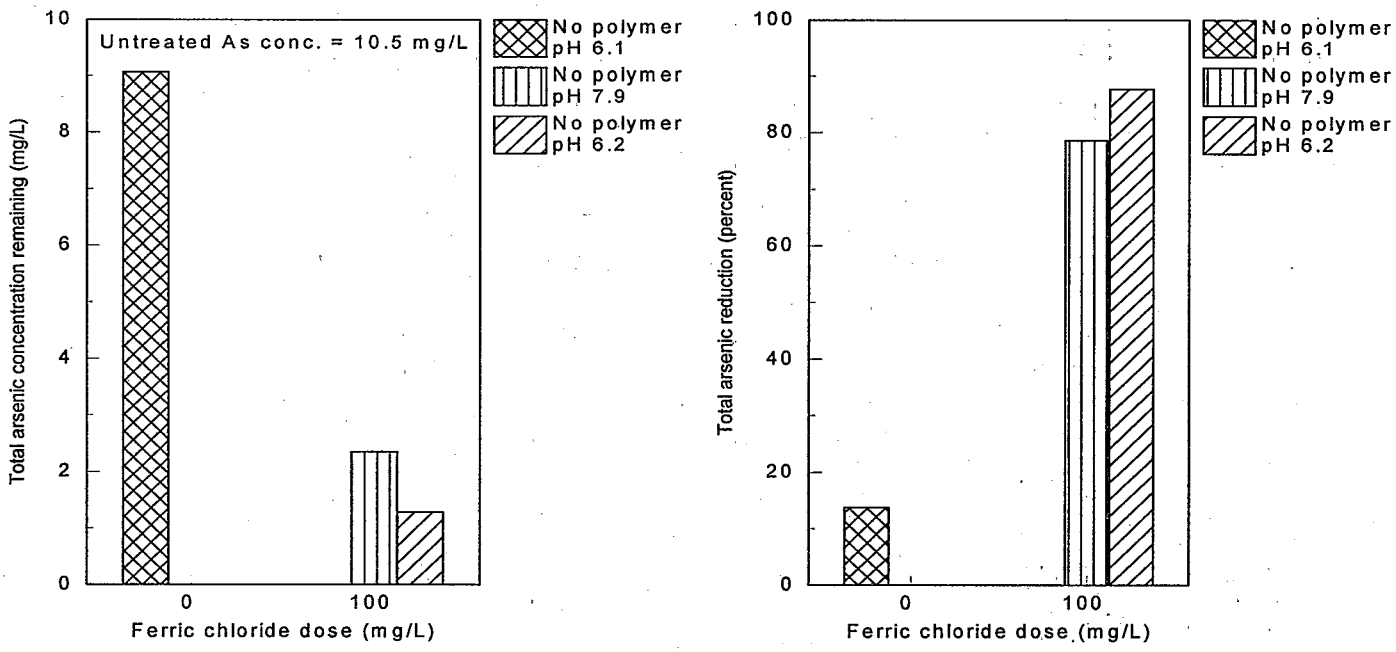

Figure A-2. Total arsenic removal and total arsenic remaining in the supernatant after ferric chloride precipitation for ion exchange (A) composite

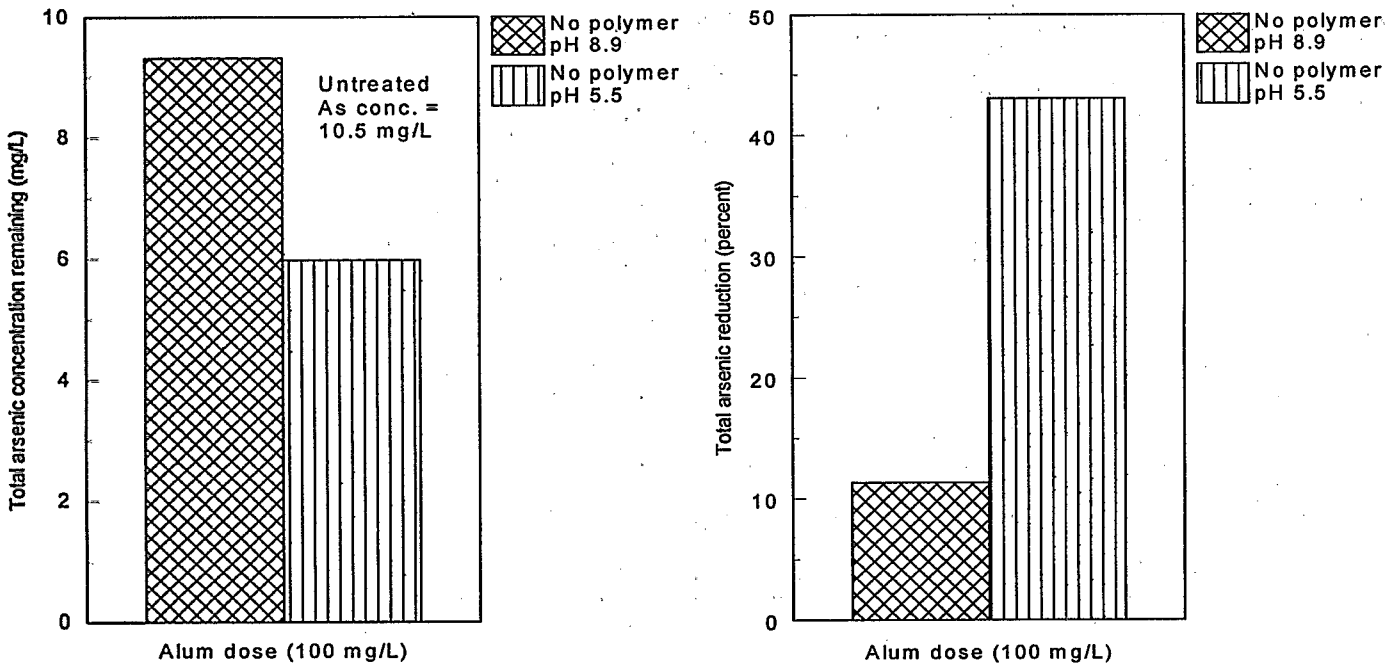

Figure A-3. Total arsenic removal and total arsenic remaining in the supernatant after alum precipitation for ion exchange (A) composite

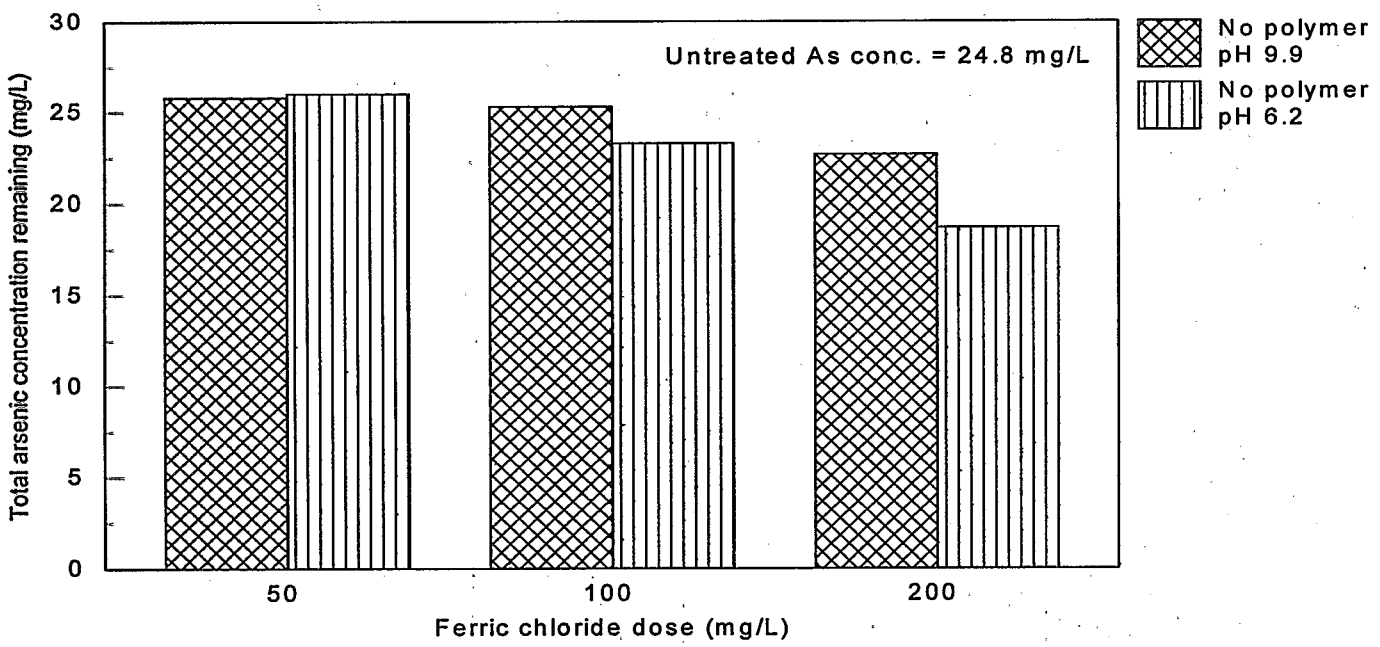

Figure A-4. Total arsenic remaining in the supernatant after ferric chloride precipitation for ion exchange (B) composite

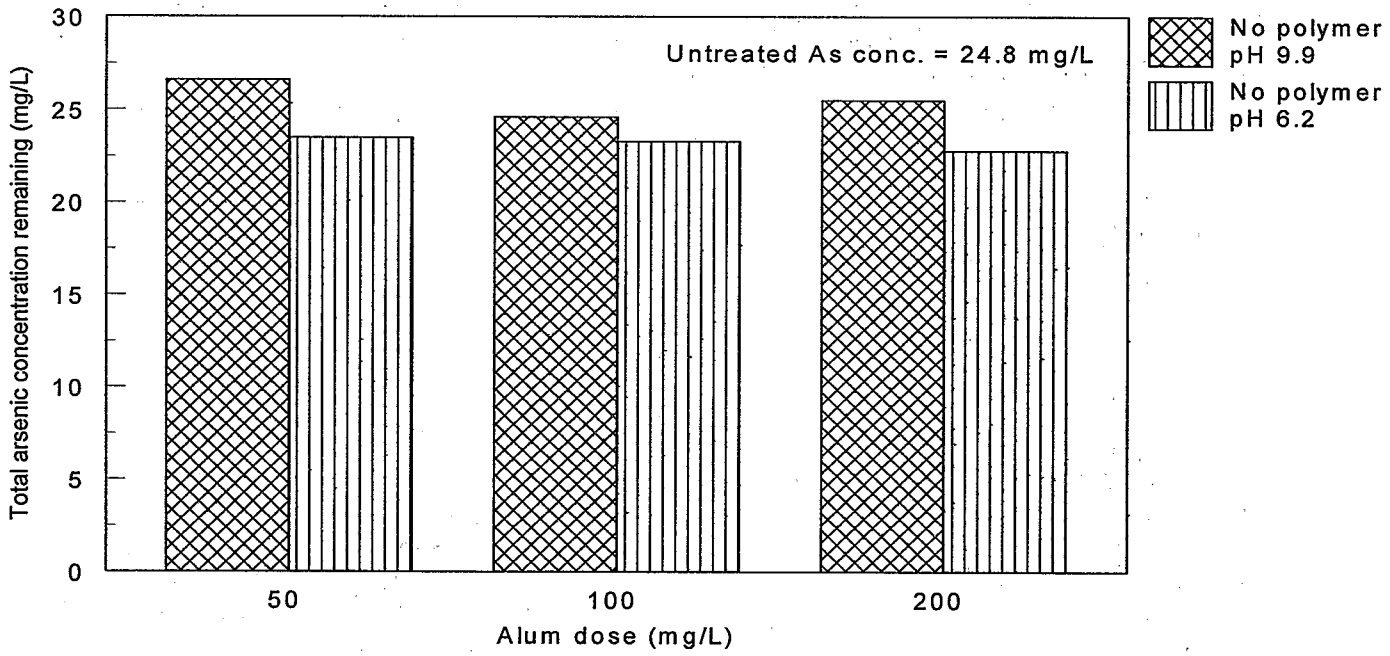

Figure A-5. Total arsenic remaining in the supernatant after alum precipitation for ion exchange (B) composite

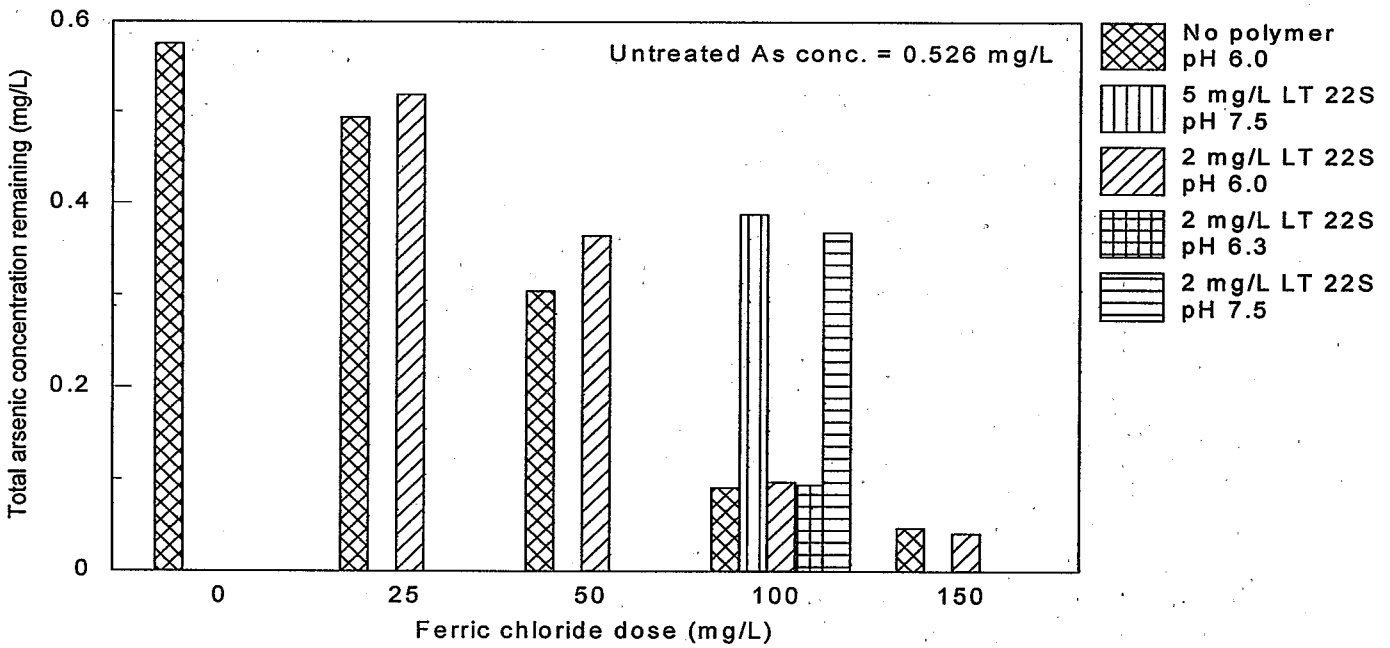

Figure A-6. Total arsenic concentration remaining in the supernatant after ferric chloride precipitation for reverse osmosis (A) concentrate

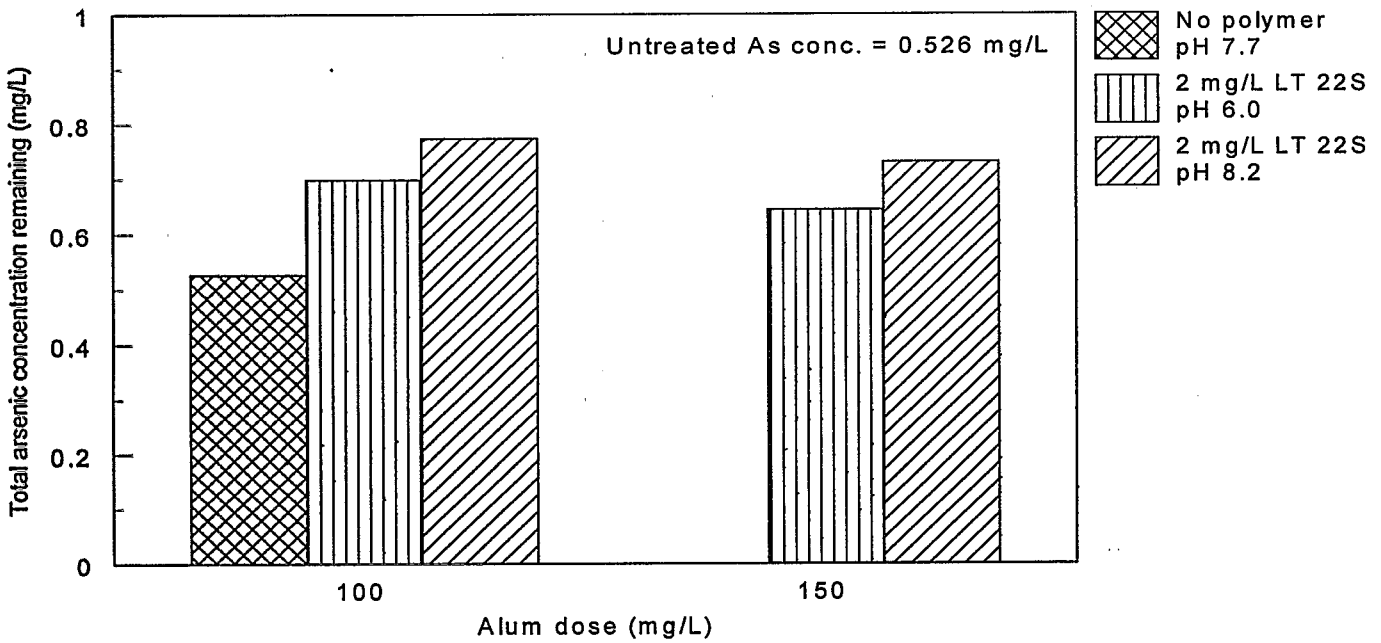

Figure A-7. Total arsenic remaining in the supernatant after alum precipitation for reverse osmosis (A) concentrate

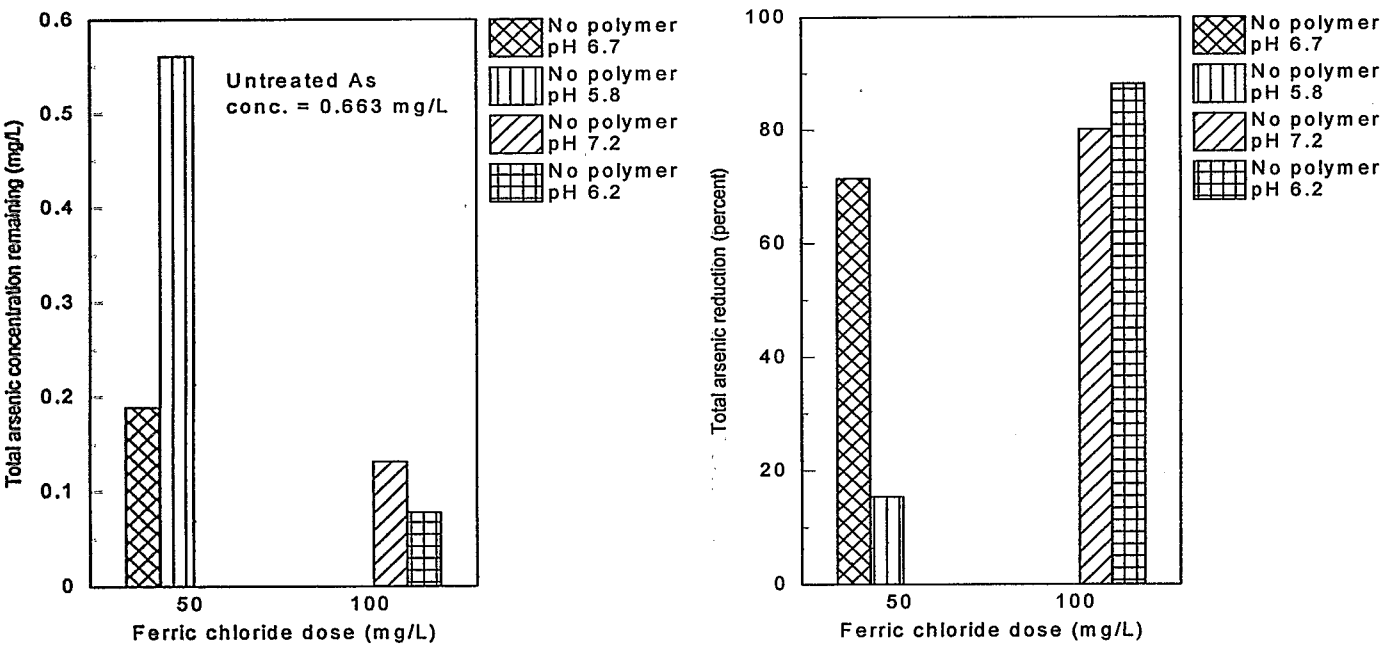

Figure A-8. Total arsenic removal and total arsenic remaining in the supernatant after ferric chloride precipitation for reverse osmosis (B) concentrate

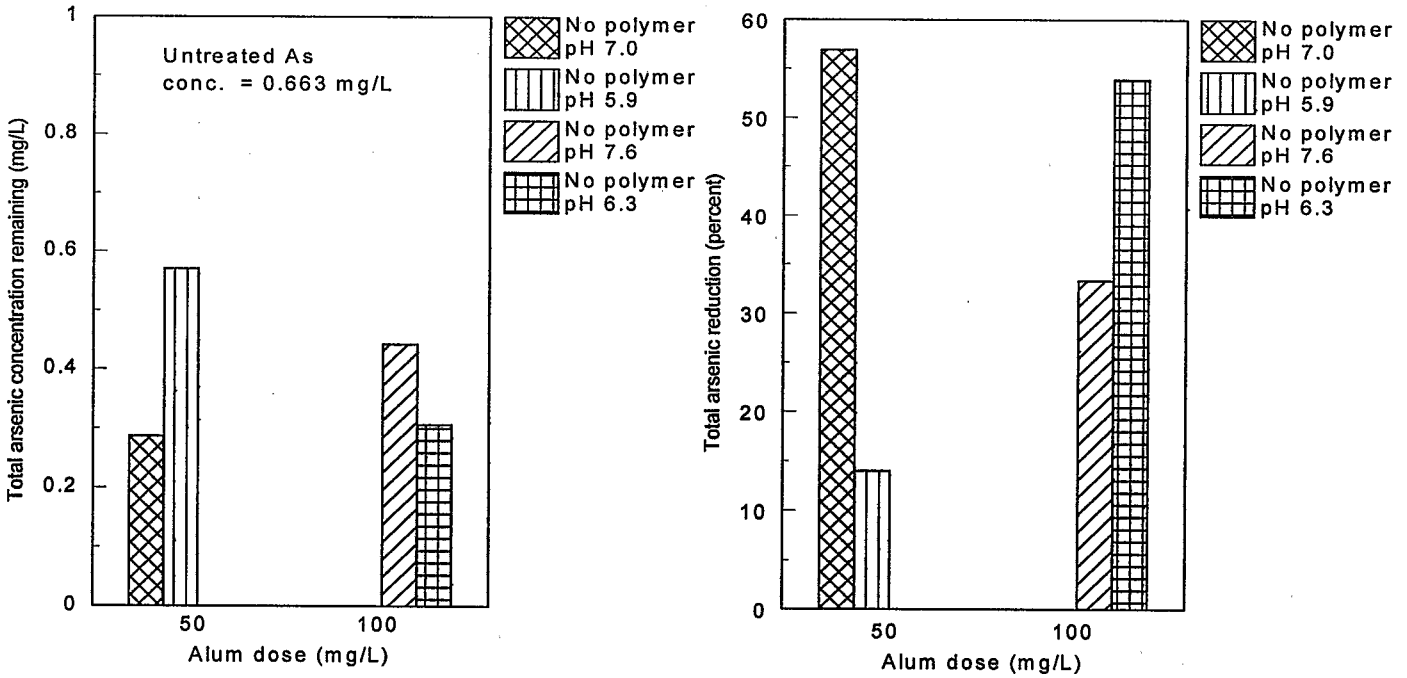

Figure A-9. Total arsenic removal and total arsenic remaining in the supernatant after alum precipitation for reverse osmosis (B) concentrate

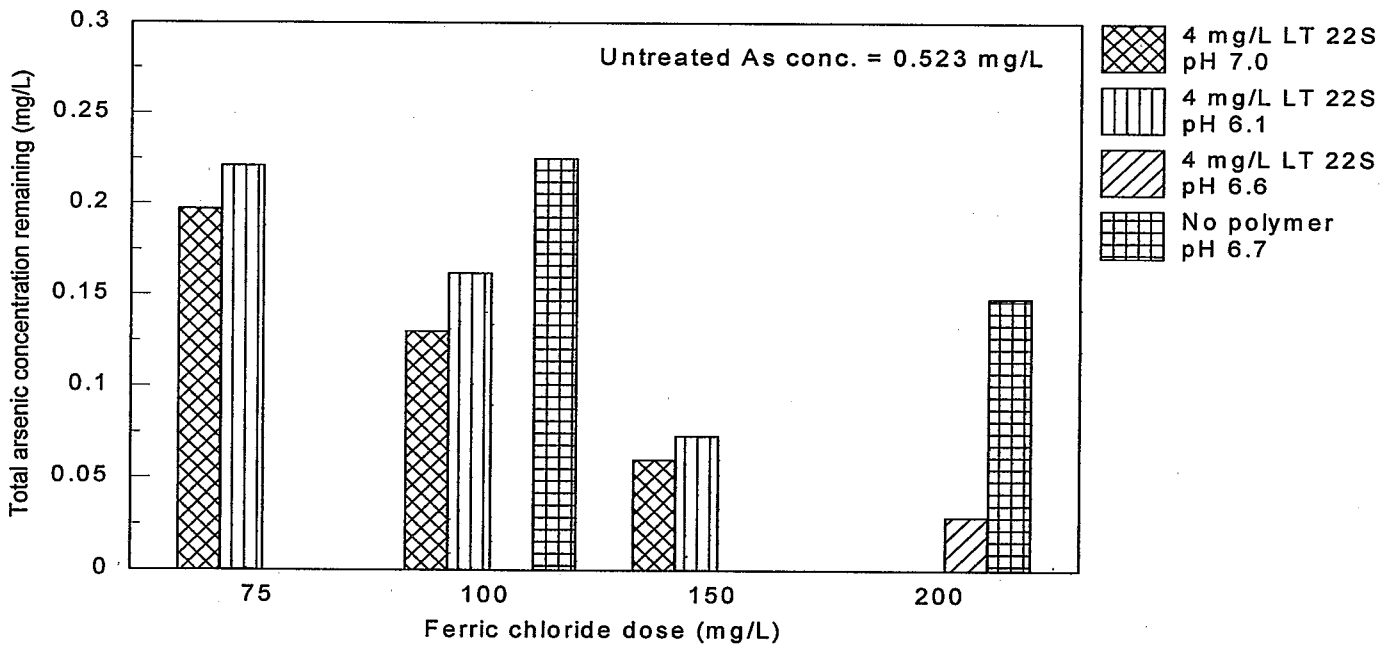

Figure A-10. Total arsenic remaining in the supernatant after ferric chloride precipitation for nanofiltration (A) concentrate

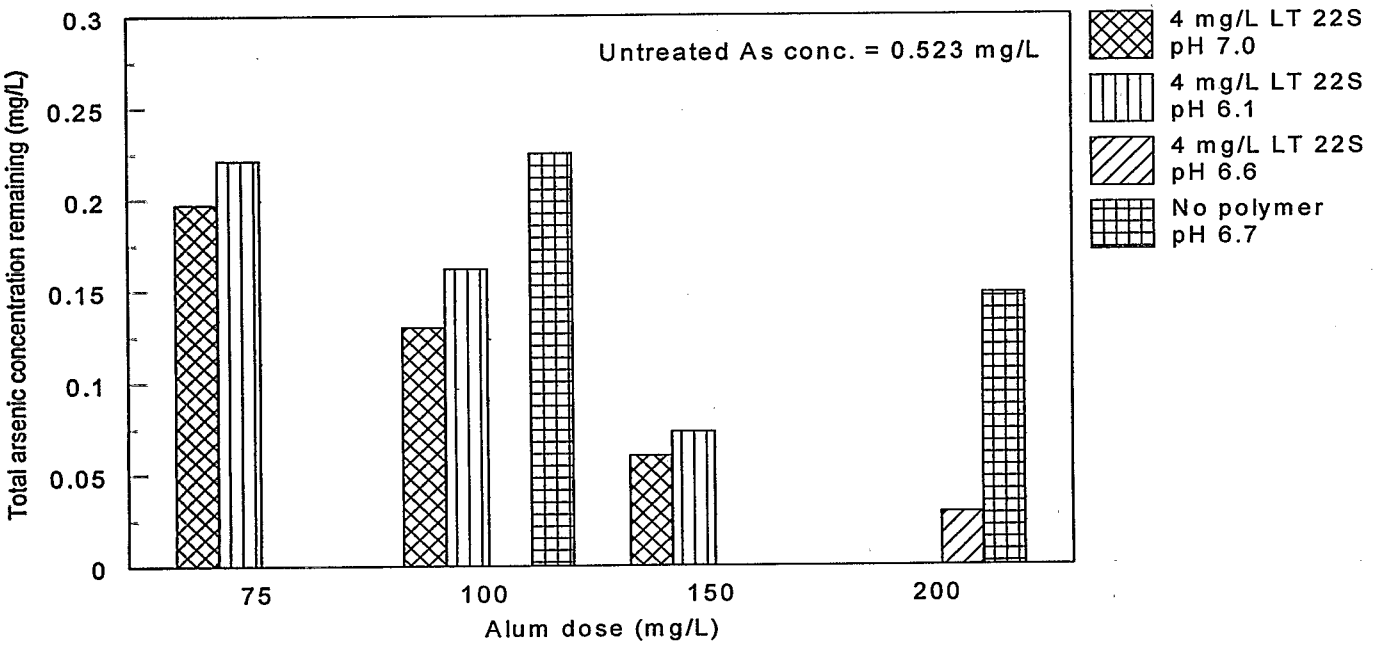

Figure A-11. Total arsenic remaining in the supernatant after alum precipitation for nanofiltration (A) concentrate

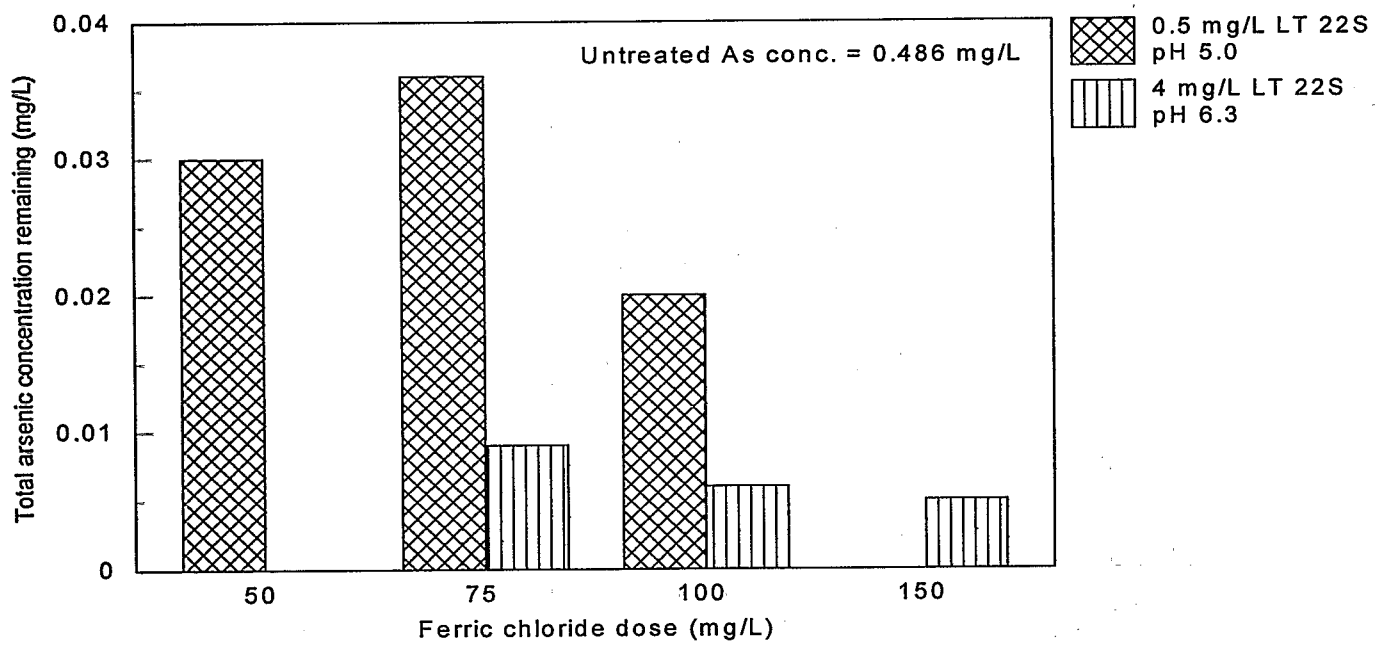

Figure A-12. Total arsenic remaining in the supernatant after ferric chloride precipitation for nanofiltration (B) concentrate

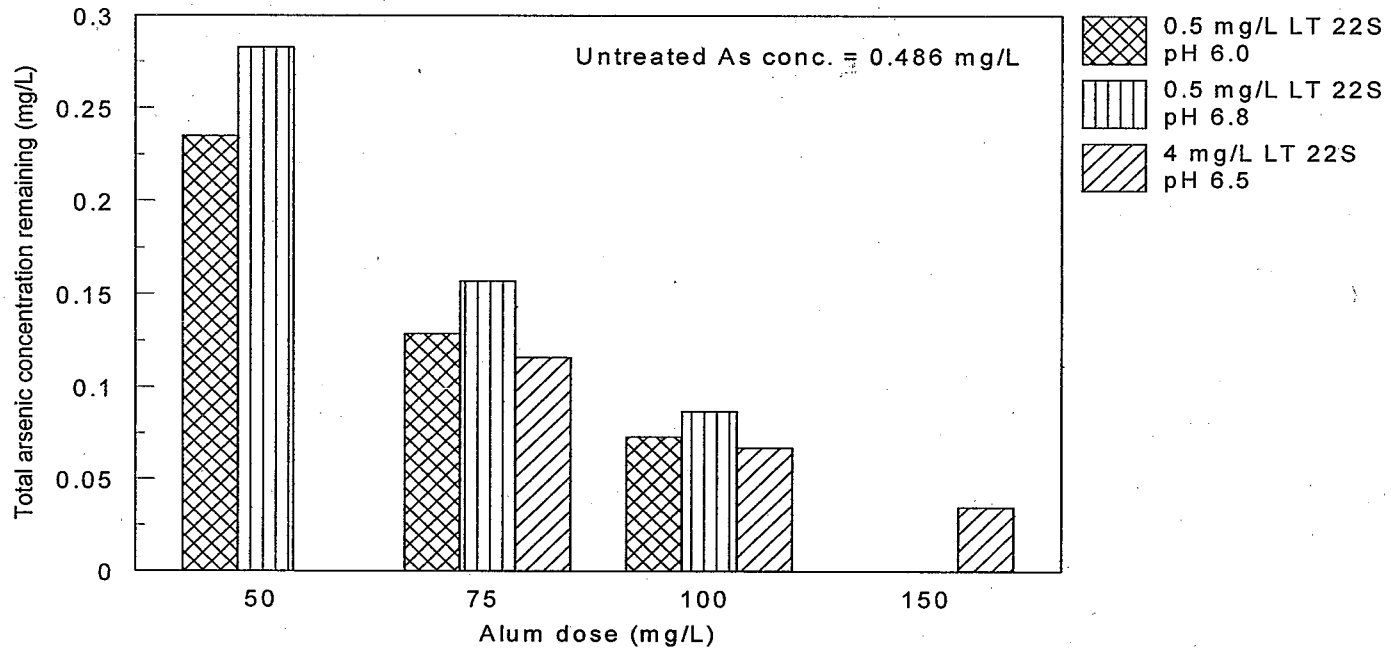

Figure A-13. Total arsenic remaining in the supernatant after alum precipitation for nanofiltration (B) concentrate

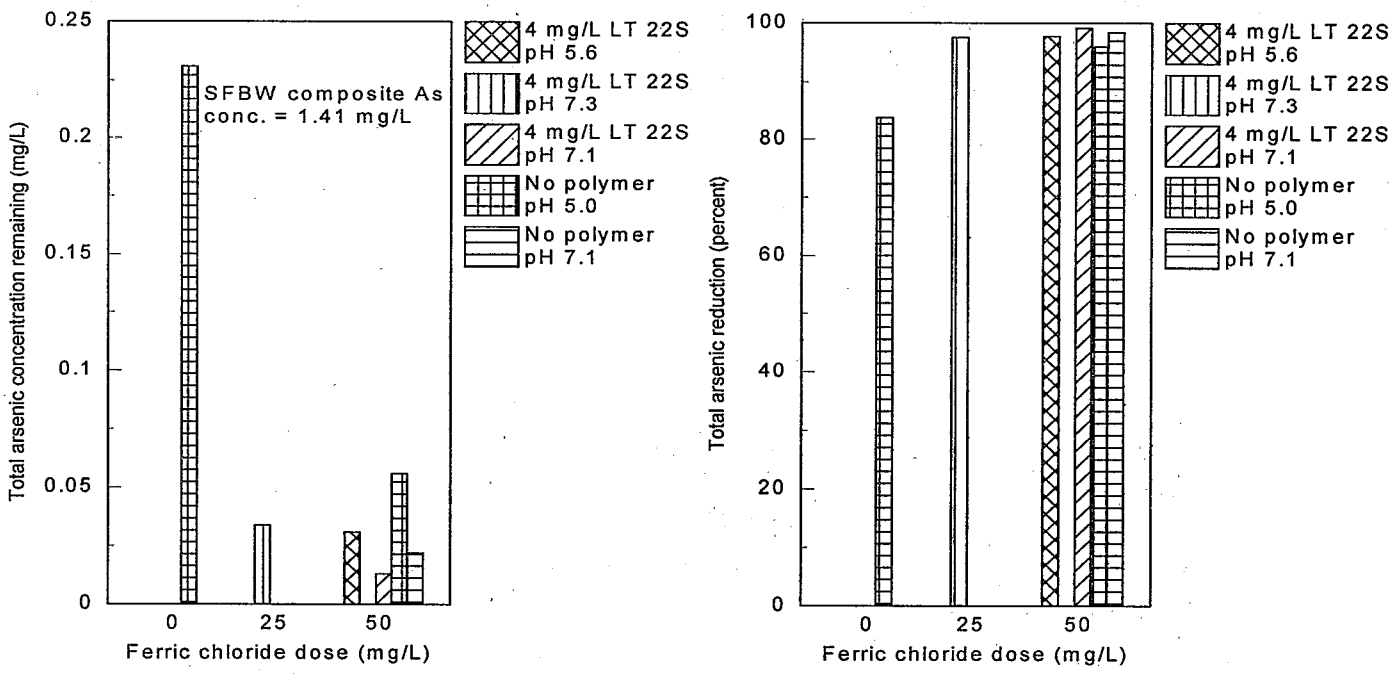

Figure A-14. Total arsenic removal and total arsenic remaining in the supernatant after ferric chloride precipitation for spent filter backwash (A) composite (unsettled)

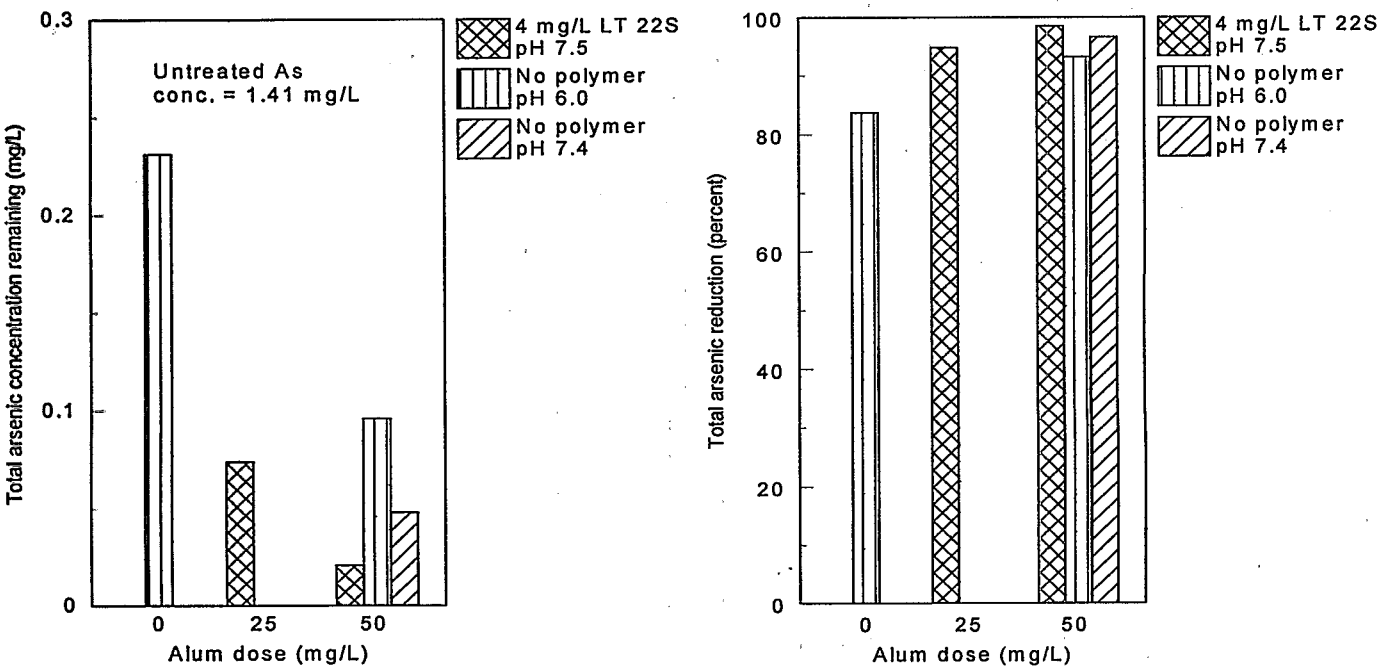

Figure A-15. Total arsenic removal and total arsenic remaining in the supernatant after alum precipitation for spent filter backwash (A) composite

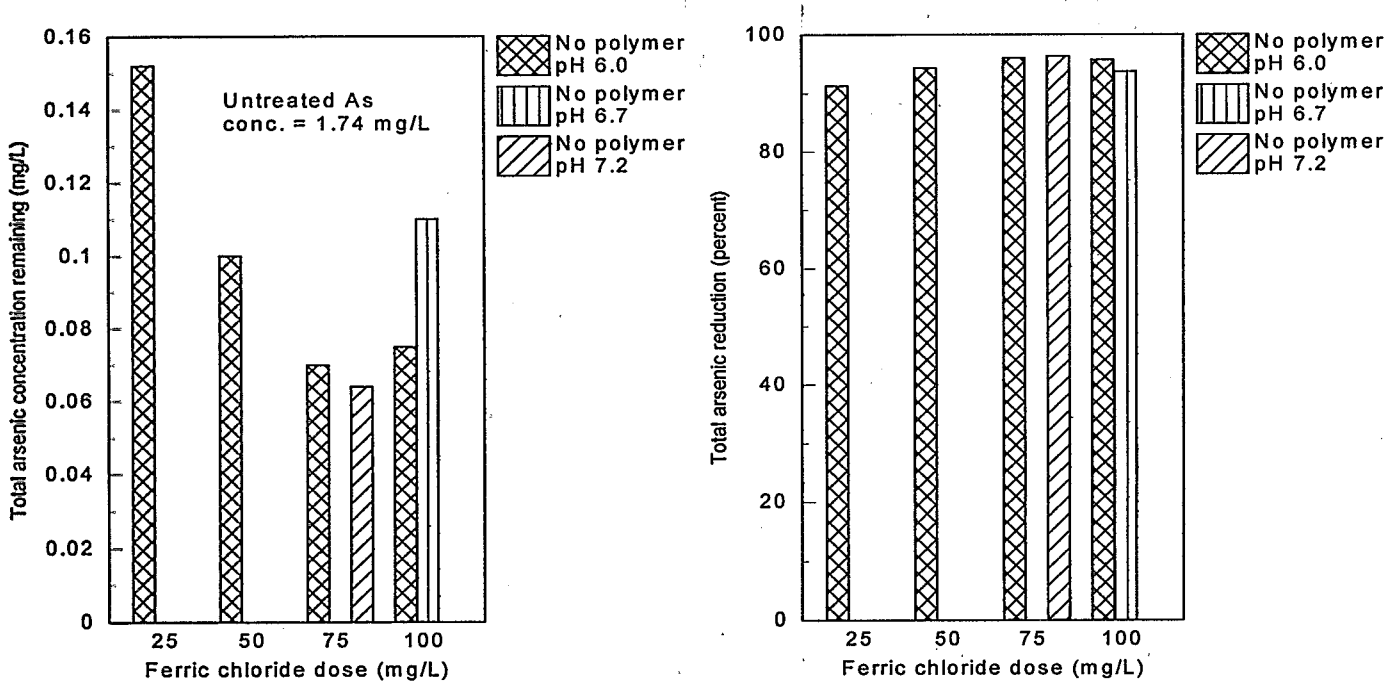

Figure A-16. Total arsenic removal and total arsenic remaining in the supernatant after ferric chloride precipitation for spent filter backwash (B) composite (unsettled)

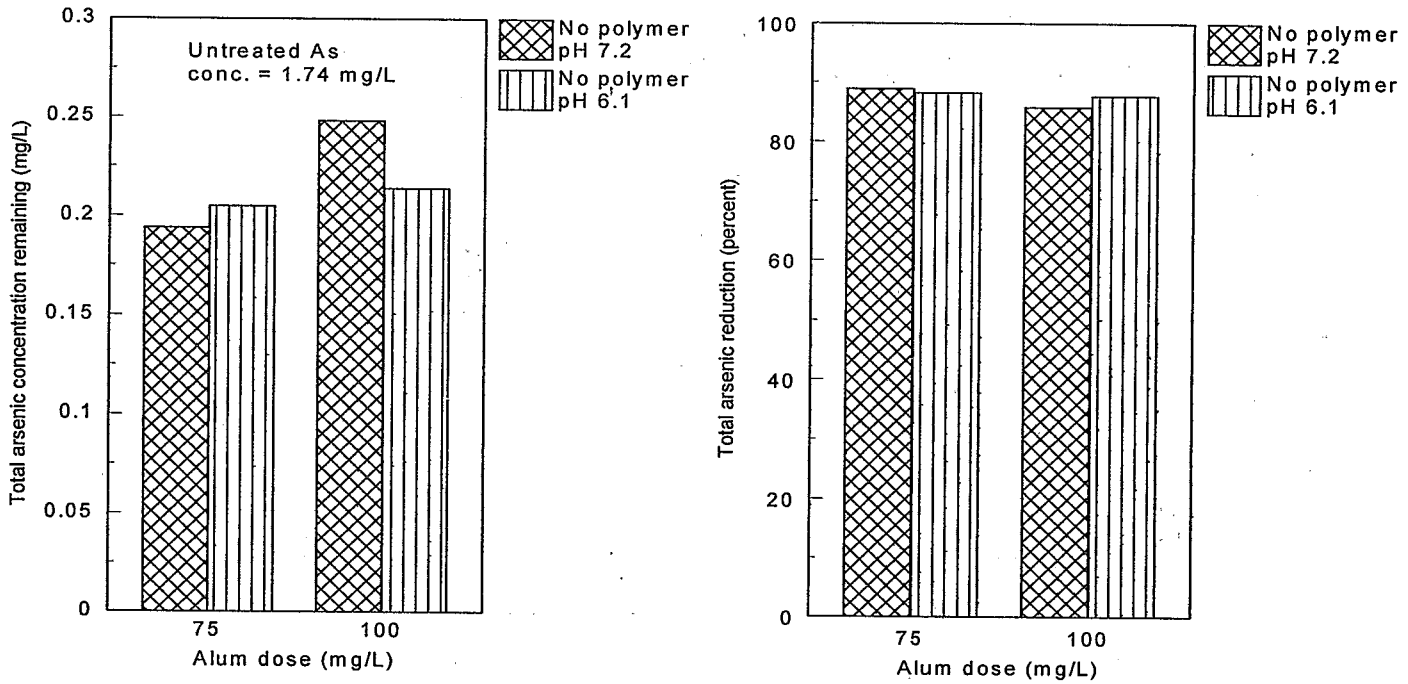

Figure A-17. Total arsenic removal and total arsenic remaining in the supernatant after alum precipitation for spent filter backwash (B) composite

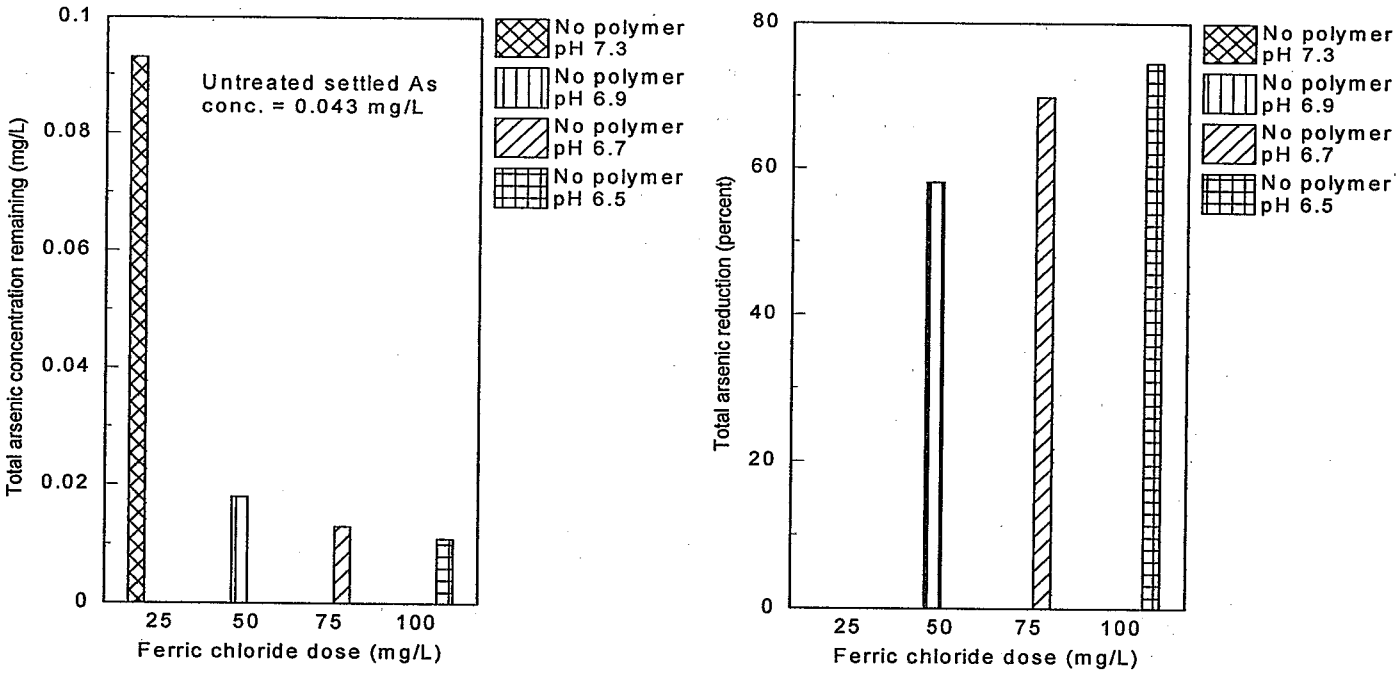

Figure A-18. Total arsenic removal and total arsenic remaining in the supernatant after ferric chloride precipitation for spent filter backwash (B) composite (settled)

Appendix B. QA/QC Results

Results

The QA/QC results contain data from the instrumental methodologies employed for the analysis of metal ions (As, Al, Fe, Mn) and sulfate (SO_4^{2-}). Valid QA and analytical data were obtained through the use of duplicate and spiked samples. The QA/QC results for the key analyses conducted during the study are provided in Table B-1. This table reports the relative percent deviation (RPD) of duplicate analyses, spike recovery percentages, and the continuing calibration value (CCV). These data quality indicators are provided for each day that samples were analyzed (for each measurement) throughout the project. The spike and CCV values used along with the calibration ranges are listed as table footnotes.

The QA/QC results presented in Table B-1 indicate that the objectives outlined by the QAPP were achieved. The RPD for each QA/QC analysis was less than 25 percent, demonstrating good analytical precision. The spike recoveries were within the 75 to 125 percent accuracy range. The CCV percent recovery data ranged between 95 and 110 percent for each spiked analyte evaluated.

Corrective Actions

During the study there were no deviations from the sampling procedures outlined by the QAPP. All sampling for analytical tests performed were conducted at EE&T and either analyzed by EE&T Laboratory or hand-delivered to James R. Reed Laboratory for analysis.

There were also no deviations from the analytical procedures that were outlined in the QAPP. Analytical or calculation errors, if present, were found and corrected after completion of each set of analyses. All data were evaluated by the QA officer to determine if re-analysis was necessary. Overall, there were no modifications to the original QAPP and any corrective actions required were taken during the analytical runs and corrections were made prior to proceeding.

Table B-1. QA/QC summary

Analysis date	Analyte	1st analysis (mg/L)	2nd analysis (mg/L)	Duplicate RPD (percent)	Spike recovery (percent)	CCV recovery (percent)
5/26/99	Arsenic	0.550	0.545	0.9	110	95
	Iron	0.724	0.744	2.7	95	97
	Manganese	0.552	0.552	0.0	98	98
6/8/99	Arsenic	< 0.002	< 0.002	N/A	112	104
	Iron	1.47	1.45	1.4	115	100
	Manganese	0.100	0.099	1.0	100	101
	Sulfate	1,808	1,698	6.5	79.7	87
6/10/99	Arsenic	0.514	0.518	0.8	103	105
	Iron	0.561	0.566	0.9	97	102
6/30/99	Arsenic	< 0.002	< 0.002	N/A	119	103
	Iron	0.774	0.767	0.9	99	96
	Manganese	0.093	0.092	1.1	107	96
7/6/99	Arsenic	< 0.002	< 0.002	N/A	103	108
	Arsenic	1.560	1.530	2.0	121	103
	Iron	0.277	0.272	1.8	108	100
	Iron	146	144	1.4	127	102
	Aluminum	0.258	0.228	13.2	100	107
7/8/99	Arsenic	0.520	0.517	0.6	104	102
7/12/99	Arsenic	1.060	1.060	0.0	116	103
	Iron	105	105	0.0	101	99
	Manganese	9.54	9.54	0.0	106	100
7/19/99	Arsenic	< 0.002	< 0.002	N/A	116	102
	Iron	0.654	0.668	2.1	96	102
	Manganese	1.03	1.05	1.9	100	100
7/21/99	Sulfate	19.71	17.16	14.9	114	100
7/22/99	Arsenic	< 0.002	< 0.002	N/A	101	103
	Iron	6.34	6.40	0.9	99	101
7/23/99	Arsenic	0.039	0.040	2.5	103	105
	Arsenic	33.1	33.4	0.9	101	103
	Iron	< 0.010	< 0.010	N/A	75	104
	Manganese	0.010	0.010	0.0	94	105
8/10/99	Arsenic	0.052	0.051	2.0	75	104
	Arsenic	0.035	0.033	6.1	94	106
	Arsenic	3.60	3.60	0.0	93	105
	Iron	2.54	2.52	0.8	101	109
	Iron	3.37	3.38	0.3	100	110
	Aluminum	0.217	0.210	3.3	115	100

Table B-1. Continued

Analysis date	Analyte	1st analysis (mg/L)	2nd analysis (mg/L)	Duplicate RPD (percent)	Spike recovery (percent)	CCV recovery (percent)
8/17/99	Arsenic	0.286	0.286	0.0	106	103
	Arsenic	0.720	0.718	0.3	104	105
	Arsenic	< 0.002	< 0.002	N/A	103	104
	Iron	7.86	7.75	1.4	93	98
	Iron	0.821	0.827	0.7	96	98
	Iron	0.107	0.106	0.9	95	97
	Aluminum	0.225	0.231	2.6	93	103
8/31/99	Arsenic	0.096	0.095	1.1	115	103
	Arsenic	0.044	0.043	2.3	102	103
	Iron	0.559	0.555	0.7	101	101
	Aluminum	0.325	0.344	5.5	111	102
9/1/99	Arsenic	0.471	0.475	0.8	120	104
	Arsenic	0.004	0.004	0.0	120	106
	Iron	< 0.010	< 0.010	N/A	100	103
	Aluminum	0.499	0.509	2.0	122	101
	Aluminum	0.170	0.180	5.6	118	106
9/17/99	Arsenic	< 0.002	< 0.002	N/A	114	101
	Arsenic	0.003	0.004	25.0	110	104
	Iron	0.042	0.040	5.0	112	99
	Manganese	0.045	0.045	0.0	108	100
9/29/99	Arsenic	0.531	0.524	1.3	106	104
	Arsenic	< 0.002	< 0.002	N/A	104	105
	Iron	0.600	0.594	1.0	115	102
	Iron	0.055	0.056	1.8	93	103
10/4/99	Arsenic	0.248	0.251	1.2	107	100
	Aluminum	1.14	1.16	1.7	104	92
10/5/99	Arsenic	0.093	0.095	2.1	105	104
	Iron	3.65	3.65	0.0	111	102
10/12/99	Arsenic	0.147	0.158	7.0	107	100
	Iron	4.54	4.87	6.8	106	98
10/14/99	Arsenic	< 0.002	0.002	N/A	111	102
	Iron	1.08	1.04	3.8	110	101
	Manganese	0.864	0.862	0.2	116	101
10/15/99	Arsenic	< 0.002	< 0.002	N/A	115	102
	Iron	0.104	0.105	1.0	109	101
	Manganese	0.030	0.031	3.2	114	102
	Aluminum	0.219	0.215	1.9	121	108

Table B-1. Continued

Analysis date	Analyte	1st analysis (mg/L)	2nd analysis (mg/L)	Duplicate RPD (percent)	Spike recovery (percent)	CCV recovery (percent)
10/19/99	Sulfate	1,082	1,091	0.8	98	101
10/22/99	Arsenic	0.522	0.524	0.4	110	104
	Arsenic	0.020	0.021	4.8	116	103
	Iron	1.21	1.21	0.0	111	100
	Manganese	0.057	0.057	0.0	112	101
	Aluminum	0.206	0.192	7.3	115	104
10/26/99	Arsenic	0.654	0.647	1.1	112	103
10/27/99	Arsenic	0.014	0.015	6.7	109	100
	Aluminum	0.282	0.278	1.4	109	109
11/1/99	Arsenic	< 0.002	< 0.002	N/A	110	101
11/8/99	Arsenic	< 0.002	< 0.002	N/A	112	98
	Iron	0.145	0.145	0.0	97	94
11/10/99	Arsenic	0.005	0.004	25.0	109	102
	Aluminum	0.181	0.162	11.7	111	106
11/18/99	Arsenic	< 0.002	< 0.002	N/A	101	104
	Arsenic	< 0.002	0.002	N/A	101	100
	Arsenic	0.067	0.067	0.0	102	99
	Iron	0.268	0.270	0.7	111	103
	Iron	0.184	0.186	1.1	98	99
	Manganese	0.012	0.012	0.0	101	100
	Aluminum	0.160	0.140	14.3	115	99
11/22/99	Arsenic	< 0.002	< 0.002	N/A	104	101
	Iron	0.131	0.127	3.1	93	100
	Aluminum	0.115	0.128	10.2	117	100
11/29/99	Arsenic	< 0.002	< 0.002	N/A	103	101
	Aluminum	0.130	0.130	0.0	115	100
12/2/99	Arsenic	< 0.002	< 0.002	N/A	102	100
	Aluminum	0.288	0.289	0.3	107	100
	Sulfate	1,194	1,221	2.2	98	98
12/7/99	Arsenic	0.436	0.442	1.4	105	104
	Iron	0.446	0.482	7.5	100	106
	Aluminum	0.212	0.249	14.9	105	99
12/15/99	Arsenic	0.269	0.269	0.0	109	99
	Iron	1.00	0.997	0.3	87	100
	Aluminum	0.146	0.163	10.4	117	100
12/16/99	Arsenic	0.011	0.013	15.4	105	103
1/31/00	Arsenic	0.494	0.495	0.2	115	101

Table B-1. Continued

Analysis date	Analyte	1st analysis (mg/L)	2nd analysis (mg/L)	Duplicate RPD (percent)	Spike recovery (percent)	CCV recovery (percent)
	Iron	7.03	7.07	0.6	100	98
2/9/00	Arsenic	0.518	0.520	0.4	114	102
	Iron	0.992	0.981	1.1	109	100
2/11/00	Arsenic	< 0.002	< 0.002	N/A	106	100
	Iron	0.203	0.202	0.5	99	96
	Manganese	0.009	0.009	0.0	101	98
2/14/00	Arsenic	34.3	34.3	0.0	100	99
	Iron	< 0.010	< 0.010	N/A	106	99
	Manganese	0.006	0.006	0.0	106	101
2/16/00	Arsenic	0.029	0.029	0.0	105	99
	Arsenic	0.004	0.003	33.3	109	99
	Iron	0.299	0.297	0.7	100	99
	Aluminum	0.677	0.669	1.2	121	99
2/17/00	Arsenic	19.3	19.3	0.0	100	102
	Arsenic	23.9	24.0	0.4	112	101
	Iron	1.01	1.01	0.0	111	102
	Aluminum	0.249	0.268	7.1	113	100
2/24/00	Sulfate	2,118	1,864	13.6	89	92
3/2/00	Arsenic	0.768	0.778	1.3	104	103
	Aluminum	5.29	5.26	0.6	92	99
3/6/00	Arsenic	< 0.002	< 0.002	N/A	106	101
	Iron	0.037	0.035	5.7	109	98
	Aluminum	0.608	0.584	4.1	109	110
3/27/00	Arsenic	32.9	33.0	0.3	85	102
	Iron	15.5	15.5	0.0	99	102

Spike value = 0.5 ppm (As, Fe, Al, Mn)
1.0 ppm (SO_4^{2-})
CCV value = 1.0 ppm (As, Fe, Al, Mn)
CCV value = 0.3 ppm (SO_4^{2-})

Calibration ranges:

As	0.0 - 2.0 ppm
Al	0 - 25 ppm
Fe	0 - 10 ppm
Mn	0.0 - 2.0 ppm
SO_4^{2-}	0 - 10 ppm

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