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Arsenic Removal from Drinking Water by Ion Exchange and Activated Alumina Plants

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Foreword

The United States Environmental Protection Agency (EPA) 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 action 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 (NRMRL) is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods 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 and groundwater; and prevention and control of indoor air. The goal of this research effort is to evaluate the performance on a full-scale level of five processes, including coagulation/filtration, lime softening, iron oxidation/filtration, ion exchange, and activated alumina, to consistently remove arsenic over a sustained period of time (1 year).

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E. Timothy Oppelt, Director
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Abstract

This report documents treatment plant information as well as results of year-long sampling and analysis at two ion exchange (IX) plants (referred to as Plants A and B) and two activated alumina (AA) plants (referred to as Plants C and D), with capacities varying from 800 to 3,000 gallons per day (gpd). The objective of sampling and analysis was to evaluate the performance of the full-scale water treatment plants to consistently remove arsenic from source water. Additionally, data were collected to evaluate the chemical characteristics of residuals produced by these treatment processes.

The study was divided into three phases: source water sampling, preliminary sampling, and long-term evaluation. Source water sampling was conducted to evaluate source water characteristics at each plant. Preliminary sampling was initiated in August 1998 and consisted of four sampling events conducted at each facility on either a weekly or biweekly basis to refine procedures for subsequent events during the third phase. Long-term evaluation consisted of weekly or biweekly sampling at each facility from September 1998 to September 1999. Samples from resin regeneration were collected at Plant A from March to June 1999. Spent AA samples were collected at Plants C and D during the media change-out events in December 1998 and May 1999, respectively.

Results from the long-term evaluation demonstrated that both the IX and AA systems are capable of achieving arsenic levels of less than 5 µg/L in the treated water, provided that the IX resin was regenerated or the AA medium was changed out before arsenic breakthrough occurred. The two IX systems had inlet arsenic concentrations between 45 and 65 µg/L [primarily As(V)]. When Plant A was operated beyond 3,000 to 3,200 bed volumes (BV) of water, arsenic chromatographic peaking occurred. Arsenic breakthrough was not observed at Plant B where an average 97% of removal efficiency was achieved, leaving only 0.8 to 4.5 µg/L arsenic in the finished water.

Both AA systems consisted of two parallel treatment trains with a roughing AA column followed by a polishing column in each train. The systems operated on a media throwaway basis. The average arsenic removal efficiencies achieved at Plants C and D were 87% and 98%, respectively. The raw water at Plant C (34 to 76 µg/L total arsenic) contained approximately 0.3 to 28.8 µg/L As(III), which was nearly completely removed, even though no oxidation treatment was provided. The water at Plant D contained slightly higher total arsenic concentrations (53.3 to 87 µg/L) but no As(III), which was consistently removed to less than 5 µg/L in the finished water. The AA media in the roughing tanks were exhausted and disposed of about every 1 to 1.5 years after treating approximately 9,600 BV at Plant C and 5,260 BV at Plant D.

The regeneration process at Plant A recovered from 67 to 86% of arsenic from the spent brine. The spent AA at Plants C and D passed the Toxicity Characteristic Leaching Procedure (TCLP) test for metals including arsenic, and therefore was disposed of as nonhazardous waste.

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Acronyms and Abbreviations

AA	activated alumina
ADD	average daily demand
As	arsenic
AWWA	American Water Works Association
BV	bed volumes
DA	disinfectant addition
DI	distilled
DL	detection limit
EBCT	empty bed contact time
EDR	electrodialysis reversal
EPA	United States Environmental Protection Agency
GAC	granular activated carbon
GFAAS	graphite-furnace atomic-absorption spectrophotometer
GI	gastrointestinal
gpd	gallons per day
gpm	gallons per minute
GW	groundwater
HCl	hydrochloric acid
HDPE	high-density polyethylene
hp	horsepower
ICP-MS	inductively coupled plasma-mass spectrometry
ID	identification
IN	inlet sampling location
IOCS	iron oxide-coated sand
IX	ion exchange
MCL	maximum contaminant level
MDL	method detection limit
MS	matrix spike
MSD	matrix spike duplicate
MSDS	material safety data sheet
NA	not available
ND	not detected
NOM	natural organic matter
NS	not sampled
NTU	nephelometric turbidity units

O&M	operations and maintenance
OU	outlet sampling location
pCi	picocuries
POC	point of contact
POE	point of entry
ppm	parts per million
psi	pounds per square inch
PVC	polyvinyl chloride
QA	quality assurance
QAPP	quality assurance project plan
QA/QC	quality assurance/quality control
RPD	relative percent difference
SBA	strong-base anion
SDWA	Safe Drinking Water Act
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids
TOC	total organic carbon
TSS	total suspended solids
WA	work assignment
WAM	Work Assignment Manager
WBA	weak-base anion
XRD	x-ray diffraction
ZPC	zero point charge
%R	percent recovery

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1.0 Introduction

This project consists, in part, of a field study in which two water treatment processes were evaluated for their ability and effectiveness at reducing arsenic (As) levels in source water. The first part of the study involved collecting water samples from various locations at two ion exchange (IX) and two activated alumina (AA) plants. The second part of the study involved sampling and analysis of spent brine and spent AA media to determine the quantities and chemical characteristics of residuals produced by the IX and AA treatment processes, respectively. This report describes the design and operation of four treatment plants and presents the analytical results of the samples collected from the plants during 1 year of operation.

1.1 Background

The Safe Drinking Water Act (SDWA) of 1974 mandates that the United States Environmental Protection Agency (EPA) identify and regulate drinking water contaminants that may have an adverse human health effect and that are known or anticipated to occur in public water supply systems. Arsenic is a naturally occurring contaminant that has known adverse human health effects. Excessive amounts of arsenic can cause acute gastrointestinal (GI) and cardiac damage. Chronic doses can cause vascular disorders such as blackfoot disease (Chen et al., 1994a), and epidemiological studies have linked arsenic to skin and lung cancer (Tate and Arnold, 1990). In 1975, under the SDWA, the EPA established a maximum contaminant level (MCL) for arsenic at 0.05 mg/L. Since that time, revision of the MCL has been considered a number of times, but no change has been made. The SDWA was amended in 1996 and these amendments require that the EPA develop an arsenic research strategy and publish a proposal to revise the arsenic MCL by January 2000.

A draft arsenic research plan was prepared by the EPA in December 1996 and was finalized in February 1998 based upon a technical review by the EPA's Board of Scientific Counselors (EPA, 1998). The plan identifies the research needed by the EPA to support a proposed revision of the arsenic MCL. The plan also identifies a number of treatment technologies available for arsenic removal, and recognizes the need to determine the capability of these technologies to remove arsenic to a level significantly lower than the current MCL.

This field study was conducted as part of an EPA Work Assignment (WA) to evaluate the performance of nine full-scale water treatment plants to remove arsenic from drinking water. These nine plants represent five arsenic removal unit processes: conventional coagulation/filtration, lime softening, iron/manganese removal, IX, and AA. Long-term operational data were developed in these studies to support the ability and effectiveness of these treatment processes to consistently remove arsenic from drinking water.

1.1.1 General Chemistry of Arsenic

Arsenic is a common, naturally occurring drinking water contaminant that originates from arsenic-containing rocks and soil and is transported to natural waters through erosion and dissolution. Arsenic occurs in natural waters in both organic and inorganic forms. However, inorganic arsenic is predominant in natural waters and is the most likely form of arsenic to exist at concentrations that cause regulatory concern (Edwards et al., 1998).

The valence and species of inorganic arsenic are dependent on the oxidation-reduction conditions and the pH of the water. As a general rule of thumb, the reduced, trivalent form [As(III)] normally is found in groundwater (assuming anaerobic conditions) and the oxidized, pentavalent form [As(V)] is found in surface water (assuming aerobic conditions); this rule does not always hold true for groundwater, where both forms have been found together in the same water source. Arsenate exists in four forms in aqueous solution, depending on pH: H_3AsO_4, $H_2AsO_4^-$, $HAsO_4^{2-}$, and AsO_4^{3-}. Similarly, arsenite exists in five forms: $H_4AsO_3^+$, H_3AsO_3, $H_2AsO_3^-$, $HAsO_3^{2-}$, and AsO_3^{3-}. As shown in Figure 1-1, which contains solubility diagrams for As(III) and As(V), ionic forms of arsenate dominate at pH>3, while arsenite is neutral at pH<9 and ionic

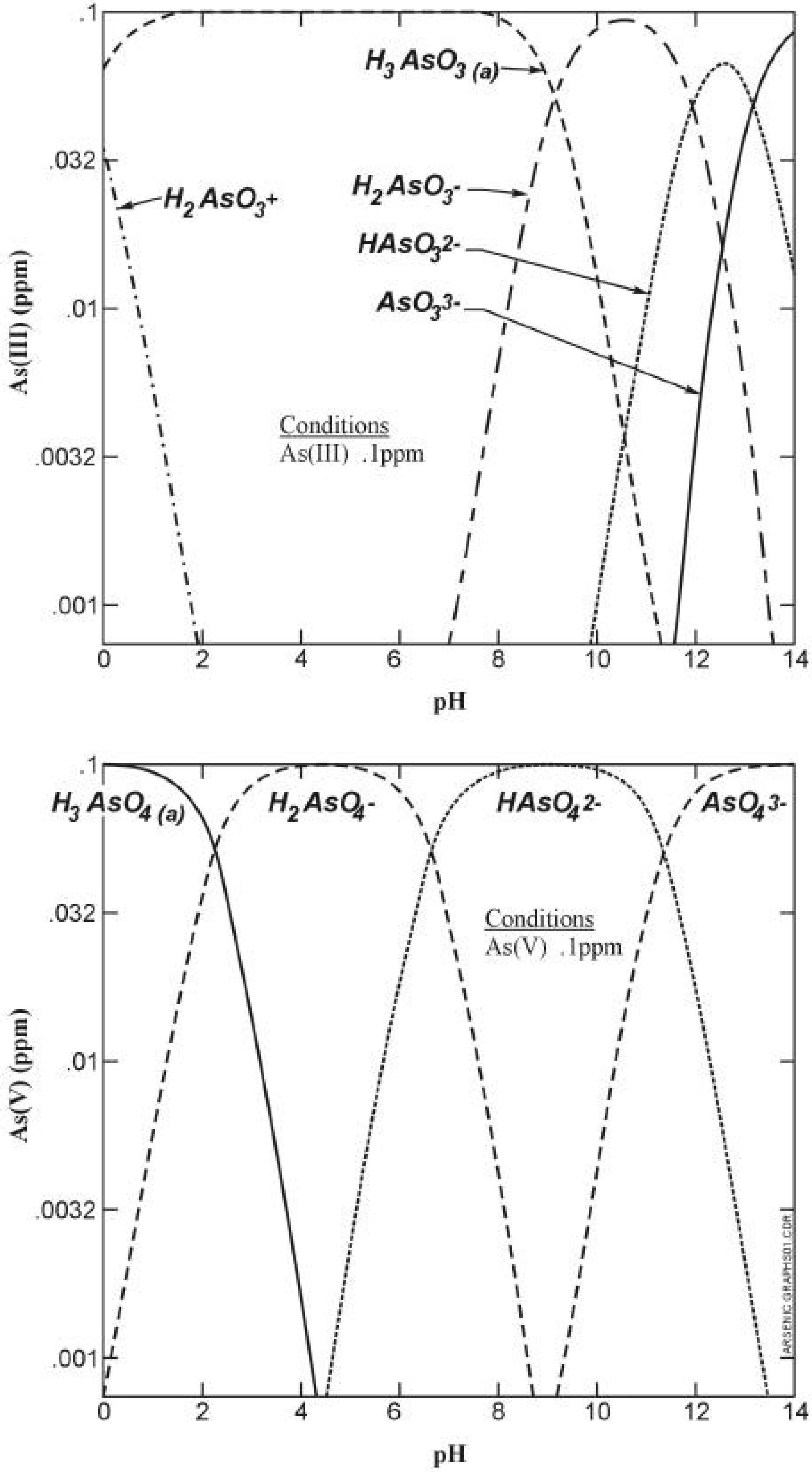


Figure 1-1. Concentration–pH Diagrams for As(III) and As(V)

at pH>9. Ion exchange and AA treatment technologies, often used by small drinking water systems for arsenic removal, function by exchanging arsenate with counter ions of an anionic resin (e.g., Cl^-) and by adsorbing arsenate onto alumina granules, respectively. Therefore, the valence and species of soluble arsenic are very important in evaluating arsenic removal.

1.1.2 Determination of Arsenic Species

Although total arsenic can be effectively preserved in field samples, presently no method exists to consistently preserve inorganic arsenic species in field samples. Preservation of total arsenic is accomplished by acidifying the sample to pH<2 in the field. However, a high level of uncertainty over exact levels of As(III) and As(V) exists when acids such as nitric acid (HNO_3) or hydrochloric acid (HCl) are used to preserve inorganic species of arsenic. Interconversion of As(III) and As(V) in samples preserved with 0.05 N HCl have been reported to occur within 1 day (Andreae, 1977). Another laboratory study conducted by Eaton et al. (1997) examined the preservation of arsenic using humic acid, ascorbic acid, and HCl; the study concluded that no effective methods exist for preserving As(III) and As(V) in water samples. Some researchers have frozen samples to preserve the inorganic species of arsenic. However, freezing is neither a cost-effective nor a practical method for field sampling.

In response to the lack of techniques available for adequately preserving arsenic species, field speciation protocols have been developed by Ficklin (1983), Clifford et al. (1983), and Edwards et al. (1998). In each of these studies, an anion exchange resin column was used for field speciation of arsenic. Ficklin (1983) used a strong anion exchange resin (Dowex 1 × 8, 100-200 mesh, acetate form) in a 10 cm × 7 mm glass column to separate As(III) from As(V) in water samples that had been filtered through a 0.45-µm membrane filter and acidified with 1% HCl. The resin was supplied in chloride form and was converted to the acetate form. However, in the protocol by Clifford et al. (1983), a chloride-form strong base anion resin (ASB-2, 30-60 mesh) was used to separate As(III) from As(V). In this method, the sample was not filtered or preserved with acid. Both Ficklin and Clifford used a graphite-furnace atomic-absorption spectrophotometer (GFAAS) to determine the arsenic concentration.

More recently, Edwards et al. (1998) made the following modifications to Ficklin's method: (1) Substituted 50-100 mesh resin for the 100-200 mesh resin to allow faster sample flow. (2) Used 12 cm × 15 mm polypropylene columns to improve safety and speed of sample treatment. (3) Used 0.05% H_2SO_4 instead of 1% HCl to acidify samples prior to resin treatment. Edwards et al.'s use of H_2SO_4 helped to prevent potential problems associated with overacidification of the sample, and also helped to prevent Cl^- from interfering with the inductively coupled plasma-mass spectrometry (ICP-MS) analysis. The reported recoveries of As(III) and As(V) ranged from 80 to 120% by Ficklin (1983), 95 to 117% by Clifford et al. (1983), and 100 to 105% by Edwards et al. (1998). For this study, the decision was made to use a field speciation technique similar to that used by Edwards et al. (1998).

1.1.3 Treatment Technologies for Arsenic Removal

Several common treatment technologies are used for removal of inorganic contaminants, including arsenic, from drinking water supplies. Large-scale treatment facilities often use conventional coagulation with alum or iron salts followed by filtration to remove arsenic (Chen et al., 1994b; Hering et al., 1996; Scott et al., 1995; and Sorg, 1993). Lime softening and iron removal also are common, conventional treatment processes that can potentially remove arsenic from source waters (McNeill and Edwards, 1997). Small-scale systems and point-of-entry (POE) systems often use IX and AA adsorption because of their ease of handling and sludge-free operations. Recently, iron-based adsorption media, such as granular ferric hydroxide, have been developed and shown high arsenic removal capacities in laboratory and pilot tests (Joshi and Chaudhuri, 1996; Driehaus, et al. 1998). Their full-scale applications, however, are still limited. Other technologies that also have been used for arsenic removal include manganese greensand, reverse osmosis, electrodialysis reversal (EDR), nanofiltration, and adsorption on activated carbon.

This report focuses on the IX and AA treatment processes used primarily by small drinking water systems. Two additional reports also have been developed to cover conventional treatment processes, including coagulation/filtration and lime softening (Battelle, 1999) and iron removal (Battelle, 2000a).

1.1.3.1 Ion Exchange

Ion exchange is a physical/chemical process in which ions held electrostatically on the surface of a solid phase are exchanged for ions of similar charge in a solution (i.e., drinking water). The solid is typically a synthetic anion exchange resin which is used to preferentially remove particular contaminants of concern. Ion exchange is commonly used in drinking water treatment for softening (i.e., removal of calcium, magnesium, and other cations in exchange of sodium), as well as removing nitrate, arsenate, chromate, and selenate from municipal water (Clifford, 1999). Due to its higher treatment cost compared to conventional treatment technologies, IX application is limited primarily to small/medium-scale and POE systems.

Anion exchange resins come in two classes, strong-base anion (SBA) and weak-base anion (WBA). The quaternary ammonium functional groups ($–R_3{}'N^+$ where R′ represents organic radicals such as CH_3) on the SBA resins are strongly basic and ionized to act as ion exchangers over the pH range of 0 to 13. The WBA resins are useful only in the acidic pH region where the primary, secondary, and tertiary amine functional groups are protonated to form positively charged exchange sites for anions. Both SBA and WBA resins may be present in the hydroxide or chloride form. Typically, SBA resins are used for arsenic removal because they tend to be more effective over a larger pH range than WBA resins.

Ion exchange does not remove As(III) because As(III) occurs predominantly as an uncharged ion (H_3AsO_3) in water with a pH value of less than 9.0 (Ficklin, 1983; Clifford, 1999). The predominant species of As(V), $H_2AsO_4^-$ and $HAsO_4^{2-}$, are negatively charged, and thus are removable by IX. If As(III) is present, it is necessary to oxidize As(III) to As(V) before removal by IX (Fox, 1989; Clifford and Lin, 1986).

To remove arsenic from drinking water, water is passed through one or more IX resin beds. Arsenate ions ($H_2AsO_4^-$ and $HAsO_4^{2-}$) and several other anions (most notably sulfate) are preferentially removed according to the order of preference for exchange. When all available sites on the resin have been exhausted, the bed is regenerated with a brine solution (chloride exchange).

The efficiency of the IX process for arsenic removal is strongly affected by competing ions, such as total dissolved solids (TDS) and sulfate (Clifford 1999). Other factors affecting the use of the IX process include empty bed contact time (EBCT) and spent regenerant disposal.

Competition from background ions for available IX sites can greatly affect the efficiency and economics of IX systems. The level of these background ions often determines the applicability of the IX process at a particular site. The following selectivity sequence was established for SBA resins (Clifford, 1999):

$$SO_4^{2-} > NO_3^- > HA_SO_4^{2-} > NO_2^-, Cl^- > H_2A_SO_4^-, HCO_3^- >> Si(OH)_4, H_3A_SO_4$$

Therefore, high sulfate and TDS levels can significantly reduce arsenic removal efficiency (Clifford and Lin, 1986, 1991). In general, the IX process is not economically attractive if source water contains high TDS (>500 mg/L) and sulfate (>150 mg/L) (Clifford, 1999). Also, the presence of Fe(III) in feed water can affect arsenic removal by forming Fe(III)-arsenic complexes, which cannot be removed by IX resins (Clifford et al., 1998).

When the sulfate concentration is high, sulfate may displace previously sorbed ions (such as arsenate) from a resin bed, thereby causing higher arsenic concentrations in the effluent than in the influent. This phenomenon is called chromatographic peaking (dumping), and is a potentially risky situation when toxic ions such as arsenic are involved. To avoid peaking, the resin bed must be monitored and regenerated well in advance of the onset of the peaking.

For chloride-form resins, concentrated NaCl solution commonly is used as a regenerant. Arsenic elutes readily from IX columns mainly because it is subject to selectivity reversal in a high ionic strength (>1 M) solution (Clifford and Lin, 1995). The regenerated resin then is ready for another exhaustion cycle.

Clifford et al. (1998) found that dilute regenerants at 0.5-1.0 M were more efficient than concentrated ones at 2.0-4.0 M for eluting arsenic (in terms of the ratio of regenerant equivalent to resin equivalent). However, dilute regenerants could require longer regeneration time and produce larger volumes of spent regenerant.

1.1.3.2 Activated Alumina

AA adsorption is a physical/chemical process by which ions in solution (i.e., drinking water) are removed by the available adsorption sites on an oxide surface. AA is usually prepared through dehydration of $Al(OH)_3$ at high temperatures and consists of amorphous and gamma alumina oxide (Chen and Snoeyink, 1987). AA is used primarily in packed beds to remove contaminants such as fluoride, arsenic, selenium, silica, and natural organic matter (NOM). To remove contaminants, feed water is passed continuously through one or more AA beds. When all available adsorption sites are occupied, the AA media may be regenerated with a strong base, NaOH, or simply disposed of.

Many studies have shown that AA is an effective treatment technique for arsenic removal. Factors such as arsenic oxidation state, pH, competing ions, and EBCT significantly affect arsenic removal. Other factors affecting the use of the AA process include regeneration practice, spent regenerant disposal, and alumina disposal. The following subsections briefly discuss some of these factors.

Effects of Arsenic Oxidation State. Like all other treatment technologies, the AA process is more effective in removing As(V) than As(III). In a study by Frank and Clifford (1986), an AA column treating water containing 0.1 mg/L As(V) was able to treat about 23,400 BV before the effluent arsenic levels reached 0.05 mg/L. A similar column treating water containing 0.1 mg/L As(III), however, began to break through after treating only 300 BV of water. Therefore, preoxidation of As(III) to As(V) often is recommended when treating water containing As(III).

Effect of pH. The AA process is sensitive to pH. Anions (including arsenic) are best adsorbed below pH 8.2, a typical zero point charge (ZPC) for AA. Below this pH, the AA surface has a net positive charge that can be balanced by adsorbing anions, such as hydroxide, fluoride, and arsenate. Several studies have shown that the optimum pH for arsenic removal ranges from 5.5 to 6.0 (Singh and Clifford, 1981; Rosenblum and Clifford, 1984). The arsenic capacity of AA deteriorates as the pH increases from 6.0 to 9.0 (Hathaway and Rubel, 1987). Column studies conducted by Clifford and Lin (1991) also showed a similar trend. For a target arsenic effluent concentration of 0.05 mg/L, a column operating at pH 6.0 was able to treat 8,760 BV of water, but a column operating at pH 7.3 treated only 1,944 BV.

Some small AA systems are operated on a media throwaway basis without pH adjustments for an optimal run length. These systems save costs for pH adjustments and for operations and maintenance (O&M) related to media regeneration. Upon breakthrough, however, AA must be replaced and the spent AA must pass the Toxicity Characteristic Leaching Procedure (TCLP) to be disposed of as a nonhazardous waste.

Effect of Competing Ions. Like IX resins, AA exhibits preferences for certain ions. The order of preference, however, can be quite different from those of IX resins. Activated alumina appears to have a higher preference for arsenic than for most competing ions in water (including sulfate) (Clifford, 1999; Vagliasindi et al., 1996). Further, as indicated by the general selectivity sequence shown below (Clifford, 1999), AA preferentially adsorbs $H_2AsO_4^-$ over H_3AsO_3 [As(III)]:

$$OH^- > H_2AsO_4^- > Si(OH)_3O^- > F^- > HSeO_3^- > TOC > SO_4^{2-} > H_3AsO_3$$

Several studies have examined the effects of some of these competing ions. Vagliasindi et al. (1996) found that increasing sulfate from 0 to 100 mg/L had only a small impact on the sorption of As(V), and the presence of chloride did not affect As(V) removal at all. The addition of 4 mg/L dissolved organic matter, however, reduced As(V) sorption about 50%. Also, the addition of 360 mg/L of sulfate and almost 1,000 mg/L TDS reduced the sorption of As(V) by approximately 50%, compared to sorption from deionized (DI) water (Clifford and Lin, 1986). Rosenblum and Clifford (1984) also reported that sulfate and chloride significantly reduced AA's ability to remove arsenic from water. For water containing approximately 530 mg/L of chloride, the arsenic removal was 16% lower than that for a nonchloride-containing water. And for water containing 720 mg/L sulfate, the arsenic removal was 50% lower than that for a nonsulfate-containing water.

Effect of Empty Bed Contact Time. Simms and Azizian (1997) conducted AA column tests using 3-, 6-, and 12-minute EBCTs and found a linear relationship between EBCT and arsenic adsorption. However, Vagliasindi and Benjamin (1997) found that arsenic adsorption increased only slightly with increasing EBCTs.

1.1.4 Data Gaps

The removal of arsenic from drinking water by IX and AA has been studied extensively at laboratory- and pilot-scale levels. Although some short-term full-scale evaluations have been performed for both treatment processes, few data exist on the capability of these processes to reduce arsenic on a sustained basis. Thus, a need exists to determine the effectiveness of IX and AA to produce drinking water containing low levels of arsenic on a long-term basis and under varying operational and seasonal conditions.

Another data gap that exists is the production and disposal of spent regenerants and spent media. Due to high arsenic concentrations in the spent regenerants, direct discharge to a sanitary sewer may not be always possible depending on the local regulations. Therefore, the spent regenerants may need to be treated prior to disposal. Arsenic can be removed from regenerants by coprecipitation with ferric iron or aluminum salts, and the arsenic-laden sludge can be subsequently dried and landfilled if toxicity limits are not exceeded. Brine reuse has recently been studied to examine its potential in reducing the brine consumption and the discharge volume (Clifford et al., 1998). Also, the spent AA media from throwaway systems may be landfilled as a nonhazardous waste if they pass the TCLP tests.

Few data currently exist on the amounts and the chemical compositions of residuals generated by the IX and AA processes and on the methods that are environmentally acceptable for their disposal. Therefore, information needs to be collected on the chemical characteristics of the wastes produced by these processes.

1.2 Objectives

The primary objective of this study was to evaluate the effectiveness of IX and AA systems to consistently reduce arsenic concentrations in source water to low levels. This report presents the results of weekly and biweekly monitoring for approximately 1 year at two IX plants and two AA plants.

The second objective of this study was to examine residuals produced during IX and AA treatment processes. Information was collected on the quantities and chemical characteristics of the wastes produced by these two treatment processes.

The third objective of this study was to conduct two short-term special studies to collect more definitive data to help explain unusual performance conditions or variations observed during long-term sampling at the IX and AA plants.

1.3 Report Organization

Section 1.0 provides background information for this field study and project objectives. Section 2.0 of this report presents the conclusions from the study of the two IX plants and two AA plants. Section 3.0 describes the materials and methods used to conduct this study. Section 4.0 discusses the results of the study and Section 5.0 provides specific information on quality assurance/quality control (QA/QC) procedures. Section 6.0 is a list of references cited in the text. Appendices A, B, C, and D present the complete set of analytical data and miscellaneous information collected at Plants A, B, C, and D, respectively, during long-term sampling.

2.0 Conclusions

The EPA currently is in the process of revising the arsenic MCL. A proposed arsenic MCL of 0.005 mg/L was published in the *Federal Register* on June 22, 2000, which is significantly lower than the current MCL of 0.05 mg/L. The low arsenic standard will inevitably affect many water treatment facilities with high arsenic concentrations in water supplies. Therefore, there is a need to evaluate the ability of existing treatment processes to consistently remove arsenic to low levels. The primary objectives of this project were to document arsenic removal at two IX plants (Plants A and B) and two AA plants (Plants C and D), and to assess chemical characteristics of residuals (spent brine and spent AA) at these treatment plants.

The primary focus of this study was the long-term evaluation of arsenic removal at the IX and AA plants. The two IX plants demonstrated the ability to consistently achieve low levels of arsenic in the treated water (i.e., <5 µg/L) when the resin was properly regenerated. During the long-term study, Plants A and B achieved an average of 53% and 97% arsenic removal, respectively. Initially, Plant A was regenerated once every 3 months; however, early arsenic breakthrough (50 µg/L) was detected in the treated water before the scheduled regeneration of the system. Also, chromatographic effect was observed, which likely was caused by sulfate in the source water, resulting in effluent arsenic concentrations exceeding the influent levels. After a run length to arsenic breakthrough (50 µg/L) of approximately 3,000-3,200 BV was determined, a monthly regeneration schedule was recommended and implemented at Plant A. As such, early arsenic breakthrough did not happen again. During the Plant A study, up to 23.4 µg/L of arsenic was detected immediately after the regeneration. Further study revealed that this "leakage" actually was due to an artifact caused by the arsenic already present in the 2,400-gal storage tank located just upstream from the sampling point. At Plant B, noticeable arsenic breakthrough was not detected throughout the course of the study because of the frequent column regeneration (i.e., once every 6 days). As(III) removal was not observed at either plant because source water contained primarily As(V).

The two AA plants evaluated also were capable of achieving arsenic levels of 5 µg/L or less in the treated water, provided that the AA was changed out at the proper time before arsenic breakthrough. Both AA plants are operated on a media throwaway basis under raw pH conditions (i.e., pH 8.0 to 8.6). Arsenic removal efficiencies achieved at Plants C and D during the long-term study were 87% and 98%, respectively. The AA medium in the roughing tanks was exhausted and disposed of about every 1 to 1.5 years after treating 9,600 BV at Plant C and 5,260 BV at Plant D. Near complete As(III) removal by AA was observed at Plant C, as the source water contained 0.3 to 28.8 µg/L As(III), and the finished water contained less-than-detect levels of As(III).

The secondary focus of this study was on residual production and the chemical characteristics of the residuals. Data from resin regeneration at Plant A demonstrated that the regeneration efficiency at Plant A ranged from 67% to 86%, comparable with literature data. None of the spent AA sampled at Plants C and D qualified as a hazardous waste based on TCLP testing for metals including arsenic. Therefore, the spent AA was disposed of as nonhazardous waste. Using caustic wash, it was possible to recover approximately 50% of the arsenic from the spent AA at Plant D. The AA capacity obtained from the column operation at Plant D (0.25 g/kg) was less than that obtained from the batch adsorption isotherm (1.09 g/kg).

3.0 Materials and Methods

This section discusses the materials and methods used for performing the source water, preliminary, and long-term sampling and data collection at two IX plants and two AA plants. Section 3.1 describes the general project approach. Section 3.2 describes the preparation of arsenic speciation kits and sample coolers. Section 3.3 provides detailed sampling procedures. Section 3.4 discusses the technical approach for the short-term special studies. Section 3.5 discusses pertinent analytical procedures.

3.1 General Project Approach

Several consecutive tasks were performed to accomplish the project objectives described in Section 1.2. These tasks involved the following activities:

- Select treatment plants and conduct an initial site visit to collect source water samples at each selected plant
- Prepare a preliminary sampling and data collection plan for each plant
- Finalize the sampling and data collection plan after completion of four weekly (Plants A and B) or biweekly (Plants C and D) preliminary sampling events at each plant
- Implement the final sampling and data collection plan with weekly or biweekly sampling events at each plant for 9 months up to one full year
- Select treatment plants with unusual performance conditions or variations and conduct two short-term special studies.

For initial plant selection, the EPA Work Assignment Manager (WAM) initiated contacts with representatives of the states of Maine and New Hampshire for small-scale IX and AA systems currently in operation. Two IX plants (designated as Plants A and B) and three AA plants (designated as Plants C, D, and E) were selected for initial site visits and source water sampling. The information collected during the site visits, including the concentration and speciation of arsenic in each source water, was tabulated and used as the basis for the final plant selection.

Following the final plant selection (Plants A, B, C, and D were selected), a preliminary sampling and data collection plan was prepared for each plant to document the plant's operation and performance for arsenic removal and the critical parameters that would impact the removal. Each preliminary plan also described the data collection effort to characterize the residuals produced by the treatment process. The approved preliminary plans were implemented at Plants A and B during a 4-week trial period, and Plants C and D during an 8-week trial period. Two Battelle staff members revisited the plants during the first week of the trial period to perform sampling, conduct training of plant support personnel, and establish/coordinate all required logistics (such as receiving/shipping of sample coolers, chain-of-custody coordination, communication methods, and emergency/contingency plans). The remaining three sampling events during the preliminary sampling were performed by a designated point of contact (POC) or an alternate at each plant. The experience gained during the trial period was used to finalize the long-term sampling and data collection plans.

All water and residual samples were collected and analyzed in accordance with the Category III Quality Assurance Project Plan (QAPP) prepared by Battelle (1998) for this project. Water samples (source water and treated water) were collected weekly from Plants A and B. Water samples were collected biweekly from Plants C and D at the following four locations: (1) inlet; (2) after the first AA tank of train 1; (3) after the second AA tank of train 1; and, (4) after treatment through both trains. During the preliminary and long-term sampling phases, field arsenic speciation was conducted once every 4 weeks for Plants A and B and once every 8 weeks for Plants C and D. Starting from March 1999, backwash and spent brine samples were collected from Plant A when regeneration was performed once every 4 weeks. Spent AA samples also were collected during the media change-out at Plant C in December 1998 and at Plant D on May 25, 1999.

All sample containers and arsenic speciation kits were prepared and sent in coolers on a weekly or biweekly basis from Battelle to each plant via Federal Express. The coolers were returned to Battelle immediately after the sample collection had been completed. Analyses of arsenic, aluminum, iron, and manganese in water were conducted by Battelle's ICP-MS laboratory. Wilson Environmental Laboratories of Westerville, OH, was subcontracted to perform all other chemical analyses. Battelle coordinated all sampling logistics.

3.2 Preparation of Sampling Kits and Sample Coolers

All arsenic speciation kits and sample coolers were prepared at Battelle. The following sections describe the relevant preparation procedures.

3.2.1 Preparation of Arsenic Speciation Kits

The arsenic field speciation method used an anion exchange resin column to separate the soluble arsenic species, As(V) and As(III). A 250-mL bottle (identified as bottle A) was used to contain an unfiltered sample, which was analyzed to determine the total arsenic concentration (both soluble and particulate). The soluble portion of the sample was obtained by passing the unfiltered sample through a 0.45-µm screw-on disc filter to remove any particulate arsenic and collecting the filtrate in a 125-mL bottle (identified as bottle B). Bottle B contained 0.05% (volume/volume) ultra-pure sulfuric acid to acidify the sample to about pH 2. At this pH, As(III) was completely protonated as H_3AsO_3, and As(V) was present in both ionic (i.e., $H_2AsO_4^-$) and protonated forms (i.e., H_3AsO_4) (see Figure 1-1). A portion of the acidified sample in bottle B was run through the resin column. The resin retained As(V) and allowed As(III) (i.e., H_3AsO_3) to pass through the column. (Note that the resin will retain only $H_2AsO_4^-$ and that H_3AsO_4, when passing though the column, will be ionized to $H_2AsO_4^-$ due to elevated pH values in the column caused by the buffer capacity of acetate exchanged from the resin.) The eluate from the column was collected in another 125-mL bottle (identified as bottle C). Samples in bottles A, B, and C were analyzed for total arsenic using ICP-MS. As(III) concentration was the total arsenic concentration of the resin-treated sample in bottle C. The As(V) concentration was calculated by subtracting As(III) from the total soluble arsenic concentration of the sample in bottle B.

Arsenic speciation kits were prepared in batch at Battelle based on a method modified from Edwards et al. (1998). Each arsenic speciation kit contained the following:

- One anion exchange resin column
- Primary and duplicate A, B, and C bottles
- One 400-mL disposable beaker
- Two 60-mL disposable syringes
- Several 0.45-µm syringe-adapted disc filters.

Each speciation kit was packed in a plastic zip-lock bag along with latex gloves and a step-by-step speciation sampling instruction sheet. All chemicals used for preparing the kits were of analytical grade or higher. The arsenic speciation kits were prepared according to the following procedures:

- **Resin Preparation.** Before packing into columns, the anion exchange resin (Dowex 1-X8, 50-100 mesh) was converted from the chloride form (as supplied by Supelco) to the acetate form according to the method used by Edwards et al. (1998). First, 1 kg of the resin was placed in a 3-L beaker. One liter of 1 N NaOH was then added to the resin, stirred for an hour using an overhead stirrer, and drained. This NaOH rinse was repeated sequentially for three times. The NaOH-treated resin then was rinsed with two 1-L batches of reagent-grade water, followed by three acetic acid rinses. Each acetic acid rinse consisted of adding 1 L of 1 N reagent grade acetic acid to the resin, stirring for 5 minutes, and draining the spent acid. The acetic acid-treated resin was subsequently rinsed with 3-L batches of reagent-grade water. The resin slurry was stored in a 2-L bottle and kept moist until use.
- **Anion Exchange Column Preparation.** The resin columns used were 12 cm × 15 mm in size and made of polypropylene (Bio-Rad Laboratories, CA). Each column was slurry packed with about 20 g (drained weight) of the prepared resin, yielding a resin depth of approximately 10.5 cm. The column was sealed with two plastic caps (one each on top and bottom) to prevent contamination and retain moisture prior to use.
- **Sample Bottles.** VWRbrand™ TraceClean™ high-density polyethylene (HDPE) sample bottles (250 and 125 mL) were used to prepare bottles A, B, and C. Bottles A and C were spiked with 500 and 250 µL of concentrated ultra-pure nitric acid (HNO_3), respectively; and bottle B was spiked with 1.25 mL of 5% (volume/volume) ultra-pure sulfuric acid (H_2SO_4). H_2SO_4 was used to acidify the sample in bottle B because chloride (Cl^-) in HCl could interfere with the ICP-MS arsenic detection and HNO_3 (an oxidizing agent) could damage the resin or form nitric acid-arsenic redox couples (Edwards et al., 1998).

- **Beaker, Syringes, and Filters.** One 400-mL disposable plastic beaker was used to collect a water sample. Samples were filtered using 60-mL disposable plastic syringes with 0.45-µm screw-on disc filters. All disposable beakers, syringes, and filters were rinsed with DI water and air-dried before being packed into the sampling kits.

3.2.2 Preparation of Sample Coolers

Sample containers for analysis of all water quality parameters except for total As, Al, Fe, and Mn were provided by Wilson Environmental Laboratories. These containers were new, rinsed with DI water, allowed to air dry, and contained appropriate preservatives before being delivered to Battelle. These bottles were labeled with the letter D, E, F, or G, designating the specific analysis to be performed. Table 3-1 lists the sample container size and type (for water and solid samples), sample preservation used, analysis to be performed, and holding time. All sample containers were labeled prior to shipment.

Figure 3-1 presents an example sample bottle label. The sample identification (ID) consisted of five parts, including a two-letter code for a water treatment plant, the sampling date (mm/dd/yy), a two-letter code for a specific sampling location (e.g., IN for inlet water, TA for after the first tank, TB for after the second tank, and OU for outlet water), a one-letter code (A through G) designating the analyses to be performed (see Table 3-1), and a code indicating whether the sample was a primary sample or a field duplicate sample. A field duplicate was identified by adding a "dup" to the label and a primary sample used no additional coding.

After the sample bottles were labeled, they were placed in coolers subdivided into two or four compartments, each corresponding to a specific sampling location at each plant. Color coding was used to identify sampling locations and all associated sample bottles. For example, red, blue, green, and yellow were used to designate sample locations for inlet, TA, TB, and outlet locations, respectively. Other sampling and shipping-related materials, including latex gloves, chain-of-custody forms, prepaid Federal Express air bills, sampling instructions, ice packs, and bubble wrap, also were packed into coolers. When arsenic speciation or residual samples were to be collected, arsenic speciation kits or bottles for residual samples also were included in the cooler. After preparation, sample coolers were sent to all plants every Thursday via Federal

Table 3-1. Sample Containers and Preservation Methods

Container Size	Container Type	Preservation Method	Analyte	Hold Time
Arsenic Speciation Samples				
250 mL (A)	certified clean HDPE bottles	4°C HNO_3 for pH <2	Total As, Al, Fe, Mn	6 months
125 mL (B)	certified clean HDPE bottles	4°C 0.05 % H_2SO_4	Dissolved As, Al, Fe, Mn	6 months
125 mL (C)	certified clean HDPE bottles	4°C HNO_3 for pH <2	Dissolved As, Al, Fe, Mn	6 months
Backwash/Spent Brine Samples				
250 mL (D)	plastic	4°C	pH TSS	immediate 7 days
250 mL (A)	certified clean HDPE bottles	4°C HNO_3 for pH <2	Total As, Al, Fe, Mn	6 months
Water Quality Parameter Samples				
250 mL (D)	plastic	4°C	Alkalinity pH	14 days immediate
250 mL (D)	plastic	4°C	Turbidity Sulfate Fluoride	48 hours 28 days 28 days
250 mL (E)	plastic	4°C HNO_3 for pH<2	Hardness	6 months
250 mL (F)	plastic	4°C H_2 SO_4 for pH <2	NO_3^-/NO_2^-	28 days
500 mL (G)	glass	4°C H_2SO_4 for pH<2	TOC	14 days
Spent AA Samples				
8 oz (AA1)	glass jar	4°C	Total As, Al, Fe, Mn	6 months
4 oz (AA2)	glass jar	4°C	Water content, pH, TCLP metals	14 days
4 oz (AA2)	glass jar	4°C	Water content, pH, TCLP metals	14 days

TOC = total organic carbon.
TSS = total suspended solids.

AP-09/15/98-IN-B-DUP

Date: 09/15/98 **Time:** 11a.m.
Collector's Name: Sample Collector
Location: Any Plant
Sample ID: AP-02/15/98-PF-B-DUP
Send to: Battelle
Analysis Required: Total As, Al, Fe, and Mn
Preservative: 0.05% sulfuric acid

Figure 3-1. Example of Sample Bottle Label

Express for the following week's sampling activity. Figure 3-2 shows photographs of a sample cooler with four sample compartments and a color-coded instruction sheet placed under the lid of the cooler.

3.3 Sampling Procedures

3.3.1 General Approach and Sampling Schedules

One Battelle staff member and the EPA WAM traveled to each plant to collect source water samples, meet plant operators, solicit interest in participating in this year-long sampling program, and obtain system design and operating information and historical water quality data. After the plant selection, two Battelle staff members returned to each plant to collect samples at selected sampling locations and train the plant operator or a designated POC to perform sampling and field arsenic speciation. The remaining three preliminary sampling events and long-term sampling events then were conducted by the trained plant personnel. Residuals sampling, including monthly collection of backwash and spent brine samples during the resin regeneration at Plant A and a single spent AA sampling event at Plants C and D also were collected by the designated plant employees with detailed instructions provided by Battelle over the telephone. Table 3-2 summarizes the sampling activities conducted at each plant.

During the preliminary and long-term sampling, sample collection was conducted on a 4- or 8-week cycle, with each week having unique sampling requirements. Tables 3-3 (for Plants A and B) and 3-4 (for Plants C and D) summarize the schedules for the initial source water, the preliminary, the long-term, and the residual sampling.

After receipt of the weekly sample coolers, plant personnel began sampling activities at the selected locations on the scheduled dates. Upon completion, all sample bottles were sealed with tape and placed in the same coolers for return shipment to Battelle by Federal Express. Upon receipt of the samples, the designated Battelle sample custodian immediately examined and compared the conditions of all sample bottles with those indicated in the chain-of-custody forms. Samples then were distributed to Battelle's ICP-MS laboratory and Wilson Environmental Laboratories for chemical analyses.

Throughout the duration of the study, Battelle staff maintained frequent telephone contact with each plant to ensure that all sampling activities were carried out as planned. For example, after the scheduled arrival of sample coolers, one Battelle staff member would call to confirm the receipt of the coolers, answer any questions, discuss irregular plant operations and unusual observations, and propose/suggest corrective actions. When available, results of the chemical analyses also were discussed over the telephone and data sheets were sent quarterly to the plants for review. Also, water usage and historic water quality data were sent along with sample coolers or transmitted via facsimile to Battelle for information/evaluation.

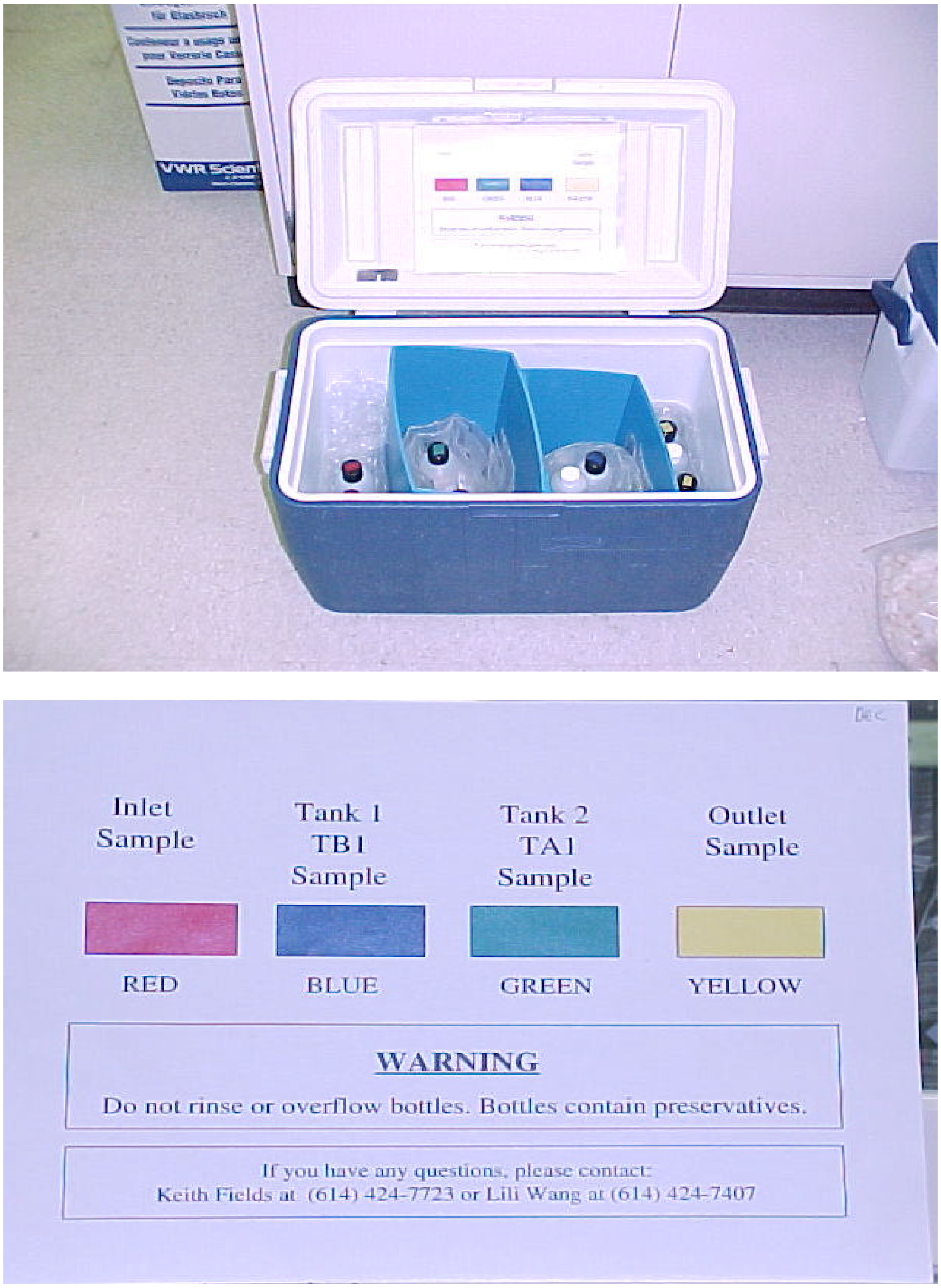
3.3.2 Arsenic Field Speciation Procedure

The procedures for performing the field arsenic speciation are shown in Figure 3-3 and are described as follows ("steps" refer to Figure 3-3):

- **Bottle A**: A 400-mL disposable plastic beaker was rinsed thoroughly with the water to be sampled. The beaker then was used to collect a water sample and to fill bottle A with an aliquot of that sample (step 3). If necessary, additional sample water was added to the beaker after bottle A was filled to complete arsenic speciation sampling.

  Bottle B: A 60-mL disposable plastic syringe was rinsed thoroughly with the water in the plastic beaker by completely filling and emptying the syringe (step 4). After attaching a 0.45-µm disc filter and wasting about 10 drops of the filtrate, the syringe was used to filter the water sample from the beaker and fill bottle B. Bottle B then was tightly capped and vigorously shaken for about 15 seconds to allow thorough mixing of the filtered water and sulfuric acid (step 5).

- **Bottle C**: The protective caps on the top and bottom of a resin column were removed and approximately 40 mL of the water in bottle B was wasted through the column. This initial 40 mL was used to displace the water in the resin column and to ensure attainability of a representative sample from the column. The resin column then was positioned



Inlet Sample	Tank 1 TB1 Sample	Tank 2 TA1 Sample	Outlet Sample
🟥	🟦	🟩	🟨
RED	BLUE	GREEN	YELLOW

WARNING

Do not rinse or overflow bottles. Bottles contain preservatives.

If you have any questions, please contact:
Keith Fields at (614) 424-7723 or Lili Wang at (614) 424-7407

Figure 3-2. Photographs of a Typical Sample Cooler (with Four Sample Compartments) and a Color-Coded Instruction Sheet

over bottle C, and the water from bottle B was passed through the column until approximately 20 mL of the resin-treated sample had been collected in bottle C (step 6).

- The procedures described under the above three bullets were repeated to obtain duplicate bottles A, B, and C.
- Upon completion, the individual performing the speciation signed a chain-of-custody form (step 7). All sample bottles (for arsenic speciation and other water quality parameters), along with the signed chain-of-custody form, were placed in the original cooler with ice packs and shipped via Federal Express to Battelle (step 8).

Table 3-2. Summary of Sampling Activities at Plants A, B, C, and D

Sampling Activities	Sampling Frequency	Plants A and B	Plant C	Plant D
Initial source water sampling	Once	06/10/98	06/11/98	06/11/98
Preliminary sampling	Weekly or biweekly	08/06/98 through 08/26/98	08/05/98 through 09/16/98	08/05/98 through 09/16/98
Long-term sampling	Weekly[(a)] or biweekly	09/01/98 through 06/17/99	09/30/98 through 06/09/99	09/30/98 through 09/01/99
Spent AA sampling	Once	Not applicable	12/29/98	05/25/99
Backwash and spent brine sampling	4-week	03/21/99 through 06/13/99 (Plant A only)	Not applicable	Not applicable

(a) Except for the holiday weeks of 11/23/98, 12/21/98, and 12/28/98.

3.3.3 Backwash, Spent Brine, and Spent AA Sampling Procedure

Backwash and spent brine samples were collected at Plant A on a monthly basis starting on March 21, 1999. When the IX tank was regenerated, eluate from each of the four regeneration steps (i.e., backwash, brine regeneration, slow rinse, and fast rinse) was collected alternately in two 32-gal buckets through a garden hose. A stopwatch was used to measure the time elapsed to assist in determining the start and end points of each regeneration step. At the end of each regeneration step, the content in the bucket was thoroughly mixed, and a portion of the water was transferred to sample bottles for pH, TSS, total As, Al, Fe, and Mn analyses.

Spent AA samples were collected from Plants C and D during the medium replacement. At Plant C, AA samples were collected from roughing tanks, TA1 and TA2. At Plant D, AA samples were collected from the top, middle, and bottom sections of the roughing tank in train 1 (TB1). With a bed depth of 3.2 ft, the top, middle, and bottom sections were defined as 0-0.5, 1.1-1.6, and 2.2-2.7 ft from the top of the bed. The AA was vacuumed from each section, placed in a container, and mixed thoroughly before a representative sample was collected. The sample collection was performed by the plant POC with assistance from a certified operator. When the samples arrived at Battelle, subsamples were sent to Wilson Environmental Laboratories for TCLP testing. Another portion of the AA samples were regenerated with caustic

Table 3-3. Summary of Sampling Schedule for Plants A and B

	Water Sampling								
	Initial Source Water Sampling	Preliminary Sampling Cycle				Long-Term Sampling Cycle			
Analyte	(Once)	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4
As (total)	W*	W*	W	W	W	W*	W	W, RG	W
As (total soluble)	W*	W*				W*			
As (particulate)	W*	W*				W*			
As(III)	W*	W*				W*			
As(V)	W*	W*				W*			
Al (total)	W*	W*	W	W	W	W*	W	W, RG	W
Fe (total)	W*	W*	W	W	W	W*	W	W, RG	W
Mn (total)	W*	W*	W	W	W	W*	W	W, RG	W
Al (dissolved)		W*				W*			
Fe (dissolved)		W*				W*			
Mn (dissolved)		W*				W*			
Alkalinity	W*	W	W*	W	W	W	W*	W	W
Sulfate	W*	W	W*	W	W	W	W*	W	W
NO_3-NO_2 (N)	W*	W	W*			W			
TOC	W*								
Turbidity	W*	W	W*	W		W			
Hardness	W*	W	W*			W			
Ca Hardness	W*	W	W*			W			
Mg Hardness	W*	W	W*			W			
pH	W*	W	W*	W	W	W	W*	W, RG	W
TSS	W*							RG	

* = Duplicate samples collected and analyzed.
W = Water samples collected from the inlet and outlet locations.
RG = Regeneration wastewater samples collected at Plant A.
Empty cells indicate no samples taken.

Table 3-4. Summary of Sampling Schedule for Plants C and D

	Water Sampling									
	Initial Source Water Sampling (Once)	Preliminary Sampling Cycle				Long-Term Sampling Cycle				Spent AA Sampling (Once)
Analyte		Week 1	Week 3	Week 5	Week 7	Week 1	Week 3	Week 5	Week 7	
As (total)	W*	W*	W	W	W	W*	W	W	W	
As (total soluble)	W*	W*				W*				
As (particulate)	W*	W*				W*				
As (III)	W*	W*				W*				
As (V)	W*	W*				W*				
Al (total)	W*	W*	W	W	W	W*	W	W	W	
Fe (total)	W*	W*	W	W	W	W*	W	W	W	
Mn (total)	W*	W*	W	W	W	W*	W	W	W	
Al (dissolved)		W*				W*				
Fe (dissolved)		W*				W*				
Mn (dissolved)		W*				W*				
Alkalinity	W*	W	W*	W	W	W	W*	W	W	
Fluoride	W*	W	W*	W	W	W	W*	W	W	
Sulfate	W*	W	W*	W	W	W	W*	W	W	
NO_3-NO_2 (N)	W*	W				W				
TOC	W*									
Turbidity	W*	W	W*			W				
pH	W*	W	W*	W	W	W	W*	W	W	
Hardness	W*	W				W				
Ca Hardness	W*	W				W				
Mg Hardness	W*	W				W				
TCLP Metals										AA
Percent moisture										AA
As (total)										AA

* = Duplicate samples collected and analyzed.
W = Water samples collected from the inlet, after Tank A, after Tank B, and outlet locations.
AA = Spent AA samples collected at Plants C and D.
Empty cells indicate no samples taken.

solutions to remove the adsorbed arsenic from AA. Detailed experimental procedures are described in Section 3.4.2.

3.3.4 Sampling Procedure for Other Water Quality Parameters

All other water quality parameters identified in Tables 3-3 and 3-4 were analyzed using samples either in bottles A, B, and C or in bottles provided by Wilson Environmental Laboratories (i.e., bottles D, E, F, and G). All bottles D, E, F, and G were filled directly from sample taps and preserved according to the respective analytical methods. These sample bottles along with bottles A, B, and C were placed in the original coolers with ice packs and shipped via Federal Express to Battelle.

3.4 Technical Approaches for Special Studies

During the long-term evaluation studies, several observations were made on the performance of the treatment processes at Plants A and D that suggested a need for short-term special studies. At Plant A, arsenic breakthrough was detected in the effluent before the IX resin was regenerated; therefore, a revisit of the system, especially its regeneration process, was made to enhance the understanding of the IX system performance. At Plant D, a laboratory study using the spent and virgin AA was designed to assist in evaluating the performance of the AA system.

The following sections discuss the technical approaches used for the special studies at Plants A and D, respectively, including experimental setup, test procedures, and sampling procedures.

3.4.1 Short-Term Special Study at Plant A

During June 12 to 14, 1999, Battelle staff performed a resin regeneration study to evaluate the effectiveness of the renegeration process and determine the quantities and chemical characteristics of the regeneration residuals.

The flowrate and duration of each regeneration step were measured by continuously monitoring the eluate's flowrate and TDS levels using an Omega ACCUM-U-FLO totalizer and a Hanna HI 9635 conductivity/TDS meter (Hanna Instruments, Inc., Woonsockett, RI), respectively. The pH of the eluate also was monitored using a VWR Model 2000 pH meter and a nonrefillable combination pH electrode. All meters and probes were

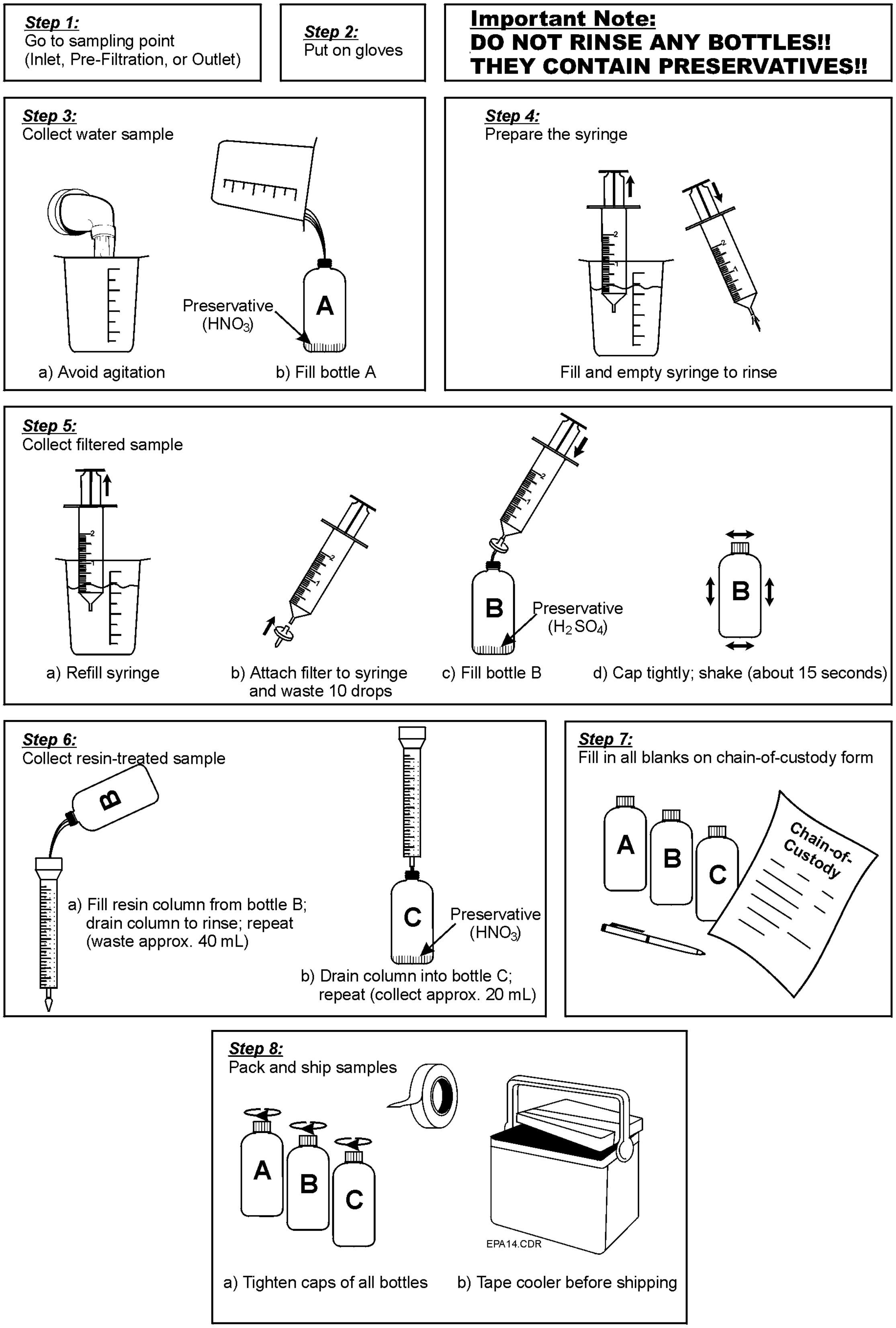


Figure 3-3. Instruction Sheet for Arsenic Field Speciation

calibrated prior to use according to the manufacturers' instruction manuals.

The test apparatus was set up as follows: (a) The eluate from the resin column was directed through a garden hose and the totalizer to a 250-mL plastic beaker holding the TDS and pH probes. (b) The beaker was placed just inside the rim of a 32-gal plastic bucket, allowing the eluate to overflow, after measurements, into the bucket. (c) Two 32-gal plastic buckets were used alternately during the sampling. (d) A stopwatch was used to measure the time elapsed.

The following test procedures were used for sampling during the regeneration:

- Collect one influent and one effluent sample.
- Turn on the power and start the stopwatch after water had entered the resin column.
- Record the time elapsed, TDS, pH, temperature, volume, and flowrate on a datalogger every 30 to 60 seconds.
- Collect grab samples once every 4 to 6 minutes by filling up sample bottles with the overflow from the beaker.
- Collect a composite sample from the bucket at the end of each regeneration step.
- Collect two influent and two effluent samples after regeneration was complete and the system returned to service.
- Collect two influent and two effluent samples each day on Day 2 and Day 3.
- Place sample bottles in a cooler with ice packs and have the cooler shipped via Federal Express to Battelle at the end of the test.

The number of samples collected at each step is listed in Table 3-5. All samples were analyzed for total As and sulfate. Because the IX resins prefer sulfate ions to arsenic ions, and because sulfate was present in the water (up to 25 mg/L), the sulfate content in the influent, effluent, spent regenerant, and rinse water was determined.

The percent recovery of arsenic from the regeneration was calculated using Equation 3-1:

$$\%R = M_{recovered}/M_{removed} \times 100\% \qquad (3\text{-}1)$$

where: $\%R$ = percent recovery
$M_{recovered}$ = the amount of arsenic recovered from the resin column, g
$M_{removed}$ = the amount of arsenic removed from the source water, g.

Table 3-5. Sampling Schedule for the Special Study at Plant A

	Tank Activities	Sampling Time	Number of Samples Grab	Composite
Preregeneration	Service	Day 1	2	0
Regeneration	Backwash	Day 1: 0-18 min	3	1
	Brine regeneration	Day 1: 18-42 min	6	1
	Slow rinse	Day 1: 42-68 min	5	1
	Fast Rinse	Day 1: 68-78 min	2	1
Post-regeneration	Service	Day 1	4	0
	Service	Day 2	4	0
	Service	Day 3[(a)]	2	0
Total			28	4

(a) The Day 3 samples were collected by the plant POC.

$M_{recovered}$ was calculated using the arsenic concentration and the volume of the eluate from each regeneration step; $M_{removed}$ was estimated based on the water usage data and arsenic concentrations in the inlet and outlet water.

3.4.2 Short-Term Special Study at Plant D

A special study was conducted on the AA system at Plant D to determine AA's capacity for arsenic removal under the field and laboratory conditions. The spent AA sampling has been described in Section 3.3.3. A virgin AA sample and five gallons of raw water were collected and shipped to Battelle. Upon receiving these samples, the following tests were performed by Battelle:

Test 1: Characteristics of the Spent AA

A subsample of each spent AA sample was sent to Wilson Environmental Laboratories for TCLP testing. Another subsample was digested with nitric acid and analyzed for total arsenic. The resulting concentration was compared with the concentration desorbed from the spent AA using caustic solutions.

Prior to use, the spent AA samples were air-dried in clean glass trays for several days and stored and homogenized in glass bottles. A subsample of each air-dried sample was analyzed for moisture content according to Standard Method ASTM D2216.

Three subsamples of each air-dried AA sample (from the top, middle, and bottom of the column) were weighed (approximately 2.00 g) and digested using 100 mL each of concentrated nitric acid according to EPA Method 3051. The digestate was analyzed for total arsenic. The amount of arsenic recovered per unit dry weight from each AA sample was calculated using Equation3-2:

$$q_e = C_{As} \times V/W_{dry} \quad (3\text{-}2)$$

where: q_e = Arsenic recovered, mg/g dry AA
C_{As} = arsenic concentration in digestate, mg/L
V = digestive fluid volume, L
W_{dry} = dry weight of AA, g.

Test 2: Regeneration of Spent AA Using Caustic Solutions

Caustic solutions of 1-2% (by weight) NaOH have been reported to be effective in stripping inorganic ions such as fluoride, arsenic, and phosphate from spent AA (Chen and Snoeyink, 1987). Higher NaOH concentrations (i.e., 4%) have also been suggested for stripping arsenic because arsenic is much more difficult to remove from AA than fluoride (Clifford, 1999), thus a 4% NaOH solution was used in this study. Studies have also showed that comparable regeneration results have been obtained with 30 minutes to 3 days of contact time (Chen et al., 1989). Therefore, the regeneration test was run for approximately 16 hours.

Spent AA samples collected from the top, middle, and bottom sections of the column were stripped with a 4% NaOH solution to determine the amount of arsenic that might be desorbed from each sample. The experiment was conducted in duplicate at room temperature (about 22°C) according to the following procedures:

- Weigh approximately 70 g of a wet spent AA sample into one of six 250-mL plastic bottles containing 150 mL of 4% NaOH solution.
- Cap the bottles and place them on a tumbler for overnight mixing (approximately 16 hrs).
- Remove the contents from each bottle and filter them through a ZAPCAP-S 0.45-µm disposable cellulose acetate membrane filter (Schleicher & Schuell, Keene, NH).
- Rinse the residual AA three times with a total of 200 mL Millipore DI water and filter the rinsate.
- Combine and mix the filtrate from each bottle and analyze the sample for total arsenic (preserved with nitric acid) and fluoride and sulfate (unpreserved).

The amount of arsenic, fluoride, and sulfate recovered from the caustic wash was calculated using Equation 3-2 except that the digestive fluid volume was replaced by the total volume of the NaOH solution and the rinse water used in the experiment.

Test 3: Adsorption Isotherm Experiment

Isotherm tests were conducted to determine the capacity of the virgin AA (Alcoa CPN type granular AA, 28 × 48 mesh) used at Plant D. To increase the initial As(V) concentration in the raw water from 50 µg/L to approximately 500 µg/L, 450 µL of 1.0-µg/µL As(V) standard solution was spiked to 1 L of raw water. A kinetic study was performed to determine the time required to reach equilibrium. A series of 250 mg of virgin AA was accurately weighed, placed in a 250-mL plastic bottle containing 200 mL of the spiked raw water, and adjusted to the raw water pH of 7.7 ± 0.2. The bottles were placed on a tumbler for 7 days at room temperature (~22 °C). During the test period, the pH values of all test solutions were periodically checked and adjusted to 7.7 ±0.2. After 1, 2, 5, 6, and 7 days, one bottle each was removed from the tumbler and its content was decanted and filtered through a ZAPCAP-S 0.45-µm disposable cellulose acetate membrane filter. The filtrate was collected in a plastic bottle preserved with nitric acid for total arsenic analysis.

For the isotherm experiment, identical volumes of an arsenic solution were exposed to different quantities of AA. The control contained only arsenic solution, without alumina. During the test period, the pH values of all test solutions were periodically checked and adjusted to 7.7 ±0.2. Final arsenic concentrations were determined, and the difference between test and control final concentrations was attributed to adsorption onto AA. The procedure for batch tests is as follows:

- Pour 200-mL aliquots of arsenic-spiked raw water into 250-mL plastic bottles with measured quantities (100 to 1,000 mg) of granular AA.
- Adjust the pH of solution in each bottle to 7.7 ±0.2.
- Cap bottles and place them on the tumbler.
- Remove bottles from the tumbler after 6 days and filter their contents as described above.
- Analyze filtrate samples for total arsenic concentration.

3.5 Analytical Procedures

The analytical procedures used for this project were described in Section 4.0 of the QAPP prepared by Battelle (1998). Table 3-6 presents a summary of all analytical methods used. All of the methods used are standard EPA methods. Analyses of As, Al, Fe, and Mn in water samples were accomplished by ICP-MS using EPA Method 200.8. ICP-MS was chosen as the method for As, Al, Fe, and Mn analyses because it has a low method detection limit (MDL) and was a relatively low-cost method (about $35/sample). ICP-MS analyses were conducted on a Perkin Elmer Sciex Model 6000 equipped with a crossflow pneumatic nebulizer and an automatic

Table 3-6. Summary of Analytical Methods for Arsenic Treatment Study

Sample Matrix	Analyte	Method	Analytical Laboratory
Aqueous	As (total)	EPA 200.8	Battelle ICP-MS
	Total Al	EPA 200.8	Battelle ICP-MS
	Total Fe	EPA 200.8	Battelle ICP-MS
	Total Mn	EPA 200.8	Battelle ICP-MS
	Alkalinity	EPA 310.1	Wilson Environmental
	pH	EPA 150.1	Wilson Environmental
	Turbidity[(a)]	EPA 180.1	Wilson Environmental
	Hardness	EPA 215.1/242.1	Wilson Environmental
	SO_4^{2-}	EPA 375.4	Wilson Environmental
	F^-	EPA 340.2	Wilson Environmental
	TOC	EPA 415.1	Wilson Environmental
	NO_3^-/NO_2^-	EPA 353.2	Wilson Environmental
Spent AA	Moisture content	ASTM D 2216	Wilson Environmental
	pH	SW-846 9045	Wilson Environmental
	TCLP metals	SW-846 1311	Wilson Environmental
	Total As	SW-846 3051, 6020	Wilson Environmental
	Total Fe	SW-846 3051, 6020	Wilson Environmental

(a) Turbidity was analyzed in the laboratory, not on site.

sampler. Yttrium ($^{88.9}$Y) was added to all samples as an internal standard to correct for instrument drift. Because arsenic is monoisotopic, all measurements were made at a mass/charge ratio of 75. To eliminate an appreciable interference from a chloride molecular species ($^{40}Ar^{35}Cl$), all ion current data at m/e 75 were corrected using chloride measurements in all samples, and the MDL was 0.1 µg/L As. All the unfiltered water samples (i.e., in bottle A) were digested using EPA Method 200.8 prior to analysis. Filtered water samples (i.e., in bottles B and C) were analyzed directly without digestion. Wilson Environmental Laboratories was subcontracted to perform all other chemical analyses. QA/QC of all methods followed the guidelines provided in the QAPP (Battelle, 1998) and the data quality in terms of precision, accuracy, MDL, and completeness is discussed in Section 5.0 of this report.

4.0 Results and Discussion

This section presents the results of the treatment plant selection process, which resulted in the selection of two IX plants, referred to as Plants A and B, and two AA plants, referred to as Plants C and D. In addition, results from water and residuals sampling and analysis at Plants A, B, C, and D are summarized and discussed. Complete analytical results from long-term water sampling at Plants A, B, C, and D are presented in Appendices A.1, B.1, C.1, and D.1, respectively.

4.1 Plant Selection

The plant selection process consisted of identifying potential treatment facilities, contacting these facilities via telephone, and conducting initial site visits during which source water samples were collected and analyzed. Initially, a list was prepared consisting of two potential IX treatment facilities and three AA facilities (Plants A, B, C, D, and E; see Table 4-1 for plant details). Staff at these potential candidate facilities were contacted to discuss the study and determine details of plant operation.

All plants except Plant E were selected for the subsequent phases of the study. Results from source water sampling at each of these four facilities are presented in the following subsections.

4.2 Plant A

Water and residual samples were collected and analyzed at Plant A, an IX plant, during three phases of the study. The first phase consisted of source water sampling used to help determine if the plant should be considered for subsequent phases. Source water sampling at Plant A was performed in June 1998. Following source water sampling, the second phase of the study was initiated. This second phase consisted of weekly water sampling over a 4-week period in August 1998 and was designed to determine if the sampling locations and proposed water quality analyses were appropriate for the third phase, long-term evaluation. The third phase was initiated in September 1998 and continued through June 1999. This long-term evaluation consisted of weekly sampling and analysis of raw and finished water. Also, arsenic speciation sampling was conducted every fourth week. The third phase of the study also included sampling and analysis of residuals. Backwash and spent brine samples were collected monthly beginning in March 1999.

4.2.1 Plant A Description

The IX system in Plant A supplies treated water to a school and is used by approximately 350 students and teachers. The IX system was installed by Lowry Engineering at Unity, ME in August 1990 and was designed based on an average daily demand (ADD) of 1,200 gallons per day (gpd) of water. The system is operated intermittently and the treated water is stored in a storage tank to supply daily demand. This system consists of a Filox™ oxidizing filter followed by an A300X IX resin system. Figure 4-1 is a schematic diagram of the treatment process, which consists of the following major components:

Table 4-1. Initial List of Treatment Facilities Identified for the Study

Plant ID	Process	Source Water Arsenic Concentration (µg/L)	Sampling Date	Population Served	Historical Data	Source Water Type
A	IX	23-34 (effluent)	July 1995 ~ March 1997	350	Limited	GW
B	IX	52	November 12,1995	35	NA	GW
C	AA	42	December 30, 1994	600	Yes	GW
D	AA	40-80	NA	200	Yes	GW
E	AA	51-63	1988	97 families	Yes	GW

NA = not available; GW = groundwater.

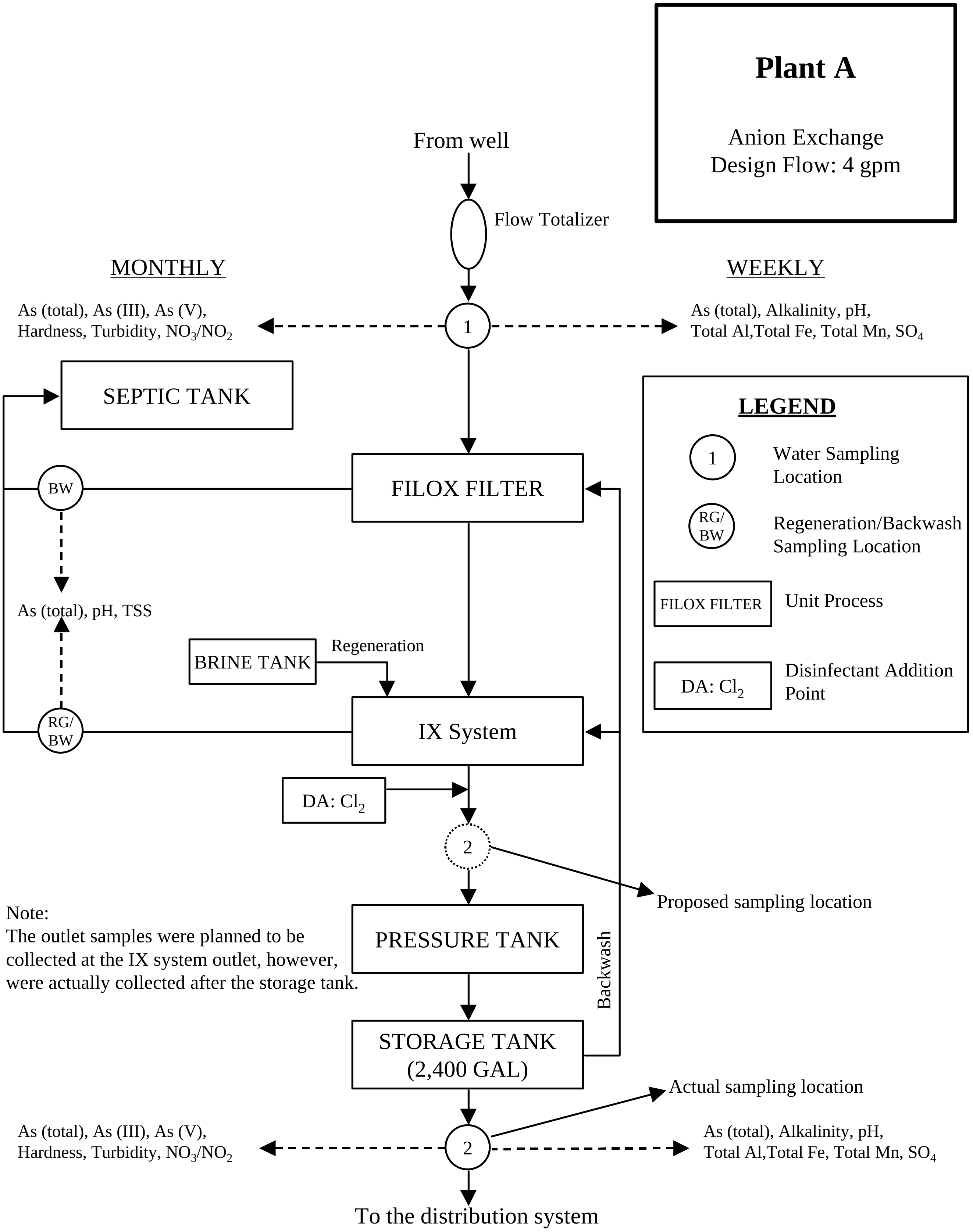


Figure 4-1. Process Flow Diagram and Sampling Locations at Plant A

- **Intake.** The raw water is pumped from an 800-ft-deep bedrock well located in the eastern vicinity of the school building (Well 1) and flows directly into the Filox™ filter. Well 1 was drilled in 1987-88 and has a 6-inch steel casing. Another well, Well 2, is located about 125-150 ft northeast of Well 1. Well 2 was drilled in 1957 with a depth of 250 ft and an 8-inch steel casing, but is not currently in use.
- **Oxidizing Filter.** The Filox™ filter was installed to oxidize possible arsenite [As(III)] in water to arsenate [As(V)]. As shown in Figure 4-2, the Filox™ filter is a 65-inch-long by 14-inch-diameter Polyglass® vessel filled with a 22.5-inch-deep MnO_2-based medium. Because the source water contains primarily As(V) and almost no As(III), the oxidizing filter has functioned only as a prefiltration unit to remove particulate from the raw water. The Filox™ filter is backwashed every 3 days with treated water from the storage tank. The backwash lasts for 15 to 20 minutes at a flowrate of 11 gallons per minute (gpm).
- **Anion Exchange System.** After passing through the Filox™ filter, water flows into the A300X resin column. The A300X column has the same dimensions and configuration as the Filox™ column except that it is filled with a 22.5-inch-deep Purolite A-300 anionic resin bed (Figure 4-2). The Purolite A-300 anionic resin (The Purolite Company, Bala Cynwyd, PA) is a strongly basic gel IX resin in chloride form. Typical physical and chemical properties of this resin are presented in Table 4-2. Detailed technical data on the resin can be found in Appendix A.2. At a design flowrate of 4 gpm, the hydraulic loading rate to the filter is 4 gpm/ft^2 and the EBCT is 3.7 minutes.
- **Resin Regeneration.** The original design called for a regeneration frequency of every 3 months using a brine solution at 10 lb salt/ft^3 resin. Because early arsenic breakthrough was detected during this study, a more frequent (once every 4 weeks) regeneration schedule was recommended to the plant personnel and has been implemented since March 1999. Discussion on the resin regeneration is provided in Section 4.2.4.4. The brine solution is stored in a 35-inch-tall by 18-inch-diameter tank. The regeneration of the A300X resin column consists of four steps: upflow backwash, downflow brine, downflow slow rinse, and downflow fast rinse. The approximate flowrate and duration of each regeneration step are listed in Table 4-3 and were verified during the special study at Plant A.
- **Chlorination**. To disinfect the water, chlorine is added to the treated water through a conventional chemical feed pump.
- **Storage Tank.** The treated, chlorinated water is stored in a 2,400-gallon steel tank, and is pressurized through two booster pumps and two pressure tanks before it enters the school distribution system.

The cost of the system at the time of installation was $6,886 with an additional $2,000 installation fee.

4.2.2 Initial Source Water Sampling

Source water sampling was conducted during the initial site visit on June 9, 1998. Table 4-4 presents the analytical results from the source water sampling. The average total arsenic concentration was 23.1 µg/L. Particulate arsenic was less than detection; thus, soluble arsenic, primarily As(V), accounted for the majority of the total arsenic. The average As(III) concentration was 0.5 µg/L.

4.2.3 Preliminary Sampling

During the preliminary sampling phase of this study, water samples were collected only at the inlet and the outlet of the system because of the lack of a sampling tap after the oxidizing filter. The inlet samples were collected from a tap located on the pipe connecting to the well. The outlet samples, originally planned to be collected between the resin tank and the storage tank, were actually collected after the storage tank. The outlet sampling location was changed because it was difficult to draw water samples from the resin tank outlet when the system was turned off. The sampling locations and the associated sample analyses performed at each location are shown on Figure 4-1.

Alkalinity, sulfate, turbidity, pH, total hardness, nitrate-nitrite, total Al, total Fe, total Mn, and total arsenic were analyzed on samples collected every week at both sampling locations. Arsenic speciation was conducted once during the preliminary study on samples collected from both sampling locations. Soluble and particulate arsenic were determined as part of the arsenic speciation, as were the species (arsenite and arsenate) making up the soluble fraction of the total arsenic. Dissolved Al, Fe, and Mn concentrations at each sampling location were determined using a sample from bottle B of the arsenic speciation kits. Table 4-5 presents the results of the 4-week preliminary sampling period.

As shown on Table 4-5, inlet total arsenic concentrations ranged from 17.8 to 26.6 µg/L. Arsenic in the source water was primarily As(V) and contained almost no As(III) and particulate arsenic, consistent with the results of the initial source water sampling (Table 4-4). On August 6, 1998, the total arsenic concentration in the finished water

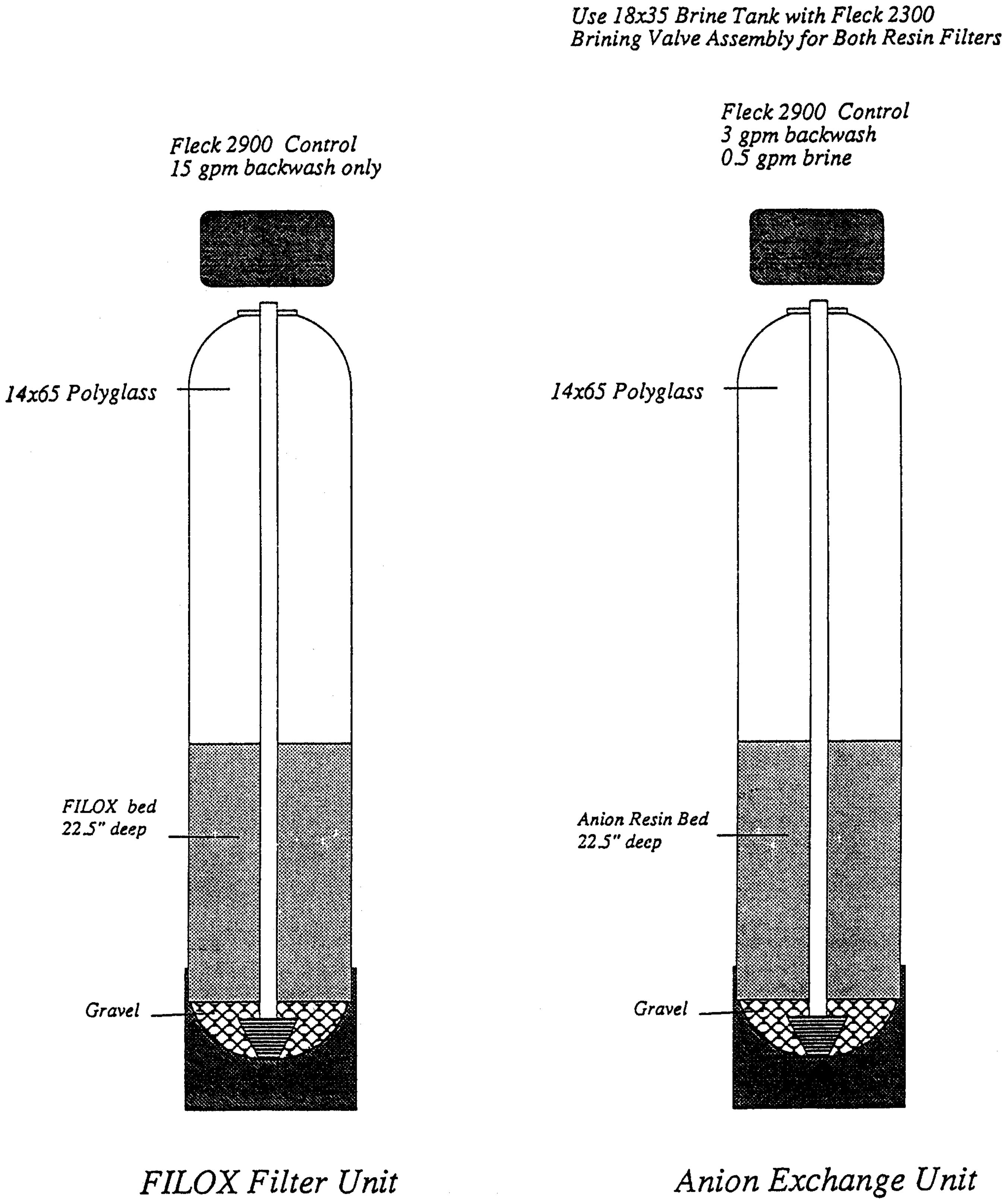


Figure 4-2. Cross Section of Filox™ Filter and A300X IX Filter at Plant A (Source: Lowry Engineering, Inc., 1990)

Table 4-2. Typical Chemical and Physical Characteristics of Purolite A-300 Anion Exchange Resin

Polymer Structure	Polystyrene crosslinked with divinylbenzene
Functional Groups	$R(CH_3)_2(C_2H_4OH)N^+$
Physical Appearance	Clear spherical beads
Ionic Form	Chloride
Screen Size, U.S. Std.Mesh (Wet)	16-50
Particle Size Range	+16 mesh < 5%; -50 mesh < 1%
Uniformity Coefficient	1.7 maximum
Water Retention	40-45%
Swelling	Salt –OH, 10%
pH Limitations	None
Temperature Limitations	185ºF maximum
Chemical Resistance	Unaffected by dilute acids, alkalis, and most solvents
Whole Clear Beads	92% minimum
Shipping Weight	44 lb/ft^3 (705 g/L)
Total Capacity	1.45-1.6 meq/mL min. Volumetric; 3.5-3.7 meq/gm min. Weight

Table 4-3. Regeneration Schedule of the A300X Resin Column at Plant A

Regeneration Step	Flow Direction	Duration (min)	Flowrate (gpm)
Backwash	Upflow	18	5.0
Brine	Downflow	24	1.0
Slow Rinse	Downflow	18	1.0
Fast Rinse	Downflow	10	3.2

exceeded the concentration in the raw water, indicating arsenic breakthrough. Therefore, the IX column was regenerated immediately after the samples had been collected. Over the following 3 weeks, the arsenic concentrations in the finished water decreased slowly from 7.2 to 0.6 µg/L, corresponding to 62% to 98% arsenic removal. At the time, it was not clear why the IX column continued to leak even about 2 weeks after the resin regeneration. Further study revealed that this “leakage” actually was due to an artifact caused by the arsenic already present in the 2,400-gal storage tank located just upstream from the sampling point. The storage tank contained relatively high arsenic water before the regeneration and was replenished by the low arsenic water produced after the regeneration. Therefore, the arsenic concentrations in the effluent samples gradually decreased to low levels depending on how quickly the storage tank was replenished. It is expected that the water at the resin tank outlet immediately after the resin regeneration contained even lower arsenic concentrations (i.e., <1.0 µg/L). This hypothesis is being verified by a short-term special study.

During the preliminary sampling period, the inlet alkalinity concentrations ranged from 69 to 92 mg/L (as $CaCO_3$), and the inlet sulfate concentrations ranged from 23 to 25 mg/L. According to the selectivity sequence discussed in Section 1.1.3.1, an SBA resin prefers sulfate over $HAsO_4^{2-}$ and $H_2AsO_4^-$; HCO_3^- is less preferred than $HAsO_4^{2-}$ but has a similar affinity to the resin as $H_2AsO_4^-$. Clifford and Rosenblum (1982) found that the presence of 720 mg/L sulfate reduced arsenic removal by more than 50%. When arsenic broke through the IX column on August 6, 1998, both sulfate and alkalinity (mainly HCO_3^- at a neutral pH) showed little removal (20-25%). After resin regeneration, sulfate was consistently reduced to

Table 4-4. Source Water Analytical Results at Plant A (June 9, 1998)

Parameter	Unit	Primary Sample	Duplicate Sample	Average
Alkalinity	mg/L$^{(a)}$	84	84	84
Sulfate	mg/L	20	20	20
Turbidity	NTU	0.06	0.06	0.06
pH	—	7.6	7.6	7.6
Total Hardness	mg/L$^{(a)}$	100	98	99
Ca Hardness	mg/L$^{(a)}$	88.9	87.4	88.2
Mg Hardness	mg/L$^{(a)}$	10.9	10.7	10.8
Total Al	µg/L	<400	<400	<400
Total Fe	µg/L	<30	40	30
Total Mn	µg/L	<20	30	20
NO_3–NO_2 (N)	mg/L$^{(b)}$	0.75	0.78	0.77
TOC	mg/L	1.1	1.1	1.1
As (total)	µg/L	22.5	23.6	23.1
As (total soluble)	µg/L	24.6	24.4	24.5
As (particulate)	µg/L	<0.1	<0.1	<0.1
As(III)	µg/L	0.4	0.6	0.5
As(V)	µg/L	24.2	23.8	24.0

(a) As $CaCO_3$.
(b) Combined NO_3–N and NO_2–N.
NTU = nephelometric turbidity units.

Table 4-5. Analytical Results from Preliminary Sampling at Plant A (August 6, 1998 to August 26, 1998).

		Sampling Date/Location							
		8/6/98(a)		8/11/98		8/18/98		8/26/98	
Parameter	Units	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(b)	92	71	69 69	23 23	72	41	76	67
Sulfate	mg/L	25	20	24 22	<5 <5	23	<5	24	<5
Turbidity	NTU	0.3	<0.1	<0.1 <0.1	<0.1 <0.1	<0.1	<0.1	NS	NS
pH		7.7	7.5	7.3 7.3	7.0 6.9	7.5	7.4	7.3	7.4
Total Hardness	mg/L(b)	82.1	62.2	68.0 68.0	69.0 71.0	NS	NS	NS	NS
Ca Hardness	mg/L(b)	72.7	54.4	60.4 60.4	61.7 62.9	NS	NS	NS	NS
Mg Hardness	mg/L(b)	9.5	7.7	7.5 7.3	7.5 7.6	NS	NS	NS	NS
Nitrate-Nitrite	mg/L	0.5	0.8	0.7 0.7	0.5 0.6	NS	NS	NS	NS
As (total)	µg/L	17.8 20.0	23.2 21.3	19.0	7.2	26.0	1.9	26.6	0.6
As (total soluble)	µg/L	18.8 19.1	22.1 22.7	NS	NS	NS	NS	NS	NS
As (particulate)	µg/L	ND 0.9	1.1 ND	NS	NS	NS	NS	NS	NS
As (III)	µg/L	ND ND	ND ND	NS	NS	NS	NS	NS	NS
As (V)	µg/L	18.8 19.1	22.1 22.7	NS	NS	NS	NS	NS	NS
Total Al	µg/L	9.7 13.9	9.8 16.6	30.8	18.2	158	19.7	64.5	25.0
Total Fe	µg/L	42.8 68.1	0.3 4.8	31.8	1.0	37.0	16.0	47.0	ND
Total Mn	µg/L	2.9 2.7	0.3 0.4	1.5	1.6	2.6	1.3	6.0	0.4
Dissolved Al	µg/L	1.7 0.7	2.6 2.4	NS	NS	NS	NS	NS	NS
Dissolved Fe	µg/L	ND ND	ND ND	NS	NS	NS	NS	NS	NS
Dissolved Mn	µg/L	3.0 2.5	0.2 0.2	NS	NS	NS	NS	NS	NS

(a) Samples were taken prior to resin regeneration.
(b) As $CaCO_3$.

IN = inlet.
OU = outlet.

NS = not sampled.
ND = not detected.

<5 mg/L throughout the subsequent 3 weeks. However, the alkalinity was reduced by 67%, 43%, and 12%, respectively, showing a decreasing trend with time. This decreasing trend probably was caused by the fact that the less-preferred bicarbonate was replaced from the resin by the more preferred sulfate and arsenic ions. The pH values ranged from 7.3 to 7.7 in the inlet and 7.0 to 7.5 in the outlet. Because the IX process is not pH sensitive in the range of pH 6.5 to 9.0 (Section 1.1.3.1), the effect of inlet pH on the IX process is insignificant. The slightly lower pH value at the outlet presumably was caused by the removal of alkalinity.

Iron compounds can clog and foul IX resins, thereby lowering the arsenic removal capacities and reducing the water throughput. However, at Plant A, both total and dissolved Fe and Mn concentrations were very low. Therefore, the effects of Fe and Mn on the process were insignificant.

Based on the results of the preliminary sampling effort, no changes were made to the approach for the long-term evaluation. Sampling locations and primary analytes remained unchanged.

4.2.4 Long-Term Sampling

Long-term sampling and analysis consisted of a total of 37 weeks of sampling and included 10 arsenic speciation sampling events. During the long-term sampling phase, water samples were collected at the same two locations that were used during the preliminary sampling phase: inlet and outlet (Figure 4-1). Alkalinity, sulfate, turbidity, pH, total aluminum, total iron, total manganese, and total arsenic analyses were performed on samples collected each week. Arsenic speciation sampling was conducted 10 times during the long-term sampling phase on samples collected from each sampling location. Dissolved aluminum, iron, and manganese concentrations at each sampling location were determined monthly using a sample from bottle B of the arsenic speciation kits. Additionally, residual sampling was performed during this phase and consisted of collection and analysis of backwash wastewater and spent brine from the regeneration of the A300X column. The following subsections summarize the analytical results for arsenic, other water quality parameters, and backwash/regeneration wastewater.

4.2.4.1 Arsenic

Table 4-6 provides a summary of the arsenic analytical results collected from the inlet and outlet locations at Plant A. Total arsenic concentrations at the inlet varied widely from 23.3 µg/L to 59.2 µg/L and averaged 40.6 µg/L. Consistent with previous phases of the study, particulate arsenic concentrations were low, averaging 0.4 µg/L and 0.5 µg/L at the inlet and outlet sampling locations, respectively. As(III) concentrations averaged 0.7 µg/L at the inlet and 0.2 µg/L at the outlet, indicating that As(V) made up the majority of the soluble arsenic.

The effluent arsenic concentration ranged from 0.7 to as high as 82 µg/L, which exceeded the corresponding inlet arsenic concentration and the current 0.050 mg/L MCL level. This chromatographic peaking, most likely was caused by the sulfate in the source water. After two 3-month regeneration cycles and one 6-week regeneration cycle, it was determined that the system should be regenerated more frequently. The effluent data collected since April 18, 1999 indicated that if the system was regenerated every 4 weeks or less, the system would be able to achieve arsenic effluent levels of less than 5 µg/L. Again, the column leak, which was observed during the preliminary sampling, still existed, as indicated by the data collected on March 23, May 18, and June 14 through 17, 1999. Because the effluent sampling location did not change throughout the study, the reason for the column leak was again attributed to the storage tank (see Section 4.2.3). Figure 4-3 is a graph showing the total arsenic concentrations at the inlet and outlet of the IX column and removal percentages during the long-term sampling.

Based on the water usage data recorded at each regeneration event since 1994 (see Appendix A.4), the run length of each regeneration cycle is calculated and plotted in Figure 4-4 both in gallons and in BV. Bed volume was calculated by dividing the volume of water processed by the volume of the resin bed (2 ft^3 or 14.96 gal). With the 3-month regeneration schedule (before March 1999), the run length varied from 5,760 to 9,670 BV with an average of 7,890 BV. With the 4-week regeneration schedule, the run length was significantly shortened, ranging from 2,220 to 3,780 BV with an average of approximately 3,000 BV. This run length is reasonable compared with the 4,200 BV and 2,800 BV reported by Clifford and Lin (1986) and Hathaway and Rubel (1987), respectively.

Assuming an average daily demand of 1,200 gpd, a 3000-BV cycle (equivalent to 44,880 gal) would last for 37 days. However, due to variations in water demand with the school schedule (e.g., low water demand during summer when school is dismissed), the regeneration frequency based on total flow rather than time of operation was recommended in place of a time schedule.

Table 4-6. Summary of Arsenic Analytical Results at Plant A (September 1, 1998 to June 17, 1999)

Parameter	Sampling Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	Inlet	µg/L	47	23.3	55.4	40.6	8.0
	Outlet	µg/L	47	0.7	81.5	19.0	20.3
As (total soluble)	Inlet	µg/L	20	30.8	60.9	45.9	9.0
	Outlet	µg/L	20	0.9	97	18.0	29.1
As (particulate)	Inlet	µg/L	20	0	3.4	0.4	1.0
	Outlet	µg/L	20	0	5.9	0.5	1.5
As (III)	Inlet	µg/L	20	0.1	1.4	0.7	0.3
	Outlet	µg/L	20	0	0.5	0.2	0.2
As (V)	Inlet	µg/L	20	30.2	60.2	45.2	9.1
	Outlet	µg/L	20	0.8	96.7	17.8	29.1

One-half of the detection limit was used for nondetect samples for calculations.
Primary and duplicate samples were averaged for calculations.

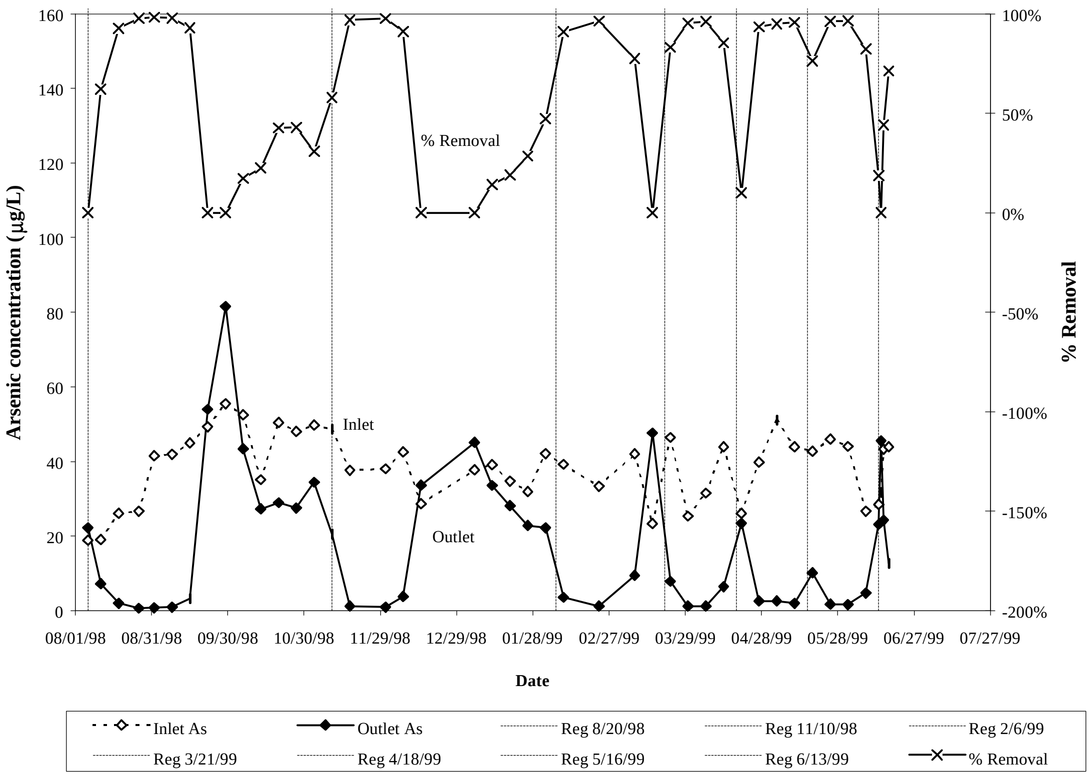


Figure 4-3. Total Arsenic Analytical Results during Long-Term Sampling at Plant A

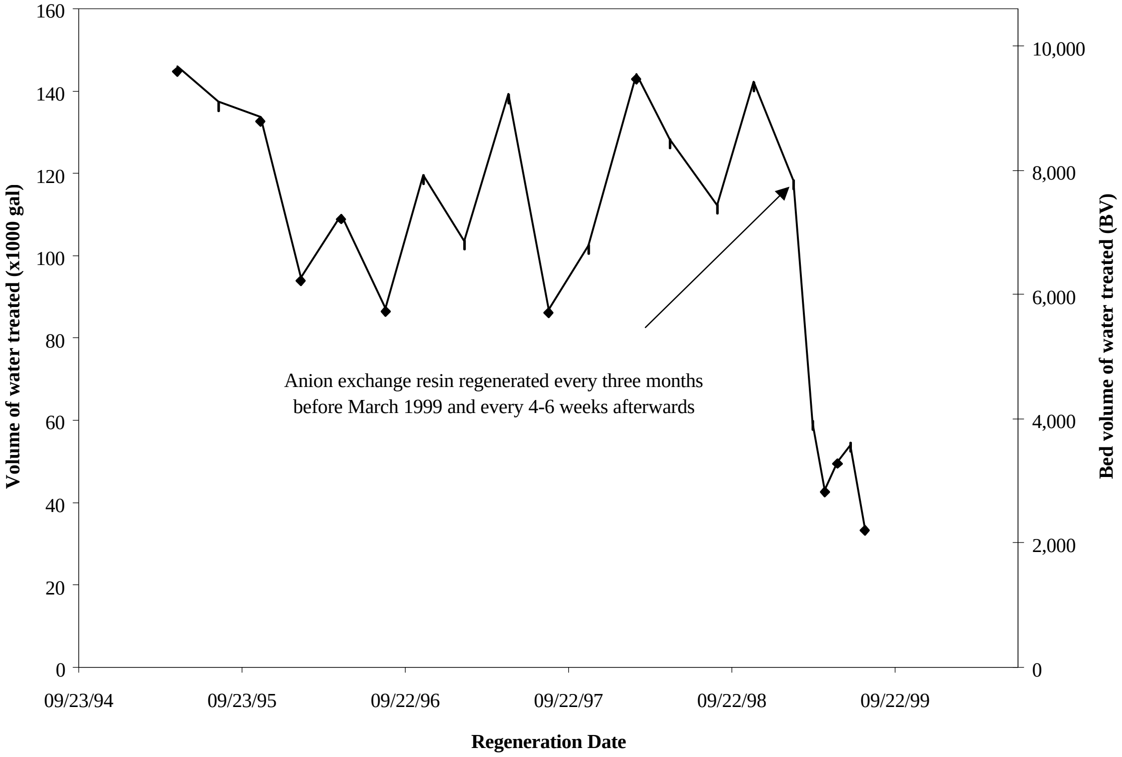


Figure 4-4. Water Treated between Regenerations of the IX System at Plant A

4.2.4.2 Other Water Quality Parameters

In addition to arsenic analysis, other water quality parameters were analyzed to provide possible insight into the chemical processes occurring at the treatment facility. Table 4-7 summarizes the analytical results for several water quality parameters obtained during the long-term sampling.

Inlet sulfate concentrations ranged from 19 to 28 mg/L with an average of 23.7 mg/L. As shown on Figure 4-5, sulfate concentrations were reduced to <5 mg/L at the outlet after the column was properly regenerated. Just after the arsenic breakthrough, the effluent sulfate concentrations increased rapidly, approaching but never exceeding their influent levels. This sharp breakthrough is typical for a most preferred species like sulfate (Clifford, 1999). Because sulfate is more preferred than arsenate by the resin, it can elute arsenate from the resin, causing chromatographic peaking, as observed during the long-term sampling.

Figure 4-6 plots the inlet and outlet alkalinity concentrations and pH throughout the long-term sampling. Alkalinity concentrations ranged from 61 to 93 mg/L (as $CaCO_3$) in the inlet with an average of 84.7 mg/L. The alkalinity was partially removed by the treatment, resulting in its outlet concentrations ranging from 21 to 92 mg/L with an average of 74.6 mg/L. Because bicarbonate is a less-preferred ion, it broke through earlier than sulfate and arsenic. The pH values ranged from 7.2 to 7.8 in the inlet with an average of 7.5. After the treatment, the pH values were slightly reduced, ranging from 7.0 to 7.7, presumably due to the removal of some alkalinity.

During the long-term sampling, the turbidity was low, averaging 0.1 NTU at both the inlet and the outlet. Total hardness also was low, ranging from 64 to 83.9 mg/L (as $CaCO_3$). As expected, the hardness was not removed by the IX column and remained constant at the inlet and the outlet. Nitrate-nitrite concentrations of the inlet water were very low and thus did not have any significant impact on arsenic removal.

The maximum total Al, Fe, and Mn concentrations were 105, 80.2, and 3.1 µg/L, respectively, at the inlet, and 60, 117, and 1.4 µg/L, respectively, at the outlet. As expected, the low metal concentrations of these cations did not have any effects on arsenic removal.

4.2.4.3 Backwash/Regeneration Wastewater

Backwash wastewater and spent brine were sampled on August 6, 1998 and on March 21, April 18, May 16, and June 13, 1999. Composite samples were collected from each of the four regeneration steps (i.e., backwash, brine

Table 4-7. Summary of Water Quality Parameter Analytical Results at Plant A (September 1, 1998 to June 17, 1999)

Parameter	Sampling Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
Alkalinity	Inlet	mg/L	47	61	93	84.7	7.4
	Outlet	mg/L	47	21	92	74.6	16.9
Sulfate	Inlet	mg/L	47	19	28	23.7	1.8
	Outlet	mg/L	47	2.5	25	9.5	9.0
Turbidity	Inlet	NTU	20	0.05	0.3	0.1	0.1
	Outlet	NTU	20	0.1	0.1	0.1	0
pH	Inlet	—	47	7.2	7.8	7.5	0.1
	Outlet	—	47	7.0	7.7	7.5	0.2
Total Hardness	Inlet	mg/L	20	64	83.9	69.5	6.7
	Outlet	mg/L	20	61	79.0	67.3	5.0
Nitrate-Nitrite	Inlet	mg/L	20	0.3	0.8	0.5	0.1
	Outlet	mg/L	20	0.1	3.3	0.7	0.9
Total Al	Inlet	µg/L	47	5.5	105	16.7	15.7
	Outlet	µg/L	47	5.5	60	10.5	8.4
Total Fe	Inlet	µg/L	47	15	80.2	21.3	14.2
	Outlet	µg/L	47	15	117	19.4	15.9
Total Mn	Inlet	µg/L	47	0.3	3.1	0.9	0.7
	Outlet	µg/L	47	0.3	1.4	0.5	0.3
Dissolved Al	Inlet	µg/L	20	3.9	12.9	5.8	1.7
	Outlet	µg/L	20	5.5	19.5	6.2	3.1
Dissolved Fe	Inlet	µg/L	20	11.5	15.6	14.9	0.8
	Outlet	µg/L	20	15	15	15	0
Dissolved Mn	Inlet	µg/L	20	0.3	1.2	0.5	0.3
	Outlet	µg/L	20	0.3	2.7	0.5	0.6

One-half of the detection limit was used for calculating concentrations of nondetect samples.
Primary and duplicate samples were averaged for calculations.

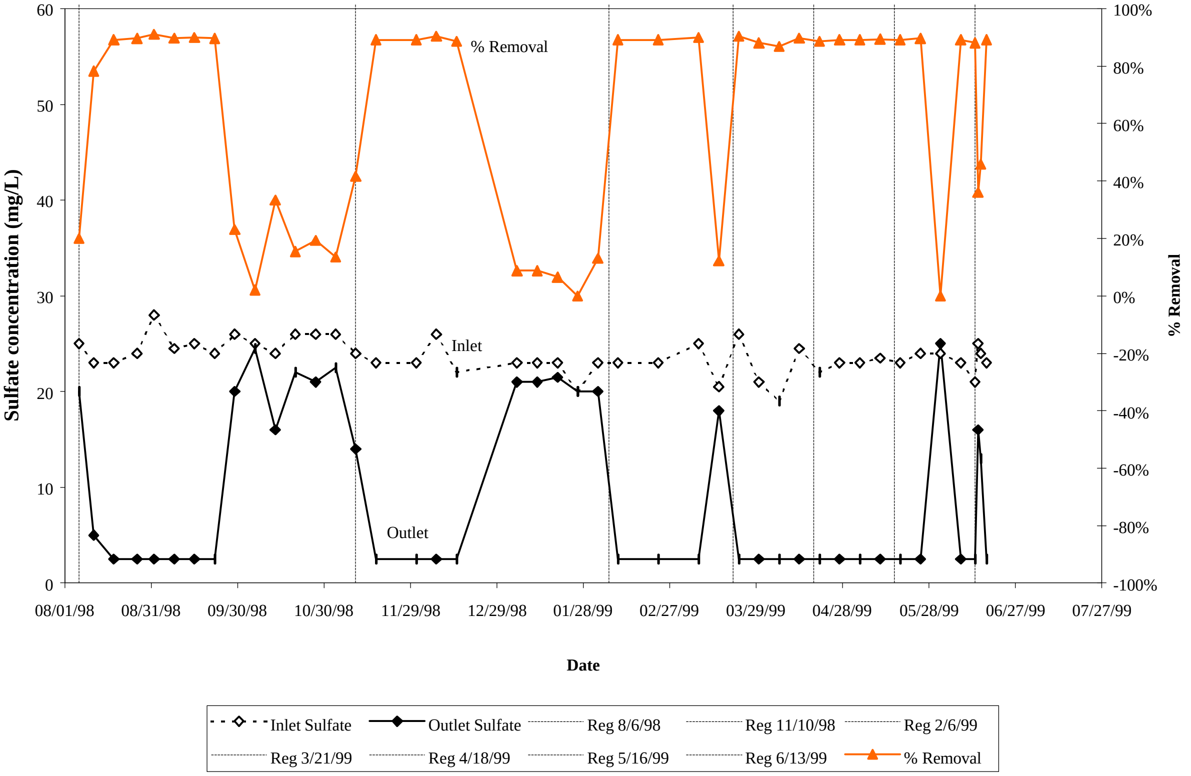


Figure 4-5. Inlet and Outlet Sulfate Concentrations and Percent Removal at Plant A

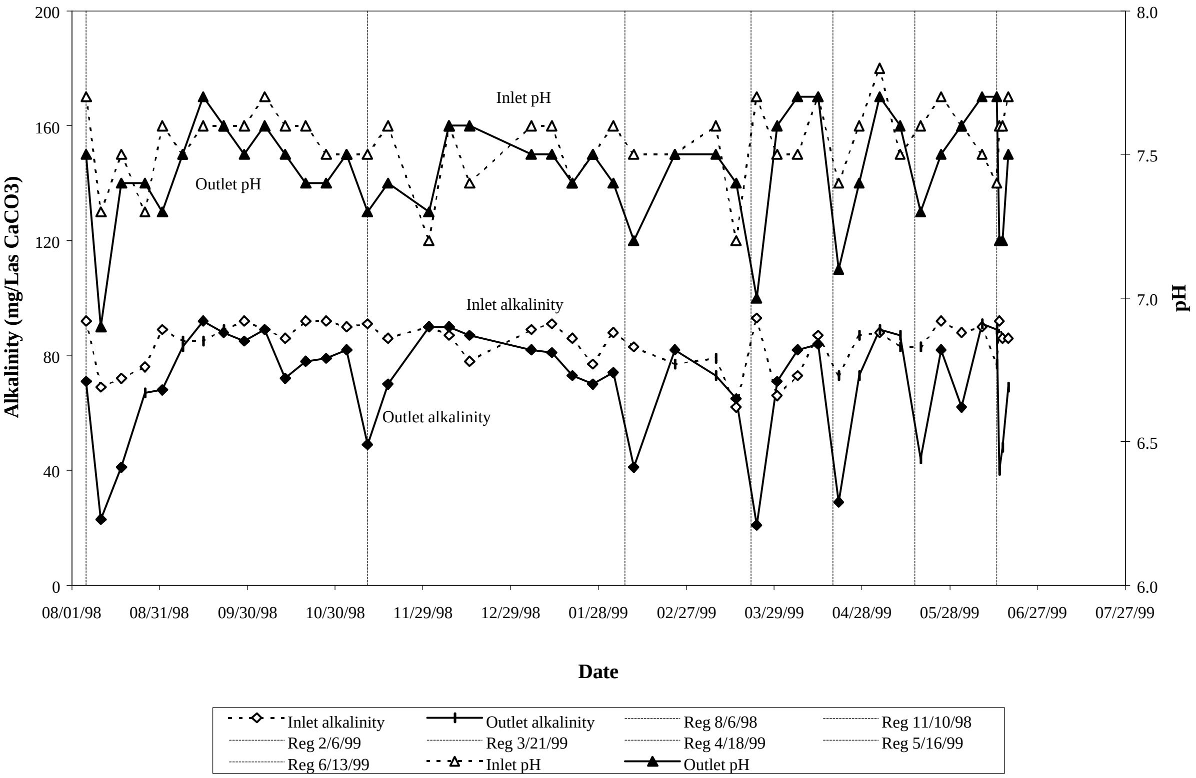


Figure 4-6. Inlet and Outlet pH and Alkalinity Analytical Results at Plant A

regeneration, slow rinse, and fast rinse). Analytical results of these sampling events are summarized in Table 4-8. As expected, the majority of arsenic was eluted from the column during the brine regeneration; the arsenic concentrations ranged from 1.83 to 38.5 mg/L with an average of 15.6 mg/L. The arsenic concentrations in the elutes from the backwash, slow rinse, and fast rinse averaged 59.4, 1,332, and 108 µg/L, respectively. The arsenic concentrations along with the respective volumes were used to calculate the mass of arsenic recovered from the regeneration to determine the regeneration efficiency (to be discussed in Section 4.2.4.4). The elevated pH value observed during the brine regeneration is presumably due to the elution of bicarbonate ions from the resin column.

4.2.5 Special Study at Plant A

During June 12 to 14, 1999, a special study was performed to evaluate the regeneration efficiency and to determine the quantity and chemical characteristics of the regeneration residuals.

Figure 4-7 plots total arsenic, TDS, and sulfate concentrations vs. time during the regeneration process. For the first 24 minutes during backwash and the initial stage of brining, all three parameters stayed at low levels. Afterwards, TDS concentrations increased sharply and reached a maximum level of 26.1 mg/L. Meanwhile, sulfate concentrations jumped from about 20 mg/L to as high as 24 g/L. Arsenic also was eluted with sulfate; arsenic concentrations increased sharply from less than 1 mg/L to more than 77 mg/L. Figure 4-7 also seems to indicate that arsenic was easier to elute than sulfate, most likely due to the selectivity reversal in the high-ionic strength (>1 M) environment (Clifford, 1999). The ease of regeneration is a strong point in favor of IX as compared to AA.

Figure 4-8 indicates that a flowrate of 3.0 gpm was applied to the backwash and fast rinse, which is lower than the 5 gpm specified in the service manual, and that approximately 1 gpm was maintained during the brine regeneration and slow rinse. The pH of the eluate was close to neutral (~7.5) during backwash, increased to up to pH 9.0 after the introduction of the brine solution, and returned to neutral by the end of the process. Again, the change in the pH value is probably related to bicarbonate desorption from the column.

Table 4-8. Summary of Analytical Results from Backwash/Regeneration Samples at Plant A (August 6, 1998 to June 13, 1999)

Parameter	Units	Number of Sample Events	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
Backwash						
pH	—	5	7.2	7.6	7.4	0.1
TSS	mg/L	5	6.0	24.0	14.0	8.5
Total As	µg/L	5	28.9	74.4	59.4	18.5
Total Al	µg/L	5	86.4	847	432	325
Total Fe	µg/L	5	264	1,982	1,102	733
Total Mn	µg/L	5	15.3	59.8	40.2	19.4
Brine Rinse						
pH	—	5	8.1	8.9	8.5	0.3
TSS	mg/L	5	6.0	13.0	9.0	2.9
Total As	µg/L	5	1,830	38,522	15,623	15,109
Total Al	µg/L	5	5.5	28.0	20.5	8.9
Total Fe	µg/L	5	43.5	445	207	153
Total Mn	µg/L	5	2.3	3.4	3.0	0.5
Slow Rinse						
pH	—	5	7.6	8.7	8.1	0.4
TSS	mg/L	4	0.5	22.0	9.6	10.2
Total As	µg/L	5	253	3,060	1,332	1,084
Total Al	µg/L	5	13.5	236	65.2	96.3
Total Fe	µg/L	5	15.0	1,567	336	688
Total Mn	µg/L	5	1.6	42.0	12.6	16.6
Fast Rinse						
pH	—	5	7.0	8.4	7.7	0.5
TSS	mg/L	5	0.5	4.0	1.2	1.6
Total As	µg/L	5	6.9	356	108	141
Total Al	µg/L	5	5.5	30.3	13.5	10.0
Total Fe	µg/L	5	3.7	15.0	11.8	5.0
Total Mn	µg/L	5	1.3	9.5	4.7	3.8

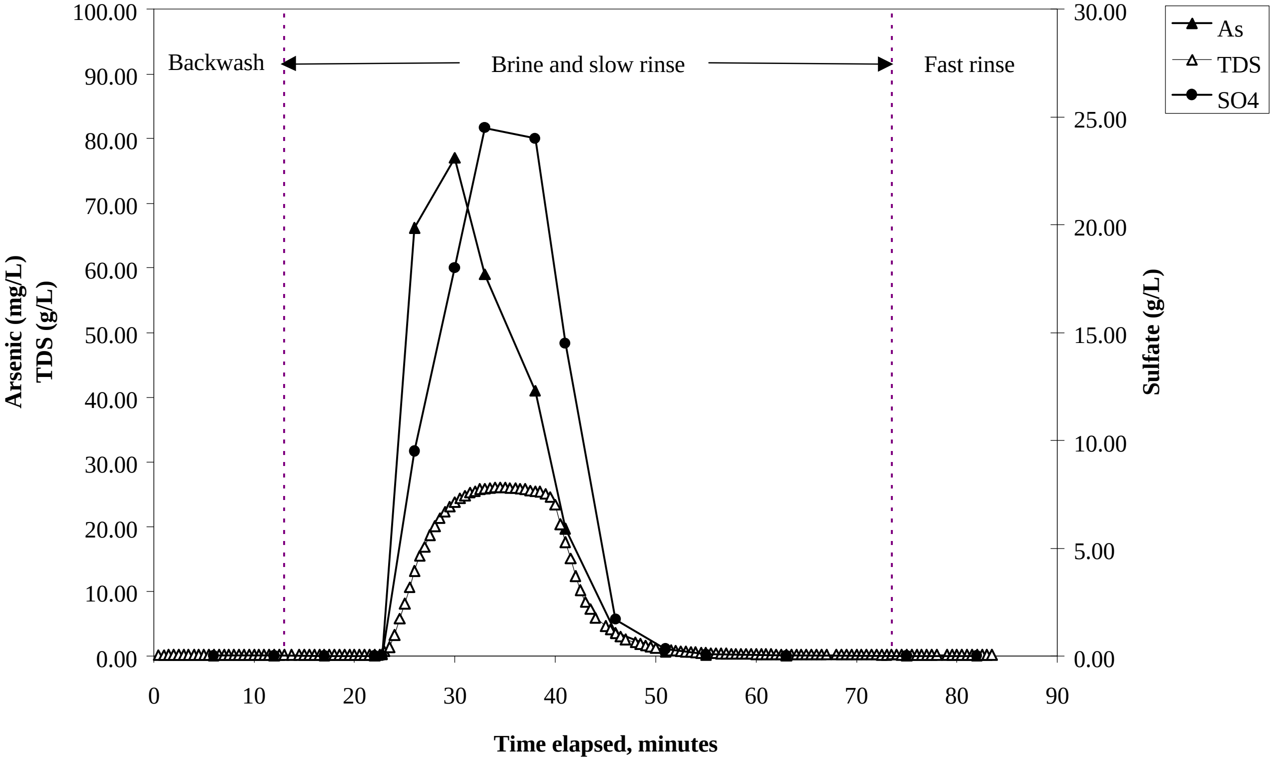


Figure 4-7. TDS, Total Arsenic, and Sulfate during the IX System Regeneration at Plant A (June 13, 1999)

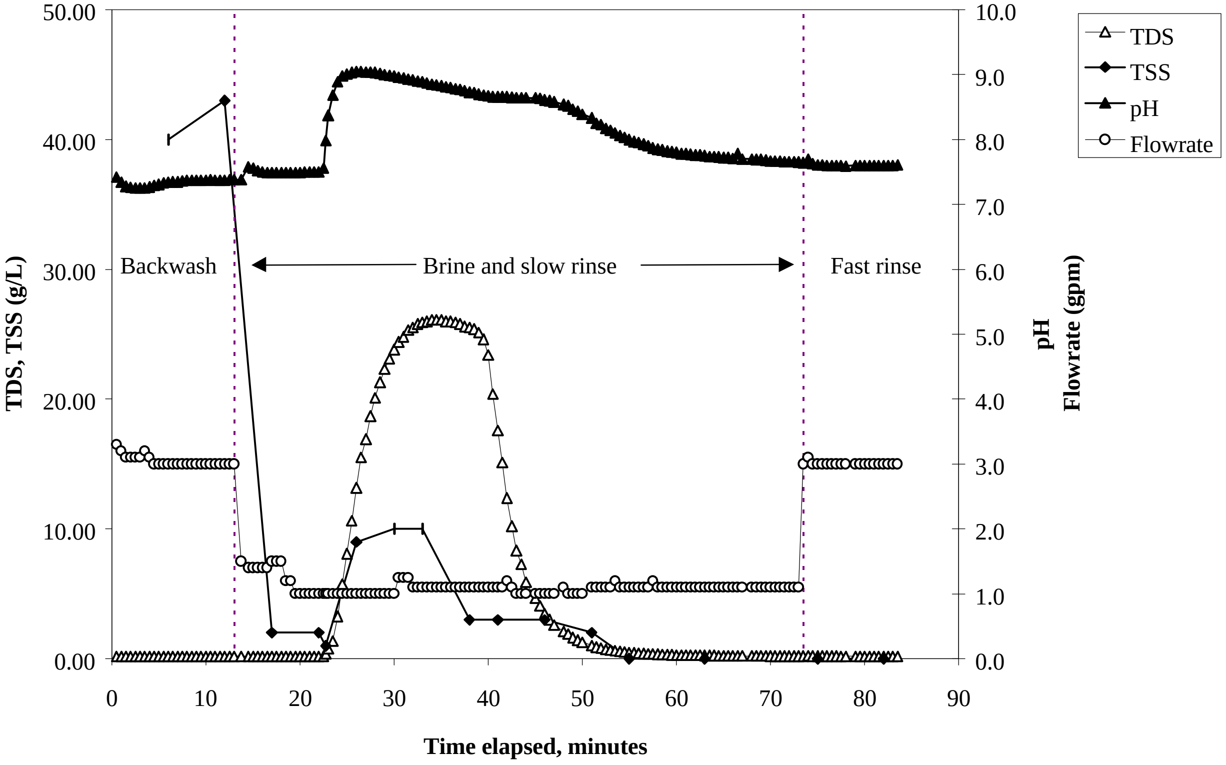


Figure 4-8. TDS, TSS, pH, and Flowrate during the IX System Regeneration at Plant A (June 13, 1999)

Based on the water usage data and arsenic concentrations in the inlet and outlet, the mass of arsenic removed from the raw water was estimated and is presented in Table 4-9 (see data listed under June 13, 1999). Furthermore, the amount of arsenic recovered from the regeneration also was calculated using the arsenic concentrations and the volume of the eluate from each regeneration step. The percent recoveries of arsenic calculated by Equation 3-1 were 71.9-78.5%. Substituting the arsenic for sulfate, the percent recovery of sulfate was 78.7%.

Table 4-9 also presents the percent recoveries of arsenic from previous regeneration events. Excluding the data of March 21, 1999, the percent recoveries ranged from 66.5% to 85.5% with an average of approximately 75%. This average value is somehow lower than the reported values (85-100%) (Clifford, 1999), which could be due to aged resin or the grab sampling.

4.3 Plant B

Water samples were collected and analyzed at Plant B, an IX plant, during the following three phases of the study: source water sampling, preliminary sampling, and long-term evaluation. Source water sampling at Plant B was performed in June 1998. Preliminary sampling consisted of weekly water sampling for a 4-week period in August 1998 and was designed to determine if the sampling locations and proposed water quality analysis were appropriate for the third phase, long-term evaluation. The third phase was initiated in September 1998 and continued through June 1999. Arsenic speciation sampling was conducted every fourth week. Backwash/regeneration sample collection and analysis were not performed at Plant B due to lack of information on the automatic regeneration schedule.

4.3.1 Plant B Description

Plant B supplies water to approximately 35 employees of a medical facility. The water source is a 260-ft-deep bedrock well drilled in October 1995. The capacity of this well is 2 gpm based on a 48-hr pump test. The water treatment system treats approximately 800 gpd.

During this test, arsenic and gross alpha radiation levels in the well water were found to exceed maximum regulatory levels required by the EPA (Table 4-10). Gross alpha in source water was remeasured at 31.00 pCi/L on December 28, 1995, and the concentration of total uranium (U-234 and U-238) was measured at 27.72 pCi/L. Subtracting the concentration of total uranium from the concentration of gross alpha leaves a level of 3.28 pCi/L, which falls under the 5 pCi/L MCL for gross alpha radiation. Although treatment for gross alpha radiation was determined to be unnecessary, a system capable of treating both the arsenic and gross alpha was installed by Norlen's Water Treatment Service at Orrington, ME, in March 1996.

Plant B uses an oxidizing filter followed by a cation-anion mixed-bed filtration system. Figure 4-9 is a schematic diagram of the treatment process used, which consists of the following major elements:

- **Intake.** Raw water is pumped from a 260-ft-deep bedrock well and flows through a pressure tank.
- **Oxidizing Filter.** An MN1054AF oxidizing filter tank was installed after the pressure tank to oxidize possible As(III) to As(V). The oxidizing filter tank is a 54-inch-long and 10-inch-diameter fiberglass tank with automatic control valves. An MnO_2-based material is used as the oxidizing medium and is regenerated by potassium permanganate solution.
- **Ion Exchange System.** After passing through the oxidizing filter, water flows into an LAT-32 IX tank filled with both cation and anion exchange resins. The IX tank has the same size as the oxidizing filter and the resin bed is 1.5 ft^3 (containing both cation and anion resins). At a design flow of 2 gpm, the hydraulic loading rate to the filter is 3.7 gpm/ft^2

Table 4-9. Percent Recoveries of Arsenic during the Resin Regeneration at Plant A

Date	Volume of Water Treated (gal)	Volume of Water Treated (BV)	As Removed from Raw Water[a] (mg)	As Recovered from Regeneration[b] (mg)	Percent Recovery (%)
3/21/99	49,000	3,275	6,200	1,091	17.6
4/18/99	42,600	2,848	5,260	3,496	66.5
5/16/99	49,500	3,309	6,099	5,212	85.5
6/13/99	53,500	3,576	5,931	4,262 4,654[c]	71.9 78.5
Average	48,650	3,250	—	—	74.6[d]

(a) Expressed as $M_{removed}$ in Equation 3-1.
(b) Expressed as $M_{recovered}$ in Equation 3-1.
(c) Calculation was based on grab sample data.
(d) Excluded data of 3/21/99.

Table 4-10. Typical Source Water Quality Data at Plant B (November 12, 1995)

Parameter	Unit	Concentration
Turbidity	NTU	0.85
Fluoride	mg/L	1.77
pH	—	8.2
Hardness	mg/L[(a)]	39.9
Sodium	mg/L	13.9
Iron	mg/L	0.16
Arsenic	µg/L	52
Gross alpha	pCi/L	36.02

(a) Measured as $CaCO_3$.

and the EBCT is 5.6 min. Information on the type and volume of anionic resin was not available at the time of study. Figure 4-10 shows a photograph of the IX system.

- **Regeneration/Backwash.** The oxidizing filter is regenerated with potassium permanganate stored in a 1.5-ft^3 canister. The IX filter is regenerated with Softouch™, a potassium chloride-based regenerant, stored in a brine tank. Regeneration and backwash of both filters take place automatically once every 6 days. Detailed information on flowrates and durations of regeneration and backwash were unavailable. The spent regenerant and backwash wastewater are disposed of to the facility's septic tank.

The arsenic removal system (shown in Figure 4-10) is fully automatic. The total cost of the system, including installation, piping and fittings, 1-year supply of Softouch™, and 1-year service warranty, was $2,975.80 at the time of installation.

4.3.2 Initial Source Water Sampling

Plant B influent water is supplied by a 260-ft-deep bedrock well drilled in October 1995. Table 4-10 presents the source water quality data on samples collected after the well installation. As can be seen, the arsenic concentration in the source water exceeded the 0.05 mg/L arsenic MCL. The source water arsenic was not speciated.

A site visit to Plant B was conducted on June 9, 1998 to collect source water samples. During this sampling event, samples were collected for arsenic [total, particulate, soluble, As(III), As(V)] and various other water quality parameters that may affect arsenic removal. Table 4-11 presents the analytical results from the source water sampling. These results are similar to those of the previous sampling events shown in Table 4-10. The total arsenic concentration in the source water averaged 55.0 µg/L; of this, approximately 0.8 µg/L was particulate arsenic and 0.8 µg/L was As(III). The majority of the soluble arsenic was As(V). This speciation information suggests that the oxidizing step of the Plant B treatment system is unnecessary. The inlet total iron concentrations averaged 150 µg/L. Aluminum concentrations were less than the detection limit, and manganese concentrations averaged 20 µg/L.

Alkalinity concentrations averaged 62.5 mg/L (as $CaCO_3$) and total hardness concentrations averaged 36 mg/L (as $CaCO_3$). This low hardness concentration suggests that the softening function of the cation resin seems unnecessary. Turbidity concentration was relatively low, averaging 0.45 NTU and the pH averaged 8.3. Sulfate concentrations averaged 45.5 mg/L, which was higher than the sulfate level in the raw water at Plant A.

4.3.3 Preliminary Sampling

During the preliminary sampling phase, only the inlet and outlet samples were collected because of the lack of a sampling tap between the oxidizing filter and the IX filter. The inlet sample was collected from a tubing connecting to the inlet piping to the system. A sink faucet was used for the outlet sampling. The sampling locations and the associated sample analyses are shown on Figure 4-9.

Alkalinity, sulfate, turbidity, pH, total hardness, nitrate-nitrite, total Al, total Fe, total Mn, and total arsenic analyses were performed on all water samples collected. Arsenic speciation sampling was conducted at the two sampling locations once during the preliminary study. Arsenic form (soluble and particulate) and species (arsenate and arsenite) were determined as part of the arsenic speciation. Table 4-12 presents the results of the 4-week preliminary sampling period.

Results from the preliminary sampling events indicated that inlet total arsenic concentrations ranged from 53.2 to 57.1 µg/L, and were consistently higher than the arsenic MCL. As found during the source water sampling, the total arsenic in the source water was primarily As(V), and contained only little or no As(III) or particulate arsenic. Except for the week of August 11, 1998, the average total arsenic removal was more than 95%, leaving less than 1.0 µg/L arsenic in the finished water. The finished water in August 11, 1998 had an abnormally high total arsenic concentration (16.8 µg/L), hardness concentration (24 mg/L as $CaCO_3$), pH (10.1), and turbidity (1.9 mg/L). The reason for these abnormal results was not clear. It was suspected that the samples might have been contaminated.

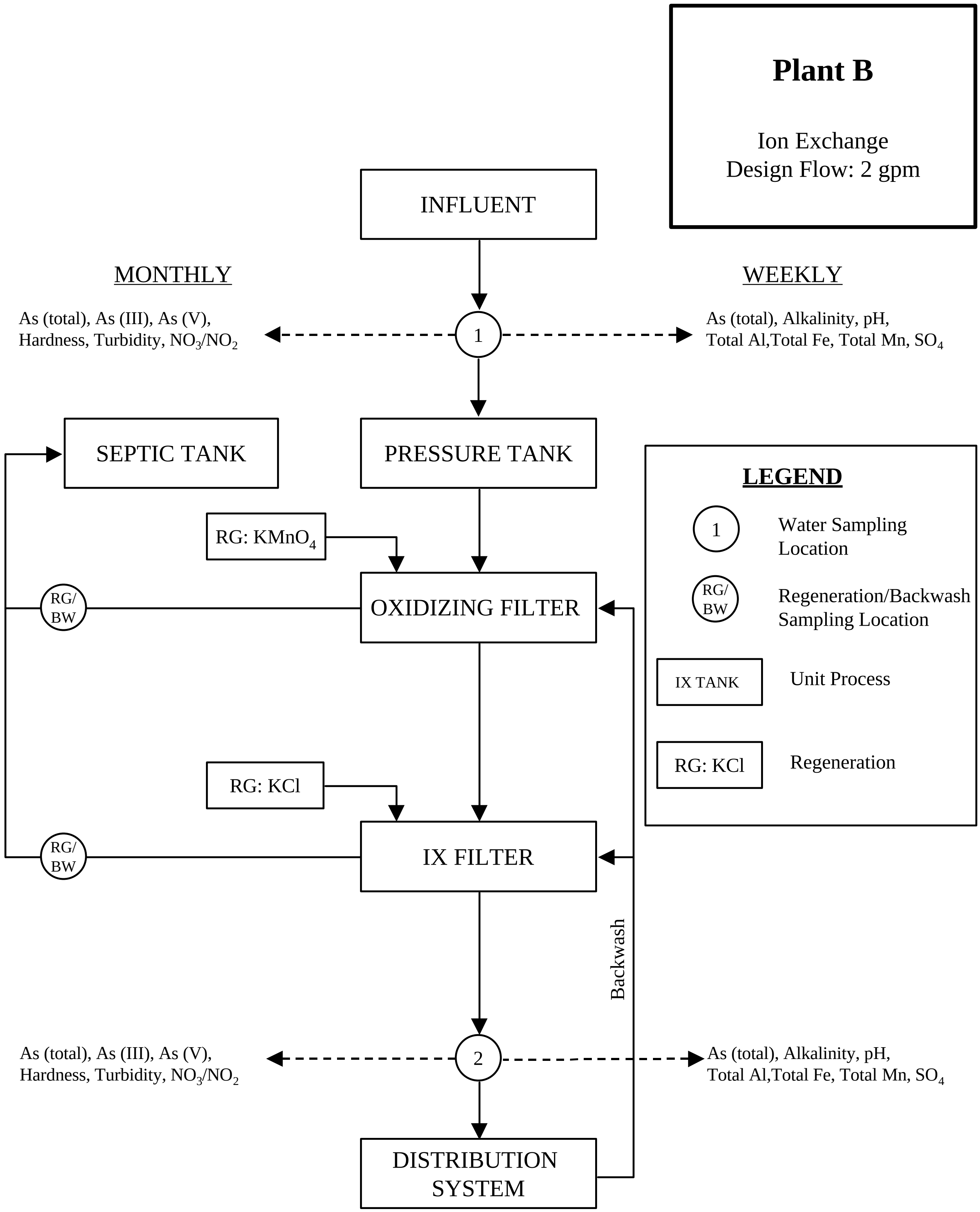


Figure 4-9. Process Flow Diagrams and Sampling Locations at Plant B

Figure 4-10. Photograph of the IX System at Plant B

Table 4-11. Source Water Analytical Results at Plant B (June 9,1998)

Parameter	Unit	Primary Sample	Duplicate Sample	Average Concentration
Alkalinity	mg/L[(a)]	63	62	62.5
Sulfate	mg/L	46	45	45.5
Turbidity	NTU	0.45	0.44	0.45
pH	—	8.3	8.3	8.3
Hardness	mg/L[(a)]	36	36	36
Ca Hardness	mg/L[(a)]	29.7	30	29.9
Mg Hardness	mg/L[(a)]	5.9	5.8	5.9
Total Al	µg/L	<400	<400	<400
Total Fe	µg/L	200	100	150
Total Mn	µg/L	30	<20	20
NO_3–NO_2 (N)	mg/L[(b)]	<0.02	<0.02	<0.02
TOC	mg/L	<1.0	<1.0	<1.0
As(total)	µg/L	53.8	56.2	55.0
As(total soluble)	µg/L	53.5	54.9	54.2
As(particulate)	µg/L	0.3	1.3	0.8
As(III)	µg/L	0.8	0.8	0.8
As(V)	µg/L	52.7	54.1	53.4

(a) As $CaCO_3$.

(b) Combined NO_3–N and NO_2–N.

Table 4-12. Analytical Results from Preliminary Sampling at Plant B (August 6 through 25, 1998)

		Sampling Date/Location							
		8/6/98		8/11/98		8/18/98		8/25/98	
Parameter	Units	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	63	27	64 64	34 34	65	12	64	17
Sulfate	mg/L	44	<5	47 48	<5 <5	44	<5	47	<5
Turbidity	NTU	0.3	<0.1	0.2 0.2	1.8 1.9	0.5	<0.1	–	–
pH	–	8.4	7.2	8.2 8.4	10.1 10.1	8.2	8.5	8.4	7.9
Total Hardness	mg/L(a)	33.8	<2.0	32.0 32.0	28.0 20.0	NS	NS	NS	NS
Ca Hardness	mg/L(a)	28.0	0.5	26.2 26.2	26.7 18.7	NS	NS	NS	NS
Mg Hardness	mg/L(a)	5.8	0.8	5.6 5.6	<0.8 <0.8	NS	NS	NS	NS
Nitrate-Nitrite	mg/L	<0.02	<0.02	0.02 0.02	0.04 0.02	NS	NS	NS	NS
As (total)	µg/L	53.2 56.6	0.8 1.1	57.1	16.8	54.7	0.8	54.1	0.9
As (total soluble)	µg/L	59.6 59.1	1.0 0.7	NS	NS	NS	NS	NS	NS
As (particulate)	µg/L	ND ND	ND 0.4	NS	NS	NS	NS	NS	NS
As (III)	µg/L	0.7 0.8	ND ND	NS	NS	NS	NS	NS	NS
As (V)	µg/L	58.9 58.3	0.9 0.7	NS	NS	NS	NS	NS	NS
Total Al	mg/L	23.1 14.6	3.2 9.1	31.2	28.2	17.8	25.1	24.2	21.9
Total Fe	µg/L	120 100	ND 2.5	88.2	78.8	105	9.4	98.6	2.4
Total Mn	µg/L	2.1 1.8	0.1 0.2	3.9	0.7	2.5	0.3	2.7	0.2
Dissolved Al	µg/L	1.7 2.7	1.5 1.7	NS	NS	NS	NS	NS	NS
Dissolved Fe	µg/L	ND ND	ND ND	NS	NS	NS	NS	NS	NS
Dissolved Mn	µg/L	1.2 1.2	0.1 0.1	NS	NS	NS	NS	NS	NS

(a) As $CaCO_3$.

Because Plant B uses a mixed resin bed, it removes both cations and anions from the source water. Total hardness was reduced to nondetect level. Alkalinity decreased from approximately 64 mg/L (as $CaCO_3$) at the inlet to 12-27 mg/L at the outlet, concurrent with the decreased pH values of the outlet samples. The inlet sulfate concentrations, ranging from 44 to 48 mg/L, were significantly reduced to less than the detection limit (5 mg/L) after treatment. Turbidity and nitrate-nitrite concentrations were extremely low in the raw water, so no significant changes were observed after the treatment. Total and dissolved Al, Fe, and Mn concentrations also were low in the raw water, and therefore, their effects on the process were insignificant.

4.3.4 Long-Term Sampling

Long-term sampling and analysis consisted of 36 weeks of water sampling at the same two locations used during the preliminary sampling phase (see Figure 4-9). All weekly samples were analyzed for alkalinity, sulfate, pH, total aluminum, total iron, total manganese, and total arsenic. Arsenic speciation sampling was conducted at each sampling location nine times during the long-term sampling phase on samples collected from each sampling location. Analysis included determination of hardness, nitrate-nitrite, and dissolved aluminum, iron, and manganese concentrations. Backwash and regeneration wastewater was not sampled due to lack of information on the automatic regeneration schedule. The following subsections summarize the analytical results of arsenic and other water quality parameters.

4.3.4.1 Arsenic

Table 4-13 provides a summary of the arsenic analytical results collected at the inlet and outlet sampling locations. Total arsenic concentrations at the inlet ranged from 40.8 to 64.5 µg/L with an average of 56.7 µg/L, which are comparable with the data collected during the previous phases of the study. Total arsenic concentrations at the outlet ranged from 0.8 to 4.5 µg/L with an average of 1.6 µg/L. Therefore, an average removal rate of 97% was achieved, corresponding well with the removal rates observed during the preliminary sampling phase. Figure 4-11 is a graph showing the total arsenic concentrations at both sampling locations throughout the study.

Particulate arsenic concentrations averaged 0.5 µg/L at the inlet and 0.3 µg/L at the outlet. As(III) concentrations averaged 0.8 µg/L in the raw water and 0.2 µg/L in the finished water. These results were consistent with those of the source water and preliminary sampling. As(V) concentrations averaged 56.7 µg/L in the raw water and 1.4 µg/L in the finished water. Therefore, As(V) made up the majority of the soluble arsenic, which suggests that the oxidizing filter may not be necessary; however, the filter can act as a safeguard against any occurrence of As(III).

Throughout the study, the IX system was able to consistently remove arsenic to <5 µg/L (or <2 µg/L at 90% of the time). The satisfactory performance of this treatment process is likely due to the frequent regeneration of the system. The maximum run length of the system (in terms of BV), however, might not have been reached before each regeneration cycle. The maximum run length was not estimated because of lack of information on the anion resin bed volume and water usage data.

4.3.4.2 Other Water Quality Parameters

Several other water quality parameters also were analyzed to provide information on the performance of the treatment plant. Table 4-14 summarizes the analytical results for the other water quality parameters obtained during the long-term sampling.

The inlet sulfate concentrations, ranging from 36 to 49 mg/L with an average of 44.5 mg/L, were consistently reduced to <5 mg/L after the treatment process. Figure 4-12 shows the inlet and outlet sulfate concentrations as well as removal percentages. Due to the frequent regeneration of the IX filter, the sulfate in the inlet water did not seem to impact the system performance for arsenic removal.

Figure 4-13 plots the inlet and outlet alkalinity and pH values throughout the study. Inlet alkalinity concentrations remained constant at levels of 62 to 65 mg/L (as $CaCO_3$). The alkalinity was removed through exchange of bicarbonate ions with the chloride ions on the resin. Inlet pH values were relatively constant throughout the duration of the study. The outlet pH values varied from 6.1 to 8.8 and were below the inlet pH values most of the time, presumably due to the removal of alkalinity. The elevated outlet pH did not seem to impact arsenic removal.

Turbidity and nitrate-nitrite concentrations were very low in the raw and finished water, and no significant changes were found after the treatment. Total and dissolved Al,

Table 4-13. Summary of Arsenic Analytical Results at Plant B (September 1, 1998 to May 25, 1999)

Parameter	Sampling Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	Inlet	µg/L	45	40.8	64.5	56.7	4.6
	Outlet	µg/L	45	0.8	4.5	1.6	0.7
As (total soluble)	Inlet	µg/L	18	43.9	62.7	57.4	5.5
	Outlet	µg/L	18	0.9	2.9	1.7	0.7
As (particulate)	Inlet	µg/L	18	0.1	1.6	0.5	0.6
	Outlet	µg/L	18	0.1	1.2	0.3	0.4
As(III)	Inlet	µg/L	18	0.4	1.3	0.8	0.3
	Outlet	µg/L	18	0.1	0.6	0.2	0.2
As(V)	Inlet	µg/L	18	43.2	62.0	56.7	5.6
	Outlet	µg/L	18	0.8	2.6	1.4	0.6

One-half of the detection limit was used for nondetect samples for calculations.
Primary and duplicate samples were averaged for calculation.

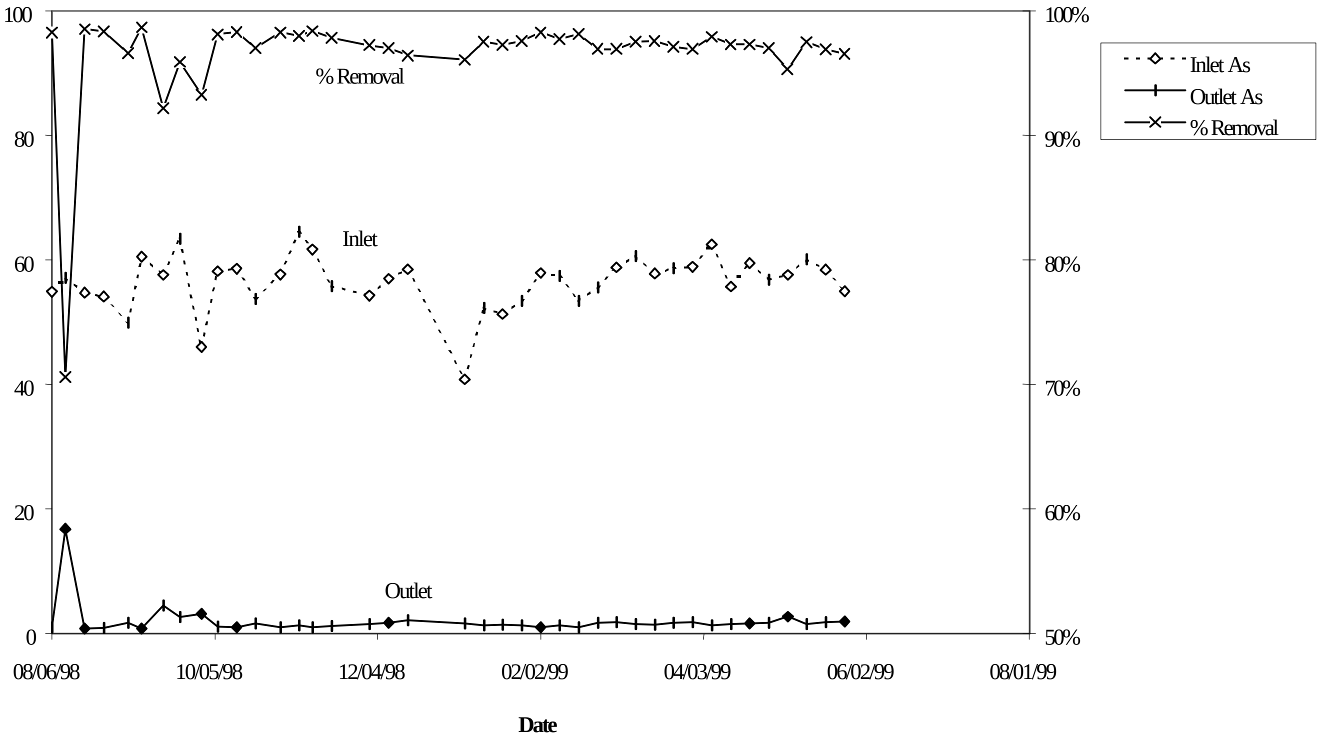


Figure 4-11. Total Arsenic Analytical Results during Long-Term Sampling at Plant B

Table 4-14. Summary of Water Quality Parameter Analytical Results at Plant B (September 1, 1998 to May 25, 1999)

Parameter	Sampling Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
Alkalinity	Inlet	mg/L	45	62	65	63.8	0.7
	Outlet	mg/L	45	3	17	8.2	3.8
Sulfate	Inlet	mg/L	45	36	49	44.5	2.4
	Outlet	mg/L	45	<5	<5	<5	0
Turbidity	Inlet	NTU	18	<0.1	0.6	0.4	0.2
	Outlet	NTU	18	<0.1	0.2	0.1	0.1
pH	Inlet	—	45	7.8	8.6	8.3	0.1
	Outlet	—	45	6.1	8.8	7.3	0.9
Total Hardness	Inlet	mg/L	18	33.0	46.7	38.4	4.3
	Outlet	mg/L	18	<2.0	8.3	2.1	2.5
Nitrate-Nitrite	Inlet	mg/L	18	<0.02	0.06	0.03	0.02
	Outlet	mg/L	18	<0.02	0.03	0.01	0.01
Total Al	Inlet	µg/L	45	<11	68.3	15.2	13.3
	Outlet	µg/L	45	<11	131	12.9	21.1
Total Fe	Inlet	µg/L	45	<30	139	69.5	39.7
	Outlet	µg/L	45	<30	72.7	21.5	14.0
Total Mn	Inlet	µg/L	45	<0.5	3.6	2.1	0.8
	Outlet	µg/L	45	<0.5	5.5	0.5	0.9
Dissolved Al	Inlet	µg/L	18	<11	21.8	7.3	5.4
	Outlet	µg/L	18	<11	10.4	6.0	1.6
Dissolved Fe	Inlet	µg/L	18	<30	113.5	35.1	35.9
	Outlet	µg/L	18	<30	31.2	16.8	5.4
Dissolved Mn	Inlet	µg/L	18	1.4	2.8	2.0	0.5
	Outlet	µg/L	18	<0.5	<0.5	<0.5	0

One-half of the detection limit was used for nondetect samples for calculations.
Primary and duplicate samples were averaged for calculations.

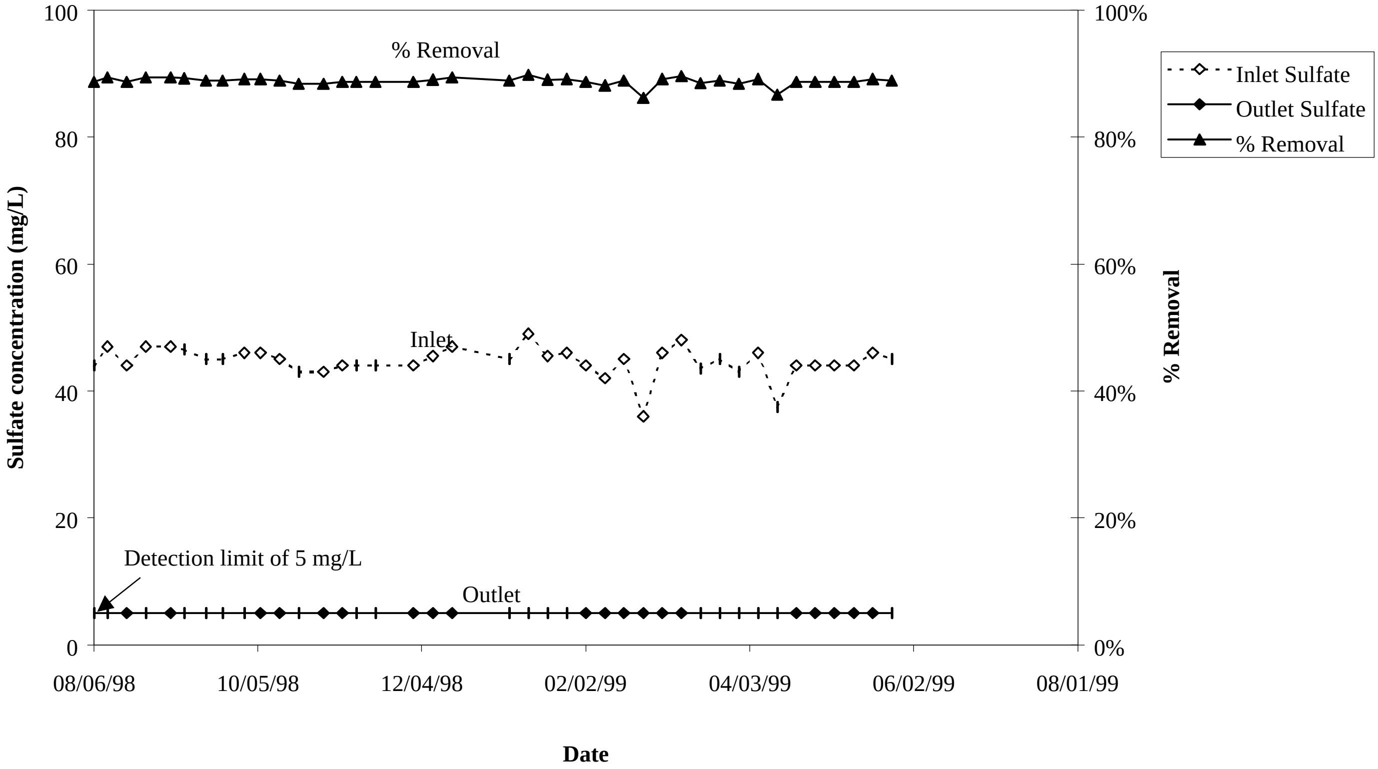


Figure 4-12. Inlet and Outlet Sulfate Analytical Results and Percent Removal at Plant B

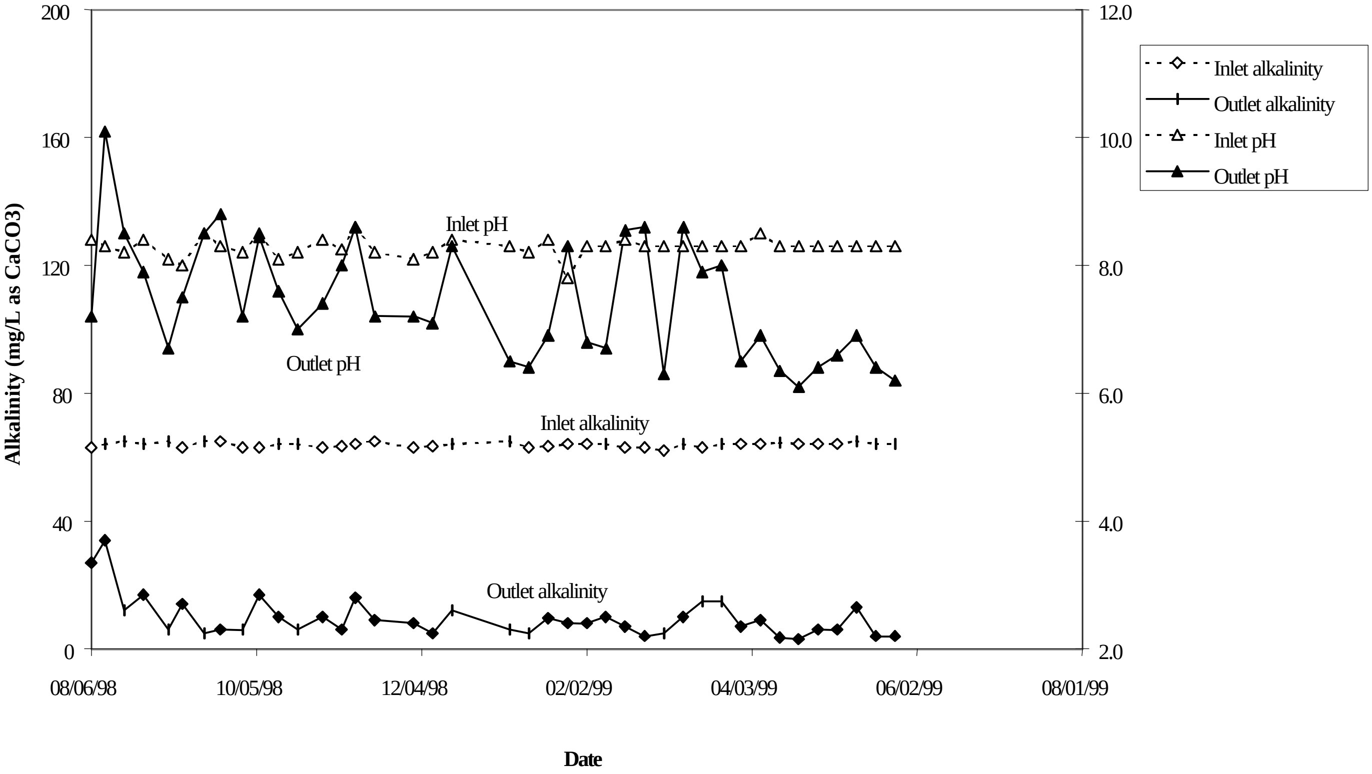


Figure 4-13. Inlet and Outlet Alkalinity and pH Analytical Results at Plant B

Fe, and Mn concentrations were low in the raw water, so their effects on the arsenic removal process were minimal.

4.4 Plant C

Water samples were collected and analyzed at Plant C, an AA plant, during the following three phases of the study: initial source water sampling (June 10, 1998), preliminary sampling (August 5 through September 16, 1998), and long-term sampling (September 30, 1998 through June 9, 1999). Water sampling was performed biweekly during the preliminary and long-term sampling. Arsenic speciation sampling was conducted during the initial source water sampling, once during preliminary sampling, and once every 8 weeks during the long-term sampling. Spent AA samples were collected once from two roughing tanks during AA change-out on December 29, 1998.

4.4.1 Plant C Description

Plant C supplies water to a school used by approximately 600 students and teachers. The ADD of the school is approximately 2,000-2,500 gpd. The AA system was installed by Aqua Specialties of Northwood, NH, in August 27, 1997 with a design flowrate of 14 gpm. Figure 4-14 is a schematic of the AA system.

As shown on Figure 4-14, Plant C consists of four AA tanks that are arranged as two parallel sets of two tanks in series. Figure 4-15 shows a cross section of an AA tank. The first set of the tanks (TA1 and TA2) are used as roughing filters and the second set (TB1 and TB2) are used as polishing filters. The major elements of the treatment process are described as follows:

- **Intake.** Raw water is supplied by a 700-ft-deep well and flows through the water system control room. A water flowmeter was installed to measure the volume of water entering the treatment system.
- **Cartridge Filters.** Two Ametek "Big Blue" cartridge filters were installed in parallel on the raw water header to remove particles from the well water. The cartridge filters are approximately 9¾ inches tall and 5 inches in diameter. The nominal rating of the cartridge is 30 µm.
- **Activated Alumina Tanks.** After passing through the cartridge filters, the filtered water splits into the two AA treatment trains. Gate valves exist to isolate each train and control the split ratio; however, no water meter is available on either train to confirm the exact split ratio. Each fiberglass mineral tank (52 inches tall by 16 inches in diameter) contains approximately 4 ft^3 of Alcoa DD-2 AA. The depth of the AA bed is approximately 33 inches, leaving a free board distance of approximately 9 inches between the top header and the top of the medium. The AA medium/gravel support interface material is approximately 6 inches above the floor. The influent flows downward through the AA bed and the treated water returns to the top of the tank through a 1-inch polyvinyl chloride (PVC) riser tube. The differential pressure across the medium was approximately 3 psi.

  Alcoa DD-2 (14 × 28 mesh) is a successor of F-1 AA. Typical physical and chemical properties of this medium are presented in Table 4-15, and the material safety data sheet (MSDS) is attached in Appendix C.2. At a design flowrate of 7 gpm (assuming water is split evenly into each train), the hydraulic loading rate to each tank is 5.0 gpm/ft^2 and the EBCT is 4.3 minutes.
- **Media Replacement.** The AA system at Plant C is operated on a media-throwaway basis. When the AA medium in the roughing filters reaches its arsenic removal capacity, the spent AA is removed and replaced with virgin medium. The polishing filters are moved to the roughing filter position by physically repositioning the filters. The tanks with the new virgin medium then are placed in the polishing position. The AA in all four tanks was virgin in September 1997. The AA in the two roughing tanks (TA1 and TA2) was replaced with virgin AA on December 29, 1998 due to arsenic breakthrough. Also on that date, tanks TB1 and TB2 were moved to the roughing positions and the recharged TA1 and TA2 were moved to the polishing positions.
- **Backwash.** Backwash is not performed on a routine basis. Since their installation, the AA tanks have been backwashed only twice with the pressurized treated water. Backwash of TA1 was performed during Battelle's visit on August 5, 1998 and lasted for approximately 5 minutes at a flowrate of 3 gpm. Backwash wastewater was disposed of to the school's leach field.
- **Storage Tank.** The treated water from each train is combined and flows to a 15,000-gal steel storage tank buried outside the school building. The storage tank invert is at an elevation of approximately 20 ft above the school's floor grade. Water in the storage tank also serves the school's fire sprinkler system. Before distribution, the treated water is pressurized by two Flint & Walling 2-horsepower (hp) centrifugal booster pumps buffered by four 119-gal pressure tanks.

Quarterly sampling for arsenic has been conducted by a plant staff since March 1996 on raw water, between the

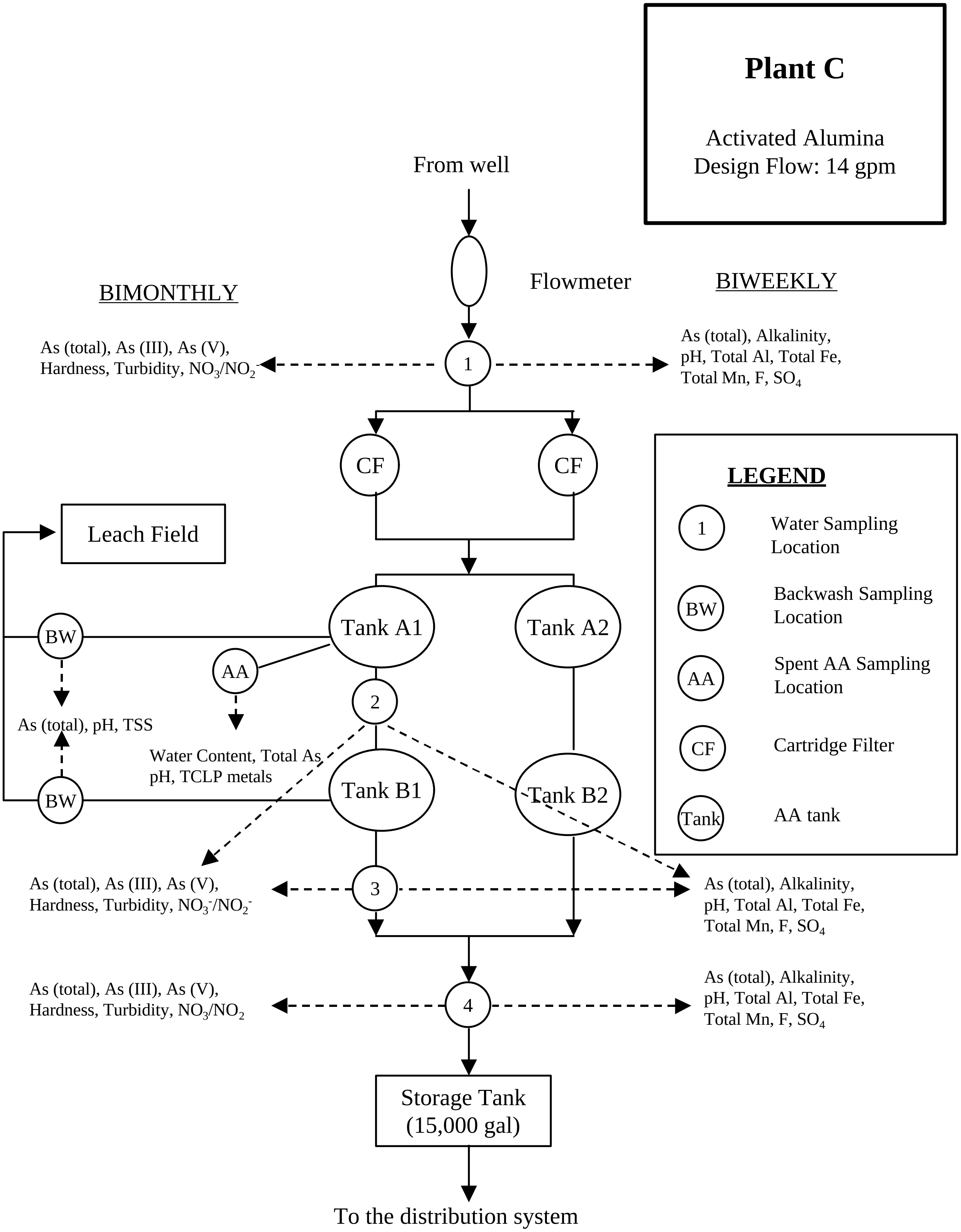
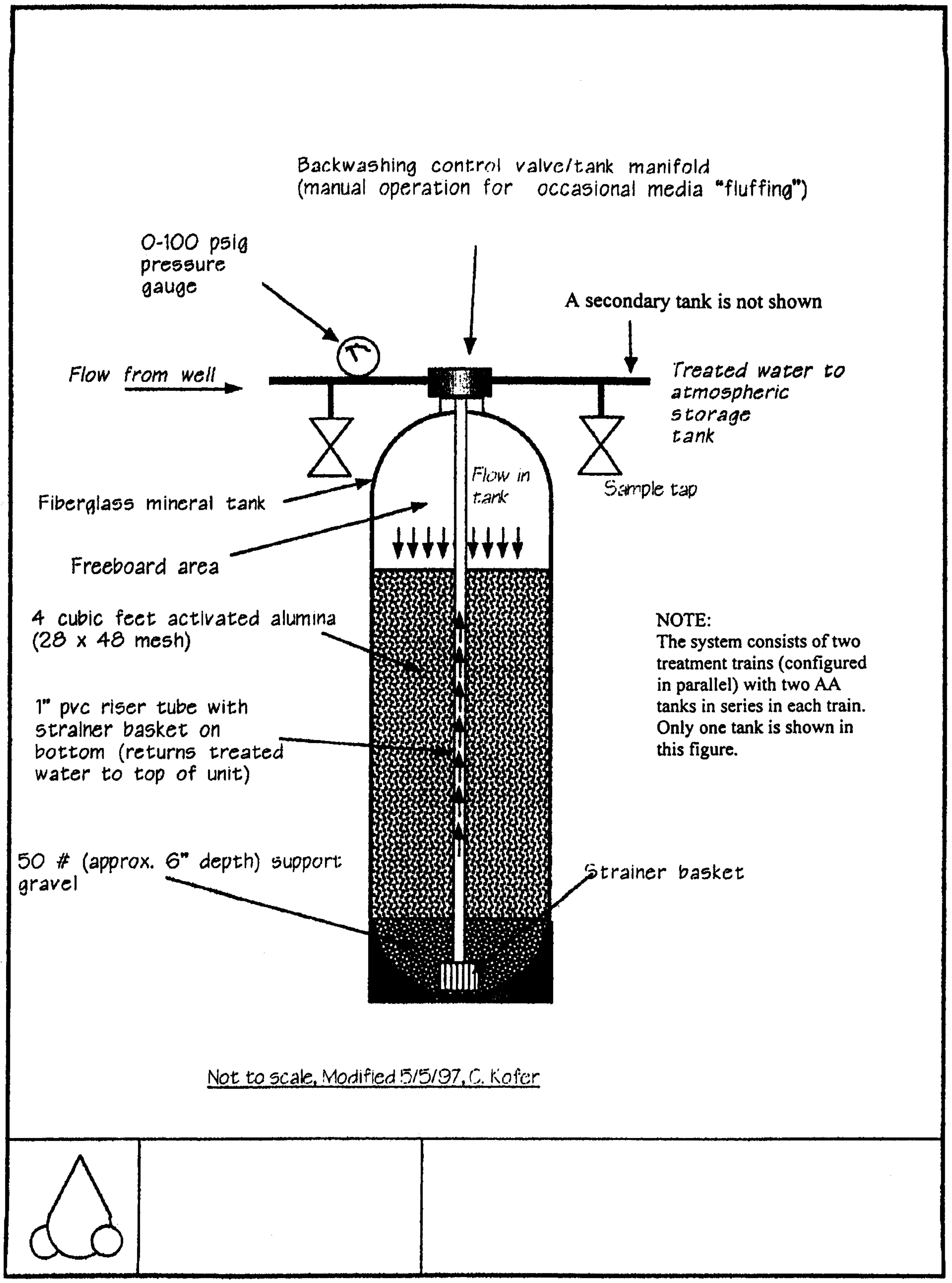


Figure 4-14. Process Flow Diagrams and Sampling Locations at Plant C



NOTE:
The system consists of two treatment trains (configured in parallel) with two AA tanks in series in each train. Only one tank is shown in this figure.

Figure 4-15. Cross Section of AA Tank at Plant C (Source: Aqua Specialties, 1999)

Table 4-15. Typical Characteristics of DD-2 Activated Alumina

Physical Characteristics	DD-2 AA (14x28 mesh)
Appearance (color, shape)	White, granule
Surface area, m^2/g	250
Total pore volume, cc/g	0.395
Total porosity, %	56.2
Bulk density, kg/m^3	620-830
Abrasion loss, wt%	1.6
Chemical Composition (wt%)	
Al_2O_3	92.2
Na_2O	0.90
Fe_2O_3	0.08
SiO_2	0.09
Loss on ignition (Water)	6.5
Alumina XRD phase	Amorphors, boehmite, and gamma
Price, \$/lb	1.01

roughing and the polishing tanks in each train, and from treated water. The arsenic concentration data are summarized in Table 4-16. The data show that the arsenic concentrations in samples collected between TA2 and TB2 on October 13, 1998 reached the 0.05 mg/L arsenic MCL, indicating arsenic breakthrough in TA2. Water usage data have been recorded since the AA system installation and are attached in Appendix C.3.

Table 4-16. Arsenic Concentrations (µg/L) from Quarterly Water Sampling at Plant C

Date	Raw Water	A1B1[(a)]	A2B2[(b)]	Treated Water
03/11/96	37	—	—	—
06/13/96	46	—	—	—
9/18/96	47	—	—	—
11/12/96	50	—	—	—
02/11/97	50	—	—	—
06/11/97	42	—	—	—
08/12/97	37	—	—	—
08/14/97	—	—	—	<5
08/27/97[(c)]	—	—	—	13
10/23/97	78	—	—	<5
1/15/98	—	12	20	<10
04/23/98	—	16	17	<10
08/04/98	—	33	36	7
10/13/98	—	—	50	17
01/08/99	43	37	29	5

(a) Water collected from a tap between TA1 and TB1.
(b) Water collected from a tap between TA2 and TB2.
(c) The AA system was installed.
— = No data collected.

4.4.2 Initial Source Water Sampling

Source water for Plant C is supplied by a 700-ft-deep bedrock well (drilled in 1994) through a submersible pump (Model No. 13GS20). The capacity of this well is 12-14 gpm based on a 48-hr continuous pump test. Source water quality measurements on samples collected on December 30, 1994 are presented in Table 4-17. The historic quarterly sampling data shown in Table 4-16 indicate significant variation in raw water arsenic concentrations, which ranged from 37 to 78 µg/L. These concentrations were close to or exceeded the arsenic MCL. Information on arsenic speciation was unknown prior to this study.

Table 4-17. Source Water Quality Measurements at Plant C (December 30, 1994)

Parameter	Unit	Concentration
Alkalinity	mg/L[(a)]	105
Turbidity	NTU	<1.0
Fluoride	mg/L	1.91
Chloride	mg/L	4.0
Sulfate	mg/L	23
pH	—	8.3
Hardness	mg/L[(a)]	52.2
Sodium	mg/L	38.4
Specific Conductance	µmhos/cm	259
Arsenic	µg/L	42

(a) Measured as $CaCO_3$.

On June 10, 1998, an initial site visit to Plant C was conducted and source water samples were collected. The analytical results as presented in Table 4-18 are consistent with previous plant sampling data shown in Table 4-17. The total soluble arsenic concentration was relatively high, averaging 61.9 µg/L. Approximately 30% of the soluble arsenic existed as As(III) (18.1 µg/L) and the rest was As(V) (43.8 µg/L). Particulate arsenic was not detected in the raw water.

4.4.3 Preliminary Sampling

During the preliminary sampling phase of this study, water samples were collected at four locations: (1) at the inlet; (2) after the roughing tank of train 1 (TA1); (3) after the polishing tank of train 1 (TB1); and (4) at the combined effluent of trains 1 and 2. Sampling taps were available at all four sampling locations. Sampling locations and sample analyses are indicated on Figure 4-14.

Preliminary sampling consisted of biweekly sample collection and analysis of various parameters (alkalinity, turbidity, pH, hardness, fluoride, sulfate, total arsenic, total

Table 4-18. Source Water Sampling Analytical Results at Plant C (June 10, 1998)

Parameter	Units	Primary Sample	Duplicate Sample	Average
Alkalinity	mg/L[(a)]	86	82	84
Fluoride	mg/L	1.5	1.5	1.5
Sulfate	mg/L	26	26	26
Turbidity	NTU	1.27	0.28	0.78
pH	—	8.1	8.1	8.1
Hardness	mg/L[(a)]	50.2	53.7	52.0
Ca Hardness	mg/L[(a)]	31.7	35.2	33.5
Mg Hardness	mg/L[(a)]	18.5	18.5	18.5
Total Al	µg/L	ND	ND	ND
Total Fe	µg/L	110	100	105
Total Mn	µg/L	100	90	95
NO_3–NO_2 (N)	mg/L[(b)]	0.06	0.04	0.05
TOC	mg/L	1.3	1.1	1.2
As (total)	µg/L	60.0	58.0	59.0
As (total soluble)	µg/L	61.4	62.5	61.9
As (particulate)	µg/L	ND	ND	ND
As (III)	µg/L	18.1	18.2	18.1
As (V)	µg/L	43.3	44.3	43.8

(a) As $CaCO_3$.
(b) Combined NO_3–N and NO_2–N.

Al, total Fe, and total Mn analyses). Arsenic speciation sampling was conducted once on samples collected from inlet and TA1 locations. Table 4-19 presents the results of the biweekly preliminary sampling events.

Similar to the results of historic quarterly sampling, inlet total arsenic concentrations varied significantly, ranging from 21.3 to 56.1 µg/L. During the arsenic speciation sampling on August 5, 1998, the inlet water contained an average of 5.9 µg/L As(III), which is lower than the concentration measured during the source water sampling (18.1 µg/L). Most As(III) was removed by the roughing filter, as indicated by the As(III) concentrations (1.1 µg/L) measured after the roughing filter. Particulate arsenic was not measured at significant levels in any of the samples collected during preliminary sampling.

During the first sampling event on August 5, 1998, the roughing filter removed close to 50% of the total arsenic from the raw water. However, the total arsenic concentrations after the roughing filter approached or was over the influent levels during two subsequent sampling events (i.e., August 19 and September 16, 1998), which indicated the exhaustion of the AA medium in the roughing filter. Regardless of the arsenic breakthrough from the roughing filter, the polishing filter still was able to reduce arsenic concentrations to low levels (e.g., 1.6 to 9.3 µg/L). The combined treated water from both trains had total arsenic concentrations ranging from 2.8 to 11.6 µg/L.

Fluoride concentrations ranged from 1.1 to 1.6 mg/L in the raw water and 1.3 to 1.6 mg/L in the finished water. Therefore, fluoride was not removed by the AA tanks. Similarly, sulfate concentrations remained relatively constant at 22 to 27 mg/L throughout the treatment process. Fluoride is known to be a major competing ion with arsenate for adsorption sites on AA surface, especially in an optimal pH range of 5.5-6.0. Sulfate also has some affinity for the AA surface (see Section 1.1.3.2). Removal of sulfate and fluoride by AA was not observed during these sampling events, thus confirming AA's higher order of preference for arsenate. Other factors such as high pH values of the inlet water and near-exhaustion AA capacity, also might have contributed to the low reduction of sulfate and fluoride. Clifford et al. (1986) reported that the addition of 360 mg/L sulfate and 1,000 mg/L TDS decreased the As(V) adsorption on AA by almost 50%. Vagliasindi et al. (1996) found that arsenate adsorption was insensitive to sulfate concentrations in the range of 0 to 100 mg/L. Therefore, sulfate concentrations in raw water were not high enough to significantly affect the As(V) removal. Alkalinity, total hardness, and nitrate/nitrite remained relatively constant after the treatment.

Total aluminum concentrations slightly increased after the roughing and polishing tanks. The increase in aluminum concentration might have resulted from the dissolution of AA medium. Total iron and manganese concentrations in the raw water were rather low and did not appear to impact arsenic removal.

Based on the results of the preliminary sampling, only minor changes were made to the approach for the long-term evaluation. Sampling locations and analytes remained unchanged. However, arsenic speciation was performed at all four locations during the long-term evaluation instead of just at the inlet and TA1 locations.

4.4.4 Long-Term Sampling

Biweekly long-term sampling and analysis was performed for 36 weeks (18 events) for alkalinity, fluoride, sulfate, turbidity, pH, hardness, nitrate-nitrite, total aluminum, total iron, total manganese, and total arsenic. Long-term sampling also included five arsenic speciation sampling events at each sampling location. The four sampling locations used during the preliminary sampling also were used during long-term sampling. Additionally, spent AA samples were collected once during AA replacement.

4.4.4.1 Arsenic

Table 4-20 summarizes the arsenic analytical results collected at the four sampling locations. Total arsenic concentrations at the inlet ranged from 34.4 to 76.0 µg/L with an average of 53.5 µg/L. These concentrations were consistent with the historic arsenic data (Table 4-16).

Table 4-19. Analytical Results from Preliminary Sampling at Plant C (August 5 through September 16, 1998)

		Sampling Date and Location															
		8/5/98				8/19/98				9/2/98				9/16/98			
		IN	TA1	TB1	OU	IN	TA1	TB1	OU	IN	TA1	TB1	OU	IN	TA1	TB1	OU
Alkalinity	mg/L[(a)]	72	69	77	67	69 66	72 70	75 84	65 66	71	81	82	80	87	88	88	87
Fluoride	mg/L	1.4	2.0	1.5	1.5	1.1 1.2	1.3 1.3	1.4 1.4	1.3 1.3	1.2	1.3	1.4	1.4	1.6	1.6	1.6	1.6
Sulfate	mg/L	22	23	23	22	23 24	24 23	23 24	23 23	23	23	23	23	27	28	27	27
Turbidity	NTU	0.2	<0.1	<0.1	<0.1	0.3 0.3	<0.1 <0.1	<0.1 <0.1	<0.1 <0.1	–	–	–	–	–	–	–	–
pH	–	7.9	7.9	7.7	7.9	8.0 8.0	8.0 8.0	7.9 7.9	7.9 7.9	8.5	8.3	8.0	8.2	8.2	8.1	7.8	7.4
Total Hardness	mg/L[(a)]	54	51	54	50	–	–	–	–	–	–	–	–	–	–	–	–
Ca Hardness	mg/L[(a)]	35.5	33.5	35.7	31.7	–	–	–	–	–	–	–	–	–	–	–	–
Mg Hardness	mg/L[(a)]	18.3	17.9	18.3	17.8	–	–	–	–	–	–	–	–	–	–	–	–
NO_3-NO_2 (N)	mg/L[(b)]	0.1	0.1	<0.1	0.1	–	–	–	–	–	–	–	–	–	–	–	–
As (total)	µg/L	38.8 37.3	17.8 19.5	2.3 2.5	2.8 2.8	21.3	22.8	2.9	4.0	38.5	18.6	1.6	3.0	56.1	41.4	9.3	11.6
As (total soluble)	µg/L	37.1 35.4	19.7 21.2	–	–	–	–	–	–	–	–	–	–	–	–	–	–
As (particulate)	µg/L	1.7 1.9	<0.1 <0.1	–	–	–	–	–	–	–	–	–	–	–	–	–	–
As (III)	µg/L	7.0 4.8	0.2 2.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
As (V)	µg/L	30.1 30.6	19.5 19.2	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Total Al	µg/L	<11 14.8	33.0 29.7	48.6 45.2	30.5 29.4	19.0	34.4	41.6	32.8	18.6	38.5	41.8	39.2	29.5	36.9	33.2	37.9
Total Fe	µg/L	73.2 48.5	<30 30.1	49.8 59.9	<30 <30	70.0	<30	<30	<30	64.3	<30	<30	<30	50.6	<30	<30	<30
Total Mn	µg/L	95.1 88.1	77.2 78.8	71.9 75.0	76.3 75.0	112	83.1	88	77.2	88.8	90.8	85.3	93.3	67.6	78.1	76.9	78.6
Dissolved Al	µg/L	<11 <11	14.3 12.1	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Dissolved Fe	µg/L	<30 <30	<30 <30	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Dissolved Mn	µg/L	88.2 89.4	81.8 81.8	–	–	–	–	–	–	–	–	–	–	–	–	–	–

(a) Measured as $CaCO_3$.

(b) Combined NO_3 -NO_2 as N.

IN = inlet; TA1 = after Tank A1; TB1 = after Tank B1; OU = effluent.

– = No analysis performed.

Table 4-20. Summary of Arsenic Analytical Results at Plant C (September 30, 1998 to June 9, 1999)

Parameter	Sampling Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	Inlet	µg/L	23	34.4	76.0	53.5	9.4
	After 1st tank	µg/L	22	14.2	50.4	39.3	8.7
	After 2nd tank	µg/L	23	0.4	26.7	6.8	9.2
	Outlet	µg/L	23	1.3	21.8	7.2	6.8
As (total soluble)	Inlet	µg/L	10	42.3	63.6	54.9	8.1
	After 1st tank	µg/L	10	33.9	50.1	43.0	6.1
	After 2nd tank	µg/L	10	0.4	26.0	7.1	9.9
	Outlet	µg/L	10	1.8	18.6	6.8	6.5
As (particulate)	Inlet	µg/L	10	<0.1	13.4	5.1	6.2
	After 1st tank	µg/L	9	<0.1	<0.1	<0.1	0
	After 2nd tank	µg/L	10	<0.1	0.6	0.2	0.2
	Outlet	µg/L	10	<0.1	6.9	0.8	2.2
As (III)	Inlet	µg/L	10	<0.1	28.8	7.9	11.2
	After 1st tank	µg/L	10	0.3	9.1	3.0	3.3
	After 2nd tank	µg/L	10	0.1	2.6	0.6	0.8
	Outlet	µg/L	10	<0.1	1.9	0.7	0.7
As (V)	Inlet	µg/L	10	34.4	55.4	45.2	6.9
	After 1st tank	µg/L	10	33.6	48.3	39.9	6.4
	After 2nd tank	µg/L	10	<0.1	25.6	6.6	10.0
	Outlet	µg/L	10	<0.1	17.6	6.0	6.6

One-half of the detection limit was used for nondetect samples for calculations.
Primary and duplicate samples were averaged for calculations.
The first tank was TA1 before the medium change-out on December 29, 1998 and TB1 after the medium change-out.
The second tank was TB1 before the medium change-out on December 29, 1998 and TA1 after the medium change-out.

Samples collected after the roughing tank contained total arsenic of 14.2 to 50.4 µg/L with an average of 39.3 µg/L. Samples collected after the polishing tank contained total arsenic of 0.4 to 26.7 µg/L with an average of 6.8 µg/L. The combined treated water (i.e., outlet) had total arsenic concentrations ranging from 1.3 to 21.8 µg/L with an average of 7.2 µg/L. The average removal percentages were 26.5% and 87.3% by the roughing and polishing tanks, respectively. The average overall arsenic removal efficiency was 86.5% during the long-term sampling.

Figure 4-16 provides charts showing the fractions of the total arsenic concentration made up by particulate arsenic, As(III), and As(V) at each sampling location. The inlet water contained primarily the oxidized species of arsenic [i.e., As(V)] with various amounts of As(III) (0 to 45%) and particulate arsenic (0 to 22%). Particulate arsenic was only detected in the inlet water on September 30, 1998 and May 26, 1999 with concentrations averaging 12.8 and 11.8 µg/L, respectively. Because total iron concentrations in the inlet samples also were abnormally high, it was suspected that some arsenate might have clung to some iron particles, resulting in high particulate arsenic concentrations. Except for September 30, 1998, most particulate arsenic was removed by the system.

As(III) concentrations averaged 7.9 µg/L at the inlet, 3.0 µg/L after the roughing tank, 0.6 µg/L after the polishing tank, and 0.7 µg/L at the outlet location. Therefore, As(III) was almost completely removed by AA. Because no oxidative treatments were performed ahead of the AA columns, conversion of As(III) to As(V) was rather unlikely. The removal of As(III) would occur either through a direct sorption of As(III) or via some unexplained conversions of As(III) to As(V) prior to adsorption. Clifford and Lin (1984; 1991) had observed some unplanned oxidation of As (III) to As(V) within alumina columns, which resulted in better-than-expected performance for arsenic removal. Nonetheless, the adsorption of As(III) onto AA has been reportedly far less than that of As(V) (Vagliasindi, and Benjamin, 1997; Clifford, 1999). Therefore, arsenite should be oxidized to arsenate prior to AA treatment.

The average As(V) concentrations were 45.2 µg/L at the inlet, 39.9 µg/L after the roughing tank, 6.6 µg/L after the polishing tank, and 6.0 µg/L at the outlet location. The arsenic in the finished water consists almost entirely of As(V).

Figure 4-17 presents the total arsenic concentrations at each sampling location and the overall removal percentages for each sampling event. The data were plotted twice, with one graph showing the sampling date and the other showing the BV of the water treated. BV was calculated using the amount of water treated divided by the AA volume in each tank (4 ft^3 or 29.92 gallons).

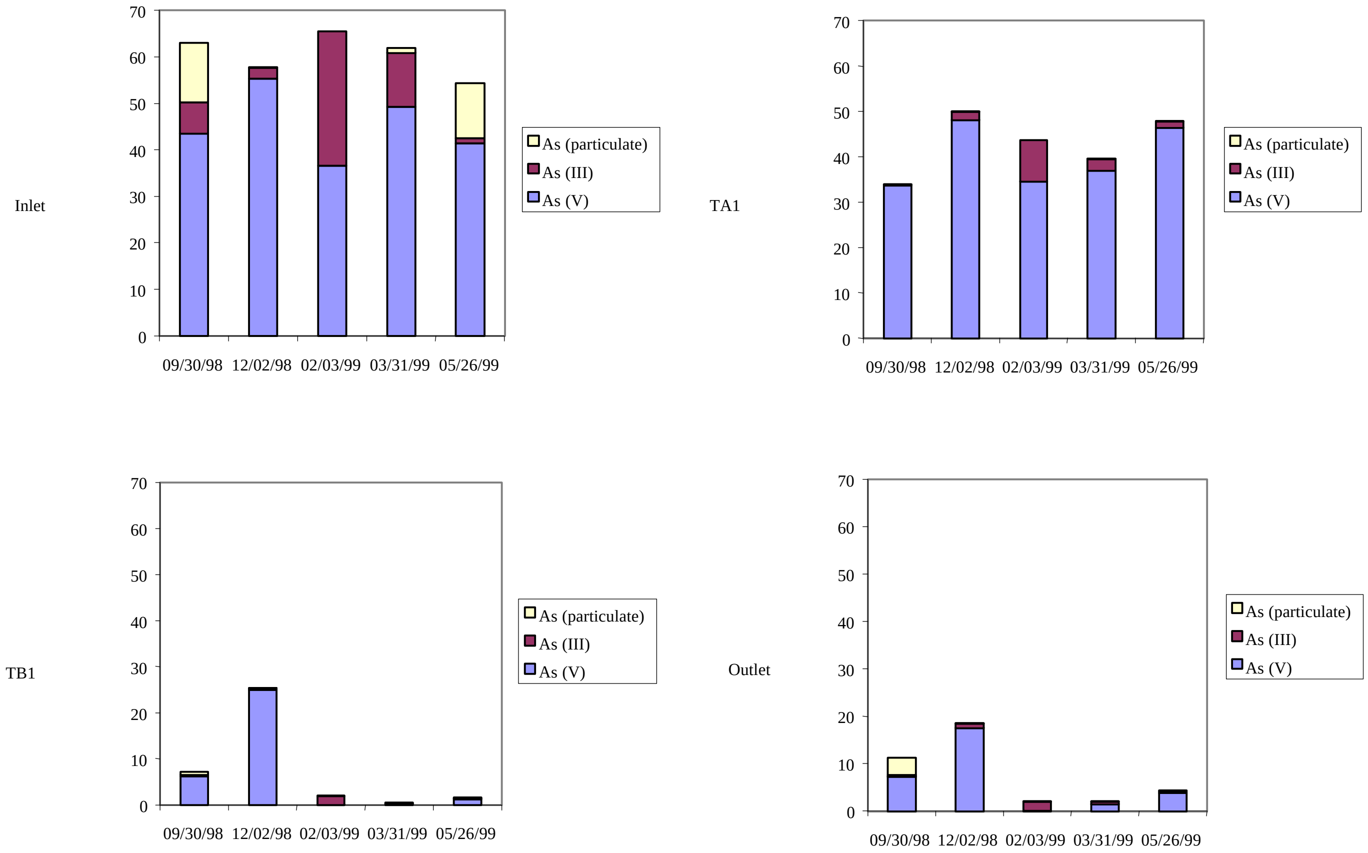


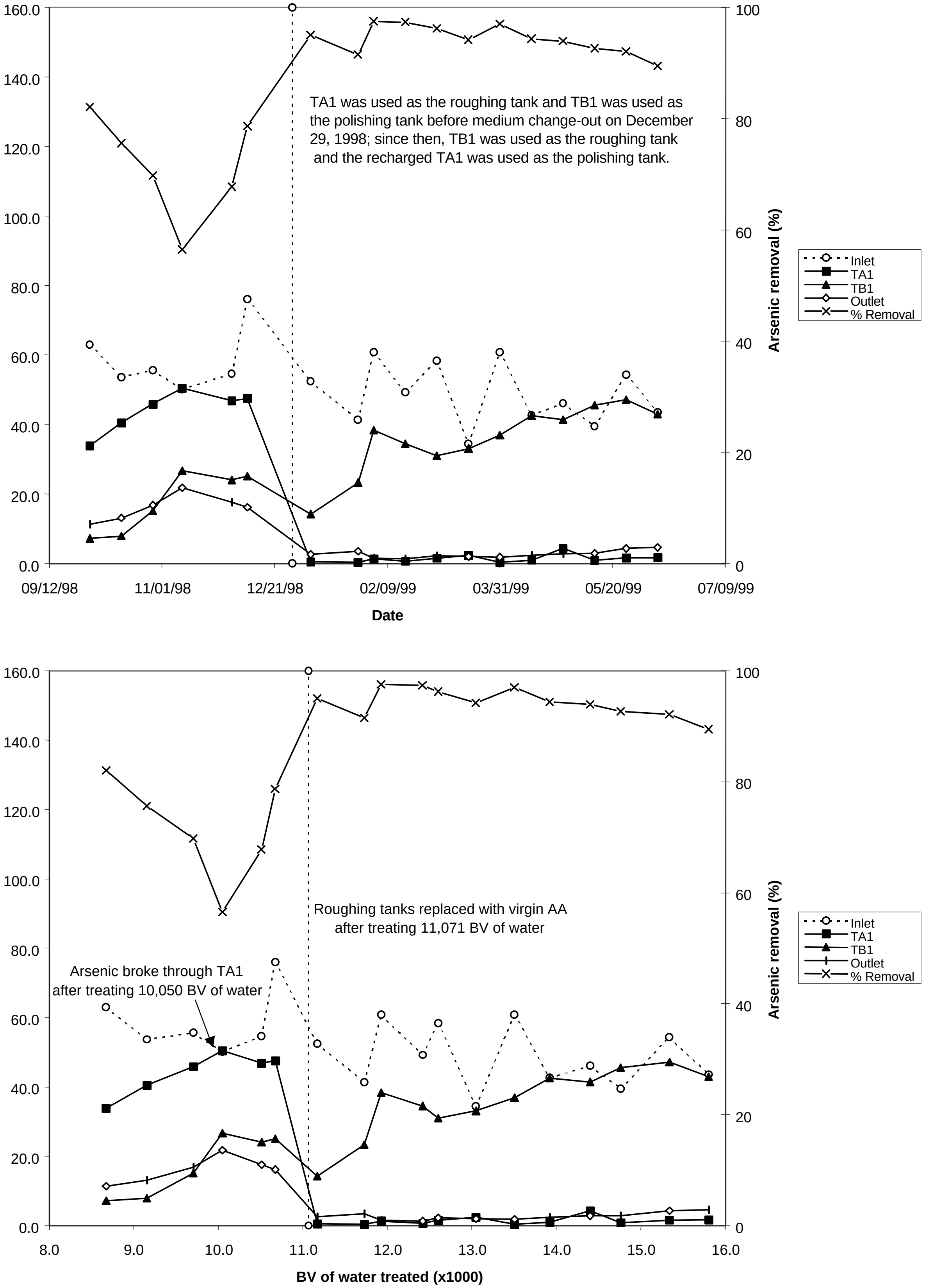
Figure 4-16. Arsenic Form and Species Analytical Results during Long-Term Sampling at Plant C

As shown in Figure 4-17, the AA capacity of TA1 (the roughing tank of train 1) was nearly exhausted after treating 10,050 BV of water. The plant record also indicated that arsenic breakthrough occurred in TA2 (the roughing tank of train 2) on October 13, 1998 after treating 9,156 BV of water (see Table 4-16). Therefore, both TA1 and TA2 were recharged with virgin AA and repositioned to become polishing tanks. TB1 and TB2 then were moved to the first position and used as roughing tanks. Within 1 to 2 weeks after the medium replacement and tank rearrangement, the total arsenic concentrations dropped to <20 µg/L after the roughing tank and <5 µg/L in the system effluent. Afterwards, the arsenic concentrations after the roughing tank gradually increased to inlet levels again, indicating arsenic breakthrough from the roughing tank (TB1). Nonetheless, the arsenic concentrations measured after the polishing tank were consistently below 5 µg/L.

To estimate the AA capacity for arsenic in TA1 and TA2, the following assumptions were made: (1) 9,600 BV of water were treated before arsenic breakthrough from TA1 and TA2; (2) 53.5 µg/L total arsenic were in the raw water (see Table 4-20); (3) 30.7 µg/L total arsenic were in TA1 and TA2 effluent (calculated based on available data from the plant record, preliminary sampling events, and long-term evaluation); and (4) the density of the AA was 730 kg/m^3 (see Table 4-15). Using the above assumptions, 49.6 g of total arsenic was removed from the raw water by the two roughing tanks prior to 50-µg/L arsenic breakthrough, equivalent to an AA capacity of 0.30 g/kg (219 g/m^3). This value is comparable to the AA capacity of 0.26 g/kg (to 50 µg/L arsenic breakthrough) reported by Fox (1989) in his study with a source water of pH 8.3 and containing 50 to 350 µg/L As(V). Clifford (1999) estimated the practically achievable column capacity based on pH 6.0 operation with a source water containing 100 µg/L As(V) to be 1,400 g As(V)/m^3 of alumina, which was much higher than the capacity obtained for Plant C. Because Plant C operated under less ideal conditions (i.e., higher pH), it would not be expected to achieve the same level of arsenic removal.

4.4.4.2 Other Water Quality Parameters

Sampling and analysis of other water quality parameters were performed to provide insight into the arsenic removal efficiency at the plant. Table 4-21 summarizes the analytical results for several water quality parameters obtained during long-term sampling at Plant C. Figure 4-18


TA1 was used as the roughing tank and TB1 was used as the polishing tank before medium change-out on December 29, 1998; since then, TB1 was used as the roughing tank and the recharged TA1 was used as the polishing tank.

Roughing tanks replaced with virgin AA after treating 11,071 BV of water

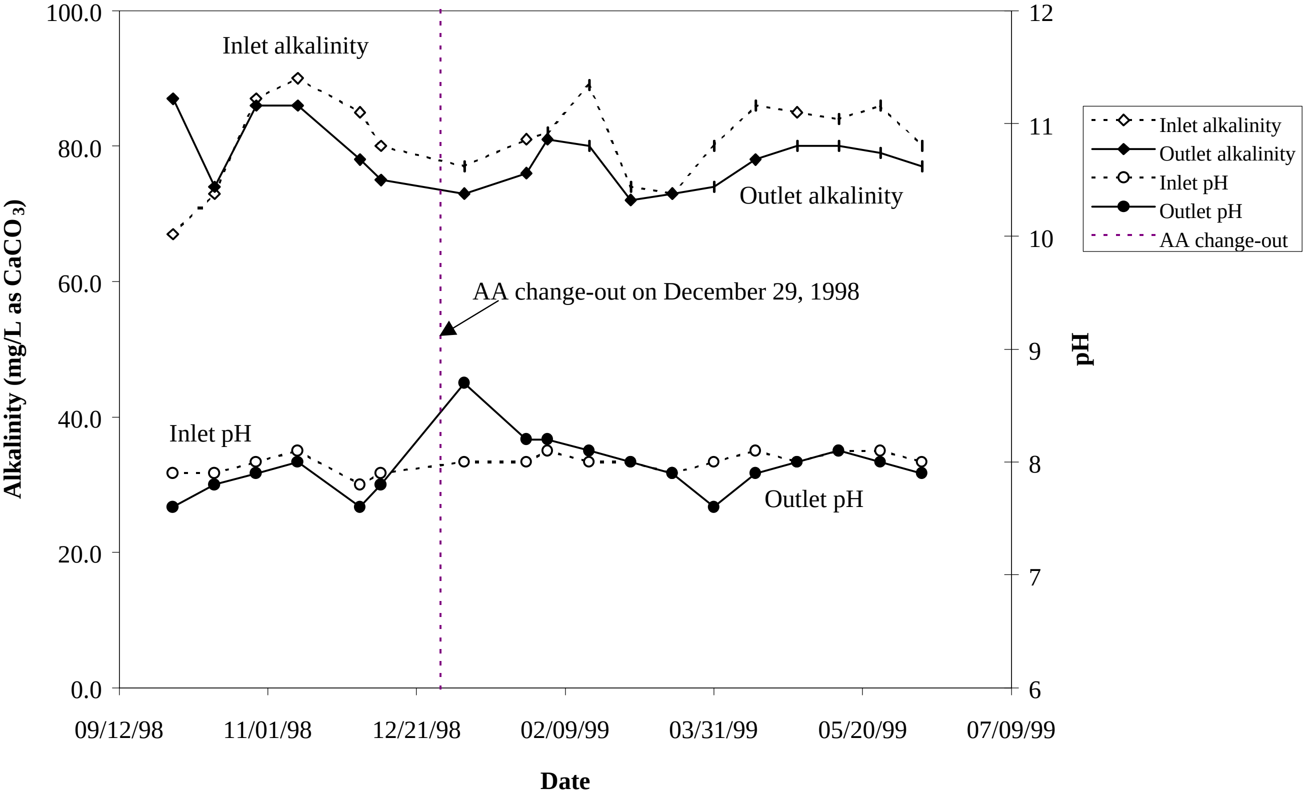
Arsenic broke through TA1 after treating 10,050 BV of water

Figure 4-17. Total Arsenic Analytical Results during Long-Term Sampling at Plant C

Table 4-21. Summary of Water Quality Parameter Analytical Results at Plant C (September 30, 1998 to June 9, 1999)

Parameter	Sampling Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
Alkalinity	Inlet	mg/L	23	67	90	81.1	6.3
	After 1st tank	mg/L	23	73	89	83.3	4.1
	After 2nd tank	mg/L	23	73	89	80.9	4.4
	Outlet	mg/L	23	72	87	78.3	4.6
Fluoride	Inlet	mg/L	23	1.2	1.6	1.4	0.11
	After 1st tank	mg/L	23	0.9	1.7	1.4	0.17
	After 2nd tank	mg/L	23	0.3	1.6	1.3	0.33
	Outlet	mg/L	23	0.2	1.6	1.2	0.36
Sulfate	Inlet	mg/L	23	22	27	25.2	1.2
	After 1st tank	mg/L	23	23	27	25.3	1.0
	After 2nd tank	mg/L	23	18	35	25.9	3.5
	Outlet	mg/L	23	19	29	25.2	2.1
Turbidity	Inlet	NTU	5	<0.1	0.3	0.14	0.11
	After 1st tank	NTU	5	<0.1	<0.1	<0.1	0
	After 2nd tank	NTU	5	<0.1	<0.1	<0.1	0
	Outlet	NTU	5	<0.1	0.15	0.07	0.04
pH	Inlet	—	23	7.8	8.1	8.0	0.1
	After 1st tank	—	23	7.8	8.1	7.9	0.07
	After 2nd tank	—	23	7.6	8.6	8.0	0.2
	Outlet	—	23	7.6	8.7	8.0	0.3
Total Hardness	Inlet	mg/L	5	47	57	52.4	4.6
	After 1st tank	mg/L	5	49	53	50.9	1.7
	After 2nd tank	mg/L	5	48	52	49.2	1.8
	Outlet	mg/L	5	48	53	50.3	1.8
NO_3-NO_2 (N)	Inlet	mg/L	5	0.01	0.1	0.04	0.03
	After 1st tank	mg/L	5	0.01	0.3	0.14	0.11
	After 2nd tank	mg/L	5	0.05	0.6	0.25	0.22
	Outlet	mg/L	5	0.02	1.3	0.31	0.55
Total Al	Inlet	µg/L	23	<11	97.4	18.3	21.1
	After 1st tank	µg/L	23	12.7	59	27.5	12.3
	After 2nd tank	µg/L	23	<11	109	29.4	24.2
	Outlet	µg/L	23	12.6	112	32.5	23.2
Total Fe	Inlet	µg/L	23	<30	178	53.4	49.0
	After 1st tank	µg/L	23	<30	60.5	20.0	12.4
	After 2nd tank	µg/L	23	<30	25.6	15.6	2.5
	Outlet	µg/L	23	<30	125	36.3	36.4
Total Mn	Inlet	µg/L	23	48.9	90.7	67.2	11.9
	After 1st tank	µg/L	23	30.4	88.7	69.2	17.9
	After 2nd tank	µg/L	23	1.9	87.9	55.2	25.9
	Outlet	µg/L	23	6.4	86	46.5	28.6
Dissolved Al	Inlet	µg/L	10	<11	<11	<11	0
	After 1st tank	µg/L	10	<11	15.1	10.5	3.6
	After 2nd tank	µg/L	10	<11	23.3	12.6	7.7
	Outlet	µg/L	10	<11	23.3	13.4	7.7
Dissolved Fe	Inlet	µg/L	10	<30	<30	15	0
	After 1st tank	µg/L	10	<30	<30	15	0
	After 2nd tank	µg/L	10	<30	<30	15	0
	Outlet	µg/L	10	<30	<30	22.6	17.1
Dissolved Mn	Inlet	µg/L	10	52.2	68.1	63.1	6.3
	After 1st tank	µg/L	10	30.2	81.3	67.2	21.4
	After 2nd tank	µg/L	10	16.0	76.3	56.2	24.6
	Outlet	µg/L	10	10.3	75.8	45.7	25.2

One-half of the detection limit was used for nondetect samples for calculations.
Primary and duplicate samples were averaged for calculations.
The 1st tank was TA1 before the medium change-out on December 29, 1998 and TB1 after the medium change-out.
The 2nd tank was TB1 before the medium change-out on December 29, 1998 and TA1 after the medium change-out.



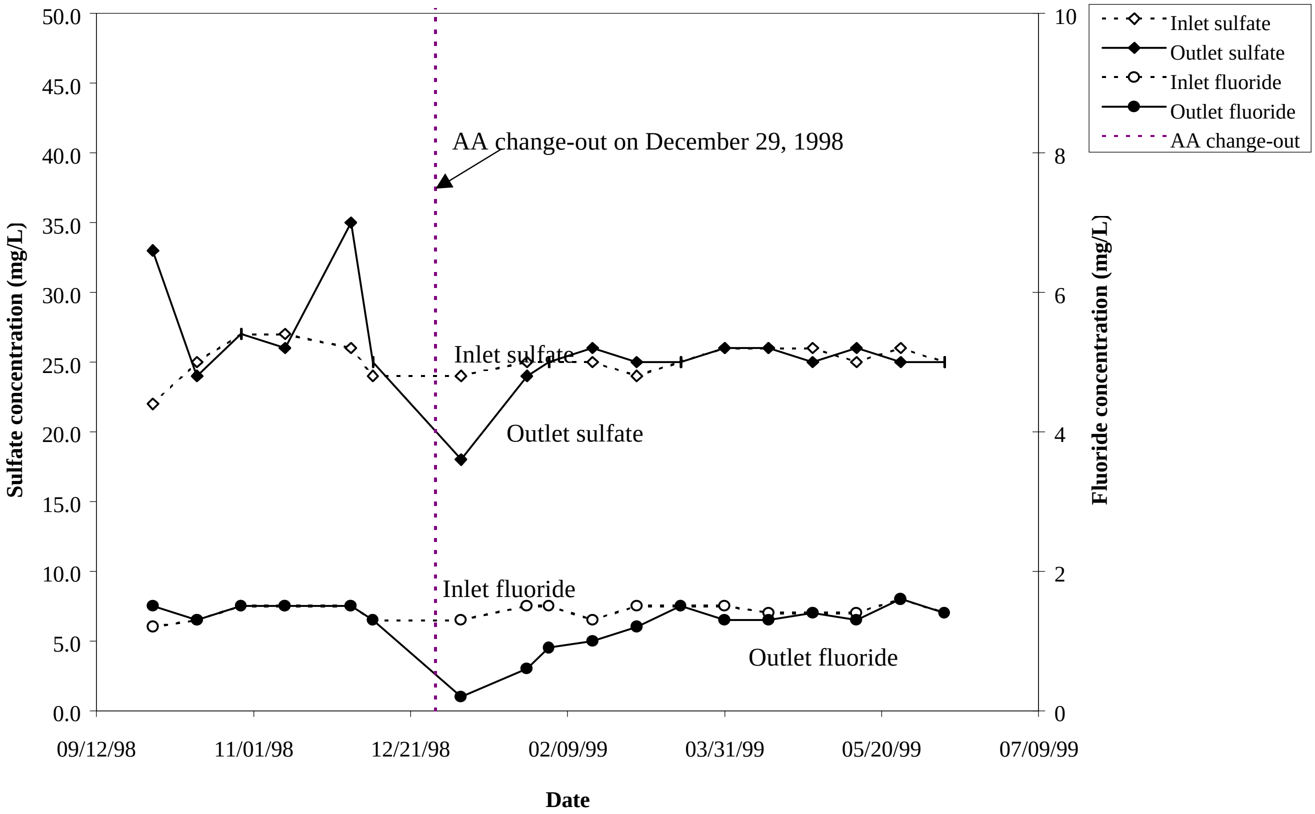


Figure 4-18. Inlet and Outlet Alkalinity, pH, Fluoride, and Sulfate Analytical Results at Plant C

plots the inlet and outlet water alkalinity, pH, fluoride, and sulfate at Plant C.

Inlet alkalinity concentrations were relatively constant, ranging from 67 to 90 mg/L (as $CaCO_3$) with an average of 81.1 mg/L. Alkalinity remained relatively constant across all four sampling locations. Inlet pH values ranged from 7.8 to 8.1 with an average of 8.0. This pH was higher than the optimal pH for the AA process, which ranges from 5.5 to 6.0. Because pH adjustment was not applied, the AA system was not operated for an optimal run length (or an AA adsorption capacity). Therefore, the run length of 9,600 BV (219 g/m^3) achieved at Plant C was shorter than the 15,536 BV (1,242 g/m^3) reported by Hathaway and Rubel (1987) who operated the AA columns at pH 5.5. Nonetheless, the performance of the AA system demonstrated that a throwaway AA treatment system operating without pH adjustments is able to consistently remove arsenic to low levels (i.e., <5 µg/L). The ease of operation and low O&M cost of such a throwaway system make this AA system an appealing option for small water treatment plants and POE systems.

Fluoride and sulfate in the raw water are the major competing ions for adsorption on AA. As shown on Figure 4-18, inlet fluoride and sulfate concentrations were relatively constant, ranging from 1.2 to 1.6 mg/L for fluoride and 22 to 27 mg/L for sulfate. Removal of either ion through the treatment process was insignificant most of the time, except for several weeks immediately after the medium replacement. For example, during the first week after medium replacement, fluoride concentrations decreased from 1.2 to 0.9, 0.3, and 0.2 mg/L across the treatment process. The same trend lasted for subsequent sampling events until the fluoride removal capacity was reached. Sulfate removal appeared to be less significant than that of fluoride.

Turbidity, hardness, NO_3-NO_2 (N), total Al, Fe, and Mn contents in the inlet water were relatively low. Therefore, their effects on the arsenic removal efficiency were insignificant. In some cases, turbid source water, which can be caused by iron precipitates if iron concentration is high, may clog the AA filter and reduce the treatment efficiency. Therefore, a cartridge filter often is installed prior to the AA bed to prevent medium clogging and fouling.

After the media replacement, total Al concentrations increased significantly in the tank effluent and combined finished water, indicating alumina dissolution. An example can be found from the data of January 6, 1999, when total Al concentrations increased from nondetect levels to 42, 109 and 112 µg/L at the TA1, TB1, and outlet locations, respectively.

4.4.4.3 Spent AA Samples

Spent AA samples were collected from two roughing tanks (TA1 and TA2) during AA replacement on December 29, 1998. Subsamples were analyzed for TCLP metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) and percent moisture. As shown in Table 4-22, arsenic was not detected in leachate of the spent AA sample from TA1, and slightly above the detection limit in leachate of the spent AA sample from TA2. None of the results from analyses of spent AA from Plant C indicate exceedances of TCLP limits.

Table 4-22. Analytical Results of Spent AA Samples at Plant C

Parameter	Unit	MDL	Tank A1	Tank A2
TCLP Metals				
As-TCLP	mg/L	0.05	<0.05	0.066
Ba-TCLP	mg/L	1.0	1.2	1.2
Cd-TCLP	mg/L	0.020	<0.02	<0.02
Cr-TCLP	mg/L	0.030	<0.03	<0.03
Pb-TCLP	mg/L	0.20	<0.2	<0.2
Hg-TCLP	mg/L	0.0002	<0.0002	<0.0002
Se-TCLP	mg/L	0.05	<0.05	<0.05
Ag-TCLP	mg/L	0.020	<0.02	<0.02
TCLP extraction	NA	NA	Complete	Complete
Percent moisture	%	0.1	36	24

			NaOH Rinse Time (min)			
Parameter	Unit	MDL	30 minutes	120 minutes	30 minutes	120 minutes
Caustic Wash(b)						
Total As	g/kg, dry	0.1(a)	0.09	0.11	0.07	0.10
Total Al	g/kg, dry	11(a)	0.20	0.23	0.35	0.40
Fluoride	g/kg, dry	0.1(a)	0.27	0.31	0.39	0.47
Sulfate	g/kg, dry	5(a)	3.16	3.17	NA	NA

(a) MDL is in units of µg/L for digestate.

(b) Spent AA was washed with 1% NaOH solution for 30 and 120 minutes, respectively.

Spent AA subsamples were rinsed with 1% NaOH solution for 30 and 120 minutes, respectively, to strip arsenic, fluoride, and sulfate from the AA surface. The waste solution was analyzed for total arsenic, total aluminum, fluoride, and sulfate. As shown in Table 4-22, the contact time of 120 minutes yielded higher arsenic concentrations than the contact time of 30 minutes, suggesting that it might take longer than 30 minutes to reach desorption equilibrium. For the contact time of 120 minutes, the arsenic loading was 0.11 and 0.10 g/kg dry AA for TA1 and TA2, respectively. Compared with the 0.30 g/kg adsorption capacity estimated in Section 4.4.4.1, only one-third of the arsenic was recovered by the caustic wash. Clifford and Lin (1986) found that 50 to 70% of arsenic could be recovered from the AA columns during regeneration. Hathway and Rubel (1987) recovered 80-82% of the arsenic during their pilot studies. In both studies, a 4% NaOH solution was used to regenerate the AA media. Therefore, a 4% NaOH solution and a 16-hr contact time were used in a similar test performed on spent AA samples collected from Plant D.

4.5 Plant D

Water samples were collected and analyzed at Plant D, an AA plant, during the following three phases of the study: initial source water sampling (June 10, 1998), preliminary sampling (August 5 through September 16, 1998), and long-term sampling (September 30, 1998 through September 1, 1999). Similar to Plant C, water sampling was performed biweekly during the preliminary and long-term sampling. Arsenic speciation sampling was conducted during the initial source water sampling, once during preliminary sampling, and every 8 weeks during the long-term sampling. Spent AA samples were collected once from one roughing tank in Plant D during medium replacement on May 25, 1999.

4.5.1 Plant D Description

Plant D serves approximately 200 employees in a manufacturer's warehouse. The ADD is approximately 3,000 gpd. The AA system was installed by Secondwind Environmental of Manchester, NH, in February 1996 with a design flowrate of 20 gpm. The plant consists of four AA tanks, which are positioned as two parallel sets of two tanks in series. The first set of tanks are used as roughing filters and the second set of tanks as polishing filters (Figure 4-19).

The treatment process at Plant D consists of the following major elements:

- **Intake.** Raw water is supplied from a 500-ft-deep well by a submersible pump at a flowrate of 20 gpm. Influent water is pressurized in a WX 205 captive-air hydropneumatic tank.
- **Chlorination.** Approximately 1 mg/L chlorine is added to the water through a single conventional LMI chemical feed pump. The purposes of chlorination are to convert all arsenite [As(III)] to arsenate [As(V)] and to disinfect the water.
- **Cartridge Filter.** One Harmsco cartridge filter was installed on the raw water header to remove particles from the well water. The filter is approximately 21 inches long and 13 inches in diameter, and is reusable. The nominal rating of the cartridge is 20 µm.
- **Activated Alumina Tanks.** The effluent from the cartridge filter splits into two AA treatment trains of two tanks in series. Gate valves exist to isolate each train and control the split ratio. A flowmeter is available on each train to confirm the exact split ratio. Each fiberglass mineral tank (6-ft-tall by 2-ft-diameter) contains approximately 10 ft^3 of Alcoa CPN AA (28 by 48 mesh). Table 4-23 lists typical physical and chemical properties of this medium. The influent flows downward through the AA bed and the effluent is collected at the bottom of the tank. At a design flowrate of 10 gpm (assuming water is split evenly into each train), the hydraulic loading rate to each tank is 3.18 gpm/ft^2 and the EBCT is 7.5 min. The differential pressure across the medium was approximately 3 psi.
- **Medium Replacement.** Same as Plant C, the AA system at Plant D is operated on a throwaway basis without pH adjustments. When the AA medium in the roughing filters reaches its total arsenic removal capacity, the spent AA is removed and replaced with a virgin medium. The polishing filters are moved to the roughing filter position, and the tanks with the new virgin medium then are placed in the polishing position. The tank rearrangement is accomplished by changing the water flow through valving, which is different from Plant C where the medium tanks need to be physically repositioned. A diagram of the system plumbing is provided in Appendix D.2.

  All four tanks contained virgin AA in February 1996 when the system was installed. The roughing tanks, TA1 and TA2, were replaced with virgin AA in November 1997 due to arsenic breakthrough.

  Approximately 1 month later, TB1 and TB2 were recharged with virgin AA because the medium had cemented. The spent AA passed the TCLP test and was disposed of as a nonhazardous waste. From November 11, 1997 to May 25, 1999, TB1

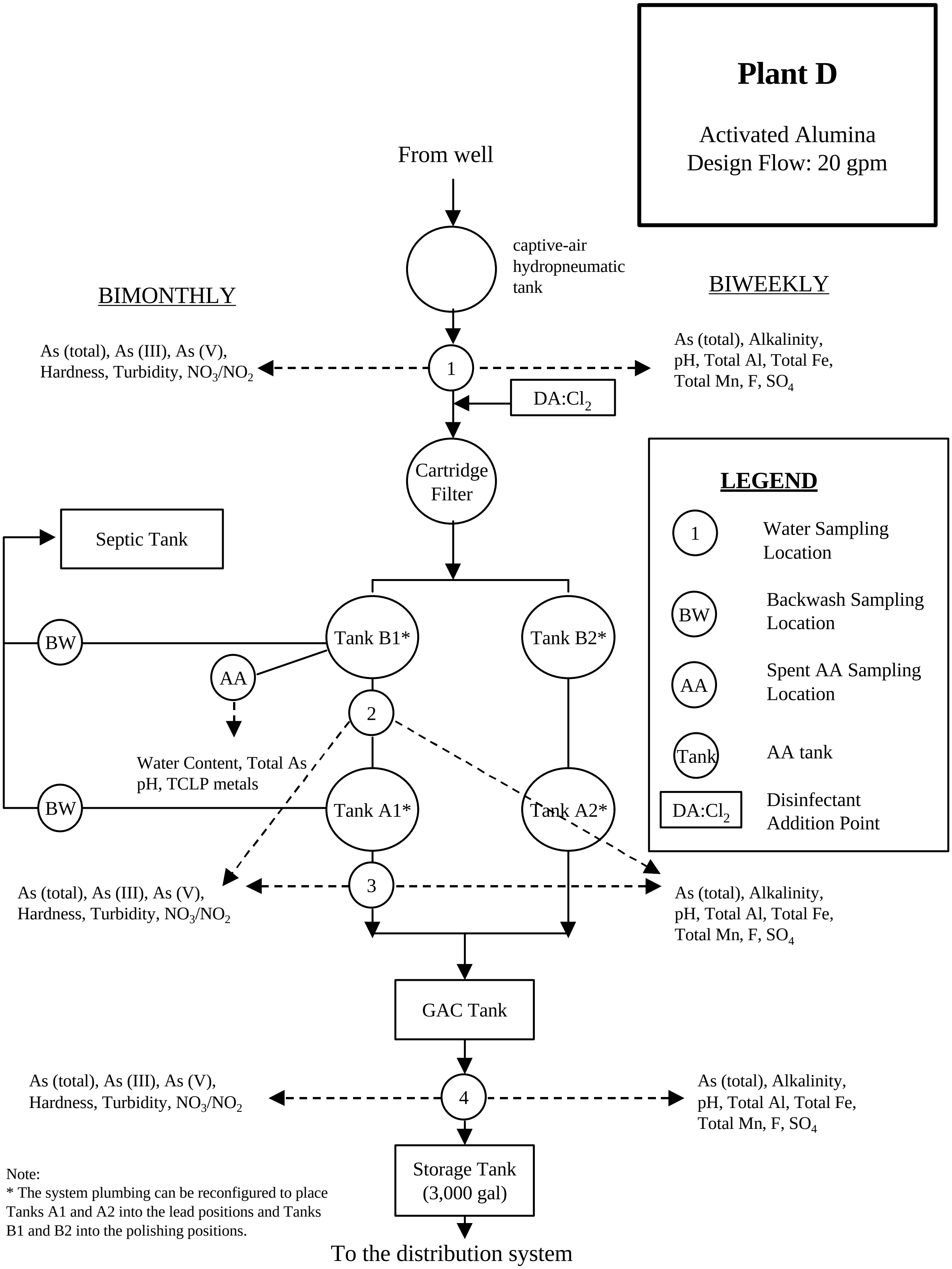


Figure 4-19. Process Flow Diagrams and Sampling Locations at Plant D

Table 4-23. Typical Characteristics of CPN Activated Alumina

Physical Characteristics	CPN AA (28x48 mesh)
Appearance (color, shape)	White, granule
Surface area, m^2/g	300 -340
Total pore volume, cc/g	0.5
Total porosity, %	60.6
Bulk density, lb/ft^3 (kg/m^3)	47 (752)
Abrasion loss, wt%	0.2
Chemical Composition (wt%)	
Al_2O_3	94.1
Na_2O	0.3
Fe_2O_3	0.03
SiO_2	0.02
Loss on ignition (Water)	5.5
Alumina XRD phase	Amorphors, chi, and gamma
Price, $/lb	1.98

and TB2 were operated in the roughing position and TA1 and TA2 operated in the polishing position. TB1 and TB2 were recharged again on May 25, 1999 due to arsenic breakthrough. TA1 was recharged on July 23, 1999. Since May 25, 1999, TA1 and TA2 have been used as roughing filters and TB1 and TB2 used as polishing filters.

- **Backwash.** Backwash of each AA filter was originally scheduled every 4 months using untreated water. The last two backwashes occurred in January and May 1998. Backwash wastewater was disposed of to a septic tank. Currently, backwash is not performed on a routine basis.
- **Granular Activated Carbon Tank.** Water from the two AA treatment trains combines and flows into a granular activated carbon (GAC) tank to be dechlorinated. The GAC tank is 66 inches tall and 18 inches in diameter, and is rebedded every 2 years. Based on the plant record, residual Cl_2 was not detected in effluent after dechlorination.
- **Storage Tank.** The treated water from the GAC tank is stored in a 3,000-gal atmosphere tank located inside the building. The water is pressurized through two booster pumps buffered by two pressure tanks before release to the distribution system.

Water samples are collected monthly by a certified operator from the raw water, between the roughing and the polishing tanks in each train, and from treated water. Table 4-24 summarizes arsenic concentration results from the monthly sampling events. The data show that the arsenic concentrations in water samples collected at A2B2 and A1B1 locations (i.e., after tanks TA2 and TA1, respectively, which both serve as roughing tanks) approached the 0.05 mg/L arsenic MCL on June 12 and August 15, 1997, again respectively, which indicated arsenic breakthrough. Therefore, both tanks were rebedded with virgin AA in November 1997. Water meter readings were recorded during monthly sampling at Plant D and are attached in Appendix D.3.

4.5.2 Initial Source Water Sampling

Source water for Plant D is supplied by a 500-ft-deep bedrock well drilled in 1975 through a submersible pump. The historic sampling data listed in Table 4-24 show that the raw water arsenic concentrations ranged from 39 to 81 µg/L since March 1992. Arsenic speciation was not conducted prior to this study. Typical source water quality measurements made at Plant D are presented in Table 4-25.

On June 10, 1998, an initial site visit to Plant D was conducted during which time source water samples were collected. Table 4-26 presents the analytical results from the source water sampling. Consistent with plant records (Table 4-25), the total soluble arsenic concentration was relatively high, averaging 61.1 µg/L. Almost all of the soluble arsenic existed as As(V) (60.6 µg/L). Particulate arsenic was not detected in the raw water.

4.5.3 Preliminary Sampling

During the preliminary sampling phase of this study, water samples were collected at four locations: (1) at the inlet; (2) after the roughing tank TB1; (3) after the polishing tank TA1; and (4) after the GAC tank. Sampling taps were available at all four sampling locations. Sampling locations and sample analyses are indicated on Figure 4-19.

Preliminary sampling consisted of biweekly sample collection and analysis of various parameters (alkalinity, turbidity, pH, hardness, fluoride, sulfate, total arsenic, total Al, total Fe, and total Mn analysis). Arsenic speciation sampling was conducted once on samples collected from the inlet and after TB1. Speciation was not performed on samples collected after TA1 and GAC tank because As(V) is the dominant species in the source water based on source-water sampling results. Table 4-27 presents the results of the biweekly preliminary sampling.

As shown on Table 4-27, the inlet total arsenic concentrations were relatively constant, ranging from 56.0 to 62.1 µg/L. During the first week of speciation sampling, the raw water contained an average of 61.6 µg/L As(V), 0.2 µg/L As(III), and no particulate arsenic, which is consistent with the source water sampling results.

The roughing AA filter removed 55 to 70% of the total arsenic from the raw water. The polishing filter further

Table 4-24. Arsenic Concentrations (µg/L) from Monthly Water Sampling at Plant D (March 6, 1992 to December 29, 1999)

Date	Raw water	A1B1(a)	A2B2(b)	B1A1(c)	B2A2(d)	Treated Water	Remarks
03/06/92	54	–	–	–	–	–	
03/16/95	62	–	–	–	–	–	
03/21/96	45	<5	<5	–	–	<5	AA system installed in 2/96; TA1 and TA2 were roughing tanks; TB1 and TB2 were polishing tanks
04/16/96	40	<5	<5	–	–	<5	
05/08/96	46	<5	<5	–	–	<5	
06/19/96	39	<5	<5	–	–	<5	
07/22/96	51	<5	<5	–	–	<5	
08/20/96	50	<5	<5	–	–	<5	
09/06/96	52	<5	<5	–	–	<5	
10/15/96	45	<5	<5	–	–	<5	
11/13/96	48	<5	<5	–	–	<5	
12/20/96	77	<5	<5	–	–	<5	
01/09/97	58	–	<5	–	–	<5	
02/21/97	60	36	<5	–	–	<5	
03/21/97	70	<5	<5	–	–	<5	
04/17/97	61	24	42	–	–	<5	
05/15/97	77	32	43	–	–	<5	
06/12/97	61	38	50	–	–	<5	Arsenic breakthrough TA2 (50 μg/L)
07/14/97	60	36	65	–	–	<5	
08/15/97	81	47	57	–	–	<5	Arsenic breakthrough TA1 (50 μg/L)
09/12/97	60	42	48	–	–	<5	
10/15/97	58	45	44	–	–	<5	TA1and TA2 rebedded and moved to polishing positions in 11/97; TB1and TB2 moved to roughing positions
11/18/97	62	–	–	<5	7	<5	
12/23/97	54	–	–	26	13	<5	TB1and TB2 rebedded in 12/97 and stayed in roughing positions
01/19/98	71	–	–	<5	<5	<5	
02/24/98	57	–	–	<5	<5	<5	
03/25/98	63	–	–	<5	<5	<5	
04/15/98	62	–	–	<5	<5	<5	
05/19/98	61	–	–	<5	<5	<5	
06/15/98	61	–	–	15	<5	<5	
07/23/98	72	–	–	17	<5	<5	
08/27/98	60	–	–	23	<5	<5	
09/16/98	68	–	–	39	<5	<5	
10/15/98	67	–	–	34	<5	<5	
11/12/98	54	–	–	39	<5	<5	
01/19/99	47	–	–	41	<5	<5	
02/16/99	46	–	–	30	6	<5	
03/18/99	50	–	–	40	17	<5	
04/28/99	66	–	–	48	23	<5	TB1 and TB2 rebedded and moved to polishing positions on 5/25/99; TA1and TA2 moved to roughing positions
06/22/99	61	<5	<5	–	–	<5	
07/14/99	61	<5	<5	–	–	<5	TA1 rebedded on 7/23/99, remained at roughing position
08/25/99	68	<5	5	–	–	<5	
09/17/99	66	<5	7	–	–	<5	
10/29/99	57	<5	12	–	–	<5	
11/22/99	47	<5	11	–	–	<5	
12/29/99	54	<5	17	–	–	5	

(a) Water collected from a tap between the roughing tank TA1 and the polishing tank TB1.
(b) Water collected from a tap between the roughing tank TA2 and the polishing tank TB2.
(c) Water collected from a tap between the roughing tank TB1 and the polishing tank TA1.
(d) Water collected from a tap between the roughing tank TB2 and the polishing tank TA2.
– = Not sampled.

Table 4-25. Typical Source Water Quality Measurements at Plant D

Parameter	Unit	Concentration
Alkalinity	mg/L[(a)]	56.8
Fluoride	mg/L	1.15
Chloride	mg/L	8.0
Sulfate	mg/L	10
pH	—	8.3
Hardness	mg/L[(a)]	55
Sodium	mg/L	13.9
Specific Conductance	µmhos/cm	166
Arsenic	µg/L	40-80

(a) Measured as $CaCO_3$

Table 4-26. Source Water Sampling Analytical Results at Plant D (June 10, 1998)

Parameter	Units	Primary Sample	Duplicate Sample	Average
Alkalinity	mg/L[(a)]	56	55	55.5
Fluoride	mg/L	1.13	1.13	1.13
Sulfate	mg/L	15	15	15
Turbidity	NTU	0.31	0.3	0.31
pH	—	8.3	8.3	8.3
Hardness	mg/L[(a)]	49	46	47.5
Ca Hardness	mg/L[(a)]	42.2	39	40.6
Mg Hardness	mg/L[(a)]	7.1	7.1	7.1
Total Al	µg/L	<400	<400	<400
Total Fe	µg/L	50	60	55
Total Mn	µg/L	<20	<20	<20
NO_3–NO_2 (N)	mg/L[(b)]	0.36	0.37	0.37
TOC	mg/L	1.0	ND	ND
As (total)	µg/L	60.0	58.1	59.0
As (total soluble)	µg/L	60.8	61.4	61.1
As (particulate)	µg/L	ND	ND	ND
As (III)	µg/L	0.5	0.5	0.5
As (V)	µg/L	60.3	60.9	60.6

(a) As $CaCO_3$.
(b) Combined NO_3–N and NO_2–N.

reduced the total arsenic concentrations to 0.6-1.1 µg/L. The combined treated water after the GAC tank contained concentrations of total arsenic ranging from 0.7 to 1.1 µg/L, corresponding to an overall removal efficiency of greater than 98%.

Fluoride concentrations were constant throughout the treatment process, with 1.1 mg/L in the raw water and 1.2 mg/L in the finished water. Therefore, fluoride was not removed by the AA filters. Similarly, sulfate concentrations remained at constant levels of 11 to 14 mg/L throughout the treatment process, except for one sample collected on August 5, 1998 with 30 mg/L of sulfate detected after TB1. The reason for this anomaly is unknown. Although both fluoride and sulfate have certain affinities for the AA surface, their removal by AA was not observed here; this result is most likely due to the nearly exhausted AA arsenic removal capacity (similar results observed at Plant C, as discussed in Section 4.4.3).

Alkalinity, total hardness, and nitrate/nitrite remained relatively constant after the AA tanks because these ions hardly reacted with the AA surface. Total aluminum concentrations in the water slightly increased after the treatment, presumably due to the dissolution of AA medium. Total iron and manganese concentrations in the raw water were less than detection limit.

The preliminary sampling effort at Plant D resulted in no changes to the long-term sampling approach.

4.5.4 Long-Term Sampling

Long-term sampling and analysis consisted of 24 biweekly sampling events, including six arsenic speciation sampling events. The four sampling locations used during the preliminary sampling also were used during long-term sampling. Additionally, spent AA samples were collected once during medium replacement on May 25, 1999. A special short-term study was conducted using the spent and a virgin medium. The following subsections summarize the analytical results for arsenic, other water quality parameters, spent AA, and the special study.

4.5.4.1 Arsenic

Table 4-28 provides a summary of the arsenic analytical results at different sampling locations. Total arsenic concentrations at the inlet ranged from 53.3 to 87.0 µg/L with an average of 63.0 µg/L, exceeding the 0.05 mg/L arsenic MCL. The inlet water contained primarily As(V) with only minor concentrations of As(III) and particulate arsenic. Particulate arsenic was detected at the inlet only on September 30, 1998 with a highest concentration of 12.7 µg/L. An abnormally high total Fe concentration also was detected in the same samples. The maximum As(III) concentrations were 0.5 µg/L at the inlet and 0.4 µg/L after the first tank. Should the As(III) concentration in the source water increase, As(III) would be oxidized to As(V) by chlorination before the AA adsorption.

Figure 4-20 presents the total arsenic concentrations at each sampling location and the corresponding overall removal percentages throughout the long-term sampling. The figures were plotted against both sampling date and BV of treated water, respectively. As shown on these plots, the total arsenic concentrations after the roughing tank (TB1) gradually approached influent levels, indicating breakthrough. Based on the water usage data, roughing tank TB1 treated approximately 4,350 BV of water before arsenic breakthrough occurred on March 3, 1999. The medium was replaced with virgin AA on May

Table 4-27. Analytical Results from Preliminary Sampling at Plant D (August 5 through September 16, 1998)

		Sampling Date and Location															
		8/5/98				8/19/98				9/2/98				9/16/98			
		IN	TB1	TA1	AC	IN	TB1	TA1	AC	IN	TB1	TA1	AC	IN	TB1	TA1	AC
Alkalinity	mg/L(a)	59	48	61	59	58 58	59 59	55 55	53 53	57	58	57	56	58	56	55	56
Fluoride	mg/L	1.1	1.3	1.4	1.2	1.0 1.0	1.2 1.2	1.3 1.4	1.2 1.2	1.1	1.2	1.3	1.1	–	–	–	–
Sulfate	mg/L	11	30	15	14	13 13	14 14	14 14	14 14	14	14	14	14	14	14	14	14
Turbidity	NTU	<0.1	<0.1	<0.1	<0.1	<0.1 <0.1	<0.1 <0.1	<0.1 <0.1	<0.1 <0.1	–	–	–	–	–	–	–	–
pH	–	8.5	8.3	7.9	8.0	8.2 8.2	8.0 8.1	8.0 7.9	7.9 7.9	7.9	7.9	7.8	7.7	8.2	8.1	7.8	7.8
Total Hardness	mg/L(a)	53.0	51.0	52.0	54.0	–	–	–	–	–	–	–	–	–	–	–	–
Ca Hardness	mg/L(a)	45.4	43.9	45.2	46.2	–	–	–	–	–	–	–	–	–	–	–	–
Mg Hardness	mg/L(a)	7.2	7.2	7.2	7.5	–	–	–	–	–	–	–	–	–	–	–	–
NO_3-NO_2 (N)	mg/L(b)	0.6	0.4	0.4	0.4	–	–	–	–	–	–	–	–	–	–	–	–
As (total)	µg/L	59.7 57.8	18.1 21.1	1.1 0.9	1.0 1.1	62.1	26.3	0.6	0.7	56.0	19.6	0.8	0.7	61.0	27.6	0.9	0.9
As (total soluble)	µg/L	61.4 62.1	21.4 21.4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
As (particulate)	µg/L	<0.1 <0.1	<0.1 <0.1	–	–	–	–	–	–	–	–	–	–	–	–	–	–
As (III)	µg/L	0.2 0.1	0.2 0.2	–	–	–	–	–	–	–	–	–	–	–	–	–	–
As (V)	µg/L	61.2 62.0	21.2 21.2	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Total Al	µg/L	12.6 14.4	32.0 39.4	37.7 44.2	49.3 45.2	44.0	34.9	29.9	46.7	16.2	23.1	31.5	36.1	22.8	36.6	41.0	44.4
Total Fe	µg/L	<30 <30	<30 51.2	<30 <30	<30 37.2	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Total Mn	µg/L	<0.5 <0.5	<0.5 1.4	<0.5 <0.5	<0.5 <0.5	0.6	<0.5	<0.5	<0.5	0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Dissolved Al	µg/L	<11 <11	14.5 14.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Dissolved Fe	µg/L	<30 <30	<30 <30	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Dissolved Mn	µg/L	<0.5 <0.5	<0.5 <0.5	–	–	–	–	–	–	–	–	–	–	–	–	–	–

(a) Measured as $CaCO_3$.
(b) Combined NO_3 -NO_2 as N.
IN = inlet; TB1 = after Tank B1; TA1 = after Tank A1; AC = after the GAC tank.
– = No analysis performed.

Table 4-28. Summary of Arsenic Analytical Results at Plant D (September 30, 1998 to September 1, 1999)

Parameter	Sampling Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	Inlet	µg/L	30	53.3	87.0	63.0	6.8
	After 1st Tank	µg/L	30	1.3	60.8	31.6	21.8
	After 2nd Tank	µg/L	30	0.6	3.2	1.3	0.7
	Effluent	µg/L	30	0.4	9.6	1.2	1.8
As (total soluble)	Inlet	µg/L	10	61.1	70.4	66.3	2.8
	After 1st Tank	µg/L	10	1.4	60.6	38.2	21.5
As (particulate)	Inlet	µg/L	10	<0.1	12.7	2.1	4.2
	After 1st Tank	µg/L	9	<0.1	0.7	0.1	0.2
As (III)	Inlet	µg/L	10	<0.1	0.5	0.2	0.1
	After 1st Tank	µg/L	10	0.1	0.4	0.2	2.8
As (V)	Inlet	µg/L	10	61.1	70.1	66.1	21.4
	After 1st Tank	µg/L	10	1.3	60.4	37.9	0.0

One-half of the detection limit was used for nondetect samples for calculations.
Primary and duplicate samples were averaged for calculations.
The 1st tank was TB1 before the medium change-out on May 25, 1999 and TA1 after the medium change-out.
The 2nd tank was TA1 before the medium change-out on May 25, 1999 and TB1 after the medium change-out.

medium change-out) consistently contained <5 µg/L arsenic. Except for one spike (9.6 µg/L) on May 26, 1999, the combined treated water had total arsenic concentrations similar to those in samples collected after the second tank, indicating that the other treatment train performed in similarly effective fashion. During the entire study, the system arsenic effluent was consistently below 5 µg/L, corresponding to an average arsenic removal of greater than 98%.

Using an average 5,260 BV of water treated prior to 50-µg/L arsenic breakthrough, an inlet arsenic concentration of 62.1 µg/L, an arsenic concentration of 26.5 µg/L after the roughing tanks, and a density of 752 kg/m^3, it was estimated that approximately 106 g of arsenic was removed from the raw water by the roughing filters, corresponding to an arsenic loading of 0.25 g/kg (155 g/m^3). This value is comparable to that obtained from Plant C (0.30 g/kg or 219 g/m^3) and to reported values (Fox, 1989).

4.5.4.2 Other Water Quality Parameters

As with Plant C, sampling and analysis of other water quality parameters were performed to provide insight into the arsenic removal efficiency at the plant. Table 4-29 summarizes the analytical results of the water quality parameters measured during long-term sampling at Plant D. Figure 4-21 plots the inlet and outlet alkalinity, pH, fluoride, and sulfate concentrations.

Inlet alkalinity concentrations were relatively constant, ranging from 44 to 59 mg/L (as $CaCO_3$) with an average of 56.9 mg/L. Alkalinity also remained constant throughout all four sampling locations. Inlet pH values ranged from 7.8 to 8.4 with an average of 8.2. This pH was higher than the reported optimal pH for the AA process. Even though the pH of the inlet water was not adjusted to the optimal value, the system consistently removed arsenic to below 5 µg/L before the medium was exhausted.

Fluoride and sulfate in the raw water are the major competing ions for adsorption on AA. As shown on Table 4-29 and Figure 4-21, inlet fluoride and sulfate concentrations were relatively constant, ranging from 0.9 to 1.4 mg/L and 11 to 15 mg/L, respectively. Removal of either ion through the treatment process was not significant before the medium replacement on May 25, 1999. However, both fluoride and sulfate were removed to nondetect levels by the freshly recharged tank on June 6, 1999. Afterwards, the removal of fluoride lasted until the end of this study; however, the sulfate removal capacity was quickly exhausted.

Turbidity, hardness, NO_3-NO_2 (N), total Al, Fe, and Mn contents in the inlet water were relatively low, so their effects on the arsenic removal efficiency were determined insignificant. Similar to Plant C, after the medium replacement, total Al concentrations increased significantly at the second tank and effluent sampling locations, indicating medium dissolution. For example, total Al concentration was as high as 7.5 mg/L at the second tank and effluent sampling locations.

4.5.4.3 Spent AA Samples

Spent AA samples were collected from the roughing tank TB1 during the medium replacement on May 25, 1999. Subsamples were analyzed for TCLP metals and percent moisture. Analytical results are presented in Table 4-30. All three samples had arsenic TCLP testing results of less than 0.05 mg/L, far below the arsenic TCLP limit of 5.0 mg/L. Only minor concentrations of barium were detected in the leachates of samples from the middle

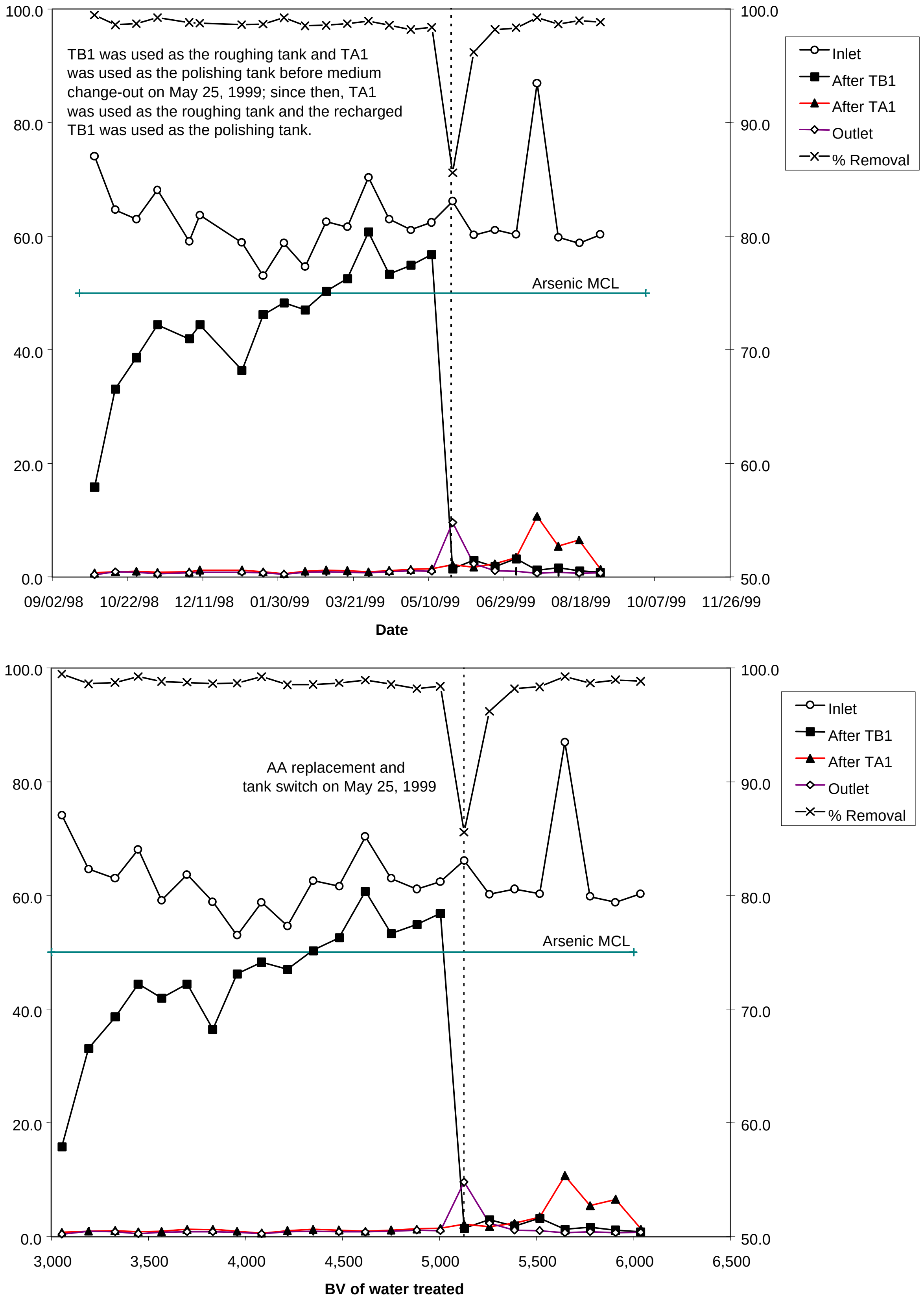
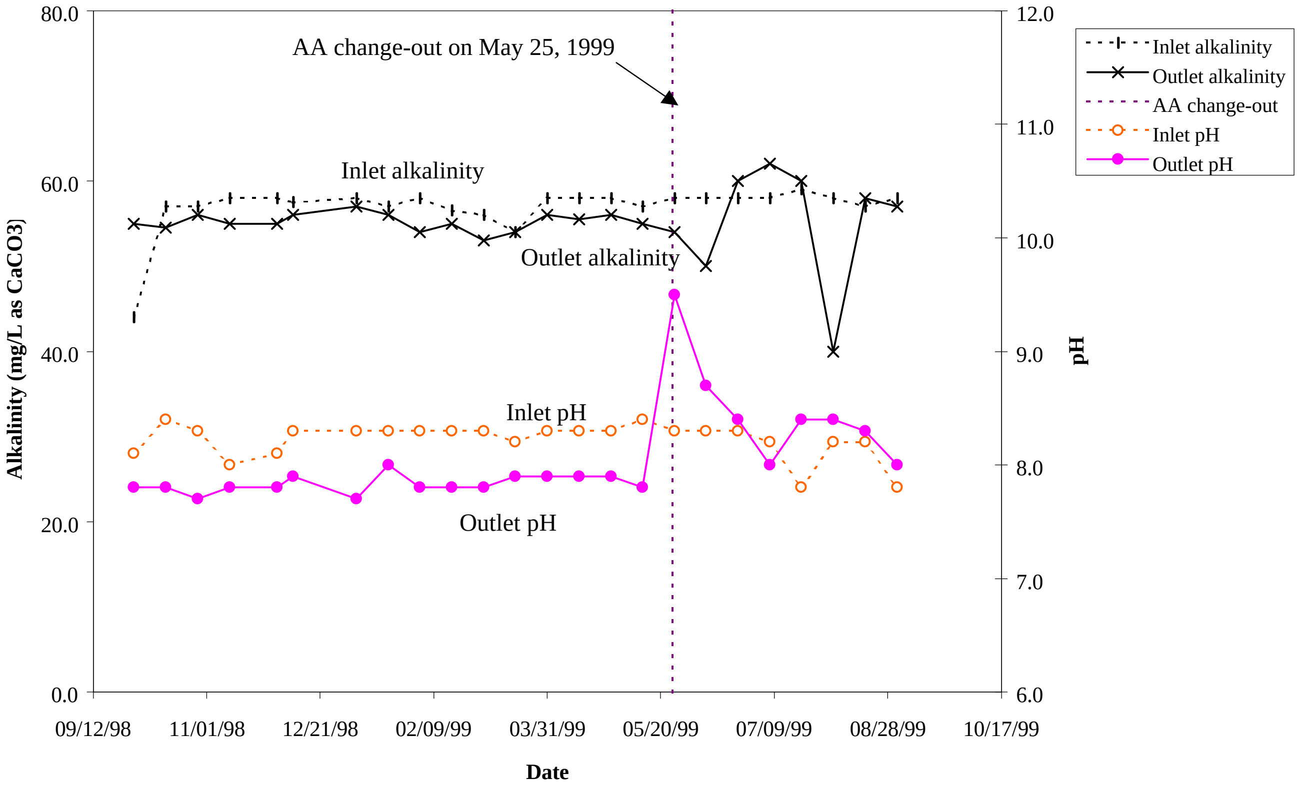


Figure 4-20. Total Arsenic Analytical Results during Long-Term Sampling at Plant D

Table 4-29. Summary of Water Quality Parameter Analytical Results at Plant D (September 30, 1998 to September 1, 1999)

Parameter	Sampling Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
Alkalinity	Inlet	mg/L	30	44	59	56.9	2.9
	After 1st Tank	mg/L	30	47.5	63	56.8	2.6
	After 2nd Tank	mg/L	30	52	65	56.8	2.6
	Effluent	mg/L	30	40	62	55.2	4.1
Fluoride	Inlet	mg/L	30	0.9	1.4	1.1	0.1
	After 1st Tank	mg/L	30	<0.1	1.4	1.1	0.3
	After 2nd Tank	mg/L	30	<0.1	1.5	1.0	0.5
	Effluent	mg/L	30	<0.1	1.6	1.0	0.5
Sulfate	Inlet	mg/L	30	11	15	13.5	1.0
	After 1st Tank	mg/L	30	7.5	17	13.5	1.8
	After 2nd Tank	mg/L	30	<5	16	12.3	3.9
	Effluent	mg/L	30	<5	15	12.2	3.9
Turbidity	Inlet	NTU	6	0.2	0.4	0.3	0.1
	After 1st Tank	NTU	6	<0.1	0.2	0.1	0.1
	After 2nd Tank	NTU	6	<0.1	<0.1	0.05	0.0
	Effluent	NTU	6	<0.1	<0.1	0.05	0.0
pH	Inlet	—	30	7.8	8.4	8.2	0.2
	After 1st Tank	—	30	7.8	8.4	8.1	0.1
	After 2nd Tank	—	30	7.0	9.9	8.1	0.5
	Effluent	—	30	7.7	9.5	8.0	0.4
Total Hardness	Inlet	mg/L	6	46	51	48.8	1.8
	After 1st Tank	mg/L	6	47	51	49.7	1.5
	After 2nd Tank	mg/L	6	<2	50	39.8	19.1
	Effluent	mg/L	6	<2	50	40.2	19.2
NO_3-NO_2 (N)	Inlet	mg/L	6	0.3	0.8	0.4	0.2
	After 1st Tank	mg/L	6	0.3	1.3	0.6	0.4
	After 2nd Tank	mg/L	6	0.3	1.4	0.6	0.4
	Effluent	mg/L	6	0.3	0.5	0.4	0.1
Total Al	Inlet	µg/L	30	<11	44.7	14.1	10.2
	After 1st Tank	µg/L	30	<11	471	55.1	103
	After 2nd Tank	µg/L	30	<11	148(a)	54.9(a)	47.5(a)
	Effluent	µg/L	30	<11	190(a)	55.5(a)	51.7(a)
Total Fe	Inlet	µg/L	30	<30	483	44.4	97.7
	After 1st Tank	µg/L	30	<30	127	21.1	23.1
	After 2nd Tank	µg/L	30	<30	53.7	18.1	9.5
	Effluent	µg/L	30	<30	54.3	17.1	8.2
Total Mn	Inlet	µg/L	30	<0.5	11.2	0.9	2.3
	After 1st Tank	µg/L	30	<0.5	0.7	0.3	0.1
	After 2nd Tank	µg/L	30	<0.5	<0.5	0.3	0.0
	Effluent	µg/L	30	<0.5	<0.5	0.3	0.1
Dissolved Al	Inlet	µg/L	10	<11	<11	<11	0.0
	After 1st Tank	µg/L	9	13.3	19.2	15.5	2.1
Dissolved Fe	Inlet	µg/L	10	<30	<30	<30	0.0
	After 1st Tank	µg/L	10	<30	<30	<30	0.0
Dissolved Mn	Inlet	µg/L	10	<0.5	<0.5	<0.5	0.0
	After 1st Tank	µg/L	10	<0.5	1.5	0.4	0.4

One-half of the detection limit was used for nondetect samples for calculations.
Primary and duplicate samples were averaged for calculations.
The 1st tank was TB1 before the medium change-out on May 25, 1999 and TA1 after the medium change-out.
The 2nd tank was TA1 before the medium change-out on May 25, 1999 and TB1 after the medium change-out.
(a) High total Al concentrations measured on May 26, 1999 after the polishing tank and at the outlet due to medium dissolution were not included for calculations.



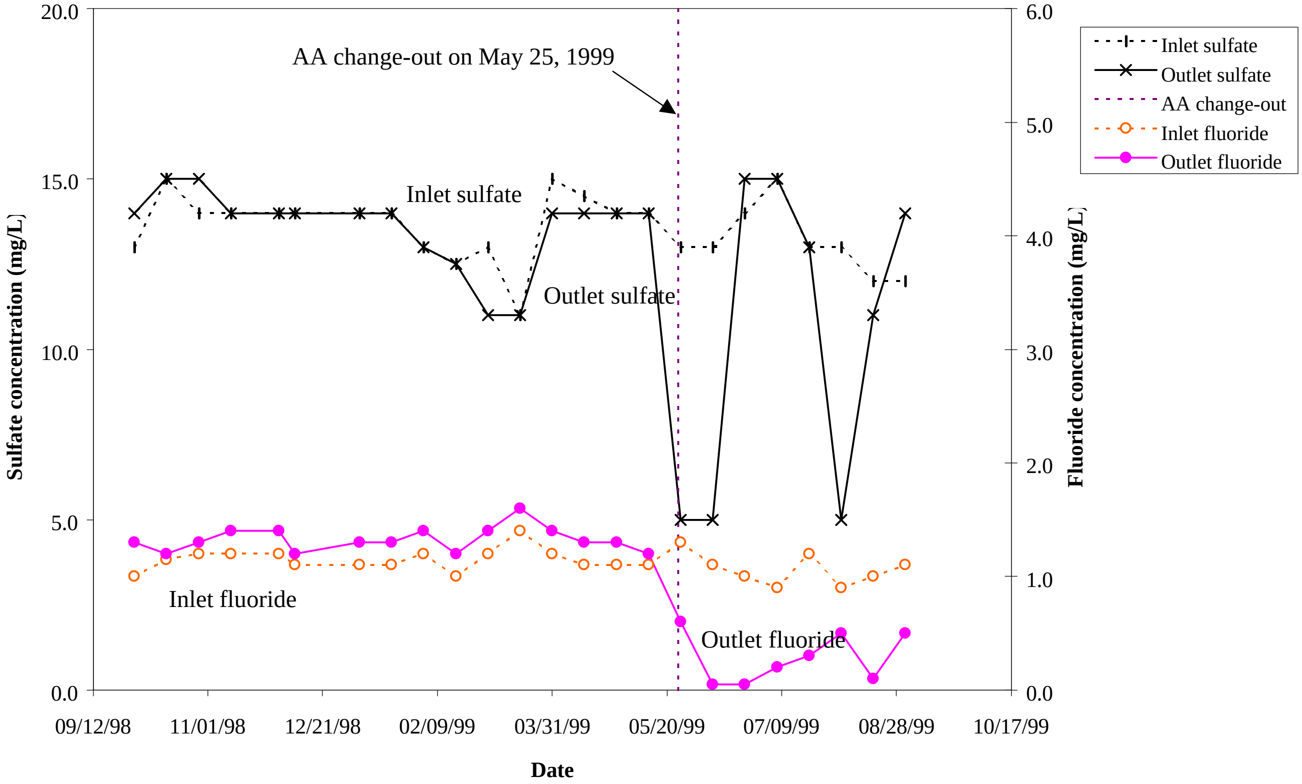


Figure 4-21. Inlet and Outlet Alkalinity, pH, Fluoride, and Sulfate Analytical Results at Plant D

Table 4-30. Analytical Results of Spent AA Samples at Plant D

Parameter	Unit	MDL	TB1-Top	TB1-Middle	TB1-Bottom
TCLP Metals					
As-TCLP	mg/L	0.05	<0.05	<0.05	<0.05
Ba-TCLP	mg/L	1.0	<1.0	1.1	1.4
Cd-TCLP	mg/L	0.020	<0.02	<0.02	<0.02
Cr-TCLP	mg/L	0.030	<0.03	<0.03	<0.03
Pb-TCLP	mg/L	0.20	<0.2	<0.2	<0.2
Hg-TCLP	mg/L	0.0002	<0.0002	<0.0002	<0.0002
Se-TCLP	mg/L	0.05	<0.05	<0.05	<0.05
Ag-TCLP	mg/L	0.020	<0.02	<0.02	<0.02
TCLP extraction	NA	NA	Complete	Complete	Complete
Percent moisture	%	0.1	31.6	31.3	32.0

and bottom sections of TB1. None of the spent AA analytical results indicate exceedances of regulatory levels. Therefore, the spent alumina could be disposed of as a nonhazardous waste material.

4.5.5 Special Study at Plant D

4.5.5.1 Regeneration of Spent AA Using Caustic Solution

Spent AA samples collected from the top, middle, and bottom sections of TB1 were mixed with caustic solution (4% NaOH) overnight to strip arsenic, fluoride, and sulfate from the AA surface. The rinsates were analyzed for total arsenic, fluoride and sulfate. The amounts of arsenic, fluoride, and sulfate desorbed from the AA medium were calculated as described in Section 3.4.2, and the results are presented in Table 4-31. The same samples also were digested with concentrated nitric acid and the digestates were analyzed for total arsenic. As shown on Table 4-31, the amounts of arsenic and fluoride recovered from the spent AA showed a slightly increasing trend from the top to the bottom sections of the tank. The data based on the acid digestion are higher, but showing a similar increasing trend. The average arsenic removal capacity based on acid digestion is 0.41 g/kg, higher than the one estimated based on column operation (0.25 g/kg AA) (Section 4.5.4.1). Therefore, the arsenic removal capacity based on column operation might have been underestimated. The arsenic removal capacities can be placed in the following order:

caustic wash (0.21 g/kg)

< column operation (0.25 g/kg)

< acid digestion (0.41 g/kg)

Based on the capacities from the column operation and acid digestion, approximately 84% and 50% of arsenic were recovered by the caustic wash respectively, which fell in the ranges reported by Hathway and Rubel (1987) and Clifford and Lin (1986).

Table 4-31. Analytical Results of Caustic Wash and Acid Digestion of Spent AA Samples at Plant D

Parameter	Unit	TB1-Top	TB1-Middle	TB1-Bottom	Average
Caustic Wash with 4% NaOH					
Total As	g/kg	0.19 0.19	0.21 0.21	0.23 0.23	0.21
Fluoride	g/kg	0.36 0.40	0.42 0.42	0.43 0.43	0.41
Sulfate	g/kg	0.40 0.48	0.56 0.59	0.39 0.36	0.46
Acid Digestion with HNO_3					
Total As	g/kg	0.38	0.39	0.50	0.41

4.5.5.2 Adsorption of Arsenic onto AA

The results of the kinetic study as shown on Figure 4-22 indicated that arsenic adsorption on AA had reached equilibrium within 2 days, consistent with previous studies by Rosenblum and Clifford (1984). As a result, all subsequent isotherm batch tests were maintained for 6 days to ensure equilibrium had been reached.

The As(V) adsorption isotherm on AA at pH 7.7 ±0.2 is presented in Figure 4-23. The following data were fitted with both Freundlich and Langmuir models and the resulting equations are shown:

Freundlich model:

$$q_e = 0.1679 \times C_e^{(0.452)},\ r^2 = 0.9632 \qquad (4\text{-}1)$$

Langmuir model:

$$q_e = 0.6778 \times 0.2957 \times C_e/(1+0.2957 \times C_e),\ r^2 = 0.9677 \qquad (4\text{-}2)$$

where q_e and C_e are the solid (mg/g AA) and liquid phase (µg/L) equilibrium As(V) concentrations, respectively.

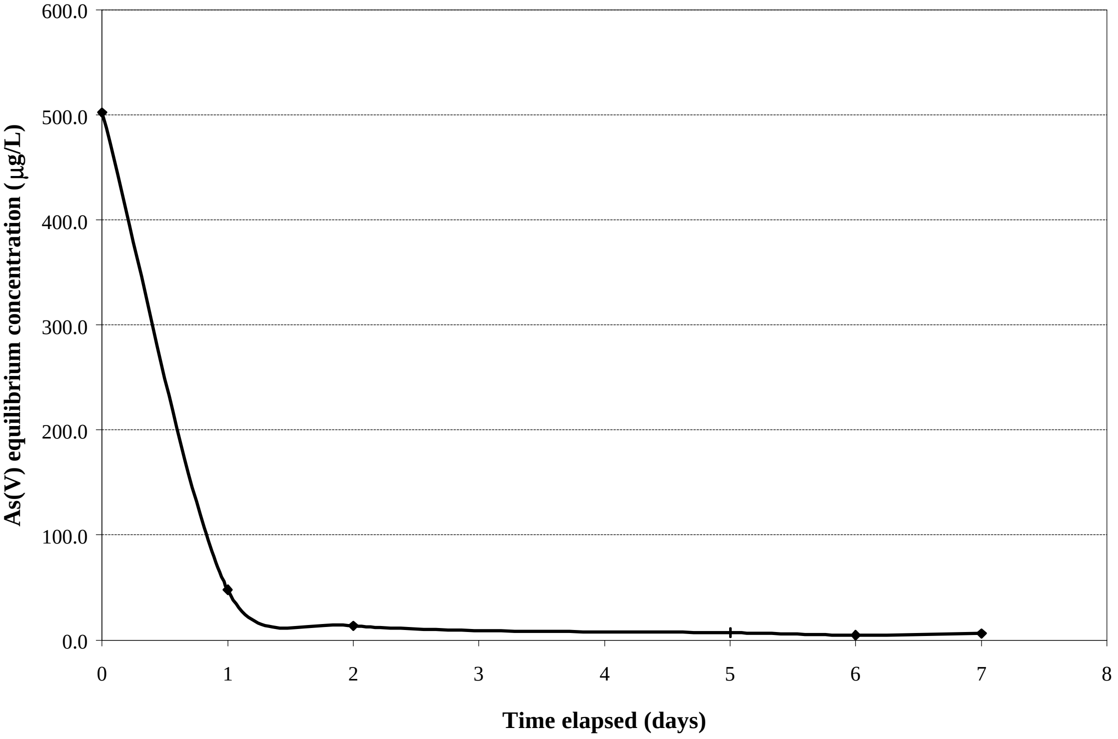


Figure 4-22. Kinetics of Arsenic Adsorption on AA Media

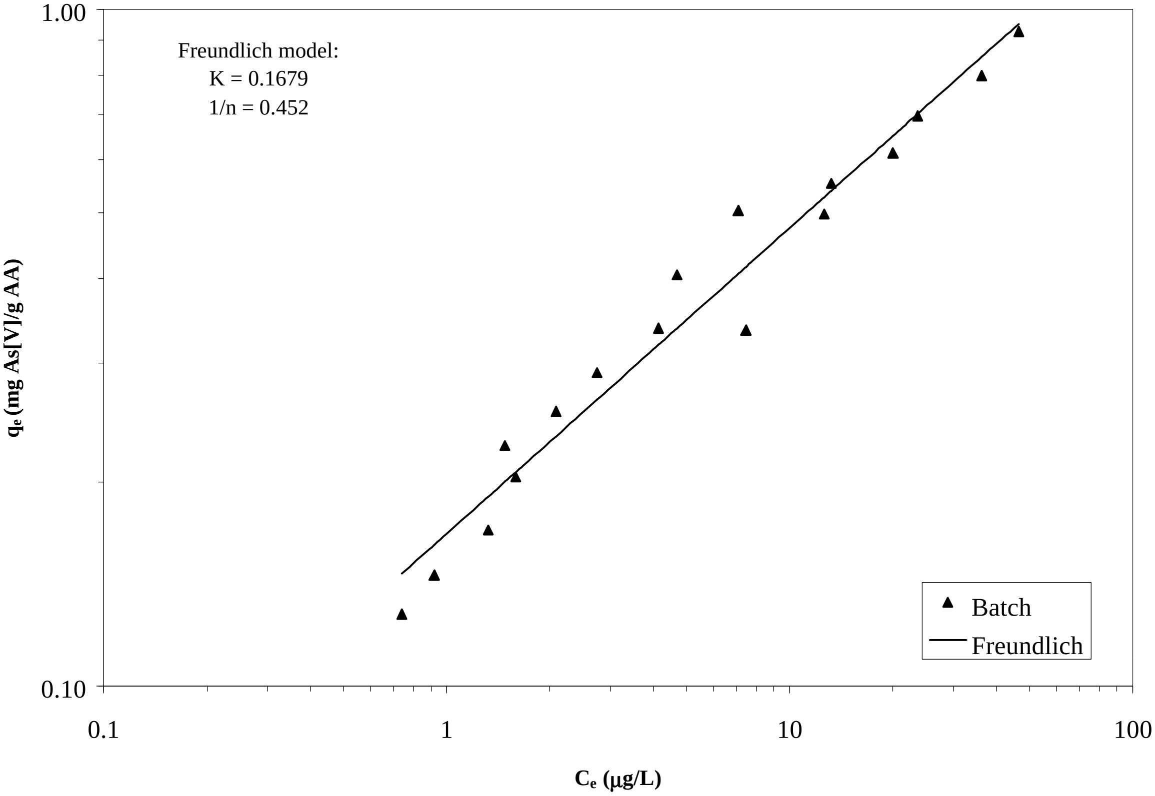


Figure 4-23. Arsenic Adsorption Isotherm on AA Media

Because q_e did not reach plateau under the experimental conditions, the Freundlich model seemed to fit the data better than the Langmuir model. The significance of the Freundlich model with respect to As(V) adsorption onto AA lies primarily in the assumption of heterogeneous adsorption site energies and multilayer adsorption. In batch tests performed by Rosenblum and Clifford (1984), a similar relation between the solid and liquid phase arsenic concentrations was established; however, at much higher aqueous equilibrium As(V) concentrations (i.e., up to 4 mg/L).

Based on the Freundlich model, at an inlet arsenic concentration of 63.0 µg/L, the AA adsorption capacity is predicted to be 1.09 g As(V)/kg AA. This value is higher than the capacities obtained from the column operation (0.25 g/kg), caustic wash (average of 0.21 g/kg), or acid digestion (0.41 g/kg). Because the column operated at an average pH of 8.3, higher than the pH of the isotherm study (pH 7.7), the pH most likely affected the adsorption capacity. In actual column operation, the arsenic capacity obtainable should be far less than the equilibrium values obtained from the adsorption isotherm. The competing anions and the nonequilibrium mass transfer limitations are some of the reasons for the low column capacities. An additional reason for the low capacity is the possible fouling of the porous alumina by particulate and colloidal constituents such as colloidal silica and mica (Clifford and Lin, 1986), which were not monitored during this study.

5.0 Quality Assurance/Quality Control

5.1 Quality Assurance Objectives

The precision, accuracy, MDL, and completeness for each of the analytical measurements required for this study were established in the QAPP (Battelle, 1998) and are listed in Table 1 of the *QA/QC Summary Report* (Battelle, 2000b), which was prepared under separate cover. These terms serve as indicators of data quality and were calculated in accordance with the formulas provided in the QAPP. The precision, accuracy, and MDL of each of the measurements performed during the present study are presented in the summary report. These quality assurance (QA) data are organized according to the date of sample receipt or sample analysis and are not site-specific. Therefore, the QA/QC section of this report shares the same QA data with other water treatment plants that have been included in the study.

5.2 Overall Assessment of Data Quality

Quantitative QA objectives listed in the *QA/QC Summary Report* include precision as relative percent difference (RPD), accuracy as percent recovery (%R), MDL, and completeness. The precision, accuracy, and MDL or reporting limit of each of the measurements performed during this study are presented in the *QA/QC Summary Report*. Total arsenic, aluminum, iron, and manganese analyses on water samples were conducted in Battelle's ICP-MS laboratory. The QA data associated with these metal analyses also are presented in the *QA/QC Summary Report*. Other water quality parameters including alkalinity, pH, turbidity, hardness, nitrate-nitrite, sulfate, fluoride, TDS, and TSS were analyzed by Wilson Environmental Laboratories, and their QA data were summarized in the *QA/QC Summary Report*. QA data for TOC analysis performed by CT&E Environmental Laboratory are presented in the *QA/QC Summary Report*. The TCLP metal analysis on sludge samples also was conducted by Wilson Environmental Laboratories and its associated QA data are summarized in the *QA/QC Summary Report*. Overall, the QA objectives of precision, accuracy, MDL, and completeness were achieved by all laboratories. Therefore, all the valid data were used to evaluate the effectiveness of the treatment processes and support conclusions.

5.2.1 Total Arsenic, Aluminum, Iron, and Manganese

At the early phase of the study, total As analysis was performed by Battelle's ICP-MS laboratory, and total Al, Fe, and Mn were analyzed by Wilson Environmental Laboratories. Starting from June 1998, all four metals were analyzed by Battelle's ICP-MS laboratory. Therefore, QA data for only the total arsenic analysis before June 16, 1998 and QA data for all four metals afterwards are presented.

The laboratory duplicate and matrix spike (MS) analyses were performed every 10 samples (instead of 20 samples as required by the QAPP [Battelle, 1998]). All the samples were analyzed for four metals although metals other than arsenic may not be required for every sample. Therefore, Battelle's ICP-MS laboratory performed more QA/QC analyses than what were specified in the QAPP.

Greater than 99% of the precision results for all metals met the QA objective of ±25% (with only two Fe outliers: 27% on August 8, 1998 and 74% on December 22, 1998; three As outliers: 27% on August 18, 1998, 182% on October 1, 1998, and 27% on July 30, 1999; and four Al outliers: 26% and 33% on August 18, 1998, 48% on December 15, 1998, and 48% on January 25, 1999). The majority of the accuracy data associated with matrix spike analysis on August 31, 1998 exceeded the QA limits of 75 to 125%. It is suspected that MS analyses were not performed correctly on that day. After this problem had been identified, Battelle's Work Assignment Leader, laboratory QA officer, and Battelle's task leaders met to discuss the cause of the deviation. Corrective actions were taken including re-analyzing samples and adjusting the amount of spike added to samples (i.e., the Fe spike was increased from 50 to 100, 200, 225, or even as high as 2,000 µg/L because most of samples contain much more than 50 µg/L of Fe). As indicated in the *QA/QC Summary Report*, the MS data quality was significantly improved since November 3, 1998. Excluding the data on August 31, 1998, only five arsenic data were outside the acceptable range for accuracy. However, 15 Al, 26 Fe, and 14 Mn accuracy data did not meet the QA objective. With exceptions of one 23% and one 38% of accuracy, the Al accuracy data range from 65 to 125%. The Mn accuracy data range from 67 to 106% with the exception of one 37%. The Fe accuracy data range from 55 to 142% with exceptions of one 14%, one 23%, and one 38%.

All laboratory control samples showed %R within the acceptable QA limit of 75 to 125% except for six outliers for total Fe with %R ranging from 73 to 143%. Al was not spiked to laboratory control samples until November 3, 1998 after corrective actions were taken. The MDL of Fe is the same as target MDL; however, MDLs of other three metals were far below the target levels as specified in the QAPP (Battelle, 1998).

5.2.2 Water Quality Parameters

Water quality parameters include alkalinity, pH, turbidity, hardness (Ca and Mg), nitrate-nitrite, sulfate, fluoride, TDS, TSS and TOC. As shown in Table 3 of the *QA/QC Summary Report*, all the precision data were within the acceptable QA limit of ±25% except for two Mn analyses with a 29% RPD (April 10 and 17, 1998) and three nitrate-nitrite analyses with 40% RPD (August 6, 1998, January 13, 1999, and February 11, 1999). The high RPDs of these analyses might have been caused by the low measured concentrations in the samples that were close to the detection limits for Mn and nitrate-nitrite. The accuracy data indicate that only one Al (70% on March 2, 1998), two Mn (66% and 64% on May 12, 1998), and one Mg (126% on August 7, 1998) %R slightly exceeded the QA objectives of 75 to 125%. Although the matrix spike duplicate (MSD) analysis was not required by the QAPP, the accuracy and the precision data relating to MSD also were presented. The MS/MSD analyses are not applicable to pH and turbidity measurements, though. The laboratory did not perform MS/MSD analyses on Ca and Mg hardness analyses until October 15, 1998 upon Battelle's request. All laboratory control samples showed %R within the acceptable QA limit of 75 to 125%. Reporting limits were below the required levels for all the analytes except for sulfate. The reporting limits of sulfate was 5 mg/L, exceeding the required MDL of 3.66 mg/L. All precision, accuracy, and %R values for the TOC analysis were within acceptable QA limits with the exception of one accuracy value, which was slightly below the 75 to 125% range at 72% (February 21, 1999).

5.2.3 TCLP Metals

The TCLP metals analyzed in the spent AA samples included As, Se, Hg, Ba, Cd, Cr, Pb, and Ag. The precision data were within QA limits of ±25%. The accuracy of matrix spikes and percent recovery of laboratory control samples were all within QA limits of 75 to 125% except for one slightly elevated RPD for TCLP Se MS/MSD at 26% (November 17, 1998).

6.0 References

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APPENDIX A

Plant A Data

A.1 Complete Analytical Results from Long-Term Sampling at Plant A

A.2 Technical Data on Purolite® A-300

A.3 Water Usage Report

A.1 Complete Analytical Results from Long-Term Sampling at Plant A

Table A-1. Analytical Results from Long-Term Sampling, Plant A (September 1 to 22, 1998)

Sampling Date		9/1/98		9/8/98		9/15/98		9/22/98	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	89	68	85 84	83 83	85	92	89	88
Sulfate	mg/L	28	<5	25 24	<5 <5	25	<5	24	<5 (c)
Turbidity	NTU	<0.1	<0.1						
pH		7.6	7.3	7.5 7.5	7.5 7.5	7.6	7.7	7.6	7.6
Total Hardness	mg/L(a)	64.7	63.7						
Ca Hardness	mg/L(a)	57.4	56.7						
Mg Hardness	mg/L(a)	7.3	7.0						
Nitrate-Nitrite	mg/L(b)	0.3	0.2						
As (total)	µg/L	43.9 39.1	0.7 0.7	41.9	0.9	44.9	3.2	49.3	54.0
As (total soluble)	µg/L	45.4 47.9	1.2 1.2						
As (particulate)	µg/L	<0.1 <0.1	<0.1 <0.1						
As (III)	µg/L	0.4 0.4	<0.1 <0.1						
As (V)	µg/L	45.0 47.5	1.2 1.2						
Total Al	µg/L	16.4 21.5	<11 13.4	23.9	13.4	32.2	21.7	23.8	19.4
Total Fe	µg/L	<30 <30	<30 <30	<30	<30	<30	<30	<30	<30
Total Mn	µg/L	2.1 1.8	<0.5 <0.5	0.9	<0.5	2.8	<0.5	0.8	<0.5
Dissolved Al	µg/L	<11 <11	<11 <11						
Dissolved Fe	µg/L	<30 <30	<30 <30						
Dissolved Mn	µg/L	1.2 1.0	<0.5 <0.5						

(a) Measured as $CaCO_3$.
(b) Combined NO_3–N and NO_2–N.
(c) Confirmed by sample re-analysis.
IN = inlet; OU = outlet.

Table A-2. Analytical Results from Long-Term Sampling, Plant A (September 29 to October 20, 1998)

Sampling Date		9/29/98		10/6/98		10/13/98		10/20/98	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	92	85	89 89	89 88	86	72	92	78
Sulfate	mg/L	26	20	25 25	25 24	24	16	26	22
Turbidity	NTU	0.1	<0.1						
pH		7.6	7.5	7.7 7.7	7.6 7.6	7.6	7.5	7.6	7.4
Total Hardness	mg/L(a)	83.9	79.0						
Ca Hardness	mg/L(a)	75.4	70.4						
Mg Hardness	mg/L(a)	8.4	8.6						
Nitrate-Nitrite	mg/L(b)	0.5	0.8						
As (total)	µg/L	51.6 59.2	81.0(c) 82.0	52.5	43.4	35.1	27.2	50.4	28.9
As (total soluble)	µg/L	60.9 59.9	95.5 97.0						
As (particulate)	µg/L	<0.1 <0.1	<0.1 <0.1						
As (III)	µg/L	0.7 0.6	0.3 0.3						
As (V)	µg/L	60.2 59.3	95.2 96.7						
Total Al	µg/L	14.4 15.8	15.6 16.0	24.3	<11	26.4	13.9	15.7	11.7
Total Fe	µg/L	<30 <30	<30 <30	<30	<30	<30	<30	<30	<30
Total Mn	µg/L	0.6 0.5	<0.5 <0.5	1.0	<0.5	1.3	<0.5	0.7	<0.5
Dissolved Al	µg/L	<11 <11	<11 <11						
Dissolved Fe	µg/L	<30 <30	<30 <30						
Dissolved Mn	µg/L	<0.5 <0.5	<0.5 <0.5						

(a) Measured as CaCO$_3$.
(b) Combined NO$_3$–N and NO$_2$–N.
(c) Confirmed by sample re-analysis.
IN = inlet; OU = outlet.

Table A-3. Analytical Results from Long-Term Sampling, Plant A (October 27 to November 17, 1998)

Sampling Date		10/27/98		11/3/98		11/10/98(c)		11/17/98	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	92	79	90 90	82 82	91	49	86	70
Sulfate	mg/L	26	21	27 25	23 22	24	14	23	<5
Turbidity	NTU	<0.1	<0.1						
pH		7.5	7.4	7.5 7.5	7.5 7.5	7.5	7.3	7.6	7.4
Total Hardness	mg/L(a)	75.6	70.7						
Ca Hardness	mg/L(a)	67.7	62.9						
Mg Hardness	mg/L(a)	7.9	7.8						
Nitrate-Nitrite	mg/L(b)	0.6	0.8						
As (total)	µg/L	48.9 47.2	27.9 27.0	49.7	34.4	48.6	20.5	37.6	1.2
As (total soluble)	µg/L	59.8 59.5	32.3 32.5						
As (particulate)	µg/L	<0.1 <0.1	<0.1 <0.1						
As (III)	µg/L	0.2 0.1	<0.1 <0.1						
As (V)	µg/L	59.6 59.4	32.3 32.5						
Total Al	µg/L	19.0 <11	<11 11.9	<11	<11	12.0	<11	<11	<11
Total Fe	µg/L	<30 <30	<30 <30	<30	<30	<30	<30	<30	<30
Total Mn	µg/L	0.6 0.5	<0.5 <0.5	0.8	<0.5	0.6	<0.5	0.5	<0.5
Dissolved Al	µg/L	<11 <11	<11 <11						
Dissolved Fe	µg/L	<30 <30	<30 <30						
Dissolved Mn	µg/L	0.5 <0.5	<0.5 <0.5						

(a) Measured as $CaCO_3$.

(b) Combined NO_3–N and NO_2–N.

(c) Samples were collected after the AX300 tank was regenerated on 11/10/98.

IN = inlet; OU = outlet.

Table A-4. Analytical Results from Long-Term Sampling, Plant A (Nov. 24 to Dec. 15, 1998)

Sampling Date		11/24/98(c)		12/01/98		12/08/98		12/15/98	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)			90	90	87 88	90 90	78	87
Sulfate	mg/L			23	<5	26 26	<5 <5	22	<5
Turbidity	NTU			<0.1	<0.1				
pH				7.2	7.3	7.6 7.6	7.6 7.6	7.4	7.6
Total Hardness	mg/L(a)			70	67				
Ca Hardness	mg/L(a)			61.7	59.7				
Mg Hardness	mg/L(a)			7.9	7.7				
Nitrate-Nitrite	mg/L(b)			0.5	0.1				
As (total)	µg/L			37.3 38.7	0.9 0.9	42.5	3.8	28.6	33.6
As (total soluble)	µg/L			42.0 43.6	0.9 1.0				
As (particulate)	µg/L			<0.1 <0.1	<0.1 <0.1				
As (III)	µg/L			0.7 0.7	0.1 0.1				
As (V)	µg/L			41.3 42.9	0.8 0.9				
Total Al	µg/L			14.4 17.3	11.6 11.1	13.6	11.5	<11	<11
Total Fe	µg/L			32.1 31.2	34.8 33.4	<30	<30	<30	<30
Total Mn	µg/L			0.8 0.9	<0.5 <0.5	1.4	<0.5	<0.5	<0.5
Dissolved Al	µg/L			2.9 3.9	<11 <11				
Dissolved Fe	µg/L			15.6 11.5	<30 <30				
Dissolved Mn	µg/L			0.8 0.6	<0.5 <0.5				

(a) Measured as $CaCO_3$.
(b) Combined NO_3–N and NO_2–N.
(c) No sampling due to Thanksgiving holiday.
IN = inlet; OU = outlet.

Table A-5. Analytical Results from Long-Term Sampling, Plant A (Dec. 22,1998 to Jan. 12, 1999)

Sampling Date		12/22/98(c)		12/29/98(c)		01/05/99		01/12/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)					89	82	91	81
Sulfate	mg/L					23	21	23	21
Turbidity	NTU							<0.1	<0.1
pH						7.6	7.5	7.6	7.5
Total Hardness	mg/L(a)							70	67
Ca Hardness	mg/L(a)							62.4	59.4
Mg Hardness	mg/L(a)							7.6	7.2
Nitrate-Nitrite	mg/L(b)							0.5	0.7
As (total)	µg/L					37.7	45.1	39.4 38.7	34.9 32.2
As (total soluble)	µg/L							41.5 42.1	29.0 28.7
As (particulate)	µg/L							<0.1 <0.1	5.9 3.5
As (III)	µg/L							0.8 0.7	0.3 0.4
As (V)	µg/L							40.7 41.4	28.7 28.3
Total Al	µg/L					<11	<11	22.1 20.3	13.6 12.2
Total Fe	µg/L					40.1	40.3	80.2 74.1	<30 <30
Total Mn	µg/L					<0.5	<0.5	<0.5 0.8	0.8 1.4
Dissolved Al	µg/L							<11 <11	<11 <11
Dissolved Fe	µg/L							<30 <30	<30 <30
Dissolved Mn	µg/L							1.0 0.7	2.7 <0.5

(a) Measured as CaCO$_3$.
(b) Combined NO$_3$–N and NO$_2$–N.
(c) No sampling due to Christmas holiday.
IN = inlet; OU = outlet.

Table A-6. Analytical Results from Long-Term Sampling, Plant A (Jan 19 to Feb 9, 1999)

Sampling Date		01/19/99		01/26/99		02/02/99		02/09/99(c)	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	86 85	73 73	77	70	88	74	83	41
Sulfate	mg/L	23 23	22 21	20	20	23	20	23	<5
Turbidity	NTU							<0.1	<0.1
pH		7.4 7.4	7.4 7.4	7.5	7.5	7.6	7.4	7.5	7.2
Total Hardness	mg/L(a)							74	69
Ca Hardness	mg/L(a)							65.7	61.9
Mg Hardness	mg/L(a)							8.0	7.2
Nitrate-Nitrite	mg/L(b)							0.5	0.4
As (total)	µg/L	34.7	28.1	31.9	22.8	42.1	22.2	39.1 39.3	3.7 3.4
As (total soluble)	µg/L							39.7 41.9	3.6 3.5
As (particulate)	µg/L							<0.1 <0.1	0.1 <0.1
As (III)	µg/L							0.7 0.8	<0.1 <0.1
As (V)	µg/L							39.0 41.1	3.6 3.5
Total Al	µg/L	14.0	<11	<11	<11	34.1	60.0	27.4 19.9	<11 11.8
Total Fe	µg/L	<30	<30	41.3	48.3	<30	<30	41.9 <30	<30 <30
Total Mn	µg/L	1.2	0.7	0.6	<0.5	<0.5	<0.5	3.1 2.0	<0.5 <0.5
Dissolved Al	µg/L							<11 <11	<11 <11
Dissolved Fe	µg/L							<30 <30	<30 <30
Dissolved Mn	µg/L							<0.5 <0.5	<0.5 <0.5

(a) Measured as $CaCO_3$.
(b) Combined NO_3–N and NO_2–N.
(c) The AX300 tank was regenerated on 2/6/99.
IN = inlet; OU = outlet.

Table A-7. Analytical Results from Long-Term Sampling, Plant A (Feb 16 to Mar 9, 1999)

Sampling Date		02/16/99(c)		02/23/99		03/2/99(d)		03/9/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)			77 77	82 82			79	73
Sulfate	mg/L			23 23	<5 <5			25	<5
Turbidity	NTU							<0.1	<0.1
pH				7.5 7.5	7.5 7.5			7.6	7.5
Total Hardness	mg/L(a)							64	61
Ca Hardness	mg/L(a)							56.2	53.9
Mg Hardness	mg/L(a)							7.5	7.2
Nitrate-Nitrite	mg/L(b)							0.8	0.9
As (total)	µg/L			33.3	1.2			42.5 41.5	9.3 9.6
As (total soluble)	µg/L							39.4 38.1	11.3 11.4
As (particulate)	µg/L							3.1 3.4	<0.1 <0.1
As (III)	µg/L							0.6 0.5	0.3 0.2
As (V)	µg/L							38.8 37.6	11.0 11.2
Total Al	µg/L			<11	<11			<11 <11	15.0 <11
Total Fe	µg/L			36.6	36.5			<30 <30	<30 <30
Total Mn	µg/L			0.6	0.5			<0.5 <0.5	0.6 0.6
Dissolved Al	µg/L							<11 <11	<11 <11
Dissolved Fe	µg/L							<30 <30	<30 <30
Dissolved Mn	µg/L							<0.5 <0.5	<0.5 <0.5

(a) Measured as CaCO$_3$.
(b) Combined NO$_3$–N and NO$_2$–N.
(c) No sampling due to sampler's vacation.
(d) No sampling due to FedEx mis-delivery of sample cooler.
IN = inlet; OU = outlet.

Table A-8. Analytical Results from Long-Term Sampling, Plant A (Mar 16 to Apr 6, 1999)

Sampling Date		03/16/99(c)		03/23/99		03/30/99		04/06/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	63 61	65 64	93	21	66	71	73	82
Sulfate	mg/L	21 20	18 18	26	<5	21	<5	19	<5
Turbidity	NTU							0.3	<0.1
pH		7.2 7.2	7.4 7.4	7.7	7.0	7.5	7.6	7.5	7.7
Total Hardness	mg/L(a)							65	63
Ca Hardness	mg/L(a)							57.9	55.7
Mg Hardness	mg/L(a)							7.4	7.2
Nitrate-Nitrite	mg/L(b)							0.6	0.1
As (total)	µg/L	23.3	47.6	46.4	7.8	25.3	1.2	31.1 31.9	1.2 1.2
As (total soluble)	µg/L							31.4 30.8	1.2 1.2
As (particulate)	µg/L							<0.1 1.1	<0.1 <0.1
As (III)	µg/L							0.6 0.6	0.2 0.1
As (V)	µg/L							30.8 30.2	1.0 1.1
Total Al	µg/L	14.2	<11	18.0	<11	19.4	<11	<11 <11	<11 <11
Total Fe	µg/L	<30	<30	<30	<30	<30	<30	<30 <30	<30 <30
Total Mn	µg/L	1.3	0.8	1.5	1.4	<0.5	<0.5	<0.5 <0.5	<0.5 <0.5
Dissolved Al	µg/L							<11 <11	<11 <11
Dissolved Fe	µg/L							<30 <30	<30 <30
Dissolved Mn	µg/L							<0.5 <0.5	<0.5 <0.5

(a) Measured as CaCO$_3$.
(b) Combined NO$_3$–N and NO$_2$–N.
(c) The AX300 tank was regenerated on 3/21/99 after samples were collected.
IN = inlet; OU = outlet.

Table A-9. Analytical Results from Long-Term Sampling, Plant A (Apr 13 to May 4, 1999)

Sampling Date		04/13/99		04/20/99(C)		04/27/99		05/04/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	87 87	84 85	73	29	87	73	88	89
Sulfate	mg/L	25 24	<5 <5	22	<5	23	<5	23	<5
Turbidity	NTU							0.2	<0.1
pH		7.7 7.6	7.7 7.7	7.4	7.1	7.6	7.4	7.8	7.7
Total Hardness	mg/L(a)							64	68
Ca Hardness	mg/L(a)							56.7	60.2
Mg Hardness	mg/L(a)							7.3	7.5
Nitrate-Nitrite	mg/L(b)							0.4	3.3
As (total)	µg/L	43.9	6.4	26.0	23.4	39.8	2.6	53.8 48.2	2.6 2.6
As (total soluble)	µg/L							52.7 52.9	2.5 2.3
As (particulate)	µg/L							1.1 <0.1	0.1 0.3
As (III)	µg/L							1.4 1.2	0.5 0.4
As (V)	µg/L							51.3 51.7	2.0 1.9
Total Al	µg/L	13.2	<11	<11	<11	49.4	12.1	14.0 13.1	<11 <11
Total Fe	µg/L	<30	<30	<30	<30	<30	<30	<30 <30	<30 <30
Total Mn	µg/L	0.6	0.6	0.5	1.0	1.4	0.8	0.8 0.8	0.7 0.7
Dissolved Al	µg/L							<11 12.9	19.5 <11
Dissolved Fe	µg/L							<30 <30	<30 <30
Dissolved Mn	µg/L							0.5 0.6	0.8 0.8

(a) Measured as CaCO$_3$.
(b) Combined NO$_3$–N and NO$_2$–N.
(c) The AX300 tank was regenerated on 4/18/99.
IN = inlet; OU = outlet.

Table A-10. Analytical Results from Long-Term Sampling, Plant A (May 11, to Jun 1, 1999)

Sampling Date		05/11/99		05/18/99[(C)]		05/25/99		06/01/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L[(a)]	83 84	87 86	83	44	92	82	88	62
Sulfate	mg/L	24 23	<5 <5	23	<5	24	<5	24	25
Turbidity	NTU							<0.1	<0.1
pH		7.5 7.5	7.6 7.6	7.6	7.3	7.7	7.5	7.6	7.6
Total Hardness	mg/L[(a)]							64	65
Ca Hardness	mg/L[(a)]							56.7	58.2
Mg Hardness	mg/L[(a)]							7.0	7.1
Nitrate-Nitrite	mg/L[(b)]							0.3	0.2
As (total)	µg/L	43.9	1.9	42.7	10.1	45.9	1.7	44.1 43.9	1.6 1.5
As (total soluble)	µg/L							44.9 44.7	1.5 1.5
As (particulate)	µg/L							<0.1 <0.1	0.1 <0.1
As (III)	µg/L							1.1 1.1	0.4 0.2
As (V)	µg/L							43.7 43.6	1.0 1.3
Total Al	µg/L	18.3	13.4	12.0	<11	16.3	13.5	<11 <11	<11 <11
Total Fe	µg/L	<30	<30	<30	<30	31.7	<30	<30 <30	<30 <30
Total Mn	µg/L	1.1	0.5	3.1	0.8	0.6	0.8	0.7 0.8	0.7 0.7
Dissolved Al	µg/L							<11 <11	<11 <11
Dissolved Fe	µg/L							<30 <30	<30 <30
Dissolved Mn	µg/L							0.5 0.5	0.7 0.8

(a) Measured as $CaCO_3$.
(b) Combined NO_3–N and NO_2–N.
(c) The AX300 tank was regenerated on 5/16/99.
IN = inlet; OU = outlet.

Table A-11. Analytical Results from Long-Term Sampling, Plant A (June 8, to Jun 17, 1999)

Sampling Date		06/08/99		06/13/99[c]		06/14/99		06/15/99		06/17/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L[a]	90 91	91 92	77	89	92	40	86	48	86	69
Sulfate	mg/L	23 23	<5 <5	21	<5	25	16	24	13	23	<5
Turbidity	NTU										
pH		7.5 7.6	7.7 7.7	7.4	7.7	7.6	7.2	7.6	7.2	7.7	7.5
Total Hardness	mg/L[a]										
Ca Hardness	mg/L[a]										
Mg Hardness	mg/L[a]										
Nitrate-Nitrite	mg/L[b]										
As (total)	µg/L	26.6	4.7	28.4	23.1	31.7	45.5	43.3	24.2	43.9	12.6
As (total soluble)	µg/L										
As (particulate)	µg/L										
As (III)	µg/L										
As (V)	µg/L										
Total Al	µg/L	11.3	13.8	12.6	11.3	<11	12.5	105	13.8	<11	11.3
Total Fe	µg/L	<30	<30	37.1	<30	<30	<30	<30	<30	33.6	117
Total Mn	µg/L	0.6	0.8	0.7	0.5	0.8	0.7	1.2	0.8	0.9	1.0
Dissolved Al	µg/L										
Dissolved Fe	µg/L										
Dissolved Mn	µg/L										

(a) Measured as $CaCO_3$.
(b) Combined NO3–N and NO2–N.
(c) The AX300 tank was regenerated on 6/13/99 after samples were collected.
IN = inlet; OU = outlet.

A.2 Technical Data on Purolite® A-300

PUROLITE® Technical Data A-300, A-300E

Strong Base Type II Anion Exchange Resin

PRODUCT DESCRIPTION

Purolite A-300 is a Type II, strongly basic gel anion exchange resin with outstanding operating capacity and excellent regeneration efficiency. A-300 removes all ions including silica and CO_2, however, it operates best on waters having a high percentage of strong acids (FMA). A-300 can be used in all types of demineralization equipment where regeneration efficiency and high operating capacities are needed. Purolite A-300 has excellent physical stability which allows for long life and better efficiency within the operating bed. Whole bead counts are a minimum of 92% clear beads with mechanical strengths ranging over 300 grams. Purolite A-300 can be regenerated with sodium chloride to remove alkalinity from different water supplies. This dealkalization by ion exchange prevents the formation of insoluble carbonate precipitates and stops corrosion due to the formation of carbonic acid. A-300 can also remove nitrates when regenerated with salt. In some dealkalization cases, small amounts of caustic is used in combination with salt during the regeneration in order to enhance the resin operation. This addition gives higher operating capacity and lower silica leakage.
Purolite A-300E is a type 2 strong base anion devoid of taste and odor. A-300E meets the requirements of paragraph 121.1148 of the Food Additives Regulation of the FDA.
Capacities and Leakages of A-300 or A-300E are based on the regenerant reaching the bed at either 70° or 95°F. With some water supplies, it will be necessary to preheat the beds prior to the introduction of the regenerant.
In water supplies where the alkalinity is in excess of 50%, keep in mind that you may be unable to achieve these leakages and capacities. This is because CO_2 passing from the cation reacts with anionic sites forming HCO_3. During the regeneration process of the anion, HCO_3 is displaced by NaOH. Additional NaOH then reacts with the HCO_3 forming Na_2CO_3. Since the above leakages and capacities are based on having excess NaOH above theory, it may be necessary to compensate for this problem.

Typical Chemical and Physical Characteristics

Polymer Structure	Polystyrene crosslinked with divinylbenzene
Functional Groups	$R\,(CH_3)_2\,(C_2H_4OH)N^+$
Physical Appearance	Clear Spherical Beads
Ionic Form (as shipped)	Chloride
Screen Size, U.S. Std. Mesh (Wet)	16-50
Particle Size Range	+16 mesh<5%, -50 mesh<1%
Uniformity Coefficient	1.7 maximum
Water Retention	40-45% (Cl form)
Swelling	Salt –OH, 10%
pH Limitations	None
Temperature Limitations	120°F in OH form max., 185°F in Cl form max.
Chemical Resistance	Unaffected by dilute acids, alkalies, and most solvents
Whole Clear Beads	92% minimum
Shipping Weight	44 lbs./ft.^{3} (705 g/l)
Total Capacity	1.45-1.6 meq./ml. min. Volumetric 3.5-3.7 meq./gm. min. Weight
Standard Packaging	5 cu. ft. double polyethylene-lined fiber drums

PUROLITE® The Purolite Company
Division of Bro-tech Corporation 150 Monument Road, Bala Cynwyd, PA 19004

STANDARD OPERATING CONDITIONS
(TWO STAGE DEMINERALIZER)

Operation	**Rate**	**Solution**	**Minutes**	**Amount**
Service	1-5 gpm/ft³	Effluent from Cation exchanger		
Backwash	2-3 gpm/ft² (50-70°F)	Influent Water	5-20	10-25 gals./ft³
Regeneration	0.2-0.8 gpm/ft³	4% NaOH	60	4-10 lbs.
Rinse (Slow)	0.2-0.8 gpm/ft³	Decationized Water	60	15-30 gals./ft³
Rinse (Fast)	1-5 gpm/ft³ (same as Service Flow Rate)	Decationized Water		25-45 gals./ft³

Backwash Expansion	50-75%
Design Rising Space	100%

HYDRAULICS

Pressure drop of a fluid passing through an ion exchange column is related to the flow rates, viscosity and temperature of the fluid. Typical values of pressure drop are found in Figure 2.

Backwash removes all particulate matter filtered out by the exchanger and regrades the bed eliminating any channels which may have formed. Normally a backwash rate that expands the bed 50-75% for 5 to 10 minutes or till the effluent is clear is recommended. Flow rate for the backwash should be achieved gradually to prevent resin loss. See Figure 1.

REGENERATION

Purolite A-300 is supplied in the chloride form and must be regenerated with a good grade of sodium hydroxide.

Both the slow and fast rinse remove the excess regenerant from the exchanger bed. The slow rinse displaces the regenerant while the fast rinse rinses out all excess regenerant.

INFLUENT LIMITATION

Maximum Free Chlorine	0.05 ppm
Maximum Turbidity	5 A.P.H.A. Units
Maximum Iron and Heavy Metals	0.1 ppm

DEALKALIZATION CAPACITY

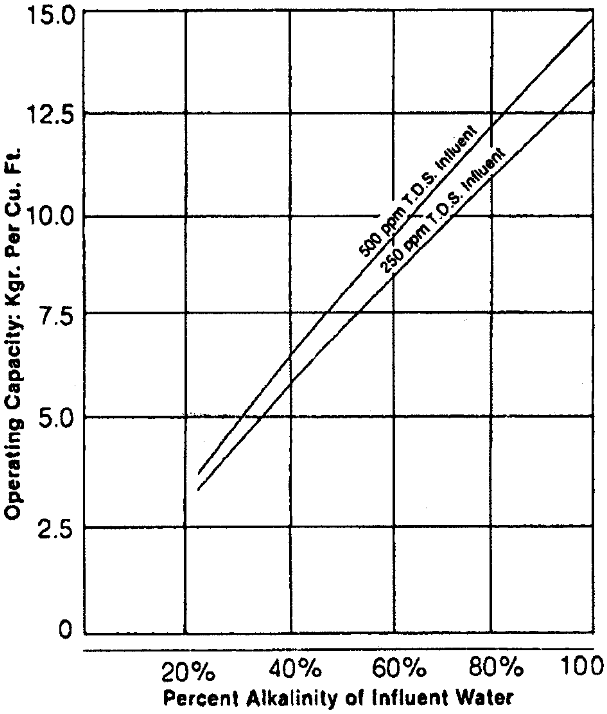


Fig. 3

Capacity for Dealkalization
5 lbs. NaCl/cubic foot
0.25 lbs. NaOH/cubic foot

Down Flow Regeneration
30 inch Bed Depth
Flowrate of 2 gpm/cubic foot
To 10% alkalinity End Point

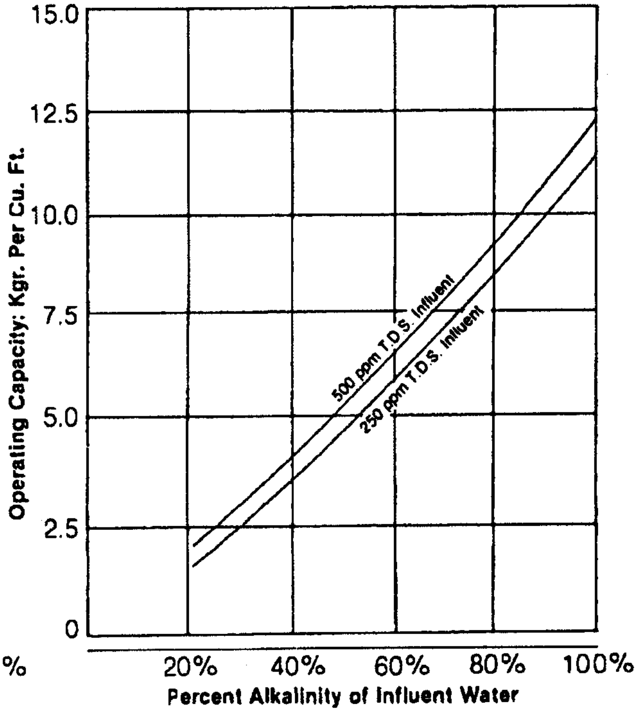


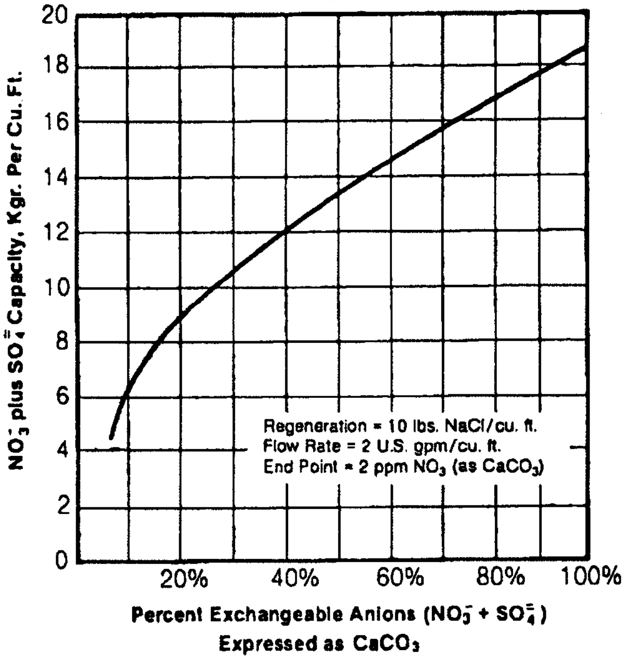
Fig. 4

Capacity for Dealkalization
5 lbs. NaCl/cubic foot

Down Flow Regeneration
30 inch Bed Depth
Flowrate of 2 gpm/cubic foot
To 10% Alkalinity End Point

NITRATE REMOVAL

CAPACITY FOR NITRATE (NO_3) PLUS SULFATE (SO_4) REMOVAL



CAPACITY IN KILOGRAINS/Cu. ft.

Lbs. NaOH/Cu. Ft. @ 70°F(21°C) 100% Concentration	% Silica of Total Anion Analysis			
	10%	20%	30%	40%
4	20.0	19.0	17.9	17.3
5	22.7	21.0	19.9	19.0
6	24.0	22.6	21.8	20.4
7	25.2	23.7	23.1	21.8
8	25.8	24.6	24.0	22.9
9	26.3	25.2	24.7	23.7
10	26.6	25.5	25.0	24.3

Base Operating Capacity (Kgr.)

Lbs. NaOH/Cu. Ft. @ 95°F(35°C) 100% Concentration	% Silica of Total Anion Analysis			
	10%	20%	30%	40%
4	22.9	22.0	21.0	20.1
5	24.1	23.1	22.2	21.3
6	25.0	24.0	23.0	22.2
7	26.0	24.9	23.8	23.1
8	26.7	25.4	24.5	23.8
9	26.9	26.0	25.2	24.4
10	27.0	26.2	25.4	24.6

Base Operating Capacity (Kgr.)

A.3 Water Usage Report

Plant A Water Usage Report

Date of Regeneration	Cumulative Usage (gal)	Water Treated per Regeneration (gal)	(BVs)
02/01/1995	1,886,500		
05/01/1995	2,031,200	144,700	9,672
08/01/1995	2,167,400	136,200	9,104
11/03/1995	2,300,000	132,600	8,864
02/01/1996	2,393,900	93,900	6,277
05/01/1996	2,502,800	108,900	7,279
08/09/1996	2,589,300	86,500	5,782
11/01/1996	2,707,800	118,500	7,921
02/01/1997	2,810,400	102,600	6,858
05/10/1997	2,948,500	138,100	9,231
08/08/1997	3,034,600	86,100	5,755
11/05/1997	3,136,100	101,500	6,785
02/20/1998	3,279,000	142,900	9,552
05/06/1998	3,406,200	127,200	8,503
08/20/1998	3,517,500	111,300	7,440
11/10/1998	3,658,500	141,000	9,425
02/06/1999	3,775,700	117,200	7,834
03/21/1999	3,834,500	58,800	3,930
04/18/1999	3,877,100	42,600	2,848
05/16/1999	3,926,600	49,500	3,309
06/13/1999	3,980,100	53,500	3,576
07/16/1999	4,013,300	33,200	2,219

Bed volume = 2 cu ft = 14.96 gal.

* Regeneration performed on a quarterly basis prior to 2/6/99 and on a monthly basis after March 21, 1999.

APPENDIX B

Plant B Data

B.1 Complete Analytical Results from Long-Term Sampling at Plant B

Table B-1. Analytical Results from Long-Term Sampling, Plant B (September 3 to 22, 1998)

Sampling Date		9/3/98		9/8/98		9/16/98		9/22/98	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	65	6	63 63	12 16	65	5	65	6
Sulfate	mg/L	47	<5	47 46	<5 <5	45	<5	45	<5
Turbidity	NTU	0.5	<0.1	–	–	–	–	–	–
pH		8.1	6.7	8.0 8.0	7.5 7.5	8.5	8.5	8.3	8.8
Total Hardness	mg/L(a)	37	4.0	–	–	–	–	–	–
Ca Hardness	mg/L(a)	31.2	3.2	–	–	–	–	–	–
Mg Hardness	mg/L(a)	5.4	0.8	–	–	–	–	–	–
NO_3–NO_2 (N)	mg/L(b)	0.04	0.03	–	–	–	–	–	–
As (total)	µg/L	52.7 47.1	1.7 1.7	60.5	0.8	57.6	4.5	63.4	2.6
As (soluble)	µg/L	57.7 –	2.8 3.0	–	–	–	–	–	–
As (particulate)	µg/L	<0.1 –	<0.1 <0.1	–	–	–	–	–	–
As (III)	µg/L	0.9 –	0.3 0.3	–	–	–	–	–	–
As (V)	µg/L	56.8 –	2.5 2.7	–	–	–	–	–	–
Total Al	µg/L	24.0 20.7	20.0 14.3	17.3	17.1	26.8	20.1	28.1	27.5
Total Fe	µg/L	142 134	<30 <30	87.2	<30	<30	<30	126	<30
Total Mn	µg/L	3.0 2.7	<0.5 <0.5	2.3	<0.5	<0.5	<0.5	2.5	<0.5
Dissolved Al	µg/L	<11 –	<11 <11	–	–	–	–	–	–
Dissolved Fe	µg/L	<30 –	<30 <30	–	–	–	–	–	–
Dissolved Mn	µg/L	2.0 –	<0.5 <0.5	–	–	–	–	–	–

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; OU = outlet.

Table B-2. Analytical Results from Long-Term Sampling, Plant B (September 30 to October 20, 1998)

Sampling Date		9/30/98		10/6/98		10/13/98		10/20/98	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	63	6	63 63	17 17	64	10	64	6
Sulfate	mg/L	46	<5	46 46	<5 <5	45	<5	43	<5
Turbidity	NTU	0.6	0.1						
pH		8.2	7.2	8.5 8.5	8.5 8.4	8.1	7.6	8.2	7.0
Total Hardness	mg/L(a)	46.7	8.3						
Ca Hardness	mg/L(a)	40.7	7.5						
Mg Hardness	mg/L(a)	6.0	0.8						
NO_3–NO_2 (N)	mg/L(b)	0.04	<0.02						
As (total)	µg/L	58.0 34.0(c)	2.4 3.8	58.2	1.1	58.6	1.0	53.7	1.6
As (soluble)	µg/L	57.1 56.2	2.0 1.9						
As (particulate)	µg/L	0.9 <0.1	0.4 1.9						
As (III)	µg/L	1.3 1.3	0.2 0.3						
As (V)	µg/L	55.8 54.9	1.8 1.6						
Total Al	µg/L	23.6 21.6	19.0 16.8	15.2	<11	<11	<11	12.0	12.3
Total Fe	µg/L	116 89.6	<30 <30	82.3	<30	49.6	<30	56.2	<30
Total Mn	µg/L	3.4 3.3	<0.5 <0.5	2.3	<0.5	2.2	0.5	2.2	<0.5
Dissolved Al	µg/L	<11 <11	15.2 <11						
Dissolved Fe	µg/L	<30 <30	<30 <30						
Dissolved Mn	µg/L	2.8 2.9	<0.5 <0.5						

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
(c) Confirmed by sample reanalysis.
IN = inlet; OU = outlet.

Table B-3. Analytical Results from Long-Term Sampling, Plant B (October 29 to November 17, 1998)

Sampling Date		10/29/98		11/5/98		11/10/98		11/17/98	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	63	10	63 64	6 6	64	16	65	9
Sulfate	mg/L	43	<5	44 44	<5 <5	44	<5	44	<5
Turbidity	NTU	0.5	<0.1						
pH		8.4	7.4	8.2 8.3	8.0 8.0	8.6	8.6	8.2	7.2
Total Hardness	mg/L(a)	40	<2.0						
Ca Hardness	mg/L(a)	34.5	<0.5						
Mg Hardness	mg/L(a)	5.8	<0.8						
NO_3–NO_2 (N)	mg/L(b)	0.03	<0.02						
As (total)	µg/L	57.7 57.7	1.1 1.0	64.5	1.3	61.7	1.0	55.8	1.2
As (soluble)	µg/L	56.7 55.9	0.9 0.9						
As (particulate)	µg/L	1.0 1.8	0.2 0.1						
As (III)	µg/L	0.8 0.7	0.2 0.1						
As (V)	µg/L	55.9 55.2	0.7 0.8						
Total Al	µg/L	<11 12.6	<11 <11	14.0	16.9	11.0	<11	19.7	15.0
Total Fe	µg/L	137 88.4	<30 <30	50.5	<30	91.4	<30	<30	<30
Total Mn	µg/L	3.5 2.5	<0.5 <0.5	2.1	<0.5	3.0	<0.5	1.4	<0.5
Dissolved Al	µg/L	<11 <11	<11 <11						
Dissolved Fe	µg/L	<30 <30	<30 <30						
Dissolved Mn	µg/L	2.5 2.6	<0.5 <0.5						

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; OU = outlet.

Table B-4. Analytical Results from Long-Term Sampling, Plant B (November 24 to December 15, 1998)

Sampling Date		11/24/98(c)		12/01/98		12/08/98		12/15/98	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)			63	8.0	63 64	5 5	64	12
Sulfate	mg/L			44	<5	46 45	<5 <5	47	<5
Turbidity	NTU			<0.1	<0.1				
pH				8.1	7.2	8.2 8.2	7.1 7.1	8.4	8.3
Total Hardness	mg/L(a)			37	<2.0				
Ca Hardness	mg/L(a)			31.5	<1.0				
Mg Hardness	mg/L(a)			5.8	<1.0				
NO_3–NO_2 (N)	mg/L(b)			0.02	<0.02				
As (total)	µg/L			54.4 54.3	1.5 1.6	57.0	1.7	58.5	2.1
As (soluble)	µg/L			43.7 44.0	1.6 1.6				
As (particulate)	µg/L			10.7 10.3	<0.1 <0.1				
As (III)	µg/L			0.8 0.6	0.1 0.1				
As (V)	µg/L			42.9 43.4	1.5 1.5				
Total Al	µg/L			22.0 23.3	18.5 12.3	<11	13.5	<11	<11
Total Fe	µg/L			104 85.4	51.2 42.4	<30	<30	<30	<30
Total Mn	µg/L			2.2 2.1	<0.5 <0.5	1.8	<0.5	1.0	<0.5
Dissolved Al	µg/L			<11 <11	<11 <11				
Dissolved Fe	µg/L			<30 <30	<30 <30				
Dissolved Mn	µg/L			1.7 1.7	<0.5 <0.5				

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
(c) No sampling due to Thanksgiving holiday.
IN = inlet; OU = outlet.

Table B-5. Analytical Results from Long-Term Sampling, Plant B (Dec 22, 1998 to Jan 12, 1999)

Sampling Date		12/22/98(c)		12/29/98(c)		01/05/99		01/12/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)					65	6	63	5
Sulfate	mg/L					45	<5	49	<5
Turbidity	NTU							0.1	<0.1
pH						8.3	6.5	8.2	6.4
Total Hardness	mg/L(a)							35	<2.0
Ca Hardness	mg/L(a)							29.7	<0.5
Mg Hardness	mg/L(a)							5.3	<0.8
NO_3–NO_2 (N)	mg/L(b)							<0.02	<0.02
As (total)	µg/L					40.8	1.6	51.9 52.7	1.5 1.0
As (soluble)	µg/L							60.5(d) 60.3(d)	1.5 1.5
As (particulate)	µg/L							<0.1 <0.1	<0.1 <0.1
As (III)	µg/L							0.2 0.6	<0.1 <0.1
As (V)	µg/L							60.3 59.7	1.5 1.5
Total Al	µg/L					<11	<11	26.0 26.3	13.0 13.3
Total Fe	µg/L					90.7	51.7	124 118	<30 <30
Total Mn	µg/L					<0.5	<0.5	2.2 2.1	<0.5 <0.5
Dissolved Al	µg/L							<11 38.0	<11 <11
Dissolved Fe	µg/L							<30 212	<30 <30
Dissolved Mn	µg/L							3.0 1.4	<0.5 <0.5

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
(c) No sampling due to Christmas holiday.
(d) Confirmed by sample re-run.
IN = inlet; OU = outlet.

Table B-6. Analytical Results from Long-Term Sampling, Plant B (Jan 19 to Feb 9, 1999)

Sampling Date		01/19/99		01/26/99		02/02/99		02/09/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	63 64	10 9	64	8	64	8	64	10
Sulfate	mg/L	46 45	<5 <5	46	<5	44	<5	42	<5
Turbidity	NTU							0.6	0.2
pH		8.4 8.4	6.9 6.9	7.8	8.3	8.3	6.8	8.3	6.7
Total Hardness	mg/L(a)							39	<2.0
Ca Hardness	mg/L(a)							33.7	<1.0
Mg Hardness	mg/L(a)							5.6	<1.0
NO_3–NO_2 (N)	mg/L(b)							0.02	<0.02
As (total)	µg/L	51.3	1.4	53.4	1.3	57.9	1.0	57.1 57.6	1.3 1.3
As (soluble)	µg/L							63.7 61.7	1.3 1.3
As (particulate)	µg/L							<0.1 <0.1	<0.1 <0.1
As (III)	µg/L							0.8 0.6	0.1 0.1
As (V)	µg/L							62.9 61.1	1.2 1.2
Total Al	µg/L	21.4	<11	<11	<11	68.3	131	66.4 35.0	<11 <11
Total Fe	µg/L	139	<30	51.3	<30	123	48.9	111 114	<30 <30
Total Mn	µg/L	3.0	1.1	0.6	0.7	1.6	<0.5	1.3 1.5	<0.5 <0.5
Dissolved Al	µg/L							<11 <11	<11 <11
Dissolved Fe	µg/L							79.0 74.3	<30 <30
Dissolved Mn	µg/L							1.4 1.4	<0.5 <0.5

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; OU = outlet.

Table B-7. Analytical Results from Long-Term Sampling, Plant B (Feb 16 to Mar 9, 1999)

Sampling Date		02/16/99		02/23/99		03/02/99		03/9/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L[a]	63 63	7 7	63	4	62	5	64	10
Sulfate	mg/L	44 46	<5 <5	36	<5	46	<5	48	<5
Turbidity	NTU							0.3	0.2
pH		8.4 8.4	8.6 8.5	8.3	8.6	8.3	6.3	8.3	8.6
Total Hardness	mg/L[a]							35	<2.0
Ca Hardness	mg/L[a]							29.2	<1.0
Mg Hardness	mg/L[a]							5.7	<1.0
NO_3–NO_2 (N)	mg/L[b]							0.06	<0.02
As (total)	µg/L	53.4	1.0	55.6	1.7	58.8	1.8	59.8 61.4	1.1 1.8
As (soluble)	µg/L							60.8 60.1	1.0 1.0
As (particulate)	µg/L							<0.1 1.3	0.1 0.8
As (III)	µg/L							0.6 0.6	0.3 0.2
As (V)	µg/L							60.2 59.5	0.7 0.8
Total Al	µg/L	<11	<11	11.2	14.6	12.9	<11	<11 <11	<11 <11
Total Fe	µg/L	132	30.7	79.2	43.6	74.6	<30	40.1 51.8	<30 <30
Total Mn	µg/L	3.5	1.0	1.6	<0.5	1.9	0.6	1.5 1.6	<0.5 <0.5
Dissolved Al	µg/L							<11 <11	<11 <11
Dissolved Fe	µg/L							<30 <30	<30 <30
Dissolved Mn	µg/L							2.1 1.4	<0.5 <0.5

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; OU = outlet.

Table B-8. Analytical Results from Long-Term Sampling, Plant B (Mar 16 to Apr 6, 1999)

Sampling Date		03/16/99		03/23/99		03/30/99		04/06/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	63 63	15 15	64	15	64	7	64	9
Sulfate	mg/L	43 44	<5 <5	45	<5	43	<5	46	<5
Turbidity	NTU							0.4	0.2
pH		8.3 8.3	7.9 7.9	8.3	8.0	8.3	6.5	8.5	6.9
Total Hardness	mg/L(a)							43	<2.0
Ca Hardness	mg/L(a)							37.2	<1.0
Mg Hardness	mg/L(a)							5.9	<1.0
NO_3–NO_2 (N)	mg/L(b)							<0.02	0.02
As (total)	µg/L	57.8	1.4	58.7	1.7	58.9	1.8	63.0 62.0	1.3 1.3
As (soluble)	µg/L							60.6 61.2	1.3 1.2
As (particulate)	µg/L							2.4 0.8	<0.1 0.1
As (III)	µg/L							0.7 0.4	0.3 0.2
As (V)	µg/L							59.9 60.8	1.0 1.0
Total Al	µg/L	<11	<11	11.2	<11	<11	<11	<11 <11	<11 <11
Total Fe	µg/L	48.7	30.2	48.7	<30	52.4	<30	53.0 65.8	72.2 73.2
Total Mn	µg/L	3.6	5.5	2.0	<0.5	1.7	<0.5	2.2 2.1	<0.5 <0.5
Dissolved Al	µg/L							<11 <11	<11 <11
Dissolved Fe	µg/L							36.0 35.6	30.7 31.7
Dissolved Mn	µg/L							2.3 2.3	<0.5 <0.5

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; OU = outlet.

Table B-9. Analytical Results from Long-Term Sampling, Plant B (Apr 13 to May 4, 1999)

Sampling Date		04/13/99		04/20/99		04/27/99		05/04/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	65 64	3 4	64	3	64	6	67	6
Sulfate	mg/L	38 37	<5 <5	44	<5	44	<5	44	<5
Turbidity	NTU							0.3	<0.1
pH		8.3 8.3	6.4 6.3	8.3	6.1	8.3	6.4	8.3	6.6
Total Hardness	mg/L(a)							33	<2.0
Ca Hardness	mg/L(a)							28.0	<1.0
Mg Hardness	mg/L(a)							5.4	<1.0
NO_3–NO_2 (N)	mg/L(b)							0.02	<0.02
As (total)	µg/L	55.7	1.5	59.5	1.6	56.8	1.7	57.7 57.6	2.8 2.7
As (soluble)	µg/L							57.7 57.6	2.4 2.5
As (particulate)	µg/L							<0.1 <0.1	0.3 0.2
As (III)	µg/L							1.1 0.9	0.6 0.6
As (V)	µg/L							57.0 56.8	1.8 1.8
Total Al	µg/L	<11	<11	20.3	<11	<11	13.9	<11 11.6	<11 <11
Total Fe	µg/L	73.6	<30	37.3	<30	<30	<30	<30 <30	<30 <30
Total Mn	µg/L	2.8	<0.5	2.0	<0.5	2.2	<0.5	1.7 1.6	<0.5 <0.5
Dissolved Al	µg/L							<11 <11	<11 <11
Dissolved Fe	µg/L							<30 <30	<30 <30
Dissolved Mn	µg/L							1.5 1.5	<0.5 <0.5

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; OU = outlet.

Table B-10. Analytical Results from Long-Term Sampling, Plant B (May 11 to May 25, 1999)

Sampling Date		05/11/99		05/18/99		05/25/99	
Sampling Location Parameter	Unit	IN	OU	IN	OU	IN	OU
Alkalinity	mg/L(a)	65 65	13 13	64	4	64	4
Sulfate	mg/L	44 44	<5 <5	46	<5	45	<5
Turbidity	NTU						
pH		8.3 8.3	7.0 6.8	8.3	6.4	8.3	6.2
Total Hardness	mg/L(a)						
Ca Hardness	mg/L(a)						
Mg Hardness	mg/L(a)						
NO_3–NO_2 (N)	mg/L(b)						
As (total)	µg/L	60.1	1.5	58.4	1.8	55.0	1.9
As (soluble)	µg/L						
As (particulate)	µg/L						
As (III)	µg/L						
As (V)	µg/L						
Total Al	µg/L	12.6	<11	<11	<11	<11	11.6
Total Fe	µg/L	39.3	<30	<30	<30	76.1	30.1
Total Mn	µg/L	2.4	<0.5	1.6	<0.5	2.5	1.1
Dissolved Al	µg/L						
Dissolved Fe	µg/L						
Dissolved Mn	µg/L						

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; OU = outlet.

APPENDIX C

Plant C Data

C.1 Complete Analytical Results from Long-Term Sampling at Plant C

C.2 Technical Data on DD-2 AA

C.3 Water Usage Report

C.1 Complete Analytical Results from Long-Term Sampling at Plant C

Table C-1. Analytical Results from Long-Term Sampling, Plant C (September 30 to November 11, 1998)

Sampling Date		9/30/98				10/14/98				10/28/98				11/11/98			
Sampling Location Parameter	Unit	IN	TA1	TB1	OU	IN	TA1	TB1	OU	IN	TA1	TB1	OU	IN	TA1	TB1	OU
Alkalinity	mg/L(a)	67	88	85	87	73 74	73 73	74 74	72 76	87	84	89	86	90	89	84	86
Fluoride	mg/L	1.2	1.4	1.5	1.5	1.3 1.3	1.3 1.4	1.5 1.4	1.4 1.3	1.5	1.5	1.5	1.5	1.5	1.6	1.5	1.5
Sulfate	mg/L	22	26	33	27	26 24	24 23	24 24	23 24	27	27	27	27	27	26	26	27
Turbidity	NTU	0.3	<0.1	<0.1	<0.1												
pH		7.9	7.9	7.6	7.6	7.9 7.9	7.9 7.9	7.9 7.9	7.8 7.8	8.0	7.9	7.9	7.9	8.1	8.1	8.1	8.0
Total Hardness	mg/L(a)	57	52	48	53												
Ca Hardness	mg/L(a)	38.7	34.5	30	35												
Mg Hardness	mg/L(a)	18.2	17.5	17.7	18.2												
NO_3-NO_2 (N)	mg/L(b)	0.1	0.2	0.2	0.2												
As (total)	µg/L	62.8 63.3	33.8 –	7.3 7.1	14.5 8.0	53.7	40.5	7.9	13.1	55.6	45.9	15.1	16.8	50.1	50.4	26.7	21.8
As (total soluble)	µg/L	50.6 49.9	33.9 34.0	6.7 6.6	7.6 7.6												
As (particulate)	µg/L	12.2 13.4	<0.1 –	0.6 0.5	6.9 0.4												
As (III)	µg/L	6.7 6.7	0.3 0.3	0.4 0.3	0.3 0.3												
As (V)	µg/L	43.9 43.2	33.6 33.7	6.3 6.3	7.3 7.3												
Total Al	µg/L	16.3 21.5	31.3 30.0	33.8 34.6	31.3 26.8	21.3	28.2	14.8	27.0	12.5	48.2	22.6	33.0	30.4	39.0	30.6	34.9
Total Fe	µg/L	114 131	<30 <30	<30 <30	<30 <30	<30	<30	<30	<30	<30	38.1	<30	<30	43.9	<30	<30	<30
Total Mn	µg/L	70.8 70.4	75.7 72.7	78.5 78.5	73.8 77.1	85.7	86.2	83.4	79.7	80.6	81.6	82.1	85.0	70.3	78.7	87.9	86.0
Dissolved Al	µg/L	<11 <11	16.6 13.5	17.5 17.5	16.5 16.1												
Dissolved Fe	µg/L	<30 <30	<30 <30	<30 <30	<30 <30												
Dissolved Mn	µg/L	65.4 66.4	76.3 75.7	76.4 76.2	75.9 75.7												

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; TA1 = after the roughing tank; TB1 = after the polishing tank; OU = outlet.

Table C-2. Analytical Results from Long-Term Sampling, Plant C (December 2, 1998 to January 6, 1999)

Sampling Date		12/2/98				12/9/98				12/23/98[c][d]				1/6/99			
Sampling Location Parameter	Unit	IN	TA1	TB1	OU	IN	TA1	TB1	OU	IN	TA1	TB1	OU	IN	TB1	TA1	OU
Alkalinity	mg/L[a]	85	87	84	78	80 80	84 84	80 80	75 76					77	79	73	73
Fluoride	mg/L	1.5	1.5	1.5	1.5	1.3 1.4	1.3 1.4	1.3 1.3	1.3 1.3					1.3	0.9	0.3	0.2
Sulfate	mg/L	26	25	35	29	25 24	26 26	25 26	26 26					24	23	18	19
Turbidity	NTU	<0.1	<0.1	0.1	0.1												
pH		7.8	7.8	7.8	7.6	7.9 8.0	7.9 7.9	7.9 7.9	7.8 7.8					8.0	8.0	8.6	8.7
Total Hardness	mg/L[a]	57	53	50	50												
Ca Hardness	mg/L[a]	37.7	34.7	32.2	32.5												
Mg Hardness	mg/L[a]	19.4	18.1	17.9	18.0												
NO_3-NO_2 (N)	mg/L[b]	0.02	0.1	0.1	0.1												
As (total)	µg/L	54.8 54.4	46.9 46.8	24.0 24.1	17.8 17.5	76.0	47.5	25.1	16.2					52.5	14.2	0.5	2.6
As (total soluble)	µg/L	57.6 57.6	50.1 49.8	26.0 24.8	18.6 18.3												
As (particulate)	µg/L	<0.1 <0.1	<0.1 <0.1	<0.1 <0.1	<0.1 <0.1												
As (III)	µg/L	2.5 2.2	1.8 1.8	0.4 0.3	1.0 0.9												
As (V)	µg/L	55.1 55.4	48.3 48.0	25.6 24.5	17.6 17.4												
Total Al	µg/L	18.9 16.2	27.7 24.1	28.3 24.8	26.6 26.3	<11	22.7	19.4	16.4					<11	41.7	109	112
Total Fe	µg/L	41.0 31.2	53.0 68.0	<30 <30	78.1 119	<30	<30	<30	<30					56.9	36.9	<30	68.2
Total Mn	µg/L	69.8 69.9	82.9 81.9	76.7 76.2	61.6 62.0	73.9	88.7	78.4	45.1					90.7	67.2	1.9	6.4
Dissolved Al	µg/L	<11 <11	11.2 11.2	11.1 11.6	<11 <11												
Dissolved Fe	µg/L	<30 <30	<30 <30	<30 <30	<30 <30												
Dissolved Mn	µg/L	68.1 68.1	80.8 80.7	75.2 74.0	58.5 59.2												

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
(c) No sampling during the Christmas week.
(d) Tanks A1 and A2 were recharged with virgin activated alumina on 12/29/98; they were moved to polishing positions and Tanks B1 and B2 were moved to roughing positions afterwards.
IN = inlet; TA1 = after the roughing tank; TB1 = after the polishing tank; OU = outlet.

Table C-3. Analytical Results from Long-Term Sampling, Plant C (January 27, 1999 to March 3, 1999)

Sampling Date		01/27/99				02/03/99				02/17/99				03/03/99			
Sampling Location Parameter	Unit	IN	TB1	TA1	OU	IN	TB1	TA1	OU	IN	TB1	TA1	OU	IN	TB1	TA1	OU
Alkalinity	mg/L(a)	81	87	81	76	82	83	82	81	90 89	82 82	83 80	81 80	74	81	73	72
Fluoride	mg/L	1.5	1.4	0.8	0.6	1.5	1.5	0.9	0.9	1.3 1.3	1.3 1.3	1.0 1.0	1.0 1.0	1.5	1.6	1.2	1.2
Sulfate	mg/L	25	25	24	23	25	25	25	25	26 25	25 25	26 26	26 25	24	25	25	24
Turbidity	NTU					0.2	<0.1	0.1	<0.1								
pH		8.0	7.9	8.3	8.2	8.1	8.0	8.1	8.2	8.0 8.0	7.9 7.9	8.0 8.0	8.1 8.0	8.0	7.9	8.0	8.0
Total Hardness	mg/L(a)					52	51	52	51								
Ca Hardness	mg/L(a)					34.5	33.7	34.2	32.7								
Mg Hardness	mg/L(a)					17.8	17.7	18.2	18.0								
NO_3-NO_2 (N)	mg/L(b)					<0.02	0.02	0.3	0.05								
As (total)	µg/L	41.3	23.3	0.4	3.5	59.1 62.4	37.3 39.4	1.3 1.3	1.5 1.5	49.2	34.5	0.7	1.3	58.4	31.0	1.5	2.2
As (total soluble)	µg/L					63.2 63.6	43.7 43.7	1.5 1.4	1.8 1.8								
As (particulate)	µg/L					<0.1 <0.1	<0.1 <0.1	<0.1 <0.1	<0.1 <0.1								
As (III)	µg/L					28.8 28.8	9.1 9.1	2.6 1.2	1.9 1.9								
As (V)	µg/L					34.4 38.8	34.6 34.6	<0.1 <0.1	<0.1 <0.1								
Total Al	µg/L	11.4	15.8	30.4	52.7	98.2 96.5	67.0 52.0	88.4 53.7	26.1 89.5	<11	23.9	23.7	24.3	<11	25.3	31.8	33.5
Total Fe	µg/L	35.9	<30	<30	125	86.8 75.8	<30 <30	36.1 <30	<30 <30	41.8	<30	<30	<30	<30	<30	<30	<30
Total Mn	µg/L	55.8	78.8	35.1	9.8	64.9 67.5	79.8 80.2	50.3 49.4	49.9 49.9	57.6	68.1	59.3	60.0	76.9	80.8	69.9	66.6
Dissolved Al	µg/L					<11 <11	11.9 <11	22.5 24.0	22.8 23.8								
Dissolved Fe	µg/L					<30 <30	<30 <30	<30 <30	<30 <30								
Dissolved Mn	µg/L					65.4 65.8	80.7 81.9	50.8 51.8	50.3 51.2								

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; TB1 = after the roughing tank; TA1 = after the polishing tank; OU = outlet.

Table C-4. Analytical Results from Long-Term Sampling, Plant C (Mar 17, 1999 to April 28, 1999)

Sampling Date		03/17/99				03/31/99				04/14/99				04/28/99			
Sampling Location Parameter	Unit	IN	TB1	TA1	OU	IN	TB1	TA1	OU	IN	TB1	TA1	OU	IN	TB1	TA1	OU
Alkalinity	mg/L(a)	73	79	77	73	80	83	79	74	86 86	87 88	85 85	78 78	85	88	85	80
Fluoride	mg/L	1.5	1.7	1.6	1.5	1.5	1.5	1.4	1.3	1.4 1.4	1.4 1.4	1.4 1.4	1.3 1.3	1.4	1.4	1.4	1.4
Sulfate	mg/L	25	25	25	24	26	26	26	26	26 26	27 27	26 27	26 26	26	25	25	26
Turbidity	NTU					0.4	<0.1	<0.1	0.3								
pH		7.9	8.0	7.9	7.9	8.0	7.9	7.9	7.6	8.1 8.1	8.0 8.0	8.0 8.0	7.9 7.9	8.0	7.9	7.8	8.0
Total Hardness	mg/L(a)					47	49	48	48								
Ca Hardness	mg/L(a)					30.5	31.5	30.2	30.2								
Mg Hardness	mg/L(a)					16.9	17.1	17.4	17.3								
NO_3-NO_2 (N)	mg/L(b)					0.05	0.3	0.6	0.1								
As (total)	µg/L	34.4	33.1	2.4	2.0	61.7 59.8	37.0 36.7	0.5 0.4	1.8 1.9	42.6	42.5	1.0	2.4	46.1	41.4	4.3	2.8
As (total soluble)	µg/L					60.3 61.4	39.6 39.5	0.4 0.4	2.0 1.9								
As (particulate)	µg/L					1.4 <0.1	<0.1 <0.1	0.1 <0.1	<0.1 <0.1								
As (III)	µg/L					11.8 11.4	2.6 2.5	0.1 0.1	0.5 0.4								
As (V)	µg/L					48.5 50.0	37.0 37.0	0.3 0.3	1.5 1.5								
Total Al	µg/L	25.2	21.8	20.2	30.8	<11 <11	29.0 16.7	16.7 13.3	21.4 18.1	19.9	15.3	16.6	21.7	13.0	22.4	30.8	13.7
Total Fe	µg/L	131	<30	<30	45.6	<30 <30	<30 <30	<30 <30	<30 <30	98.1	<30	<30	<30	<30	<30	<30	34.2
Total Mn	µg/L	76.7	81.4	67.3	79.7	62.2 59.2	68.0 66.8	63.7 64.9	34.2 34.3	59.6	71.2	52.2	28.6	55.6	46.9	40.4	25.5
Dissolved Al	µg/L					<11 <11	<11 <11	<11 <11	<11 <11								
Dissolved Fe	µg/L					<30 <30	<30 <30	<30 <30	<30 <30								
Dissolved Mn	µg/L					63.9 64.0	68.0 67.2	62.8 62.9	32.1 32.0								

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; TB1 = after the roughing tank; TA1 = after the polishing tank; OU = outlet.

Table C-5. Analytical Results from Long-Term Sampling, Plant C (May 12, 1999 to Jun 9, 1999)

Sampling Date		05/12/99				05/26/99				06/09/99			
Sampling Location Parameter	Unit	IN	TB1	TA1	OU	IN	TB1	TA1	OU	IN	TB1	TA1	OU
Alkalinity	mg/L[(a)]	84	84	82	80	86.0	82	82	79	80 80	81 80	79 80	77 78
Fluoride	mg/L	1.4	1.4	1.3	1.3	1.6	1.5	1.6	1.6	1.4 1.4	1.4 1.4	1.4 1.4	1.4 1.4
Sulfate	mg/L	25	25	26	26	26	26	25	25	25 25	25 25	26 25	25 25
Turbidity	NTU					<0.1	<0.1	<0.1	<0.1				
pH		8.1	8.0	8.0	8.1	8.1	8.0	8.0	8.0	8.0 8.0	7.9 8.0	8.0 8.0	7.9 7.9
Total Hardness	mg/L[(a)]					49.0	49.3	48.0	49.7				
Ca Hardness	mg/L[(a)]					32.0	32.7	31.5	32.2				
Mg Hardness	mg/L[(a)]					16.6	16.6	16.5	16.5				
NO_3-NO_2 (N)	mg/L[(b)]					0.04	0.1	0.05	1.3				
As (total)	µg/L	39.5	45.6	0.9	2.9	54.5 54.0	47.2 47.1	1.7 1.6	4.3 4.3	43.6	43.0	1.7	4.6
As (total soluble)	µg/L					42.3 42.6	47.7 48.0	1.5 1.4	4.3 4.3				
As (particulate)	µg/L					12.2 11.4	<0.1 <0.1	0.2 0.2	0.1 0.1				
As (III)	µg/L					1.1 1.1	1.5 1.4	0.2 0.2	0.4 0.4				
As (V)	µg/L					41.2 41.6	46.2 46.6	1.3 1.2	3.8 3.9				
Total Al	µg/L	16.3	15.1	<11	18.1	<11 <11	11.5 13.9	15.4 14.8	20.7 20.3	12.8	22.7	14.7	12.6
Total Fe	µg/L	<30	<30	<30	<30	178 177	<30 <30	<30 <30	101 101	30.5	<30	<30	<30
Total Mn	µg/L	48.9	49.8	28.6	23.2	58.7 58.5	30.4 30.5	17.1 16.4	12.0 11.9	52.2	31.0	21.0	8.9
Dissolved Al	µg/L					<11 <11	12.0 11.9	<11 <11	20.2 12.4				
Dissolved Fe	µg/L					<30 <30	<30 <30	<30 <30	91.4 <30				
Dissolved Mn	µg/L					51.8 52.6	30.3 30.2	16.0 16.0	10.4 10.2				

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; TB1 = after the roughing tank; TA1 = after the polishing tank; OU = outlet.

C.2 Technical Data on DD-2 AA

Aluminum Company of America ALCOA

Material Safety Data Sheet
acc. to 91/155/EEC

Printing date 02/28/97 Reviewed on 12/19/96

* 1 CHEMICAL PRODUCT AND COMPANY IDENTIFICATION

- **Product details:**

- **Product Name:** Activated Aluminas 149
- **Other Designations:**
Active bed supports, CG-20, CPA series, CPN, CSS series, DD-2, DD-410, DD-420, DD-422, DD-431, DD-440, DD-450, DD-460, DD-471, DD-6, F-200, HF-200, HPX, LD-5, LD-350, PSD-350, RC-400, RF-200, S-100, S-400, S-431, and SRU.

- **Manufacturer/Supplier:**
Aluminum Company of America
425 Sixth Avenue Alcoa Building
Pittsburgh, PA 15219-1850 USA
Health & Safety: +1-412-553-4649

Alcoa Alumina & Chemicals, L.L.C.
HC-63 Box 4, Vidalia, LA 71373
Emergency +1-318-336-9601

3502 South Riverview Drive
Port Allen, LA 70767
Tel. +1-504-389-9945

- **Emergency information:**
USA: Chemtrec: +1-703-527-3887 +1-800-424-9300 ALCOA: +1-412-553-4001

* 2 Composition/Data on components:

- **Chemical characterization**
Components:

1333-84-2	Aluminum oxide (non fibrous) EINECS: 215-691-6	<97 %
14504-95-1	Aluminum silicate EINECS: 238-509-7	<0.2 %

- **Additional information:**
Loss on ignition (water) 4.0-7.0 %

•1333-84-2 (See Section 15)

* 3 Hazards identification

- **Chemical ingredient and possible processing hazards:**

Alumina is a low health risk by inhalation and should be treated as a nuisance dust as specified by the ACGIH.

This product contains total silicates at <1% by weight. Total silicates content includes metal silicates, amorphous and crystalline silica. No analytical method exists to detect and differentiate between amorphous and crystalline silica and other silicates at <1% by weight. Based on

(Contd. on page 2)

(Contd. of page 1)

the chemistry of bauxite-derived products, crystalline silica is not expected to be present in·this product.

- **Hazard description:**
- **Medical conditions aggravated by exposure to the product:**
  Asthma, chronic lung disease, and skin rashes.
- **Information pertaining to particular dangers for man and environment**
  not applicable
- **Classification system**
  The classification was made according to the latest editions of the EU-lists, and expanded upon from company and literature data.

* 4 First aid measures

- **After inhalation**
  Remove to fresh air.
  Check for clear airway, breathing, and pulse.
  Provide cardiopulmonary resuscitation for persons without pulse or respirations.
  Consult a physician.
- **After skin contact**
  Wash with soap and water for at least 15 minutes.
  Consult a physician.
- **After eye contact**
  Immediately flush eyes with plenty of water for at least 15 minutes.
  Consult a physician.
- **After swallowing**
  Do not induce vomiting.
  Never give anything by mouth to a convulsing or unconscious person.
  If swallowed, dilute by drinking large amounts of water.
  Consult a physician.

5 Fire fighting measures

- **Suitable extinguishing agents**
  Use fire fighting measures that suit the environment.
- **Protective equipment:**
  Wear self-contained respiratory protective device.
  Wear fully protective suit.

* 6 Accidental release measures

- **Person-related safety precautions:**

Wear protective clothing.

- **Measures for environmental protection:** No special measures required.
- **Measures for cleaning/collecting:**
  Clean up using dry procedures; avoid dusting.
- **Additional information:** No dangerous substances are released.

* 7 **Handling and storage**

- **Handling**
- **Information for safe handling:**
  Ensure good ventilation/exhaust at the workplace.
  Prevent formation of dust.
  Provide suction extractors if dust is formed.
- **Information about protection against explosions and fires:**
  No special measures required.

- **Storage**
- **Requirements to be met by storerooms and receptacles:**
  Keep material dry.
- **Information about storage in one common storage facility:** Not required.
- **Further information about storage conditions:** None.

* 8 **Exposure controls and personal protection**

- **Additional information about design of technical systems:**
  No further data; see item 7.

Components with limit values that require monitoring at the workplace:

1333-84-2 Aluminum oxide (non fibrous)
MAK (GERMANY): 6 R (respirable) mg/m3
OSHA: 15 total, 5 respirable mg/m3
TLV: 10 mg/m3

- **Personal protective equipment**
- **General protective and hygienic measures**
  Do not inhale dust.
  Avoid contact with the eyes.
- **Breathing equipment:**
  Use suitable respiratory protective device in case of insufficient ventilation.
  Short term filter device:
  Filter P2.
- **Protection of hands:** Impervious gloves.
- **Eye protection:** Safety glasses.

* 9 **Physical and chemical properties:**

- **Form:**
  Crystalline powder
  Gelatinous
  Balls
  Granules
  Pellets
- **Color:** Whitish
- **Odor:** Characteristic

	Value/Range	Unit	Method
Change in condition			
Melting point/Melting range:	2038	° C	
Boiling point/Boiling range:	undetermined		

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Product Name: Activated Aluminas **149**

(Contd. of page 3)

- **Flash point:** Not applicable.
- **Auto igniting:** Product is not self igniting.
- **Danger of explosion:**
  Product does not present an explosion hazard.
- **Density:** at 20 ° C 0.62-0.83 g/cm3
- **Solubility in / Miscibility with**
- **Water:** Insoluble
- **pH-value:** at 20 ° C 9.4-10.1 10% in water

10 Stability and reactivity

- **Thermal decomposition / conditions to be avoided:**
  No decomposition if used according to specifications.
- **Dangerous reactions** Heating occurs when water is added.
- **Dangerous products of decomposition:**
  No dangerous decomposition products known
- **Additional information:** Non-corrosive.

* 11 Toxicological information

- **Primary irritant effect:**
- **On the skin:** Can cause mild irritation.
- **On the eye:** Can cause mild irritation.
- **Inhalation:** Can cause mild upper respiratory tract irritation.
- **Ingestion:** Can cause mild irritation.
- **Additional toxicological information:**
  The product is not subject to classification according to the calculation method of the General EU Classification Guidelines for Preparations as issued in the latest version:

12 Ecological information:

- **General notes:**
  Water hazard class 0 (German Regulation) (Self-assessment): generally not hazardous for water.

* 13 Disposal considerations

- **Product:**
- **Recommendation**
  Collect in containers, bags, or covered dumpster boxes. If reuse or recycling is not possible, material may be disposed of at an industrial landfill.
- **Waste disposal key:** 16 03 01 513 05

- **Uncleaned packagings:**

(Contd. on page 5)

Material Safety Data Sheet
acc. to 91/155/EEC

(Contd. of page 4)

- **Recommendation:**
  Disposal must be made according to official regulations.

* 14 Transport information

- **DOT regulations:**
- **Remarks:**
  U.S.A. DOT: Not regulated - Enter the proper freight classification. "MSDS Number," and "Product Name" on the shipping paperwork.
  Canadian TDG Hazard Class & PIN: Not regulated.

- **Maritime transport IMDG:**
- **Marine pollutant:** No

* 15 Regulations

- **U.S. Federal Regulations:**
- **TSCA STATUS:**
  All components of this product are listed on the TSCA inventory.
  *For TSCA inventory reporting purposes, CAS No. 1344-28-1 was assigned for all forms of aluminum oxide instead of the CAS No. 1333-84-2 as indicated in Section 2.
- **CERCLA REPORTABLE QUANTITY:** None.
- **SARA TITLE III:**
  Section 302 Extremely Hazardous Substances:
  None.
- **Section 311/312 Hazardous Categories:** Immediate (acute).
- **Section 313 Toxic Categories:** None.
- **OTHER INFORMATION:**
  In reference to Title VI of the Clean Air Act of 1990, this material does not contain nor was it manufactured using ozone-depleting chemicals.

- **Markings according to EU guidelines:**
  Observe the general safety regulations when handling chemicals.
  The product is not subject to identification regulations under EU Directives and the Ordinance on Hazardous Materials (GefStoffV).

- **National regulations**

- **Classification according to VbF:** Void

- **Water hazard class:**
  Water hazard class 0 (German Regulation): generally not hazardous for water.
- **International Regulations:**
- **CANADIAN DOMESTIC SUBSTANCES LIST:**
  All components of this product are listed on the Canadian DSL.
- **AUSTRALIAN INVENTORY OF CHEMICAL SUBSTANCES:**
  All components of this product are listed on the AISC.
- **JAPAN Ministry of International Trade Industry (MITI):**
  All components of this product are listed on MITI.

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Product Name: Activated Aluminas **149**

* 16 **Other information:**

This information is based on our present knowledge. However, this shall not constitute a guarantee for any specific product features and shall not establish a legally valid contractual relationship.

- **Department issuing MSDS:**
  Hazardous Materials Control Committee, Alcoa, Pittsburgh, PA 15219 USA
  19.12.96
- **Alcoa HAZMIN #:** 000445
- **Appendix:**
  - Guide to Occupational Exposure Values 1995, Compiled by the American Conference of Governmental Industrial Hygienists (ACGIH).
  - Documentation of the Threshold Limit Values and Biological Exposure Indices, Sixth Edition, 1991, Compiled by the American Conference of Governmental Industrial Hygienists, Inc. (ACGIH).
  - NIOSH Pocket Guide to Chemical Hazards, U.S. Department of Health and Human Services, June 1994.
  - Dangerous Properties of Industrial Materials, Sax, N. Irving, Van Nostrand Reinhold Co., Inc., 1984.
  - Patty's Industrial Hygiene and Toxicology: Volume II: Toxicology, 4th ed., 1994, Patty, F. A.; edited by Clayton, G. D. and Clayton, F. E.: New York: John Wiley & Sons, Inc.
- **LEGEND:**

ACGIH	American Conference of Governmental Industrial Hygienists
CAS	Chemical Abstract Services
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
DOT	Department of Transportation
DSL	Domestic Substances List (Canada)
ECOIN	European Core Inventory
EINECS	European Inventory of Existing Commercial Chemical Substances
EWC	European Waste Catalogue
EPA	Environmental Protective Agency
IARC	International Agency for Research on Cancer
LC	Lethal Concentration
LD	Lethal Dose
MAK	Maximum Workplace Concentration (Germany) "maximale Arbeitsplatz-Konzentration"
NDSL	Non-Domestic Substances List (Canada)
NIOSH	National Institute for Occupational Safety and Health
NTP	National Toxicology Program
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
PIN	Product Identification Number
RCRA	Resource Conservation and Recovery Act
SARA	Superfund Amendments and Reauthorization Act
STEL	Short Term Exposure Limit
TCLP	Toxic Chemicals Leachate Program
TDG	Transportation of Dangerous Goods
TLV	Threshold Limit Value
TSCA	Toxic Substances Control Act

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Product Name: Activated Aluminas **149**

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TWA	**Time Weighted Average**

m meter, cm centimeter, mm millimeter, in inch,
g gram, kg kilogram, lb pound, μg microgram,
ppm parts per million

USA

C.3 Water Usage Report

Plant C Water Usage Report

Date	Cumulative Water Usage (gal)	Water Treated Since AA Installed (gal)	(BVs)	Remarks
08/28/1997	1,357,900	0	0	AA System Installed
06/11/1998	1,753,200	395,300	6,606	
07/13/1998	1,796,200	438,300	7,325	
08/19/1998	1,801,900	444,000	7,420	
09/03/1998	1,806,200	448,300	7,492	
09/08/1998	1,830,300	472,400	7,894	
09/11/1998	1,840,700	482,800	8,068	
09/14/1998	1,843,600	485,700	8,117	
09/15/1998	1,847,300	489,400	8,178	
09/16/1998	1,851,700	493,800	8,252	
09/17/1998	1,854,800	496,900	8,304	
09/18/1998	1,860,100	502,200	8,392	
09/21/1998	1,863,300	505,400	8,446	
09/22/1998	1,865,100	507,200	8,476	
09/23/1998	1,866,800	508,900	8,504	
09/24/1998	1,868,700	510,800	8,536	
09/25/1998	1,870,800	512,900	8,571	
09/28/1998	1,872,700	514,800	8,603	
09/29/1998	1,874,700	516,800	8,636	
09/30/1998	1,876,900	519,000	8,673	
10/01/1998	1,880,100	522,200	8,727	
10/02/1998	1,884,800	526,900	8,805	
10/05/1998	1,888,000	530,100	8,859	
10/06/1998	1,890,300	532,400	8,897	
10/07/1998	1,892,800	534,900	8,939	
10/08/1998	1,895,100	537,200	8,977	
10/12/1998	1,899,600	541,700	9,052	
10/13/1998	1,902,800	544,900	9,106	
10/14/1998	1,905,800	547,900	9,156	Arsenic breakthrough in TA2 (50-µg/L)
10/15/1998	1,909,100	551,200	9,211	
10/16/1998	1,912,400	554,500	9,266	
10/19/1998	1,919,700	561,800	9,388	
10/20/1998	1,922,200	564,300	9,430	
10/21/1998	1,924,100	566,200	9,462	
10/22/1998	1,926,500	568,600	9,502	
10/23/1998	1,929,400	571,500	9,550	
10/26/1998	1,932,300	574,400	9,599	
10/27/1998	1,935,300	577,400	9,649	
10/28/1998	1,938,600	580,700	9,704	
10/30/1998	1,942,800	584,900	9,774	
11/02/1998	1,944,700	586,800	9,806	
11/03/1998	1,947,300	589,400	9,850	
11/06/1998	1,955,100	597,200	9,980	
11/09/1998	1,957,300	599,400	10,017	
11/10/1998	1,959,300	601,400	10,050	Arsenic breakthrough in TA1 (50-µg/L)
11/12/1998	1,959,700	601,800	10,057	
11/16/1998	1,963,000	605,100	10,112	
11/17/1998	1,964,900	607,000	10,144	
11/18/1998	1,966,700	608,800	10,174	
11/19/1998	1,968,800	610,900	10,209	
11/20/1998	1,970,900	613,000	10,244	
11/23/1998	1,973,400	615,500	10,286	
11/24/1998	1,976,400	618,500	10,336	
11/25/1998	1,979,100	621,200	10,381	
11/30/1998	1,981,000	623,100	10,413	
12/01/1998	1,985,200	627,300	10,483	
12/02/1998	1,987,000	629,100	10,513	
12/03/1998	1,988,300	630,400	10,535	
12/04/1998	1,990,200	632,300	10,567	
12/07/1998	1,992,200	634,300	10,600	
12/08/1998	1,994,500	636,600	10,638	
12/09/1998	1,996,600	638,700	10,673	
12/10/1998	1,998,500	640,600	10,705	
12/11/1998	2,000,600	642,700	10,740	
12/14/1998	2,002,700	644,800	10,775	

Plant C Water Usage Report (continued)

Date	Cumulative Water Usage (gal)	Water Treated Since AA Installed		Remarks
		(gal)	(BVs)	
12/16/1998	2,007,000	649,100	10,847	
12/17/1998	2,009,200	651,300	10,884	
12/18/1998	2,011,300	653,400	10,919	
12/21/1998	2,013,700	655,800	10,959	
12/22/1998	2,015,900	658,000	10,996	
12/23/1998	2,019,100	661,200	11,049	
12/28/1998	2,020,400	662,500	11,071	AA changeout in TA1 and TA2
01/04/1999	2,020,800	662,900	11,078	
01/05/1999	2,024,100	666,200	11,133	
01/06/1999	2,026,500	668,600	11,173	
01/07/1999	2,028,000	670,100	11,198	
01/08/1999	2,031,300	673,400	11,253	
01/11/1999	2,033,900	676,000	11,297	
01/12/1999	2,035,900	678,000	11,330	
01/13/1999	2,039,000	681,100	11,382	
01/14/1999	2,041,300	683,400	11,420	
01/19/1999	2,043,400	685,500	11,456	
01/20/1999	2,043,600	685,700	11,459	
01/21/1999	2,045,800	687,900	11,496	
01/22/1999	2,048,000	690,100	11,532	
01/25/1999	2,055,200	697,300	11,653	
01/26/1999	2,057,600	699,700	11,693	
01/27/1999	2,059,700	701,800	11,728	
01/28/1999	2,062,200	704,300	11,770	
02/02/1999	2,067,800	709,900	11,863	
02/03/1999	2,071,700	713,800	11,928	
02/04/1999	2,073,300	715,400	11,955	
02/05/1999	2,077,200	719,300	12,020	
02/08/1999	2,084,100	726,200	12,136	
02/09/1999	2,087,700	729,800	12,196	
02/10/1999	2,090,700	732,800	12,246	
02/11/1999	2,092,500	734,600	12,276	
02/12/1999	2,094,500	736,600	12,309	
02/15/1999	2,096,600	738,700	12,345	
02/16/1999	2,098,500	740,600	12,376	
02/17/1999	2,101,000	743,100	12,418	
02/18/1999	2,102,700	744,800	12,447	
02/19/1999	2,104,800	746,900	12,482	
02/23/1999	2,107,100	749,200	12,520	
03/01/1999	2,108,300	750,400	12,540	
03/02/1999	2,110,000	752,100	12,569	
03/03/1999	2,112,100	754,200	12,604	
03/04/1999	2,116,000	758,100	12,669	
03/05/1999	2,119,700	761,800	12,731	
03/08/1999	2,122,300	764,400	12,774	
03/10/1999	2,130,700	772,800	12,914	
03/11/1999	2,133,200	775,300	12,956	
03/16/1999	2,137,200	779,300	13,023	
03/17/1999	2,138,800	780,900	13,050	
03/18/1999	2,140,900	783,000	13,085	
03/19/1999	2,143,800	785,900	13,133	
03/22/1999	2,149,800	791,900	13,234	
03/23/1999	2,152,100	794,200	13,272	
03/24/1999	2,154,200	796,300	13,307	
03/25/1999	2,156,300	798,400	13,342	
03/26/1999	2,158,200	800,300	13,374	
03/29/1999	2,160,800	802,900	13,417	
03/30/1999	2,162,800	804,900	13,451	
03/31/1999	2,166,100	808,200	13,506	
04/02/1999	2,175,000	817,100	13,655	
04/05/1999	2,177,100	819,200	13,690	
04/06/1999	2,179,500	821,600	13,730	
04/08/1999	2,186,800	828,900	13,852	
04/14/1999	2,191,100	833,200	13,924	

Plant C Water Usage Report (continued)

	Cumulative Water Usage	Water Treated Since AA Installed		
Date	(gal)	(gal)	(BVs)	Remarks
04/15/1999	2,199,200	841,300	14,059	
04/16/1999	2,201,400	843,500	14,096	
04/19/1999	2,200,000	842,100	14,073	
04/20/1999	2,208,300	850,400	14,211	
04/21/1999	2,210,400	852,500	14,246	
04/22/1999	2,213,800	855,900	14,303	
04/23/1999	2,216,000	858,100	14,340	
04/29/1999	2,219,800	861,900	14,403	
05/03/1999	2,220,100	862,200	14,408	
05/04/1999	2,223,000	865,100	14,457	
05/05/1999	2,225,600	867,700	14,500	
05/06/1999	2,230,900	873,000	14,589	
05/07/1999	2,233,500	875,600	14,632	
05/10/1999	2,236,600	878,700	14,684	
05/11/1999	2,239,200	881,300	14,728	
05/12/1999	2,241,200	883,300	14,761	
05/15/1999	2,246,500	888,600	14,850	
05/17/1999	2,253,100	895,200	14,960	
05/18/1999	2,258,400	900,500	15,048	
05/19/1999	2,261,500	903,600	15,100	
05/20/1999	2,263,600	905,700	15,135	
05/21/1999	2,267,800	909,900	15,206	
05/25/1999	2,273,200	915,300	15,296	
05/26/1999	2,275,700	917,800	15,338	
05/27/1999	2,279,800	921,900	15,406	
06/01/1999	2,288,900	931,000	15,558	
06/02/1999	2,291,700	933,800	15,605	
06/04/1999	2,290,600	932,700	15,587	
06/09/1999	2,303,500	945,600	15,802	
06/10/1999	2,308,100	950,200	15,879	
06/11/1999	2,310,100	952,200	15,912	
06/14/1999	2,327,700	969,800	16,207	
06/15/1999	2,334,200	976,300	16,315	
06/17/1999	2,337,600	979,700	16,372	
06/18/1999	2,339,800	981,900	16,409	
07/16/1999	2,358,200	1,000,300	16,716	

Bed volume = 4 cu ft per tank = 29.92 gal.

APPENDIX D

Plant D Data

D.1 Complete Analytical Results from Long-Term Sampling at Plant D

D.2 Technical Data on CPN AA

D.3 System Plumbing Diagram

D.4 Water Usage Report

D.1 Complete Analytical Results from Long-Term Sampling at Plant D

Table D-1. Analytical Results from Long-Term Sampling, Plant D (September 30 to November 11, 1998)

Sampling Date		9/30/98				10/14/98				10/28/98				11/11/98			
Sampling Location Parameter	Unit	IN	TB1	TA1	AC	IN	TB1	TA1	AC	IN	TB1	TA1	AC	IN	TB1	TA1	AC
Alkalinity	mg/L(a)	44	55	58	55	57 57	58 58	56 56	54 55	57	60	59	56	58	56	56	55
Fluoride	mg/L	1.0	1.1	1.2	1.3	1.2 1.1	1.1 1.1	1.3 1.3	1.2 1.2	1.2	1.2	1.3	1.3	1.2	1.3	1.4	1.4
Sulfate	mg/L	13	13	13	14	15 15	15 15	15 14	15 15	14	14	15	15	14	14	14	14
Turbidity	NTU	0.4	0.2	<0.1	<0.1												
pH	–	8.1	8.1	7.9	7.8	8.4 8.4	8.2 8.2	7.9 7.8	7.8 7.8	8.3	8.1	7.9	7.7	8.0	7.8	7.8	7.8
Total Hardness	mg/L(a)	50	51	48	48												
Ca Hardness	mg/L(a)	42.9	43.9	41.7	41.7												
Mg Hardness	mg/L(a)	6.9	6.8	6.7	6.8												
NO_3-NO_2 (N)	mg/L(b)	0.4	1.3	0.4	0.4												
As (total)	µg/L	77.7 70.5	– 31.6	0.7	0.4	64.6	33.1	0.9	0.9	63.0	38.6	1.0	0.8	68.1	44.4	0.8	0.5
As (total soluble)	µg/L	65.0 64.0	32.4 31.5														
As (particulate)	µg/L	12.7 6.5	– 0.1														
As (III)	µg/L	0.3 0.2	0.2 0.2														
As (V)	µg/L	64.7 63.8	32.2 31.3														
Total Al	µg/L	30.1 34.7	35.6 31.9	40.0	40.1	28.6	22.5	27.0	38.2	<11	23.3	20.6	31.6	14.4	36.5	36.9	31.5
Total Fe	µg/L	626 340	<30 <30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Total Mn	µg/L	4.4 3.8	<0.5 <0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Dissolved Al	µg/L	<11 <11	18.2 17.1														
Dissolved Fe	µg/L	<30 <30	<30 <30														
Dissolved Mn	µg/L	<0.5 <0.5	<0.5 <0.5														

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; TB1 = after the roughing tank; TA1 = after the polishing tank; AC = after the GAC tank.

Table D-2. Analytical Results from Long-Term Sampling, Plant D (December 2, 1998 to January 6, 1999)

Sampling Date		12/2/98				12/9/98				12/23/98(c)				01/06/99			
Sampling Location Parameter	Unit	IN	TB1	TA1	AC	IN	TB1	TA1	AC	IN	TB1	TA1	AC	IN	TB1	TA1	AC
Alkalinity	mg/L(a)	58	57	54	55	57 58	57 58	55 55	56 56					58	63	58	57
Fluoride	mg/L	1.2	1.2	1.4	1.4	1.1 1.1	1.1 1.1	1.2 1.2	1.2 1.2					1.1	1.2	1.3	1.3
Sulfate	mg/L	14	17	14	14	14 14	14 14	14 14	14 14					14	14	14	14
Turbidity	NTU	0.2	0.2	<0.1	<0.1												
pH	–	8.1	8.1	7.9	7.8	8.3 8.3	8.2 8.2	8.0 8.0	7.9 7.9					8.3	8.1	7.4	7.7
Total Hardness	mg/L(a)	50	49	48	49												
Ca Hardness	mg/L(a)	43.2	42.4	41.5	41.7												
Mg Hardness	mg/L(a)	7.0	7.0	6.9	6.8												
NO_3-NO_2 (N)	mg/L(b)	0.3	0.4	0.8	0.3												
As (total)	µg/L	58.3 59.9	41.6 42.3	0.9 0.8	0.7 0.7	63.7	44.4	1.2	0.8					58.9	36.4	1.2	0.8
As (total soluble)	µg/L	68.9 65.7	45.8 44.4														
As (particulate)	µg/L	<0.1 <0.1	<0.1 <0.1														
As (III)	µg/L	<0.1 <0.1	0.3 0.2														
As (V)	µg/L	68.9 65.7	45.5 44.2														
Total Al	µg/L	13.0 14.0	24.7 29.4	29.6 34.0	27.4 39.9	<11	21.0	38.4	25.0					44.7	17.2	30.0	16.1
Total Fe	µg/L	<30 <30	<30 <30	<30 32.6	31.0 77.5	<30	<30	<30	<30					150	34.7	53.7	25.4
Total Mn	µg/L	<0.5 <0.5	<0.5 <0.5	<0.5 <0.5	<0.5 <0.5	<0.5	<0.5	<0.5	<0.5					<0.5	<0.5	<0.5	<0.5
Dissolved Al	µg/L	<11 <11	14.4 14.5														
Dissolved Fe	µg/L	<30 <30	<30 <30														
Dissolved Mn	µg/L	<0.5 <0.5	<0.5 <0.5														

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
(c) No sampling during the Christmas week.
IN = inlet; TB1 = after the roughing tank; TA1 = after the polishing tank; AC = after the GAC tank.

Table D-3. Analytical Results from Long-Term Sampling, Plant D (January 20, 1999 to March 3, 1999)

Sampling Date		01/20/99				02/03/99				2/17/99				03/03/99			
Sampling Location Parameter	Unit	IN	TB1	TA1	AC	IN	TB1	TA1	AC	IN	TB1	TA1	AC	IN	TB1	TA1	AC
Alkalinity	mg/L$^{(a)}$	57	55	55	56	58	56	56	54	56 57	57 56	56 56	55 55	56	57	55	53
Fluoride	mg/L	1.1	1.1	1.2	1.3	1.2	1.2	1.3	1.4	1.0 1.0	1.1 1.1	1.1 1.1	1.2 1.2	1.2	1.2	1.4	1.4
Sulfate	mg/L	14	14	14	14	13	13	13	13	12 13	12 13	13 13	12 13	13	11	12	11
Turbidity	NTU					0.2	0.1	<0.1	<0.1								
pH	–	8.3	7.8	7.7	8.0	8.3	8.2	7.0	7.8	8.3 8.3	8.1 8.1	7.9 7.9	7.8 7.8	8.3	8.2	8.0	7.8
Total Hardness	mg/L$^{(a)}$					51	51	50	48								
Ca Hardness	mg/L$^{(a)}$					44.2	43.7	43.2	41.0								
Mg Hardness	mg/L$^{(a)}$					7.0	7.0	6.8	6.8								
NO_3-NO_2 (N)	mg/L$^{(b)}$					0.3	0.5	1.4	0.5								
As (total)	µg/L	53.0	46.2	0.9	0.7	56.5 61.1	47.5 49.0	0.6 0.5	0.5 0.4	54.6	47.0	1.0	0.8	62.6	50.3	1.2	0.9
As (total soluble)	µg/L					65.3 66.9	52.3 50.7										
As (particulate)	µg/L					<0.1 <0.1	<0.1 <0.1										
As (III)	µg/L					<0.1 <0.1	0.2 0.2										
As (V)	µg/L					65.3 66.9	52.1 50.5										
Total Al	µg/L	<11	24.1	21.2	30.2	14.6 27.2	23.5 27.3	16.5 23.9	22.3 40.1	11.3	22.1	21.6	19.1	<11	41.0	24.4	22.3
Total Fe	µg/L	<30	<30	<30	<30	62.0 40.6	<30 44.6	<30 <30	<30 <30	<30	<30	<30	<30	36.3	<30	42.1	<30
Total Mn	µg/L	0.5	<0.5	<0.5	<0.5	<0.5 <0.5	<0.5 <0.5	<0.5 <0.5	<0.5 <0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Dissolved Al	µg/L					<11 <11	14.9 14.2										
Dissolved Fe	µg/L					<30 <30	<30 <30										
Dissolved Mn	µg/L					<0.5 <0.5	<0.5 <0.5										

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; TB1 = after the roughing tank; TA1 = after the polishing tank; AC = after the GAC tank.

Table D-4. Analytical Results from Long-Term Sampling, Plant D (Mar 17 to April 28, 1999)

Sampling Date		03/17/99				03/31/99				04/14/99				04/28/99			
Sampling Location Parameter	Unit	IN	TB1	TA1	AC	IN	TB1	TA1	AC	IN	TB1	TA1	AC	IN	TB1	TA1	AC
Alkalinity	mg/L$^{(a)}$	54	55	55	54	58	57	57	56	58 58	57 57	57 56	55 56	58	58	57	56
Fluoride	mg/L	1.4	1.4	1.5	1.6	1.2	1.2	1.3	1.4	1.1 1.1	1.1 1.1	1.2 1.2	1.3 1.3	1.1	1.1	1.2	1.3
Sulfate	mg/L	11	12	12	11	15	14	14	14	15 14	14 14	14 14	14 14	14	14	14	14
Turbidity	NTU					0.3	0.2	<0.1	<0.1								
pH	–	8.2	8.1	8.0	7.9	8.3	8.2	7.9	7.9	8.3 8.3	8.3 8.3	8.0 8.0	7.9 7.9	8.3	8.2	8.0	7.9
Total Hardness	mg/L$^{(a)}$					46	50	45	45								
Ca Hardness	mg/L$^{(a)}$					39.5	42.9	38.0	38.7								
Mg Hardness	mg/L$^{(a)}$					6.6	6.9	6.5	6.5								
NO_3-NO_2 (N)	mg/L$^{(b)}$					0.4	0.4	0.4	0.3								
As (total)	µg/L	61.6	52.5	1.1	0.8	71.2 69.5	60.8 60.7	0.9 0.9	0.8 0.7	63.0	53.3	1.1	0.9	61.1	54.9	1.3	1.1
As (total soluble)	µg/L					69.9 70.4	60.1 60.6										
As (particulate)	µg/L					1.3 <0.1	0.7 0.1										
As (III)	µg/L					0.5 0.3	0.4 0.2										
As (V)	µg/L					69.4 70.1	59.7 60.4										
Total Al	µg/L	13.5	18.2	16.7	18.8	<11 <11	24.4 24.7	22.6 18.7	27.4 24.8	<11	17.3	29.1	18.7	<11	18.5	33.5	24.4
Total Fe	µg/L	<30	<30	<30	<30	<30 <30	<30 <30	<30 <30	<30 <30	<30	<30	<30	<30	<30	<30	<30	<30
Total Mn	µg/L	11.2	<0.5	<0.5	<0.5	<0.5 <0.5	<0.5 <0.5	<0.5 <0.5	<0.5 <0.5	<0.5	0.8	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Dissolved Al	µg/L					<11 <11	13.6 13.3										
Dissolved Fe	µg/L					<30 <30	<30 <30										
Dissolved Mn	µg/L					<0.5 <0.5	<0.5 <0.5										

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; TB1 = after the roughing tank; TA1 = after the polishing tank; AC = after the GAC tank.

Table D-5. Analytical Results from Long-Term Sampling, Plant D (May 12 to June 23, 1999)

Sampling Date		05/12/99				05/26/99[(C)]				06/09/99				06/23/99			
Sampling Location Parameter	Unit	IN	TB1	TA1	AC	IN	TA1	TB1	AC	IN	TA1	TB1	AC	IN	TA1	TB1	AC
Alkalinity	mg/L[(a)]	57	58	58	55	58	57	55	54	58 58	56 56	52 52	50 50	58	57	59	60
Fluoride	mg/L	1.1	1.1	1.1	1.2	1.3	1.4	0.6	0.6	1.1 1.1	1.2 1.2	<0.1 <0.1	<0.1 <0.1	1.0	1.1	<0.1	<0.1
Sulfate	mg/L	14.0	14.0	14.0	14.0	13.0	14.0	<5	<5	13.0 13.0	14.0 14.0	<5 <5	<5 <5	14.0	15.0	15.0	15.0
Turbidity	NTU					0.3	<0.1	<0.1	<0.1								
pH	–	8.4	8.3	8.0	7.8	8.3	8.1	9.9	9.5	8.3 8.3	8.1 8.1	8.4 8.4	8.7 8.7	8.3	8.0	8.3	8.4
Total Hardness	mg/L[(a)]					48	47	<2.0	<2.0								
Ca Hardness	mg/L[(a)]					42.2	41.0	0.7	0.8								
Mg Hardness	mg/L[(a)]					6.3	6.4	0.8	0.8								
NO_3-NO_2 (N)	mg/L[(b)]					0.8	0.3	0.3	0.5								
As (total)	µg/L	62.4	56.8	1.4	1.0	65.9 66.4	1.4 1.4	2.1 2.1	9.5 9.6	60.2	1.7	2.9	2.3	61.1	2.3	1.8	1.1
As (total soluble)	µg/L					66.6 66.0	1.4 2.3										
As (particulate)	µg/L					<0.1 <0.1	<0.1 <0.1										
As (III)	µg/L					0.5 0.4	0.1 0.1										
As (V)	µg/L					66.1 65.7	1.3 2.1										
Total Al	µg/L	<11	17.6	17.6	21.5	<11 <11	14.6 19.0	7,457	7,566	<11	21.5	121	190	12.1	22.4	108	115
Total Fe	µg/L	<30	<30	<30	<30	40.1 40.9	<30 <30	<30 <30	<30 <30	33.3	<30	<30	<30	<30	<30	<30	<30
Total Mn	µg/L	<0.5	<0.5	<0.5	<0.5	<0.5 <0.5	0.8 <0.5	<0.5 <0.5	<0.5 <0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Dissolved Al	µg/L					1.5 2.7	19.2										
Dissolved Fe	µg/L					<30 <30	<30 <30										
Dissolved Mn	µg/L					<0.5 <0.5	1.5 <0.5										

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
(c) Tanks B1 and B2 were replaced with virgin activated alumnia on 5/25/99; they were used as polishing tanks and Tanks A1 and A2 used as roughing tanks afterwards.
IN = inlet; TB1 = after the roughing tank; TA1 = after the polishing tank; AC = after the GAC tank.

Table D-6. Analytical Results from Long-Term Sampling, Plant D (July 7 to August 18, 1999)

Sampling Date		07/07/99				7/21/99				8/04/99				8/18/99			
Sampling Location Parameter	Unit	IN	TA1	TB1	AC	IN	TA1	TB1	AC	IN	TA1	TB1	AC	IN	TA1	TB1	AC
Alkalinity	mg/L(a)	58	59	65	62	59	58	60	60	58 58	47 48	55 55	40 40	57	56	56	58
Fluoride	mg/L	0.9	1.1	0.2	0.2	1.2	1.2	0.3	0.3	0.9 0.9	<0.1 <0.1	0.7 0.7	0.5 0.5	1.0	0.5	0.5	0.1
Sulfate	mg/L	15	16	16	15	13	14	13	13	13 13	7 8	<5 <5	<5 <5	12	12	10	11
Turbidity	NTU					0.30	0.10	<0.10	<0.10								
pH	–	8.2	8.0	8.3	8.0	7.8	8.0	8.3	8.4	8.2 8.2	8.3 8.4	8.4 8.5	8.4 8.4	8.2	8.3	8.4	8.3
Total Hardness	mg/L(a)					48	50	47	50								
Ca Hardness	mg/L(a)					41.7	42.9	40.5	42.9								
Mg Hardness	mg/L(a)					6.5	6.6	6.6	6.8								
NO_3-NO_2 (N)	mg/L(b)					0.3	0.4	0.5	0.4								
As (total)	µg/L	60.3	3.4	3.2	1.0	87.9 86.0	10.9 10.4	1.2 1.2	0.7 0.6	59.8	5.4	1.6	0.8	58.8	6.5	1.1	0.6
As (total soluble)	µg/L					100 68.8	9.5 10.0										
As (particulate)	µg/L					<0.1 17.2	1.4 0.4										
As (III)	µg/L					*	*										
As (V)	µg/L					<0.1 <0.1	6.1 10.0										
Total Al	µg/L	20.5	23.7	133	124	16.0 18.8	28.1 29.4	128 132	155 139	16.9	471	148	143	22.4	80.4	111	107
Total Fe	µg/L	<30	<30	<30	<30	<30 <30	<30 <30	<30 <30	<30 <30	<30	<30	<30	<30	<30	127	<30	<30
Total Mn	µg/L	<0.5	<0.5	<0.5	<0.5	<0.5 <0.5	<0.5 <0.5	<0.5 <0.5	<0.5 <0.5	<0.5	0.7	<0.5	<0.5	<0.5	0.7	<0.5	<0.5
Dissolved Al	µg/L					<11 <11	13.1 14.6										
Dissolved Fe	µg/L					<30 <30	<30 <30										
Dissolved Mn	µg/L					<0.5 <0.5	<0.5 <0.5										

(a) Measured as $CaCO_3$.
(b) Combined NO_3 and NO_2 as N.
IN = inlet; TA1 = after the roughing tank; TB1 = after the polishing tank; AC = after the GAC tank.
* Abnormal results due to contaminated resin column.

Table D-7. Analytical Results from Long-Term Sampling, Plant D (September 1, 1999)

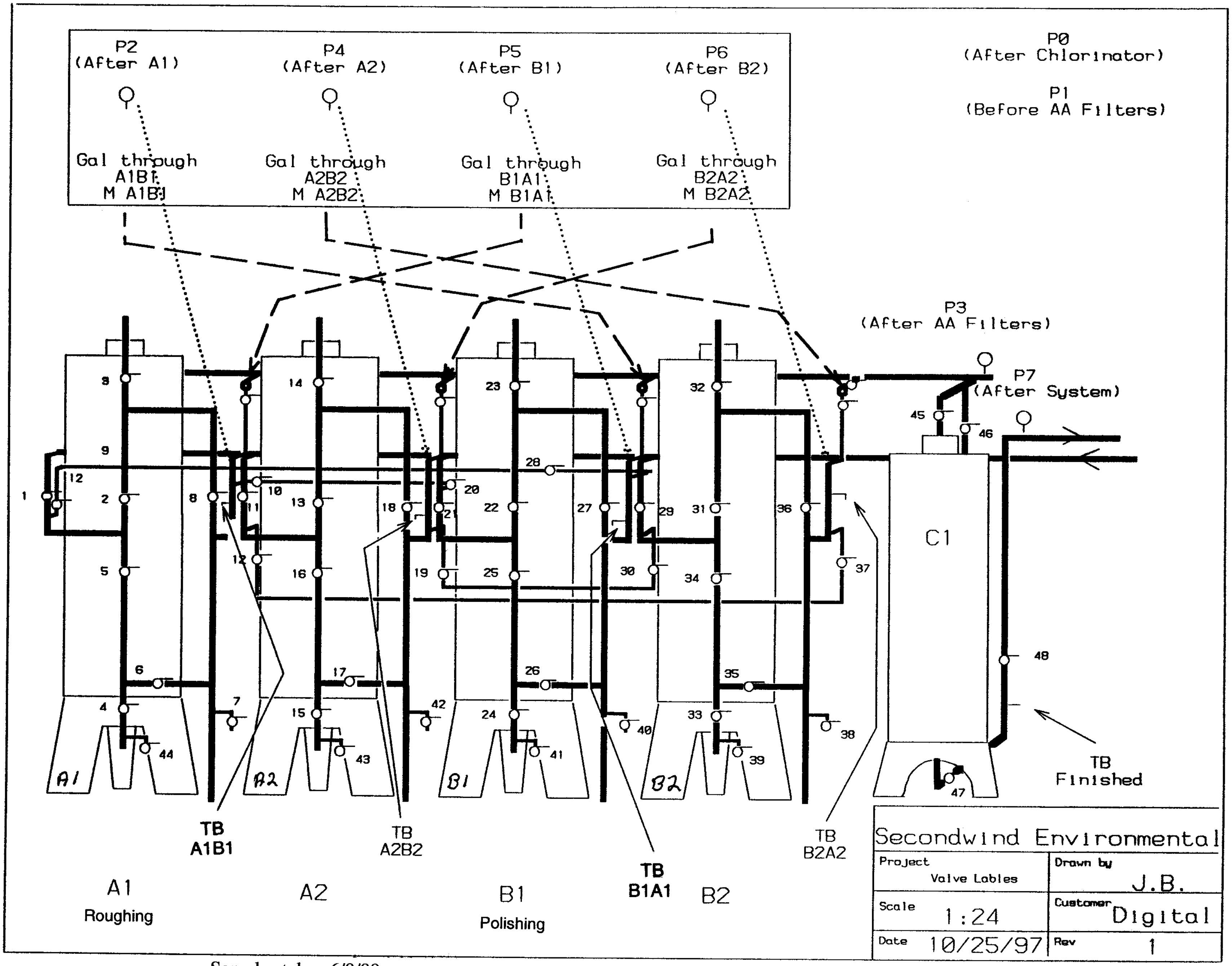
Sampling Date		9/1/99			
Sampling Location Parameter	Unit	IN	TA1	TB1	AC
Alkalinity	mg/L[(a)]	58	57	59	57
Fluoride	mg/L	1.1	0.5	0.2	0.5
Sulfate	mg/L	12	13	14	14
Turbidity	NTU				
pH	–	7.8	8.2	8.1	8.0
Total Hardness	mg/L[(a)]				
Ca Hardness	mg/L[(a)]				
Mg Hardness	mg/L[(a)]				
NO_3-NO_2 (N)	mg/L[(b)]				
As (total)	µg/L	60.3	1.3	0.8	0.7
As (total soluble)	µg/L				
As (particulate)	µg/L				
As (III)	µg/L				
As (V)	µg/L				
Total Al	µg/L	14.9	277	129	68.8
Total Fe	µg/L	<30	<30	<30	<30
Total Mn	µg/L	<0.5	<0.5	<0.5	<0.5
Dissolved Al	µg/L				
Dissolved Fe	µg/L				
Dissolved Mn	µg/L				

(a) Measured as $CaCO_3$.

(b) Combined NO_3 and NO_2 as N.

IN = inlet; TA1 = after the roughing tank; TB1 = after the polishing tank; AC = after the GAC tank.

D.2 System Plumbing Diagram



Samples taken 6/9/99.

D.3 Water Usage Report

Plant D Water Usage Report

	Water Meter Readings (gal)					Cumulative Water Treated (BV)				
Date	Entrance	A1B1	A2B2	B1A1	B2A2	A1B1	A2B2	B1A1	B2A2	Remarks
04/16/96	2,295,800	400	42,900	200	300	0	0	0	0	AA system installed in 2/96
05/08/96	2,333,260	18,800	61,600	200	300	246	250	0	0	
06/19/96	2,409,900	56,200	100,200	200	300	746	766	0	0	
07/22/96	2,466,374	83,800	128,600	200	300	1,115	1,146	0	0	
08/20/96	2,523,670	111,900	157,300	200	300	1,491	1,529	0	0	
09/06/96	2,553,380	126,400	172,300	200	300	1,684	1,730	0	0	
10/15/96	2,631,240	164,700	211,400	200	300	2,197	2,253	0	0	
11/13/96	2,703,750	200,300	247,800	200	300	2,672	2,739	0	0	
12/20/96	2,770,410	233,000	281,200	200	300	3,110	3,186	0	0	
01/09/97	2,800,240	247,700	296,100	200	300	3,306	3,385	0	0	
02/21/97	2,888,940	291,900	339,900	200	300	3,897	3,971	0	0	
03/21/97	2,948,004	321,000	369,400	200	300	4,286	4,365	0	0	
04/17/97	3,000,610	346,900	395,700	200	300	4,632	4,717	0	0	
05/15/97	3,059,700	376,000	425,200	200	300	5,021	5,111	0	0	
06/12/97	3,108,910	400,300	449,800	200	300	5,346	5,440	0	0	Arsenic breakthrough in TA2 (50-µg/L)
07/14/97	3,157,310	424,500	473,900	200	300	5,670	5,762	0	0	
08/15/97	3,208,400	449,300	499,400	200	300	6,001	6,103	0	0	Arsenic breakthrough in TA1 (50-µg/L)
09/12/97	3,250,280	469,900	520,300	200	300	6,277	6,382	0	0	
10/15/97	3,295,576	492,200	543,000	200	300	6,575	6,686	0	0	
11/18/97	3,357,040	504,800	557,100	17,200	17,600	6,743	6,874	-	-	TA1, TA2 rebedded in 11/97
12/23/97	3,411,900	504,800	557,100	43,200	45,100	0	0	0	0	TB1, TB2 rebedded in 12/97
01/19/98	3,447,000	504,800	557,100	60,500	62,200	0	0	231	254	
02/24/98	3,509,210	504,800	557,100	91,200	93,100	0	0	642	667	
03/25/98	3,560,110	504,800	557,100	116,400	118,400	0	0	979	1,005	
04/15/98	3,594,940	504,800	557,100	133,600	135,700	0	0	1,209	1,237	
05/19/98	3,661,900	504,800	557,100	167,100	168,600	0	0	1,656	1,676	
06/15/98	3,720,820	504,800	557,100	196,200	197,600	0	0	2,045	2,064	
07/23/98	3,778,580	504,800	557,100	224,800	226,200	0	0	2,428	2,447	
08/27/98	3,830,990	504,800	557,100	250,800	252,100	0	0	2,775	2,793	
09/16/98	3,856,690	504,800	557,100	263,600	264,900	0	0	2,947	2,964	
10/15/98	3,897,300	504,800	557,100	283,800	285,000	0	0	3,217	3,233	
11/12/98	3,936,270	504,800	557,100	303,000	304,300	0	0	3,473	3,491	
12/21/98	3,982,560	504,800	557,100	326,000	327,200	0	0	3,781	3,797	
01/19/99	4,015,700	504,800	557,100	342,500	343,600	0	0	4,001	4,016	
02/16/99	4,055,600	504,800	557,100	362,300	363,400	0	0	4,266	4,281	
03/18/99	4,095,300	504,800	557,100	382,000	383,100	0	0	4,529	4,544	*
04/28/99	4,147,400	504,800	557,100	407,900	408,900	0	0	4,876	4,889	
05/25/99	4,181,200	504,800	557,100	424,600	425,600	0	0	5,099	5,112	Rebedded TB1, TB2 on 5/25/99
06/22/99	4,218,500	522,800	575,800	424,600	425,600	241	250	0	0	
07/14/99	4,269,800	548,000	601,700	424,600	425,600	578	596	0	0	Rebedded TA1 on 7/23/99
08/25/99	4,346,800	585,200	641,300	424,600	425,600	1,075	1,126	0	0	
09/17/99	4,376,700	599,600	656,700	424,600	425,600	1,267	1,332	0	0	
10/29/99	4,438,700	629,600	688,600	424,600	425,600	1,668	1,758	0	0	
11/22/99	4,470,300	644,800	704,800	424,600	425,600	1,872	1,975	0	0	
12/29/99	4,517,500	667,500	729,100	424,600	425,600	2,175	2,299	0	0	

Bed volume = 10 cu ft per tank = 74.8 gal.

* Arsenic breakthrough was detected in TB1 based on Battelle's sampling results of 3/3/99.