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Removal of Arsenic from Drinking Water by Ion Exchange

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Design Manual:

Removal of Arsenic from Drinking Water by Ion Exchange

by

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Foreword

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Hugh W. McKinnon, Director
National Risk Management Research Laboratory

Abstract

This design manual is an in-depth presentation of the steps required to design and operate a water treatment plant for removing arsenic in the As(V) form from drinking water using the anion exchange process. Because As(III) occurs as an uncharged anion in ground water in the pH range of 6.5 to 8, the process will not remove As(III) unless it is first oxidized to As(V). The manual also discusses the capital and operating costs, including many of the variables that can raise or lower costs for identical treatment systems.

The anion exchange treatment process is very reliable, simple, and cost-effective. The treatment process removes arsenic using a strong base anion exchange resin in either the chloride or hydroxide form, with chloride the preferred form because salt can be used as the regenerant. The process preferentially removes sulfate over arsenic; and, therefore, as the sulfate increases in the raw water, the process becomes less efficient and more costly. Furthermore, because sulfate occurs in significantly higher concentrations than arsenic, treatment run lengths are dependent almost entirely on the sulfate concentration of the raw water. The ion exchange process is a proven efficient and cost-effective treatment method for removing As(V) from water supplies with low sulfate levels.

The configuration of an anion exchange system for As(V) removal can take several forms. The method presented in this design manual uses three vertical cylindrical pressure vessels operating in a downflow mode. Two of the three treatment vessels are piped in parallel to form the primary arsenic removal stage. The third treatment vessel is piped in series in the lag position. In the primary stage, raw water flows through one of the two treatment vessels while the second vessel is held in the standby position. When the treatment capacity of the first vessel approaches exhaustion, it is removed from service and replaced by the second primary stage vessel. While out of service, the first vessel is regenerated and placed in the standby position. The role of the third treatment vessel in the lag position is to ensure that any arsenic that breaks (peaking) through one of the lead vessels does not enter the distribution system. Although this design concept results in higher capital costs, it prevents high arsenic concentrations in the treated water, if operated properly.

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Abbreviations and Acronyms

ANSI	American National Standards Institute
APHA	American Public Health Association
ASME	American Society of Mechanical Engineers
AWWA	American Water Works Association
BAT	best available technology
BV	bed volume(s)
CPVC	chlorinated polyvinyl chloride
EBCT	empty bed contact time
EPDM	ethylene propylene diene monomer
ETV	Environmental Technology Verification
FRP	fiberglass reinforced polyester
GFAA	graphite furnace atomic absorption
GHAA	gaseous hydroxide atomic absorption
gpd	gallons per day
gpm	gallons per minute
ICP-MS	inductively coupled plasma–mass spectrometry
MCL	maximum contaminant level
N/A	not applicable
NPT	National Pipe Thread
NSF	NSF International
O&M	operations and maintenance
OSHA	Occupational Safety and Health Administration
PL	Public Law
PLC	programmable logic controller
psi	pounds per square inch
psig	pounds per square inch gage
PVC	polyvinyl chloride
SBA	strong base anion
SDWA	Safe Drinking Water Act (of 1974)
STP	stabilized temperature platform
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids
U.S. EPA	United States Environmental Protection Agency
WEF	Water Environment Federation

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1.0 Introduction

1.1 Purpose and Scope

This manual has been prepared to present up-to-date information on designing central treatment plants for removing arsenic from water supplies using the strong base anion (SBA) exchange process. Although the information in this manual is provided to serve small central water treatment plants ranging in capacity from 30,000 to 1,000,000 gallons per day (gpd), the treatment information can be adapted to both larger and smaller systems. For very small systems having capacities of less than 30,000 gpd (20 gallons per minute [gpm]), some of the equipment may be different and less expensive (for example, fiberglass-reinforced polyester [FRP] tanks and automatic control valves would probably be used). The detailed design information presented herein applies exclusively to ion exchange technology employing SBA resin in the chloride form for removing arsenic from water supplies.

When arsenic is present above the maximum contaminant level (MCL) in a water supply and is combined with quantities of other organic and/or inorganic contaminants that exceed their respective MCLs, this method may not be the best selection. Such water supplies should be evaluated on a case-by-case basis to select the appropriate treatment method or combination of methods.

1.2 Background

The Safe Drinking Water Act (SDWA) of 1974 mandated that the United States Environmental Protection Agency (U.S. 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 (Public Law, 1974). In 1975, under the SDWA, U.S. EPA established a MCL for arsenic at 0.05 mg/L (U.S. EPA, 1975). During the 1980s and early 1990s, U.S. EPA considered, but did not make, changes to the MCL. In 1996, Congress amended the SDWA, and these amendments required that the U.S. EPA develop an arsenic research strategy, publish a proposal to revise the arsenic MCL by January 2000, and publish a final rule by January 2001 (Public Law, 1996).

On January 22, 2001, U.S. EPA published a final Arsenic Rule in the *Federal Register* that revised the MCL for arsenic to 0.01 mg/L (10 µg/L) (U.S. EPA, 2001). Two months later, in March 2001, the effective date of the rule was extended to provide time for the National Academy of Sciences to review new studies on the health effects of arsenic and for the National Drinking Water Advisory Council to review the economic issues associated with the standard. After considering the reports by the two review groups, the U.S. EPA finalized the arsenic MCL at 0.01 mg/L (10 µg/L) in January 2002. In order to clarify the implementation of the original rule, U.S. EPA revised the rule text on March 25, 2003 to express the MCL as 0.010 mg/L (U.S. EPA, 2003). The final rule requires all community and nontransient, noncommunity water systems to comply with the rule by February 2006.

Ion exchange is one of several treatment processes that the U.S. EPA has listed as a best available technology (BAT) for removing arsenic [As(V)] in the final Arsenic Rule (U.S. EPA, 2001). By placing it on the BAT list, U.S. EPA determined that the process met the seven criteria required of BAT, including its ability for high arsenic removal, a history of full-scale operation, and its reasonable cost and service life. However, the process was recommended as a BAT in the final Arsenic Rule primarily for sites with a low sulfate contaminant level (50 mg/L or less) because sulfate is preferred over arsenic. In the proposed Arsenic Rule (U.S. EPA, 2000a), the practical application was listed for sites with sulfate contaminant levels below 120 mg/L. The upper bound was lowered in the final Arsenic Rule because of several factors, including cost and the ability to dispose of the brine stream.

The ion exchange process for arsenic removal is similar to the ion exchange softening process except that the resin employed is an anion resin rather than a cation

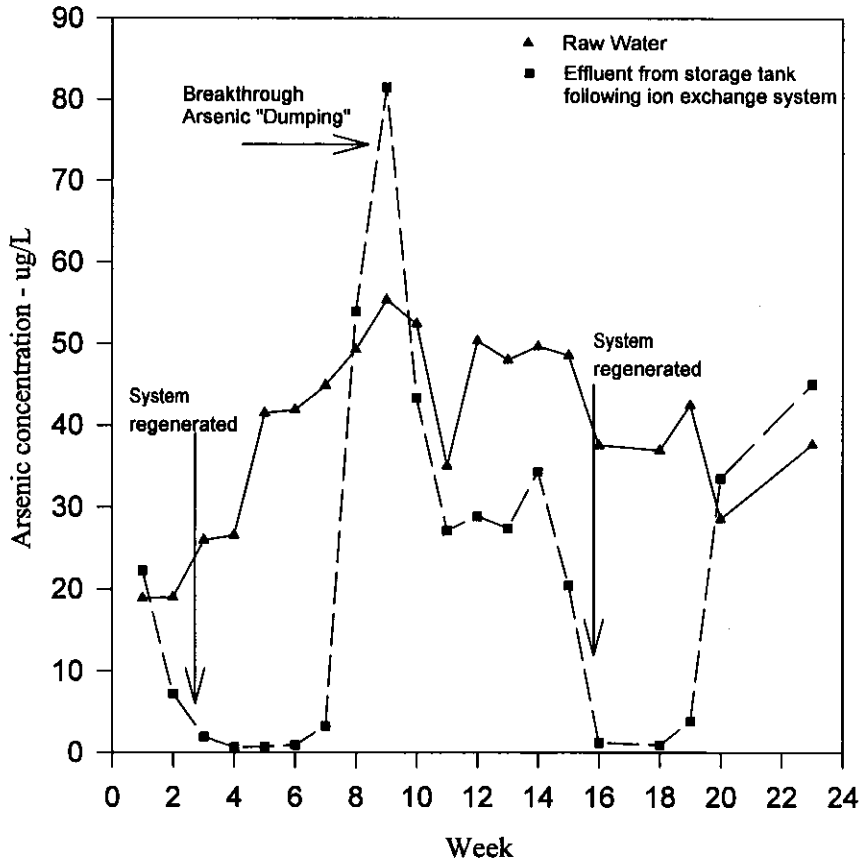
resin. Arsenic [As(V)] is removed by passing the source water under pressure through a packed bed resin column; the resin being an SBA exchange resin in either the chloride or hydroxide form. The chloride form is preferred because regeneration is accomplished with salt rather than caustic that is more costly and more difficult to handle. The operation consists of two cycles; treatment followed by regeneration (backwash, brine addition, rinse, and fast rinse). During the treatment cycle, the arsenic [As(V)] and other competing anions such as sulfate, nitrate, and bicarbonate are exchanged with the chloride ions on the resin. When the resin reaches its removal capacity, it is regenerated using a concentrated chloride solution (salt brine) that results in the chloride (because of the high concentration) replacing the arsenic and other anions on the exhausted resin.

The efficiency of the anion exchange process for arsenic removal is very dependent on the concentrations of other competing anions, particularly sulfate, that is more preferred by the resin than As(V). Clifford (1999) reported the selectivity sequence for SBA resin as follows:

$$UO_2(CO_3)_3^{-4} > SO_4^{-2} > HAsO_4^{-2} > NO_3^{-1} > SeO_3^{-2} > NO_2^{-1} > Cl^{-1} > HCO_3^{-1} > F^{-1}$$

Because the anion exchange with the sulfate is preferred over that with the As(V) and because sulfate occurs in significantly (mg/L) higher concentrations than As(V) (µg/L), the removal capacity for arsenic is directly dependent on the sulfate level of the source water. What is more important, however, is that the more preferred sulfate can replace the less preferred anions of arsenic and nitrate and cause them to be eluted from the resin column if regeneration is not performed at the appropriate time. When sulfate replaces less preferred ions, the concentration of the arsenic (or nitrate) in the effluent water can be many times higher than the concentration of the arsenic in the source water. This phenomenon is referred to as "chromatographic peaking" or "dumping."

An example of arsenic dumping that occurred with a small, full-scale arsenic removal ion exchange system is shown in Figure 1-1. When this ion exchange system was first put on line, the system was set to be regenerated



Influent water: pH 7.5, alk 90 mg/L ($CaCO_3$), Fe <0.03 mg/L

Figure 1-1. Arsenic Breakthrough Results of Full-Scale Arsenic Removal Anion Exchange System (Wang, 2002)

after four months of treatment based on the estimated average daily flow and sulfate level of the raw water. After several years of operation, the average flow increased, and the system was run past arsenic breakthrough because regeneration was established on a time basis rather than a flow basis. As shown in Figure 1-1, the arsenic levels of the treated water following a storage tank that was immediately downstream of the ion exchange system exceeded that in the raw water by about 100%. The storage tank immediately following the ion exchange system provided for some blending of the treated water from the ion exchange system. If the water samples had been collected immediately following the ion exchange system, the chromatographic peak would have been even higher. Shortly after the arsenic peaking problem was discovered, the treatment run time before regeneration time was shortened to four weeks.

Because bicarbonate is also removed by SBA resins, a drop in the pH of the effluent water will generally occur, particularly during the beginning part of the treatment cycle. The pH decrease is water quality dependent and, if significant, it could require post-pH adjustment.

The potential problems of arsenic "dumping" and pH decrease can be minimized by system design. Very small, simple design systems of one column provide the greatest opportunity for these conditions to occur, and extreme care must be taken in operation to prevent dumping. Operation of multiple columns in parallel and/or in series, in combination with storage, can decrease the risk of arsenic dumping and the potential need for post-pH adjustment. Examples of system configuration for the anion exchange process for arsenic removal are provided in Figure 1-2.

The treatment system presented in this design manual is shown in Figure 1-2(e)—a three-column system with the first two columns in parallel followed by the third column in series. As discussed in the following chapters, this

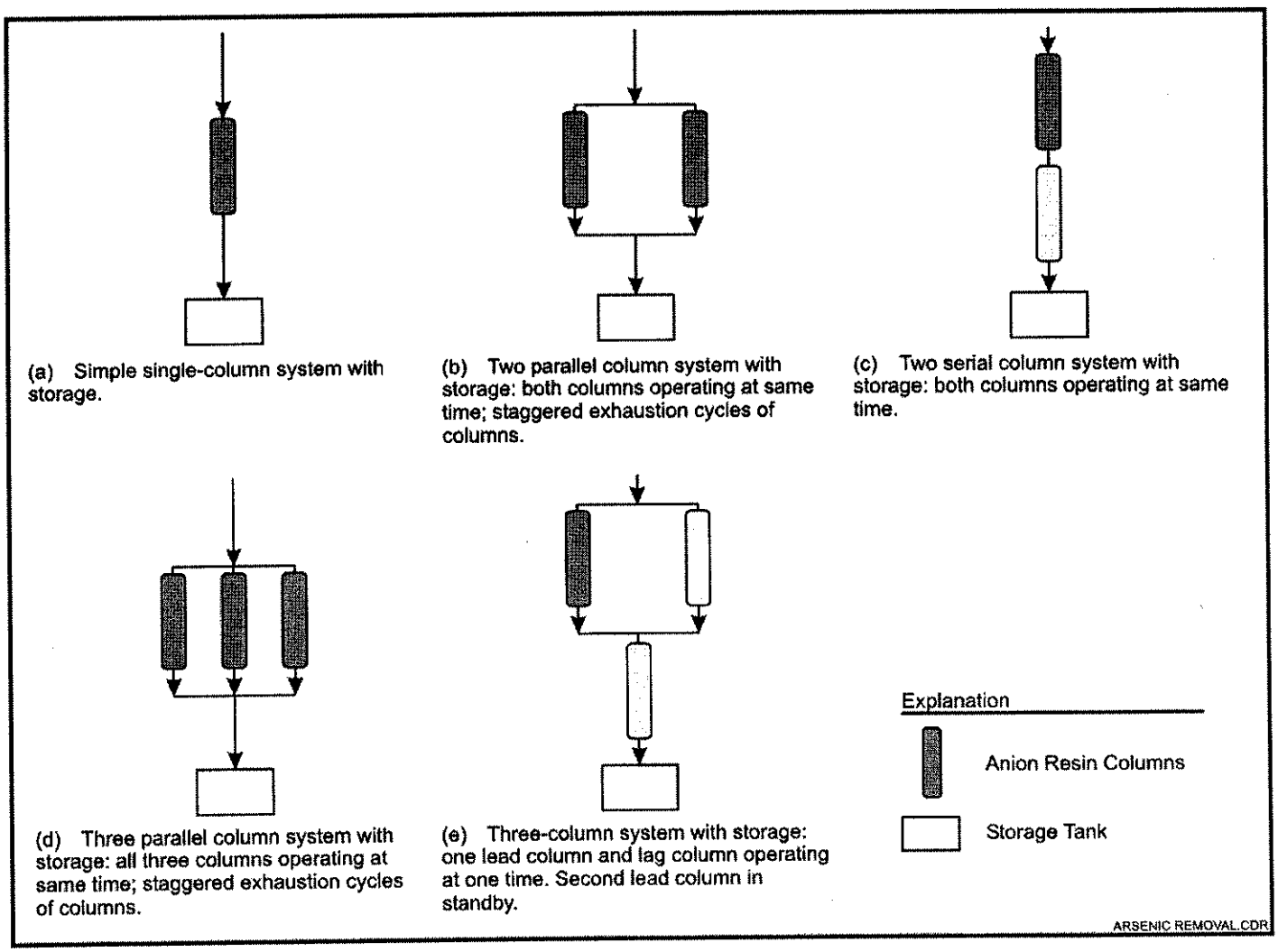


Figure 1-2. Examples of Arsenic Removal Ion Exchange System Designs

design is conservative and minimizes the risk of arsenic dumping. Although the design results in higher capital cost, if operated properly, it prevents high arsenic levels in the finished water.

1.3 Arsenic in Water Supplies

Arsenic occurs in combination with other ions as arsenic compounds. Unless contaminated by arsenic-bearing wastes, the concentrations in surface water supplies are normally less than the MCL. Ground water has higher arsenic concentrations than surface water, which may exceed the MCL due to the exposure to arsenic-bearing materials. Because of the revision of the arsenic MCL, a large number of systems that had previously been in compliance will require treatment for the removal of arsenic.

1.4 Arsenic Speciation

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.

The valence and species of inorganic arsenic are dependent on oxidation-reduction conditions and the pH of the water. As a general rule of thumb, arsenite, the reduced, trivalent form [As(III)], is found in ground water (assuming anaerobic conditions) and arsenate, the oxidized, pentavalent form [As(V)], is found in surface water (assuming aerobic conditions). This rule, however, does not always hold true for ground water. Some ground water has only As(III), some only As(V), and some the combination of both As(III) and As(V). 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-}. In the common ground water pH range of 6 to 9, the predominant As(III) species is neutral (H_3AsO_3), whereas the As(V) species are monovalent ($H_2AsO_4^-$) and divalent ($HAsO_4^{2-}$).

Until recently (Gallagher et al., 2001), studies on the preservation of the arsenic species concluded that there was no effective method for preserving As(III) and As(V) in water samples. Because of the lack of a good preservation method, field separation methods developed by Ficklin (1982), Clifford et al. (1983), and Edwards et al. (1998) have been used that employ an anion exchange column as the separation procedure. All the methods are effective, and their use is recommended to determine the oxidation state of the arsenic in the source water to be treated.

1.5 Removal of Arsenic

In water supplies where the arsenic level exceeds the MCL, steps should be taken to reduce the level to below the MCL. This design manual addresses removal of excess arsenic by means of the ion exchange method. However, other treatment methods exist, such as adsorptive media, membrane separation, chemical coagulation/filtration, and iron removal. Also, other options, including alternate sources of supply, may offer lower-cost solutions. The first choice is to locate an existing water supply within the service area with known quality that complies with the arsenic MCL in addition to all other MCLs (both organic and inorganic). If another source complies with the arsenic MCL, but exceeds another MCL (or MCLs), it may still be feasible to blend the two sources and achieve a water quality that complies with all MCLs. Other features associated with this option may present liabilities, including, but not limited to high temperature, or undesirable quantities of nontoxic contaminants such as turbidity, color, odor, hardness, iron, manganese, chloride, and/or sodium.

A second option is to pump good quality water to the service area from another service area. Similar to the alternate source within the service area, this imported source can be blended. However, the costs of installing the delivery system and delivering the water become increasingly unfavorable as the distance increases, the elevation rises, and/or physical barriers are encountered. The reliability, the cost, and the assurance that the consumers will only use that source are factors to be considered. Another option (which includes an element of risk) is to drill a new well (or wells) within the service area. This approach should be attempted only when there is sound reason to believe that a sufficient quantity of acceptable quality water can be located. The cost (both capital and operating) of a new well should not exceed the cost of treating the existing source. Other options such as point-of-use treatment systems are viable alternatives. However, the treatment reliability of such systems cannot be assured unless stringent controls govern their operation and maintenance. Also, the problem of assuming that all users consume only water that has been treated where untreated water is also available must be addressed.

2.0 Arsenic Removal by Ion Exchange Treatment

2.1 Introduction

Several central treatment methods can remove excess arsenic from drinking water supplies, including chemical coagulation/filtration, adsorptive media, ion exchange, iron removal processes, and membrane separation (Chowdhury et al., 2002; Sorg and Logsdon, 1978; U.S. EPA, 2001). This manual addresses the ion exchange method, specifically anion exchange, that has been demonstrated to effectively remove arsenic from ground water to below the MCL of 0.01 mg/L (Wang et al., 2002). This chapter provides an overview of the ion exchange process, including the advantages and disadvantages of the process for arsenic removal.

2.2 Ion Exchange Process

The ion exchange process with regeneration capability is a proven efficient and cost-effective treatment method for removing As(V) from water supplies and has been listed as a BAT by U.S. EPA for source water with low sulfate levels (<50 mg/L) (U.S. EPA, 2001). This process does not remove As(III) unless the As(III) is preoxidized to As(V) prior to entry into the ion exchange process. Moreover, this process preferentially removes sulfate before As(V); and, therefore, as the sulfate concentration in the raw water increases, the process becomes less efficient.

The treatment method presented in this design manual for the ion exchange method uses three vertical cylindrical pressure vessels containing SBA resin beds operating in a downflow mode (Figure 1-2[e]). Two of the three treatment vessels are piped in parallel to form the primary arsenic removal stage. The third treatment vessel is piped in series in the lag position to form the secondary treatment stage. In the primary stage, the raw water flows through one of the two treatment vessels in which the arsenic is removed while the second vessel is held in the standby position. As the treatment capacity of the first vessel approaches exhaustion, it is removed from service and replaced by the second primary stage vessel. While out of service, the first vessel is regenerated and placed in the standby position. It remains there until the arsenic removal capacity of the second vessel approaches exhaustion, at which time that vessel is removed from service and replaced by the first vessel.

Care must be exercised to prevent arsenic breakthrough from occurring. Breakthrough results in discharge of the arsenic removed during the entire treatment cycle from the treatment vessel in a surge that is much higher than the arsenic concentration in the raw water (chromatographic peaking or dumping), as explained in Section 1.2. To ensure that such an event does not result in treated water with a high arsenic concentration entering the distribution system, the second stage treatment vessel is provided. Though this design concept results in higher capital costs, it reduces the risk of high arsenic concentrations in the treated water. Use of the second stage treatment vessel provides insurance against a potential dumping event that could expose consumers to high arsenic levels in treated water.

Several papers and reports have been written on the application of the ion exchange method for removing arsenic from water (Clifford, 1999; Chowdhury et al., 2002; U.S. EPA, 2000b). The process consists of passing As(V)-containing raw water through a bed of chloride-form SBA resin (designated by $\overline{RCl}$), during which the chloride arsenate ion exchange reaction, Eq. (1), takes place to yield resin in the arsenate form ($\overline{R_2HAsO_4}$). When the column capacity for arsenic is exhausted, the arsenic breaks through into the effluent, and its concentration rises rapidly and can exceed the influent arsenic concentration if the treatment run goes beyond breakthrough. The reaction is easily reversed; and regeneration, according to Eq. (2), returns the resin to the chloride form, ready for another treatment cycle:

$$2\,\overline{RCl} + HAsO_4^{-2} = \overline{R_2HAsO_4} + 2Cl^- \qquad (1)$$

$$\overline{R_2HAsO_4} + 2NaCl = 2\,\overline{RCl} + Na_2HAsO_4 \qquad (2)$$

The advantages of the ion exchange process for removing arsenic from water are as follows:

1. The process is simple. The process is considered economical for removing As(V) from water with sulfate levels less than 50 mg/L.

2. The process can be operated manually or automatically.

3. The process is capable of lowering As(V) to a level that meets regulatory requirements.

4. The process is effective in the pH range of 6.5 to 9.0 in which As(V) is present. Feedwater pH adjustment is, therefore, not required.

5. The exchange kinetics are very fast, resulting in empty bed contact times as low as 1.5 to 3.0 min.

6. The process can remove other contaminants including, but not limited to, nitrate, nitrite, uranium, chromate, and selenium.

7. Exhausted resin can be regenerated using NaCl brine.

8. Spent regenerant may be reusable.

The disadvantages of the ion exchange process are as follows:

1. The process does not remove As(III). When present, As(III) must be oxidized to As(V). Excess oxidizing chemical might degrade the resin; therefore, its removal may be required prior to contact with the resin.

2. Sulfate is removed preferentially to As(V). The length of an ion exchange treatment run is, therefore, directly dependent on the sulfate concentration. The higher the sulfate concentration, the shorter the treatment run.

3. There is a potential for discharge of higher arsenic concentrations in the treated water. For water supplies also containing nitrate, there is potential for discharging high concentrations of both nitrate and arsenic.

4. Chloride ions will increase in the treated water at an exchange rate of up to two for each sulfate and arsenic ion removed.

5. Effluent pH may be reduced to an unacceptably low level due to bicarbonate conversion to carbonate and CO_2 by the resin. If the treated water pH is too low, post-treatment chemical addition including pH adjustment and/or corrosion inhibitor addition may be required.

6. Foulant formation on resin beads rapidly degrades process performance. Prefiltration upstream of the ion exchange column may be required for removing silica, colloidal matter, etc., to prevent resin fouling.

7. The process will remove uranium that could potentially create a waste handling and disposal problem of the spent brine when the resin is regenerated.

8. Spent brines require disposal. Spent brines containing more than 5.0 mg/L of arsenic will be classified as a hazardous waste based on the U.S. EPA Toxicity Characteristic Leaching Procedure (TCLP).

2.2.1 *Effect of Sulfate on Arsenic Removal*

Because arsenic is a trace species, its concentration does not greatly accelerate the run length to arsenic breakthrough. However, because ion exchange with sulfate, a common ion, is preferred over arsenate, nitrate, bicarbonate, and other common anions, its concentration largely determines the run length to arsenic breakthrough (Ghurye et al., 1999). The results of ion exchange pilot tests for arsenic removal with several resins and varying sulfate concentrations in the raw water are shown in Figure 2-1. Higher sulfate concentrations lead to shorter arsenic removal runs, and this can lead to chromatographic peaking of arsenic after arsenic breakthrough. These peaks are avoided by stopping a run prior to arsenic breakthrough. Concern for potential breakthrough of arsenic must be eliminated. One design that can reduce the risk of arsenic breakthrough is the inclusion of a second stage polishing vessel in series that will remove any arsenic that might exit the primary stage treatment vessel (Figure 1-2[e]).

2.2.2 *Effect of Multiple Contaminants*

If nitrate is present along with arsenic and sulfate, the SBA resin will remove the nitrate along with the arsenic and sulfate. Because nitrate is less preferred than arsenic and sulfate, nitrate will break through prior to both arsenic and sulfate. Although nitrate is less preferred than arsenic, arsenic levels occur in significantly lower concentrations (µg/L) than nitrate (mg/L). Therefore, arsenic will not have a major effect on nitrate dumping if the system is run beyond nitrate breakthough. However, substantial nitrate dumping, similar to arsenic dumping, can occur in the effluent if the treatment cycle

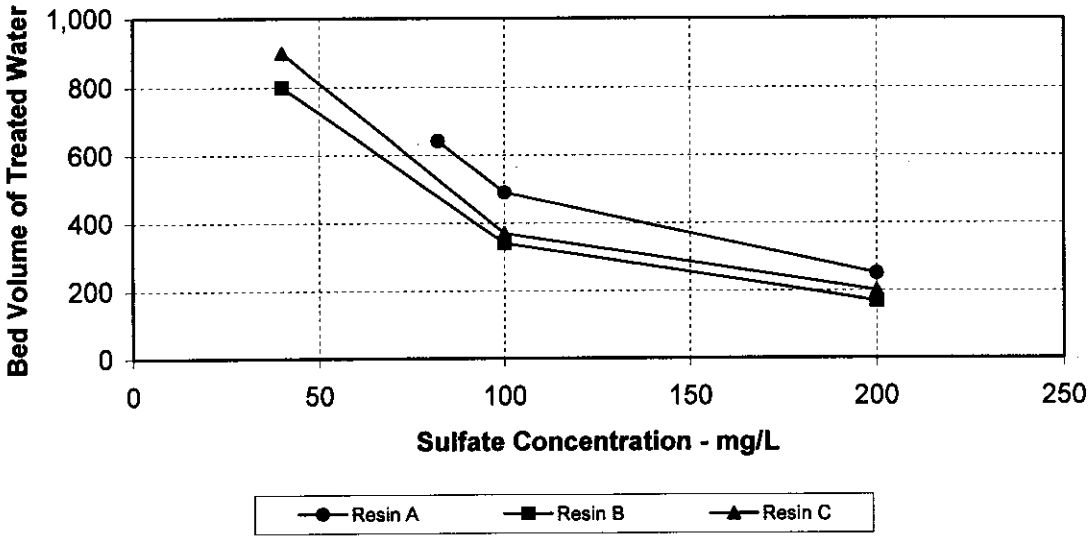


Figure 2-1. Treatment Runs (Experimental) to Arsenic Breakthrough with Varying Sulfate Concentrations in Raw Water (Ghurye et al., 1999)

is allowed to run past sulfate breakthrough. To prevent the possibility of nitrate dumping, the treatment run should be terminated prior to nitrate breakthrough. This results in shorter run lengths, but will avoid exceeding the nitrate MCL. Concern for potential breakthrough of nitrate and arsenic should be eliminated. This risk can be reduced by including the above-mentioned second stage treatment vessel in series, which will remove any nitrate and arsenic that might exit the primary stage treatment vessel.

2.2.3 Low Effluent pH in the Early Stages of a Treatment Cycle

When a chloride-form SBA resin is used to treat natural water as in the arsenic ion exchange process, the effluent pH during the first 50 to 300 bed volumes can be significantly reduced compared with the influent pH. Effluent pH as low as 5.0 has been observed (Clifford, 1999). The reason for the pH reduction is the conversion of bicarbonate to carbonate by the resin (Horng and Clifford, 1997). This conversion occurs with the resulting expulsion of a proton (H^+ ion), which increases the H^+ ion concentration and lowers the pH. The bicarbonate-to-carbonate reaction occurs because all standard SBA resins prefer divalent (e.g., carbonate) to monovalent (e.g., bicarbonate) ions at the typical total dissolved solids (TDS) levels found in drinking water supplies.

The extent of the pH lowering depends primarily on the characteristics of the resin and the bicarbonate concentration in the raw water. If the treated water pH is low or possesses corrosive characteristics, corrective measures, including pH adjustment and/or addition of a corrosion inhibitor, might be required. Post-treatment chemical feed may be required for such adjustments.

2.2.4 Spent Brine Reuse

Direct reuse of the spent arsenic-contaminated ion exchange brine is possible to regenerate the spent resin (Clifford and Ghurye, 1998). Brine reuse can substantially cut down on (a) the volume of brine discharged, and (b) the amount of salt (NaCl) consumed by the process. This option, which can be incorporated into the process in various ways, has not been tried in full-scale systems and, therefore, is not included in the scope of this manual.

2.3 Manual vs. Automatic Operation

The water utility owner should be informed of the advantages and disadvantages of the operational options prior to finalizing the decision relating to the mode of operation. The system can be operated manually, automatically, or semiautomatically. Automatic operation reduces operator effort, but increases the cost of instrumentation and control equipment, as well as the skill level required of the operator, who should be able to maintain more sophisticated equipment.

Treatment systems using ion exchange resin are suitable for manual operation. That operational mode requires the treatment plant operator to accomplish the following:

1. Start/stop operation. Adjust flowrate.
2. Start/stop and adjust rate of brine feed. Monitor concentration.
3. Monitor and adjust system operating pressure.
4. Start/stop/control backwash, drain, regeneration, and rinse steps.
5. Monitor arsenic concentration of raw water, treated water, and intermediate sample points.
6. Monitor pH of treated water.

A fully automatic instrumentation and control system includes a programmable logic controller (PLC), an operator interface (screen with graphics), software, automatic instrumentation (sensors, transmitters, controllers, alarms, electrical conductors, pneumatic tubing, etc.) and automatically controlled equipment (valves, pumps, chemical feed pumps, air compressor, etc.). The instruments can monitor and control flow, level, pressure, pH, and temperature. Arsenic concentration analyses require a manual laboratory procedure.

Semiautomatic operation entails automating any part of the instrumentation and control functions, while the remainder are accomplished manually. Not included are the PLC, operator interface, and required software. This operational mode reflects choices made by the owner with the advice of the designer. The choices require analysis of risk and treatment process efficiency vs. investment in equipment and labor. This design manual presents information regarding instrumentation and control functions, all of which can be accomplished automatically or manually. The only exception is the laboratory analysis requirement for determination of arsenic concentration in raw water, treated water, wastewater, and at intermediate sample points.

3.0 Design of Central Treatment System

The design of the ion exchange system presented in this manual provides information to adapt anion resins in the chloride form to remove As(V) from drinking water sources. Because As(III) cannot be removed by ion exchange SBA resin, all As(III) in the source water must be preoxidized to As(V) to accomplish maximum arsenic removal.

As(III) can be easily converted to As(V) by several commonly used chemical oxidants. A laboratory study on six chemical oxidants has recently been completed by Ghurye and Clifford (2001). The results of this study showed that chlorine, potassium permanganate, and ozone were very effective oxidants, whereas chlorine dioxide and monochloramine were not. The actual amounts necessary to oxidize As(III) must take into account other oxidant demand substances in the source water such as iron, manganese, and sulfide. The study also showed that a solid oxidizing media used for iron and manganese removal has the ability to oxidize As(III). Air oxidation that is effective for oxidizing iron has been found to be ineffective for As(III) oxidation (Lowry and Lowry, 2002). The selection of the oxidation method should be based on a number of factors, including the capital and operation costs, water quality, disinfection requirements, and impact on resin.

It is very important to thoroughly investigate the individual resin that will be applied to the treatment system. The physical performance characteristics vary among resins. The variables include, but are not limited to, resin capacity, backwash requirements, treatment flowrate, regeneration brine flowrate, brine concentration, brine volume, etc. The information included in this manual allows flexibility to adapt to any combination of the above variables.

A four-step design process is employed in this manual. The steps are as follows:

1. Assemble design input data and information.
2. Conceptual design.
3. Preliminary design.
4. Final design.

3.1 Assemble Design Input Data and Information

The design input data and information should be collected prior to initiating the conceptual design. The design input data and information include, but are not limited to, the following:

1. Chemical analyses (see Figure 3-1) of representative raw water samples (includes all historical analyses). Comprehensive raw water analyses of all inorganic, organic, radionuclide, and bacteriological contaminants are also required to verify that the ion exchange process is the best available method for the treatment system requirements.
2. Treated water quality compliance standards issued by the regulatory agency with jurisdiction in the area where the system resides.
3. Regulatory design standards.
4. Wastewater and waste solids disposal ordinances issued by the responsible regulatory agency.
5. Data on system production and consumption requirements (present and future).
6. Manual vs. automatic operation.
7. State and local codes, and Occupational Safety and Health Administration (OSHA) requirements.
8. Comprehensive climatological and seismic design data.

The treatment system is a subsystem within the larger water utility system. Other subsystems include the raw water feed pump, the storage reservoirs, the pressurization subsystem, and the distribution subsystem. This design manual is applicable when arsenic removal is the

EXAMPLE
ARSENIC REMOVAL WATER TREATMENT PLANT
REPORT OF WATER ANALYSIS

NAME AND ADDRESS

SOURCE OF WATER
CONTAINER
SAMPLE DATE
TAKEN BY:

Analysis No.								
Calcium								
Magnesium								
Sodium								
Total Cations								
Total Alkalinity (M)[a]								
Phenolphthalein Alkalinity (P)[a]								
Total Hardness[a]								
Sulfate								
Chloride								
Nitrate								
Total Noncarbonate Solids								
Silica – SiO_2								
Free Carbon Dioxide								
Iron (Fe) Unfiltered								
Iron (Fe) Filtered								
Manganese								
Turbidity (NTU)								
Color (Units)								
Fluoride								
Arsenic - Total								
Soluble Arsenic								
Particulate Arsenic								
Arsenic (III)								
Arsenic (V)								
pH								
Specific Conductance (micro-mhos)								
Temperature (°F)								

(a) mg/L as $CaCO_3$.
All units expressed as mg/L except as noted.

Figure 3-1. Water Analysis Report

only treatment requirement. However, removal of other contaminants such as bacteria, suspended solids, hardness, organic and/or inorganic contaminants, may also be required. In those cases, alternative treatment processes and/or additional treatment processes should be evaluated.

The sequence of additional treatment steps should be compatible with the ion exchange arsenic removal method. Removal of suspended solids, organics, and other contaminants that might foul the resin should take place upstream of the ion exchange arsenic removal process. Preoxidation of As(III) takes place upstream of the ion exchange process. If a preoxidizing chemical is required, the resin manufacturer should be contacted to determine if the chemical has detrimental effects on the resin or the acceptable exposure concentration and the possible need to take steps to prevent the chemical from coming in contact with the resin. Other treatment processes may be required upstream or downstream of the arsenic removal process, but that decision shall be made on a case-by-case basis.

For ground water systems, the most practical concept is to install the treatment plant in the immediate vicinity of the well (space permitting). The well pump will then deliver the water through treatment into distribution and/or storage. If the existing well pump is oversized (pumps at a much higher flowrate than the maximum daily flowrate requirement), it should be resized to deliver slightly more (i.e., 125% minimum) than the peak requirement. The flowrate dictates the treatment equipment size and capital cost. The design rate should be minimized to the extent possible to ensure that the capital cost of the treatment system is minimized. Reducing flowrate for an oversized pump can result in excessive equipment wear and energy costs. The treatment media volume is a function of flowrate. The treatment vessels, pipe sizes, and chemical feedrates all increase as the flowrate increases. A well-matched pump can handle any additional head loss associated with the treatment system without a significant drop in pump efficiency. If the additional head loss cannot be met with the existing pump, several options exist: increasing the size of the motor, increasing the size of the impeller, or replacing the pump. Storage should be provided to contain a minimum of one half the maximum daily consumption requirement. This is based on the premise that maximum consumption takes place during 12 hours of the day. Then, if the treatment system operates during the entire 24 hours, storage drawdown occurs during 12 hours and recovers during the remaining 12 hours.

Construction materials must comply with OSHA standards, local building codes, health department and possibly other requirements in addition to being suitable for the applicable pH range and compatible with any pretreatment oxidizing chemicals used (e.g., chlorine, ozone). Both drinking water treatment chemicals and system components should comply with NSF International/American National Standards Institute (NSF/ANSI) STD 61.

Treatment system equipment should be protected from climatic conditions. Although not mandatory, in some locations, it is prudent to house the system within a building.

Wastewater resulting from backwash and regeneration of the resin can only be disposed of in a manner permitted by state and/or local regulatory ordinances (SAIC, 2001). There are several options for disposal; however, they are subject to climate, space, and other environmental limitations. Because each of the variables can significantly affect both capital and operating costs, the available wastewater handling options should be evaluated carefully prior to making conceptual selections. Waste disposal plays an important role in treatment process selection. Waste disposal regulatory requirements and disposal options (MacPhee et al., 2000) may be an important factor in selecting an anion exchange treatment process because the brine wastewater probably will be classified as a hazardous waste.

3.2 Conceptual Design

The second step in the design process is the Conceptual Design, which provides a definition of the process. However, this step does not provide equipment size, arrangement, material selection, details, or specifications.

There are four basic options from which a Conceptual Design can be selected. Every combination of options may not be able to perform the process. Therefore, the options should be screened to determine which combinations are applicable. The options are as follows:

1. Gravity or pressure flow.
2. Upflow or downflow treatment flow direction.
3. Single or multiple treatment vessel(s).
4. Series or parallel treatment vessel arrangement.

A gravity flow system is not compatible with the ion exchange process. Downflow treatment consistently yields higher treatment efficiency than upflow. Because the downflow concept uses a packed bed, flow distribution is superior. If the upflow beds are restrained from expanding, they would in effect also be packed. However, they would forfeit the necessary capability to backwash.

Examples of several designs of treatment vessel arrangements are shown in Figure 1-2. Each design has its advantages and disadvantages when considering the potential of arsenic dumping, decreases in the pH of the effluent water, and the problems associated with each situation.

The design concept presented in this manual provides sound, risk-reduction features for a pressure system using a primary stage, downflow treatment vessel, followed in series by a second stage downflow treatment vessel (Figure 1-2[e]). For maximum risk reduction, two treatment vessels in series are recommended. The simple single-treatment unit configuration introduces a greater risk of release of a high (peak) arsenic concentration in the treated water (Figure 1-2[a]).

The primary stage (of the two vessels in series design) consisting of two parallel treatment vessels provides an operating treatment vessel and a standby treatment vessel. As the operating treatment vessel approaches exhaustion of ion exchange capacity, it is removed from service and replaced by the standby treatment vessel. Ion exchange capacity exhaustion is discussed in Chapter 5.0. The backwash/regeneration/rinse then takes place at a time scheduled by the plant operator prior to exhaustion of the other primary stage treatment vessel. To reduce the risk of arsenic breakthrough entering the distribution system, the second stage treatment vessel is permanently piped in series in the lag position with the two primary stage treatment vessels permanently in the lead position.

For economy of treatment, an optional raw water bypass and reblending capability can be included. For systems in which the raw water arsenic concentration is slightly above the arsenic MCL, bypassing and reblending a fraction of the raw water with the remaining fraction that is treated should be evaluated. This option saves treatment chemicals, extends treatment media cycle life, and reduces operating cost. If bypassing and blending is feasible, the treatment system can be sized to treat less than 100% of the total flow.

Once the bed configuration is defined, a basic schematic flow diagram is prepared (see Figure 3-2). This diagram presents all of the subsystems.

Prior to proceeding with the Preliminary Design, financial feasibility should be determined. Funding limits for the project should be defined. A determination that funding is available to proceed with the project should be made. This requires a preliminary rough project estimate with an accuracy of ±30%. If the preliminary rough estimate exceeds the available funds, adjustments should be made to increase funding or reduce project costs.

3.2.1 Manual Operation

In manual operation, the treatment plant operator personally performs all of the operating functions and makes all operating decisions. The treatment plant equipment does not accomplish any function independent of the operating personnel. The equipment is simple and performs the basic functions that the operator implements. Manual operation includes the following:

1. Motors (pumps, chemical pumps, etc.) with manual start/stop controls. Some motors have manual speed adjustment capability. Chemical pumps have manual speed and stroke length adjustment capability.
2. Valves with manual handle, lever, handwheel, or chainwheel operators.
3. Instrumentation sensors with indicators. Instrumentation is installed in-line where operating data (flowrate, total flow, pressure, and pH) are indicated. In-line pH sensors are the only instruments that require electric service.

3.2.2 Automatic Operation

In an automatic operation the treatment plant is operated by a PLC, which initially is programmed by the operator, the designer, the computer supplier, or an outside specialist. If programmed by someone other than the plant operator, the operator should be trained by that individual to adjust program variables and, if necessary, modify the program. The operator interface and printer are the equipment items that the operator uses during the performance of treatment plant functions. In addition, the operator should calibrate and check all of the components of the automatic operating equipment system on a routine periodic basis. Finally, the treatment plant operator or a designated instrumentation and control specialist should be capable of performing emergency maintenance and/or repairing all components. Every function included in an automatic system should include a manual override.

The equipment is more sophisticated and costly than that used in manual operation. When functioning normally, automatic operation can function continuously with minimal operator attention. This is recommended for treatment systems in remote areas, or areas that are difficult to access, and for systems for which operator availability is limited. Automatic operation includes the following:

1. Motors (pumps, chemical pumps, air compressors, etc.) with automatic start/stop and speed adjustment

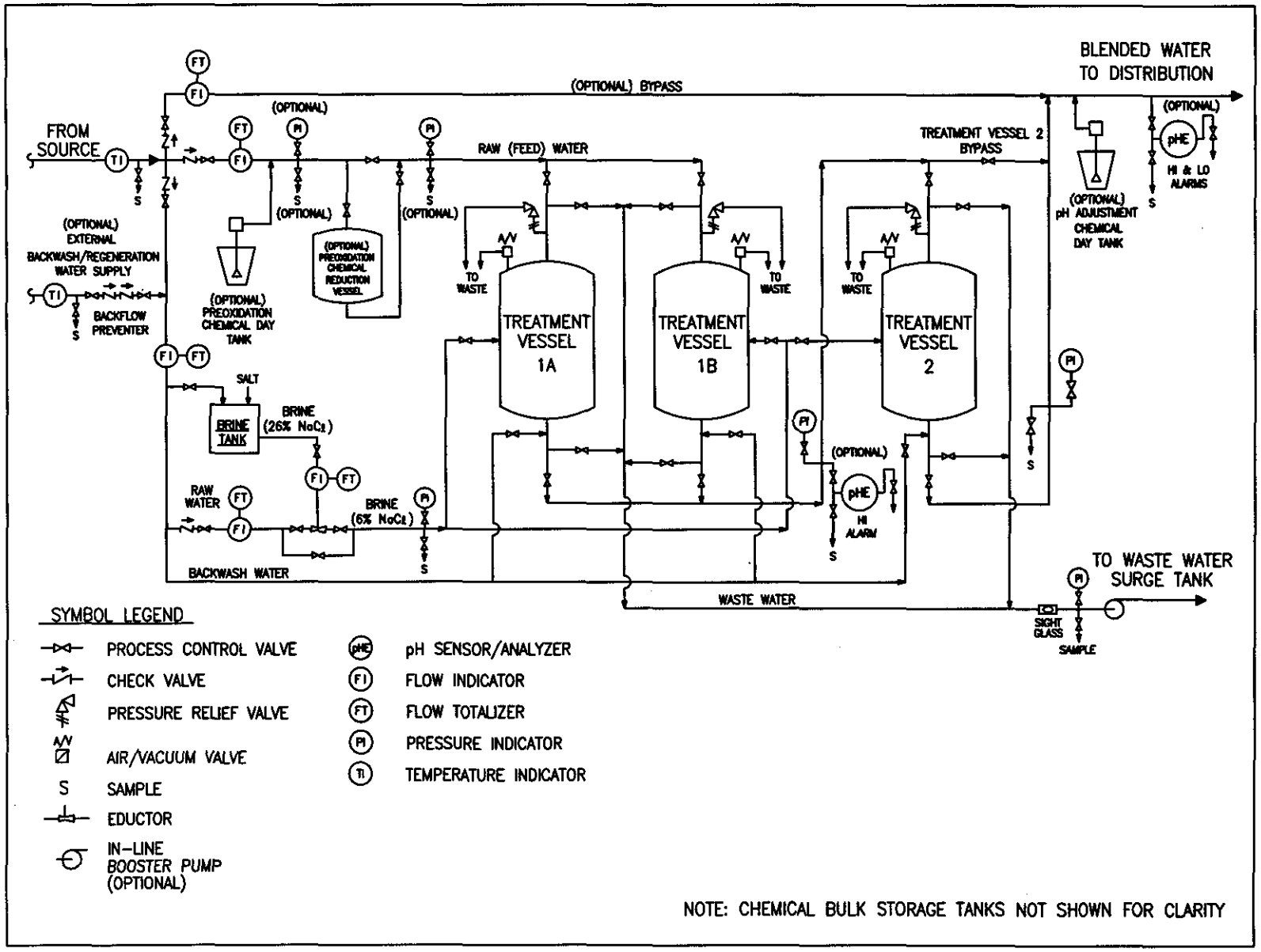


Figure 3-2. Ion Exchange Treatment System Flow Diagram

controls. Chemical pumps may also have manual stroke length adjustment. Motors should also have manual on/off controls.

2. Valves with either pneumatic or electric operators. Flow or pressure control valves with electronic positioners for valves with automatic operators. Valves require manual overrides for operation during start-up, power failure, or compressed air failure. Valves should have opening and closing speed controls to prevent water hammer during automatic operation. Valve electronic position indicators are optional.

3. Automatic instrumentation may be electronic, pneumatic, or a combination. The instruments and controls should always be capable of transmitting and receiving electronic information to and from the PLC. In a fully automatic system, all of the control, monitoring, and alarm functions are monitored and controlled by the PLC. Backup manual instruments (e.g., flowrate indicators, pressure indicators, pH indicators, and liquid level indicators) are recommended to provide verification of automatic instrumentation if treatment plant budget is available. Comprehensive automatic alarms that notify operators and/or shut down increments or the entire treatment system relating to every type of system malfunction at the moment such events occur is a necessary function that should be incorporated in all applicable instrumentation components.

3.2.3 Semiautomatic Operation

Semiautomatic operation that employs individual controllers to automatically start/stop or adjust some, but not all, of the operational items in the system, can contribute significantly to the treatment system operation without computer control of the entire operation. Semiautomatic functions can include alarms that notify operators of process functions exceeding limits established for effective and/or safe operation. Alarm events can be staged at single (e.g., high) or dual (e.g., high-high) levels. In a dual-level alarm, the first level notifies the operator that the performance is out of tolerance; and the second level shuts down either a single process function (e.g., a pump) or the entire process. Examples of semiautomatic operational functions include, but are not limited to, the following:

1. Flow control loop — includes an electronic flow sensor with totalizer (e.g., magnetic flowmeter) that sends an electronic signal to an electronic flow controller (with high or low flowrate alarms), which in turn sends an electronic signal to a flow control valve (butterfly valve or ball valve) with an actuator and electronic positioner. The plant operator designates the required flowrate at the flow controller. The controller receives the flowrate measurement from the flow sensor and transmits signals to the flow control valve positioner to adjust the valve position until the flowrate matches that required by the process. If the flowrate deviates from the limits established for the process, a high flowrate or low flowrate alarm will be issued.

2. Pressure control loop — includes an electronic pressure transmitter that sends an electronic signal to an electronic pressure controller (with high or low pressure alarms), which in turn sends an electronic signal to a pressure control valve with an actuator and electronic positioner. The plant operator designates the required pressure at the pressure controller. The controller receives the pressure measurement from the pressure transmitter and transmits signals to the pressure control valve positioner to adjust the valve position until the pressure matches that required by the process. If the pressure deviates from the limits established for the process, a high pressure or low pressure alarm should be issued.

3. Treated water pH control loop — includes an (optional) electronic pH sensor that transmits a pH signal to a pH analyzer (with high or low level alarms), which in turn sends an electronic signal to shut off the raw water feed pump. The plant operator designates the required pH at the pH analyzer. The pH analyzer receives the pH measurement from the pH sensor and transmits signals to a chemical feed pump. If the pH deviates from the limits established for the process, a pH alarm should be issued.

4. Liquid level control loop — includes an electronic liquid level sensor (e.g., ultrasonic level sensor), which transmits an electronic liquid level signal to a level controller that indicates the liquid level and transmits an electronic signal to one or more motors (pump, etc.) to start or stop. At the level controller, the plant operator designates the required liquid levels at which motors (pumps or mixers) are to start and stop. The level controller receives the liquid level measurement from the liquid level sensor and transmits signals to the motor(s) to start or stop. If the liquid level deviates from the limits established for the process, then a high or low liquid level alarm should be issued.

Many other process functions are performed automatically by means of relays and other electrical devices. An example is the electrical interlock of chemical feed pumps with raw water pumps, which prevents chemical feed into the process without the flow of process water.

Another example is the use of a flow switch in a pressure relief valve discharge pipe that, upon detection of water flow, issues an alarm and stops the process feed pump. The list of individual fail-safe automatic functions is extensive and beyond the scope of this design manual. All applicable codes, standards, and OSHA requirements should be reviewed to determine which requirements are applicable to the project. Then, based on sound judgment, available budget, and treatment plant operator capability and availability, a decision should be made as to whether a given function should be automatic or manual.

3.3 Preliminary Design

After completion and approval of the Conceptual Design by the client, the regulatory agency(s), and any other affected party, the Preliminary Design should be developed. This includes sizing the equipment, selecting construction materials, determining an equipment layout, and upgrading the preliminary capital cost estimate to an accuracy of ±20%. The deliverable items are:

1. Schematic flow diagrams (see Figure 3-2).
2. Preliminary process equipment arrangement drawings (see Figures 3-3 and 3-4).
3. Outline specifications.
4. Preliminary capital cost estimate.

3.3.1 Treatment Equipment Preliminary Design

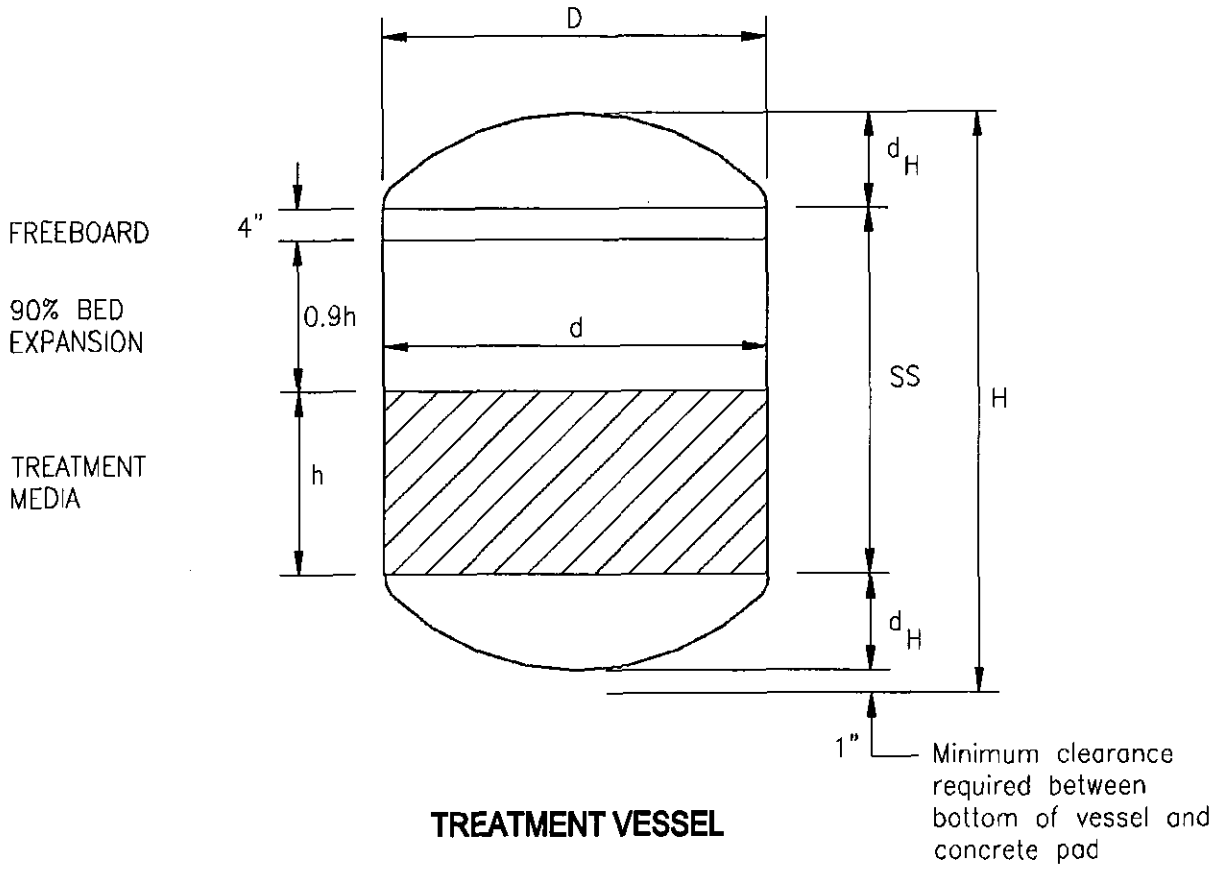
This section provides the basic methodology for sizing equipment items and selecting construction materials for arsenic removal treatment systems using the ion exchange treatment method with preoxidation of As(III) and regeneration of exhausted resin. An example illustrating this method is provided in Appendix B. The example is based on use of a chloride-form SBA resin with preoxidation of As(III), reduction of free preoxidation chemical, regeneration of exhausted resin, and manual operation. The empty bed contact time (EBCT) selected for this design example is 3 min. For systems using different process parameters, the design information presented in this document is easily adjusted. For automatic or semiautomatic operation, the system's basic design does not change; however, equipment material and installation costs can vary significantly.

3.3.1.1 Treatment Bed and Vessel Design

As discussed in Section 2.2, the recommended treatment concept is based on the use of two vertical cylindrical pressure vessels piped in parallel followed by a single vertical cylindrical pressure vessel piped in series in the lag position. The treatment mode is downflow. Treatment vessel piping should be configured to also provide for resin backwashing (upflow). The treatment vessel material employed in the design example presented in Appendix B is carbon steel (grade selection based on cost-effective availability). Its fabrication, assembly, and testing should comply with American Society of Mechanical Engineers (ASME) Code — Section VIII, Division 1. The interior should be lined with abrasion-resistant material. Interior lining material should be NSF-certified for potable water application and suitable for exposure to 10% sodium chloride (NaCl) regeneration solution. Vessel pressure rating should be 50 pounds per square inch gage (psig) (or the minimum necessary to satisfy system requirements). FRP pressure vessels frequently are used in place of lined carbon steel. For very small systems, FRP pressure vessels are preferred. For pressure vessels larger than 36 inches in diameter, the lined carbon steel material is preferred. Other vessel materials of construction (e.g., fiberglass), internal lining materials (e.g., abrasion resistant epoxy, rubber), and stainless steel without lining may also be employed.

Basic technology that has evolved from experience indicates that the downflow treatment process flowrate should be 8 to 12 gpm/ft^2. The data presented in this design manual is based on a flowrate of 10 gpm/ft^2 through the treatment bed. Then, using a 4-ft-deep bed, the volume of resin (V) in each treatment vessel provides a 2.5 gpm process water flowrate per cubic foot of resin. This provides an EBCT of 3 min. An EBCT as low as 1.5 min has been successfully used with some resins. Standard FRP pressure vessels are available with 6-ft straight sides and other sizes. A bed depth of 3 ft is recommended for those treatment vessels. FRP pressure vessels utilizing 3-ft-deep beds will reduce the flowrate to 7.5 gpm/ft^2 to achieve the same 3-min EBCT. Because the space between the grains of resin is approximately 50% of the total bed volume, actual residence time is approximately half the EBCT time. See Figure 3-3 for treatment vessel design procedure.

When raw water is bypassed and blended back with treated water, only the treated water is included in sizing the treatment bed. To minimize wall effects, bed diameter (d) should be equal to or greater than one-half the bed depth (h). Good practice indicates that bed depth should be a minimum of 30 inches and a maximum 6 ft. However, deeper beds have been applied successfully. At less than minimum depth, distribution problems may develop; and, at greater than maximum depth, fine material removal and pressure loss become problems.



TREATMENT VESSEL

SYMBOLS

q – TREATED WATER FLOW RATE (gpm)

d – TREATMENT BED DIAMETER (ft.), $d = \sqrt{4V/\pi h}$

h – TREATMENT BED DEPTH (ft.)

V – TREATMENT BED VOLUME – $\frac{\pi d^2 h}{4}$ ($ft.^3$)

EBCT = $\frac{V}{q}$

M_d – DENSITY OF TREATMENT MEDIA ($lb./ft.^3$)

M_W – WEIGHT OF MEDIA (lbs.)

D – OUTSIDE DIAMETER OF TREATMENT VESSEL (ft.)

d_H – DEPTH OF DISHED PRESSURE HEAD (ft.)

H – OVERALL HEIGHT OF TREATMENT VESSEL (ft.)

SS – STRAIGHT SIDE (ft.)

GIVEN

$d > h/2$, $2'-6" < h < 6'-0"$

$H = 2\ d_H + h + 0.9h + 6" + 1"$

$D = d + 1"$

$M_d = 42\ lb./ft^3$ (VARIES WITH ION EXCHANGE RESIN)

$M_W = M_d \times V = 42V$ (lb.)

Figure 3-3. Treatment Bed and Vessel Design Calculations

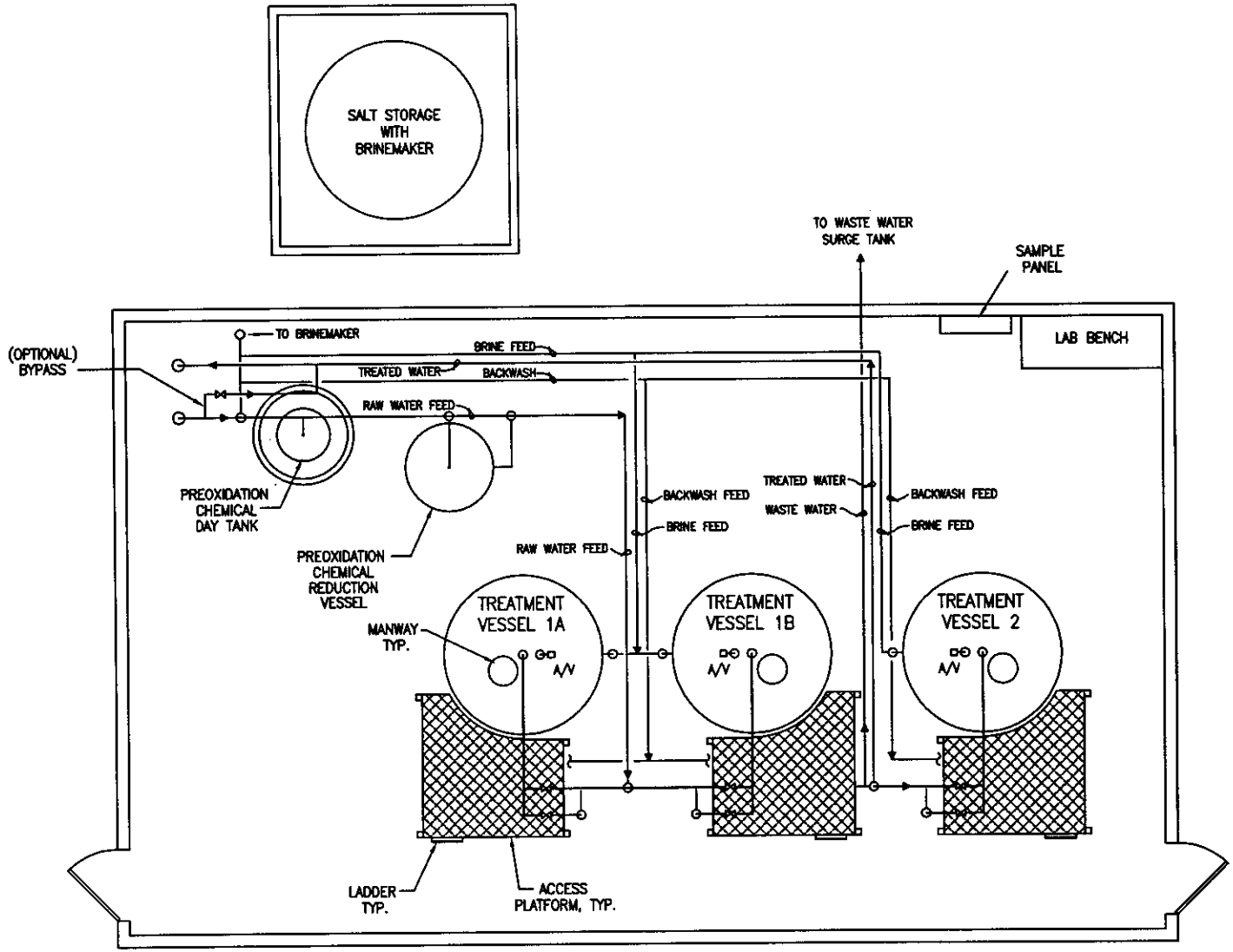


Figure 3-4. Treatment System Plan (see Figure 3-2 for symbol legend)

As stated above, 3 min is the EBCT (2.5 gpm/ft^3) employed in the example in Appendix B. As the EBCT decreases, regeneration of spent resin frequency increases, requiring more operator attention and proportionately more downtime. Conversely, decreasing the treatment flowrate below the suggested 2.5 gpm/ft^3 (3 min EBCT) rate increases the size of the treatment beds and the treatment vessels, thereby increasing capital cost and space requirements.

Carbon steel cylindrical pressure vessel fabrication is standardized by diameter in multiples of 6-inch outside diameter increments. Tooling for manufacture of pressure vessel dished heads is set up for that standard. Design dimensions differentiate between pressure vessel and treatment bed diameters. The vessel outside diameter (D) is approximately 1 inch greater than the bed (or vessel inside) diameter, which conservatively provides for both vessel walls with lining as well as fabrication tolerances. If the pressure is high (100 psig or greater), the 1 inch will increase to reflect the increased vessel wall thickness. Unless system requirements dictate higher operating pressure, low pressure (50 psig) results in lower equipment cost.

Although there are many methods of distributing the water flow through an ion exchange treatment bed, a method that has been successfully used in operation is recommended. The water is piped downward into the vessel through an inlet diffuser. This diverts the flow into a horizontal pattern. From there it radiates in a horizontal plane prior to starting its downward flow through the resin bed. The bed, in turn, is supported by a false flat bottom, which is supported by the bottom head of the pressure vessel by means of concentric support rings. The false flat bottom also supports the horizontal header and perforated plastic, fabric-sleeved lateral collection system. Resin is placed in the vessel through circular manway(s) with hinged cover(s) in the top head of the vessel. The regeneration brine is fed into the treatment bed through an injection distributor that penetrates into the vessel through the vessel's straight side at a level 2 inches above the top of the resin bed. The injector is supported by brackets integral with the treatment vessel wall. A viewing window to determine water level during the regeneration procedure vessel drain steps described later in this design manual is also provided in the treatment vessel wall. The treatment bed and vessel design are illustrated in Figure 3-3. A typical example for determining treatment bed and treatment vessel dimensions is presented in Appendix B.

3.3.1.2 Pipe Design

Material should be suitable for ambient temperature, exposure up to 10% NaCl solution, system pressure, and potable water service. Because of the high chloride concentration, except for Alloy 20 and Hastalloy, metallic materials are not suitable. Plastic materials such as PVC or CPVC are satisfactory. PVC is usually the best selection because of its availability, NSF certification for potable water service, low cost, and ease of fabrication and assembly. The drawbacks of PVC are its loss of strength at elevated temperatures (above 100°F), high coefficient of thermal expansion, external support requirements, deterioration from exposure to sunlight, and vulnerability to damage from impact. Nevertheless, these liabilities are outweighed by the low cost and suitability for the service. The piping should be protected from all of the above concerns, except elevated water temperatures. If elevated temperature exists (>100°F), the use of FRP pipe is recommended. This material provides the strength and support that is lacking in pure plastic.

The piping system should be economically sized to allow for delivery of design flow without excessive pressure losses. If water velocities present conditions for water hammer (due to fast-closing valves, etc.), shock-absorbing equipment should be provided.

Isolation and process control valves should be wafer-style butterfly type, except in low flowrate systems where small pipe size dictates the use of true union ball valves. Using inexpensive, easily maintained valves that operate manually minimizes capital cost. The valves can be automated by the inclusion of pneumatic or electric operators with electronic positioners.

Pressure regulators and flow control valves are recommended for safe operation of manually controlled treatment systems. See Appendix B for pipe size design using the example previously employed for vessel and resin bed design.

3.3.1.3 Instrumentation Design

System functional requirements that are adapted to commercially available instruments should be specified. Included are:

Instrument	Range	Accuracy
1. Flow sensor (indicator/totalizer)	Varies[a]	±2%
2. Pressure indicator	Varies[a]	±1%
3. pH sensor/analyzer/alarm	0-14	±0.1
4. Level sensor/indicator	Varies[a]	±1%
5. Temperature indicator (optional)	30-120°F	±1%

(a) Range to be compatible with application, maximum measurement not to exceed 90% of range.

3.3.1.4 Salt (NaCl) Storage and Feed Subsystem

Salt feed and storage subsystems are required for regeneration for each arsenic removal ion exchange treatment plant. Depending on the size of the treatment plant, salt can be procured in bags loaded on pallets, or in 48,000-lb truckload bulk quantities. The salt grade is normally coarse solar, with particle sizes ranging from 0.1 to 0.375 inch and a specific gravity of 70 lb/ft^3. Bulk delivery provides the lowest unit price for this commodity; but an atmospheric vertical cylindrical bulk storage tank is required. The bulk storage tank capacity should have a minimum of 72,000 lb (1.5 truckloads); giving the treatment plant operator adequate time for salt delivery prior to consuming the remaining salt.

The bulk salt is fed by means of chute, hopper, conveyor, or other mechanism into a brine tank that also receives water for dissolving the salt. A brine tank is required to produce saturated brine solution whether it is fed salt mechanically from a storage tank or manually by the treatment plant operator. Saturated (26% NaCl) brine solution is produced in the brine tank. The brine tank volume requirement should be 150% (minimum) of the brine required for regeneration of one treatment vessel. The brine amount and concentration requirement vary among resins. Therefore, the regeneration procedure and brine quantity requirements should be obtained directly from the resin manufacturer.

The storage tank and brine tank can be processed as a single FRP unit. The storage tank (or brinemaker) should be protected from the elements and include a containment basin located outside of the treatment building. Typically the containment basins are sized for 110% of the liquid contents of the brine tank. Except for the fresh water feed pipe, no freeze protection is required. A feed line from the brine tank is connected to an eductor that will draw the concentrated brine into a dilution water stream to form a concentration recommended by the resin manufacturer. There should be flowrate indicators and flow totalizers in both the brine and dilution water lines feeding the eductor so brine concentrations can be controlled precisely. The example in Appendix B illustrates the method of designing the components for this subsystem.

3.3.2 Preliminary Treatment Equipment Arrangement

Once all of the major equipment size and configuration information is available, a layout (arrangement drawing) is prepared. The layout provides sufficient space for proper installation, operation, and maintenance of the treatment system, as well as each individual equipment item. OSHA standards should be applied during the layout stage. These requirements may be supplemented or superceded by state or local health and safety regulations or, in some cases, insurance regulations. A compact arrangement to minimize space and resulting costs should be furnished. Figure 3-4 illustrates a typical preliminary arrangement plan. These arrangements provide no frills, but do include ample space for ease of operation and maintenance. Easy access to all valves and instruments reduces plant operator effort.

The type of building used to protect the treatment system (and operator) from the elements depends on the climate. Standard pre-engineered steel buildings are low-cost, modular units. Concrete block or other material also may be used. Standard building dimensions that satisfy the installation, operation, and maintenance space requirements for the treatment system should be selected. The building should provide access doors, lighting, ventilation, emergency shower and eye wash, and a laboratory bench with sink. All other features are optional.

Manual operation is the method employed in the design example in Appendix B. The basic process requirements should be reviewed at each stage of design to assure that every item required to operate the process is included. Although detailed design occurs during the final phase, provision for operator access for every equipment item should be provided.

Automatic operation does not require total accessibility; access may only be necessary for maintenance functions, for which ladder or scaffold access will suffice. The extra equipment items required solely for automatic operation (including, but not limited to, PLC, operator, interface) occupy minimal space and are placed in locations that are most accessible to the operator.

3.3.3 Preliminary Cost Estimate

The preliminary cost estimate is prepared based on the equipment selected, the equipment arrangement, and the building selected. The material/equipment quantities, labor quantities, labor unit pricing, and material/equipment unit pricing should be summarized in a format that is preferred by the owner. (See Table 3-1 for an example.) This estimate should have an accuracy of ±20%. To assure sufficient budget for the project, it is prudent to estimate on the high side at this stage of design. This may be accomplished by means of a contingency to cover unforeseen costs and/or an inflation escalation factor.

Table 3-1. Preliminary Capital Cost Estimate Examples for Two Types of Ion Exchange Arsenic Removal Water Treatment Plants at a Typical Location

Location: Flowrate: 620 gpm Date:	Cost ($1,000)	
	Manual Operation	Automatic Operation
Process Equipment		
Treatment Vessels	100	100
Ion Exchange Resin (750 ft^3)	130	130
Process Piping, Valves, and Accessories	60	88
Instruments and Controls	13	70
Salt and Brine Storage	22	22
Subtotal	325	441
Process Equipment Installation		
Mechanical	35	45
Electrical	12	42
Painting and Miscellaneous	16	16
Subtotal	63	103
Miscellaneous Installed Items		
Regeneration Wastewater Surge Tank	70	70
Building and Concrete	80	80
Site Work, Fence, and Miscellaneous	20	20
Subtotal	170	170
Contingency 20%	112	143
Total[a]	670	857

(a) Engineering, exterior utility pipe and conduit, wastewater and waste solids processing system, finance charges, real estate cost, and taxes not included.

3.3.4 Preliminary Design Revisions

The Preliminary Design package (described above) is submitted for approval prior to proceeding with the Final Design. This package may require the approval of regulatory authorities, as well as the owner. If any changes are requested, they should be incorporated and resubmitted for approval. Once all requested changes are implemented and Preliminary Design approval is received, the Final Design can proceed.

3.4 Final Design

After completion and approval of the Preliminary Design, the Final Design is developed. This includes designing all of the process equipment and piping, analyzing the process system, designing the building (including site work), and estimating the capital cost within 10%. The deliverable items are:

1. Complete set of construction plans and specifications.
2. Final capital cost estimate (see Table 3-2).
3. Design report (includes design calculations for regulatory agency review).

The Final Design starts with the treatment system equipment, continues with the building (including concrete slabs and foundations, earthwork excavation/backfill/compaction, heating, cooling, painting, lighting, utilities, laboratory, personnel facilities, etc.); and completes with the site work (including utilities, drainage, paving, and landscaping). The latter items apply to every type of treatment plant; although they are integral to the treatment system, they are not addressed in this manual. The only portions of the Final Design that will be addressed are the pertinent aspects of the treatment equipment that are not covered in the Preliminary Design section. During Conceptual Design and Preliminary Design, the basic equipment that accomplishes the required functions is defined. The decisions are cost-conscious, using minimum sizes (or standard sizes) and the least expensive materials that satisfy the service and/or environment. However, in the Final Design, this effort can be defeated by not heeding simple basic cost control principles. Some of these are:

1. Minimize detail (e.g., pipe supports—use one style, one material, and components common to all sizes).
2. Minimize the number of bends in pipe runs (some bends are necessary—those that are optional increase costs).
3. Minimize field labor; shop fabricate where possible (e.g., access platforms and pipe supports can be mounted on brackets that are shop fabricated on vessel).

Table 3-2. Final Capital Cost Estimate Examples for Two Types of Ion Exchange Arsenic Removal Water Treatment Plants at a Typical Location

Location:
Flowrate: 620 gpm
Date:

	Cost ($1,000)	
	Manual Operation	Automatic Operation
Process Equipment		
Treatment Vessels	99	99
Ion Exchange Resin (750 ft^3)	127	127
Process Piping, Valves, and Accessories	45	88
Instruments and Controls	12	73
Salt and Brine Storage	20	20
Subtotal	303	407
Process Equipment Installation		
Mechanical	45	50
Electrical	10	40
Painting and Miscellaneous	14	14
Subtotal	69	104
Miscellaneous Installed Items		
Regeneration Wastewater Surge Tank	67	67
Building and Concrete	74	74
Site Work, Fence, and Miscellaneous	17	17
Subtotal	158	158
Contingency 10%	53	67
Total[a]	583	736

(a) Engineering, exterior utility pipe and conduit, wastewater and waste solids processing system, finance charges, real estate cost, and taxes not included.

4. Skid-mount major equipment items (skids, in place of piers and spread footings, distribute the weight of vessels over small mat foundations, thereby eliminating costly foundation work).

5. Where ambient conditions permit, use treatment vessels as a heat sink to provide insulated building cooling or heating or both (eliminates heating and/or cooling equipment in addition to reducing energy cost.) Consideration must be given, however, to humid climates where cold tanks will result in sweating problems.

6. Simplify everything.

All subsystems should be analyzed (refer to schematic flow diagram in Figure 3-2) to account for all components in both equipment specifications and installation drawings. The drawings and specifications should provide all information necessary to manufacture and install the equipment. Extra effort to eliminate ambiguity in detail and/or specified requirements should be exercised. All items should be satisfactory for service conditions besides being able to perform required functions. Each item should be easy to maintain; spare parts necessary for continuous operation should be included with the original equipment. All tools required for initial startup, as well as operation and maintenance, should be furnished during the construction phase of the project.

Once construction, equipment installation, and check out are complete, the treatment plant should proceed into operation without disruption. After all components in each of the subsystems have been selected, hydraulic analysis calculations should be made to determine the velocities and pressure drops through the system. Calculations should be prepared for normal treatment flow and backwash flow. The latter is more severe, but of short duration. If pressure losses are excessive, the design should be modified by decreasing or eliminating losses (e.g., increase pipe size, eliminate bends or restrictions).

Upon completion of installation, functional checkout requirements should be accomplished. All piping should be cleaned and hydrostatically pressure-tested prior to startup. All leaks should be corrected and retested. Recommended test pressure is 150% of design pressure. Potable water piping and vessels should be disinfected prior to startup. Disinfection procedures should be in compliance with regulatory agency requirements and material/equipment manufacturers' requirements/limitations. All electrical systems should satisfy a functional checkout. All instruments should be calibrated; if accuracy does not meet requirements stated in Section 3.3.1.3, the instruments should be replaced.

When the plant operation begins, a check on actual system pressure drop is required. If there is a discrepancy between design and actual pressure drop, the cause should be determined (obstruction in line, defective valve, installation error, design error, etc.) and rectified. Pressure relief valves should be tested; if not accurate, they should be adjusted or replaced.

3.4.1 Treatment Equipment Final Design

This section provides details that apply specifically to arsenic removal water treatment plants.

3.4.1.1 Treatment Bed and Vessel Design

The resin volume was determined based on bed dimensions and the resulting weight in the Preliminary Design (see Section 3.3.1.1). It is recommended that a minimum of 10% extra resin be procured. For the lowest price and ease of handling, the resin should be ordered in fiber drums (5 to 8 ft^3) on pallets. Several sources of SBA resin are available for service in the application. If an "equal" is to be furnished, a pilot test should demonstrate that the process capability as well as the physical durability of the substitute material is equal to that of the specified material.

The vessel design should be simple. The vessel should have a support system to transfer its loaded weight to the foundation and ultimately to the soil. The loaded weight includes the resin, the water, attached appurtenances (platform, pipes filled with liquid, etc.), the vessel, and applicable seismic and/or wind loads. The support legs or skirt should be as short as possible to reduce head room requirements as well as cost.

If the vessels are skid-mounted, the support legs should be integral, with a support frame (skid) that will distribute the weight over an area greater than the dimensions of the vessel. This distribution eliminates point loads of vessel support legs, so costly piers, footings, and excavation requirements are eliminated. The skid should have provisions for anchoring to the foundation. Exterior brackets (if uniform and simply detailed) are not costly and provide supports that eliminate the need for cumbersome costly field fabrications. Conversely, interior brackets though required to anchor (or support) vessel internal distribution or collection systems should be held to a bare minimum because they are costly to line. Interior linings should be abrasion-resistant. Alternatively, vessels may be constructed of stainless steel (no lining required). Vessel interior lining should extend through the vessel opening to the outside edge of the flange faces. Openings in the vessels should be limited to the following:

1. Influent pipe — enters vertically at center of top head.
2. Effluent pipe — exits horizontally through vertical straight side immediately above false flat bottom in front of vessel or vertically at the center of the bottom head.
3. Brine feed pipe — enters horizontally through vertical straight side three inches above top of treatment bed.
4. Air/vacuum valve (vent) — mounts vertically on top head adjacent to influent pipe.
5. Resin removal — exits horizontally through vertical straight side immediately above false flat bottom at orientation assigned to this function.
6. Sight glass (12 inches high × 2 inches wide) — located vertically with centerline at top of treatment bed (serves to locate liquid level during drain steps and to observe level of top of bed).
7. Manway — 16-inch-diameter (minimum) mounted on top head with center line located within 3 ft of center of vessel and oriented toward work platform. Manway cover to be hinged or davited.

Pad flanges are recommended for pipe interfaces in place of nozzles. Pad flanges are integral with the tank wall. The exterior faces should be drilled and tapped for threaded studs. Pad flanges save the cost of material and labor and are much easier to line; they also reduce the dimensional requirements of the vessel. The vessel also requires lifting lugs suitable for handling the weight of the empty vessel during installation. Once installed, the vessel should be shimmed and leveled. All space between the bottom surface of the skid structure and the foundation should be sealed with an expansion-type grout; provisions should be included to drain the area under the vessel.

The type of vessel internal distribution and collection piping used in operational arsenic removal plants is described in the Preliminary Design (see Section 3.3.1.1). Because there are many acceptable vessel internal design concepts, configuration details will be left to sound engineering judgment. The main points to consider in the design are as follows:

1. Maintain uniform distribution.
2. Provide minimum pressure drop through internal piping (but sufficient to assure uniform distribution).
3. Prevent wall effects, channeling, and dead areas.

4. Collect treated water within two inches of bottom of treatment bed.

5. Anchor internal piping components to vessel to prevent any horizontal or vertical movement during operation.

6. Ensure that construction materials are resistant to corrosive inorganic ions (PVC and stainless steel are acceptable).

Underdrain failures create significant problems; resin loss, service disruption, and labor to repair problems are very costly. A service platform with an access ladder should be required for use in loading resin into the vessel. A handrail, toe plate, and other OSHA-required features should be included.

3.4.1.2 Pipe Design

Each piping subsystem should be reviewed to select each of the subsystem components (see Figure 3-2). Exclusive of the chemical subsystems, seven piping subsystems are listed in the Conceptual Design (see Section 3.2); they are:

1. Raw water influent main.
2. Intervessel pipe manifold.
3. Treated water effluent main.
4. Raw water bypass main.
5. Backwash/regeneration feed manifold.
6. Wastewater main.
7. Sample panel (optional).

At this point, the design of each of the above subsystems proceeds. First, the equipment specifications for each equipment component in each subsystem should be defined. Then, a detailed installation drawing is developed that locates each component and provides access for operation and maintenance. As each subsystem nears completion, provisions for pipe system support and anchorage, as well as for thermal expansion/contraction, should be incorporated in the Final Design.

Easy maintenance is an important feature in all piping systems. Air bleed valves should be installed at all high points; drain valves should be installed at all low points. This assists the plant operator in both filling and draining pipe systems. Air/vacuum valve and pressure relief valve discharges should be piped to waste. This feature satisfies both operator safety and housekeeping requirements. Bypass piping for maintenance of flow control, pressure control, flowmeter, and other in-line mechanical accessories is optional. Individual equipment item bypass piping is costly and requires extra space. However, if continuous treatment plant operation is mandatory, bypass piping should be included.

3.4.1.3 Instrument Design

Ease of maintenance is very important. Instruments require periodic calibration and/or maintenance. Without removal provisions, the task creates process control problems. Temperature indicators (optional) require thermal wells installed permanently in the pipe. Pressure indicators require gauge cocks to shut off flow in the branch to the instrument. pH sensing probes (optional) require isolation valves and union type mounting connections (avoids twisting of signal cables). Supply of pH standard buffers (4.0, 7.0, and 10.0) should be specified for pH instrument calibration. A laboratory bench should be located adjacent to the sample panel. The sample panel receives flow directly from sample points located in the process piping. The sample panel consists of a manifold of PVC or polyethylene tubing with shutoff valves, which allows the plant operator to draw samples from any point in the process at the laboratory bench. Laboratory equipment should include a wall cabinet, base cabinet with chemical-resistant countertop and integral sink, 115V/1ϕ/60Hz 20-amp duplex receptacle, and laboratory equipment/glassware/reagents for analysis of pH, arsenic, sulfate, and other ions. A deionized water capability for cleaning glassware and dilution of samples should be included.

3.4.1.4 Regeneration Wastewater Surge Tank

Although treatment and disposal of regeneration wastewater are not covered in this design manual, a surge tank to receive the wastewater is provided. The wastewater surge tank should receive the entire batch of backwash and regeneration wastewater from the start of backwash to the completion of rinse steps. In the design example used in this manual, the wastewater surge tank is sized to contain 150 gal/ft^3 of ion exchange resin in the treatment vessel. However, because wastewater volumes vary for each ion exchange resin, verification with the ion exchange resin manufacturer and/or field pilot test to precisely determine the required capacity of the wastewater surge tank is recommended. This tank should be a ground-level atmospheric carbon steel tank and should include a carbon steel floor and roof and an interior epoxy lining. The tank should be placed in a reinforced concrete containment structure and should include fill, chemical feed, drain, overflow vent, multiple discharge, and multiple sample pipe connections. The tank also should include one ground-level and one roof manway (with safety ladder and handrails), provisions for a liquid level indicator, an ultrasonic liquid sludge level sensor, a liquid level controller, and a side-entry mixer.

3.4.2 Final Drawings

As stated above, all of the information required for complete installation of an arsenic removal water treatment plant should appear in the final construction drawings and specification package.

Isometric drawings for clarification of piping subsystems are recommended; these views clarify the assembly for the installer (see Figure 3-5). Cross referencing drawings, notes, and specifications are also recommended.

3.4.3 Final Capital Cost Estimate

Similar to the preparation of the preliminary cost estimate, the final cost estimate, which is based on a takeoff of the installed system, is prepared. The estimate now is based on exact detailed information rather than the general information that was used during the preliminary estimate. The estimate is presented in the same format (see Table 3-2) and is to be accurate within ±10%. Because financial commitments are consummated at this stage, this degree of accuracy is required.

3.4.4 Final Design Revisions

Upon their completion, the final construction drawings and specifications should be submitted for approval to the owner and the regulatory authorities. If changes or additional requirements are requested, they should be incorporated and resubmitted for approval. If clear communication with the approving parties is provided, time-consuming resubmittals should not be necessary. Upon receipt of approval, the owner, with assistance from the engineer, requests bids for the construction of the arsenic removal water treatment plant.

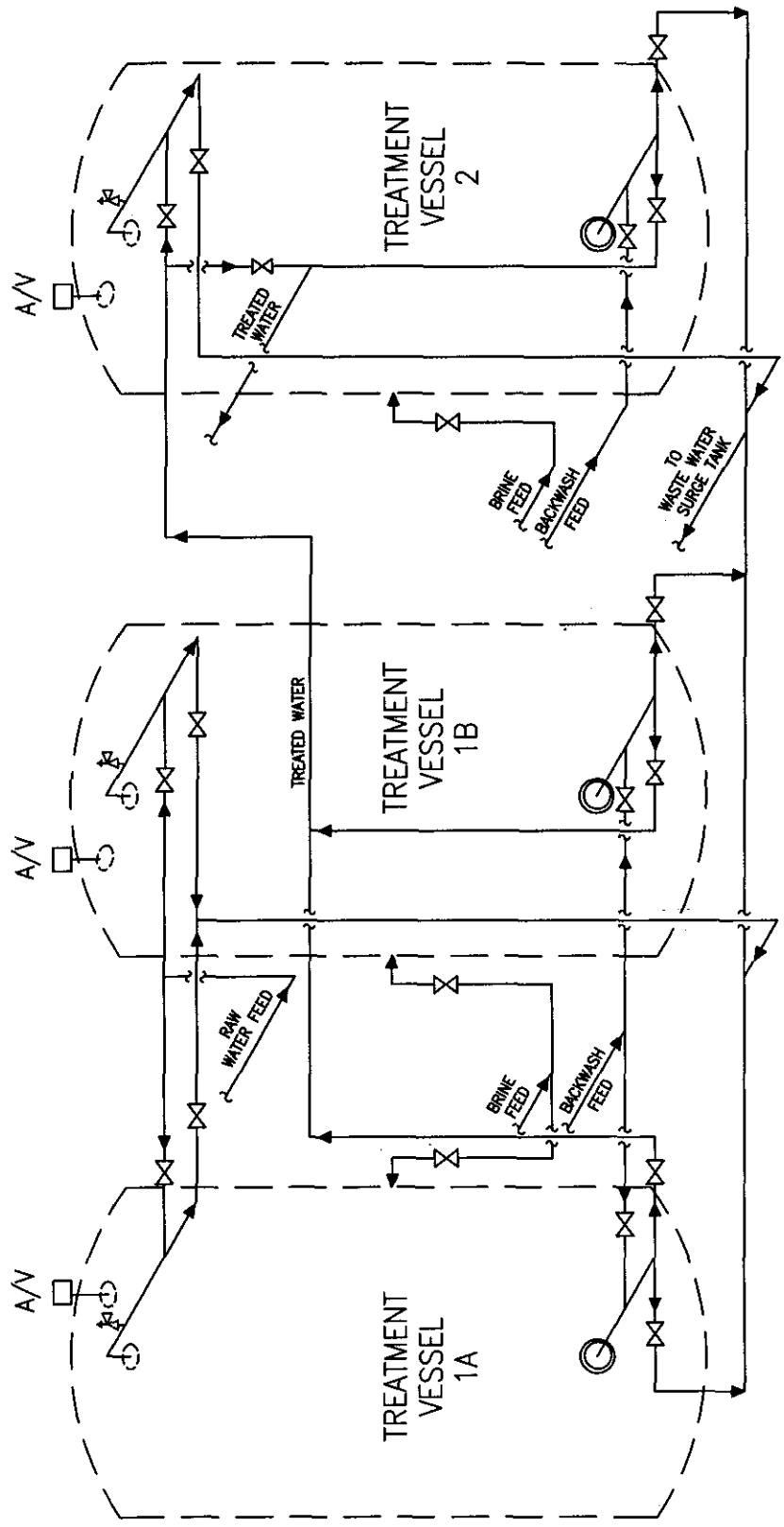


Figure 3-5. Treatment Vessels Piping Isometric (see Figure 3-2 for symbol legend)

4.0 Central Treatment System Capital Cost

4.1 Introduction

The client should be provided with the least expensive ion exchange resin central treatment system that can remove arsenic from a sufficient quantity of water that will satisfy all potable water consumption requirements. The economic feasibility evaluation should include the initial capital cost along with the follow-up operating and maintenance costs. This chapter covers the capital cost that is affected by many factors including operating costs.

The amount of water to be treated is the major, but not the only, factor affecting capital costs. Other factors that can have varying impact on the capital cost include, but are not limited to, the following:

1. Raw water quality (temperature, pH, arsenic, trivalent arsenic, sulfate, alkalinity, iron, manganese, sodium, etc.).
2. Climate (temperature, precipitation, wind, etc.).
3. Seismic zone.
4. Soil conditions.
5. 100-year flood plain.
6. Existing and planned (future) potable water system parameters:
   a) Number of wells, location, storage, distribution
   b) Water storage (amount, elevation, location)
   c) Distribution (location, peak flows, total flow, pressure, etc.)
   d) Consumption (daily, annual, seasonal).
7. Backwash and regeneration wastewater disposal concept.
8. Manual vs. automatic operation.
9. Financial conditions (cost trends, capital financing costs, cash flow, labor rates, utility rates, chemical costs, etc.).

Once the capital cost impacts that each of the above variables can create have been determined, it becomes apparent that a cost curve (or tabulation) based on flow-rate alone is inadequate. Such a curve is presented later in this chapter. A tabulation of the breakdown of these capital costs is provided in Appendix C. If the impact of these variables on the cost curve is considered, a meaningful preliminary project cost estimate (as described in Section 3.3.3) can be produced.

A user-friendly cost-estimating computer program (using Microsoft® Excel Visual Basic) recently has been developed by Battelle on the use of adsorptive media and ion exchange for arsenic removal (Battelle, 2002). This program was funded by the U.S. EPA under Work Assignment 3-20 of Contact No. 68C7-0008. A copy of the computer program and the associated document can be obtained from U.S. EPA National Risk Management Research Laboratory, Water Supply and Water Resources Division, in Cincinnati, OH 45268.

4.2 Discussion of Cost Variables

Each of the variables mentioned above has a direct impact on the total installed cost for a central treatment system. Ideally, conditions could exist that allow a minimum cost system to be designed. A hypothetical example would resemble the following:

1. Raw water quality presents no problem (no trivalent arsenic, no sulfate, moderate temperature, etc.).
2. Warm moderate climate (no freezing, no high temperature, minimal precipitation, no high wind).
3. No seismic requirements.
4. Existing concrete pad located on well compacted, high-bearing-capacity soil.

5. Single well pumping to subsurface storage reservoir with capacity for peak consumption day.

6. Existing wastewater disposal capability adjacent to treatment site.

7. Water softener salt and brinemaker on site for other purposes.

8. Manual operation by labor that is normally at the site with sufficient spare time.

9. Funding, space, etc. available.

This ideal situation, though possible, never exists in reality. Occasionally one or more of the ideal conditions occur, but the frequency is low. If the final estimate for the example used in Appendix B is revised to incorporate the above ideal conditions, the cost estimate would be reduced from $583,000 to $391,000 (see Tables 3-2 and 4-1). Conversely, adverse conditions could accumulate, resulting in a cost far in excess of that for the typical treatment system for the same treatment capability. The following subsections provide the basic insight needed to minimize the cost impact resulting from the above variables.

4.2.1 Water Chemistry

Water chemistry can affect capital as well as operating costs. With a clear picture of the raw water quality, its possible variations, and its adverse characteristics, the capital cost can be determined. High water temperature (greater than 100°F) requires higher-cost piping material and/or pipe support. To treat water that varies in temperature beyond a certain range requires special provisions for thermal expansion and contraction. Presence of trivalent arsenic, manganese, turbidity, suspended solids, colloidal material, and/or other contaminants can require the addition of pre-treatment steps to accomplish removal prior to arsenic removal.

Each of the physical and chemical characteristics of the raw water should be evaluated. The technical, as well as the economic, feasibility of the entire project could hinge on these factors.

4.2.2 Climate

Temperature extremes, precipitation, and high wind will necessitate a building to house the treatment system equipment. High temperature, along with direct sunlight, adversely affects the strength of plastic piping materials. Freezing is obviously damaging to piping and, in extreme cases, also to tanks. Temperature variation introduces requirements for special thermal expansion/contraction provisions. A building with heating and/or cooling and adequate insulation will eliminate the above problems and their costs, but will increase the cost of the building. The building cost will reflect wind loads, as well as thermal and seismic requirements. Operator comfort

Table 4-1. Final Capital Cost Estimate Examples for Two Types of Ion Exchange Arsenic Removal Water Treatment Plants at an Ideal Location

Location: Flowrate: 620 gpm Date:	Cost ($1,000)	
	Manual Operation	**Automatic Operation**
Process Equipment		
Treatment Vessels	99	99
Ion Exchange Resin (750 ft^3)	127	127
Process Piping, Valves, and Accessories	45	88
Instruments and Controls	12	73
Salt and Brine Storage	6	6
Subtotal	289	393
Process Equipment Installation		
Mechanical	42	50
Electrical	6	40
Painting and Miscellaneous	12	12
Subtotal	60	102
Miscellaneous Installed Items		
Regeneration Wastewater Surge Tank	0	0
Building and Concrete	6	6
Site Work, Fence, and Miscellaneous	0	0
Subtotal	6	6
Contingency 10%	36	50
Total[a]	391	551

(a) Engineering, exterior utility pipe and conduit, wastewater and waste solids processing system, finance charges, real estate cost, and taxes not included.

rather than economic considerations may dictate building costs.

The aggregate cost for the building and regeneration wastewater surge tank installation, along with their associated civil work, becomes a major portion of the overall capital cost (see Table 3-2). Great care should be exerted in interpreting the climatological conditions and their requirements.

4.2.3 Seismic Zone

Seismic design should comply with the requirements of the local building codes. Buildings and tall slender equipment are vulnerable to seismic loads. In zones of extreme seismic activity, low profile equipment and buildings are recommended.

4.2.4 Soil Conditions

Unless soil boring data are already available for the treatment system site, borings should be required where the foundations for heavy equipment items (e.g., treatment vessels and regeneration wastewater surge tank) will be located. If the quality of the soil is questionable (fill or very poor load bearing capacity), additional soil borings should be obtained. Poor soil may require costly excavation/backfill and foundations.

Combinations of poor soil with rock or large boulders can make foundation work more complex and costly. Rocks and boulders, combined with extreme temperatures, can result in very high installation costs for subsurface raw, treated, and wastewater pipe mains.

4.2.5 100-Year Flood Plain

For water treatment facilities located within a 100-year flood plain, the entire site should either be relocated outside the 100-year flood plain, be elevated 3 ft above the 100-year flood plain level, or be protected on all sides by an armored berm that extends a minimum of 3 ft above the 100-year flood plain level.

4.2.6 Existing and Planned (Future) Potable Water System Parameters

Many existing and planned (future) facility configurations can significantly increase or decrease capital costs. The most important factors are discussed below.

4.2.6.1 Number and Location of Wells

When there is only one well, excess arsenic should be removed from the water before it enters the distribution system. Theoretically, treatment can occur before or after entering storage. Practically speaking, treatment prior to entering storage is easier to control because the treatment plant flowrate will be constant. If treatment takes place after storage, or if there is no storage, flowrate is intermittent and variable. Treatment before storage also can reduce or possibly eliminate the need for adjusting the pH of the treatment water entering the distribution system by blending the treated water in the storage tank. As discussed in Section 2.2.3, during the early part of the treatment cycle, the pH of the treated water can be significantly reduced (bicarbonate removal). Storage after treatment allows for blending of this low pH water with the higher pH water produced during the later part of the treatment cycle. The pH of the distribution water will be the pH of the blended water in the storage tank that may not require adjustment.

When more than one well requires treatment, a decision is required regarding whether a single treatment plant, treating water from all wells manifolded together, or individual treatment plants at each well is more efficient and cost-effective. Factors such as distance between wells, distribution arrangement, system pressure, and variations in water quality should be evaluated in the decision. If all of the wells are in close proximity and pump a similar quantity and quality of water, a single treatment plant serving the entire system is preferable. When wells are widely dispersed, manifolding costs become prohibitively expensive, dictating implementation of individual treatment plants at each well. Frequently the distances may be such that the decision is not clear-cut; the designer then has to decide based on other variables such as water quality, system pressure, distribution configuration, and land availability.

Systems that require multiple treatment plants can achieve cost savings by employing an identical system at each location. This results in an assembly line approach to procurement, manufacture, assembly, installation, and operation. Material cost savings, labor reduction, and engineering for a single configuration will reduce the cost for the individual plant.

4.2.6.2 Potable Water Storage Facilities

Similar to the wells, the number, size, and location of storage tanks can affect treatment plant size (flowrate) and capital cost. If there is no storage capacity in the system, the well pump should be capable of delivering a flowrate equal to the system momentary peak consumption; this could be many times the average flowrate for a peak day. If there is no existing storage capacity, a storage tank should be added with the treatment system.

Most systems have existing storage capacity. The storage may be underground reservoirs, ground-level storage tanks, or elevated storage tanks (located on high

ground or structurally supported standpipes). The first two require repressurization; the latter does not. Elevated storage tanks apply a back pressure on the ground-level treatment system, requiring higher pressure (more costly) treatment vessels and piping systems.

The amount of storage capacity is also a factor affecting treatment system cost. The larger the storage capacity (within limits), the lower the required treatment plant flowrate (and resulting cost). A minimum storage capacity of one half of system peak day consumption is recommended.

As discussed in Section 4.2.6.1, storage after treatment also provides the benefit of blending the treated water prior to distribution. This blending may reduce or eliminate the need for pH adjustment of the distributed water.

4.2.6.3 Distribution and Consumption

The factors that determine the sizing of the treatment system are the well (or feed) pump flowrate, frequency of treatment vessel regeneration, storage capacity, and system consumption characteristics. Those factors should be coordinated to provide a capacity to deliver a treated water supply to satisfy all possible conditions of peak consumption. If there is adequate storage capacity, the momentary peaks are dampened out. The peak day then defines the system capacity. The well (or feed) pump is sized to deliver the peak daily requirement. The treatment system in turn is sized to treat a minimum of what the well (or feed) pump delivers.

The distribution system may anticipate future growth or increased consumption. The well (or feed) pump should then either pump a flow equal to or larger than the maximum anticipated peak daily flows or be able to adjust to a future increased flowrate. The treatment plant in turn should incorporate capacity to treat the ultimate peak flowrate or include provisions to increase the treatment capacity in the future.

4.2.7 Backwash and Regeneration Disposal Concept

Regeneration wastewater and waste solids processing and disposal are not covered in the scope of this document, but information on disposal options and laboratories studies have been reported on by MacPhee et al. (2001). Spent brines containing more than 5.0 mg/L of arsenic would be classified as a hazardous waste based on the U.S. EPA TCLP. Depending on wastewater discharge limits established by the U.S. EPA and state and local regulatory agencies, wastewater disposal can be a very significant cost item that should be evaluated in the capital (and operating) cost projection. Requirements for the disposal of the brine can vary from zero discharge to discharge in an available existing receiving facility.

Brine can be pre-treated by chemical coprecipitation of arsenic, with the addition of iron or aluminum coagulants and appropriate pH adjustment for minimum solubility of the precipitated metal hydroxides (MacPhee et al., 2001). Dewatering of precipitated suspended solids (precipitated iron or aluminum hydroxides) should result in the dewatered solids passing the U.S. EPA TCLP test. The supernatant wastewater, though containing very low arsenic concentration, should contain elevated levels of TDS. If the regulatory agency permits disposal of the supernatant by conventional methods (surface discharge, percolation), the disposal costs are not large.

The total volume of wastewater is normally less than 150 gal/ft^3 of ion exchange resin. The treated water per treatment cycle per cubic foot of ion exchange resin varies significantly, depending primarily on the sulfate concentration in the raw water and the capacity of the resin. For example, if the resin capacity is 1.28 eq/L (28 Kgrains as $CaCO_3$ per ft^3) of resin and the source water has a sulfate concentration of 10 mg/L and an arsenic concentration of 0.1 mg/L (0.209 meq/L – total), then the treated water per cycle is 45,765 gal/ft^3. Conversely, if the resin capacity is 0.67 eq/L (15 Kgrains as $CaCO_3$ per ft^3) and the source water has a sulfate concentration of 50 mg/L and an arsenic concentration of 0.1 mg/L (1.041 meq/L – total), then the treated water per cycle is 4,812 gal/ft^3. Therefore, the variation of the ratio of wastewater to treated water can be significant. This factor should be evaluated carefully when selecting the ion exchange treatment method versus an alternate treatment method.

4.2.8 Chemical Supply Logistics

Water softener salt (NaCl) is normally the cleanest grade of sodium chloride solid-phase material available. It is produced in various mesh sizes that can affect the dissolving rate, ease of handling, and cost. The material can be procured in truckload bulk quantities or bags. The truckload quantities are much cheaper and less labor intensive and, therefore, more desirable. Truckload quantity procurement requires bulk storage capability on site with capability to transfer the salt to the brine production/storage tank. There are commercially available stand-alone salt storage/brinemaking systems units that require very little operation time and are synergistic with automatic operation. The systems are completely contained in single vertical cylindrical fiberglass vessels. They are complete packages including piping for pneumatic transfer of granular salt from delivery trucks and dust collection. The vessels require a significant amount of headroom (25-30 ft), which might not be available.

Smaller brine tanks, sized specifically for the individual system, require operator manual transfer of salt (by means of bags) into the tank. The larger the ion exchange resin bed, the greater the operator effort. The NaCl requirement varies with the ion exchange resin selected, but 10 lb/ft^3 can be used as a rule of thumb.

4.2.9 Manual vs. Automatic Operation

Automatic operation is technically feasible. However, the periodic presence of an operator is always a requirement. The capital cost of automation (computer hardware/software, valve operators, controls, instrumentation, etc.), as well as maintenance costs may exceed budget limits. Therefore, either manual or semiautomatic operation is normally furnished. The advantages and disadvantages of manual, automatic, and semiautomatic operation require careful evaluation prior to determination of the proper selection.

4.2.10 Financial Considerations

Many financial factors should be considered by the designer and his client. The client can superimpose criteria (beyond any of the technical factors mentioned above) that result in increased (or decreased) capital cost. These include, but are not limited to, inflationary trends, interest rates, financing costs, land costs (or availability), cash flow, labor rates, electric utility rates, and chemical costs. All or part of this group of factors could affect the capital investment because interest rates are low, inflation is anticipated, cash is available, or labor and electric utility rates are high. Or the opposite can be true. The varying combinations of these factors that could develop are numerous; each will affect the ultimate capital cost.

4.3 Relative Capital Cost of Arsenic Removal

The relative capital costs of central ion exchange treatment plants based on the treated water flowrate are presented in Figures 4-1 and 4-2. Both cost curves are based on the same treatment system design criteria. Tabulations of the breakdowns of the capital costs for both curves are provided in Appendix C. The curve in Figure 4-1 is based on the facility criteria employed in the hypothetical design for the 620 gpm arsenic removal treatment system in Appendix B. These costs are representative of average capital costs. The curve in Figure 4-2 is based on the same treatment system located at an ideal location at which the facility requirements are eliminated or minimized (see Section 4.2 and Table 4-1). This information demonstrates significant differences in capital costs that can occur for the same treatment plant at different sites.

Figures 4-3, 4-4, and 4-5 provide examples of the equipment and material itemized cost data utilized during the preparation of the capital cost estimates in this manual. A complete material and labor takeoff is required for the preparation of a capital cost estimate for any given project. Current equipment and material unit cost information should be obtained from the original manufacturer or distributor for each item. The assembly/installation costs for each unit of each item should be obtained from the provider of that service. The capital material and labor costs for the installed treatment plant are then obtained by means of tabulations inclusive of all items, along with quantities of each item and the associated equipment/material/labor unit costs. Figure 4-3 provides an example of an ASME Code pressure vessel manufacturer's proposed price for a treatment vessel.

Figure 4-4 provides an ion exchange resin manufacturer's published price information for SBA resin in compliance with NSF drinking water requirements. Figure 4-5 provides pipe, fitting, and valve itemized cost estimating information based on a major material distributor's proposed material prices and an experienced mechanical system installation contractor's proposed labor prices. In addition to the basic costs provided in the above figures, additional costs include, but are not limited to, tools, miscellaneous materials (nuts, bolts, washers, gaskets, pipe supports, ladders, etc.) freight handling/storage/protection of materials/equipment, mobilization, and demobilization. Though not individually itemized in the cost tabulation presented in the tables included in this manual, all such costs have been included. Therefore, the estimated capital cost provided in the tabulations in Appendix C and the curves in Figures 4-1 and 4-2 exceed the specific costs provided in Figures 4-3, 4-4, and 4-5.

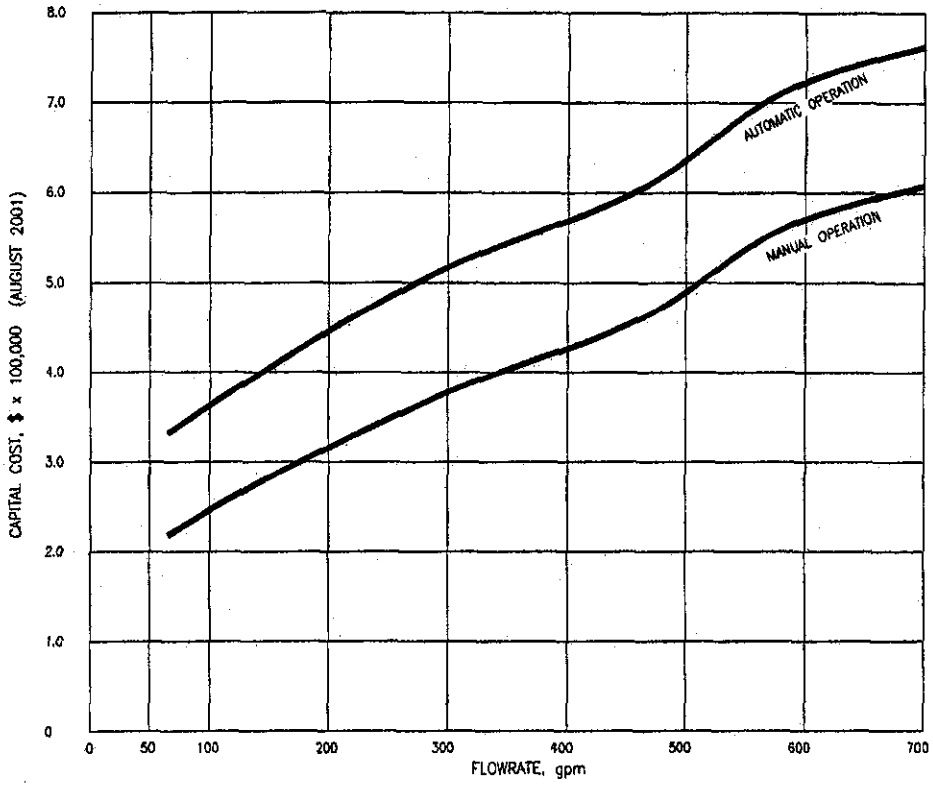


Figure 4-1. Capital Cost vs. Flowrate at Typical Locations for Arsenic Removal Water Treatment Plants by Means of the Ion Exchange Process (for itemized cost breakdown, see Appendix C)

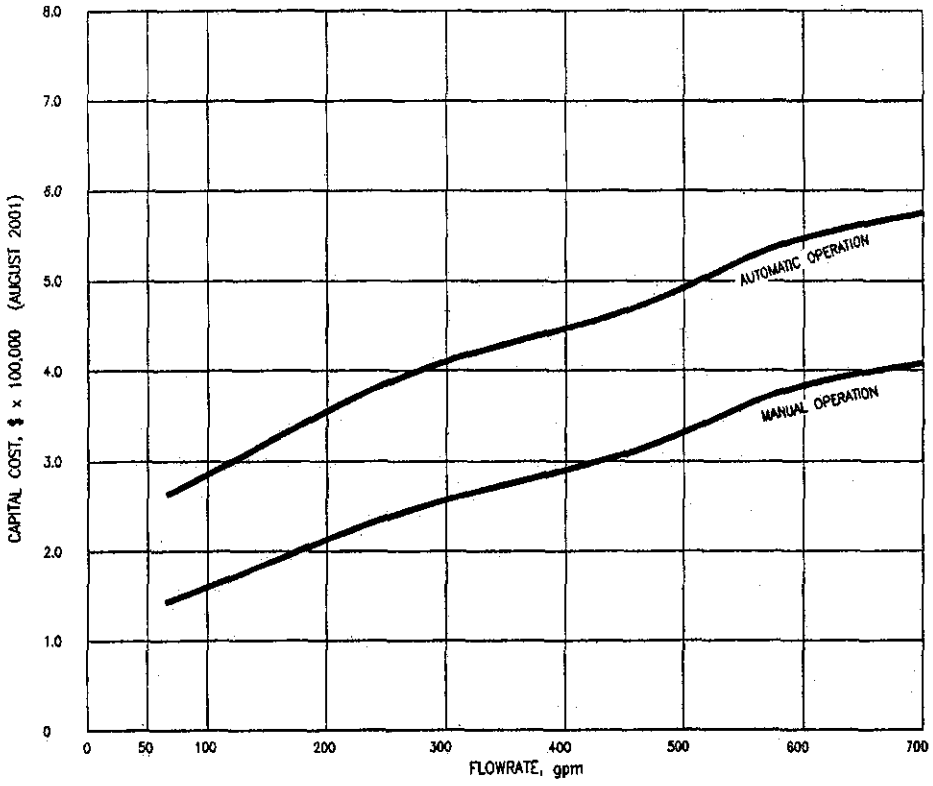


Figure 4-2. Capital Cost vs. Flowrate at Ideal Locations for Arsenic Removal Water Treatment Plants by Means of the Ion Exchange Process (for itemized cost breakdown, see Appendix C)

CODE PRESSURE VESSEL FABRICATOR QUOTATION
FOR ION EXCHANGE TREATMENT VESSELS (three required)

Vessel Specification and Quotation #1280m 07/24/01
Customer
Attention
R.F.Q. Pricing for your Arsenic Removal Water Treatment Project

Description	Vertical Skid-Mounted Vessel
Size	120" O.D. × 8' 0" S/S; Capy, 5,450 gal
Design Pressure and Temp	50 psig @ 175 degrees Fahrenheit
Corrosion Allowance	None requested or provided
Design Criteria	A.S.M.E. Section VIII, Div. 1
Radiography	Spot (RT-3)
Code Stamp	Yes and National Board Registration
Constructed of	Carbon steel
Supports	(4) carbon steel legs with skid to provide 24" to bottom seam

Nozzles and Appurtenances:

2	20" quick opening manways
1	4" - CL150 FF single-tapped pad flange, hillside-type
1	4" - CL150 FF single-tapped pad flange
2	8" - CL150 FF single-tapped pad flanges
1	12" × 3" vertical viewing window
1	False bottom
8	Interior carbon steel lateral support clips
1	Interior carbon steel header support clip
2 sets	Exterior pipe support brackets
2	Lifting lugs
1	Skid

Valves, gauges, gaskets, or any items not listed above are excluded.

Surface Preparation and Coatings:
Interior surface prep: SSPC-SP-5 white metal sandblast
Interior surface coat: Plasite 4006 HAR (35 MDFT)
Exterior surface prep: SSPC-SP-6 commercial sandblast
Exterior surface primer: Rust inhibitive primer
Exterior topcoat: None requested or provided
Note, interior coating is forced cured to meet NSF STD 61 requirements for potable water

Shipping: weight, 9,500 lb; dimensions, 10' diameter × 12.5' OAL.

Price: FOB Madera CA, $ 27,500.00 each, not including taxes.
Price based on a quantity of 2, and is valid for 90 days.

Delivery schedule: based on current schedule.
Drawings for approval: 2 weeks after order
Fabricate and ship: 12 to 14 weeks after drawing approval.

Terms: Progress payment to be arranged.

Figure 4-3. Code Pressure Vessel Fabricator Quotation for Ion Exchange Treatment Vessels

August 21, 2001

Mr. John Doe
ABC Engineering, Inc.
P.O. Box 1000
DEFG, AA 10000-1000

Ref: Municipal Bid Quotation for Arsenic Removal Ion Exchange Resin

Dear Mr. Doe,

XXXXZ is a Type I strong base anion (SBA) resin that has exhibited excellent performance for the removal of arsenic (As +5) and in its subsequent capacity regain through regeneration with salt (NaCl). XXXXZ undergoes rigorous cleaning steps for potable water application. This is to remove the organic extractables as well as taste and odor caused by leftover by-products that are common to SBA resins. This cleaning process which is designated by the postscript "Z" sets XXXXZ apart from other strong base resins with similar function. XXXXZ has been evaluated and is certified under NSF STD 61 for potable water applications.

The pricing on XXXXZ will vary with the quantity, ship to location, and exact resin specifications (such as particle size range and packaging). Although municipal applications can be very large, they can also be very modest. A good range to use would be $165 to $300 per cu ft, with the upper range being applied to volumes of less than 100 cu ft and the lower range being applied to purchases of multiple truckloads (i.e., >2,000 cu ft). Use a price of $250 for 200 cu ft, $200 for 400 cu ft, and $185 for 800 cu ft (full T/L) quantities. Beyond that, the economies of scale diminish rapidly.

We have many successful installations of XXXXZ in use for arsenic removal. The end results are generally nondetectable levels of arsenic, providing the original influent was properly speciated and, when necessary, an oxidation system was incorporated into the pre-treatment design.

Yours truly,

Jane Roe
Area Representative

Figure 4-4. Example of SBA Resin Quotation for Arsenic Removal Drinking Water Treatment Systems Provided by Prominent Manufacturer

Item	Qty	Material Unit Price[a] ($)	Total Material ($)	Labor Unit Price[b] ($)	Total Labor ($)	Total ($)
8" SCH 80 PVC Pipe (P/E)	380 ft	8.00/ft	3,040	5.00/ft	1,900	4,940
6" SCH 80 PVC Pipe (P/E)	170 ft	5.00/ft	850	4.00/ft	680	1,530
4" SCH 80 PVC Pipe (P/E)	90 ft	3.50/ft	270	3.00/ft	270	540
1½" SCH 80 PVC Pipe (P/E)	30 ft	1.00/ft	30	2.00/ft	60	90
8" SCH 80 PVC Tee (s × s × s)	24	170 ea.	4,080	15.00 ea.	360	4,440
6" SCH 80 PVC Tee (s × s × s)	6	70 ea.	420	15.00 ea.	90	510
4" SCH 80 PVC Tee (s × s × s)	5	50 ea.	250	10.00 ea.	50	300
8" SCH 80 PVC 90° ELL (s × s)	19	120 ea.	2,280	12.50 ea.	240	2,520
6" SCH 80 PVC 90° ELL (s × s)	5	45 ea.	225	12.50 ea.	65	290
4" SCH 80 PVC 90° ELL (s × s)	8	20 ea.	160	10.00 ea.	80	240
1½" SCH 80 PVC 90° ELL (s × s)	8	5 ea.	40	7.50 ea.	60	100
8" SCH 80 PVC Reducer (s × s)	8	70 ea.	560	12.50 ea.	100	660
6" SCH 80 PVC Reducer (s × s)	2	30 ea.	60	12.50 ea.	25	85
4" SCH 80 PVC Reducer (s × s)	1	25 ea.	25	10.00 ea.	10	35
8" SCH 80 PVC Coupling (s × s)	5	45 ea.	225	12.50 ea.	65	290
6" SCH 80 PVC Coupling (s × s)	5	35 ea.	175	12.50 ea.	65	240
4" SCH 80 PVC Coupling (s × s)	4	20 ea.	80	12.50 ea.	50	130
1½" SCH 80 PVC Coupling (s × s)	2	5 ea.	10	10.00 ea.	20	30
8" SCH 80 PVC Van Stone Flange (s)	62	55 ea.	3,410	12.50 ea.	775	4,185
6" SCH 80 PVC Van Stone Flange (s)	16	35 ea.	560	12.50 ea.	200	760
4" SCH 80 PVC Van Stone Flange (s)	19	20 ea.	380	10.00 ea.	190	570
8" Wafer Style PVC Butterfly Valve	14	280 ea.	3,920	50.00 ea.	700	4,620
6" Wafer Style PVC Butterfly Valve	8	225 ea.	1,800	40.00 ea.	320	2,120
4" Wafer Style PVC Butterfly Valve	7	180 ea.	1,260	25.00 ea.	175	1,435
1½" PVC Ball Valve (s × s)	2	60 ea.	120	25.00 ea.	50	170
8" PVC Wafer Style Check Valve	3	650 ea.	1,850	100.00 ea.	300	2,150
TOTALS			26,080		6,900	32,980[c]

(a) Prices effective August, 2001 (markup included).
(b) Labor rate @ $50/hour.
(c) Tools, installation equipment, pipe supports, accessories, bolts, nuts, gaskets, mobilization, material storage, etc. not included.

Figure 4-5. Process Pipe, Fittings, and Valves: Itemized Cost Estimate for a Manually Operated 620-gpm Arsenic Removal Water Treatment System

5.0 Treatment Plant Operation

5.1 Introduction

Upon completion and approval of the final design package (plans, specifications and cost estimate), the owner (client) advertises for bids to construct the treatment plant. The construction contract is normally awarded to the firm submitting the lowest bid. Occasionally, circumstances arise that disqualify the low bidder, in which case the lowest qualified bidder is awarded the contract. Upon award of the construction contract, the design engineer may be requested to supervise the work of the construction contractor. This responsibility may be limited to periodic visits to the site to assure the client that the general intent of the design is being fulfilled, or it may include day-to-day inspection and approval of the work as it is being performed. The engineer should review and approve all shop drawings and other information submitted by the contractor and/or subcontractors and material suppliers. All acceptable substitutions should be approved in writing by the engineer. Upon completion of the construction phase of the project, the engineer is normally requested to perform a final inspection. This entails a formal approval indicating to the owner that all installed items are in compliance with the requirements of the design. Any corrective work required at that time is covered by a punch list and/or warranty. The warranty period (normally one year) commences upon final acceptance of the project by the owner from the contractor. Final acceptance usually takes place upon completion of all major punch list items.

Plant operation consists of five basic modes: treatment, backwash, regeneration, slow rinse, and fast rinse. Operating details for each of these modes follow. It is important to note that each of the modes of operation uses raw water, never treated water. Before the plant is put into full operation, however, several plant preparation steps that lead up to routine operation must be completed. These steps include operation review, resin loading, resin backwashing and regeneration, and initial startup preparation.

5.2 Plant Preparation

Preparation for treatment plant startup, startup, and operator training may or may not be included in the construction contract. Although this area of contract responsibility is not germane to this manual, the activities and events that lead up to routine operation are discussed. This section discusses the steps in the sequence that the operator performs them. The operator can be the contractor, the owner's representative, or a third party.

5.2.1 Operation Review

Following construction and prior to plant startup, system operating supplies, including treatment chemicals, laboratory supplies, and recommended spare parts, should be procured and properly stored. The treatment plant operations and maintenance instructions (O&M Manual) also should be available at the project site. Included in the O&M Manual are the valve number diagram (which corresponds to tags on the valves), a valve directory, and a valve operation chart (see Figure 5-1 and Table 5-1). The operator should thoroughly review the O&M Manual, become familiar with every component of the plant, and resolve any questions that arise prior to startup.

5.2.2 Resin Loading

Before the plant can be operated, the ion exchange resin must first be placed in the treatment vessels. Before loading the resin, the treatment vessels and piping should be disinfected in accordance with American Water Works Association (AWWA) standards (C653-97) or state regulations.

The placement of the SBA resin in the treatment vessels, which takes place immediately prior to startup, is a critical step in system performance. The SBA resin is usually delivered in drums. The amount of resin is

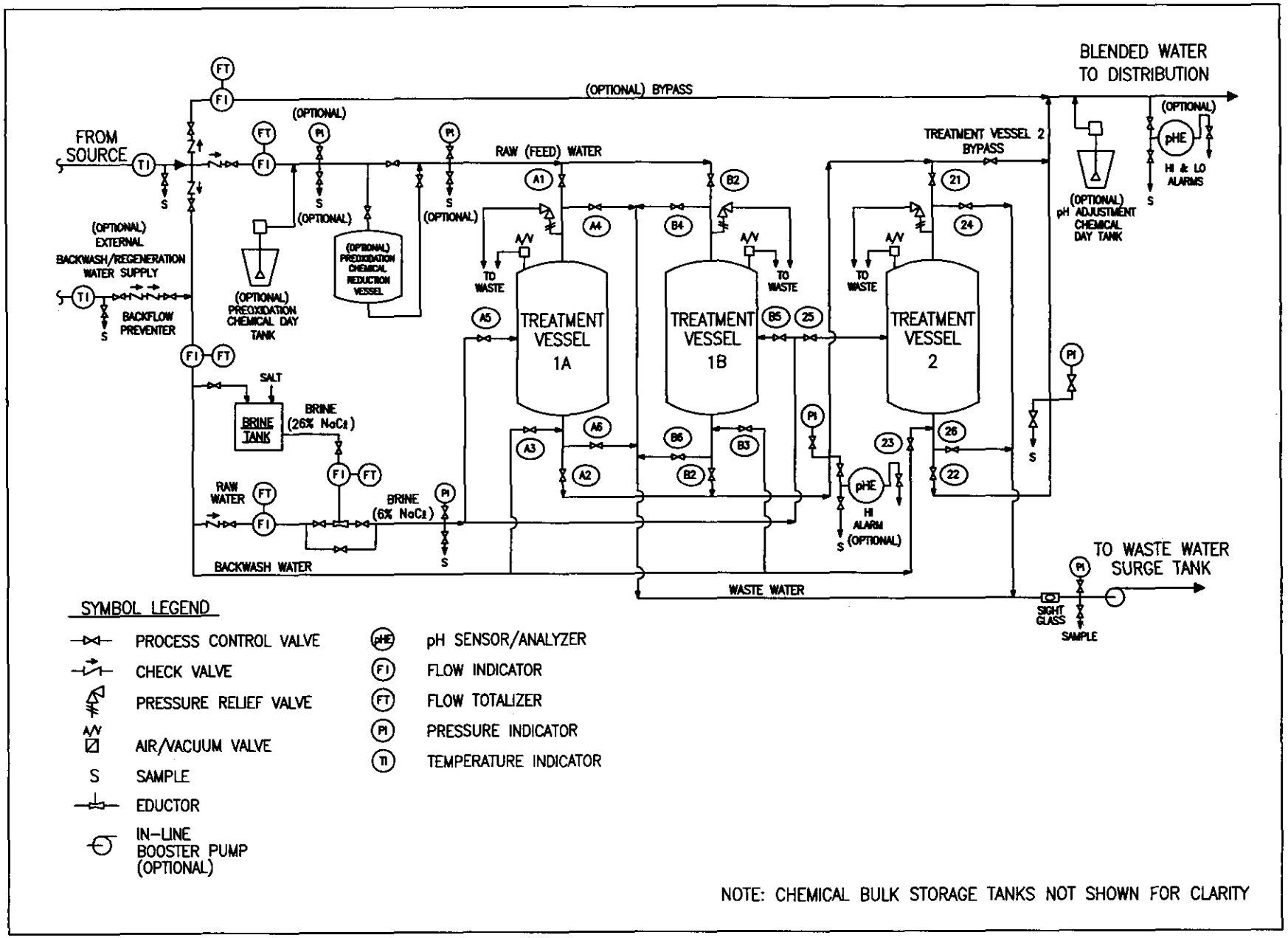


Figure 5-1. Valve Number Diagram

Table 5-1. Valve Operation Chart for Treatment Vessels in Treatment and Regeneration Operational Modes[a]

Mode	Flowrate (gpm/ft^2)	Flow Duration (min)	Valve No. 1	2	3	4	5	6
Treatment	10	[c]	•	•	x	x	x	x
Regeneration								
Backwash	3-4	20 (max.)	x	x	•	•	x	x
Drain to top of bed	Gravity	5	x	x	x	x	x	•
Fill tank with brine	2	20	x	x	x	x	•	x
Regeneration	2	20	x	x	x	x	•	•
Drain to top of bed	Gravity	5	x	x	x	x	x	•
Fill tank with water[b]	2	20	x	x	x	x	•	x
Slow rinse[b]	2	20	x	x	x	x	•	•
Fast rinse	10	30 (max.)	•	x	x	x	x	•
Standby	–	–	x	x	x	x	x	x
Treatment	10	[c]	•	•	x	x	x	x

(a) Refer to Figure 5-1 for valve location.
(b) Water feed to eductor to bypass eductor during water fill step.
(c) Treatment cycle duration.
Legend: x = valve closed; • = valve open.

Vessel 1A

Valve No.
A1 Feedwater
A2 Treated water
A3 Backwash feed
A4 Backwash to waste
A5 Brine feed
A6 Regeneration to waste

Vessel 1B

Valve No.
B1 Feedwater
B2 Treated water
B3 Backwash feed
B4 Backwash to waste
B5 Brine feed
B6 Regeneration to waste

Vessel 2

Valve No.
21 Feedwater
22 Treated water
23 Backwash feed
24 Backwash to waste
25 Brine feed
26 Regeneration to waste

determined on a volumetric basis. The actual density varies with the degree of packing of the bed and, unless instructed otherwise by the manufacturer, 42 lb/ft^3 is a recommended resin density for use in weight calculations. The resin contains a small amount of fines that can interfere with efficient process flow. Eye, skin, and inhalation protection are, therefore, recommended during vessel loading.

The vessel should be filled half way with water prior to placing the ion exchange resin through a manway in the top head of the vessel. Then the resin should be carefully distributed into the vessel from above. The water separates the fines from the resin beads, protects the underdrain assembly from impact, initiates stratification of the bed, and thoroughly wets the resin. It is recommended that the bed be placed in two lifts. In the three-bed treatment system, resin and backwashing steps can be alternated between the three treatment vessels. Thereby, the resin placement process can be a continuous operation.

Each bed should be thoroughly backwashed with raw water after each lift. The backwash should expand the bed approximately 90% unless directed otherwise by the resin manufacturer. To accomplish this, the backwash flowrate should be in the range of 3 to 4 gpm/ft^2 for the area determined by the top of the treatment bed. The backwash rate is sensitive to water temperature. During bed placement, the duration of each backwash step should be a minimum of 20 min; and, depending on the quantity of fines in the resin, should extend until the wastewater is clear. The purpose of this stringent effort is to remove all of the fines from the bed. If the fines remain in the bed, possible problems such as channeling, excessive pressure drop, or wall effects can develop. The extra backwashing effort during bed placement permits fines at the bottom of the bed to work their way up and out to waste. The backwash water should be directed to the wastewater surge tank. Care must be taken to prevent loss of resin during backwash. An in-line sight glass, plus a manual sample point incorporated in the backwash wastewater pipe, will allow the plant operator to immediately detect the presence of resin beads leaving the treatment vessel. Subsequent to backwash, each treatment vessel should undergo the entire regeneration cycle.

5.2.3 Initial Startup Preparation

After the resin has been loaded in the vessels and thoroughly backwashed, each treatment vessel should

undergo an entire regeneration cycle prior to placing the plant on line. It is highly recommended that representatives of the controls and instrumentation suppliers be on hand to assist the operator during the initial regeneration cycle.

Prior to starting operation, all instruments should be calibrated. If chemical preoxidation is required, the preoxidation feed equipment and the preoxidation chemical reduction equipment that removes excess oxidant (if required) from the feedwater stream also should be adjusted and placed into operation.

Pressure drop should be checked (see Section 3.4) just prior to plant startup. See Table 5-2 for a typical manufacturer's calculated pressure drop through a representative ion exchange resin at varying treatment downflow rates and water temperature. If there is a pressure loss problem, it should be corrected prior to treatment startup.

Table 5-2. Typical Manufacturer's Downflow Pressure Drop Data

Strong Base Anion Ion Exchange Resin	
Water flowrate (gpm/ft^2)	Pressure drop in psi per foot of bed depth
6.0	0.5
8.0	0.7
10.0	1.0
12.0	1.3
14.0	1.6
16.0	2.0

Note: Water temperature 80°F.

At this point the plant should be cleaned up. Good housekeeping should begin at this time and be continued on a permanent basis.

5.3 Treatment Mode

After the plant preparation steps have been completed, the downflow treatment for the first (virgin) run can now begin. See Table 5-1 for valve positions for this function. One of the primary stage treatment vessels is placed into operation while the other primary stage treatment vessel is placed in the standby mode. The second stage (or lag) treatment vessel is then placed into operation, where it remains as a fail-safe polishing treatment step, specifically to prevent any arsenic leakage from ever entering the distribution system. In the event that breakthrough occurs in a primary stage treatment vessel, the arsenic peak enters the second stage treatment vessel. The second stage treatment vessel then performs its designated function; prevention of the arsenic peak from entering the distribution system. The second stage should be regenerated as soon as practical following the breakthough of any arsenic into the second stage column. In no case should completion of the regeneration of the second stage treatment vessel be deployed beyond completion of the treatment cycle of the second primary stage treatment vessel. In the meantime, treatment is immediately resumed in the other primary stage treatment vessel, which is transferred from the standby to the operational mode.

The basic flow schematic for the treatment mode is illustrated in Figure 5-2.

Depending on the requirements of the state or local regulatory agency, water samples may have to be analyzed at a certified testing laboratory prior to approval of distribution of treated water.

In the parallel process using two treatment vessels, the entire arsenic removal process takes place in one vessel. The operator must understand that sulfate ions are removed preferentially over arsenic ions. Therefore, a band of arsenic ions moves through the resin column ahead of the sulfate ions that proceed downward through the bed, exhausting the ion exchange capacity until the arsenic breaks through. Breakthrough is defined as the first measurable appearance of As(V) in the effluent from a treatment vessel. Although the detectable level will vary depending on the analytical method used to measure the arsenic, it probably would be near 3 µg/L. At arsenic breakthrough, the arsenic concentration in the treated water surges to a level higher than that in the raw water. An example of this phenomenon is shown in Figure 1-1. This event must be prevented. Immediately prior to arsenic breakthrough, the process flow should be switched to the standby primary stage treatment vessel. The spent treatment vessel should then be regenerated and placed in the standby mode. Upon exhaustion of the ion exchange capacity of the other primary stage treatment vessel, the first primary stage treatment vessel should be returned to the treatment mode.

Several methods can be used to anticipate or project arsenic breakthrough from the lead vessel and the time for regeneration. First, if a pilot plant study was conducted prior to design and operation, the information from this study could be used to predict run lengths and regeneration time. Another method is doing a theoretical calculation based on the feedwater chemistry and the resin manufacturer's resin exchange capacity. As has been mentioned frequently in previous sections of this manual, run lengths are very sulfate-dependent because sulfate is preferred over arsenic, nitrate, bicarbonate, and other anions removed by the process. Consequently, a rough treatment run length can be calculated based on the sulfate concentration and the resin

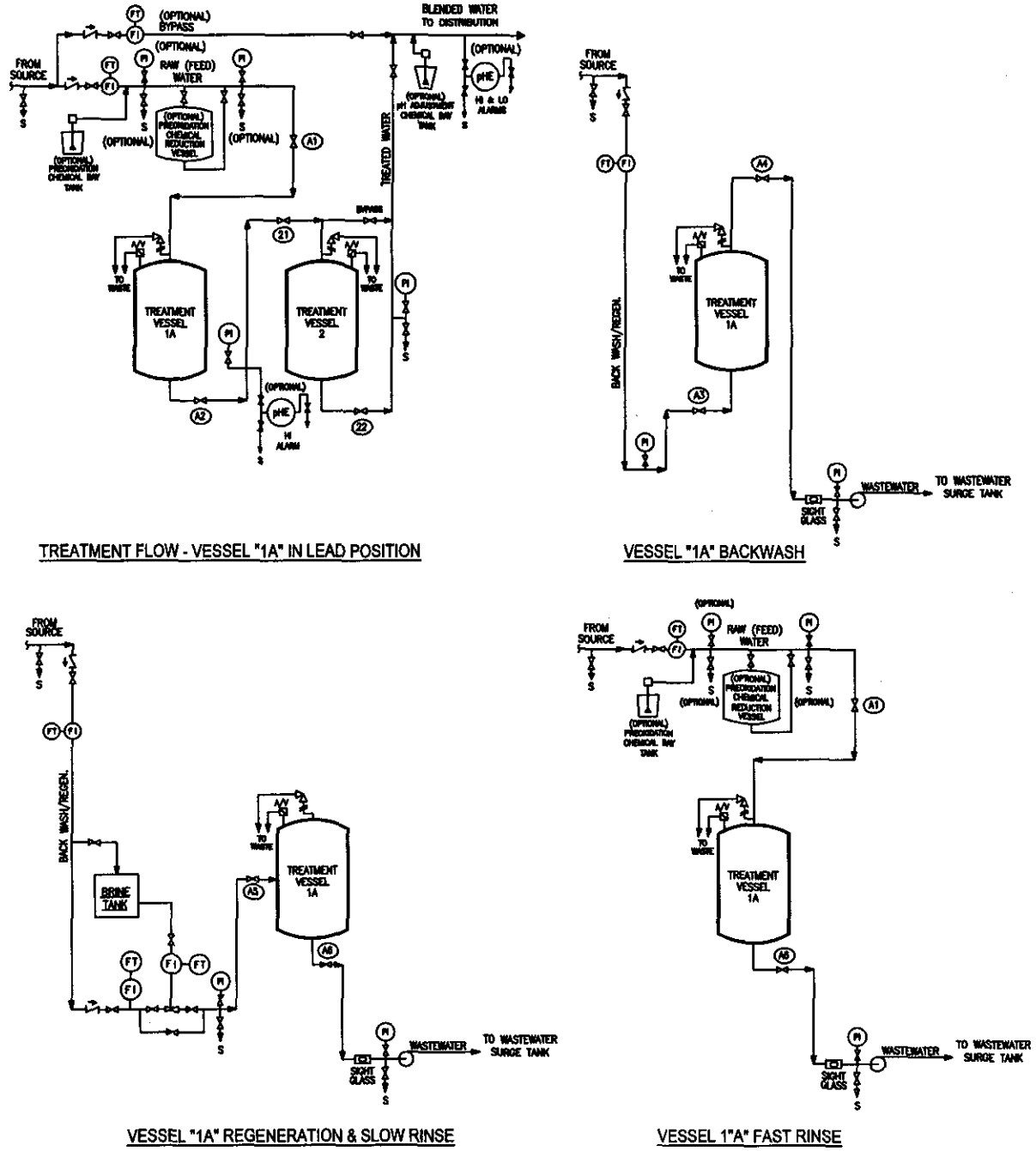


Figure 5-2. Basic Operating Mode Flow Schematics (Note: chemical bulk storage tanks not shown for clarity) (see Figure 5-1 for symbol legend)

manufacturer's published resin exchange capacity. A theoretical calculation of run length in bed volumes based solely on the sulfate concentration of the source water is shown in Figure 5-3. Actual treatment run lengths would be less because of the removal of other anions and operational variables.

Using the run length estimate from either pilot plant data or a theoretical calculation, the plant operator should initially provide a capacity cushion of 10% in determining the volume of water to be treated to prevent arsenic breakthrough at the exhaustion of ion exchange resin. Arsenic field test kits also can be used to obtain rapid

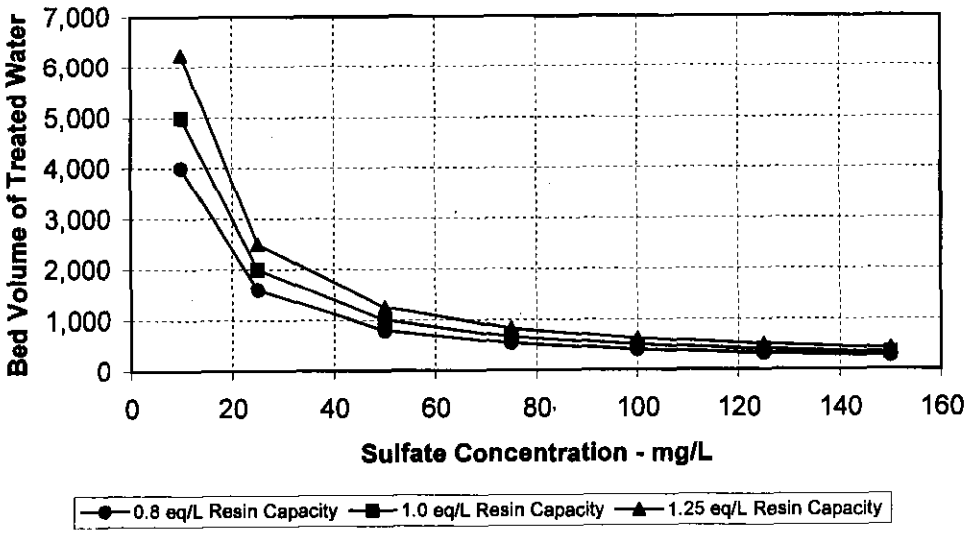


Figure 5-3. Resin Removal Capacity Based on Sulfate Concentration and Resin Capacity

detection of arsenic breakthrough events. By limiting the volume of water to be treated to 90% of the estimated capacity, a 10% cushion is provided for a category of adverse conditions/events that can reduce the estimated capacity of that resin. These adverse items include, but are not limited to, the following:

1. Flow channeling.
2. Flow wall effects.
3. Uneven flow conditions that distort the treatment wave front.
4. Defective resin beads.
5. Uneven feedwater distribution and/or treated water collection subsystems characteristics due to treatment vessel internal piping design/manufacture/assembly (including dead areas).
6. Variation of raw water sulfate and arsenic concentrations.

The treatment plant operator should focus attention on the quality of the treated water. Special attention is required as the treated water volume approaches resin capacity exhaustion. As the experience data base for the treatment system expands, a predictable performance pattern develops that results in a routine repeatable treatment cycle. If the 10% resin capacity cushion does not prevent arsenic breakthrough, the cushion should be increased until breakthrough is consistently prevented. Conversely, to reduce regeneration wastewater production and reduce treatment system operating cost, the plant operator may try to expand the treatment capacity of the first stage treatment vessel by reducing the capacity cushion below 10%. The treated water distribution system should always be protected from an arsenic breakthrough event by the second stage treatment vessel.

When the treated water is approved for distribution, it flows through an (optional) pH sensor with high and low level alarms. If there is a pH excursion exceeding the allowable limits, an interlock (incorporating the pH alarms with the feed pump magnetic starter) de-energizes the feed pump. Simultaneously, the preoxidation and (optional) pH adjustment chemical pumps shut down because their controls should be interlocked with the feed pump power circuitry. The (optional) pH override automatically prevents any treated water for which pH is out of tolerance from entering the distribution system. In the event of such an excursion, the operator (either manually or automatically) diverts the out-of-tolerance water to waste, determines the cause of the deviation, and makes corrections prior to placing the treatment system back on line.

The operator should be cognizant of the fact that the more water treated during a run, the lower the operating cost. In raw waters where the arsenic level is very low, part of the raw water can bypass treatment and be blended back with the treated water. A skilled operator develops many techniques to minimize operating costs.

High iron content in raw water can cause problems during a treatment run. The iron oxidizes, precipitates, and is filtered from solution by the ion exchange resin. This results in an increased pressure drop and shortened treatment runs. Raw water iron content greater

than 0.3 mg/L is cause for concern. However, if the iron concentration is above 0.3 mg/L, the secondary MCL, an iron removal process should be considered as the treatment process for arsenic removal in place of the ion exchange process.

5.4 Backwash Mode

It is important to backwash the bed with raw water after each treatment run prior to regeneration, for two reasons. First, any suspended solids that have been filtered from the raw water by the treatment bed tend to blind the bed. Therefore, these particles should be removed from the bed prior to regeneration. Second, even though filtration may have been negligible, the downward flow tends to pack the bed. An upflow backwash will expand the bed and break up any tendency toward wall effects and channeling. A backwash rate of 3 to 4 gpm/ft^2 (depending on water temperature) will expand the ion exchange resin approximately 90%, which is recommended by some resin manufacturers and is employed in the example presented in this manual. Some resin manufacturers recommend lower backwash flowrates, resulting in less bed expansion (but never less than 50%). As mentioned in prior sections, this rate varies with resin bead size, material density, and water temperatures. Care must be taken to avoid backwashing the resin out of the treatment unit. Backwashing normally takes 15 to 20 min to eliminate filtered suspended solids from the resin. It is important to provide sufficient time during the backwash mode to not only expand the bed, but also to carry out the backwashed particulate material.

Refer to Table 5-1 for valve positions for the backwash mode. The basic flow schematic for the backwash mode is illustrated in Figure 5-2. Backwash water samples should be inspected to determine that filtered material is being removed and resin is not being washed out of the bed. A sight glass should be provided in the wastewater pipe to observe the clarity of the backwash water. Excessive backwash causes abrasion that results in attrition of the resin beads. That also wastes raw water and increases the wastewater disposal volume. Therefore, the backwash volume should be minimized. The resin level of each treatment bed should be inspected periodically through a viewing window provided in the treatment vessel to determine whether bed volume has changed. Upon detection of resin loss, makeup resin should be added.

5.5 Regeneration Mode

The most efficient method of regenerating a treatment bed upon completion of a treatment run is by a downflow feed of a 6% to 10% NaCl brine solution. The concentration and the amount vary with each resin. Drain steps prior to and after feed of the brine solution minimize dilution of the brine. A 6% NaCl concentration is adequate for this process. If drain steps are provided during the regeneration mode, these steps must be performed by manual operation because such steps are not included in automatic control systems.

The objective of regeneration is to remove all arsenic ions from the bed before it is returned to the treatment mode. A skilled operator might be able to reduce the concentration of the NaCl to lower than 6% with the same high efficiency performance. This lower brine concentration and lower total brine feed can reduce consumption for regeneration and wastewater for disposal. As described in Chapter 3.0, the dilution of the saturated brine takes place at an eductor in the regeneration feed piping. Both the raw water and the 26% NaCl are metered prior to mixing in the eductor in the regeneration pipe. The accuracy of the metering ranges from ±2% to ±5% depending on the type of flow measurement. If using a 6% NaCl concentration, meter readings that are high for water and low for brine result in lower than planned brine concentration and loss of regeneration efficiency.

The volume of 6% brine solution required per regeneration will vary with each resin. Therefore, the requirement should be verified with each resin manufacturer. The volume of 6% NaCl brine solution per regeneration used in the example in this manual is 20 gal/ft^3 of resin. That is based on a flowrate of 0.5 gpm/ft^3 for a period of 40 min. Once again, the designer should check with the resin manufacturer to verify the regeneration requirements. The minimum time recommended for the solution to flow through the bed is 30 min. In the example in this manual, a 4-ft-deep treatment bed with a flow of 2 gpm/ft^2 for a period of 40 min is used.

For the valve position during each step of the regeneration mode, refer to Table 5-1. The basic flow schematic for the regeneration mode is illustrated in Figure 5-2. After backwash, prior to the regeneration step, the bed should be drained to remove water that dilutes the concentration. Upon completion of the regeneration, the feed is turned off, and the brine tank refilled. Again the brine is drained to within 1 inch of the top of the treatment bed to prevent dilution of the brine.

5.6 Rinse (Slow and Fast) Mode

In the example presented in this manual, for the slow rinse, the raw water flows for 40 min at a 2 gpm/ft^2 flowrate downward through the bed, flushing out the brine and the arsenic. Some manufacturers advocate that this step should be completed in 20 min, resulting in a

smaller quantity of wastewater produced. The downflow fast rinse then takes place at the treatment flowrate for a period of time sufficient for nine bed volumes to flow through the treatment bed. Therefore, for a 4-ft bed depth and a treatment flowrate of 10 gpm/ft^2, the resulting fast rinse flow volume is 270 gal/ft^2 and the flow time required is 27 min. Some manufacturers advocate fast rinses specifying only these bed volumes. The regenerated treatment vessel should then be placed into service in the standby position. It should remain there until the treatment vessel in the operating position is removed for regeneration.

5.7 Regeneration Wastewater

A summary of the regeneration process employed in the example presented in this manual is shown in Table 5-3. As previously mentioned, the regeneration may produce less wastewater. However, because it is necessary to provide a surge tank with sufficient capacity to contain a complete batch of regeneration wastewater, it is recommended that the surge tank be conservatively oversized.

The volume of wastewater produced during the regeneration of a treatment bed will vary with the physical/chemical characteristics of the ion exchange resin. Typical volumes of wastewater generated per cubic foot of resin during each regeneration cycle are shown in Table 5-3. Operational experience at a specific treatment plant will present deviations from these quantities. A conservative rule of thumb is that 150 gal of wastewater is produced per cubic foot of resin during each regeneration.

5.8 Operator Requirements

A qualified operator for an arsenic removal water treatment plant should have thorough arsenic removal process training, preferably at an existing treatment plant. The operator should be able to service pumps, piping systems, instrumentation, and electrical accessories. The operator must be totally informed about the safety requirements and physical/chemical characteristics of pre-treatment oxidizing chemicals. Corrosive chemical safety requirements as to clothing, equipment, antidotes, and procedures should be thoroughly understood. The operator should be thoroughly trained to run routine water analyses, including the method for determining arsenic levels. The operator should be well grounded in mathematics for operation cost accounting and treatment run record keeping. The operator, above all, should be dependable and conscientious.

5.9 Laboratory Requirements

In addition to the O&M Manual, the treatment plant should have the latest edition of *Standard Methods for the Examination of Water and Wastewater* prepared jointly by the American Public Health Association (APHA), AWWA, and Water Environment Federation (WEF). This manual supplies the plant operator with all necessary information for acceptable methods for analyzing water. A recommended list of items for analysis is illustrated in Figure 3-1. The primary requirement is for accurate analysis for arsenic. As long as the pH meters are calibrated and cleaned regularly, high precision measurements are easily obtained. Care should be exercised to prevent contamination of pH buffers.

Total arsenic can be preserved effectively in field samples and analyzed by several analytical methods down to the MCL of 10 µg/L or less. Total arsenic is preserved by acidifying the sample to pH <2. The Arsenic Rule lists four U.S. EPA-approved analytical methods: inductively coupled plasma–mass spectroscopy (ICP-MS), graphite furnace atomic absorption (GFAA), stabilized temperature platform (STP) GFAA, and gaseous hydroxide atomic absorption (GHAA). These methods are U.S. EPA-approved for compliance requirements and require expensive analytical equipment that is found only at extremely large water treatment plants.

During the past few years, several companies have developed portable test kits for field analysis of arsenic. Some of these tests kits have been evaluated under the U.S. EPA Environmental Technology Verification (ETV) program by the Advanced Monitoring Systems Center managed by Battelle in partnership with U.S. EPA. These kits were tested for monitoring arsenic in the 1 to

Table 5-3. Typical Regeneration Process

Step No.	Step	Liquid	Flow Direction	Rate (gpm/ft^2 or as noted)	Time (Minutes or Bed Volume)	Wastewater (gal/ft^3)
1	Backwash	Raw water	Upflow	3-4	5-20 min	20
2[(a)]	Regeneration	6-10% NaCl	Downflow	0.5 gpm/ft^3	40 min	20
3	Slow rinse	Raw water	Downflow	2	40 min	20
4	Fast rinse	Raw water	Downflow	10	9 BV	70
					Total	130

(a) Resin manufacturer should be consulted on specific regeneration requirements.

100 µg/L range. Information on the test kits can be found on the Internet (http://epa.gov/etv/verifications/vcenter1-21.html). Although these test kits may be adequate for monitoring process performance, they are not U.S. EPA-approved methods for use in reporting MCL compliance data. For regulatory data, water samples must be analyzed by U.S. EPA/state-certified testing laboratories employing U.S. EPA-approved methods.

5.10 Operating Records

A system of records should be maintained at the treatment plant covering plant activity, plant procedures, raw water chemical analyses, plant expenditures, and inventory of materials (spare parts, tools, etc.). The plant operator should have the responsibility of managing all aspects of the treatment plant operation. The operator is accountable to the water system management. The recommended records system should include, but not be limited to, the items described in the following subsections.

5.10.1 Plant Log

A daily log should be maintained in which the plant operator records daily activities at the plant. This record should include a listing of scheduled maintenance, unscheduled maintenance, plant visitors, purchases, abnormal weather conditions, injuries, sampling for state and other regulatory agencies, etc. This record should also be used as a tool for planning future routine and special activities.

5.10.2 Operation Log

The operator should maintain a log sheet for each treatment run for each treatment unit so that a permanent plant performance record will be on file. Figure 5-4 illustrates a copy of a suggested condensed form.

5.10.3 Water Analysis Reports

If the plant operator has the ability to analyze for arsenic onsite with a field test kit, a schedule for arsenic analysis of the raw water, effluent from the lead vessel, and effluent from the second vessel should be established, with the lead vessel effluent schedule based on the estimated length of the treatment run. During the first several (3 to 5) treatment cycles, it is recommended that one or more effluent samples from the lead vessel be collected toward the end of each of the treatment cycles to confirm that the arsenic has not broken through the lead vessel and entered the second vessel. Once the operator determines that a predictable and repeatable performance pattern has developed, the number and frequency of sampling can be reduced.

The schedule for sampling the raw water and effluent from the second vessel can be less frequent than for the effluent from the lead vessel. Once-per-month total raw water sampling for analysis of arsenic, sulfate, etc. generally is adequate because most ground water does not undergo a drastic change in quality. Changes in raw water can occur, however, that may necessitate changes in the treatment process. Figure 3-1 illustrates a copy of a suggested form. A permanent file of these reports will be a valuable reference tool.

5.10.4 Plant Operating Cost Records

Using accounting forms supplied by the water system's accountants, the plant operator should keep a complete record of purchases of all spare parts, chemicals, laboratory equipment and reagents, tools, services, and other sundry items. This should be supplemented by a file of up-to-date competitive prices for items that have been purchased previously.

5.10.5 Correspondence Files

The plant operator should retain copies in chronological order of all correspondence pertaining to the treatment plant, including intradepartmental notes and memos and correspondence with other individuals and/or organizations.

5.10.6 Regulatory Agency Reports

The plant operator should maintain a complete file of copies of all reports received from state, county, or other regulatory agencies pertaining to the treatment plant.

5.10.7 Miscellaneous Forms

The operator should have an adequate supply of accident, insurance, and other miscellaneous forms.

5.11 Treatment Plant Maintenance

The maintenance concept for the arsenic removal water treatment plant is to isolate the equipment to be serviced by means of shutoff valves, vent and drain lines (as required), repair or replace equipment, fill lines, open valves, and start service. To accomplish this, all equipment items should have isolating valves, and all piping systems should have vents at high points and drains at low points. Equipment manufacturers' recommended spare parts should be stocked at the treatment plant to avoid lengthy maintenance shutdowns.

If the entire treatment plant needs to be shut down and the plant has a bypass, the plant itself can be bypassed.

ARSENIC REMOVAL WATER TREATMENT PLANT
OPERATION LOG

Unit # _____ Run # _____ Date Start _____ Date End _____

TREATMENT TO RESERVOIR
Meter End _____ Meter Start _____ Total Treated _____ k-gal

BYPASS TO RESERVOIR
Meter End _____ Meter Start _____ Total Treated _____ k-gal

BACKWASH TO WASTE
Meter End _____ Meter Start _____ Total _____ k-gal

REGENERATION TO WASTE
Meter End _____ Meter Start _____ Total _____ k-gal

SLOW RINSE TO WASTE
Meter End _____ Meter Start _____ Total _____ k-gal

FAST RINSE TO WASTE
Meter End _____ Meter Start _____ Total _____ k-gal

TOTAL WASTEWATER SUMMARY
Total to Tank _____ k-gal PERCENT WASTE _____%

TREATED WATER LOG

Date	Treatment Meter (k-gal)	Δ Meter (k-gal)	∑ Δ Meter (k-gal)	Raw As (mg/L)	Treated As (mg/L)	Δ As (mg/L)	As Removed (mg)	∑ As removed (mg)

Figure 5-4. Arsenic Removal Water Treatment Plant Operation Log

This can be done by closing the butterfly valves in the raw water and treated water line and then opening the butterfly valve in the bypass line. This would result in untreated water with excessively high arsenic being pumped to distribution, an event that should not occur without the approval of the water system manager and the regulatory agency.

5.12 Equipment Maintenance

Equipment manufacturer's maintenance instructions should be included in the "Suppliers Equipment Instructions" section of the O&M Manual.

5.13 Ion Exchange Resin Maintenance

The plant operator should inspect the surface of each treatment bed at least once a month. If the level of a bed lowers more than two inches, makeup ion exchange resin should be added after completion of a treatment run, prior to backwash and regeneration. Makeup ion exchange resin should be evenly distributed. There should be a minimum depth of 2 ft of water above the surface of the existing bed, through which the makeup ion exchange resin should be added. The vessel should be closed immediately and backwashed at 4 gpm/ft^2 for at least 20 min. It is very important to flush the fines out of the virgin ion exchange resin as soon as it is wetted.

It is important that the treatment beds should not remain in the drained condition for more than 30 min. Treatment units not in use should remain flooded.

5.14 Treatment Chemical Supply

The operator should carefully monitor the consumption of salt and liquid chemicals and reorder when necessary. The operator should have a method of determining the depth of liquid in day tanks and the brine tank and equating that to the volume of liquid in the tank.

5.15 Housekeeping

The plant operator should wash down all equipment at least once per month. Floors should be swept. Bathroom and laboratory fixtures should be cleaned once per week. All light bulbs should be replaced immediately upon failure. Emergency shower and eyewash should be tested once per week. Any chemical spill should be neutralized and cleaned up immediately. Equipment should be repainted at least once every five years.

6.0 Central Treatment Plant Operating Cost

6.1 Introduction

The prime objectives of central treatment plant design are to provide the client with a low-capital cost installation that works efficiently and reliably, is simple to operate, and is inexpensive to operate. Operating costs are normally passed directly on to the water user in the monthly water bill. These costs include the following:

1. Treatment chemical costs
2. Operating labor costs
3. Utility costs
4. Replacement ion exchange resin costs
5. Replacement parts and miscellaneous materials costs
6. Wastewater and waste solids processing and disposal costs (not included this manual).

Because the consumer's water bill normally is based on metered water consumption, the costs for treatment are prorated on the unit of volume measurement. The units of volume are usually 1,000 gal or 100 ft^3 (750 gal). The rate units employed in this design manual are ¢/1,000 gal. Some systems do not meter consumption; instead they charge a flat monthly rate based on size of branch connection to the water main. Though this latter mode of distribution saves the cost of meters as well as of reading meters, it does not promote water conservation. Therefore, more water is pumped, treated, and distributed, resulting in a net increase in operating cost.

The common denominator that applies to both the operating cost and the bill for water consumption is the unit of volume, 1,000 gal. Each operating cost factor can be reduced to cost/1,000 gal. Each of the above-mentioned operating costs is discussed in the following sections. The sum total of the annual operating costs based on total water production yields the cost per 1,000 gal (the unit cost to be applied to the consumer's bill).

6.2 Discussion of Operating Costs

Similar to capital cost, many variables affect operating cost. This manual discusses the types of operating cost variables that are evaluated during each stage of the design phase of the project and during the operation of the treatment plant. The example method employed in this manual provides the user with the ability to design the treatment system with maximum capability and minimum cost. The system includes anion exchange resin with spent resin regeneration (with manual or automatic operation).

The size of system is a variable that impacts the cost of operation. Operating labor requirements generally do not vary with the size of the system, except possibly for the very small systems. Therefore, the smaller the system, the greater the labor cost per volume of water treated. Items that influence the selection of method of operation are the feedwater arsenic concentration and the arsenic removal capacity of the ion exchange resin. The frequency of regeneration, cost of treatment chemicals, cost of ion exchange resin, cost of regeneration wastewater disposal, and cost/availability of operating personnel not only vary with geographic locations, but are also sensitive to price volatility.

The manual operation method is satisfactory for the ion exchange arsenic removal process; however, automatic operation is a common method of running ion exchange systems. Although operator skill and knowledge requirements are greater for automatic operation, there is an overall benefit and cost saving potential by not requiring operator presence during regeneration. The following subsections delve into each of the operating costs previously listed.

6.2.1 *Treatment Chemical Cost*

The treatment chemicals discussed are limited to salt and pre-treatment oxidation chemicals. Other chemicals may be required for special requirements such as pH adjustment, corrosion inhibition, precipitation of regeneration wastewater contaminants, dewatering of precipitated solids in wastewater, disinfection, etc.; however, these are site-specific requirements that are not covered in this manual.

Because the chemicals are used in the treatment of water for public consumption, it is recommended that samples of each chemical delivery be analyzed for chemical content. It also is recommended that the chemical supplier be required to certify that the containers used to store and deliver the chemicals have not been used for any other chemical; or, if they have, that they have been decontaminated according to procedures required by the governing regulatory agency. Finally, the treatment chemicals should comply with NSF/ANSI STD 60.

Chemical costs are variable. Like all commodities, they are sensitive to the supply and demand fluctuation of the marketplace. The geographic location of the treatment plant site in relation to that of the supplier has a major impact on the delivered cost. In some cases, the delivery costs are greater than the cost of the chemical. The commodity price of each chemical can vary from one region of the country to another, as well as from supply/demand marketplace forces. In the Conceptual Design, the chemical logistics should be evaluated and the most cost-effective mode of procurement should be determined.

The chemistry of the raw water to be treated is the most significant factor affecting treatment chemical consumption and cost. Sulfate is the key ingredient in the raw water; the higher the sulfate, the higher the chemical cost.

6.2.1.1 Salt Cost

The most economical method of procuring softener salt is in bulk truck quantities (48,000 pounds). The trucks are loaded at the manufacturer's/distributor's site and delivered directly to the treatment plant where the salt is transferred to a storage tank equipped with dust-containment equipment. Transfer is accomplished pneumatically by a blower on the truck (unless the treatment plant can provide compressed air). From the storage tank, the salt is conveyed or transferred to the brine tank where dissolution takes place, resulting in a 26% saturated brine solution. In addition to the lower commodity price resulting from minimum handling and storage of the salt, there is minimum chance of contamination. Alternatively, the softener salt can be procured in 50-lb bags on pallets (49 bags/pallet) for easy manual loading into the brine tank by the plant operator. For potable water service, there are stringent limits on the levels of contaminants in the salt that should be rigidly enforced.

The delivered cost of truck quantities of softener salt ranges from 3 to 6¢/lb, depending on the geographic location of the treatment plant. Similarly, pallets of bags of salt range in price from 6 to 10¢/lb.

The salt is consumed in the regeneration process as the chloride ions replace the As(V), sulfate, and other anions removed from the water during treatment. The salt consumption is a function primarily of the raw water sulfate level that dictates the frequency of regeneration and the volume of water over which this cost is distributed. The higher the sulfate level, the fewer gallons treated per regeneration.

In the example in Appendix B, the cost of the salt is 4¢/1,000 gal. The actual salt cost should normally fall in the range of 1¢ to 6¢ per 1,000 gal of treated water.

6.2.1.2 Pre-Treatment Oxidation Chemical Cost

As discussed previously, various preoxidation chemicals such as chlorine, potassium permanganate, and ozone are capable of oxidation of As(III) to As(V). This design manual does not address the preoxidation chemical selection. However, it is necessary to stress that excess preoxidation chemicals can possibly be detrimental to the ion exchange resin. If preoxidation is required, the resin manufacturer should be contacted to determine if the chemical selected has detrimental effects on the resin or the acceptable exposure concentration. If the preoxidation chemical must be removed from the source water before ion exchange treatment, removal measures must be incorporated into the design. For example, sodium hypochlorite (chlorine) can accomplish the preoxidation function. If the free chlorine remaining in solution after the oxidation of As(III) to As(V) must be removed, it can be done by a bed of granular activated carbon (GAC) that will convert the excess chlorine to chloride.

Reaction time, feedrate, shelf life, degradation characteristics, selection of compatible materials for handling/storage, etc. should be determined and incorporated into the design for the selected preoxidation chemical. The cost for the equipment and consumable chemicals is not a major factor in the total capital and operating cost for the ion exchange treatment system.

6.2.2 Operating Labor Cost

Operating labor is the most difficult cost to quantify. The operator is required to be dependable and competent; however, the position is not always a full-time one. Depending on the size of the system and other duties, the operator's time should be spread over several accounting categories. Except for days when regeneration takes place for manually operated systems, the treatment plant normally requires less than 1 hour per day of operator attention. During regeneration, operator time will be approximately 4 hours.

On routine operating days, the operator merely checks the system to see that preoxidation chemical feed (if used) is being properly controlled, takes and analyzes water samples, checks instruments (flow, temperature, pressure), and makes entries in daily logs. Exceptions to the normal routine include, but are not limited to, arsenic analyses in the treatment plant laboratory, equipment maintenance, and salt truck deliveries. During the remainder of the time, the operator should be able to operate and maintain other systems (distribution, pumps, storage, etc.), read meters, or handle other municipal responsibilities (e.g., operate sewage treatment plant).

For ion exchange treatment systems with automatic operation, the operator requires specialized skills to service the automatic instruments and controls. This class of operator may justify a higher salary. There are several other variables that can influence the rate of pay for this category of operator; and, unless these skills can be utilized for other assignments, the higher pay rate may not be justified. Another factor is the availability of outside personnel for service for the automatic instruments and controls. That variable has to be evaluated on a case-by-case basis. In this manual, an increase in salary of $2.50 per hour is utilized to illustrate the cost impact. A second operator should be available to take over in case of an emergency; that individual should be well trained in the operation of the plant.

Using the example treatment plant presented in Appendix B, the cost of operating labor will be as follows: (it is assumed that the hours not used for treatment plant operation will be efficiently used on other duties).

Given:

Flowrate	= 620 gpm
Annual average utilization	= 50%
Number of regenerations per year	= 65
Operator annual salary	= $30,000
Overhead and fringe benefits	= 30%
Available manhours per year	= 2,000/man

Then:		Manual Operation	Automatic Operation
Number of hours on regeneration/year 65 × 4 hr	=	260 hr	0 hr
Number of hours on routine operation/year (365-65) × 1	=	300 hr	365 hr
Number of hours on extra tasks 50 × 2 hr	=	100 hr	100 hr
Total plant operator time	=	660 hr	465 hr

Operator hourly rate:
$30,000/2,000 hr = $15.00/hr
30% (overhead and fringe benefits) = $ 4.50/hr
Operator rate $19.50/hr $22.00/hr

Total manual operation operator cost:
660 hr × $19.50/hr = $12,870

Total automatic operation operator cost:
465 hr × $22/hr = $10,230

Total gallons water produced:
0.5 (50% utilization) (620 gpm) × 1,440 min/day × 365 days/year = 163,000,000 gal/year

Manual operation labor cost/1,000 gal:
$12,820/163,000 (1,000 gal) = $0.08/1,000 gal

Automatic operation labor cost/1,000 gal:
$10,230/163,000 (1,000 gal) = $0.06/1,000 gal.

If the operator for the manual method had no other responsibilities and the entire salary was expended against this treatment plant operation, the operating labor cost would become $0.24/1,000 gal. For the automatic method, the operating labor cost would become $0.27/1,000 gal. Obviously, there are many variables that can be controlled in different ways. Depending on the motivation of the utility management, the operating labor cost can be minimized or expanded over a very broad range. In the case of a very high production plant, the operating labor requirement is not significantly larger than that for a very small treatment plant. Therefore, depending on relative salaries, the resulting cost can range from a few cents to more than a dollar per 1,000 gal. However, the operating labor cost should always fall in the $0.02 to $0.30/1,000-gal range.

6.2.3 Utility Cost

The utility cost is normally electric utility. However, there can also be telephone and natural gas (or oil) utility costs. Telephone service to the treatment building is

recommended as a safety precaution in case of an accident, as well as operator convenience. Cost for that service should be the minimum available monthly rate. Depending on the local climate, the cost for heating can vary. The purpose of the building is to protect the equipment from elements (primarily freezing) not for operator comfort. Normally the treatment units act as heat sinks maintaining an insulated building at a temperature near that of the raw water. In cold climates, the building should have an auxiliary heat source to prevent pipes from freezing if water is not flowing. If the client determines that the treatment building is to serve additional functions, heating to a comfort temperature could be an additional required cost.

Electric power will be needed for the following functions:

1. Chemical pumps.
2. Instrumentation and alarms.
3. Lighting.
4. Convenience receptacle.
5. Extra load or feed pump for regeneration/backwash wastewater and loss of head through the treatment system.

Electric utility rates may vary considerably from one geographic location to another. In, August 2001, rates varied from $0.03 to $0.20/KWH. The electric utility cost can range from $0.001 to $0.01 per 1,000 gal under normal conditions. Under abnormal conditions, it could be $0.02/1,000 gal or higher.

6.2.4 Replacement Ion Exchange Resin Cost

The consumption of resin due to attrition during backwash/regeneration of exhausted resin and the loss of ion exchange capacity caused by performance degradation during normal operation are the primary factors requiring the addition of fresh resin in the treatment vessels. Backwash, if conducted carelessly, can result in resin carryover. An excessive backwash rate can expand the resin by an amount that carries the resin out of the vessel, resulting in a loss of resin. Monitoring the backwash water will detect and provide protection from that occurrence. If backwash water flows into the wastewater surge tank, the lost resin can be recovered.

Another way for the ion exchange resin to be lost is through the effluent underdrain (collection system) within the bed. If ion exchange resin beads ever appear in the treated effluent, the treatment vessel should immediately be taken out of service for inspection (and repair) of the underdrain system.

A conservative bed replacement estimate is 20% per year. In the Appendix B example where two 250-ft^3 beds are used, the attrition in the polishing vessel should be zero.

The cost of replacement resin is as follows:

Cost = Number of beds × volume of resin/bed × resin cost × 20% = 2 × 250 ft^3 × $165/$ft^3$ × 0.20 = $16,500

Then, the ion exchange replacement cost = $16,500/163,000 (1,000 gal) = $0.10/1,000 gal.

SBA resin costs vary significantly with the quantity of the order, as well as other market variables including, but not limited to, geographic location, competition, etc. Per price quotations presented in Figure 4-4, the cost for truckload quantities of resin is $165/$ft^3$; quotations for less than truck quantities range up to $300/$ft^3$. For cost estimating purposes in this design manual, the $165/$ft^3$ cost is used for the largest systems and graduates up to $300/$ft^3$ for the smallest system. However, the actual cost for a given treatment plant should be negotiated on a case-by-case basis. The cost for makeup ion exchange resin should range between $0.05 to $0.20 per 1,000 gal of treated water.

6.2.5 Replacement Parts and Miscellaneous Material Costs

Parts and material are very small operational cost items. Replacement parts (e.g., pump, diaphragms, seals, and replacement pump heads) should be kept in stock in the treatment plant to prevent extended plant shutdown in the event a part is required. Also included are consumables such as chemicals, laboratory reagents (and glassware), and record keeping supplies. An operating allowance of $0.01/1,000 gal of treated water is conservative.

6.3 Operating Cost Summary

The arsenic removal water treatment plant operating costs discussed above are summarized in Table 6-1. For ion exchange arsenic removal water treatment plants in which flowrates, raw water arsenic concentration, raw water sulfate concentration, ion exchange, labor rates, and utility rates vary from the values used in the example in Appendix B, the operating costs will deviate from those indicated in Table 6-1.

Table 6-1. Operating Cost Tabulation[a]

Operating Cost Items Flowrate: 620 gpm	Dollars/1,000 gal Treated Water	
	Manual Operation ($)	Automatic Operation ($)
Treatment Chemicals	0.04[b]	0.04[b]
Operating Labor	0.08	0.06
Utility	0.01	0.01
Replacement Ion Exchange Resin	0.15	0.15
Replacement Part and Misc. Material	0.02	0.02
TOTAL	0.30	0.28

(a) Wastewater and waste solids, processing and disposal not included.

(b) Cost to oxidize As(III) to As(V) not included.

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Appendix A

Summary of Subsystem Including Components

The items that are designated as "optional" are not mandatory requirements. Some of those items may already be included in systems other than treatment, and therefore would be redundant. Other items, though desirable, are not mandatory. Automatic and semiautomatic operation is optional. Therefore, for each instrument and control item, though not indicated for clarity, there is an automatic option.

For Schematic Flow Diagram, see Figure A-1.

1. Raw Water Influent Main
   a. Flow control
   b. Flowrate measurement, flow total
   c. Preoxidation chemical injection for oxidation of As(III) to As(V)
   d. Excess preoxidation chemical removal
   e. Pressure indicators
   f. Pressure control (optional)
   g. Backflow preventer
   h. Sample before preoxidation chemical injection piped to sample panel
   i. Sample after preoxidation chemical injection piped to sample panel
   j. Sample after excess preoxidation chemical removal piped to sample panel
   k. Isolation valve
   l. Temperature indicator

2. Intervessel Pipe Manifold
   a. Process control valves
   b. Pressure indicator
   c. Sample piped to sample panel (optional)
   d. pH sensor, conductor, alarm
   e. Vessel 2 bypass valve

3. Treated Water Effluent Main
   a. Process control valves
   b. Chemical injection for pH adjustment(optional)
   c. pH measurement, indicator, alarm and fail-safe control
   d. Sample after pH adjustment piped to sample panel
   e. Pressure indicator
   f. Booster or repressurization pump (optional)
   g. Disinfection injection (optional)
   h. Isolation valve

4. Raw Water Bypass Main (optional)
   a. Flow control
   b. Flowrate measurement, flow total
   c. Backflow preventer
   d. Isolation valve

5. Backwash/Regeneration Feed Manifold
   a. Process control valves
   b. Isolation valves
   c. Backflow preventers
   d. Flow controls
   e. Flowrate measurements, flow totals
   f. Brine tank
   g. Brine eductor
   h. Brine injectors
   i. Pressure indicators
   j. Backflow preventors
   k. Sample brine eductor piped to sample manifold

6. Wastewater Main
   a. Process control valves
   b. Backflow preventers
   c. Process isolation valves
   d. Sight glass
   e. Sample piped to sample panel

7. Treatment Vessels
   a. Pressure vessel
   b. Treatment media
   c. Internal distribution and collection piping
   d. Pressure relief valve
   e. Air/vacuum valve
   f. Operating platform and/or ladder (optional)

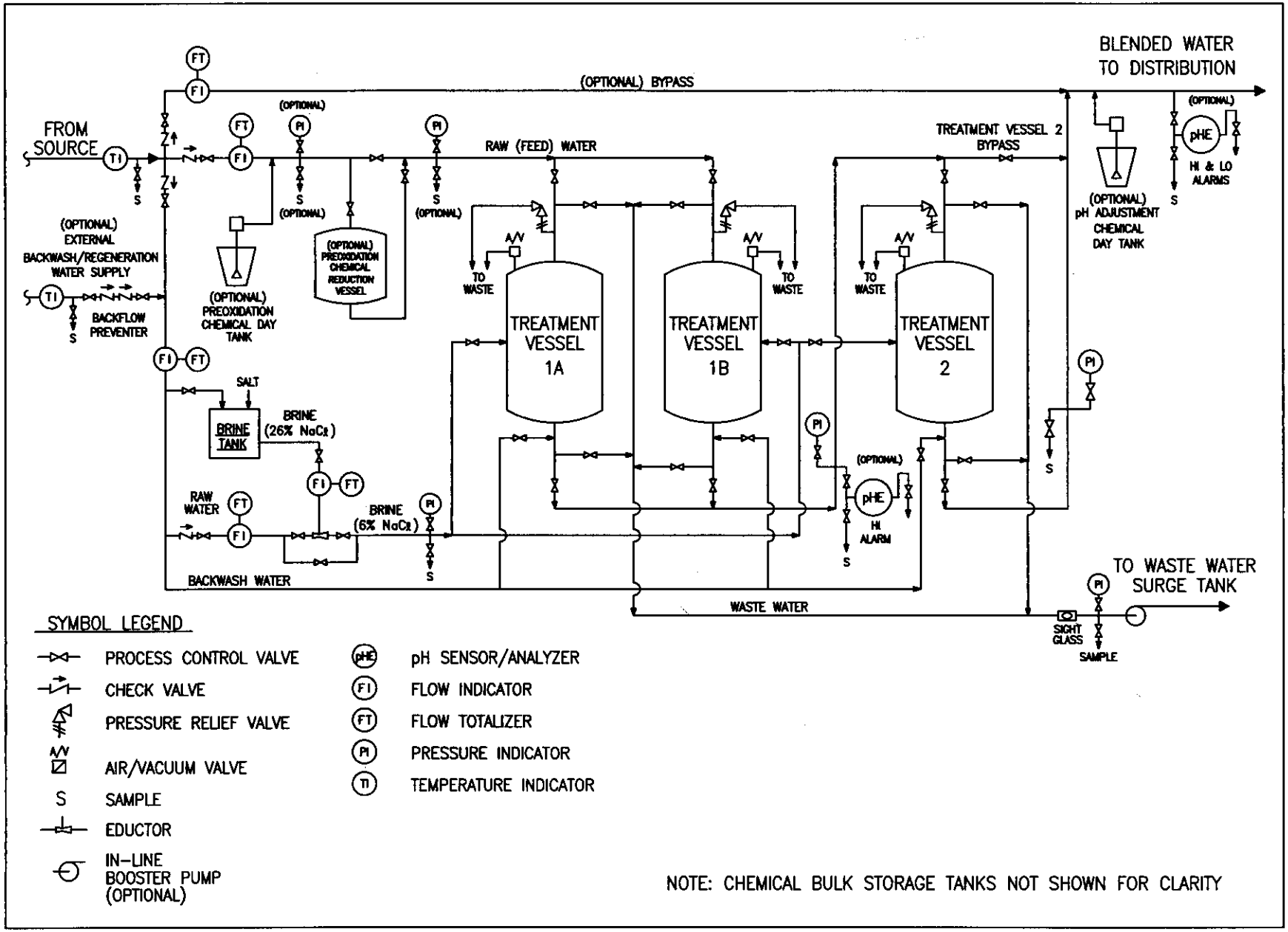

Figure A-1. Ion Exchange Treatment System Flow Diagram

8. Sample Panel (optional)
   a. Sample tubing from sample points with shut off valves
   b. Wet chemistry laboratory bench with equipment, glassware, reagents, etc.

9. Softener Salt Storage and Feed Subsystem
   a. Emergency shower and eyewash
   b. Softener salt storage tank (optional)
      i. Fill, discharge, and vent
      ii. Level sensor (optional)
      iii. Dust collection in vent
      iv. Weather protection
   c. Brine tank
      i. Water fill pipe with float valve
      ii. Softener salt feed pipe (optional)
      iii. Drain valve
      iv. Containment basin

10. Preoxidation Chemical Storage and Feed Subsystem (optional)
    a. Emergency shower and eye wash
    b. Preoxidation chemical storage tank outside treatment building (optional)
       i. Fill, discharge, drain, vent, and overflow piping
       ii. Liquid level sensor (optional)
       iii. Immersion heater with temperature control
       iv. Weather protection
       v. Containment basin (optional)
    c. Preoxidation chemical day tank (inside treatment building)
       i. Fill line float valve
       ii. Drain valve
       iii. Containment basin (optional)
    d. Preoxidation chemical piping (interconnecting piping)
       i. Between storage tank and day tank
       ii. Between feed pump and, feedwater main injection point
       iii. Backflow prevention

11. Backwash Water Disposal System (optional)
    a. Surge tank (optional)
    b. Unlined evaporation pond (optional)
    c. Sewer (optional)
    d. Drainage ditch (optional)
    e. Other discharge method (optional)

12. Toxic Regeneration Wastewater Disposal System
    a. Surge tank (optional)
    b. Wastewater reclamation system (optional)
    c. Other discharge method (optional)

Appendix B

Treatment System Design Example

This design example is applicable to a specific manually operated ion exchange arsenic removal water treatment system. This example is applicable to any of the following combinations of options:

1. Adjustment of EBCT
2. Adjustment of flowrate
3. Adjustment of arsenic concentration
4. Adjustment of raw water chemical analysis
5. Automatic operation in lieu of manual operation

Given:
q (flowrate) = 620 gpm
N (number of treatment trains) = 1
n (number of treatment vessels) = 3 (1A, 1B and 2)
Treatment vessel designations
1A - Primary Stage - (operating)
1B - Primary Stage - (standby)
2 - Second Stage - (polishing)
Raw water arsenic concentration = 0.100 mg/L (0.002 meq/L)
Raw water sulfate concentration = 34 mg/L (0.68 meq/L)
Arsenic MCL = 0.010 mg/L
Treated water arsenic design concentration = 0.008 mg/L (max)
SBA resin manufacturer's published capacity = 1.016 eq/L (22,222 grains as $CaCO_3/ft^3$ or 50,930 g/m^3)
SBA resin removal capacity† = 0.915 eq/L (20,000 grains as $CaCO_3/ft^3$ or 45,838 g/m^3)
Salt consumption rate per regeneration = 10 lb/ft^3
EBCT = 3 min
M_d (media density) = 42 lb/ft^3
h(treatment bed depth) = 4 ft
$M_w = M_d \times V$ (media volume/vessel) × n (number of treatment vessels)
Treatment flowrate = 10 gpm/ft^2
Backwash flowrate = 4 gpm/ft^2
Brine flowrate = ½ gpm/ft^2
Pipe material - Type I Schedule 80 PVC, v (pipe velocity) = 5 ft/second (max.)
p (system pressure): 50 psig (max.)
T (ambient temperature): 95°F (max.)
T_w (water temperature): 85°F (max.)

† 90% of manufacturer's theoretical capacity.

1. Vessel and Treatment Bed Design (reference: Figure 3-3)

Solve for: d (treatment bed diameter)
V (treatment bed volume)
M_w (total weight of treatment media)
D (vessel outside diameter)
H (vessel overall height)

When EBCT = 3 min, then flowrate = 2½ gpm/ft^3 media

Then, when q = 620 gpm; then

$$V = \frac{620\ gpm}{2.5\ gpm/ft^3} = 248\ ft^3$$

Then, when h = 4 ft,

$$A = \frac{V}{h} = \frac{248\ ft^3}{4\ ft} = 62\ ft^2$$

Then,

$$d^2 = \frac{4A}{\pi} = \frac{4 \times 62\ ft^2}{\pi} = 78.94\ ft^2$$

Then, d = 8.89′ = 8′ 10½″

Then, D = d + 1″ = 8′ 11½″, therefore use D = 9′ 0″

Then,

$$V = \frac{(8.92)^2 \times 5\pi}{4} = 250 \text{ ft}^3$$

Then, $M_w = 3 \times 250 \text{ ft}^3 \times 42 \text{ lb/ft}^3 = 31{,}500 \text{ lb}$

Because the media quantity is almost a 40,000-lb truckload, it is prudent to procure a truckload quantity. That will provide an initial supply of makeup media.

Then the treatment vessel dimensions are as follows:

$$H = h + 0.9h + 4'' + (2)D/4 + 1'' =$$

$$48'' + 44'' + 4'' + 2\left(\frac{108''}{4}\right) + 1'' = 151'' = 13'\ 1''$$

2. Pipe Sizing

Solve for: Sizes for water pipe mains

a. Raw and treated water mains:

q = 620 gpm (max)
Try 6", v = 7.0 ft/sec › 5 ft/sec, therefore NG
Try 8", v = 4.0 ft/sec › 5 ft/sec, therefore OK
Use 8" Schedule 80 PVC

b. Backwash pipe main:

$q = 4 \text{ gpm/ft}^2 \times 62 \text{ ft}^2 = 248 \text{ gpm}$
Try 4", v = 6.2 ft/sec, therefore NG
Try 6", v = 2.8 ft/sec, therefore OK
Use 6" Schedule 80 PVC

c. Brine (6% NaCl) pipe main:

$q = 2 \text{ gpm/ft}^2 \times 62 \text{ ft}^2 = 124 \text{ gpm}$
Try 3", v = 5.3 ft/sec, slightly over 5 ft/sec - However low pressure, therefore OK
Use 3" Schedule 80 PVC

d. Concentrated brine (26% NaCl) pipe main

$q = 0.2 \times 2 \text{ gpm/ft}^2 \times 62 \text{ ft}^2 = 25 \text{ gpm}$
Try 1½", v = 4.0 ft/sec, therefore OK
Use 1½" Schedule 80 PVC

Note: During backwash of one treatment bed, the flowrate shall not exceed 250 gpm. Backwash rate is not to exceed rate required for 100% treatment bed expansion. This rate is sensitive to raw water temperature.

3. Softener Salt System Design

a. Storage Tank Size

Storage tank size is based on logistical requirements which are a function of treatment plant salt consumption rate and tank truck deliveries of granular softener salt. The tank truck can deliver up to 48,000 lb of softener salt.

In this example, the design treatment flow is 620 gpm, and it is assumed that the salt consumption is 1.33 lb/1,000 gal treated water. Then the salt consumption is 50 lb/hr, and a truckload would supply a minimum of 960 hours of treatment operation.

A commercially available "brinemaker" includes storage capacity for 72,000 lb, which provides capacity for 1½ bulk tank truckloads of salt. Therefore, when half a truckload is consumed, there is a minimum of a 450-hour (18.75-day) salt storage available before the salt supply is exhausted. In practice, it could be two times that minimum. The 36-ton storage capacity will easily maintain operation while awaiting delivery.

b. Day Tank Size

The "brinemaker" includes brine production (26% NaCl @ 40 gpm). A 1,200-gal brine day tank will satisfy the NaCl requirement for 1,875,000 gal of treated water, which exceeds the treatment flow for two days.

4. Regeneration Wastewater Surge Tank Design

Given:
Maximum volume of regeneration wastewater per cubic foot media = 150 gal/ft^3
Number of cubic feet of media per regeneration = 250 ft^3
Tank construction - epoxy interior lined carbon steel

Find:
Volume of wastewater per regeneration = 150 gal/ft^3 × 250 ft^3 = 37,500 gal = 5,000 ft^3
Dimensions of surge tank (use height = 16 ft)

Then,

$$(\text{diameter})^2 = \frac{4 \times 5{,}000 \text{ ft}^3}{\pi\, 16 \text{ ft}} = 398 \text{ ft}^2$$

Then, diameter = 20 ft

Then, tank dimensions = 20′ ϕ × 16′ h

Preferred Containment Basin Dimensions: length 40′, width 35′, height 4′, volume = 5,600 ft^3 = 42,000 gal >37,500 gal

5. Annual Regeneration Requirements

To appropriately plan operational labor, cost, and wastewater disposal requirements, the treatment system design shall determine the number of treatment vessel regenerations that will be required per year. Due to variation in seasonal demand for treated water, treatment cycle frequency increases during high consumption and decreases during low consumption periods. As described earlier in this manual, the treatment system is designed to treat at least 125% of the maximum consumption day. During low consumption periods the treated water requirement might be one third (or less) of the maximum consumption day. For purposes of this example, it is determined that the annual average utilization is 50%. Therefore, the treatment plant shall produce treated water 50% of the time on an annual basis.

Then, number of treatment vessel regenerations/ year equals:

$$\frac{q\,(gpm) \times 1{,}440\,(min/day) \times 365\,(day/year) \times \text{average utilization} \times (As + SO_4)\,(mg/L)}{V\,(ft^3) \times 90\%\ \text{removal capacity}\,(gr/gal) \times 17.1\,(mg/L)/(gr/gal)}$$

$$\frac{620\,(gpm) \times 1{,}440\,(min/day) \times 365\,(day/year) \times 0.50 \times 34.1\,(mg/L)}{250\ ft^3 \times 20{,}000\,(gr/gal) \times 17.1\,(mg/L)/(gr/gal)} = 65$$

or calculated using meq/L units:

$$\frac{q\,(gpm) \times 3{,}785\,(L/gal) \times 1{,}440\,(min/day) \times 365\,(day/year) \times \text{average utilization} \times (As + SO_4)\,(meq/L)}{V\,(ft^3) \times 28.3\,(L/ft^3) \times 90\%\ \text{removal capacity}\,(eq/L) \times 1{,}000\,(meq/eq)}$$

$$\frac{620\ gpm \times 3{,}785\,(L/gal) \times 1{,}440\,(min/day) \times 365\,(day/year) \times 0.50 \times 0.682\,(meq/L)}{250\,(ft^3) \times 28.3\,(L/ft^3) \times 0.915\,(eq/L) \times 1{,}000\,(meq/eq)} = 65$$

These calculations do not include any regeneration of the second stage treatment vessel. Any regenerations required of the second stage treatment vessel are in addition to the regeneration count of the first stage treatment vessel.

Appendix C

Tabulations of Estimated Capital Cost Breakdowns for Arsenic Removal Water Treatment Plants by Means of the Ion Exchange Process at Typical and Ideal Locations

Contents

C-1. Tabulation of Estimated Capital Cost Breakdowns for Central Arsenic Removal Water Treatment Plants at Typical Locations by Means of the Ion Exchange Process with Manual Operation

C-2. Tabulation of Estimated Capital Cost Breakdowns for Central Arsenic Removal Water Treatment Plants at Typical Locations by Means of the Ion Exchange Process with Automatic Operation

C-3. Tabulation of Estimated Capital Cost Breakdowns for Central Arsenic Removal Water Treatment Plants at Ideal Locations by Means of the Ion Exchange Process with Manual Operation

C-4. Tabulation of Estimated Capital Cost Breakdowns for Central Arsenic Removal Water Treatment Plants at Ideal Locations by Means of the Ion Exchange Process with Automatic Operation

Table C-1. Tabulation of Estimated Capital Cost[a] Breakdowns for Central Arsenic Removal Water Treatment Plants at Typical Locations by Means of the Ion Exchange Process with Manual Operation (Multiply by $1,000)

Treatment Flowrate (gpm)		65	115	230	330	480	555	620	700
Process Equipment									
Treatment Vessels		41	47	55	63	87	95	99	104
Ion Exchange Resin		22	37	62	79	96	117	127	138
Process Piping, etc.		17	17	32	34	34	41	45	45
Instruments and Controls		8	8	10	11	11	12	12	12
Salt and Brine Storage		3	3	5	5	5	20	20	20
	Subtotal	91	112	164	192	233	285	303	319
Process Equipment Installation									
Mechanical		28	29	34	36	36	44	45	45
Electrical		7	7	8	9	9	10	10	10
Painting and Miscellaneous		6	8	11	12	12	14	14	14
	Subtotal	41	43	53	57	57	68	69	69
Misc. Installed Items									
Wastewater Surge Tank		14	16	22	34	46	60	67	74
Building and Concrete		41	53	53	64	64	74	74	74
Site Work and Miscellaneous		12	13	14	16	16	17	17	17
	Subtotal	67	82	89	114	126	151	158	165
Contingency 10%		20	24	31	36	42	50	53	55
	Total	219	261	337	399	458	554	583	608

(a) August 2001 prices.
Note: Engineering, exterior utility pipe and conduit, wastewater and waste solids processing system, finance charges, real estate cost and taxes not included.

Table C-2. Tabulation of Estimated Capital Cost[a] Breakdowns for Central Arsenic Removal Water Treatment Plants at Typical Locations by Means of the Ion Exchange Process with Automatic Operation (Multiply by $1,000)

Treatment Flowrate (gpm)		65	115	230	330	480	555	620	700
Process Equipment									
Treatment Vessels		44	47	55	63	87	95	99	104
Ion Exchange Resin		22	37	62	79	96	117	127	138
Process Piping, etc.		42	43	70	74	74	82	88	88
Instruments and Controls		57	60	68	72	72	73	73	73
Salt and Brine Storage		3	4	5	5	5	20	20	20
	Subtotal	168	191	260	293	334	387	407	423
Process Equipment Installation									
Mechanical		31	32	37	40	40	49	50	50
Electrical		29	30	32	33	35	40	40	40
Painting and Miscellaneous		7	8	11	12	12	14	14	14
	Subtotal	67	70	80	85	87	103	104	104
Misc. Installed Items									
Wastewater Surge Tank		14	16	22	34	46	60	67	74
Building and Concrete		41	53	53	64	64	74	74	74
Site Work and Miscellaneous		12	13	14	15	16	17	17	17
	Subtotal	67	82	89	113	126	151	158	165
Contingency 10%		30	34	43	49	55	64	67	67
	Total	332	377	472	540	602	705	736	761

(a) August 2001 prices.
Note: Engineering, exterior utility pipe and conduit, wastewater and waste solids processing system, finance charges, real estate cost and taxes not included.

Table C-3. Tabulation of Estimated Capital Cost[a] Breakdowns for Central Arsenic Removal Water Treatment Plants at Ideal Locations by Means of the Ion Exchange Process with Manual Operation (Multiply by $1,000)

Treatment Flowrate (gpm)		65	115	230	330	480	555	620	700
Process Equipment									
Treatment Vessels		41	47	55	63	87	95	99	104
Ion Exchange Resin		22	37	62	79	96	117	127	138
Process Piping, etc.		17	17	32	34	34	41	45	45
Instruments and Controls		8	8	10	11	11	12	12	12
Salt and Brine Storage		3	3	5	5	5	6	6	6
	Subtotal	91	112	164	192	233	271	289	305
Process Equipment Installation									
Mechanical		25	26	31	33	33	41	42	43
Electrical		3	3	4	5	5	6	6	6
Painting and Miscellaneous		5	6	7	10	10	12	12	12
	Subtotal	33	35	42	48	48	59	60	61
Misc. Installed Items									
Wastewater Surge Tank		0	0	0	0	0	0	0	0
Building and Concrete		4	4	5	5	5	6	6	6
Site Work and Miscellaneous		0	0	0	0	0	0	0	0
	Subtotal	4	4	5	5	5	6	6	6
Contingency 10%		13	15	21	25	29	34	36	37
	Total	141	166	232	270	315	370	391	409

(a) August 2001 prices.
Note: Engineering, exterior utility pipe and conduit, wastewater and waste solids processing system, finance charges, real estate cost and taxes not included.

Table C-4. Tabulation of Estimated Capital Cost[a] Breakdowns for Central Arsenic Removal Water Treatment Plants at Ideal Locations by Means of the Ion Exchange Process with Automatic Operation (Multiply by $1,000)

Treatment Flowrate (gpm)		65	115	230	330	480	555	620	700
Process Equipment									
Treatment Vessels		41	47	55	63	87	95	99	104
Ion Exchange Resin		22	37	62	79	96	117	127	138
Process Piping, etc.		42	43	72	74	74	82	88	88
Instruments and Controls		57	60	68	72	72	73	73	73
Salt and Brine Storage		3	4	5	5	5	6	6	6
	Subtotal	165	191	262	293	334	373	393	409
Process Equipment Installation									
Mechanical		31	32	37	40	40	49	50	50
Electrical		34	35	37	38	40	45	45	45
Painting and Miscellaneous		5	6	7	10	10	12	12	12
	Subtotal	70	73	81	88	90	106	107	107
Misc. Installed Items									
Wastewater Surge Tank		0	0	0	0	0	0	0	0
Building and Concrete		4	4	5	5	5	6	6	6
Site Work and Miscellaneous		0	0	0	0	0	0	0	0
	Subtotal	4	4	5	5	5	6	6	6
Contingency 10%		24	27	35	39	43	49	51	52
	Total	263	295	383	425	472	534	557	574

(a) August 2001 prices.
Note: Engineering, exterior utility pipe and conduit, wastewater and waste solids processing system, finance charges, real estate cost and taxes not included.

Appendix D

English to Metric Conversion Table

English	Multiply by	Metric
inches (in)	0.0254	meter (m)
square inches (in^2)	0.000645	m^2
cubic inches (in^3)	0.000016	m^3
feet (ft)	0.3048	m
square feet (ft^2)	0.0929	m^2
cubic feet (ft^3)	0.0283	m^3
cubic feet (ft^3)	28.3	liters (L)
cubic feet (ft^3)	7.48	gal
equivalents/liter (eq/L)	21.8	Kgrains as $CaCO_3/ft^3$
gallons (gal)	3.785	liters (L)
gallons (gal)	0.0038	kiloliter (kL)
gallons (gal)	0.0038	m^3
grains (gr)	64.8	mg
grains (gr)	0.0649	grams (g)
grains/ft^3	2.2919	g/m^3
Kgrains as $CaCO_3/ft^3$	0.0458	eq/L
pounds (lb)	0.4545	kilograms (kg)
lb/in^2 (psi)	0.00689	megapascals (MP)
lb/ft^2 (psf)	4.8922	kg/m^2
c/1,000 (gal)	0.2642	c/1,000 L

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