Feasibility of Water Treatment Technologies for Arsenic and Fluoride Removal from Groundwater

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ABSTRACT

The revised arsenic maximum contaminant level (MCL) of 0.010 mg/L is expected to impact many water utility systems, particularly those in western states, where high levels of naturally-occurring arsenic are more common. An Army installation was faced with treating groundwater (GW) to reduce arsenic and fluoride concentrations. Various water treatment technologies were evaluated based on engineering, economic, and regulatory criteria. Water conservation and source water quality issues also impacted treatment technology selection. Ultimately, activated alumina was deemed most feasible, and will be pilot tested to verify arsenic and fluoride removal efficiencies and to develop full-scale design data.

INTRODUCTION

Contaminant Overview

<u>Arsenic</u>. Arsenic is a common, naturally-occurring drinking water contaminant that originates from arsenic-containing rocks and soil, and is transported to natural waters via erosion, dissolution and air emission. Man-made sources of arsenic in the environment include mining and smelting operations; agricultural applications; and the use of industrial products and disposal of wastes containing arsenic. Ingestion of arsenic can result in both cancerous and non-cancerous effects. Large arsenic doses (above 60 mg/L) can cause death, with lower doses (0.30-30 mg/L) causing stomach and intestinal irritation and nervous system disorders (reference 1). Arsenic occurs in both organic and inorganic forms; however, the inorganic form is more prevalent in water and considered more toxic. The Environmental Protection Agency (EPA) has established arsenic as a Class A human carcinogen, with low arsenic exposure (< 0.05 mg/L) linked to cancer of the skin, liver, lung and bladder (reference 2).

<u>Fluoride</u>. Fluoride compounds are contained in minerals, particularly fluorspar (also called fluorite) and apatite (mixture containing calcium fluorides), and are found in most parts of the world, with large deposits in the United States (reference 3). Groundwater contacting fluoride-containing minerals will release fluoride ions, thus fluoride is found naturally in all waters. Typical GW concentrations range from trace to greater than 5 mg/L, with deeper GW generally having higher fluoride concentrations (reference 3). Drinking water fluoride concentrations greater than 4 mg/L can cause bone disease in adults and tooth mottling (discoloring) in children; however, moderate fluoride levels (0.7 to 1.2 mg/L, temperature-

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dependent) in drinking water are beneficial to children during the time they are developing permanent teeth.

Regulatory Overview

Arsenic. The EPA published the Arsenic Rule on January 22, 2001, which established the arsenic MCL at 0.010 mg/L (10 µg/L). The Rule was effective March 23, 2001, and becomes enforceable on January 23, 2006. The California State MCL mirrors the current 0.05 mg/L and future 0.010 mg/L Federal arsenic standards. However, California's Office of Environmental Health Hazard Assessment (OEHHA) may establish a more stringent arsenic MCL, possibly as low as 2 to 5 µg/L (references 4,5,6).

Fluoride. The Federal MCL for fluoride is 4 mg/L; however, California's OEHHA set a more stringent MCL of 2 mg/L. The Federal National Secondary Drinking Water Regulation (NSDWR) (non-enforceable) fluoride limit is also 2 mg/L (references 4,5,6).

PROJECT BACKGROUND

Location

The project located at Fort Irwin, California, located approximately 35 miles northeast of Barstow, California, in the north-central part of the Mojave Desert. The installation was faced with treating their GW to reduce naturally-occurring concentrations of arsenic and fluoride. Due to the desert environment, prudent water resource management is critical to the installation's future sustainability. Thus, process water losses were a critical factor in treatment technology selection.

Source Water

Fort Irwin employs eleven (11) GW wells from three distinct geologic basins (Irwin, Bicycle, and Langford) for source water. Bicycle and Langford Lake wellheads are connected to booster stations, where the water is chlorinated (sodium hypochorite) prior to pumping to the cantonment area. Irwin Basin well water is chlorinated at the wellhead. Only a fraction of the source water is currently treated through an existing reverse osmosis (RO) water treatment plant (WTP); most water feeds the domestic distribution system. Fort Irwin monthly water demand fluctuates based on troop rotations, non-training periods, and seasonal irrigation. The Bicycle Lake Basin is currently the predominant water source, with Langford Lake and Irwin Basins supplementing contributors (ranging from 10-50% of the total). The peak monthly water demand for 2002-2003 was 145 million gallons, corresponding to 4.7 million gallons per day (MGD).

Consumptive Use

Fort Irwin uses two separate distribution systems for potable and domestic water. The potable system delivers product water from the RO WTP for drinking water only (one tap at each household or office area), while the domestic system delivers chlorinated well water for all other uses, such as bathing, irrigation, toilet flushing, etc. In clarifying the definition of a Public Water System as part of the 1996 SDWA amendments, the EPA published guidance in 1998 that broadened the definition of "consumptive use" to more than just drinking (reference 7). The final definition, as stated in the U.S. District Court case U.S. v. Midway Heights (1988) was: "…human consumption includes drinking, bathing, showering, cooking, dishwashing, and maintaining oral hygiene". Under this definition, all consumptive use water on Fort Irwin, not just the RO-treated potable portion, would need to meet SDWA requirements, including compliance with arsenic and fluoride MCLs. Since most Fort Irwin source water contains naturally-occurring arsenic and/or fluoride above their respective MCLs, the domestic distribution system water is non-compliant with SDWA requirements, based on the Federal consumptive use definition. The new treatment strategy will require replacement of the existing dual-line (domestic and potable) water distribution system with a single-line system (potable water only), and significantly increase treated water demand from 0.15 to 5.0 million gallons per day (MGD), necessitating construction of a new WTP. The existing domestic lines can be converted to convey potable water after proper flushing and disinfection procedures are performed.

Existing Treatment

The primary purpose of the RO plant was to reduce naturally-occurring fluoride concentrations in the raw water. The plant includes granular activated carbon filters (chlorine removal for membrane protection), multimedia filtration, polishing filtration, four parallel RO units, air stripping and calcite media beds (pH adjustment), sodium hypochlorite chlorination, and raw water blending for fluoride optimization. The RO unit removes nearly all raw water fluoride; therefore, some domestic system water is blended in to achieve the desirable concentration for dental benefit. Current RO WTP production capacity is 150,000 gallons per day (gpd), with approximately 60% product water and 40% brine. The brine wastestream (about 40 gpm) is piped to a wet well that is plumbed to the sanitary sewer. Increasing WTP water production from 0.15 to 5.0 MGD may preclude brine wastestream discharge into the sanitary sewer, depending on treatment technique wastestream volumes and characteristics [affecting wastewater treatment plant (WWTP) hydraulic loading and biological treatment processes].

TREATMENT TECHNOLOGY ANALYSIS

Non-treatment and Blending Strategies

Non-Treatment. The installation's multiple source water wells provide the opportunity for treatment avoidance techniques. Here, contributions of targeted source water wells are either eliminated or combined (blended) such that the product water entering the distribution system meets the arsenic and fluoride MCLs. Treatment avoidance can only work if one (or more) of the water sources has arsenic and fluoride concentrations below the MCLs. Problematic water sources (prohibitively high fluoride and/or arsenic levels) may be simply abandoned in favor of other sources. Alternatively, multiple water sources may be blended to produce a stream with a fluoride and arsenic concentration below the MCLs. Based on the source water analytical data, abandonment and/or blending of source water wells cannot, by itself, achieve fluoride and arsenic MCL compliance. Therefore, Fort Irwin source water will require treatment.

Side-stream Treatment. Sidestream treatment involves treating only a portion of the source water, so that subsequent blending with the untreated portion produces finished water that meets fluoride and arsenic MCLs. Sidestream treatment and blending techniques are used to reduce the amount of water requiring treatment (decreasing the design flow). The reduction in the amount of water that requires treatment will depend on the source water arsenic (As)/fluoride (F) concentrations and the treatment technique efficiency. The sidestream flowrate requiring treatment can be calculated based on a simple mass balance equation shown below (note that the equation for RO is more complex to account for continuous water loss). Based on the existing data, between 10-20% of raw source water may be blended with treated water, reducing WTP design hydraulic loading. Final blending percentages will be calculated based on pilot-scale results of treatment removal efficiencies.

$$Q_{SS} = Q_1 \left(\frac{C_{As/F,1} - (1-\sigma)C_{MCL}}{\varepsilon \, C_{As/F,1}} \right) \quad \text{(reference 2)}$$

Where:
Qss = Flowrate for sidestream receiving treatment (gpm);
Q_1 = Source flowrate, total WTP influent flow (gpm);
$C_{As/F,1}$ = Source arsenic/fluoride concentration (mg/L);
C_{MCL} = Arsenic/fluoride MCL, (mg/L);
ε = Arsenic/fluoride rejection rate (% expressed as decimal);
σ = Margin of safety (% expressed as decimal, typically 20%)

Water Quality Goals

The State of California requires treatment technology designs to achieve 80% of the contaminant MCL. Thus, the treatment goals for arsenic and fluoride are 0.0080 mg/L and 1.6 mg/L, respectively. However, the CDHS specifies fluoride control ranges based on average daily air temperature, and may require a finished water fluoride concentration below the 1.6 mg/L goal. Federal and California Secondary MCLs were adopted to address the aesthetic qualities of drinking water, which may impact consumer acceptance. Different treatment techniques will remove varying amounts of secondary constituents. For example, precipitative processes, such as coagulation/microfiltration (C/MF) will coincidentally remove many secondary contaminants, such as total dissolved solids (TDS), iron and sulfates, while the activated alumina (AA) technology will primarily remove only fluoride, arsenic and sulfate, allowing TDS, iron and other constituents to pass through. Thus, some treatment technologies may provide additional benefit in terms of overall water quality.

Treatment Technique Review

EPA-established Best Available Technologies (BATs) for fluoride removal include AA and RO (reference 8), both of which are also included in the seven listed BATs for arsenic removal [coagulation/microfiltration (C/MF), ion exchange (IX), lime softening, electrodialysis reversal (EDR), and oxidation/filtration complete the list (reference 4)]. Table 1 compares the AA, RO and EDR co-removal (both fluoride and arsenic) treatment techniques; other potential treatment techniques that target primarily arsenic are also included. Activated alumina's effectiveness in removing both fluoride and arsenic has been documented in past studies (reference 9), and proven at full-scale, comparable facilities.

Source Water Considerations

General. Source water characteristics significantly affect arsenic and fluoride treatment alternative selection. Therefore, source water sampling was conducted to adequately characterize the source water and to augment historical sampling data.

Arsenic Speciation. Soluble, inorganic arsenic exists in either trivalent [As(III)] or pentavalent [As(V)] forms, depending on surrounding oxidation-reduction conditions. Arsenic(V), which has a net negative charge, is much more easily treated (removed) than As(III), which has a neutral charge, particularly for adsorptive treatment technologies (reference 2). Therefore, determination of arsenic species is critical, as source water containing predominantly As(III) may need pretreatment (oxidation) for conversion to As(V). Speciation was performed onsite using specially-prepared kits that allowed the As(III) to be isolated by running a filtered sample through a resin column [removing As(V)]. The field speciation was employed because there is no reliable method of preserving the arsenic speciation (preventing inter-conversion) during transport to the laboratory.

Arsenic and Fluoride. Source water arsenic and fluoride concentrations are summarized in Table 2. The sampling confirmed source water fluoride concentrations above the 2.0 mg/L MCL. Most source water arsenic concentrations were below the current 50 μg/L MCL, but above the future 10 μg/L MCL. Most arsenic was already in the As(V) form, and will likely not require pretreatment. Bicycle Lake source water generally contained lower fluoride levels, but higher arsenic concentrations. Conversely, Langford Lake Basin contained lower arsenic, but high fluoride concentrations. Irwin Basin source water had the poorest water quality, containing the highest fluoride and arsenic concentrations among the basins.

Table 1. Treatment Technology Comparison. (reference 2)

Co-removal BATs	**Removal Efficiency**		**Water Loss**	**Optimal Conditions**	**Operator Skill**
	As[1]	**F**			
Activated Alumina	95%	85-95%	1-2%	pH 5.5-8.3 (decreased efficiency at high pH); < 360 mg/L SO_4; < 1,000 mg/L TDS; < 250 mg/L Cl, < 0.5 mg/L Fe; < 0.05 mg/L Mn; < 4 mg/L TOC; < 30 mg/L Silica; < 0.3 NTU Turbidity;	Low
Reverse Osmosis	> 95%	85-95%	40-60%[2]	< 30 mg/L silica for <15% water loss; (per RO manufacturers) No particulates.	Medium
Other Treatment Technologies	**Removal Efficiency**		**Water Loss**	**Optimal Conditions**	**Operator Skill**
	As[1]	**F**			
Electrodialysis Reversal	> 95%	85-95%[3]	20-30%[3]	Treats most waters without preference; Process efficiency not affected by silica; Most economical for TDS of 3,000-5,000 mg/L;	Medium
Coagulation/ Micro-Filtration	90%	NS	5%	pH 5.5-8.5	High
Iron Based Sorbents	up to 98%	No	1-2%	pH 6-8.5 (decreased efficiency at high pH); < 1 mg/L PO_4; < 0.3 NTU Turbidity;	Low
Ion Exchange	95%	No	1-2%	pH 6.5-9 (decreased efficiency at high pH); < 50 mg/L SO_4; < 500 mg/L TDS; < 5 mg/L NO_3, < 0.3 NTU Turbidity;	High
Point of use/Point of entry Devices	95%	Vary	Vary	Scaled down versions of IX, AA, RO processes.	Low

SO_4 - sulfate; TOC - total organic carbon; PO_4 - phosphate; NO_3 - nitrate; TDS - total dissolved solids; Cl - chloride; Fe - iron; Mn - manganese;

[1] - based on removal of As(V);

[2]- specific to Fort Irwin WTP, general RO process water losses are 15-75%;

[3]- per manufacturer; USEPA guidance believes EDR to be uneconomical for most water treatment applications (reference 4);

NS - not studied, fluoride removal questionable due to low molecular weight of soluble complexes.

Table 2. Source Water Fluoride and Arsenic Concentration Ranges.

	Parameter			
	Fluoride (mg/L)	**Arsenic (µg/L)**		
		Total	**As(III)**	**As(V)**
Source Water Aquifer	**Range**	**Range**		
Bicycle Lake	**1.1 to 4.5**	**< 2.0 to 30.3**	**<10%**	**≥ 90%**
Langford Lake	**4.4 to 9.9**	**7.9 to 15.8**	**< 1%**	**≥ 99%**
Irwin	**8.0 to 10.6**	**32.2 to 40.1**	**< 5%**	**≥ 95%**
California State MCL	**2.0**	**Current: 50 µg/L; Future: 10 µg/L**		

TDS/pH. Source water TDS concentrations ranged from 450 to 650 mg/L. These levels may interfere with IX (< 500 mg/L optimal), but should not hinder AA or RO/EDR processes (< 1,000 mg/L optimal). Source water pH ranged from 7.6 to 8.5, and would require pH adjustment to 5.5 to 6.0 for optimal AA and IX efficiency.

Sulfate/Silica. All source water contained sulfate concentrations above 100 mg/L. High sulfate concentrations (above 50 mg/L) interfere with some adsorptive arsenic treatment techniques, particularly IX (reference 2). However, AA can treat source water sulfate concentrations up to 360 mg/L. High silica concentrations (above 30 mg/L), found primarily in Bicycle Lake and Irwin Basin wells, can interfere with both adsorptive and membrane processes. In particular, a silica concentration of 75 mg/L will limit RO water recovery to about 60%, so pretreatment for silica removal may be needed. Note that EDR is not affected by silica concentrations.

Water Loss

Treatment technique water losses will have a significant effect on the installation's future sustainability, particularly at the 5 MGD design flow. Thus, adsorption and precipitative processes would have less impact on source water stores than membrane process (see Table 1). Note that RO manufacturers claim lower water losses of 15-25% using latest membrane technology and two-pass RO treatment trains, though efficiency is highly source water-specific. Fort Irwin source water silica concentrations will limit single-pass RO water recovery to about 60%. The EDR system is not limited by silica, and would have an estimated 70% single-pass water recovery (per manufacturer). Second and third pass RO/EDR systems to treat the brine waste may increase the overall water recovery to about 90% (at significant increases in cost).

Waste Generation

Wastestreams. Adsorptive processes (AA and IX) will produce both acid (pH adjustment) and caustic (media regeneration) wastestreams. The C/MF backwash discharges will contain high solids, if solids are not treated onsite. Reverse osmosis and EDR will produce potentially large volumes of concentrated brine discharges (reference 2). These wastestreams cannot be directly discharged into the environment, but must either be treated onsite or indirectly discharged to the WWTP. Direct wastestream discharge to evaporation ponds is not acceptable due to water conservation concerns (100% water loss). Indirect discharge of wastestreams to the WWTP is a better option (if low enough in volume), since a portion of this water will serve as GW recharge. However, WWTP operators should be consulted to discuss potential impacts on hydraulic loading/biological processes. A third direct discharge option is a novel precipitation/spray irrigation system employed at the 29 Palms AA plant, CA. Here, spent regeneration solution, comprising the main wastestream, is discharged to a clarifier, where calcium chloride is added to form insoluble fluoride compounds. Clarified water is used to irrigate surrounding salt-bush vegetation, providing natural uptake of TDS while recharging GW. Dewatered sludge from the clarifier is nonhazardous and disposed of in a sanitary landfill. Finally, a vapor compression/crystallizer evaporation (VC/CE) process would provide a true zero-discharge wastestream treatment. The high capital cost and increased operation and maintenance of the VC/CE processes must be weighed against the added water recovery benefits (in terms of water source sustainability).

Sludge. The C/MF filter backwash water will contain a dilute ferric chloride [$Fe(Cl)_3$] precipitate that is typically gravity thickened and dewatered prior to landfill disposal. The AA caustic regeneration solution may also be treated via precipitation, settled, and then dewatered, with subsequent sludge landfill disposal. The RO brine discharge can be treated via precipitation (producing silica-compound sludge) before entering a second RO unit for increased water recovery. The EDR system would employ a similar sequential treatment to further concentrate the brine waste stream and reduce water loss. Regardless of the selected process, the final sludge/spent media must pass both Toxicity Characteristic Leaching Procedure (TCLP) and the more stringent California Waste Extraction Test (WET) for disposal in a non-hazardous (sanitary) landfill. Sludge/media that exceed the TCLP or WET are classified as hazardous wastes and must be disposed of in a hazardous waste landfill. Note that the WET, unlike the TCLP, includes criteria for fluoride salts. Sludges must also be dewatered (no free liquids) and pass the paint filter test to be landfilled.

FINDINGS AND DISCUSSION

Activated Alumina

General. Activated alumina is a porous, granular material that uses ion exchange properties to remove contaminants from a liquid stream. Activated alumina preferentially removes ions, that is, the media will adsorb some contaminants before adsorbing others. Activated alumina has the following ion selectivity sequence (reference 2):

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

Activated alumina removal efficiency is highly pH dependent, with optimal removal at pH 5.5-6.5, thus source water pretreatment with hydrochloric acid may be required. As the selectivity sequence shows, AA will adsorb arsenate [As(V)] more efficiently than arsenite [As(III)]. AA is also a BAT for fluoride removal (85-95% efficiency). The AA media can either be regenerated or disposed of and replaced with fresh media. Regeneration using caustic solution typically produces a waste solution high in TDS, aluminum, and soluble arsenic/fluoride concentrations, and may impact the WWTP if indirectly discharged. Alternatively, throwaway media can be used that is not likely to exceed Federal TCLP or State WET criteria, and can be disposed of in a municipal solid waste (nonhazardous) landfill (reference 2). The full scale AA design would be based on site-specific, pilot-scale tests to determine media adsorption capacities and media regeneration rates. Frequent regeneration may preclude the use of single-use, throw-away media.

Design. The AA treatment train should include two vessels in series, as this configuration has been previously shown effective in treating arsenic and fluoride-laden waters (reference 9). It is expected that arsenic would be removed in the first vessel, with subsequent fluoride removal in the second. The high source water fluoride concentrations will likely necessitate regular media regeneration using a caustic solution. The frequent need for media regeneration would make throw away media use cost prohibitive. Blending of the source water with the AA product water is assumed for re-fluoridation, thereby reducing WTP hydraulic loading by about 10-20%. A preliminary design, developed for cost estimating purposes, is summarized below (reference 10). The following was also assumed for design:

- Q (flowrate) = 5.0 MGD = 464 ft^3/min;
- Empty Bed Contact Time (EBCT) = 5 minutes;
- AA Bed depth (h) = 3 to 6 ft;
- Maximum vessel diameter (D) = 10 ft;
- As removal capacity = 1,375 g/m^3;
- Media density = 45 lb/ft^3

$$EBCT = \frac{V_{MEDIA}}{Q}; \quad \text{therefore,} \quad V_{MEDIA} = Q \times EBCT$$

$$V_{MEDIA} = 464\frac{ft^3}{\min} \times 5 \min = 2{,}300\ ft^3$$

Assume bed depth h = 5 ft, and vessel D = 10 ft,

Then volume of each vessel: $V_{VESSEL} \approx \frac{\pi D^2}{4} \times h = \frac{\pi (10)^2}{4} \times 5 = 392\ ft^3$

Number of vessels (N) needed: $N \approx \frac{V_{MEDIA}}{V_{VESSEL}} = \frac{2{,}300\ ft^3}{392\ ft^3} = 6$

Assume two vessels per treatment train (in series), with one redundant treatment train:

$$N = 6 + 6 + 2 = 14\ vessels\ .$$

Assume total vessel height (H) equals:

$$H = h \times (1.5) = 5\,ft \times 1.5 = 7.5\,ft = 8\,ft\,(freeboard\ and\ structure\ design)$$

Vessel capital cost is related to the total volume:

$$V_{TOTAL\,VESSEL} = \frac{\pi D^2}{4} \times H = \frac{\pi (10)^2}{4} \times 8 = 628\,ft^3 = 4{,}697\,gal$$

Therefore, vessel capital cost is:

$$C_{VESSEL} = 63.288 \times (V_{TOTAL\,VESSEL})^{(0.679)} = \$19{,}700 \times 14\,vessels = \$275{,}800\text{; (ref. 11)}$$

b. Media costs:

$$C_{MEDIA} = \frac{\$0.82}{lb} \times 45\frac{lb}{ft^3} \times 392\frac{ft^3}{Vessel} \times 14\,vessels = \$200{,}000\text{; (ref. 11)}$$

Comparable Facility.

A full-scale, comparable facility was contacted to assess the feasibility of the AA technology. The 29 Palms WTP, located in the Hi-Desert Water District in Yucca Valley, CA, uses AA columns to treat a design flow of 3 MGD, with an average flow of 1 MGD. It is designed to remove primarily fluoride, with coincidental arsenic removal. Ground water source concentrations are 5-7 mg/L fluoride, < 5 µg/L arsenic, and 250 mg/L TDS.

Raw water pH is acid-adjusted to 6.0 prior to the AA vessels. The media is regenerated using caustic solution, with the spent solution discharged to a clarifier, where calcium chloride is added to form fluoride precipitates. Solids are thickening and processed onsite using a filter press, with the sludge cake sent to a sanitary (non-hazardous) landfill. Clarified water is used to irrigate surrounding salt-bush vegetation, providing natural uptake of TDS in the water while recharging GW levels. The WTP uses blending techniques, bypassing about 25% of the raw water for subsequent blending with AA-treated water prior to chlorination. Total water loss through the AA process was estimated at 3%. The plant, which came online in March 2003, cost \$4.2M, including 90% plant automation. Personnel indicated that adsorption capacities increased from pilot to full scale operation, indicating that removal efficiencies may increase with larger systems.

Reverse Osmosis and Electrodialysis

General. Reverse osmosis is a membrane technology that uses pressure to force water through a semi-permeable membrane, thereby removing dissolved solutes from solution based on particle size, dielectric characteristics, and hydrophilic/hydrophobic tendencies (reference 2). RO can be used as a stand-alone treatment for most source waters, with over 97% and 92% removal of As (V) and As (III), respectively. Reverse Osmosis will also retain fluoride molecules, and is listed as a fluoride removal BAT (reference 8). RO membranes are subject to fouling (particularly with silica-containing waters), and can also act as media for microbiological growth (reference 2). Thus, RO water is typically pretreated for particle removal. Reverse osmosis systems produce concentrated brine discharges (retantate) that must be either treated onsite or indirectly discharged to a WWTP. Reverse osmosis systems may have significant water loss, typically between 35 and 65%, and would adversely impact aquifer stores and water conservation measures. Multiple pass RO systems can enhance water recovery, but at a substantial increase in capital costs.

Electrodialysis (ED) is a membrane process similar to RO, except that ED uses an applied d.c. potential (electric current), instead of pressure, to separate ionic contaminants from water. Because water does not physically pass through the membrane in the ED process, particulate matter is not removed. Thus, ED membranes are not technically considered filters. In EDR, the polarity of the electrodes is periodically reversed on a prescribed time cycle, thus changing the direction of ion movement, in order to reduce scaling and eliminate the need for chemical conditioning. The basic EDR unit consists of several hundred cell pairs bound together with electrodes on the outside and referred to as a membrane stack. Feedwater passes simultaneously through the cells to provide a continuous, parallel flow of desalted product water and brine that emerge from the stack. The single pass EDR system units typically have 20-30% water loss; sequential EDR systems to treat brackish waste streams can reduce overall water loss to 90%, or even 95% (with associated added capital and O&M costs). The EDR process product water quality is comparable to RO, and may require post-treatment stabilization. The EDR process is often used in treating brackish water to make it suitable for drinking, and tends to be most economical for source water TDS levels in excess of 4,000 mg/L (reference 12).

Design. The RO plant design would be similar to the current system, but designed to treat the entire water demand (5 MGD). RO membrane water loss is based primarily on silica concentrations. As dissolved silica concentrations build up in the retantate, silica precipitates begin to form, which foul the membrane surface. Thus, higher source water silica concentrations will foul the membrane quicker, resulting in increased water loss. Generally, influent silica concentrations below 30 mg/L result in less than 15% water loss through RO membranes, whereas a silica concentration of 75 mg/L will produce about 40% water loss. Enhanced water recoveries can be realized by treating the brine wastestream through a precipitation/sedimentation process (removing the silica), followed by a second, smaller RO system (significantly increase capital and O&M costs). Fort Irwin source water contains silica concentrations between 30 to 160 mg/L, with highest concentrations in the Bicycle Lake and Irwin Basins. The EDR system is not affected by silica, but would still need a multi-stage system to meet water conservation goals. Blending of the source water with the product water is assumed for re-fluoridation, thereby reducing WTP hydraulic loading by about 10-20%.

Planning-level capital and O&M costs were obtained from manufacturers, based on source water data and a 5.0 MGD design flow. A two-pass RO design was assumed to provide up to 80-85% water recovery (source water dependent). The second RO system would require upstream precipitation of silica (including reactor and sludge processing facilities), significantly increasing capital and O&M costs. A two-pass EDR design was also assumed, with budget capital costs obtained from manufacturers.

Coagulation/filtration

General. Coagulation/filtration is a common water treatment used to remove suspended and dissolved solids from source water. Aluminum sulfate (alum) or iron salts, such as ferric chloride, are rapidly mixed with the water to destabilize the solids to form flocs that can be subsequently removed via sedimentation and/or filtration. Coagulation assisted microfiltration (C/MF) uses pressure, in lieu of gravity, for filtration, and provides easier process control and a smaller treatment footprint. Coagulation/microfiltration is not a BAT for fluoride removal, however, a pilot scale C/MF process was tested, and reduced source water fluoride levels from 8 mg/L to 2 mg/L. Nevertheless, a full-scale C/MF system would not provide standalone treatment, and would require a polishing process for both fluoride and arsenic removal (AA or RO). The C/MF process would provide additional benefit in terms of water quality through reduction of sulfates, chlorides, TDS and other secondary contaminants that affect aesthetic qualities.

Design. C/MF is listed in EPA references as an arsenic removal technology, and so was chosen over granular media filtration processes (gravity and direct filtration) for design purposes. The molecular weight cutoff of MF typically necessitates the use of coagulants to generate arsenic and/or fluoride-laden floc that can be retained by the membrane (reference 2). Pilot-scale testing should be used to determine relative benefits of coagulant addition prior to filtration. The C/MF is not a stand-alone treatment for arsenic and fluoride removal, but provides pretreatment prior to either RO or AA. The C/MF process will coincidentally remove a wide range of water constituents along with arsenic and fluoride, potentially enhancing overall water quality. The C/MF process would also lower arsenic and fluoride loading to downstream RO or AA systems, thereby increasing process efficiencies and decreasing media exhaustion rates. However, its high capital and O&M costs may overshadow its pretreatment value.

Treatment Technology Screening

General. Each treatment alternative was screened against seven relevant criteria. Except for cost, all criteria were qualitative, and rated on a scale of 1 to 7 (7 being best, and 1 being worst). Criteria scores were then summed to derive an overall alternatives ranking, with the highest scoring alternative being the preferred choice. Criteria were weighted (2:1) toward regulatory compliance, water conservation and cost.

Cost. Table 3 summarizes estimated costs for full-scale facilities. The treatment technology cost estimates were developed based on EPA models/guidance manuals for arsenic removal (reference 11), and supplemented by vendor information. These estimates represent planning-level costs, generated for general comparison of treatment technologies; full-scale cost estimates should be refined following pilot-scale studies.

Results. Table 4 summarizes the treatment options. Based on screening criteria, the recommended alternative is Alternative #2 - AA. This option is the least expensive, allows for blending opportunities, and is a proven BAT for arsenic and fluoride removal. Additionally, its use has been proven successful at comparable facilities. Pilot-scale tests should be run to determine AA media exhaustion rates and the need for pH/solids pretreatment. If pilot-scale testing shows AA interferences/non-attainment of fluoride or arsenic MCLs, C/MF pretreatment may be required (Alternative #4a). Finally, RO/EDR (Alternatives #3 and #4b) should be chosen if the source water proves difficult to treat, and membrane water losses can be minimized.

Table 3. Summary of Alternative Costs

TREATMENT ALTERNATIVE	COST ($) Capital	COST ($) O&M/yr	ADVANTAGES	DISADVANTAGES
ALTERNATIVE #1: STATUS QUO - Maintain current operations, including separate domestic and potable water systems.	0	155,000	No capital expenditure; Same labor requirements; Familiarity with system.	WTP unable to treat total water demand; Non-compliance with F/As MCL and Permit conditions; EPA/State NOVs and fines likely; Human health/soldier readiness risk; Adverse public perception.
ALTERNATIVE #2: ACTIVATED ALUMINA - Construct AA columns at central location; - Pre and post treatment (pH/filtration) likely needed; - Blending used to decrease hydraulic loading; - Periodic regeneration/disposal of spent media.	4.3M*	455,000	EPA-listed BAT for both F and As; Low water loss (typically 3-5%); Low energy consumption; Proven effective at comparable facility; Operations can be manual or automated; Sludge typically non-hazardous; Positive public perception.	Source water pH adjustment to 6.5 needed for optimal performance; Spent regeneration solution contains high F, As, aluminum, and TDS concentrations; Chemical and sludge handling facilities needed; Efficiency dependent on source water characteristics (sulfate, silica and TDS); Unfamiliar with AA system.
ALTERNATIVE #3: REVERSE OSMOSIS/ELECTRODIALYSIS - Construct membrane units at central location; - Pre and post treatment (filtration, conditioning chemicals, pH/alkalinity adjustment), as needed; - Blending used to decrease hydraulic loading; - Multiple pass design may minimize water loss.	RO 15.0M EDR 13.0M	RO 1.35M EDR 950,000	RO is EPA-listed BAT for both F and As; Familiarity with membrane separation system; Will treat current (F/As) and possible future contaminants of concern; Positive public perception.	High water loss (20-40%) due to high source water silica concentrations (for RO); High energy consumption; High treatment technology capital costs; Pre- (filtration) and post- (pH/alkalinity adjustment) treatment may be needed; Chemical handling facilities needed; Multiple systems needed to achieve water conservation goals (<5% water loss); Skilled operator required.
ALTERNATIVE #4: COAGULATION MICRO-FILTRATION TREATMENT TRAIN - Construct C/MF units at central location; - AA or RO polishing needed for fluoride removal.	AA 24.7M RO 35.6M	AA 530,000 RO 1.43M	Co-removal of other constituents may improve overall water quality; Low water loss (5%); Positive public perception.	Not a stand-alone As/F treatment - polishing needed for F removal; Large footprint and capital investment; Chemical/sludge handling facilities needed; Added chemical and O&M costs; Skilled operator needed for coagulant dosing; Unfamiliar with C/MF system.

* - Site-specific cost factors would increase the AA capital cost to approximately $7.6M, per Fort Irwin Directorate of Public Works.

Table 4. Alternatives Screening Summary.

		Treatment Alternatives				
Criteria	Wght	#1 STATUS QUO	#2 AA ADSORPTION	#3 RO/ EDR	#4 C/MF TREATMENT TRAIN	
					#4a C/MF - AA	#4b C/MF - RO
Regulatory Compliance	.2	1 (0.2)	6 (1.2)	7 (1.4)	6 (1.2)	7 (1.4)
Water Conservation	.2	6 (1.2)	6 (1.2)	2 (0.4)	6 (1.2)	2 (0.4)
Cost	.2	1* (0.2)	6 (1.2)	3 (0.6)	3 (0.6)	1 (0.1)
Implementation	.1	1 (0.1)	5 (0.5)	4 (0.4)	5 (0.5)	4 (0.4)
Production Capacity	.1	1 (0.1)	5 (0.5)	4 (0.4)	5 (0.5)	4 (0.4)
Public Perception and Acceptance	.1	1 (0.1)	5 (0.5)	5 (0.5)	6 (0.6)	6 (0.6)
Occupational & Environmental	.1	4 (0.4)	3 (0.3)	3 (0.3)	3 (0.3)	3 (0.3)
Raw Score	49	15	36	28	34	27
Weighted Score	**(7)**	**(2.3)**	**(5.4)**	**(4.0)**	**(4.9)**	**(3.6)**

* - based on potential non-compliance penalties.

CONCLUSIONS

Fort Irwin source water wells contain fluoride concentrations above the State MCL of 2.0 mg/L and arsenic concentrations that exceeded the future MCL of 0.010 mg/L at most source water wells. The installation must provide drinking water for human consumption that meets all SDWA requirements. Consequently, the existing dual-line (domestic and potable) water distribution system must be replaced with a single-line system (potable water only), and the WTP design flow will increase from 0.15 to 5.0 MGD. Additionally, extensive distribution system infrastructure modifications will be needed to convey potable water from the new WTP to onpost customers.

The water treatment alternatives considered included activated alumina, reverse osmosis, and electrodialysis. Coagulation/microfiltration was also considered as part of an overall treatment train. Ultimately, activated alumina was selected as the preferred treatment alternative, based on engineering, economic and regulatory criteria. However, pilot-plant studies must be conducted to verify AA effectiveness and to quantify media adsorption capacities. Concurrent pilot-plant study of RO and EDR may be prudent, in case AA proves ineffective. Treatment technology wastestreams must either be treated onsite or indirectly discharged to the WWTP. Pilot-plant water loss data, along with wastestream characteristics and water conservation goals, will drive the final wastestream management strategy.

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