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MEMORANDUM

April 5, 2006

TO: DIVISION OF THE COMMISSION CLERK AND ADMINISTRATIVE SERVICES

FROM: OFFICE OF THE GENERAL COUNSEL (MELSON) RDM

RE: DOCKET NO. 050018-WU

Attached are three documents that should be placed in the docket file in Docket No. 050018-WU:

1. Evaulation of alternative technologies for control of hydrogen sulfide from groundwater sources in the Seven Springs Service Area (August 2005).

2. Letter dated December 21, 2005, from Rose, Sundstrom & Bentley attaching a non-binding conceptual capital cost estimate.

3. Letter dated February 20, 2006, from James S. Taylor attaching a Review of Conceptual Cost for Incorporation of Ion Exchange into AU Existing Water Treatment Facilities.

These are documents that were made available to the parties during the negotiation of the Settlement Agreement and that are referred to either in the Settlement Agreement or the order approving that agreement.

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Attachment

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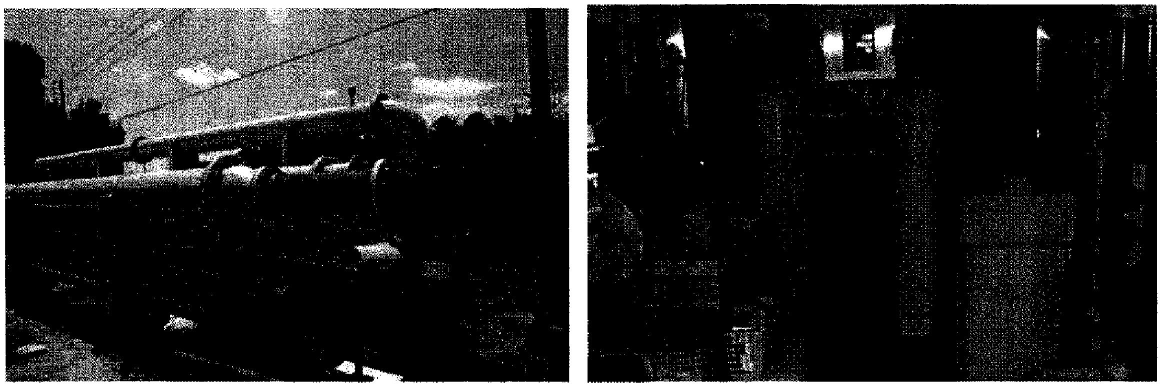
Evaluation of alternative technologies for control of hydrogen sulfide from groundwater sources in the Seven Springs Service Area



Submitted to

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August 2005

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Evaluation of alternative technologies for control of hydrogen sulfide from groundwater sources in the Seven Springs Service Area

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EXECUTIVE SUMMARY

The Seven Springs Water System of Aloha Utilities is located in a rapidly developing residential community southeast of New Port Richey, FL. The service area consists of single family homes, apartment and townhouse complexes, commercial areas, schools, and business parks. The source water, derived from 8 wells distributed through the service area, is treated at individual well-sites and supplied to about 12,000 service connections. Prior to 2005, water treatment facilities at each of the eight well sites consisted of pumps, chemical feed facilities for corrosion control, chlorinators, and reaction tanks with an average production of about 3 million gallons per day (MGD). Under typical operating conditions, the pumps at each treatment system do not operate continuously, but cycle on and off in response to pressure demands within the system. The ability to store treated water within the existing system is limited to hydropneumatic tanks at the well sites with a combined effective volume of 27,500 gallons and a 500,000 gallon ground storage tank that provides supplemental storage.

During 2005, Aloha Utilities implemented significant treatment upgrades at each of its treatment facilities in the Seven Springs system. To date, upgrades include: replacement of gaseous chlorine with liquid chlorine (sodium hypochlorite) as a primary disinfectant, relocation of treatment facilities for two of the smaller treatment systems (wells 3 and 4) to the ground storage facility, and installation of on-line process controls in conjunction with telemetry for remote monitoring of system operation. In the near future, the use of chloramination will be implemented for secondary disinfection. In addition, water from the Seven Springs system will be supplemented with treated water from Pasco County Utilities to help meet the growing demands within the service area.

While the treatment upgrades have had positive impacts on system operations and alleviated safety concerns associated with on-site storage of gaseous chlorine, additional upgrades are desired to address water quality issues related to control of hydrogen sulfide. In light of the upcoming conversion to the use of chloramines as a secondary disinfectant, it is particularly important that treatment technologies for controlling hydrogen sulfide are compatible with existing and planned treatment approaches for disinfection. It is also important that the water produced by the selected treatment alternative is not corrosive to the water distribution system and residential plumbing.

Control of hydrogen sulfide can be accomplished by removal or conversion technologies. Removal technologies have a strong advantage in that they decrease the total mass of sulfur within the system, reducing the possibility for sulfide reformation. Conversion technologies act to chemically modify the hydrogen sulfide to a more stable form. Treatment technologies that are capable of removing hydrogen sulfide include aeration, anion exchange, and oxidation coupled with filtration. As an alternative to removal technologies, oxidation technologies can be used to convert hydrogen sulfide to sulfate or other oxidized forms of sulfur.

Selection of an appropriate hydrogen sulfide control technology for the Seven Springs water system should consider multiple factors including water quality, site constraints, operational issues, and cost. Water quality considerations that impact process selection include the concentration of hydrogen sulfide, pH, alkalinity, turbidity, and the ability to meet regulatory requirements mandated under the Safe Drinking Water Act (SDWA) including primary and secondary drinking water standards, the lead and copper rule (LCR), total coliform rule (TCR), and the disinfection/disinfection byproducts rule (D/DBP). Site constraints include the area available for implementation of new equipment and the proximity of residential neighborhoods to the treatment facilities. Operational issues relate to the compatibility of the technology with the existing treatment and pumping infrastructure including the on/off operation of the high service pumps and the lack of supplemental storage. Safety issues include chemical management practices such as chemical delivery, on-site chemical storage, security, provisions for containment of chemical spills, etc.

Historically, the Seven Springs water system has been in compliance with all Federal and State drinking water requirements. In 2003, the Florida Department of Environmental Protection (FDEP) implemented a new rule pertaining to hydrogen sulfide removal under Chapter 62-555.315(5). This rule applies to the permitting process for new or altered wells in community water systems. While Aloha Utilities is not directly impacted by this new rule, it provides a context for evaluating treatment options for control of hydrogen sulfide. If the rule were applicable to the Seven Springs water system, it would recommend either forced-draft aeration with pH control or an alternative technology that is equally effective for the majority of the wells.

Project Overview

This study was conducted to develop field data on alternative hydrogen sulfide control technologies that are appropriate for use at individual well sites within the Seven Springs water system. Water quality testing was conducted to quantify variability among the individual wells with an emphasis on parameters that impact the effectiveness of various treatment technologies including hydrogen sulfide, pH, alkalinity, turbidity, organic carbon, and the distribution of dominant minerals.

Several candidate technologies for control of hydrogen sulfide in the Seven Springs water system were evaluated. The technologies were selected based on feasibility, practicability, reliability, and implementability. A key consideration was the permittability of each technology by FDEP. Cost analyses were not conducted as part of this project. The technologies evaluated included forced-draft aeration with pH control, fixed-bed anion exchange, and alternative oxidation technologies. Because aeration is widely used for groundwater treatment, the permitting process is likely to be fairly routine. Several successful installations of fixed-bed anion exchange have been permitted within the State of Florida, therefore, the permitting process should be relatively straight-forward. Oxidation technologies are widely practiced in potable water treatment and the pilot-scale data generated through this project will facilitate the permitting process.

Bench-scale screening tests were conducted of aeration and oxidation technologies to evaluate reaction rates, pH control options, chemical dosages, water quality changes associated with treatment, and to determine if follow-up pilot testing was warranted. Pilot-scale tests were conducted using a one gallon per minute (gpm) pilot plant to assess treatment effectiveness.

Key findings

A comprehensive review of sulfide control technologies was conducted in this project through literature surveys, bench-scale testing, and field testing. Control of hydrogen sulfide can be accomplished through removal technologies such as aeration or anion exchange or conversion technologies such as oxidation. All of the technologies evaluated in this project are capable of controlling hydrogen sulfide, however, there are differences among the technologies in terms of their impact on treated water quality and their overall feasibility for implementation in the Seven Springs water system. There are also operational differences that influence process selection.

Aeration is widely used as a hydrogen sulfide control technology and it works by providing concurrent removal and oxidation. Nonionized hydrogen sulfide can be removed through air stripping and the remaining sulfides are oxidized by a combination of oxygen and downstream chemical treatment (i.e. chlorination). The effectiveness and efficiency of aeration for control of hydrogen sulfide is dependent on the effective pH in the aeration tower, the method of introduction of air (natural draft or forced draft), air-to-water ratio (tray tower or packed tower), and system design. For the Seven Springs water system, chemicals (carbon dioxide and/or mineral acids) would need to be added upstream to reduce the pH of the water prior to aeration. To ensure effective removal through air stripping, the air would need to be supplied using blowers (forced-draft) and a packed tower would be needed to provide an adequate air-to-water ratio. On-site odor control (scrubbers) would be needed to contain the odorous off-gases generated by the air stripping process. Following aeration, the pH and alkalinity would need to be re-adjusted. In addition to removal of nonionized hydrogen sulfide (30 to 90% of the total hydrogen sulfide, depending on pH), the supplemental oxygen provided by aeration serves to convert the residual hydrogen sulfide to elemental sulfur or sulfate, oxidize iron and other reduced minerals, and increase the dissolved oxygen levels in the treated water. Minimal removal of other constituents occurs through aeration and there is potential for biological growth to occur within the aeration tower. Following aeration, supplemental pumps would be needed to repressurize the water in the Seven Springs water system.

Fixed-bed anion exchange involves passing water through a column-reactor containing anion exchange resin. Negatively charged constituents (anions) attach to the resin in exchange for chloride. The system is operated in-line and the operation of the system relatively straight-forward. Once the resin is saturated with anions, it needs to be regenerated using a salt solution. Anion exchange is highly effective for removal of ionized forms of sulfur including hydrogen sulfide, polysulfides, and sulfates. Anion exchange is also effective for reduction of dissolved organic carbon, other dissolved anions, and negatively charged particles.

Oxidation technology is essentially an in-pipe treatment that involves the introduction of oxidant chemicals into the water. The oxidant chemicals serve to convert the hydrogen sulfide to more oxidized forms of sulfur including elemental sulfur and sulfate. Oxidants that were tested in this project include hydrogen peroxide, ultraviolet irradiation (UV), and chlorine. Control of oxidation involves management of chemical dosages and oxidation pH. Oxidation provides for conversion of hydrogen sulfide to a more stable form of sulfur, but does not provide for removal, thus there is potential for hydrogen sulfide reformation or reversion.

A comparison of water quality impacts associated with aeration, anion exchange, and oxidation is given in Table ES-1. The individual technologies were ranked in terms of water quality, operations, design and site considerations, and feasibility for the Seven Springs system. The overall ranking (excluding cost analysis) was:

1. Fixed-bed anion exchange,
2. Centralized aeration (forced-draft-packed-tower with pH control), and
3. Oxidation

Based on the evaluation conducted in this project and the history of water quality concerns associated with the Seven Springs water system, the use of a technology that removes sulfide is preferred over technologies that convert sulfides, if the costs are reasonable. In light of the results from ranking the hydrogen sulfide control technologies in this project, fixed-bed anion exchange (highest ranking) and centralized forced-draft-packed-tower aeration with pH control (second highest ranking) are the available treatment options that warrant further consideration for the Seven Springs System.

The use of fixed-bed anion exchange has compelling advantages over the other technologies evaluated for several reasons:

- Multiple forms of sulfur are removed providing a mechanism for reducing the total mass of sulfur in the treated water and minimizing the potential for sulfide reformation in residential plumbing.
- Organic carbon levels are reduced, thereby alleviating concerns associated with disinfection byproduct formation if free chlorine is to be used for disinfection or if the chloraminated system is to be periodically treated by free chlorine as part of system-wide "chlorine burn" procedures.
- There is no mechanism for generation of turbidity within the anion exchange system. In addition, there is potential for removal of negatively charged colloidal particles through anion exchange, resulting in a net decrease in turbidity.

While the use of aeration is widely promoted throughout the State of Florida, it does not have the water quality and operational advantages associated with packed-bed anion exchange. In addition, it is impractical to implement aeration systems at the existing Seven Springs treatment sites due to several constraints including: space limitations, the likelihood of generating nuisance odors and noise that would impact adjacent residential neighborhoods, the on/off cycling of pumps at each well site, and the need for supplemental pumping to repressurize the system. If forced-draft-packed-tower aeration is to be adopted for the Seven Springs system, it is suggested that a centralized facility be designed to overcome the limitations associated with direct treatment at the well-sites. However, it is important that a location suitable for centralized treatment is identified if this option is to be further considered.

Table ES-1. Comparison of water quality impacts of hydrogen sulfide control technologies.

Water Quality Parameter	Forced-Draft-Packed-Tower Aeration with pH control	Fixed-bed Anion Exchange	Oxidation
Sulfide	>90% removal/conversion	>90% removal	>90% conversion
Sulfate	No impact	>90 % removal	No impact, minor increase due to sulfate formation (2.8 mg sulfate per mg sulfide oxidized)
Organic Carbon	No impact	60-80% removal	No impact
Turbidity	No removal mechanism; potential increase due to sloughing of biomass and chemical precipitates from oxidation/precipitation reactions that occur in the aeration tower	Removal of negatively charged colloidal particles; no mechanism for turbidity formation	No removal mechanisms; potential formation due to mineral and organic oxidation (iron, sulfur, organic colloids, etc.)
Chloride	No impact	Increases 1 mg per mg sulfide removed and 0.7 mg per mg sulfate removed	Chlorine oxidation results in 5-8 mg of chloride per mg of sulfide converted; Other oxidants have no impact on chloride levels
pH	Controlled upstream and downstream of process	No impact	Upstream control
Dissolved oxygen	Increase up to oxygen saturation	No impact	Slight increase if hydrogen peroxide is used; significant increase if ozone is used (may be super-saturated); other oxidants have no net impact on dissolved oxygen
Chlorine demand	Reduction proportional to sulfide removal	Reduction proportional to sulfide removal Additional reduction may be due to removal of oxidizable organics and particulate matter	Reduction proportional to sulfide oxidation by oxidants other than chlorine (hydrogen peroxide, ozone, UV). Supplemental chlorine demand due to partially oxidized organics and presence of residual oxidant
Potential for hydrogen sulfide reformation	Minor impact because only one form of sulfur is removed: nonionized hydrogen sulfide	Major impact because most forms of sulfur are removed	Minor impact; Hydrogen sulfide is converted to more stable form, but not removed.

Conclusions

The major conclusions from this study are:

1. Water quality varies among the wells that serve the Seven Springs system. In addition to control of hydrogen sulfide, it is important to consider the co-occurrence of other water quality constituents, particularly organic carbon and turbidity, in assessing the efficacy of various control technologies.

2. Aeration technology provides an effective approach for removing and oxidizing hydrogen sulfide. Air stripping serves to remove nonionized hydrogen sulfide. The oxygen introduced through aeration serves as an oxidant that can react with hydrogen sulfide and other reduced minerals. Biological oxidation of hydrogen sulfide can also occur within aeration systems. There is potential for turbidity to be generated through the aeration process due to biological activity coupled with chemical oxidation of sulfur and other minerals. The use of aeration also requires on-site storage of chemicals for pH control and repressurization of the water prior to disinfection and introduction of the treated water into the distribution system.

3. The implementation of aeration at individual well sites is likely to be problematic due to current method of system operation and space limitations at each treatment facility. Because most of the existing treatment sites are located in residential neighborhoods, effective control of nuisance odors and noise generated by the aeration systems is essential. In addition, the on/off cycling of pumps at each well site is likely to compromise process performance.

4. Fixed-bed anion exchange technology is effective for removing hydrogen sulfide from the Seven Springs source water. Supplementary benefits of anion exchange technology include coincident removal of other forms of sulfur including sulfates, polysulfides, thiosulfates, and sulfites. In addition, negatively charged (anionic) forms of organic carbon, color-compounds, and turbidity are removed through treatment. Anion exchange technology does not generate nuisance odors or noise, thus imposing minimal impact to neighboring property owners. Another advantage of fixed-bed anion exchange is that treatment systems can be designed to be compatible with existing treatment site constraints, thus reducing the costs and time needed for implementation. Because the water is treated directly from the wells, the implementation of anion exchange technology would not require repressurization.

5. Oxidation technology is effective for control of hydrogen sulfide through conversion reactions, however the presence of organics in the untreated water poses water quality complications that result in the generation of turbidity upon the addition of chlorine for disinfection. Oxidation technology requires additional on-site storage of chemicals and process controls for chemical dosing and water quality monitoring. Oxidation technology is essentially an "in-pipe" treatment and does not require repressurization prior to introduction of the treated water into the distribution system.

6. In the context of the FDEP rule pertaining to hydrogen sulfide removal (Chapter 62-555.315(5), fixed-bed anion exchange technology surpasses the effectiveness of aeration with pH control by removing the dominant forms of reduced sulfur without requiring pH adjustment or repressurization. In addition, other anionic forms of sulfur including sulfate, polysulfides, thiosulfate, and sulfite are removed through fixed-bed anionic exchange treatment thus yielding water with a lower total mass of sulfur and reducing the potential for sulfide reformation. Co-incident benefits of anion exchange include reduction of organic carbon and turbidity, thereby decreasing the potential for formation of disinfection byproducts and improving the effectiveness of secondary disinfection.
7. Barring unforeseen issues arising from additional testing and permitting, it is anticipated that fixed-bed anion exchange will be effective for addressing water quality concerns associated with the Seven Springs water system.

Recommendations and follow-up

All of the technologies evaluated in this study are capable of controlling hydrogen sulfide, however it is important that the hydrogen sulfide control approach adopted for the Seven Springs system is compatible with site constraints and system limitations. Fixed-bed anion exchange is the only technology evaluated that is practicable for removing hydrogen sulfide and other forms of sulfur and can be readily implemented at the well-sites. Fixed-bed anion exchange has ancillary benefits of removal of organic carbon, color compounds, and turbidity.

While this project addressed technical feasibility and water quality impacts, it is important to develop accurate cost-estimates for the candidate technologies prior to final process selection. Because the desired treatment focuses on removal of hydrogen sulfide versus conversion, the cost of fixed-bed anion exchange should be compared to the cost of centralized forced-draft-packed-tower aeration with pH control.

Based on the pilot-scale data generated through this study, it is recommended that detailed designs be developed for implementing fixed-bed anion exchange at five sites within the Seven Springs water system (wells 2,6,8,9, and the Mitchell site that treats wells 3 and 4). The permitting process should also be initiated. As part of detailed design and permitting of fixed-bed anion exchange for the Seven Springs system, it is important to quantify the exchange capacity and service-cycle duration of the resins, characterize regenerant quality and volume, and ensure that regenerant disposal practices are compatible with reclaimed water requirements. It is also suggested that corrosion control be re-optimized after the new treatment system is in place.

Evaluation of alternative technologies for control of hydrogen sulfide from groundwater sources in the Seven Springs Service Area

The Seven Springs Water System of Aloha Utilities is located in a rapidly developing residential community southeast of New Port Richey, FL. The service area consists of single family homes, apartment and townhouse complexes, commercial areas, schools, and business parks. The source water, derived from 8 wells distributed through the service area, is treated and supplied to about 12,000 service connections. Prior to 2005, water treatment facilities at each of the eight well sites consisted of pumps, chemical feed facilities for corrosion control, chlorinators, and hydropneumatic reaction tanks. Under typical operating conditions, the pumps at each treatment system do not operate continuously, but cycle on and off in response to pressure demands within the system. The ability to store treated water within the existing system is limited to the hydropneumatic tanks at the well sites with a combined effective volume of 27,500 gallons and a separate 500,000 gallon ground storage tank that provides supplemental storage.

During 2005, Aloha Utilities implemented significant treatment upgrades at each of its treatment facilities in the Seven Springs system. To date, upgrades include: replacement of gaseous chlorine with liquid chlorine (sodium hypochlorite) as a primary disinfectant, relocation of treatment facilities for two of the smaller treatment systems (wells 3 and 4) to the ground storage facility, and installation of on-line process controls in conjunction with telemetry for remote monitoring of system operation. In the near future, the use of chloramination will be implemented throughout the service area for secondary disinfection. In addition, water from the Seven Springs system will be supplemented with treated water from Pasco County Utilities to help meet the growing demands within the service area.

While the treatment upgrades have had positive impacts on system operations and alleviated safety concerns associated with on-site storage of gaseous chlorine, there are still water quality questions and customer concerns relating to the genesis of discolored and odorous water within residential plumbing. Based on a host of studies conducted over the past decade (Levine 2003, 2004, Metcalf and Eddy, 1998, Porter, 1997,2002a,b, Van Hoofnagle, 1999), improved control over chemical and biochemical reactions of sulfur species has been identified as a critical water quality issue. In light of the upcoming conversion to the use of chloramines as a secondary disinfectant, it is particularly important that treatment technologies for controlling hydrogen sulfide are compatible with existing and planned treatment approaches for disinfection. It is also important that the water produced by the selected treatment is not corrosive to the water distribution system and residential plumbing.

This report is focused on evaluation of treatment technologies appropriate for control of hydrogen sulfide in the Seven Springs water system. Water quality variables, technical limitations of the technologies, site constraints, and practical issues relating to technology implementation are discussed.

OBJECTIVES

The purpose of this report is to evaluate feasible options for mitigating water quality concerns in the Seven Springs water system. The objectives of this report are:

1. Evaluate treatment options for control of hydrogen sulfide
2. Provide results from bench-scale and pilot-scale testing of treatment alternatives for control of hydrogen sulfide including:
    a. Aeration assessment
    b. Anion exchange technology
    c. The use of alternative oxidants
3. Provide treatment recommendations appropriate for implementation within the Seven Springs System.

BACKGROUND

Pertinent definitions and general information on regulatory issues and aspects of sulfur chemistry and water quality that impact the effectiveness of individual treatment processes are discussed in this section. A summary of treatment alternatives for control of groundwater hydrogen sulfide is given. Some of the information in this section is excerpted from previous reports on the Seven Springs system (Levine 2003, 2004).

Definitions of forms of sulfides

Control of sulfur in water systems is confounded by the fact that sulfur can exist in nine oxidation states and it can be biologically or chemically transformed from one form to another depending on localized reaction conditions. The most common inorganic sulfur species are listed in Table 1. Sulfide, polysulfides, thiosulfate, polythionates, elemental sulfur, bisulfite, and sulfate are the most common forms of sulfur in natural environments (Adequyi 1989, Bruserr, 2000, Buxton and Greenstock 1988, Dohnalek and Fitzpatick 1983, Dunnette 1989, Fisher 1989, Kelly 1999, Kletzin 1989, Kotronarou and Hoffman 1991, Millero and Hershey 1989, Morse et al., 1987, O'Brien and Birkner 1977, Steudal 2000, Tabatabai 1987). Organic sulfur compounds can also be present in the environment, but tend to be in lower concentrations than inorganic sulfur compounds. Dimethyl sulfide and dimethyl sulfoxide are two forms of organic sulfur that are prevalent in the environment in addition to carbon disulfide, carbonyl sulfide, mercaptans, and thiols (Adewuyi., 1989).

Sulfides are the most reduced form of sulfur, while sulfates are the most oxidized form. For water systems, the form of sulfur that is measured most frequently is sulfate. Typically, limited data are available on the relative quantities of sulfides, elemental sulfur, organic sulfur compounds, or any of the other species listed in Table 1. The reason for the lack of data is that analysis of the individual sulfur species is complicated and sample preservation is difficult because of the potential for conversion from one form to another. In addition to analytical difficulties, monitoring of sulfide in water sources is not required, therefore most of the available data are associated with specialized studies. One study on groundwater at pH 7.4 (Barbash and Reinhard 1989) reported that the distribution of reduced sulfides consisted of 56% hydrogen sulfide, 26% polysulfides, and 18% thiosulfate.

Table 1. Dominant forms of inorganic sulfur in water[a]

Compound	Chemical formula	Oxidation state
Sulfides	H_2S, HS^-, S^{-2}	-2.
Polysulfides	$-S(S)_nS^-$	Terminal S: -1; Inner S:0
Thiosulfate	$S_2O_3^{-2}$	Sulfane S: -1; Sulfone S: 5
Disulfane	H_2S_2	-1
Pyrite	FeS_2	-1
Polythionates	$-O_3S(S)_nSO_3^-$	Inner S: 0; Sulfone S: 5
Elemental Sulfur	S_n rings	0
Dichlorodisulfane	Cl-S-S-Cl	+1
Sulfur Dichloride	SCl_2	+2
Sulfoxylate	SO_2^{-2}	+2
Dithionite	$S_2O_4^{-2}$	+3
Bisulfite	HSO_3^-	+4
Dithionate	$S_2O_6^{-2}$	+5
Sulfonate	RSO_3^-	+5
Sulfate	SO_4^{-2}	+6

[a] Adapted from Adequyi 1989, Bruserr, 2000, Buxton and Greenstock 1988, Dohnalek and Fitzpatick 1983, Dunnette 1989, Fisher 1989, Kelly 1999, Kletzin 1989, Kotronarou and Hoffman 1991, Millero and Hershey 1989, Morse et al., 1987, O'Brien and Birkner 1977, Steudal 2000, Tabatabai 1987.

The term "sulfides" refers to the total concentration of ionized and nonionized sulfide species. Definitions of the dominant forms of sulfides are provided in Table 2. The stability and distribution of sulfides in water is controlled by the pH and the degree of exposure to air or oxidant chemicals. The nonionized form of hydrogen sulfide, H_2S, is highly volatile and can impart odor to water at fairly low concentrations (<25 ppb). The reactivity, solubility, and treatability of sulfides is influenced by sulfide speciation and other water quality variables.

Table 2. Definition of the forms of sulfide present in water

Terminology	Explanation
Total Sulfide	Dissolved hydrogen sulfide (H_2S), ionized sulfide (HS- and S^{-2}) and acid-soluble metallic sulfides, polysulfides
Dissolved sulfide	Sulfide remaining after removal of suspended solids
Non-ionized hydrogen sulfide	Hydrogen sulfide (H_2S) as determined from total sulfide, pH, conductivity, and ionization constant.
Ionized reduced sulfur (dissolved)	Bisulfide (HS^-) , Sulfide (S^{-2}), polysulfides (S_n^{-2}), thiosulfate(S_2O_3), bisulfite (HSO_3^-), and sulfite (SO_3^{-2})

Regulatory Framework for control of hydrogen sulfide

While the need for controlling hydrogen sulfide in water systems has been widely recognized (Jacobs et al. 1998, Stumm 1960, Wells, 1954, White 1999), historically there have been relatively few regulations that address treatment requirements. Under the requirements of the Safe Drinking Water Act (SDWA) hydrogen sulfide is indirectly regulated through the secondary drinking water standard for taste and odor. However, there are no monitoring requirements for hydrogen sulfide in either treated or untreated water. Tampa Bay Water, a wholesale provider of water in west-central Florida, developed a performance goal for their member governments of 0.1 mg/L for hydrogen sulfide in treated water.

In 2003, the Florida Department of Environmental Protection (FDEP) implemented a new rule pertaining to hydrogen sulfide removal under Chapter 62-555.315(5). This rule applies to the permitting process for new or altered wells in community water systems. Treatment recommendations are defined based on the level of total sulfide in the untreated water and the ambient pH. A summary of the FDEP treatment recommendations is given in Table 3. No information is given on the sampling protocols for measuring hydrogen sulfide in the untreated water, the number of samples needed to categorize the hydrogen sulfide level, or monitoring frequency. The rule also allows utilities to use alternate treatment technologies as long as the treatment effectiveness is comparable to the treatment recommendations specified.

Table 3. Summary of FDEP treatment recommendations for control of total sulfide in new or altered wells (adapted from FDEP Chapter 62-555.315(5))

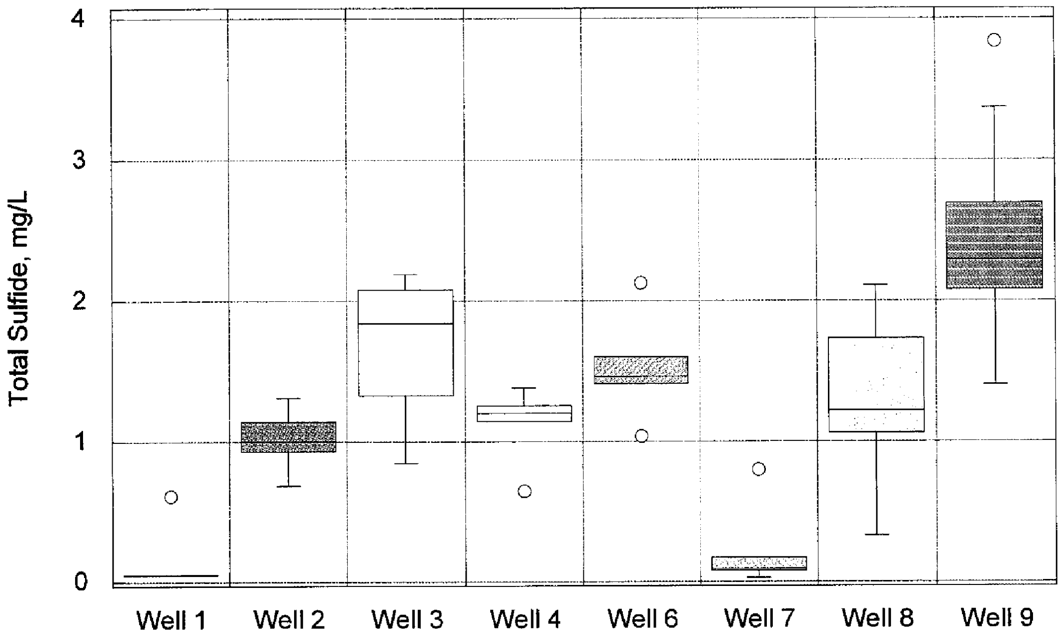
Total sulfide concentration in untreated water, mg/L	pH range			Treatment recommendations
	<7.2	7.2	> 7.2	
< 0.3	x	x	x	Chlorination
0.3 to 0.6	x	x		Conventional aeration
0.3 to 0.6			x	Conventional aeration with pH adjustment
0.6 to 3	x	x		Forced draft aeration
0.6 to 3			x	Forced draft aeration with pH adjustment
> 3.0	x	x	x	Packed tower aeration[a] with pH adjustment

[a]Packed tower aeration includes supplying air through forced draft (or induced draft)

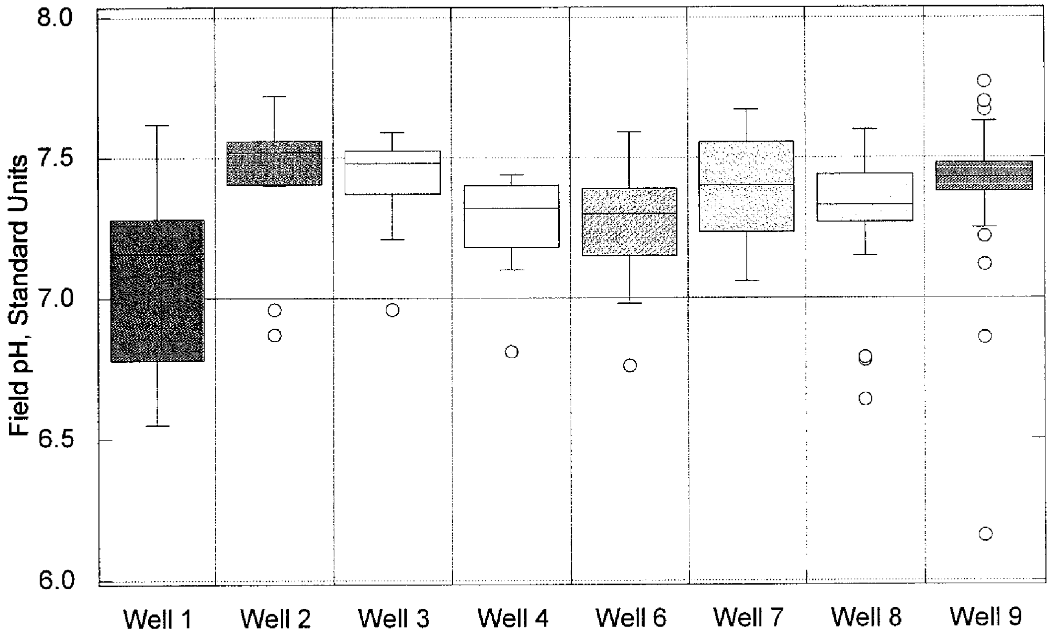
The wells in the Seven Springs system have been in active use for over a decade and have not been recently altered. Therefore, the Seven Springs system is not directly impacted by this new rule. However, the rule provides a context for evaluating treatment options for control of hydrogen sulfide. The starting point for interpretation of the rule recommendations is to assess the levels of hydrogen sulfide and pH in the untreated water.

Hydrogen sulfide monitoring for the Seven Springs water system has been conducted through various studies. A summary of hydrogen sulfide and pH levels associated with untreated water from the Seven Springs wells is given in Figure 1 in a boxplot format. The boxes represent 50% of the data and the horizontal lines represent the median value. The height of the box reflects the variability of the data. As shown, total sulfide levels in wells 1 and 7 are well below the level that would trigger the need for additional treatment under the FDEP rule (< 0.3 mg/L). Average total sulfide levels in the remaining six wells range from about 0.6 to 3 mg/L, with the highest levels associated with untreated water from well 9. With the exception of well 1, median pH values are above 7.2 for all the wells, suggesting the need for pH control if aeration technology is to be used for control of hydrogen sulfide.

Since mid 2004, sulfide levels in well 9 have been monitored on a regular basis. A comparison of sulfide variability over the last year is shown in Figure 2. As shown, there was over a two-fold variation in sulfide levels with the average day-to-day variation about 12%. There is no conclusive explanation for the variation in sulfide levels, but it most likely is related to seasonal factors such as rainfall, temperature, and the extent of pumping. Higher levels of hydrogen sulfide in untreated water from well 9 (over 6 mg/L) were reported during the height of the drought experienced in Florida during 2001 (Porter 2002) but have not been observed since that time. Because routine monitoring of hydrogen sulfide is not widely practiced, it is difficult to compare the trends observed for the Seven Springs system to hydrogen sulfide variability in other water systems.



a. Boxplot comparison of total sulfide levels in untreated water from Seven Springs wells.



b. Boxplot comparison of pH levels in untreated water from Seven Springs wells.

Figure 1. Comparison of a) total sulfide and b) pH levels in untreated water from wells serving the Seven Springs water system. Data from 1998-2005.

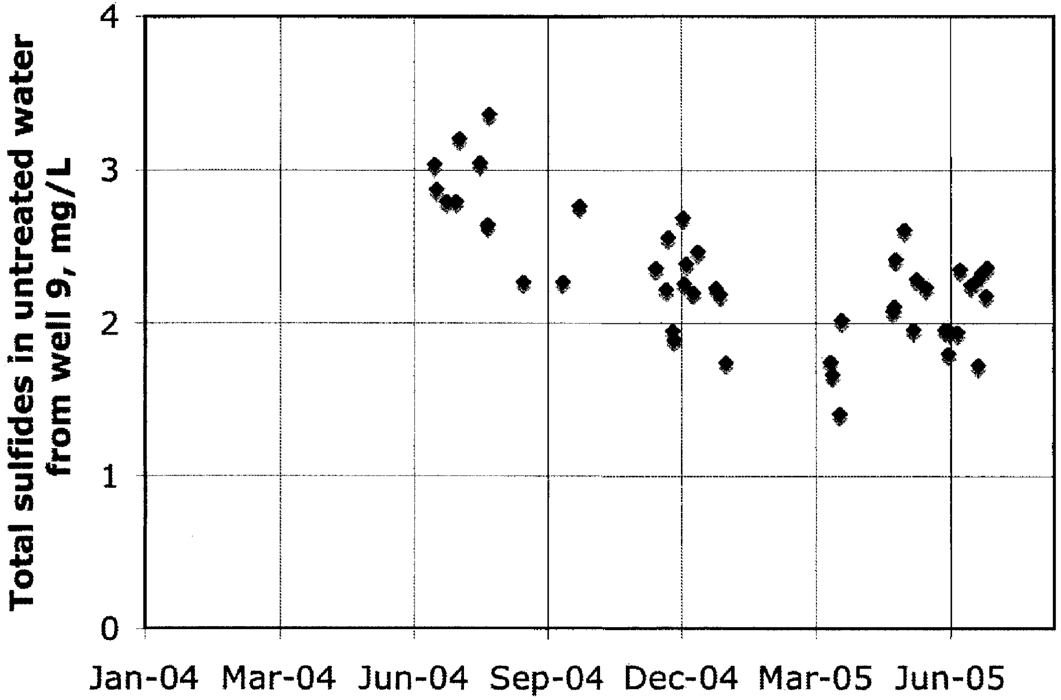


Figure 2. Variation in total sulfide levels in untreated water from well 9 from June 2004 through June 2005.

Sulfur Transformations

The dominant forms of sulfur in the environment are controlled by biological, chemical, and geochemical reactions that result in the cycling of sulfur between various oxidation states and complexation with organic and inorganic constituents. A simplified version of the sulfur cycle is shown in Figure 3. The cycle is dynamic and the turnover rate for each stage is controlled by water quality and microbial characteristics.

Reduced forms of sulfur include sulfides, thiolate ions, polysulfides, thiosulfate, and sulfite. Many of the reduced forms of sulfur are unstable in the presence of oxygen (Barbash and Reinhard 1989). Elemental sulfur is a stable form of sulfur that has an oxidation state intermediate to sulfides and sulfate. Polysulfides form as intermediates during sulfate oxidation under neutral pH and equilibrate with elemental sulfur (Kotronarou and Hoffman 1991). The predominant forms of polysulfides that have been identified in water are tetrasulfide (S_4^{2-}) and pentasulfide (S_5^{2-}) (O-Brien and Birkner 1977).

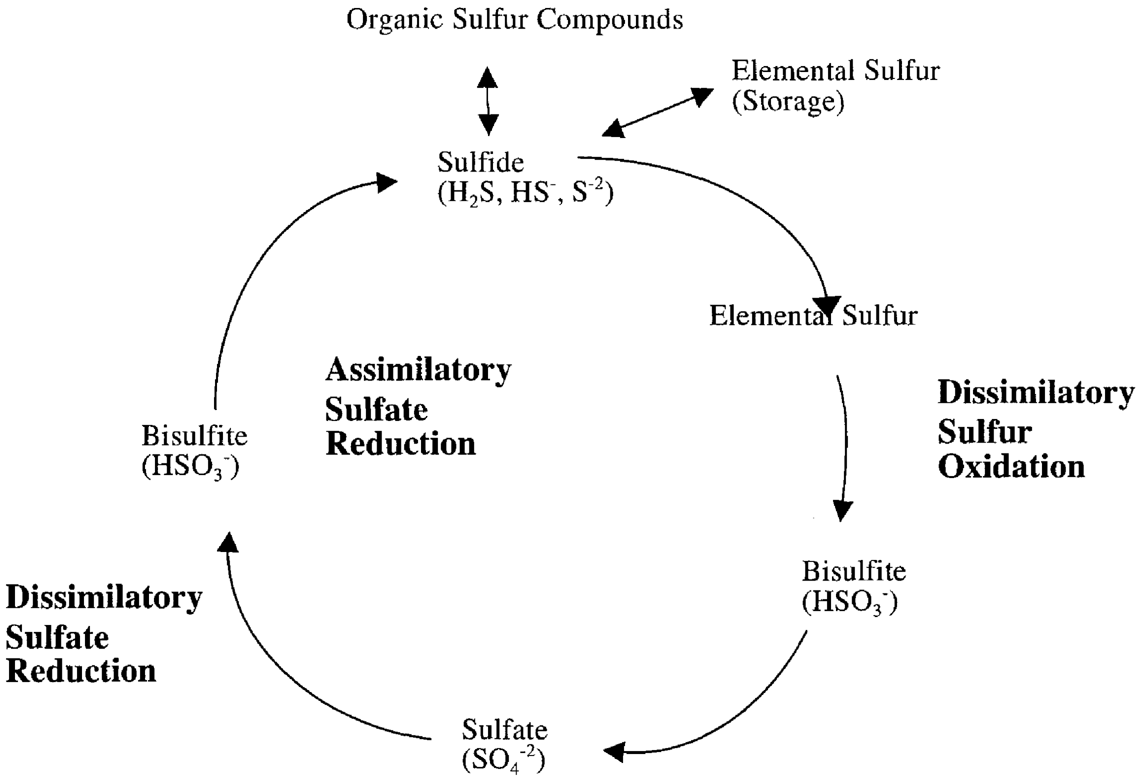


Figure 3. Simplified version of biological sulfur cycle (adapted from Bruser et al. 2000).

Sulfides are the main product of sulfate respiration by anaerobic bacteria and are also released by desulfuration of organic compounds. Sulfides can be converted to elemental sulfur or sulfate by biological or chemical oxidation. In addition to biological reactions mediated by microorganisms present in the environment, chemical oxidation reactions can convert sulfides to elemental sulfur or sulfate. Oxidizing agents available in the environment include oxygen, iron, or manganese.

Elemental sulfur can be formed through several mechanisms. The most common formation pathways are biological or chemical oxidation of sulfides. In water, elemental sulfur exists as a colloid that ranges in size from about 0.01 to 1 µm. The fate of elemental sulfur in water depends on the pH, availability of oxidants (i.e. chlorine), and the presence of sulfur bacteria. Elemental sulfur can be biologically converted to sulfite, thiosulfate, polysulfides, and sulfide through dissimilatory sulfur oxidation (Adequyi 1989, Fisher 1989, Kelly, 1999, Kletzin, 1989, Millero and Hershey 1989). Due to the intermediate oxidation state of elemental sulfur it can serve as either an oxidant or reductant for organic and inorganic materials. Some species of bacteria can grow on elemental sulfur as an electron acceptor and produce sulfide during heterotrophic or lithotrophic respiration. The presence of bioavailable organic carbon in water can impact the rate and extent of these reactions (Dunnette 1989).

Measurement of elemental sulfur is difficult because of its colloidal size. It is measured indirectly by analysis of suspended solids. However, suspended solids tests do not detect particles smaller than 1 μm accurately. In addition, non-sulfur particles can also contribute to the particulate content of water. Turbidity measurements can be used as a surrogate for suspended solids, but may give misleading results. Turbidity measurements are based on light scattering caused by particles in water. As such, the magnitude of the turbidity is related to the concentration of particles and the particle size distribution. In general, for a given concentration of suspended solids, smaller particles produce a stronger turbidity signal than do larger particles. Thus, while turbidity can give an indication of the presence of colloidal sulfur, there are no standardized tests that can be used to determine the concentration of sulfur-derived particles within a given water sample. Electron microscopy coupled with energy dispersive spectroscopy or other X-Ray based analytical techniques, such as X-Ray diffraction (XRD) can be used to identify the presence of sulfur in particulate samples and provide qualitative information, but these techniques do not provide quantitative data.

Treatment Options for Control of Hydrogen Sulfide

Treatment technologies effective for control of hydrogen sulfide levels in water can be classified as conversion processes or removal processes. Chemical or biological oxidation act to convert the sulfide to a more oxidized form of sulfur (either sulfate or elemental sulfur). It is important to note that oxidized forms of sulfur can become reduced in the absence of adequate disinfection residuals. The rate of sulfide reversion depends on the pH, oxidant concentration, temperature, and turnover time within the distribution system (water age), and the presence of sulfur reducing bacteria.

Removal of hydrogen sulfide can be accomplished by removing the sulfide as a gas, liquid, or solid. Removal of gaseous hydrogen sulfide can be accomplished using air stripping to displace the nonionized form (H_2S) from water replacing it with dissolved oxygen. The efficiency of air stripping is related to the pH of the water, temperature, and air to water ratios. The off-gas from the process contains odorous sulfur compounds and requires treatment for odor control. Dissolved sulfide removal can be accomplished using anion exchange to target anionic (negatively charged species) including hydrogen sulfide (HS^-), sulfide (S^{-2}), sulfites, thiosulfates, polysulfides, and organic-sulfides. Another approach for removal of hydrogen sulfide is to oxidize the sulfide to a particulate form and then use a filtration process to remove the sulfur particles (Levine et al. 2004). Particulate forms of sulfur include elemental sulfur, iron sulfides, and other metallo-sulfur complexes.

A summary of the treatment approaches appropriate for controlling groundwater hydrogen sulfide is given in Table 4. The treatment approaches can be categorized as removal options, conversion options, or a combination of removal and conversion. The efficacy and practicality of each treatment option is influenced by several factors including water quality, operating characteristics of the treatment systems (intermittent vs. continuous), site characteristics, the ability to manage residuals generated by the treatment system, upstream treatment, and downstream treatment and cost.

Table 4. Comparison of groundwater treatment options for control of hydrogen sulfide

Type of treatment	Description	Factors influencing process efficiency
Removal options		
Aeration	Introduction of air into water using natural or mechanical (forced or induced draft) aeration in reactors that allow for air/water contact and stripping of nonionized hydrogen sulfide into the atmosphere. Typical water treatment aeration reactors include cascade (tray aeration) or packed towers. Natural draft or forced draft aeration can be used with tray towers, with forced draft providing for more efficient removal. Forced draft is necessary for packed tower aeration. Hydrogen sulfide is either stripped from the water and released in the off-gas stream or oxidized by reacting with dissolved oxygen. Aeration systems differ in terms of the method of introduction of air, the air to water ratio, upstream process controls (pH adjustment), off-gas management, and overall process efficiency. Biological growth can occur within the aeration system necessitating consistent maintenance. Ionized species are not removed.	pH, temperature, air flowrates, and air to water ratios
Anion exchange	Use of ion exchange resin that removes ionized hydrogen sulfide (bisulfide and sulfide), polysulfides, thiosulfate, sulfite and other negatively charged constituents from water including sulfate, organic carbon, nitrate, and colloidal particles. Dissolved anions are exchanged with chloride. Effective regeneration of resin and regenerant disposal are important.	pH, temperature, resin properties, competing anions
Conversion options		
Chemical oxidation	Oxidizing chemicals such as chlorine, hydrogen peroxide, oxygen, ozone, permanganate, or other oxidants are used to convert dissolved hydrogen sulfide to elemental sulfur or sulfate. Possible to convert 100% of the hydrogen sulfide, depending on the type of chemical, dose, and reaction conditions. Elemental sulfur or sulfate may biologically revert to hydrogen sulfide in the absence of disinfection residuals.	pH, temperature, chemical dosages, reaction time, oxidant demand
Biological sulfide oxidation	Aerobic sulfur oxidizing bacteria can convert hydrogen sulfide to elemental sulfur that is entrapped in bacterial cells. Possible to convert 100% of sulfide depending on degree of aeration, contact time, and operating conditions.	pH, temperature, dissolved oxygen, reaction time, microbial activity
Conversion and removal options		
Oxidation-Filtration	Use either chemical or biological oxidation to form colloidal sulfur. The oxidation process is then followed by a filtration process that removes the colloidal particles and prevents release of turbidity into the distribution system.	Particle size, turbidity, filtration process variables
Chemical precipitation	Addition of iron salts (ferric chloride, ferric sulfate) or other coagulants to form iron sulfide particles that can be removed by solid-liquid separation processes such as filtration.	Chemical dose, particle size, filter design

Regardless of which type of treatment is implemented for control of hydrogen sulfide, the final treatment steps consist of chemical addition for disinfection and corrosion control. In the Seven Springs system, chlorine is used as a primary disinfectant, ammonia is added for chloramination, and corrosion control chemicals are applied prior to introducing the water into the distribution system. Currently, in the Seven Springs system, chlorine serves a dual role as an oxidant (for hydrogen sulfide and other reduced minerals) and as a disinfectant. Thus, in addition to satisfying water quality concerns, another benefit of implementing hydrogen sulfide control technology is that chlorine will only be required for disinfection resulting in the need to store less chlorine at each site.

Each treatment approach requires different equipment upstream of chlorination. Aeration requires upstream pH control, a packed tower forced draft aeration system, on-site scrubber, downstream pH and alkalinity control, a pump station for repressurizing the system, a method of accessing the aeration unit for routine maintenance, a method for disposal of residuals from system maintenance, and on-site storage of chemicals for pH and alkalinity control. Anion exchange requires packed bed contactors and facilities for resin regeneration and brine disposal. Solid/liquid separation processes require upstream treatment for producing elemental sulfur (biological or chemical), chemical addition, filtration, and a method of discharging or treating the filter backwash water. Oxidation processes require tanks and pumps for chemical addition, in-line mixing, and controllers for monitoring chemical dosages and water quality parameters. A comparison of the pre-treatment, treatment, post-treatment, and disinfection steps associated with each control technology is given in Table 5. As shown, fixed-bed anion exchange is the only technology that does not require pre-treatment or post-treatment.

Table 5. Comparison of pre-treatment, treatment, post-treatment, and disinfection for hydrogen sulfide control technologies

Control technology	Pretreatment	Treatment	Post treatment	Disinfection
Packed-Tower [a] Aeration with pH adjust	Adjust pH to below 6 using liquid carbon dioxide or mineral acid	Pump water to top of aeration tower; inject air into bottom of tower using a blower (forced-draft); strip nonionized hydrogen sulfide and introduce oxygen into water	Adjust pH and alkalinity; repressurize water using on-site pump station	Chlorine and ammonia
Fixed-Bed Anion Exchange		Pass water through fixed-bed anion exchange column		Chlorine and ammonia
Solid-Liquid Separation	Chemical or biological oxidation followed by coagulation-flocculation	Allow oxidation and flocculation reactions to occur	Pass water through a filter appropriate for particle removal (sand or membrane)	Chlorine and ammonia
Alternative Oxidation	Adjust pH to about 8 using caustic soda	Add oxidant chemicals and allow reaction to occur		Chlorine and ammonia

[a] Packed tower aeration includes supplying air through forced draft (or induced draft)

Water quality variables of importance for control of hydrogen sulfide

The efficiency of the treatment systems identified in Table 4 for control of hydrogen sulfide is influenced by several water quality variables including pH, alkalinity, temperature, and turbidity. The presence of iron, manganese, organic carbon or other constituents that might impose an oxidant demand can also impact process performance and treated water quality.

pH

The pH of a water is influenced by the composition of the dissolved minerals, dissolved gases (e.g. carbon dioxide and hydrogen sulfide), and the overall oxidation status. Typically, the pH of groundwater increases following exposure to air due to off-gassing of carbon dioxide. Thus there can be discrepancies between pH values measured in the field versus in the laboratory. From the perspective of hydrogen sulfide control, pH affects the degree to which the sulfide is ionized or nonionized. An overview of the dominant form of hydrogen sulfide in water as a function of pH is shown in Figure 4. The technologies in Table 4 that allow for removal of hydrogen sulfide are highly pH dependent. Aeration is only effective for removal of nonionized hydrogen sulfide. As shown in Figure 4, at pH 7, about half of the sulfide is in the nonionized form, while at pH 5, almost all of the sulfide is nonionized (H_2S). If the pH of the water is over 7, as in all of the Seven Springs wells (see Figure 1), aeration removal efficiency would be below 50% unless the pH is reduced prior to aeration. However, the oxygen introduced into the water can act to oxidize the sulfide to elemental sulfur or sulfate. Conversely, anion exchange is targeted at removal of the ionized forms of sulfide, which increase with increasing pH. Anion exchange technology also removes other negatively charged constituents from water including sulfate, organic carbon, and negatively charged (anionic) particulate matter. Oxidation technologies are effective over the entire pH range, however the products of oxidation (elemental sulfur versus sulfate or polysulfides) are impacted by pH.

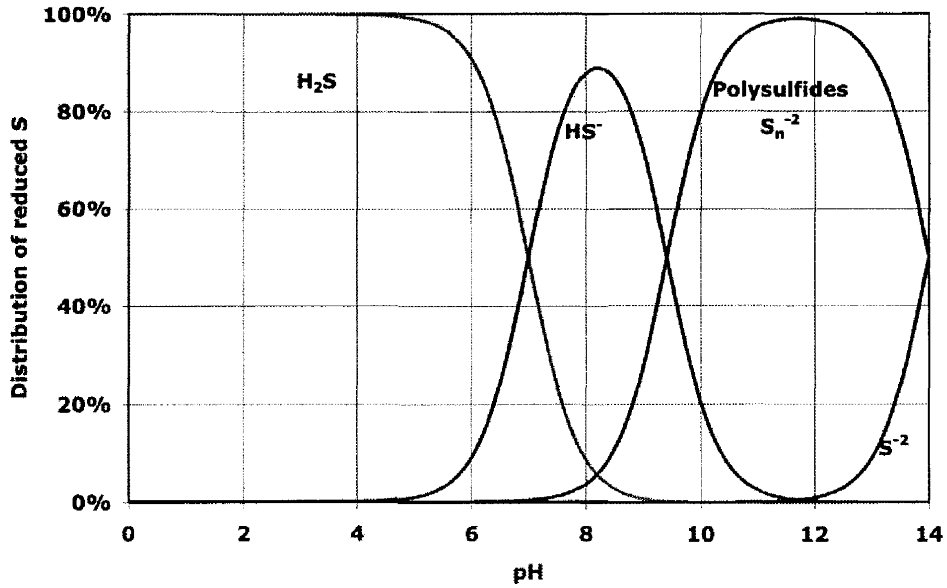


Figure 4.Theoretical distribution of hydrogen sulfide and polysulfides in water as a function of pH assuming polysulfides are in equilbrium with HS^- (equilibrium constants from Morse et al. 1987, Stumm and Morgan 1996)

A comparison of the theoretical efficiency of aeration and anion exchange is shown in Figure 5 in comparison to the pH range of untreated water from the Seven Springs wells. As shown, the maximum possible efficiency of direct aeration of water from the Seven Springs wells at ambient pH ranges from about 20 to 40%. Conversely, direct treatment of the water by anion exchange should yield substantially higher removal efficiencies. In theory, modifying the pH upstream of the treatment system can improve the overall efficiency of hydrogen sulfide removal. In addition, reactors can be designed to facilitate mass transfer and improve the overall removal efficiency.

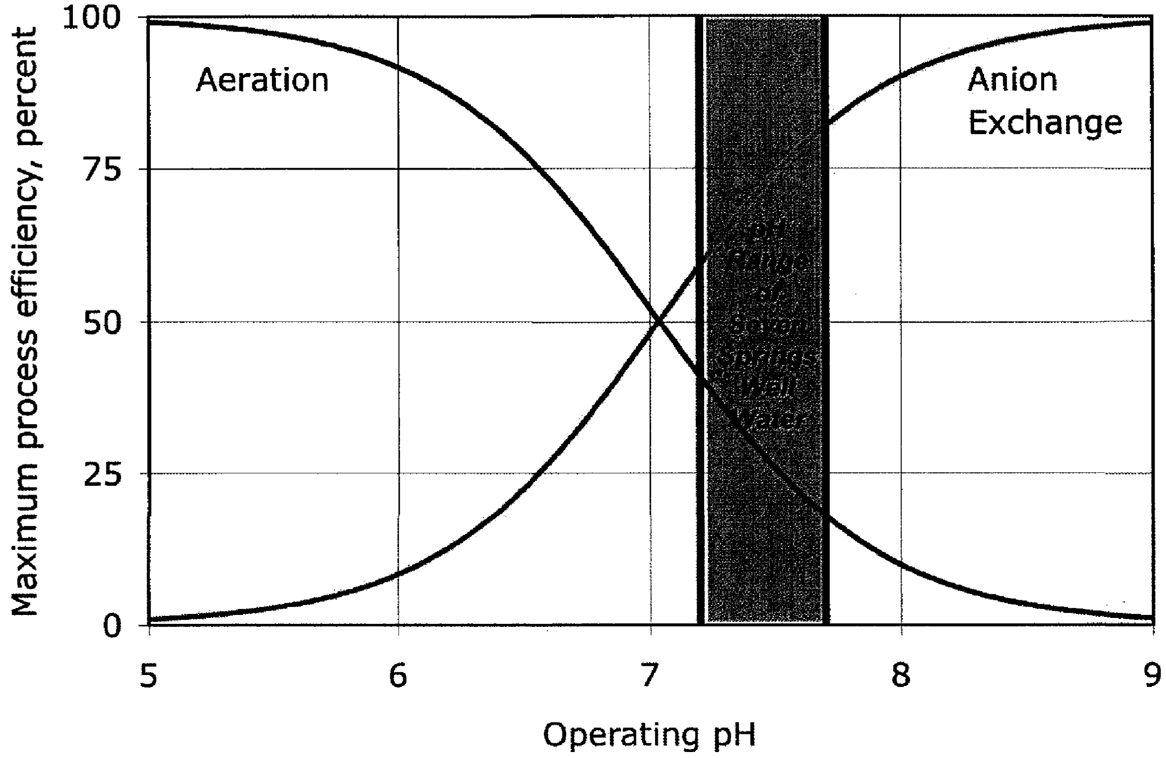


Figure 5. Comparison of the impact of pH on the theoretical process efficiency of aeration and anion exchange.

The pH of a water also impacts the solubility of various minerals and metals and the corrosivity of water. In general, the solubility of minerals and metals decreases with increasing pH. The corrosivity or scale potential of water is related to the pH, alkalinity, and concentrations of dissolved minerals. The SDWA secondary maximum contaminant level (MCL) for pH requires the treated water pH to be between 6.5 and 8.5.

Alkalinity

Alkalinity is a measure of the ability of water to resist a change in pH and is a key water quality parameter for modulating water stability and corrosivity. It is an indirect measure of the concentration of dissolved carbonates in groundwater. A comparison of alkalinity levels in untreated water from the Seven Springs water system is shown in Figure 6 in a boxplot format. As shown, there is some variability among the individual wells. In general, with the exception of Well 1, alkalinity levels range from about 130 to over 200 mg/L as $CaCO_3$ in the Seven Springs system. While the alkalinity does not directly affect the speciation of hydrogen sulfide, it affects the amount of chemical needed for pH reduction. Thus, waters with higher alkalinity levels may require higher chemical dosages to achieve an optimum pH for aeration. Alkalinity is also important for corrosion control, therefore the use of technologies that reduce alkalinity (e.g. aeration) may impact water corrosivity unless downstream controls are used (corrosion control chemicals, pH adjustment).

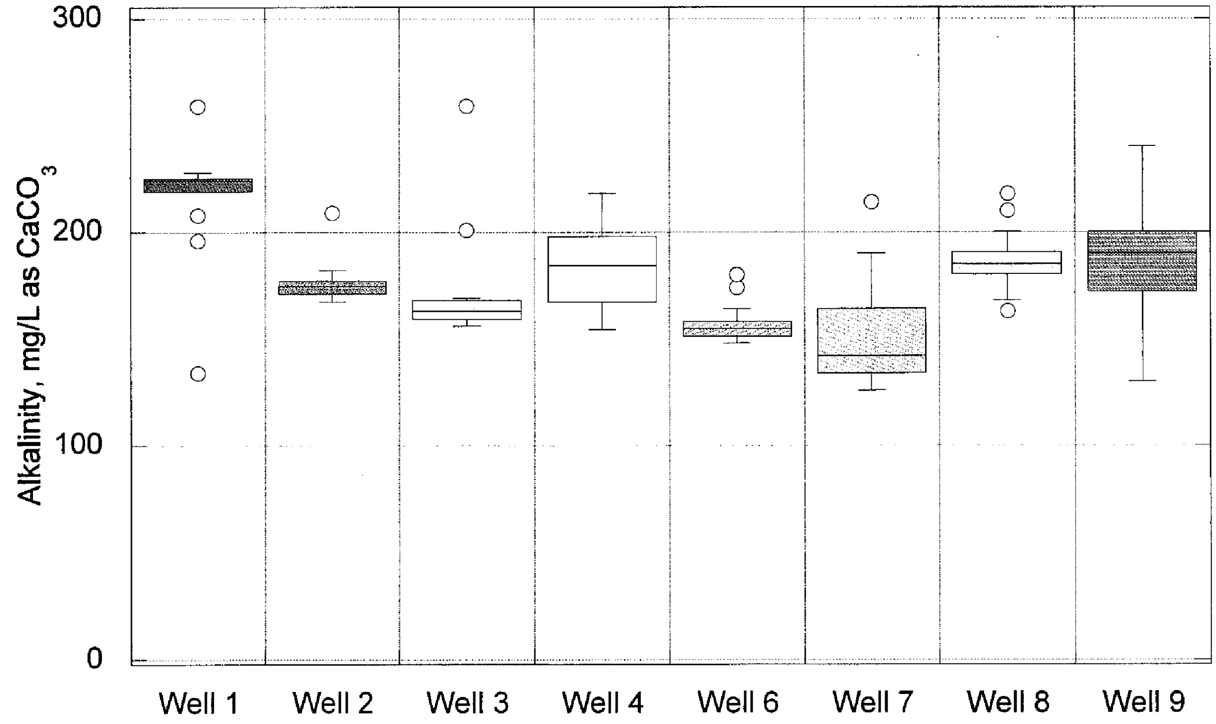


Figure 6. Comparison of alkalinity levels in untreated water from the Seven Springs water system.. Data from 1998-2005.

Temperature

While temperature is not a water quality parameter that is typically controlled in water treatment applications, it impacts process efficiency in several ways. First, the rates of chemical and biochemical reactions are influenced by temperature, with more rapid reaction rates associated with higher temperatures. In addition, temperature affects the solubility of gases and minerals in water, with decreasing solubility associated with increasing temperatures. Biological growth rates and chlorine decay rates increase with increasing temperature. The temperature of the untreated water from the Seven Springs system is fairly consistent and averages about 25 °C. However, temperature changes can occur in the distribution system, particularly in the summer months when water usage rates tend to decrease. Temperature variability can affect hydrogen sulfide control technologies by impacting reaction rates and solubility. Aeration technologies are more sensitive to temperature variations than other technologies for hydrogen sulfide control.

Turbidity

Turbidity is an indirect measure of the concentration of particles in water. The turbidity of water is a measure of the degree to which particles in water cause light shining through the water to scatter. The instrument used to measure turbidity, a turbidimeter, is based on principles of nephelometry and consists of a light source (tungsten-filament lamp) at a fixed wavelength (400-600 nm) and a detector that measures scattered light perpendicular to the light source (Crittenden et al. 2005, Sawyer et al. 2003, Standard Methods, 1998). The degree to which light is scattered by particles in water is related to the particle size distribution and physical-chemical properties of the particles with a greater degree of light scattering (turbidity) associated with smaller particles than larger particles of equivalent mass. Particles smaller than 1 micrometer (μm) tend to cause interferences in the turbidity measurement (Crittenden et al. 2005).

Particles in water can range in size from below 1 μm to over 20 μm. Bacterial particles are around 1 micron in size and protozoan pathogens range from 3-5 μm in size. It is not possible to see particles in water that are smaller than 40 μm without magnification. Thus, water can have measurable turbidity but still appear relatively clear. For purposes of comparison, turbidity levels in lakes and reservoirs range from about 1 to 20 NTU, while river water turbidity can range from about 1 to 4000 NTU depending on the watershed characteristics and local precipitation patterns (Crittenden et al. 2005). Sources of turbidity in groundwater include minerals, microorganisms, and silica; however, limited data are available on turbidity levels in groundwater. Because turbidity is generated by different types of particles suspended in water, there are no universal correlations between turbidity and the mass of suspended solids that generates the turbidity. However, turbidity measurements can provide qualitative information on the presence of particulate matter in water and changes that occur during treatment. Turbidity levels in treated surface water are regulated under the Surface Water Treatment Rule (SWTR), however, there are no MCLs for turbidity in groundwater.

The presence of turbidity in untreated water can affect the performance efficiency of hydrogen sulfide control technologies based on oxidation and filtration. The particles suspended in groundwater tend to be relatively small (< 10 µm) and negatively charged. There is potential for groundwater particles to exert an oxidant demand impacting chemical dosage requirements. In addition, the presence of particles in the water can compromise the effectiveness of disinfection by shielding microorganisms from the action of disinfectant chemicals (e.g. chlorine and chloramines).

Due to the lack of regulations pertaining to turbidity in groundwater, limited information is available on the sources and variability of groundwater turbidity. As part of this study, field data were collected on turbidity levels in the Seven Springs system. During 2004 and 2005, limited monitoring of turbidity levels in untreated well water was conducted. Data are summarized in a boxplot format in Figure 7. As shown, the highest levels of turbidity were associated with wells 7 and 8.

It is important to consider the potential impacts of turbidity on the performance of treatment technologies for hydrogen sulfide control. In general, oxidation technologies may be impacted by additional oxidant demand associated with the presence of particles. The performance of aeration or anion exchange is not likely to be impacted by turbidity. However, it is interesting to note that, since particles in water tend to be negatively charged, it is possible to achieve some particle removal through anion exchange systems. There are no particle removal mechanisms associated with the other treatment technologies evaluated for this project (with the exception of filtration).

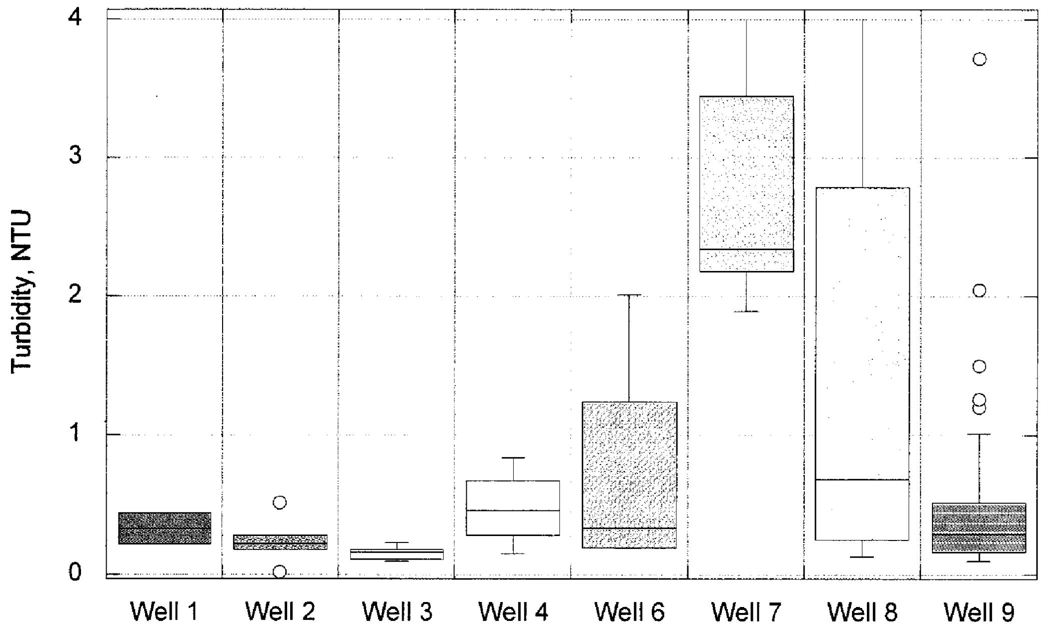


Figure 7. Boxplot comparison of turbidity levels in untreated water from the Seven Springs water system. Data from 1998-2005.

Criteria for technology selection for control of hydrogen sulfide in the Seven Springs system

There are a variety of approaches that can be used for controlling hydrogen sulfide that vary in efficiency, reliability, complexity, practicality, and cost. Constraints associated with implementing a new treatment technology in the Seven Springs water system include: site limitations, on/off cycling of pumps, management of process wastes, and proximity to residential neighborhoods. Ideally, the development of centralized treatment facilities and supplemental storage capacity would impose fewer limitations on process selection and provide more consistent water quality throughout the distribution system. However, due to cost constraints and the lack of an existing site for a centralized facility, it is preferable to develop a treatment system that can be accommodated at the existing treatment sites.

Currently, the Seven Springs water system consists of seven treatment plants. Six of the plants each have a capacity of approximately 500 gpm and the other plant (well 1) can supply 1000 gpm. In evaluating the levels of hydrogen sulfide in the untreated water, supplemental treatment would not be needed at wells 1 and 7 (see Figure 1). With the exception of the treatment facilities at the ground storage tank on Mitchell Road (wells 3 and 4), the other four treatment plant sites (wells 2,6,8, and 9) have limited available area. In addition to space constraints, noise and odors associated with the hydrogen sulfide removal technology are also of concern due to the proximity of residential neighborhoods.

The implementation of aeration technologies at four of the treatment sites would be challenging due to space limitations and height restrictions (building code, hurricane related issues) coupled with the need to control noise and odor. To achieve the desired hydrogen sulfide removal efficiencies, it would be necessary to use packed tower aeration technologies with pH control. These systems would require blowers for forced draft aeration, chemicals for pH adjustment, and on-site odor control technologies. In addition, noise barriers would be needed to contain the sounds generated by the aeration equipment due to the close proximity of residential neighborhoods. A sewer connection would be needed for disposal of waste generated by periodic maintenance of the aeration towers. Safety issues associated with delivery and on-site storage of pH control chemicals would need to be addressed. Additional traffic may be generated due to the delivery of chemicals for pH control (carbon dioxide and/or mineral acids, caustic soda).

The use of anion exchange technologies would require space for reactors and regeneration equipment. If carefully designed, these could be accommodated on the existing sites. There would be no additional noise generated from this treatment technology as the water would be directly pumped from the wells. Additional traffic may be generated due to the delivery of regeneration chemicals (salt), but this could be coordinated with delivery of other chemicals (e.g. sodium hypochlorite). A sewer connection will be required for disposal of wastes from the regeneration process (produced intermittently).

Oxidation technologies would require supplemental chemical feed equipment, but should not generate excessive noise or odors. Secondary containment and safety precautions are important for chemical handling, particularly due to the proximity of neighborhoods and playgrounds. No supplemental waste streams would be generated by using oxidation since the treatment is completely contained within the on-site reactors and pipelines. Additional process controls would be needed to control chemical feed rates.

Removal technologies that involve the use of oxidation coupled with filtration would require chemicals and reaction chambers plus filtration equipment. While filtration provides an additional barrier for water quality protection, it also has the potential to generate a significant waste stream due to filter backwashing requirements. Site constraints limit the practicality of this option and a careful assessment of the quantity of water generated by backwashing and disposal requirements would be needed to determine the feasibility of using this approach for the Seven Springs water system.

Summary

Six of the eight wells that provide source water to the Seven Springs water system have sulfide levels that are over 0.3 mg/L. Treatment technologies that are capable of removing hydrogen sulfide include aeration, anion exchange, and oxidation coupled with filtration. Oxidation technologies are capable of converting hydrogen sulfide to a more stable form. Water quality considerations that impact process selection include the level of hydrogen sulfide, pH, alkalinity, and turbidity. Site constraints include the area available for implementation of new equipment and the proximity of residential neighborhoods to the treatment facilities. Results from evaluation of the candidate technologies are provided in the next section of this report.

TECHNOLOGY EVALUATION

Technologies for control of hydrogen sulfide include removal technologies and conversion technologies. In this project, bench-scale and pilot scale tests were conducted to develop data that could be used for technology selection. The technologies evaluated in this project include aeration, anion exchange, and oxidation. An overview of the tests conducted for this project is given in Table 6.

Table 6. Summary of bench-scale and pilot-scale tests conducted on well water from the Seven Springs water system.

			Testing goals				
Technology	Type of test	Wells tested	pH optimum	Chemical dose requirements	Hydrogen sulfide removal/ conversion	Turbidity formation potential	Chlorine demand
pH control	Bench scale	1,2,3,4, 6,7,8,9	yes	yes	no	yes	no
Removal technologies							
Aeration	Bench scale	7,8,9	no	yes	no	no	yes
Anion exchange	Pilot scale	8,9	yes	yes	yes	yes	yes
Oxidation							
Chlorine	Bench scale	1,2,3,4, 6,7,8,9	yes	yes	yes	yes	yes
Chlorine-ammonia	Pilot-scale	8,9	yes	yes	yes	yes	yes
Hydrogen peroxide	Bench scale	1,2,3,4, 6,7,8,9	yes	yes	yes	yes	yes
Hydrogen peroxide	Pilot-scale	2,6,8,9	yes	yes	yes	yes	yes
UV	Pilot-scale	8,9	yes	no	yes	yes	yes
Hydrogen peroxide-UV	Pilot-scale	8,9	yes	yes	yes	yes	yes
Hydrogen-peroxide-chlorine-ammonia	Pilot-scale	8,9	yes	yes	yes	yes	yes
Hydrogen-peroxide-UV-chlorine-ammonia	Pilot-scale	8,9	yes	yes	yes	yes	yes

Methodology

This project involved water quality testing of untreated water, technology evaluation, and water quality assessment of treated water. Testing of pH adjustment using caustic soda, anion exchange and oxidation was conducted at the treatment sites associated with each well. Testing of carbon dioxide injection was conducted at the University of South Florida (USF) environmental engineering laboratory. Water quality tests were either conducted in the field using field test kits or in the USF laboratory.

Sampling

Samples were collected of untreated water and following individual stages of bench-scale and pilot-scale tests. Special precautions were taken for the collection of samples for sulfide analysis. A sampling device modified from a graduated cylinder was used to prevent exposure of the sample to air and potential volatilization. A photograph of the sampling device is shown in Figure 8. Water enters the device at the bottom of the sampler and overflows from the top. Samples for sulfide analysis are collected from the submerged tube and analyzed directly using field test methods (titration, methylene blue colorimetric test, or specific ion electrode).

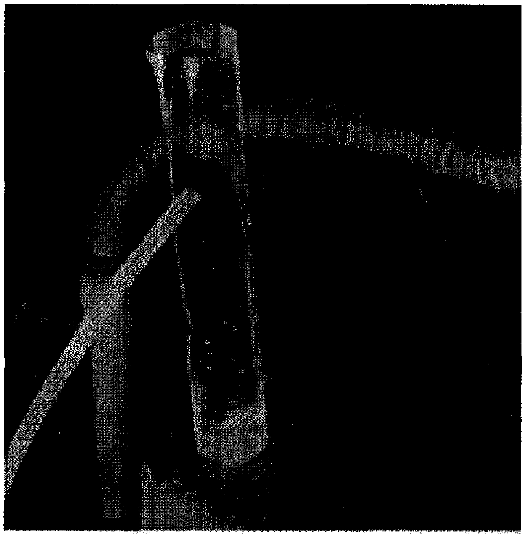


Figure 8. Sampling device for field sampling of hydrogen sulfide.

Field tests on all samples included sulfide analysis, pH, temperature, alkalinity, and conductivity. Chlorinated water (full-scale plants or bench and pilot-scale tests where chlorine was used) was tested in the field for total and free chlorine using the DPD method, chloramines and free ammonia were tested in chloraminated samples. Field analyses were also conducted for turbidity, color, UV-254 absorbance, iron, sulfate, and chloride for some of the bench and pilot scale tests. For analyses other than sulfides, samples for field testing were collected in pre-cleaned glass or plastic containers that were pre-rinsed with each sample. Probes (pH, conductivity, sulfide) were calibrated regularly. For spectrophotometric measurements of color and UV-254 absorbance, samples were syringe filtered in the field using a filter with a pore size of 0.2 μm.

Samples for laboratory analysis were collected in pre-labeled containers. Glass containers were used for total organic carbon (TOC) samples, plastic containers were used for samples for metal and anion analysis. Samples were transported to the USF lab and stored at 4 °C until analysis.

Analytical tests

The analytical tests used for this project were intended to provide information about water quality and the effectiveness of different treatment technologies. A summary of the water quality tests used in this project is given in Table 7. Field analyses were conducted at the well site and laboratory analyses were conducted in the USF environmental engineering laboratory.

Bench-scale tests

Bench-scale tests were conducted to evaluate chemical dosages, pH changes associated with different treatment approaches, turbidity formation, and reaction rates. These tests provided an opportunity to compare water quality from the individual wells. Field bench-scale tests were conducted to assess pH and turbidity changes from various dosages of caustic soda, hydrogen peroxide, chlorine, and ammonia. In general, bench-scale tests were conducted using one or two liter batch reactors at each field site. Untreated water was collected and characterized using the field parameters appropriate for the goals of the test. Parallel samples of untreated water were collected and transported to USF for more detailed characterization. At the initiation of each test, the chemicals were dosed into the reactors and samples were collected at specific time intervals for analysis. At the conclusion of the tests, samples were collected for field and/or laboratory analyses.

Bench-scale tests were also conducted to evaluate the use of carbon dioxide injection for pH reduction. Samples for carbon dioxide injection testing were collected in carboys and transported to the lab for testing. Initial levels of pH, alkalinity, and sulfides were determined in the field. Efforts were made to minimize headspace during sample and bench-scale testing was conducted as soon as practicable after testing.

Pilot-scale tests

Pilot scale tests were conducted using a pilot-test trailer constructed by Aloha Utilities for this project. The pilot system was designed to accommodate flowrates up to 2 gpm. The pilot plant consisted of an inflow connection, chemical feed ports, treatment equipment, and sample ports. The pilot treatment system was designed to simulate potential treatment scenarios for the Seven Springs waster system. Clear plastic pipes (2 inch diameter) were used to convey water through the system and provide for observation of air leakage, turbidity formation, and qualitative tracking of dye-studies used for tracer tests. The hydraulic residence time of the system was 25 minutes at 1 gpm. The treatment units that were installed in the pilot plant included two anion exchange tanks, a UV reactor, and a pipeline reactor for in-pipe chemical treatment. Bypass lines were installed to allow for bypass of anion exchange, UV, or chemical feeds. Chemical feed ports and pumps were located immediately after the water intake and at four downstream locations. In-line mixers were installed at the chemical injection ports to ensure adequate chemical dispersion. Sampling ports were located upstream and downstream of each treatment step. A photograph of the pilot plant is shown in Figure 9.

Table 7. Summary of analytical methods used for characterization of water samples from bench-scale and pilot-scale testing.

Test	Field or Laboratory	Method Reference Number (Standard Methods); Instrument	Detection Limit/sensitivity
Alkalinity	Field and Lab	2320 B Titration /Bromocresol green/ methyl red	20 mg/L as $CaCO_3$
Chlorine, total and free	Field	4500-Cl F DPD Colorimetric Method; Pocket Colorimeter II	0.01 mg/L as Cl_2
Conductivity	Field and Lab	HACH Conductivity Probe; Model 51975-03	20 µS/cm
Hydrogen Sulfide	Field	4500-S^{-2} D Methylene Blue Method; Hach Field Spectrophometer Dr/2400	0.1 mg/L as S
pH	Field and lab	HACH Platinum pH Electrode, Model 51910; HACH Portable Multiparameter Meter Sension 156	0.01 pH units
Temperature	Field	HACH Platinum pH Electrode, Model 51910	0.01 °C
Turbidity	Field and Lab	2130B Nephelometric Turbidity	0.01 NTU
Nitrogen			
Ammonia	Lab	HACH-8155	0.01 mg/L
Nitrate	Lab	HACH-8192	0.1 mg/L
Anions			
Chloride	Field and Lab	4140 B. Capillary Electrophoresis with indirect UV detection; Beckman P/ACE 5000 CE or 4500 CL Argentometric titration	1 mg/L
Sulfate	Field and Lab	4140 B. Capillary Electrophoresis with indirect UV detection; Beckman P/ACE 5000 CE or 4500 SO_4 turbidity method	1 mg/L
Metals			
Calcium	Lab	3111 Metals by Flame Atomic Absorption Spectrometry; Perkin Elmer Aanalyst 100	0.01 mg/L
Magnesium	Lab	3111 Metals by Flame Atomic Absorption Spectrometry; Perkin Elmer Aanalyst 100	0.01 mg/L
Iron (total and dissolved)	Lab	3111 Metals by Flame Atomic Absorption Spectrometry; Perkin Elmer Aanalyst 100	0.01 mg/L
Manganese	Lab	3111 Metals by Flame Atomic Absorption Spectrometry; Perkin Elmer Aanalyst 100	0.01 mg/L
Copper (total)	Lab	3111 Metals by Flame Atomic Absorption Spectrometry; Perkin Elmer Aanalyst 100	0.01 mg/L
Total Organic Carbon	Lab	5310C Persulfate-Ultraviolet Oxidation Method; Sievers TOC analyzer	0.05 mg/L
Particle characterization	Lab	Electron Microscopy/ Energy Dispersive Spectroscopy	0.5% (5000 ppm), 1 nm spot size

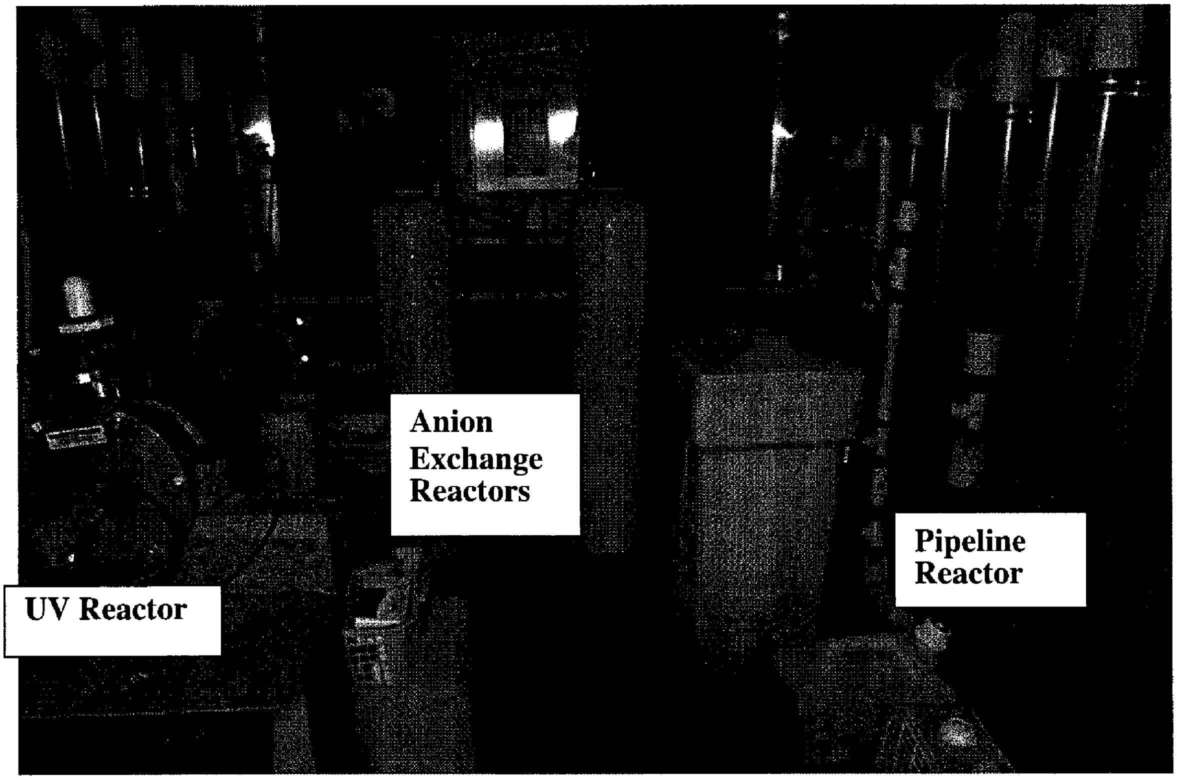


Figure 9. Photograph of inside of pilot treatment trailer showing anion exchange contact tanks, UV reactor, and pipeline reactors.

Tracer tests were conducted in the pilot plant to evaluate flow dynamics. The tests were conducted by injecting either a salt solution or dye into the first chemical injection point. Samples were collected at 30 second intervals from each downstream sampling port and analyzed colorimetrically using a spectrophotometer (for the dye tests) or using a conductivity probe. Photographs of a tracer test in progress through different parts of the pipeline reactor are shown in Figure 10 and an example of the results from a tracer test using a salt solution is shown in Figure 11. Overall, the system was able to simulate plug-flow conditions at a flowrate of 1 gpm.

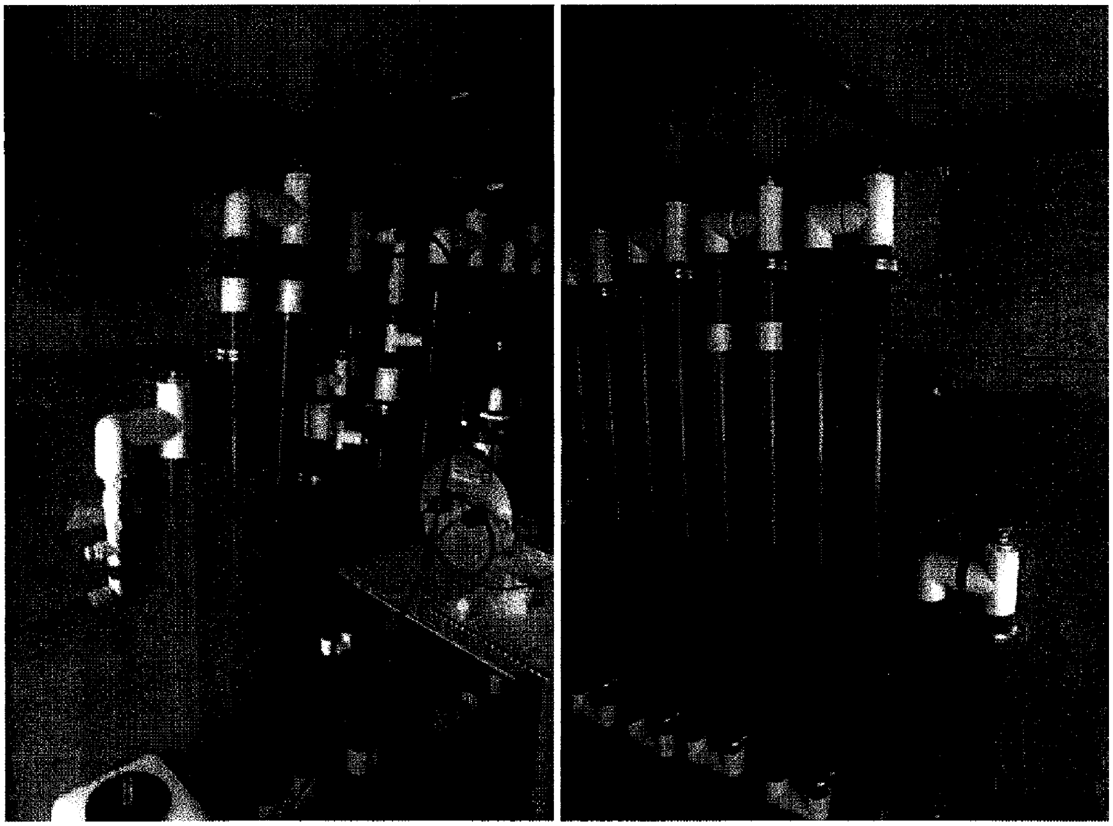


Figure 10. Photographs of tracer tests conducted in pipeline reactor using a green dye to track the flow pathway: a) downstream of UV reactor; b) downstream of chemical injection port.

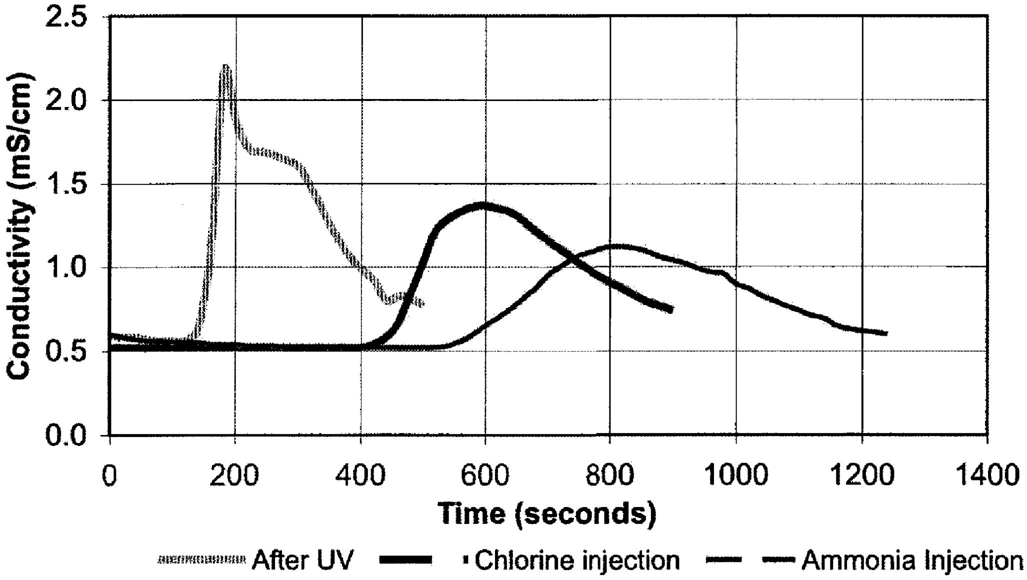


Figure 11. Results from tracer tests conducted in the pilot treatment plant using a slug injection of a salt tracer a) downstream of the UV reactor, b) at the chlorine injection port, and c) at the ammonia injection port. The flowrate was 1 gpm.

pH Control

The effectiveness of many treatment systems for control of hydrogen sulfide is influenced by pH. A summary of optimum pH ranges for each treatment approach is given in Table 8 along with the chemicals used to control pH.

Table 8. Critical pH range for treatment systems

Treatment approach	Optimum pH range	Rationale	pH Control Chemicals
Aeration	<6	Convert hydrogen sulfide into non-ionized form	Carbon dioxide or mineral acids (sulfuric acid)
Anion Exchange	>7	Apply ionized form of hydrogen sulfide to resin	Use ambient pH
Oxidation			
Chlorine	< 7.5	Nonionized form of chlorine is a more potent disinfectant	Use ambient pH
Hydrogen peroxide	> 8	Yields sulfate as an oxidation product from reaction with hydrogen sulfide	Caustic soda
Hydrogen peroxide	<8	Yields elemental sulfur and sulfate as oxidation products from reaction with hydrogen sulfide	Use ambient pH

For this project, bench-scale tests were conducted to determine chemical dosages required to reduce the pH prior to aeration. Bench scale tests were also conducted to evaluate the use of caustic soda for raising the pH. The influence of sodium hypochlorite on pH was also tested for different treatment scenarios.

pH reduction

Batch tests were conducted using water from wells 7, 8, and 9 to evaluate the dose of carbon dioxide or sulfuric acid needed for pH reduction. A photograph of the batch test set-up for carbon dioxide injection is shown in Figure 12. The test was not intended to simulate air stripping, but rather to evaluate chemical dosages needed to achieve a specific reduction in pH. The test system was open to the atmosphere allowing dissipation of excess carbon dioxide and other dissolved gases.

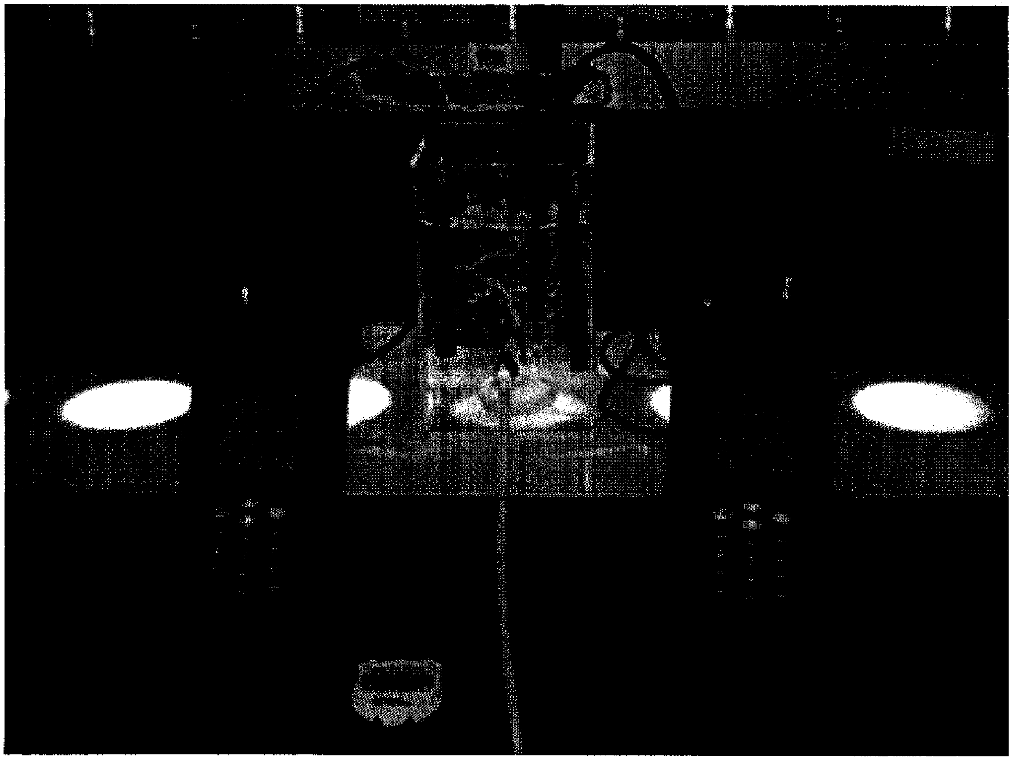


Figure 12. Bench-scale testing of carbon dioxide injection. Carbon dioxide was metered into the lower port of the reactor and mixed into the solution using a diffuser and mixer. Changes in pH, turbidity, and conductivity were monitored.

Results from injection of carbon dioxide into untreated water from wells 8 and 9 are shown in Figure 13. Chemical dosages were also estimated using a software package for corrosion assessment (Rothberg et al. 2000). Based on multiple tests, it appears that a carbon dioxide dose of about 1500 mg/L would be effective for reducing the pH to the appropriate range for aeration. If there is a need to reduce the pH below 6, carbon dioxide would need to be supplemented with a mineral acid. The dose estimated using the RTW software was somewhat lower than the results from the laboratory testing.

The rate of pH change due to carbon dioxide addition is shown in Figure 14. For all of the tested wells, the pH decreased linearly over the first 2 to 3 minutes under the test conditions (temperature of 25 ° C). This information is important in design of aeration systems to ensure that adequate reaction time is available for pH reduction prior to aeration.

Results from addition of sulfuric acid to effect a change in pH are shown in Figure 15. The acid addition yielded a fairly linear decrease in pH. About 80 mg/L of sulfuric acid were needed to reduce the pH to 6. It should be noted that the addition of 80 mg/L of sulfuric acid will result in an increase in the sulfate concentration of 78 mg/L. In evaluating the impacts of aeration on the mass of sulfur in water, about 26 mg/L of sulfur (sulfate) would be needed to effect the removal of 1-6 mg/L of sulfur (nonionized hydrogen sulfide) if sulfuric acid were used for pH control. In addition, it would be necessary to raise the pH after aeration using a strong base (e.g. caustic soda or lime).

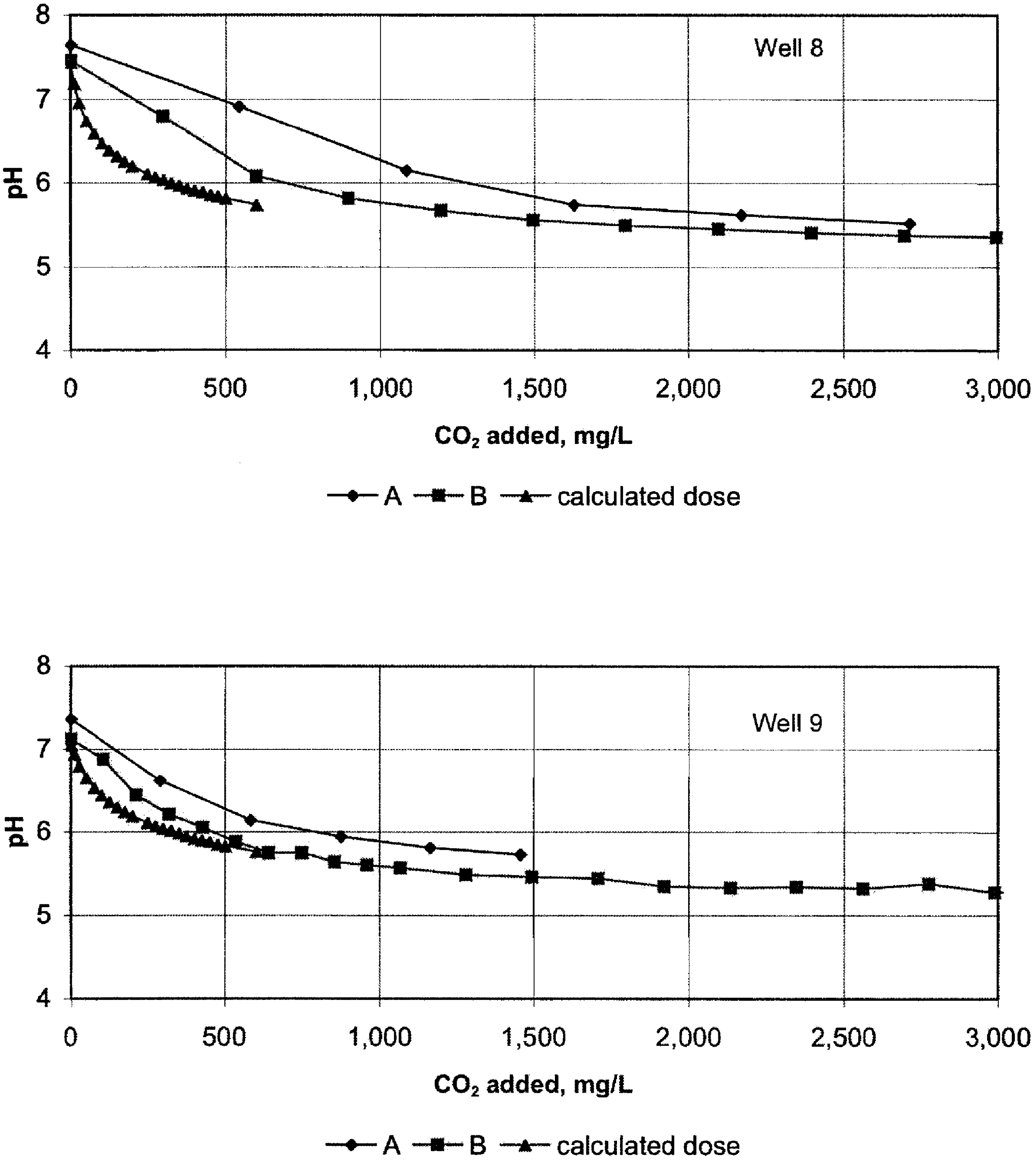


Figure 13. Impact of carbon dioxide injection on pH of untreated water from a) well 8 and b) well 9. A and B refer to replicate analysis. The calculated dose was derived from the RTW spreadsheet program.

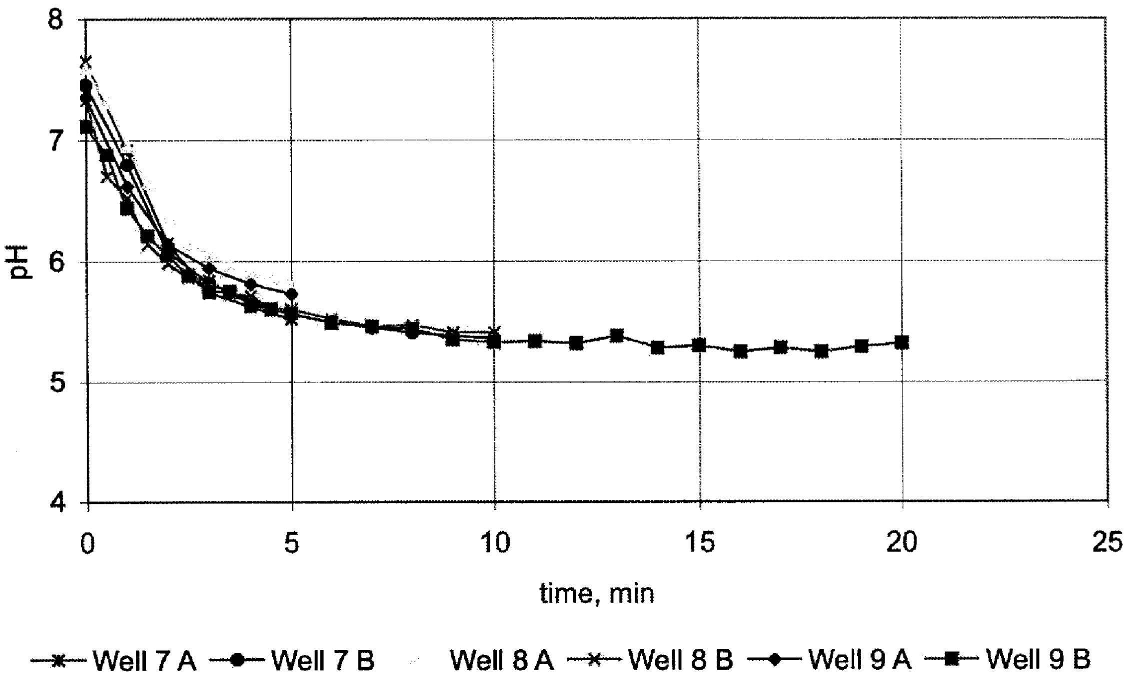


Figure 14. Rate of change of pH in water from wells 7, 8, and 9 due to the addition of carbon dioxide.

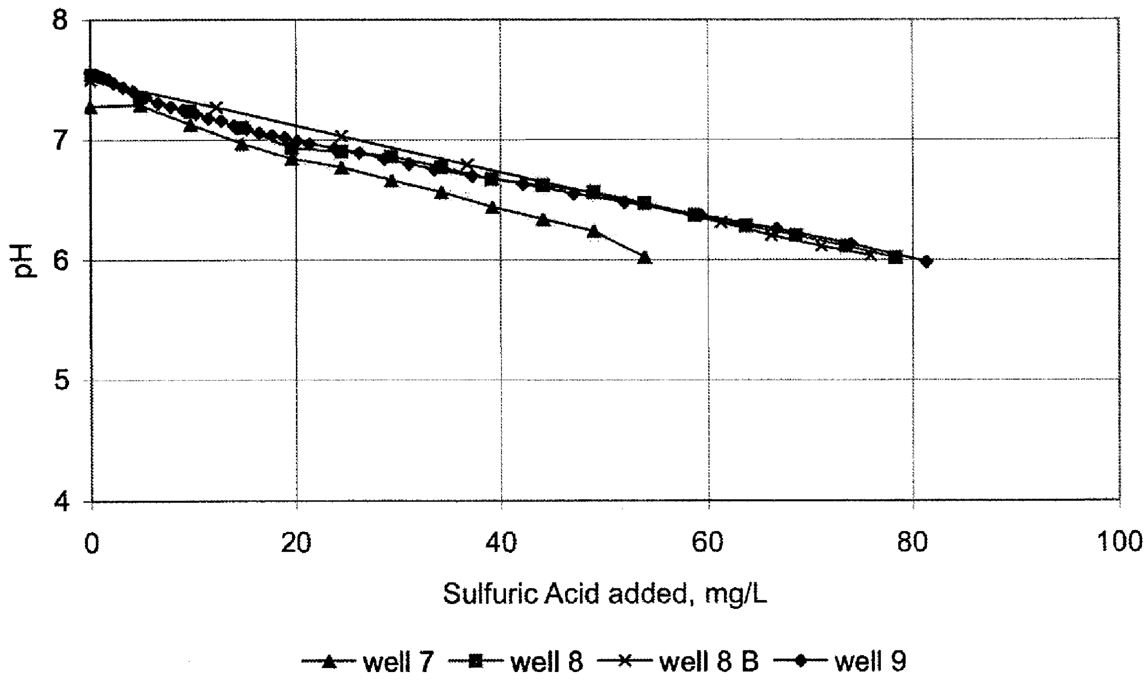


Figure 15. Change in pH due to addition of sulfuric acid to untreated water from wells 7, 8, and 9.

Downstream of aeration, it is important that the pH is restored to a more appropriate value for control of corrosion and water stability in the distribution system. When carbon dioxide is used to lower the pH, some of it will exit the solution during the aeration process resulting in a net increase in pH. If the pH is adjusted using a mineral acid, a higher dose of caustic chemical will be needed for final pH control. Chloramination will result in a slight pH increase, but additional chemicals may be needed downstream of aeration for pH optimization and/or alkalinity adjustment.

pH elevation

For several of the treatment scenarios investigated in this study, the ability to elevate the pH is important, not only to control the form of sulfide in the water, but also to control the reaction products. A complication of raising the pH is the potential for dissolved minerals, such as calcium, to precipitate. Therefore, it is important to assess, not only the chemical dosages needed to control pH for the intended application, but also the potential impacts of the elevated pH on water turbidity. The precipitation potential can also be calculated based on the pH, alkalinity, and calcium content.

Chemicals that can be used to raise the pH include caustic soda and lime. In this project, the use of caustic soda was tested. Results are shown in Figure 16. As shown, there was a linear increase in pH with chemical dose, allowing fairly good control over the pH range of relevance. The impact of chemical dose and elevated pH on turbidity is shown in Figure 17. There were no statistically significant increases in turbidity for water from any of the wells over the time frame of the bench-testing (30 minutes). For these tests, turbidity levels did not rise over background levels of 0.1 to 0.3 NTU.

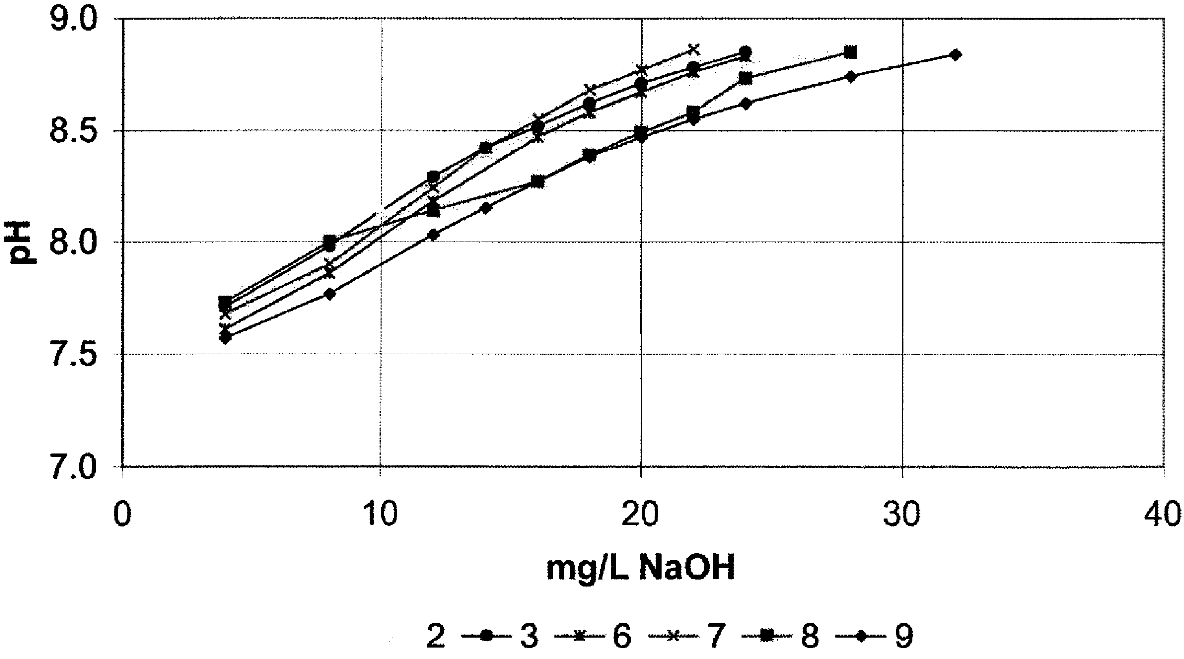


Figure 16. Impact of dose of caustic soda (NaOH) on pH in untreated water from wells 2, 3, 6, 7, 8, and 9.

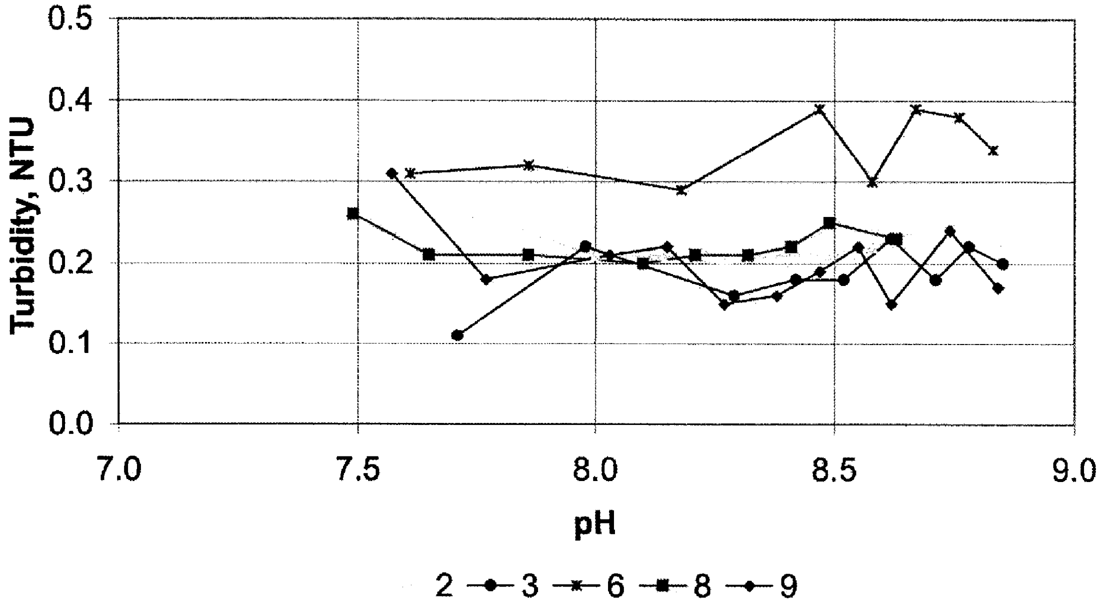


Figure 17. Impact of pH on turbidity in water from wells 2,3,6,8, and 9.

Impact of sodium hypochlorite on pH

In 2005, the disinfection system for the Seven Springs water system was converted from the use of gaseous chlorine to the use of a liquid form of chlorine, sodium hypochlorite. Typically, the addition of gaseous chlorine results in a slight drop in pH between the untreated water and the treated water, depending on the chlorine dose and the alkalinity. However, the use of sodium hypochlorite has the potential to increase the pH because it is a basic solution. Because some of the proposed treatment options for control of hydrogen sulfide require an elevated pH (oxidation processes, anion exchange), it is important to determine the additional pH impacts associated with chlorine addition.

In this project, bench scale tests were conducted to determine the pH impacts from the addition of sodium hypochlorite to untreated water and pH adjusted water from each of the Seven Springs wells. The change in pH as a function of chlorine dose for untreated water and pH adjusted water is shown in Figure 18. Except for wells 8 and 9, there was a linear increase in pH with chlorine dose, however the extent of increase varied for each well with the highest increase associated with water from well 3. When the pH was increased to 8.3 using caustic soda prior to sodium hypochlorite addition, slight pH increases were observed in water from wells 1,3, and 4. In the remaining wells (2,6,7,8,and 9), chlorine addition did not result in a significant change in pH.

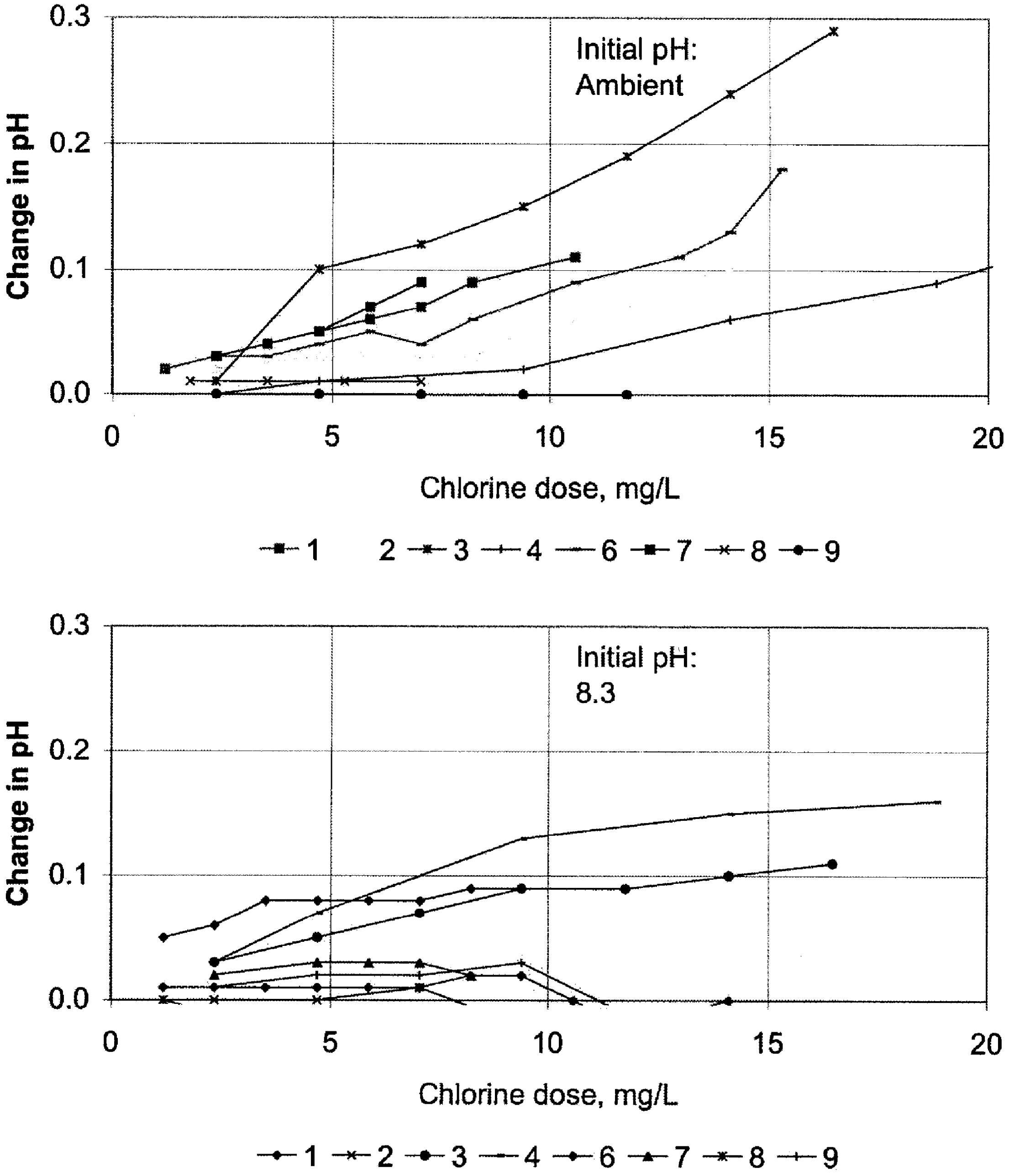


Figure 18. Change in pH as a function of dose of sodium hypochlorite (mg/L as Cl_2) for wells 1,2,3,4,6,7,8,and 9 in the Seven Springs water system a) water at ambient pH, b) water pre-treated with sodium hypochlorite to raise the pH to 8.3.

A comparison of the average change in pH normalized to the chlorine dose is shown in Figure 19 for water from wells 1, 2, 3, 4, 6, 7, 8, and 9. As shown, the pH change associated with chlorine addition varied among the wells, most likely due to differences in alkalinity and other constituents. It should be noted that, currently, the chlorine dosages used in the Seven Springs system serve a dual role. Chlorine functions both as an oxidant chemical for treatment of hydrogen sulfide and other reduced constituents and it also meets disinfection requirements for prevention of microbial growth within the distribution system. After the new treatment technology for control of hydrogen sulfide is implemented, lower dosages of chlorine will be used to treat the water resulting in negligible impacts on the finished water pH.

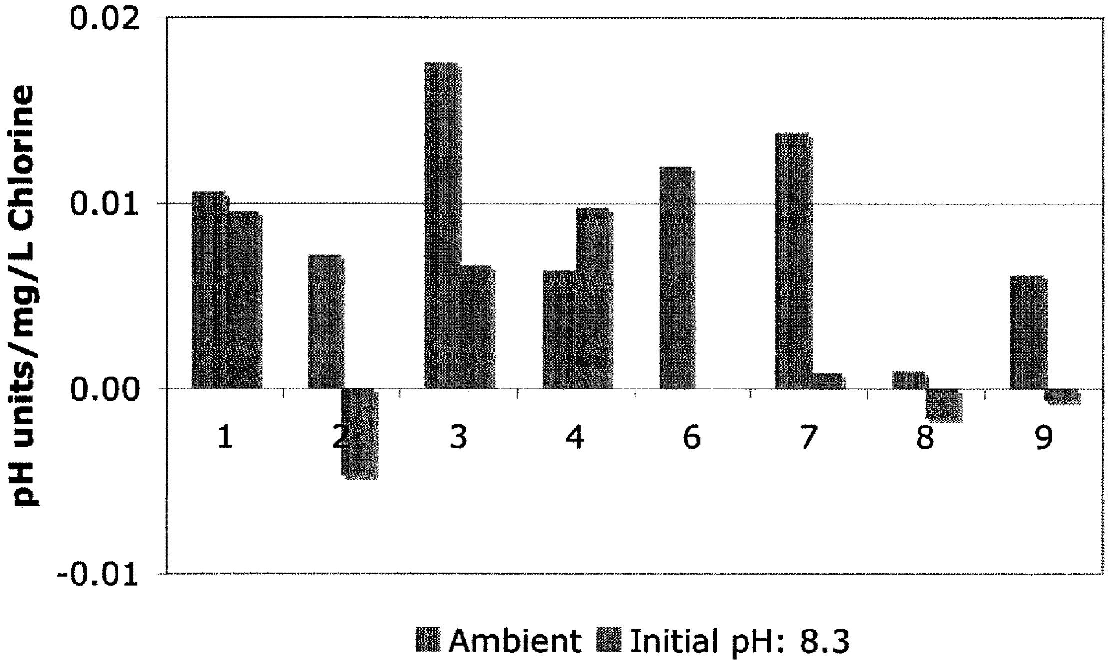


Figure 19. Comparison of the average pH increase (pH per ppm Chlorine added) associated with chlorine addition in water from wells 1,2,3,4,6,7,8, and 9. Chlorine was added to ambient water and to water that was pre-treated with sodium hydroxide to raise the pre-chlorination pH to 8.3.

The alkalinity levels in the individual wells that serve the Seven Springs system vary from about 125 to over 200 mg/L as $CaCO_3$ (see Figure 5). The average change in pH per unit mass of chlorine added is compared to the average alkalinity levels in the individual wells in Figure 20. For water from wells 2, 4, 6, 7,and 9, the pH increase associated with chlorine addition was inversely related to the alkalinity (correlation coefficient, R^2 of 0.96; slope 0.02 pH units/ppm chlorine per 100 mg/L alkalinity as $CaCO_3$). Based on these results, it is important to optimize chemical dosages for the alkalinity range relevant to each well, particularly if pH control is a critical component of the treatment technology to be used for control of hydrogen sulfide.

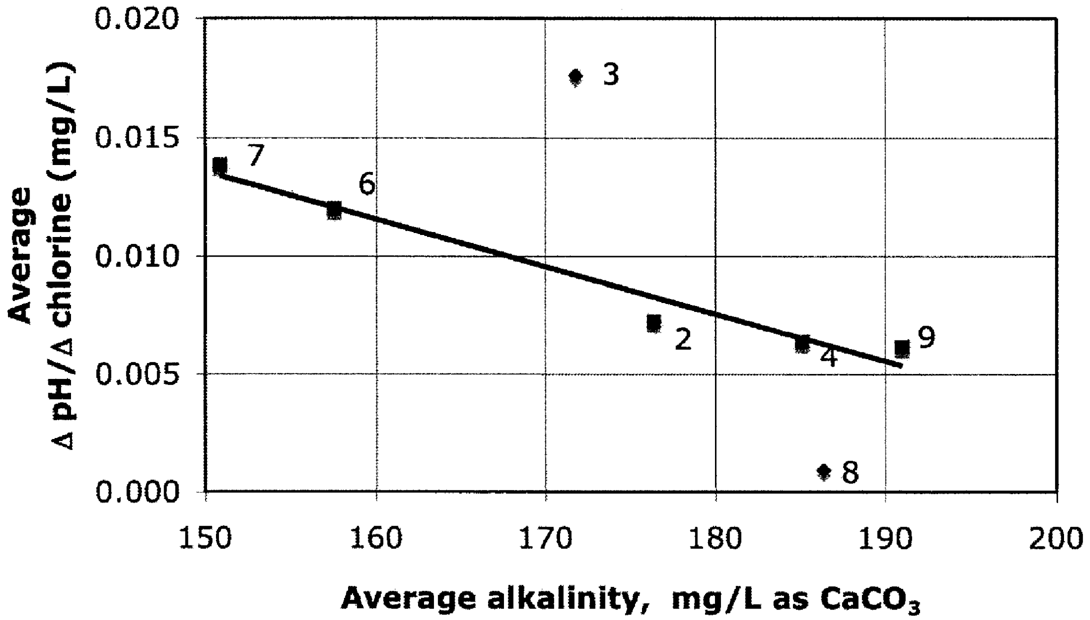


Figure 20. Comparison of incremental change in pH per ppm of chlorine to average alkalinity in untreated water from wells that serve the Seven Springs water system. Well numbers are identified on the graph. The correlation coefficient, R^2, for wells 2, 4, 6, 7,and 9 is 0.96 and the slope is 0.02 pH units/ppm chlorine per 100 mg/L alkalinity as $CaCO_3$.

Evaluation of Sulfide Removal Technologies

One approach for controlling sulfides in water systems is to apply technologies that allow for sulfide removal. Removal of sulfides provides a mechanism for reducing the net mass of sulfur in water and thereby reducing the potential for biological reversion of oxidized sulfur species to sulfides. While it is difficult to remove all forms of sulfur from water, the efficiency of removal technologies is based on the dominant form of sulfur as it moves through the treatment system. Sulfur species can be removed from water as a gas, liquid, or solid. Aeration technologies can be applied to remove the nonionized form of sulfides, H_2S. In general, the removal efficiency of aeration technologies is limited by the amount of nonionized sulfide and the efficiency of gas exchange. Removal of liquid forms of sulfur are based on providing a solid surface to which the sulfides can attach either due to ionic forces, sorption, or chemical precipitation reactions. The primary approach for removal of liquid phase sulfides tested in this project is anion exchange. Other anionic forms of sulfur, such as polysulfides, thiosulfate, sulfite, and sulfates, can be concurrently removed through anion exchange. Solid forms of sulfur include metal sulfides such as iron sulfide or copper sulfide, elemental sulfur, and particulates containing sulfur. Removal of solid forms of sulfur can be accomplished using liquid-solid separation processes such as dissolved air flotation, or filtration (diatomaceous earth, granular media, membranes).

In this project, removal technologies appropriate for the Seven Springs water system were reviewed and evaluated. Because of the wealth of information available about aeration systems, field testing was not conducted. The efficacy of using fixed-bed anion exchange technology was tested using pilot-scale tests. The potential for using solid-liquid separation processes for removal of solid forms of sulfur was evaluated, however field tests were not conducted. Details on each of these removal approaches are provided in this section.

Aeration Technologies

Aeration is a physical/chemical treatment system in which water is exposed to air resulting in removal of dissolved gases and dissolution of oxygen in the water. In aeration systems, nonionized hydrogen sulfide can be removed (stripped) from the water due to gas exchange. The form of hydrogen sulfide removed in stripping reactions is nonionized hydrogen sulfide (H_2S) and it is an odorous gas that can generate nuisance odors in the vicinity of aeration systems. In addition to stripping reactions, secondary reactions occur within aeration systems due to the introduction of dissolved oxygen. Oxidation reactions that occur in aeration systems include hydrogen sulfide oxidation (to either elemental sulfur or sulfate), and iron and manganese oxidation to form oxidized precipitates. Microbiological growth can also occur within aeration systems due to the warm, moist environment and the presence of oxygen and nutrients. Products of the secondary reactions include biofilms and deposits consisting of iron, manganese, and sulfur particles that can foul the internal surfaces of aeration systems and potentially introduce turbidity into the treated water. Sulfates and elemental sulfur formed through biological or chemical oxidation have the potential to revert to hydrogen sulfide as shown in Figure 3.

The overall efficiency of aeration technologies depends on several factors including: the ratio of air to water, water pH, temperature, and aeration system design. Chemicals can be injected to reduce the pH (carbon dioxide or a mineral acid) prior to aeration. The components of aeration systems include: chemical feed equipment, a method for introducing air into water, a treatment reactor that is sized to allow for gas exchange and hydrogen sulfide removal, a scrubber for controlling hydrogen sulfide odors generated by the process, maintenance equipment, and a pump and sump for pressurizing the water downstream of aeration.

Most aeration systems used for water treatment applications are designed for the water to be introduced at the top of an elevated reactor and flow downwards through the reactor. The internal structure of the reactor serves to break up the flowing water to provide for intermingling of air and water. In conventional aeration systems, horizontal platforms or trays are used to break up the flowing water allowing for increased opportunities for air and water contact and gas exchange. Packed tower aeration systems are filled with packing material that provides more effective air/water contact by introducing a more tortuous pathway for the water and air to move through the system.

Air can be introduced into water using spray aerators, natural convection, induced draft, or forced draft. Natural convection relies on the flow of air through the aeration system due to temperature differentials between the top and bottom of the system. Wind currents can also promote natural convection through aeration systems. In general, the efficiency of natural draft systems is limited and is influenced by temperature and wind conditions.

Forced draft or induced draft systems provide a mechanical means for moving air through the aeration system allowing for more consistent air flow and improved air stripping efficiency for removal of nonionized hydrogen sulfide as compared to natural draft aeration. In forced draft aeration, a blower is used to introduce air into the bottom of the tower, while induced draft systems use a fan to pull air through the tower. While tray towers can be operated with either natural or forced draft aeration, higher removal efficiencies can be achieved if forced draft aeration is used (depending on pH and air-to-water ratios). In contrast, it is not possible to operate packed towers effectively with natural draft aeration. Either forced draft or induced draft aeration is necessary for packed tower aeration systems because the packing material within the tower restricts the natural convection of air through the tower. A comparison of the aeration systems recommended for removal of hydrogen sulfide by the FDEP is given in Table 9.

Table 9. Comparison of aeration systems recommended by FDEP (Chapter 62-555.315(5)[a].

Type of system	Method of water introduction	Method of air introduction	Packing material	Hydraulic loading	Height, ft	Air to water ratios	Practical efficiency
Conventional							
Tray towers	Applied to top of tower through pressurized distribution system and allowed to cascade over trays	Natural draft	Trays	7-15 gpm/ft^2	12-16	30-80 to 1	30-50%, depending on pH, temperature, and wind patterns
Spray towers	Sprayed through a nozzle and released as droplets	Natural or forced draft	Trays	1-10 psi			50-70%, depending on pH, temperature
Conventional aeration with Forced draft	Distribution system	Use of blowers and/or fans	Trays	7-15 gpm/ft^2	12-16		50-70%, depending on pH, temperature
Packed tower with forced draft	Distribution system or nozzles	Use of blowers and/or fans	Plastic packing material	25-30 gpm/ft^2	15-30	80-120 to 1	50-90%, depending on pH, temperature

[a] Adapted from Crittenden 2005, HDR 2005, Health Education Services 2003, and Letterman 1999.

Because aeration systems have been adopted by many communities for control of hydrogen sulfide and significant design data exists, these systems were not tested as part of this project except for evaluating chemical requirements for pH control (see previous section of report) and overall impacts on chlorine demand. However, it should be noted that several factors impact the feasibility of using these systems for treating water from the Seven Springs system. Because the existing treatment plants are located on relatively small sites in residential neighborhoods, it is essential that nuisance odors and noise generated through the process be controlled effectively. With the exception of the treatment plant at the ground storage facility (Mitchell Road), the other sites lack adequate space to house the aeration and scrubbing equipment. In addition, the Seven Springs water system operates in response to pressure demands within the system and therefore the high-service pumps at each well cycle on and off in response to water demand. It is likely that the frequent on/off cycling of pumps associated with the method of well-site operation will compromise process efficiency and impact the extent to which biofilms and mineral deposits develop within the packing material. If an appropriate site were available in the Seven Springs service area, the development of a centralized facility in lieu of treatment at individual well sites would obviate some of the issues associated with the limited availability of space and the proximity of residential neighborhoods.

Anion Exchange

Ion exchange technology is a treatment process that removes constituents from water that are charged (ions) by reversibly entrapping the ions on a solid surface or resin. Ions entrapped on the surface are exchanged with other ions. Typically, ion exchange technologies are designed to remove positively charged ions (cations) or negatively charged ions (anions). Resins have a finite capacity for exchanging ions and once the resin is saturated, it can be regenerated and put back into service.

Ion exchange technology is a relatively mature technology and has been used for purifying water for centuries (Owens 1995, Thompson and McGarvey 1953 Wachinski and Etzel 1997). For water treatment applications, cation exchange is widely used for point-of-use water softening. Typically, in cation exchange systems, sodium (or potassium) is exchanged for hardness ions (calcium and magnesium).

Over the past ten years, spurred by increasingly stringent water quality requirements coupled with advances in resin production, the use of anion exchange technology has been adopted by many water utilities to remove negatively charged constituents including nitrates, arsenic, organic compounds, and/or other anionic contaminants such as perchlorate. In most anion exchange systems used for drinking water applications, chloride is exchanged for anionic constituents in the water. An electron micrograph of the characteristics of one of the anion exchange resins tested in this project is shown in Figure 21. The resin consists of macroporous spherical particles ranging in size from about 100 to 800 μm. The majority of ion exchange reactions occur on the resin surface and the available surface area impacts the capacity of the system for removing anions from water. There is some potential for surface adsorption to occur, but it is difficult to quantify these reactions (Crittenden et al. 2005, Crepaldi et al. 2000, HDR 2005, Letterman et al. 1999, Owens 1995).

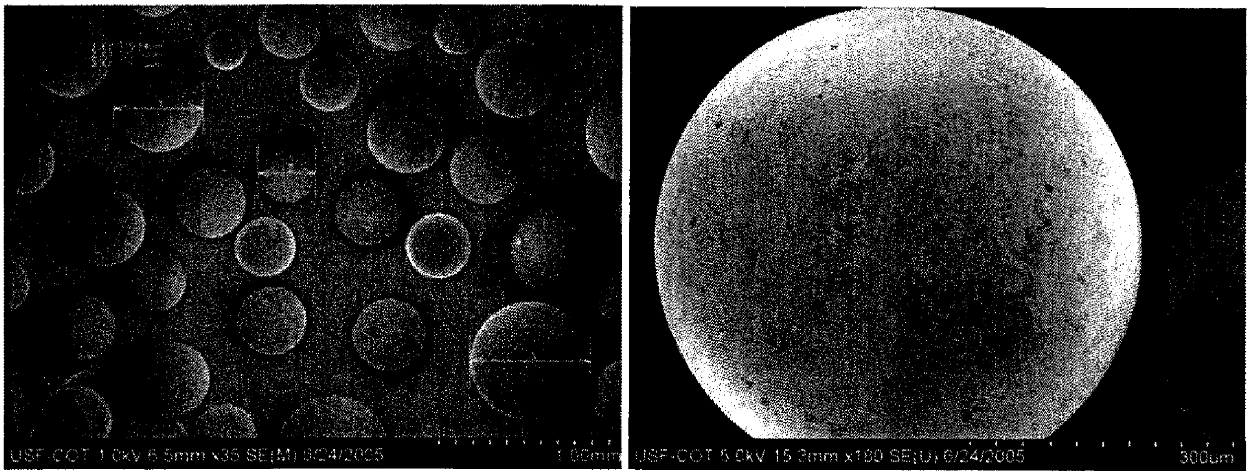


Figure 21. Scanning Electron Micrographs of Anion Exchange Resin used for testing sulfide removal from water from the Seven Springs water system.

For removal of hydrogen sulfide from water, the use of anion exchange capitalizes on the fact that, under pH ranges typical of groundwater, the majority of the sulfides are in an anionic form (HS^-, S^{-2},, polysulfides, thiosulfate, sulfite). There are a variety of anion exchange resins commercially available that have been used in water treatment applications and have been approved by the National Sanitation Foundation (NSF).

Anion exchange systems can be designed to operate as a fixed-bed column or as a completely mixed reactor. The choice of reactor type depends on the specific application. The advantage of fixed-bed columns is that they can be operated without breaking suction between the well and the reactor, thus preventing the introduction of other contaminants and eliminating the need for repressurization. Completely-mixed systems and fluidized bed systems have also been developed for water treatment applications, such as MIEX™ systems. The effectiveness of MIEX™ resin for removal of hydrogen sulfide from the Seven Springs source water was demonstrated in 2001 (Porter 2002). Completely-mixed systems generate a continuous waste stream and require more space than fixed-bed columns. In addition, there is frequently a need for filtration to prevent resin carryover.

Another advantage of fixed-bed systems over completely-mixed systems is that the reactor design provides more efficient contact between the resin and the water due to the plug-flow conditions. In general, the distribution of hydrogen sulfide between nonionized and ionized forms is controlled by pH and can be described by the equation below (see Figure 5):

$$nH_2S \leftrightarrow HS^- + bS_n^{-2} + H^+ \leftrightarrow S^{-2} + (n-b)\,S_n^{-2} + (n-1)H^+$$

As the ionized forms of sulfide are removed, the residual nonionized hydrogen sulfide re-equilibrates. As the water passes through the resin bed, the ionized forms of sulfide (and other anions) are removed, decreasing the mass of sulfur remaining in the water. As the total mass of sulfur decreases, the residual sulfide species will be redistributed to meet the new equilibrium condition. Thus, while up to 80% of the sulfide is ionized under ambient conditions (see Figure 6), it is possible to remove over 90% of the sulfide through fixed-bed anion exchange due to the sequential reactions that occur. To achieve a similar degree of removal in a complete-mix system, it would be necessary to operate the system as a series of individual complete-mix reactors.

An example of the theoretical effect of sequential reactions is shown in Figure 22 for three initial concentrations of sulfides (1, 3, and 6 mg/L) at two pH levels (7.5 and 8.0). After reaching equilibrium with the anion exchange resin during the initial contact, 24% of the sulfides would be remaining in the water at pH 7.5 while only 9% would be remaining at pH 8. After 3 sequential resin-equilibration steps, the concentration of sulfides would be below detection limits regardless of the initial concentration (1-6 mg/L) or the initial pH (7.5-8). Thus, by designing a fixed-bed column to optimize contact between the water and the resin, this treatment technology is capable of highly efficient removal of sulfides (and other anions). Once the resin in a fixed-bed reactor is saturated, it needs to be taken off-line for about a 2 hour period for regeneration. The use of multiple reactors in parallel can provide for uninterrupted treatment during the regeneration process. The waste stream generated by the process is typically discharged to a sanitary sewer for treatment.

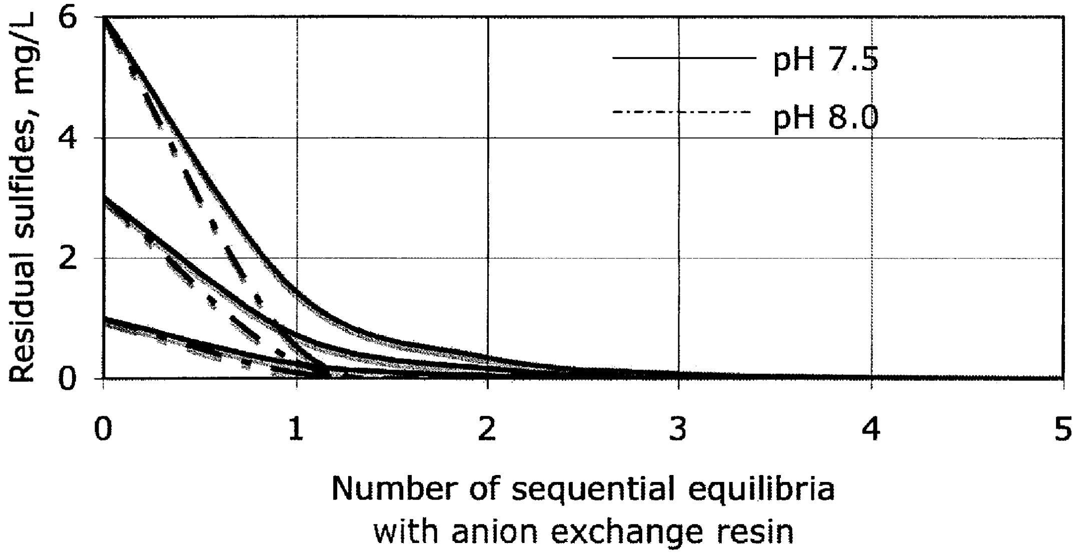


Figure 22. Comparison of theoretical residual sulfide levels in water treated by anion exchange at different initial concentrations of sulfide (1,3, and 6 mg/l) and different initial pH levels (7.5 and 8.0).

There are several installations of fixed-bed anion exchange systems in Florida for treatment of groundwater (e.g. Lantana, Pembroke Pines). These systems were designed for removal of color and organic carbon and have been operating successfully for several years. While the Florida anion exchange installations were not directly designed for control of hydrogen sulfide control, their effectiveness for treatment of Florida groundwater is well documented.

In addition to removing ionized hydrogen sulfide from water, additional benefits of anion exchange technology include removing other negatively charged constituents including sulfate, organic carbon, and turbidity. Because sulfate is an integral component of the sulfur cycle (see Figure 3), removing sulfate has the advantage of reducing the total mass of sulfur introduced into the distribution system. Sulfate and organic carbon levels in wells from the Seven Springs system are compared in Figures 23 and 24. In general, sulfate levels are relatively low in all of the wells compared to the SDWA secondary MCL of 250 mg/L. Typically the highest levels of sulfate are associated with water from well 9 with concentrations over 20 mg/L. Organic carbon levels in most of the Seven Springs wells range from 2 to 4 mg/L, a range typical for Florida groundwater. While organic carbon is not regulated in groundwater systems, it can contribute to the formation of disinfection byproducts and biofilm growth. Thus, reduction in the amount of organic carbon can decrease the potential to form disinfection byproducts and also improve the overall water quality.

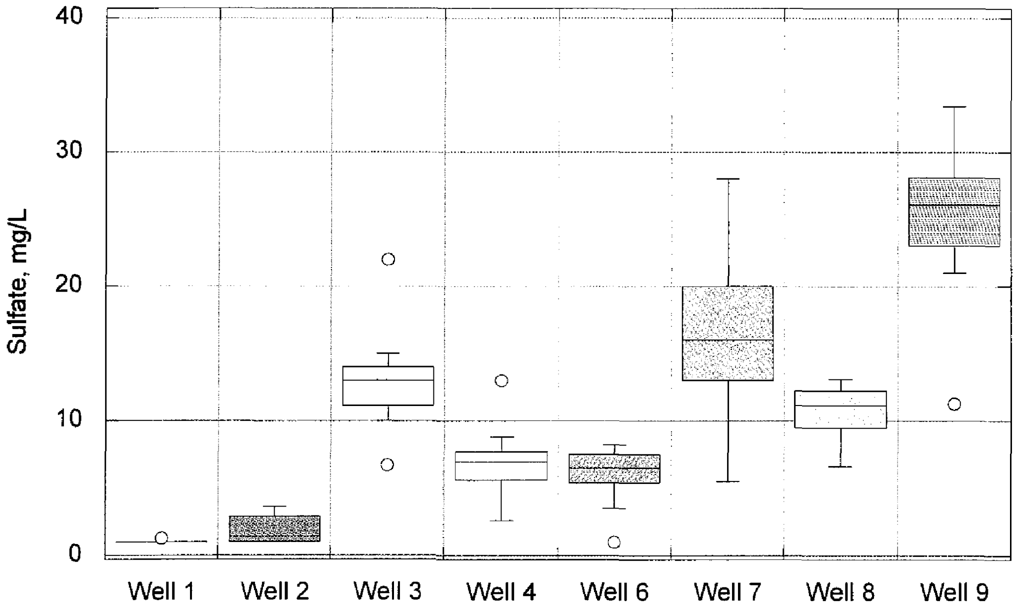


Figure 23. Boxplot comparison of sulfate levels in untreated water from wells that serve the Seven Springs water system. Data from 1998-2005.

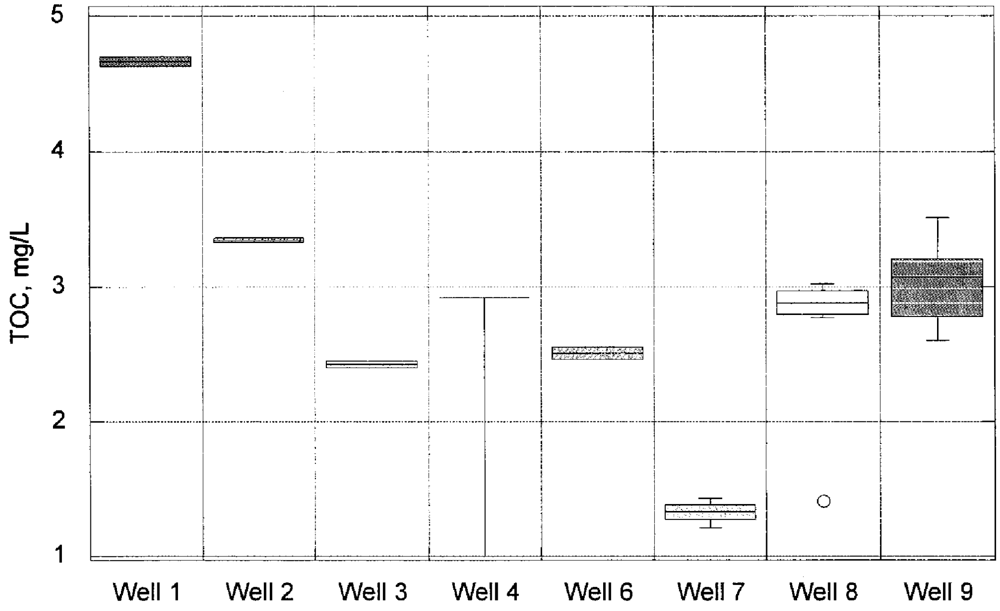


Figure 24. Boxplot comparison of organic carbon levels (TOC) in untreated water from wells that serve the Seven Springs water system. Data from 2002-2005.

The other water quality parameter impacted by the use of anion exchange technology is chloride. Chloride is exchanged for the anions removed from water so the chloride content will increase in proportion to the concentration of the anions removed. The use of anion exchange will result in an increase of about 1 mg of chloride per mg of hydrogen sulfide removed and about 0.7 mg per mg of sulfate removed. For water containing 3 mg/L of sulfides and 20 mg/L of sulfate, the chloride level would increase by about 17 mg/L due to anion exchange. In contrast, chlorination of water containing hydrogen sulfide results in an increase in the chloride content from 5 to 8 mg per mg of hydrogen sulfide oxidized. Thus, the chloride levels in a water containing 3 mg/L of sulfides would increase from 15 to 24 mg/L from chlorination. It is hard to predict chloride changes associated with removal of TOC or polysulfides. A comparison of the chloride levels in untreated water from the Seven Springs system is given in Figure 25. With the exception of well 7, chloride levels are typically below 20 mg/L. The secondary MCL for chloride is 250 mg/L and no water quality or distribution system problems are anticipated from the slight increase in chloride from anion exchange. In fact, chloride levels from some of the wells are likely to be lower than the levels in the water currently available in the Seven Springs system resulting from chlorine oxidation of hydrogen sulfide (Levine 2003).

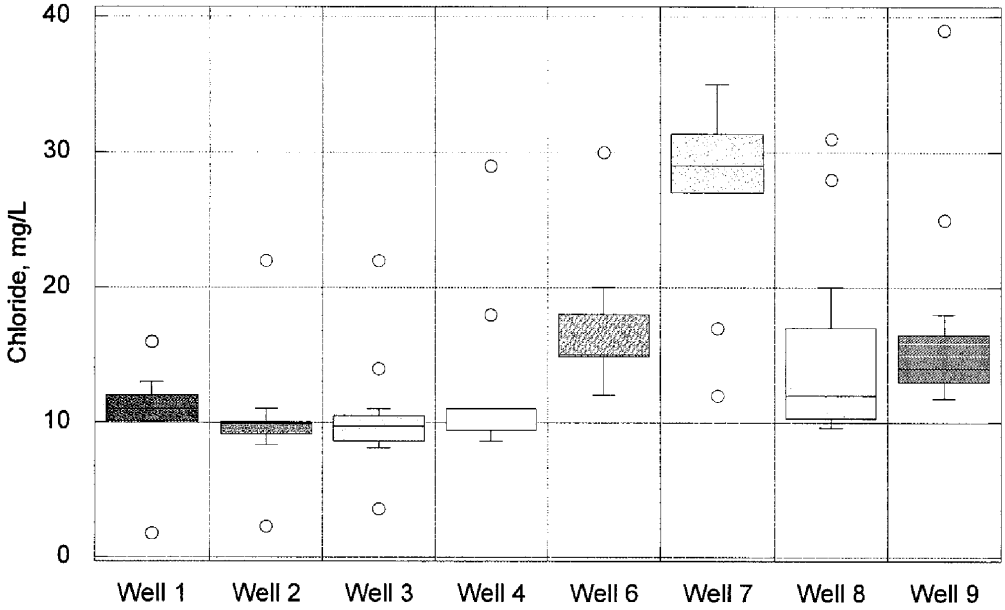


Figure 25. Boxplot comparison of chloride levels in untreated water from wells that serve the Seven Springs water system. Data from 1998-2005.

In this project, the efficacy of using fixed-bed anion exchange technology for removal of hydrogen sulfide from the Seven Springs water system was tested using a 1 gpm pilot plant. The initial tests were targeted at well 9 because it has the highest level of total sulfides compared to the other wells (see Figure 1).

Initially, screening tests were conducted using two commercially available anion exchange resins. These initial tests were conducted to evaluate the efficacy of using in-line anion exchange technology for treating water from the Seven Springs system and were intended to yield preliminary performance information on the relative effectiveness of two different commercially available NSF approved strong-base resins.

A photograph of the anion exchange contactors used in this study is shown in Figure 26 (Sta Rita; Park International; Long Beach, CA, model RT-948, Serial number 120604B: Regeneration model 5600). The units are 48 inches high with a 9 inch diameter. Each was filled with about 1 cubic foot of resin with a bed depth of about 2 ft. The characteristics of the resins are given in Table 10. The systems were operated at a flowrate of 1 to 2 gallons per minute resulting in a hydraulic loading rate of 2 to 4 gpm/ft^2 with an empty bed contact time (EBCT) of less than one minute.

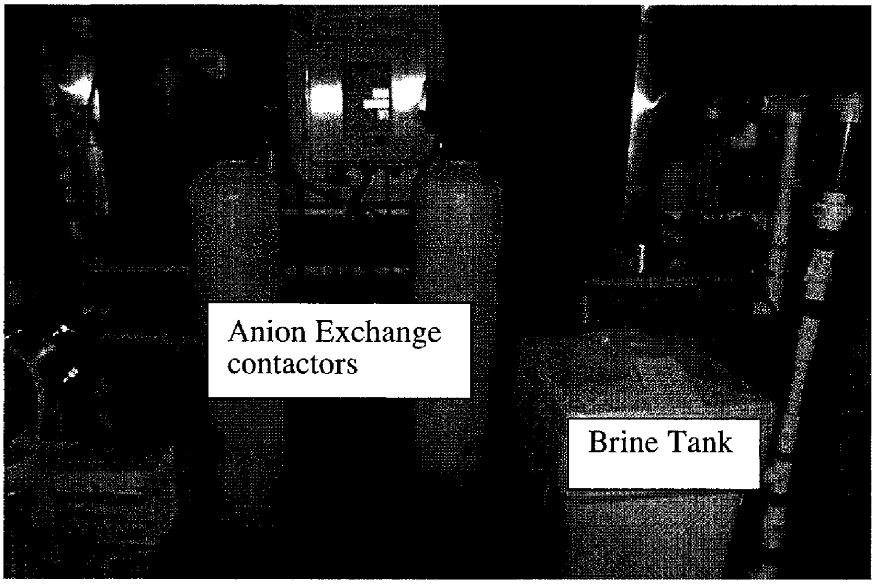


Figure 26. Anion exchange contactors used in pilot-plant testing (9 inch diameter, 48 inches high, 1 ft^3 of resin).

Table 10. Parameters of anion exchange resins tested in this project (from manufacturers' literature and MSDS sheets)

Parameter	Resin A	Resin B
Matrix structure	Macroporous Strong-base Cross-linked polystyrene	Porous Styrene with divinyl benzene (DVB)
Functional Group	Quarternary ammonium	$R-N-(CH_3)_3^+Cl^-$
Exchange capacity	1 meq/mL	not given

Each of the contactors was operated semi-continuously over a several week period. Field monitoring of hydrogen sulfide, sulfate, chloride, UV_{254} absorbance, color, alkalinity, pH, turbidity, and conductivity was conducted on samples from the anion exchanger inflow and outflow. Supplemental laboratory testing was conducted to evaluate concentrations of organic carbon, iron, calcium, magnesium, silica, aluminum, and total nitrogen in the untreated and treated water. Chlorine and ammonia were added downstream of anion exchange to evaluate chlorine demand and pH impacts associated with chloramination. The resins were regenerated using a brine solution.

Both of the resins that were tested in the screening tests were effective at removal of hydrogen sulfide. A summary of water quality changes due to anion exchange is shown in Figure 27. The resins were effective at reducing hydrogen sulfide and sulfate to below detection levels. Organic carbon removal ranged from 70-85%.

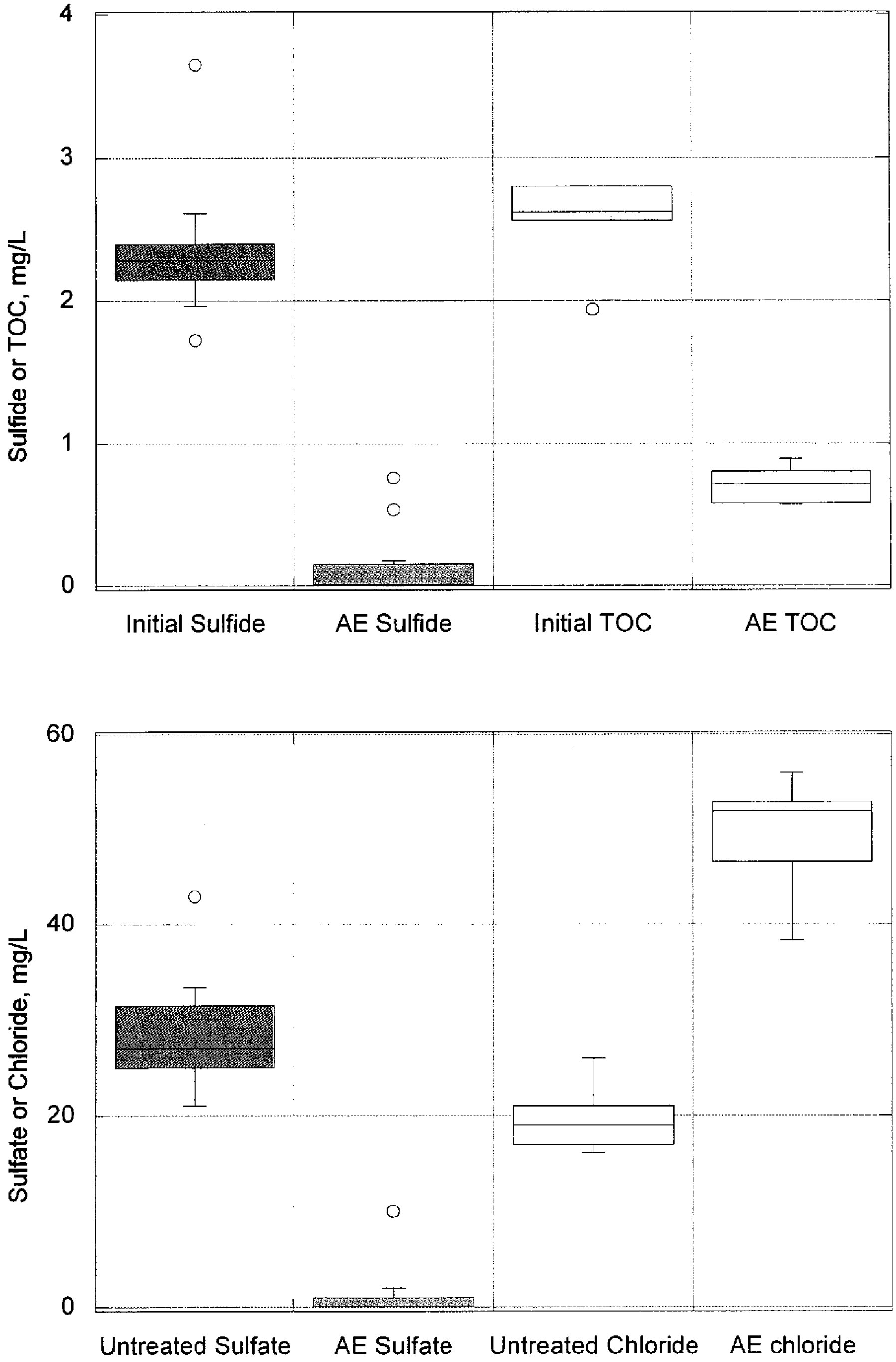


Figure 27. Comparison of impacts of anion exchange(AE) on a) hydrogen sulfide, organic carbon (TOC) and b) sulfate, and chloride in pilot tests conducted on water from Well 9 during the summer of 2005.

A comparison of the removal efficiency of one of the anion exchange resins for hydrogen sulfide, organic carbon (TOC), and turbidity is shown in Figure 28. The initial sulfide level for these tests ranged from 2 to 3 mg/L and the hydrogen sulfide in the effluent was at or near the detection limits. TOC removal was fairly consistent and ranged from 70 to 80% over the testing period. Turbidity removal was more variable due to the fluctuations in particle characteristics (size, concentration, and composition) associated with the untreated water. It should be noted that the system used for these preliminary tests was not hydraulically optimized. Further testing is in progress to evaluate the service cycle of the resin for each of the source waters.

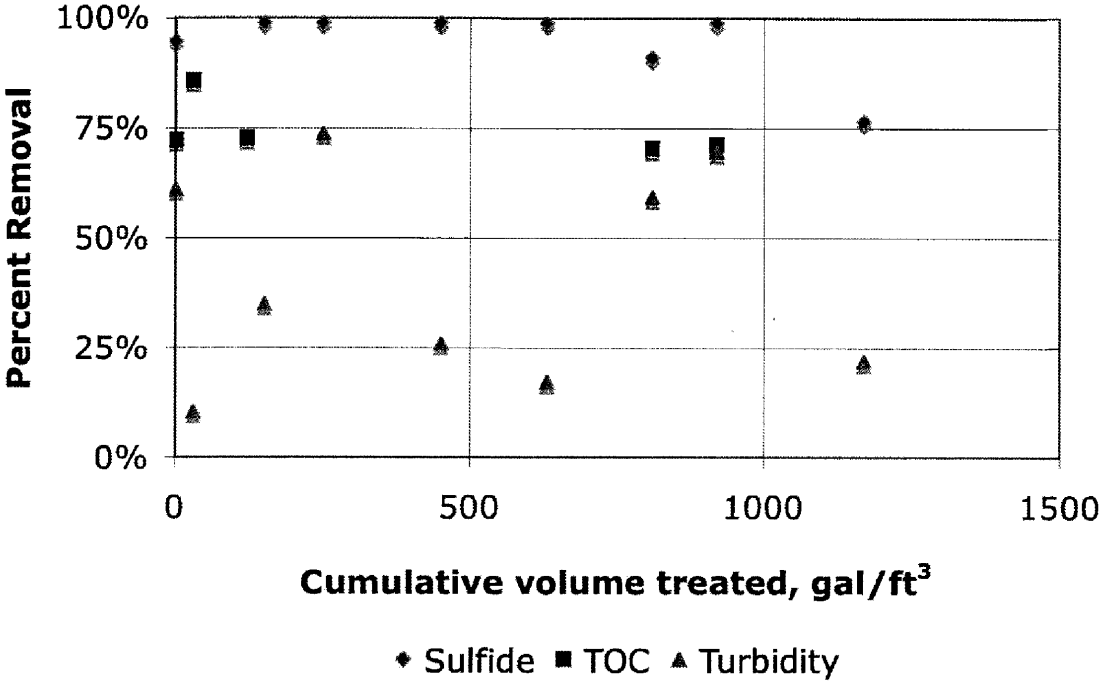


Figure 28. Percent sulfide removal following anion exchange treatment of water from well 9 as a function of volume of water treated in pilot treatment unit. Influent sulfide concentrations ranged from 2 to 3 mg/L.

Another benefit of using anion exchange to remove hydrogen sulfide is a net reduction in the chlorine demand. Over the course of this study, the chlorine demand after anion exchange varied from about 0.2 to 6 mg/L for samples containing no detectable hydrogen sulfide as compared to chlorine demand levels of over 24 mg/L for the untreated water. Another issue that was evaluated in the preliminary tests was the impact of chlorination on pH. A summary of pH changes associated with addition of chlorine to water from well 9 that had been treated by anion exchange is shown in Figure 29 as a function of chlorine dose and chlorine demand. As shown, the maximum pH increase was less than about 0.3 pH units.

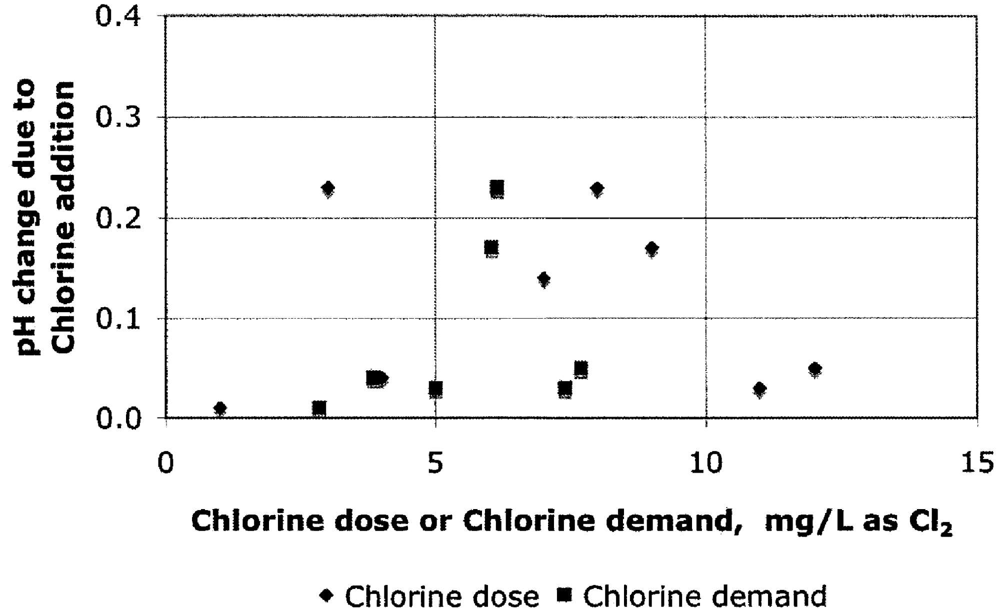


Figure 29. Comparison of incremental pH change associated with addition of chlorine to water from well 9 following treatment by anion exchange.

Development of detailed design and submittal of permit applications will require specific information pertaining to the service cycle and regeneration requirements at each well site. This information will be derived from in-line reactors sited at each treatment location. The in-line reactors are hydraulically similar to full-scale fixed-bed contactors in terms of hydraulic loading rate, empty bed contact time (EBCT), flow-conditions (plug-flow) and the method of application of water to the resin.

Solid-liquid separation

Another approach for removal of sulfides from water is to convert the sulfides to an insoluble form that can be removed by solid-liquid separation processes. Methods for converting sulfides to an insoluble form include biological sulfur oxidation, chemical oxidation, metal precipitation, or adsorption. Solid-liquid separation processes include dissolved-air flotation or filtration. Sand filters (Levine 2004a,b) and membrane filters (Reiss et al. 2003) have been used in pilot tests to remove particulate forms of sulfur and other particulate matter from groundwater, but there are no full-scale operations that have adopted this hydrogen sulfide control approach. Because of the multiple-steps involved in developing these treatment systems, they are better suited to be operated at centralized treatment facilities than at well-sites to allow for centralized process control. In addition, the well sites in the Seven Springs system lack adequate space and capacity to manage the waste streams (filter backwash) associated with this treatment approach. Therefore, the use of solid-liquid separation for controlling hydrogen sulfide in the Seven Springs system was not tested in this study.

The use of green-sand filtration has been proposed for control of hydrogen sulfide levels ranging from 1-5 mg/L (Brune and Perez 1990). Green-sand consists of granular media coated with manganese dioxide. The coating serves as a catalyst for oxidation of hydrogen sulfide and the oxidation products are either elemental sulfur or sulfate as shown below where Z represents the green-sand media (Brune and Perez 1990):

$$\text{Z-MnO}_2 + \text{H}_2\text{S} \rightarrow \text{Z-Mn}_2\text{O}_3 + \text{S}^\circ + \text{H}_2\text{O}$$

Once the manganese dioxide has been consumed, the system is regenerated using potassium permanganate ($KMnO_4$). Loading rates that have been reported range from 5-10 gpm/ft^2, however backwash rates of 15 gpm/ft^2 are needed to remove colloidal sulfur trapped within the filter. While these systems have been reported to work on a small-scale (Brune and Perez 1990), they are not appropriate for the Seven Springs system for several reasons. First, a method is needed for disposal of the backwashing and regenerant solutions. Second there is a strong potential for carryover of manganese from the filter reactions. The release of manganese dioxide or reduced manganese (Mn^{+2}) can result in undesirable water quality problems in the distribution system. Due to these constraints and water quality concerns, this type of treatment was not evaluated as part of this project.

Oxidation technologies for control of hydrogen sulfide

Oxidation technologies involve the addition of an oxidant to water to allow for chemical reactions to occur between the oxidant and hydrogen sulfide to yield more oxidized forms of sulfur including elemental sulfur and sulfate. Oxidation technologies are considered to be conversion technologies since they act to convert the sulfide to another form rather than removing it from the water as is the case for aeration, anion exchange, and solid/liquid separation. Collectively, oxidation technologies are the most common treatment approach for controlling hydrogen sulfide in groundwater. These systems have an advantage since they can be designed to operate in-line and can readily fit on most well sites. In addition, oxidant chemicals can also function as disinfectants.

Overview of Oxidation Reactions

A summary of hydrogen sulfide oxidation reactions is shown in Table 10. The most common oxidant used for groundwater treatment is chlorine. Other chemicals that are effective for oxidation of hydrogen sulfide include ferrate, hydrogen peroxide, ozone, and potassium permanganate. For drinking water applications, ozone and potassium permanganate have been used at various locations. Hydrogen peroxide is widely used in industrial applications and is also used in some drinking water systems in conjunction with ozone or UV irradiation in advanced oxidation processes for oxidation of trace organics. Ferrate has been used in industrial applications (Sharma et al. 1997).

The addition of an oxidant chemical to water serves to increase the oxidation potential and promote oxidation of reduced sulfur and other minerals. The products of the oxidation reaction depend on the pH of the water, reaction rates, and chemical equilibria. Because sulfur can exist in several oxidation states, the final form of oxidized sulfur is dependent on an array of factors. A predominance area diagram for some sulfur species is shown in Figure 30. In predominance area diagrams, the dominant form of each constituent is identified for all combinations of pE and pH (Benjamin 2002, Stumm and Morgan 1996). It should be noted that these diagrams do not provide information on the relative concentrations of each constituent, but rather provide insight into the species that are thermodynamically favored at equilibrium under specific pE and pH conditions. When oxidants are added to water, the oxidation potential increases favoring a more oxidized form of sulfur. pH control can be used to modify the water matrix and can also impact the form of sulfur. As shown, elemental sulfur tends to be favored in a fairly narrow range of pH and oxidation potential.

The addition of oxidant chemicals serves to increase the oxidation potential (pE) of a water, thus causing a vertical shift upwards in Figure 30. The extent of increase depends on the type of chemical added, the dose, and water quality constituents that may react with the oxidant, reducing the net oxidation potential available for control of hydrogen sulfide. Different oxidant chemicals have different oxidation potentials. A comparison of the oxidation potential of chemicals appropriate for use in the Seven Springs system is shown in Figure 31. The highest oxidation potential is associated with hydroxyl radicals (OH•) formed from the use of multiple oxidants such as ozone and hydrogen peroxide or hydrogen peroxide and UV. Ozone has the second highest oxidation potential and hydrogen peroxide has a slightly lower oxidation potential than ozone. Oxygen has the lowest oxidation potential. The oxidation potential associated with chlorine addition depends on the form of chlorine (hypochlorous acid, hypochlorite ion, monochloramine).

In general, oxidation reactions are somewhat nonspecific, in that chemicals can mediate oxidation reactions for sulfur species and other reduced minerals (iron and manganese), react with organics, and react with microorganisms (disinfection). For sulfide oxidation, it is important to use a chemical dose sufficient enough to mediate the reaction and satisfy oxidant demands associated with competing reactions. Because it is difficult to identify all potential competing reactions, it is important to conduct testing of oxidation reactions.

Table 11. Comparison of stoichiometric chemical reactions for oxidation of hydrogen sulfide[a]

Oxidant	Oxidation Reaction	Dose, mg/mg H_2S
Chlorine		
	$H_2S + Cl_2 \rightarrow S^o + 2HCl$	2.08
	$H_2S + 4H_2O + 4\,Cl_2 \rightarrow H_2SO_4 + 8\,HCl$	8.33
Ferrate		
	$4H_2S + 3HfeO_4^- + 7H^+ \rightarrow 3Fe^{+2} + S_2O_3^{-2} + 2S^o + 9H_2O$	2.66
	$16H_2S + 20HfeO_4^- + 10H_2O \rightarrow 20Fe(OH)_3 + 3H_2S_2 + SO_3^{-2} + 3S_2O_3^{-2} + 3SO_4^{-2} + 6OH^-$	4.44
Hydrogen peroxide		
	$H_2S + H_2O_2 \rightarrow S^o + 2H_2O$	1.03
	$HS- + 4H_2O_2 \rightarrow SO_4^{-2} + 4H_2O + H^+$ (pH>8)	4.11
Oxygen		
	$HS^- + 2O_2 \rightarrow SO_4^{-2} + H^+$	1.88
	$2HS^- + 2\,O_2 \rightarrow S_2O_3^{-2} + H_2O$	0.94
	$H_2S + 3/2O_2 \rightarrow SO_3^{-2} + 2H^+$	1.41
	$2H_2S + O_2 \rightarrow 2S^o + 2H_2O$	0.47
Ozone		
	$S^{-2} + 4O_3 + 4H_2O \rightarrow SO_4^{-2} + 4O_2$	5.64
Potassium Permanganate		
	$3H_2S + 2KmnO_4 \rightarrow 3S^o + 2MnO_2\ 2KOH + 2H_2O$	3.09
	$3S^{-2} + 8KmnO_4 + 4H_2O \rightarrow 8MnO_2 + 3SO_4^{-2} + 8KOH$	12.39

[a]From Black and Goodson (1952), Cadena and Peters (1988), Chen and Morris 1972, Dohnalek et al.(1983), Hoffman et al. (1977), Morse et al. (1987), Sharma et al. (1997), and Sullivan et al. (1988)

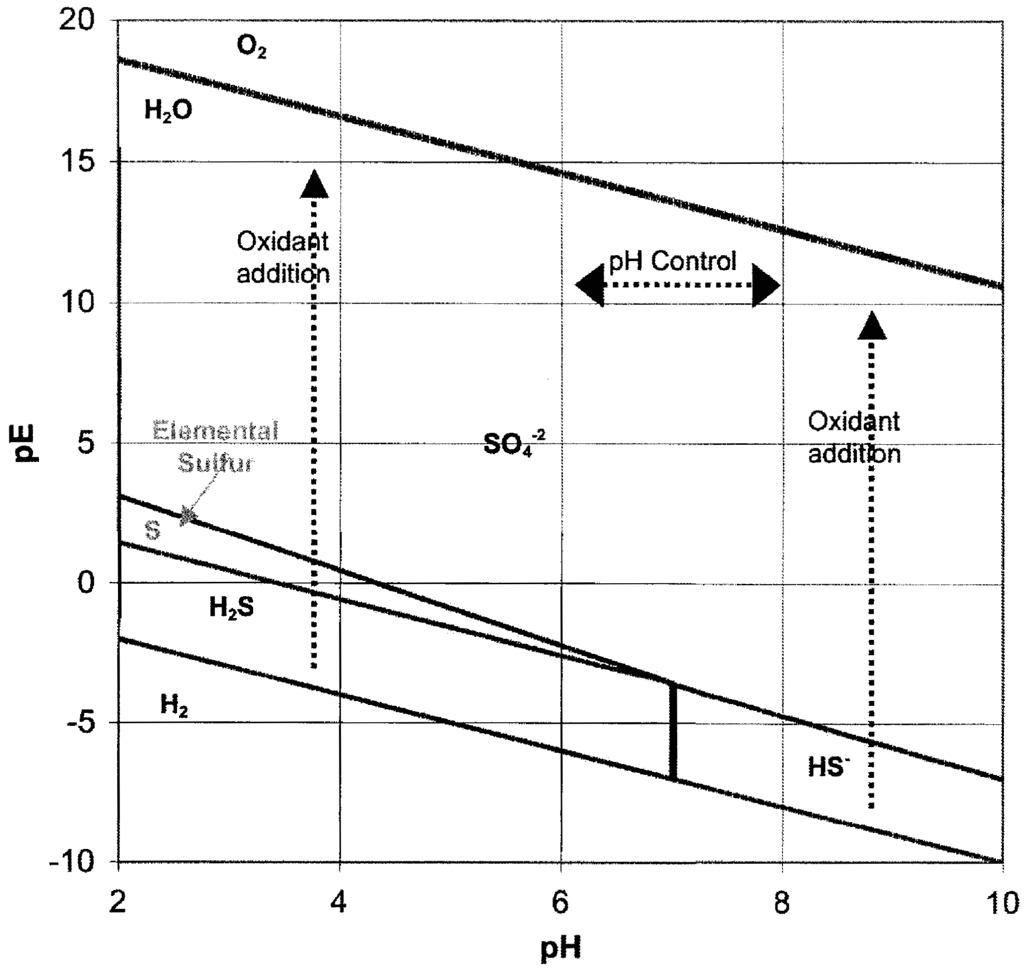


Figure 30. Predominance area diagram showing the theoretical equilibrium forms of sulfur as a function of oxidation potential (pE) and pH. Thermodynamic constants from Stumm and Morgan 1999. (pE is equal to the log of the equilibrium constant normalized to one electron transfer)

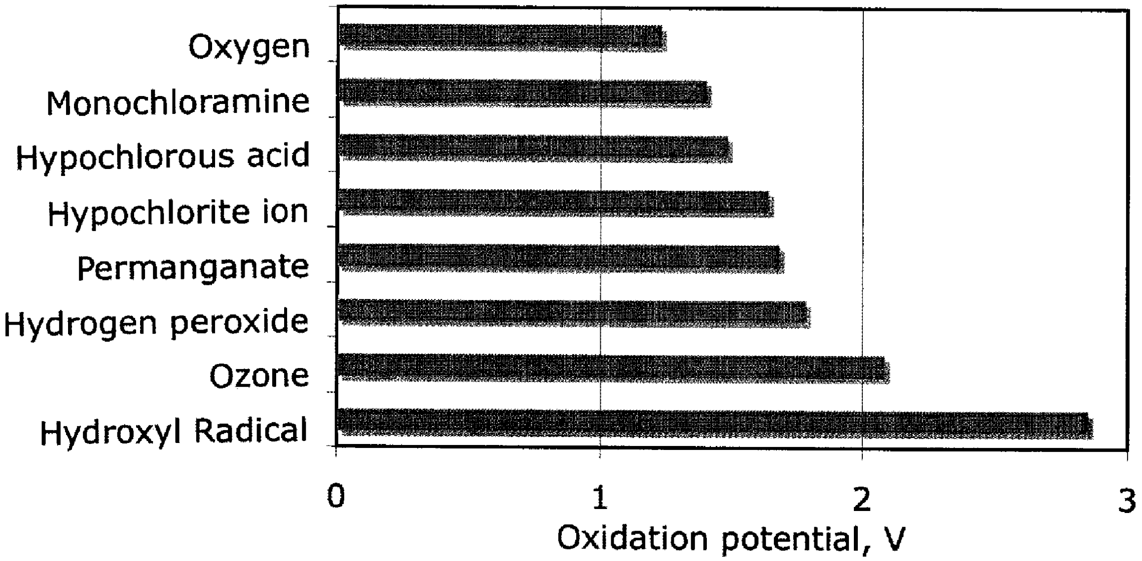


Figure 31. Comparison of oxidation potentials associated with oxidant chemicals used for chemical oxidation of hydrogen sulfide. The oxidation potential is reported in terms of volts per single electron transfer.

The selection of an oxidant chemical is based on its ability to react with hydrogen sulfide, the net oxidation potential it can impart to water, the potential for side-reactions, and the cost (chemical, feed system, and process controls). Hydrogen sulfide oxidation reaction rates have been quantified (Cadena and Peters 1988, Dohnalek and Fitzpatrick 1983, Duranceau et al. 1999, Nielsen et al. 2003, Sharma et al. 1997, Sullivan et al. 1988, Tomar and Abdullah 1994) and reactions with individual oxidants such as chlorine (Black and Goodson 1952, Lyn and Taylor 1992, White 1999), hydrogen peroxide (Hoffman 1977, Millero et al. 1989), and oxygen (Chen and Morris 1972, O'Brien and Birkner 1977) have been widely studied. Advanced oxidation reactions using two oxidants to generate hydroxyl radicals have also been studied in groundwater systems, but these studies have not directly addressed the fate of hydrogen sulfide (Acero and Von Gunten 2001, Duguet et al. 1989, Lee et al. 2004, Wang et al. 2000, 2001).

A summary of information on reported reaction rates and reaction products is given in Table 12. Reactions have been described as zero order, first order, and intermediate order with respect to sulfide depending on the oxidant, the water matrix, and the reaction pH. In many studies, rates are determined by monitoring the reduction of hydrogen sulfide, but limited information is available on reaction products. In other studies, rates are deduced by monitoring the disappearance of the oxidant. In general, reported reaction rates vary with pH, most likely due to the dominant form(s) of sulfide present and the type(s) of reaction products or reaction intermediates that are produced. Sulfide oxidation is susceptible to both catalytic (from iron) and inhibitory effects (Nielsen et al. 2003). As can be seen by this brief overview, while oxidation reactions can be fairly complex, the distribution of products appears to be related to reaction pH and the water matrix. However, because of differences in source water chemistry it is important to determine reaction rates specific for the reaction conditions and water quality.

Table 12. Summary of information on reaction rates associated with hydrogen sulfide oxidation

Oxidant	Reaction rate constant	Comments	Reference
Chlorine	Rate influenced by pH and other water quality parameters; no specific value reported	Rapid initial oxidation to sulfur; consecutive reaction to sulfate. Rate affected by pH and ratio of chlorine to sulfide. Maximum rate at pH<5.	Black and Goodson 1952
Hydrogen peroxide	0.12/min	Oxidation under acidic conditions results in elemental sulfur formation	Cadena and Peters 1988
Hydrogen peroxide	pH 6.8: 0.15-0.3 /min pH 8.1: 2.69/min	Higher rates of sulfate formation associated with higher pH levels and higher ratios of H_2O_2 to sulfide	Hoffman 1977
Hydrogen peroxide	0.13/min	Rate increased with pH (up to pH 8) and ionic strength suggesting the possibility of metal catalysis and that the ionized form of hydrogen sulfide (HS-) is more reactive	Millero et al. 1999
Iron	0.3(L/g-min)$^{0.5}$	Combined oxidation and precipitation reactions	Poulton et al. 2002
Oxygen	H_2S: 0.01 M/h HS^-: 2.5 x 10^7 M/h	Sequential reaction based on the amount of elemental sulfur available	Chen and Morris 1972
Oxygen	pH 4: 0.524 L/M-min pH 10: 2.24 L/M-min	First order with respect to sulfide, 0.8 order with respect to oxygen; Reaction products included sulfate, thiosulfate, and sulfite (elemental sulfur was not evaluated)	O'Brien and Birkner 1977
Oxygen	H_2S: 80 L/ M-h HS^-: 344 L/m-h	If pH > 8, rate independent of pH. Ionic strength did not affect rate	Millero and Hershey 1989

Several researchers have suggested that sulfide oxidation is a stepwise process with the final products dependent on the initial reaction. Several studies have reported that polysulfides can proliferate if elemental sulfur is available (Barbash and Reinhard 1989, Chen et al. 1972, Hoffman 1977, Kotronarou and Hoffman 1991). However, the formation of polysulfides tends to be negligible if the pH is over 9 as in lime softening processes (White 1999). An example of a chain reaction is shown below and is initiated by ionized reduced hydrogen sulfide (HS^-) reacting with elemental sulfur (oxidant) to form di-, tri-, and tetra- polysulfides:

$$HS^- + S^o \rightarrow S_2^{2-} + H^+$$
$$S_2^{2-} + S^o \rightarrow S_3^{2-}$$
$$S_3^{2-} + S^o \rightarrow S_4^{2-}$$

It has also been suggested that sulfites, thiosulfate, and sulfate are formed from sequential reactions, but the rates are much slower than the initial formation of elemental sulfur and polysulfides (Chen et al. 1972, Nielsen et al. 2003). O'Brien and Birkner (1977) found that tetra- and penta-polysulfides predominated in neutral (pH 7) and alkaline solutions. Other factors that have been reported to impact reaction rates and reaction products include the ratio of oxidant to hydrogen sulfide, the presence of organics and other oxidizable constituents, pH, biological activity, and temperature (Afonso and Stumm 1992, Barbash and Reinhard 1989, Black and Goodson 1952, Cadena and Peters 1988, Chen et al. 1972, Dohnalek and Fitzpatrick 1983, Duranceau et al. 1999, Hoffman 1977, Kletzin 1989, Kotronarou and Hoffman 1991, Lyn and Taylor 1992, Millero and Hershey 1989, Millero et al 1989, Morse et al. 1987, O'Brien and Birkner 1977, Poulton et al. 2002, Rickard 1985, Sharma et al. 1995, Sullivan et al. 1988, Tomar and Abdullah 1994, White 1999), White (1999) suggests using a multi-step oxidation process that involves addition of chlorine to form elemental sulfur and polysulfides followed by addition of metabisulfite or sulfur dioxide to form thiosulfate, then addition of more chlorine to convert the thiosulfates to sulfate. While this chemical addition sequence may be effective for producing sulfate, it should be noted that the addition of metabisulfite serves to introduce another source of sulfur into the water matrix increasing the potential for sulfide reversion.

One goal of this project was to identify practicable oxidant reactions that will promote the formation of sulfate and minimize the formation of turbidity. As shown in Figure 30, sulfate formation is thermodynamically favored under alkaline pH conditions (>7), while elemental sulfur may form under acidic conditions. However, results reported in published studies have reported contradictory information on the formation of elemental sulfur. Lyn and Taylor (1992) reported that the extent of sulfur turbidity formation from groundwater chlorination is related to the chlorine to sulfide ratio and the pH, with higher levels of turbidity observed at higher pH levels. However, they did not identify the elemental composition of the particulate matter formed during the testing.

Based on previous studies and practical constraints associated with the Seven Springs system, the oxidants evaluated in this project included chlorine, hydrogen peroxide, UV irradiation, and combined oxidants hydrogen peroxide-chlorine, hydrogen peroxide-chlorine. Ozone was not evaluated due to safety concerns about ozone generation at the well-sites and the relative costs of ozone as compared to the other oxidant chemicals.

Chlorine is the most widely used oxidant chemical because of its relatively low cost and its widespread use for disinfection. For many water systems, chlorine serves a dual role as an oxidant for hydrogen sulfide and other reduced constituents in addition to providing primary disinfection. In other cases, chlorine serves as a supplemental oxidant to react with residual hydrogen sulfide from other treatment technologies such as aeration.

Over the past few years, chlorination practices have undergone significant changes due to several factors. Historically, gaseous chlorine was the major source of chlorine used by utilities. However, safety and security concerns associated with on-site storage of gaseous chlorine have prompted utilities to convert to the use of liquid chlorine (sodium hypochlorite). A side effect of converting from gaseous to liquid chlorine is that the pH of chlorination tends to be higher than gaseous chlorine based systems. The higher pH impacts the form of chlorine in the water and the oxidation potential. It also affects the distribution of oxidized sulfur species (elemental sulfur, sulfate).

A comparison of the distribution of nonionized (HOCl) and ionized (OCl^-) chlorine species as a function of pH is shown in Figure 32 in comparison to the pH range of the Seven Springs water system. Among the forms of chlorine used in water treatment, the oxidation potential of the hypochlorite ion (OCl^-) is about 10% higher than the oxidation potential of hypochlorous acid (HOCl) (see Figure 31). Because pH impacts the form of hydrogen sulfide in water (see Figure 4), the stability of various sulfur oxidation states (see Figure 30), the form of chlorine that reacts with reduced forms of sulfur, and the availability of metal catalysts such as iron, it is not surprising that contradictory information on reaction products has been reported. For the Seven Springs system, a slight variation of pH will impact the speciation of chlorine and sulfur species, further complicating the analysis.

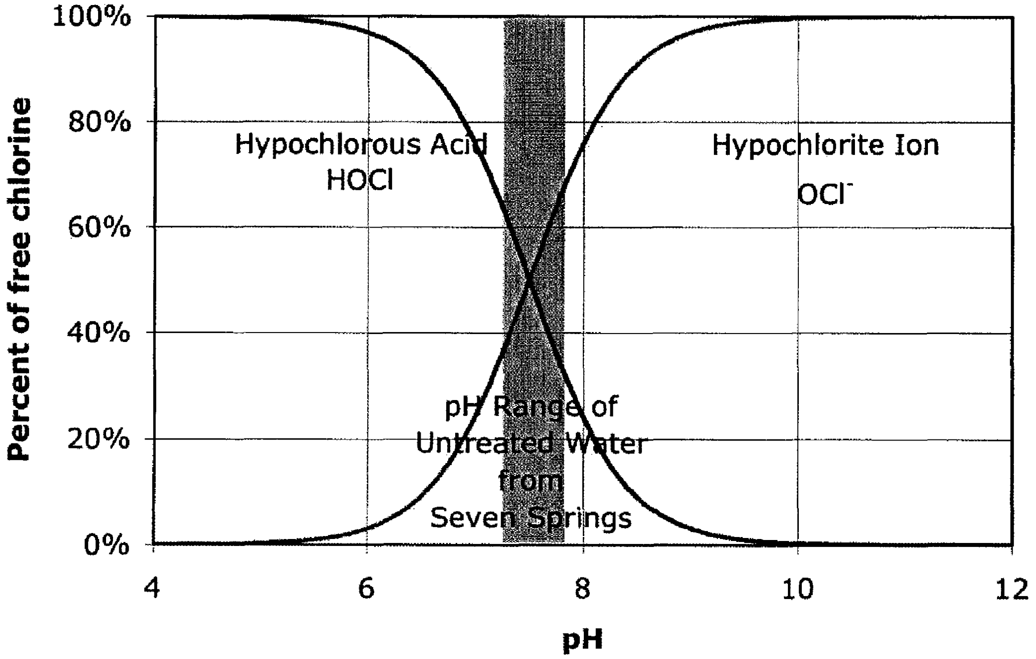


Figure 32. Comparison of distribution of chlorine species as a function of pH.

Another change in chlorination practices was spurred by recent changes in the SDWA that relate to the formation of disinfection byproducts. It is widely known that chlorine reacts with organics in water to form an array of organic byproducts including trihalomethanes (THMs) and haloacetic acids (HAAs). Recently the MCLs for THMs and HAAs have become more stringent. To prevent formation of THMs and HAAs, treatment technologies can be implemented to reduce the concentration of organic precursors in water. Alternatively, chloramines can be used as a secondary disinfectant to control biological activity within the distribution system. It is widely recognized that chloramines are less reactive than free chlorine and consequently form lower levels of THMs and HAAs. Many water systems have converted to the use of chloramines as a secondary disinfectant. Aloha Utilities is in the process of implementing chloramine conversion. As shown in Figure 31, chloramines have a lower oxidation potential than either hypochlorous acid (HOCl) or hypochlorite ion (OCl^-). Taken together, the use of liquid chlorine coupled with the use of chloramines necessitates more effective control of hydrogen sulfide to ensure that oxidation or removal is complete prior to the addition of ammonia.

Oxidation tests conducted on Seven Springs water

As part of this project, the impacts of using sodium hypochlorite on hydrogen sulfide reactions were evaluated under different pH conditions. In addition, the efficacy of using alternative oxidants, hydrogen peroxide and UV irradiation was tested. A summary of the oxidation tests conducted for this project is given in Table 13.

Table 13. Summary of oxidation tests conducted on water from the Seven Springs system

Oxidant	pH	Goal
Sodium hypochlorite	Ambient	Develop baseline kinetics for sodium hypochlorite oxidation of hydrogen sulfide; Evaluate chlorine demand; Assess turbidity formation
Sodium Hypochlorite	8-8.5	Develop reaction kinetics and assess turbidity formation
Hydrogen peroxide	7.5-8.5	Develop reaction kinetics as a function of pH; Assess characteristics or particulate matter formed in process
UV	Ambient	Develop reaction kinetics
Hydrogen peroxide followed by UV	7.5-8.5	Develop reaction kinetics as a function of pH; Assess characteristics or particulate matter formed in process
Hydrogen peroxide followed by chlorine	7.5-8.5	Develop reaction kinetics as a function of pH; Assess characteristics or particulate matter formed in process
Hydrogen peroxide followed by UV followed by chlorine	7.5-8.5	Develop reaction kinetics as a function of pH; Assess characteristics or particulate matter formed in process

Chlorine oxidation reactions

Currently, chlorine oxidation is the primary method used for control of hydrogen sulfide in the Seven Springs water system. In this project, bench-scale and pilot-scale tests were conducted to evaluate the role of pH, chlorine dose, and reaction conditions on hydrogen sulfide oxidation. These tests were intended to provide baseline conditions that could be used to compare the alternative control technologies currently under investigation.

As a starting point, the amount of chlorine used to satisfy all of the oxidation reactions or "chlorine demand" can provide an indirect measure of the quantity of oxidizable constituents in the untreated water and it can be calculated by comparing the amount of chlorine applied and the amount of chlorine remaining (residual):

Chlorine demand = Chlorine dose - Chlorine residual

A comparison of the chlorine demand associated with untreated water from each well is given in Figure 33. Because the dominant contributor to chlorine demand is hydrogen sulfide, chlorine demand parallels sulfide levels with the highest chlorine demand associated with water from well 9 and relatively low chlorine demand is associated with water from wells 1 and 7.

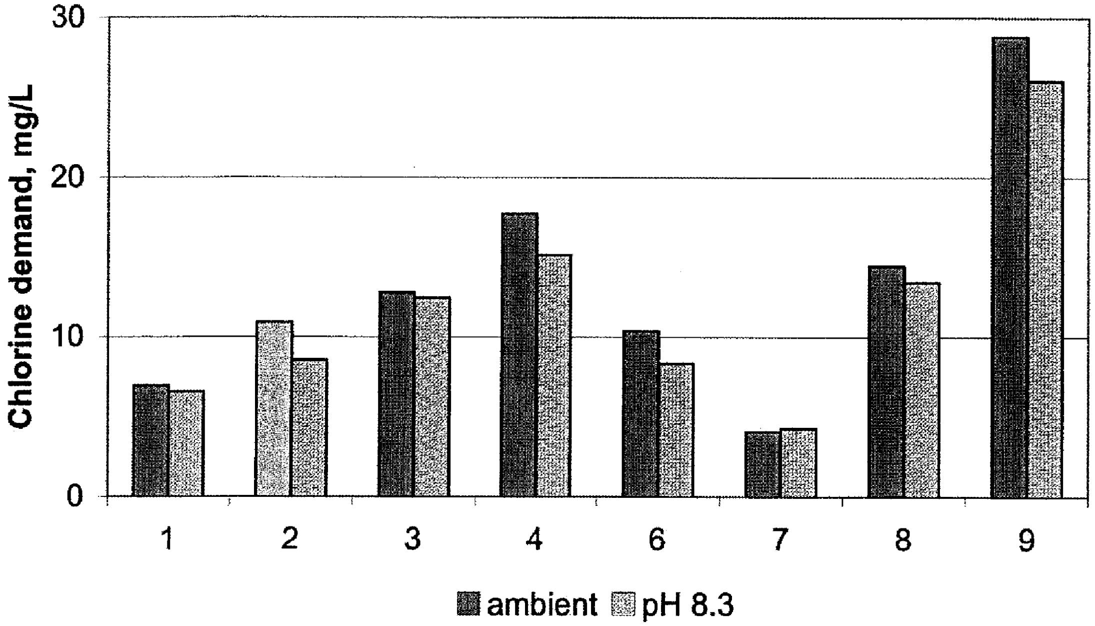


Figure 33. Comparison of chlorine demand associated with water from wells that serve the Seven Springs water system based on bench-scale chlorination tests using sodium hypochlorite.

Because chlorine is consumed due to reactions with hydrogen sulfide and other reduced constituents, the rate of chlorine consumption is an indirect measure of the oxidation rate. Based on testing conducted at the wells that serve the Seven Springs water system, the rate of chlorine consumption appears to be related to the chlorine demand (or the total amount of oxidizable material) and can be modeled as a zero-order reaction with respect to chlorine demand. A comparison of zero-order reaction rate constants calculated from testing conducted on water from the Seven Springs system and chlorine demand is shown in Figure 34. In general, there is a linear relationship between the chlorine demand and apparent zero-order reaction rate.

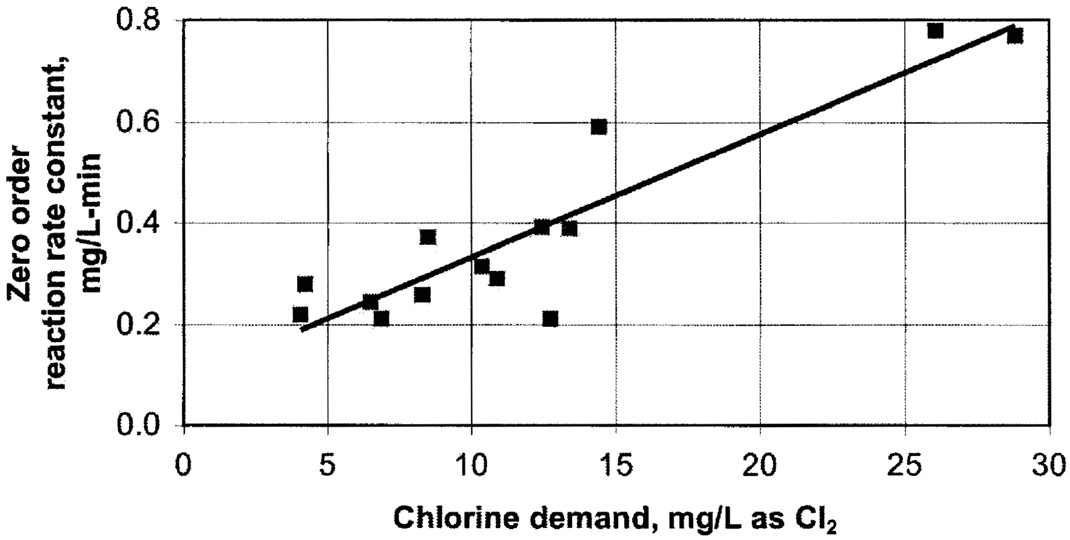


Figure 34. Comparison of chlorine demand and zero order reaction rate constants derived from bench-scale chlorination of water from the Seven Springs water system.

Bench-scale and pilot-scale tests were conducted to evaluate the extent to which turbidity is generated through chlorination at different levels of pH. An example of the chlorine demand curve and turbidity generation as a function of chlorine dose is shown in Figure 35. Each data point was derived by adding chlorine to a closed batch reactor and monitoring the residual chlorine and turbidity after a 30 minute contact time. As shown, minimal turbidity was generated at low chlorine dosages, however turbidity levels climbed to over 2 NTU once the chlorine demand was satisfied and all of the hydrogen sulfide had been oxidized. These levels of turbidity have been observed in other groundwater systems (Lyn and Taylor 1992).

To assess the impacts of oxidation pH on the generation of turbidity, bench-scale tests were conducted at several pH levels. A comparison of turbidity levels as a function of contact time and pH is shown in Figure 36. Over the pH range tested (7.5 to 8.5) turbidity levels increased with increasing contact time. Based on these results, it is clear that an alternative method of controlling hydrogen sulfide is desired, particularly for wells that have a relatively high chlorine demand.

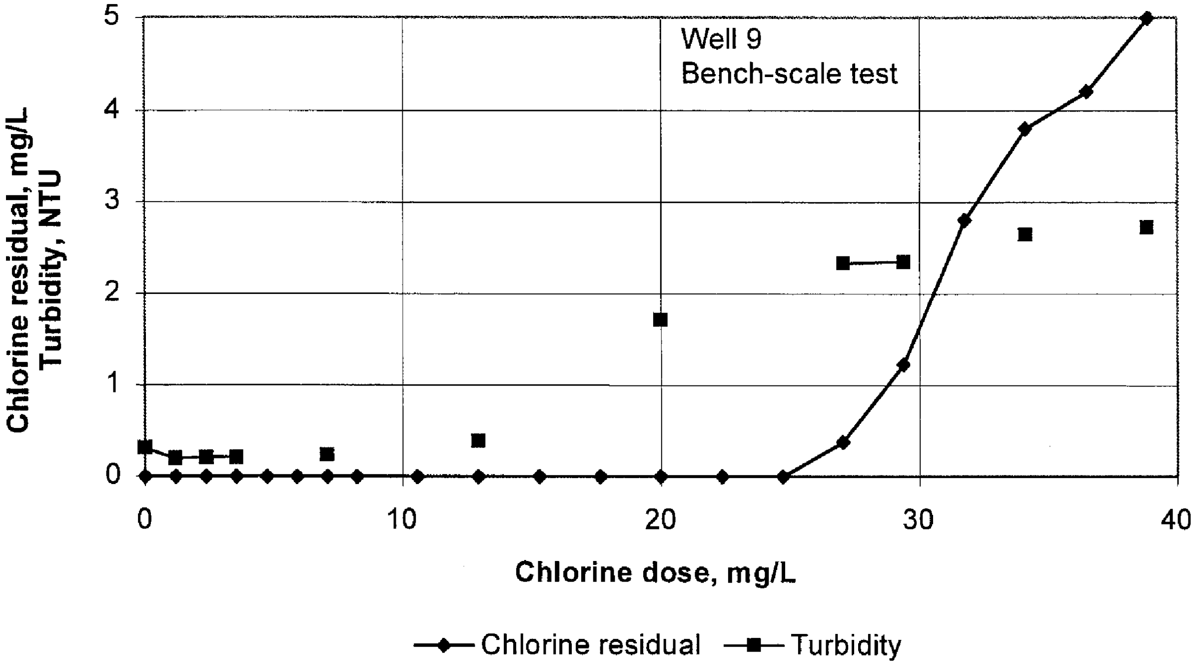


Figure 35. Example chlorine demand curve for water from bench-scale chlorination testing of water from well 9.

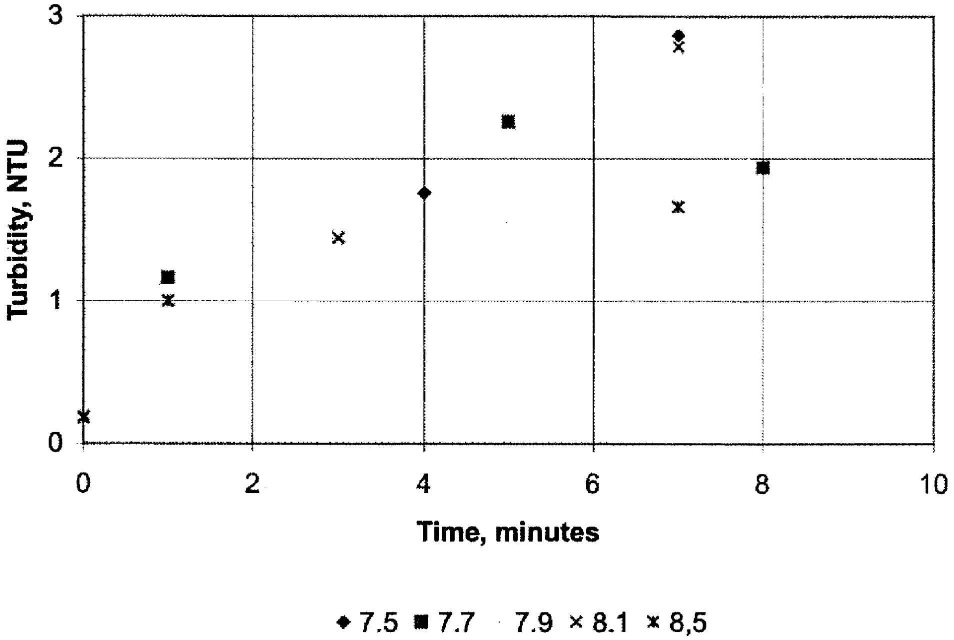


Figure 36. Influence of pH and contact time on turbidity generation during bench-scale chlorination of water from well 9.

Hydrogen Peroxide

Hydrogen peroxide is a treatment chemical that is widely used as an oxidant in various industrial applications. The product of oxidizing hydrogen sulfide with hydrogen peroxide is either elemental sulfur or sulfate, depending on the reaction pH. Polysulfides may also be generated. Generally sulfate is formed at pH levels above 8, while elemental sulfur dominates at pH levels below 8, as shown below:

$$H_2S + H_2O_2 \rightarrow S^o + 2H_2O$$

$$HS^- + 4H_2O_2 \rightarrow SO_4^{-2} + 4H_2O + H^+ \quad (pH>8)$$

The dose required to form sulfate is about four times the dose required to form elemental sulfur. Limited field information is available on reaction rates for hydrogen peroxide oxidation of hydrogen sulfide from groundwater. In addition, the combined effect of hydrogen peroxide and chlorine on the overall reaction products has not been widely studied. It is well known that chlorine will oxidize hydrogen peroxide, however, the combined effects of the two oxidants on hydrogen sulfide have not been widely evaluated.

The implementation of hydrogen peroxide as a treatment chemical upstream of chlorination is relatively straightforward. The main requirements are chemical feed equipment, storage tanks, and monitoring equipment. It is also important that adequate contact time is available for the reaction prior to chlorine addition.

As part of this project, intensive bench-scale and pilot-scale testing was conducted to determine if hydrogen peroxide could be used as a method of stabilizing hydrogen sulfide prior to chlorination. Key variables that were tested were oxidation pH, hydrogen peroxide dose, and the impacts of pH and dose on reaction rates.

A comparison of hydrogen sulfide oxidation as a function of reaction time at pH levels ranging from ambient to 8.5 is shown in Figure 37. In most cases, 50 to 70 percent of the hydrogen sulfide was oxidized within the first two to three minutes of the reaction, however the reaction appeared to plateau after the first few minutes. First order reaction rates were calculated as a function of pH for water from wells 2, 3, 4, 8, and 9 and are shown in Figure 38. As the pH increased, reaction rates decreased suggesting a shifting in reaction pathway around pH 8.2.

Hydrogen peroxide dosages ranging from 0.5 to 6.0 mg per mg of hydrogen sulfide were tested at various pH levels at several wells in the Seven Springs system. In general, because the reaction appeared to plateau after about two to three minutes, there was excess hydrogen peroxide present regardless of the dosage. Residual hydrogen peroxide is consumed by chlorine at a rate of about 2 mg of chlorine per mg of hydrogen peroxide. Therefore, to optimize chemical use, most of the follow-up tests conducted in this project were at a ratio of 0.5 mg hydrogen peroxide per mg of hydrogen sulfide.

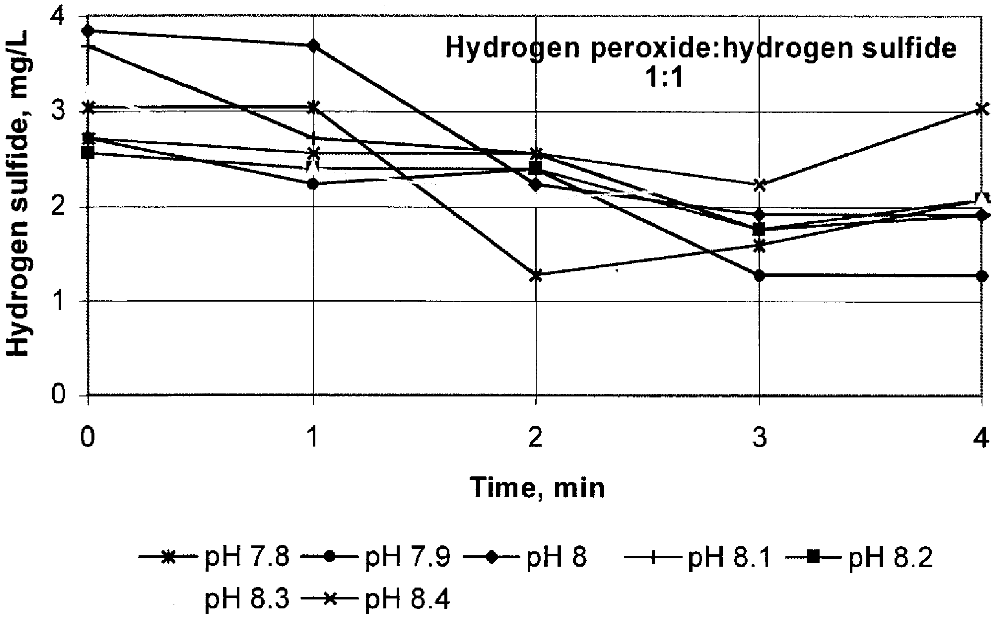


Figure 37. Hydrogen sulfide levels in batch tests of water from well 9 treated by hydrogen peroxide at pH levels between 7.8 and 8.4.

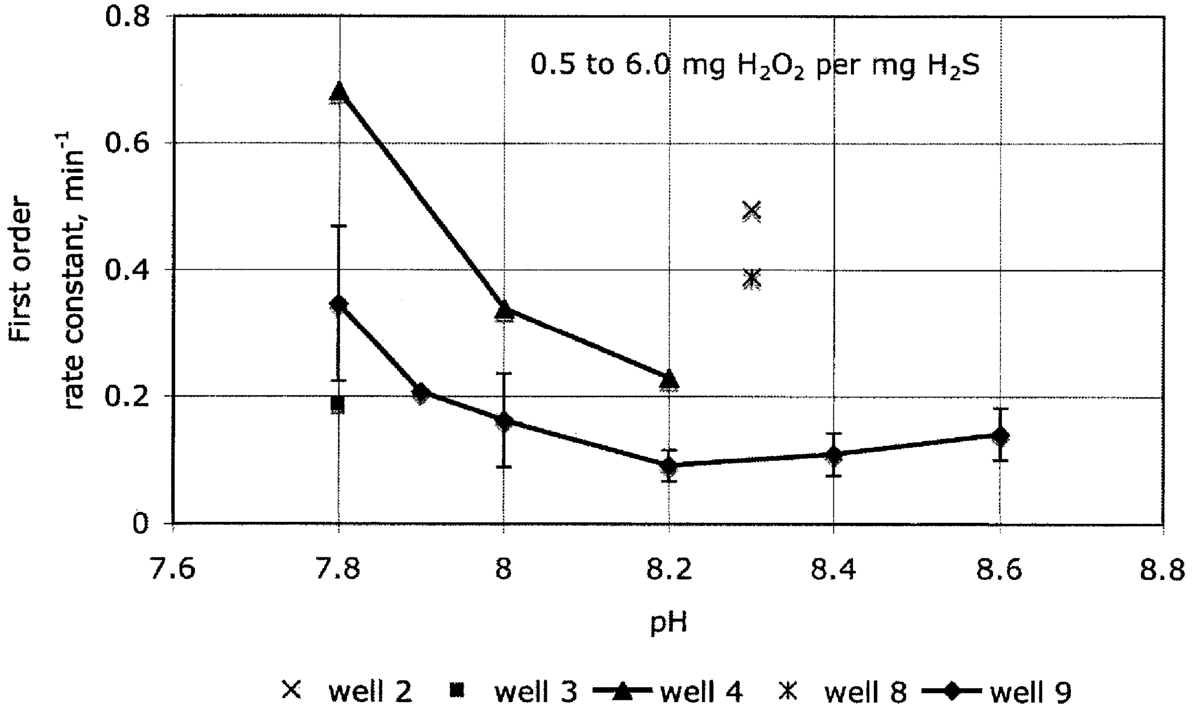


Figure 38. Comparison of calculated first-order reaction rate constants for hydrogen peroxide oxidation of hydrogen sulfide in water from wells 2, 3, 4, 8, and 9 at pH levels ranging from 7.8 to 8.6. Hydrogen peroxide dosages ranged from 0.5 to 6.0 mg hydrogen peroxide per mg of hydrogen sulfide.

Another important consideration in the use of alternative oxidants is the potential for formation of particles through the oxidation process. A comparison of turbidity levels following the oxidation reaction using hydrogen peroxide at a dose of 0.5 mg per mg of hydrogen sulfide at pH levels of 7.8 and 8.3 is shown in Figure 39 for water from wells 2, 3, 4, and 9. For some wells, lower levels of turbidity were associated with the higher pH (wells 4 and 9). For other wells (well 3), a higher turbidity level was associated with the higher pH. If the turbidity formation were associated with the generation of elemental sulfur, then lower levels of turbidity would be expected at higher pH levels where sulfate formation is thermodynamically favored, unless there is another source of turbidity in the source water.

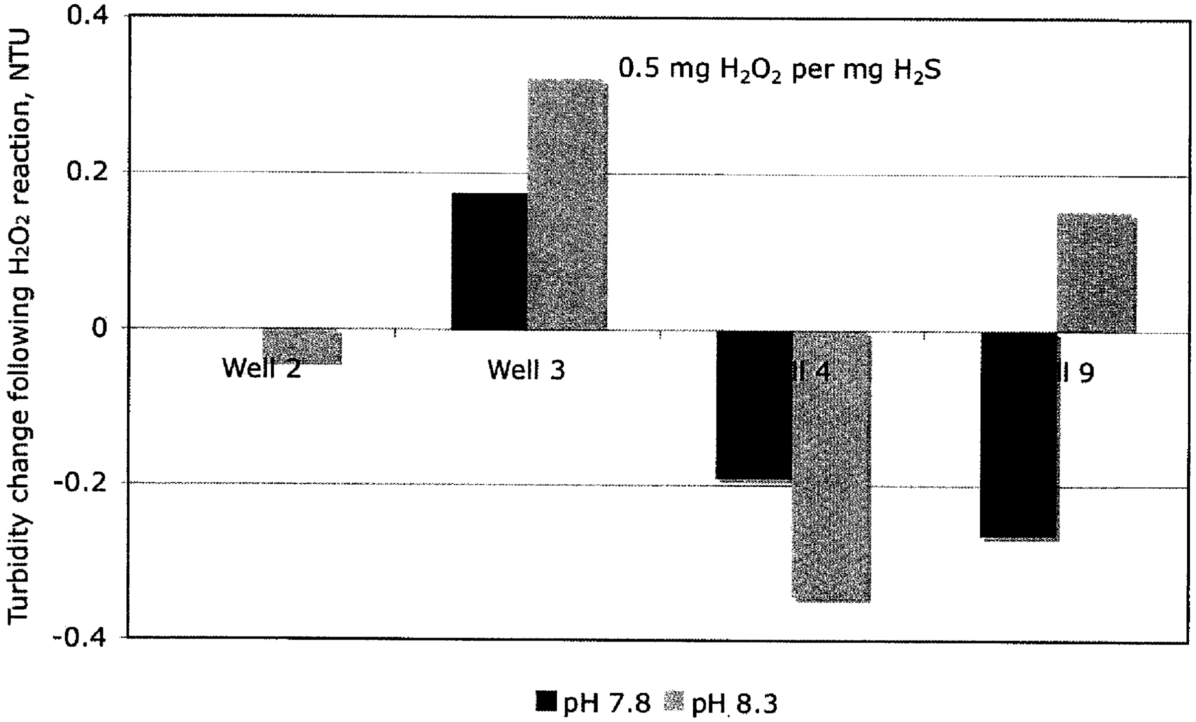


Figure 39. Comparison of changes in turbidity in water from wells 2, 3, 4, and 9 following treatment by hydrogen peroxide (0.5 mg/mg hydrogen sulfide) at pH levels of 7.8 and 8.3.

A comparison of turbidity formation as a function of hydrogen sulfide removed is shown in Figure 40 for tests conducted at two different pH levels. In these tests, the turbidity levels associated with the oxidation process varied from about 0.2 to 0.5 and did not correlate to the quantity of hydrogen sulfide removed. In some cases the turbidity decreased due to hydrogen peroxide oxidation and in other cases it increased. These changes could be due to sampling and measurement aberrations or due to solubilization of particles in the water in conjunction with the oxidation reactions. In any case, the changes in turbidity associated with these tests were relatively minimal.

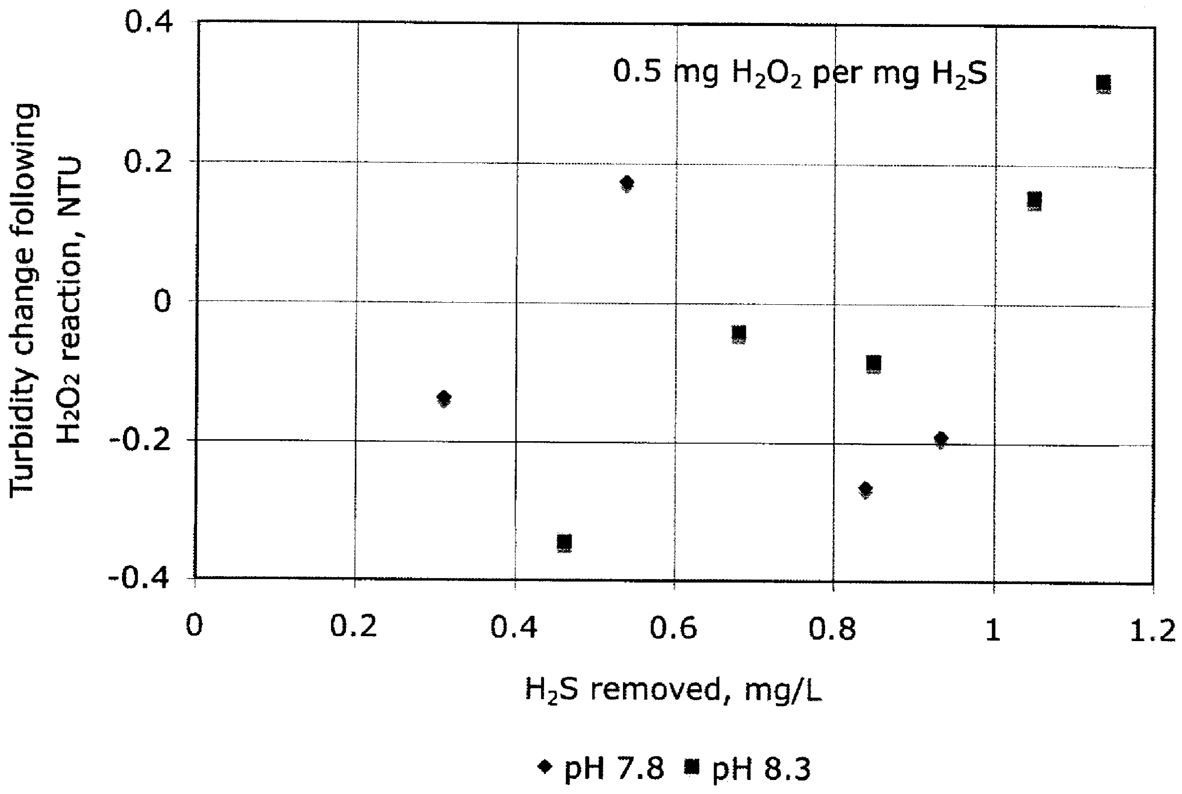


Figure 40. Comparison of turbidity formation and hydrogen sulfide oxidation in water treated by hydrogen peroxide at pH 7.8 and 8.3.

Conclusions from Bench-scale testing of oxidation

Based on the bench scale testing conducted in this project, treatment conditions identified for further testing at pilot scale were determined. Key factors were pH control, contact time for each reaction step, and monitoring parameters. A summary of bench-scale results is presented in Table 14.

Table 14. Summary of optimum oxidation conditions identified from bench scale testing.

Oxidant	pH range	Contact time	Key concerns
Chlorine	ambient	5 minutes	Turbidity formation, pH increase due to sodium hypochlorite
Hydrogen peroxide	>8	2-3 minutes	Avoid overdosing of hydrogen peroxide to prevent excess chlorine demand

Pilot-scale testing of oxidation reactions

To validate the bench-scale tests and determine the feasibility of using alternative oxidation as a hydrogen sulfide control technology for the Seven Springs system, pilot-scale tests were conducted using a 1 gpm pilot scale treatment plant. The treatment system was designed to provide for chemical addition, chemical mixing, and adequate reaction time to satisfy constraints associated with the Seven Springs system. A summary of the pilot-plant tests conducted to evaluate oxidation is shown in Table 15. A total of 42 individual tests were conducted. To facilitate conduct of the tests and interpretation of data, tests were run at either ambient pH or at pH 8.3. Limited testing was also conducted at other pH levels.

Table 15. Summary of pilot-plant tests conducted to evaluate advanced oxidation for control of hydrogen sulfide in the Seven Springs water system

Chemical addition sequence	Wells tested	Dates	Number of tests
Chlorine	2,3,4,7,8,9	Dec-04 to Mar-05	9
Hydrogen Peroxide-Chlorine	2,6,8,9	Dec-04 to Mar-05	6
Hydroxide-Hydrogen Peroxide-chlorine	2,6,8,9	Dec-04 to Mar-05	18
Hydrogen Peroxide-Hydroxide-Chlorine	9	Jan-05	3
UV-Chlorine	9	Dec-04 to Jan-05	3
Hydrogen Peroxide-UV-Chlorine	9	Jan-05	3

Chlorine oxidation

Because chlorine oxidation is the current technology used for control of hydrogen sulfide, it was evaluated to provide a basis for comparing alternative oxidation. Chlorine is effective for reducing the concentration of hydrogen sulfide to below detection limits. However, there is a concern with generation of turbidity due to chlorine oxidation reactions. A comparison of the concentration of hydrogen sulfide removed and the finished water turbidity is shown in Figure 41. As shown, the highest turbidity levels were observed in water from well 9, however, there was not a direct relationship between hydrogen sulfide removal and turbidity formation. Over the pH range tested, there did not appear to be a strong relationship between pH and turbidity formation, most likely due to other confounding variables such as organic carbon and variations in turbidity levels associated with the source water.

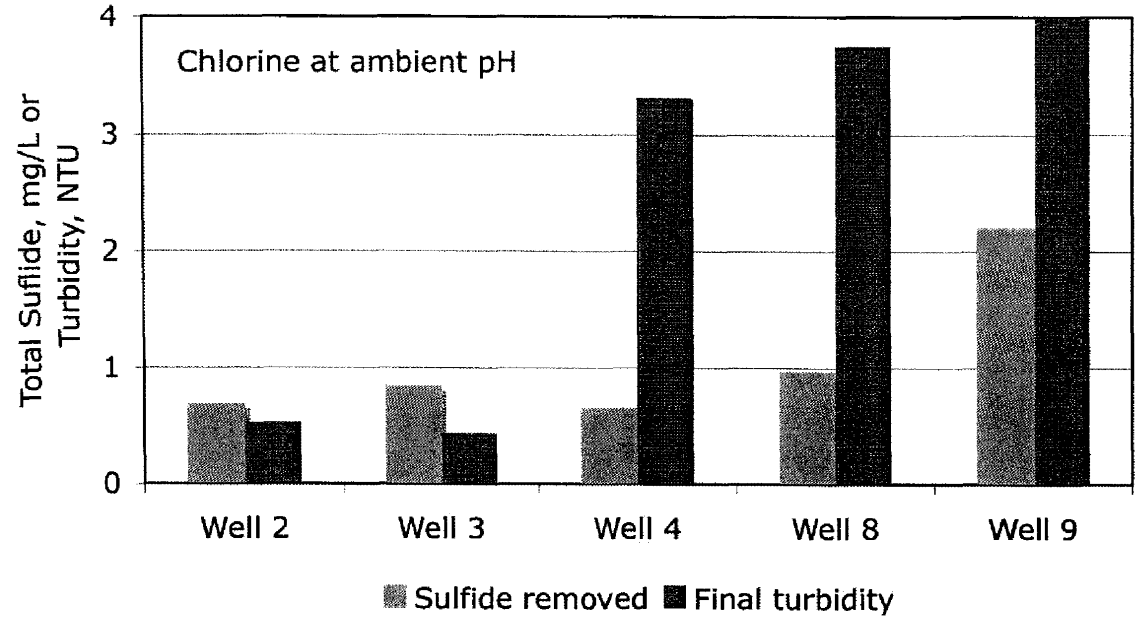


Figure 41. Comparison of the concentration of sulfide oxidized and the concentration of turbidity in chlorinated water from wells 2, 3, 4, 8, and 9 based on pilot-plant testing using sodium hypochlorite at ambient pH.

Hydrogen peroxide-chlorine oxidation

The use of hydrogen peroxide coupled with chlorine provides two-stage oxidation. Based on the reaction kinetics observed in the bench-scale testing, pilot-scale tests were developed using a 2 to 3 minute contact time for hydrogen peroxide followed by chlorine addition. Tests were conducted at ambient pH and with pH adjustment either before or after hydrogen peroxide addition. Hydrogen peroxide was dosed at a rate of about 0.5 mg per mg of hydrogen sulfide.

A summary of hydrogen sulfide removal and turbidity generation through the two-stage oxidation process at ambient pH is shown in Figure 42. As shown, about half of the hydrogen sulfide was oxidized by hydrogen peroxide and the remainder was oxidized by chlorine. However, significant levels of turbidity were generated following the addition of chlorine.

In contrast to the ambient pH condition, the water was pre-treated with caustic soda (sodium hydroxide) to raise the pH to about 8 prior to the two-stage oxidation process. Results from the elevated pH testing are summarized in Figure 43. As would be predicted by the reaction rates observed from bench-scale testing, a lower quantity of hydrogen sulfide was oxidized by hydrogen peroxide. In addition, turbidity levels associated with each stage of treatment were lower. It should be noted that the untreated water contained turbidity levels that varied over the course of this testing. If oxidation processes are conducted in-line, there are no mechanisms for removal of turbidity (unless the particulate matter is solubilized through oxidation). Obviously, some of the turbidity carries over through treatment, however additional turbidity is generated through the sequential reactions.

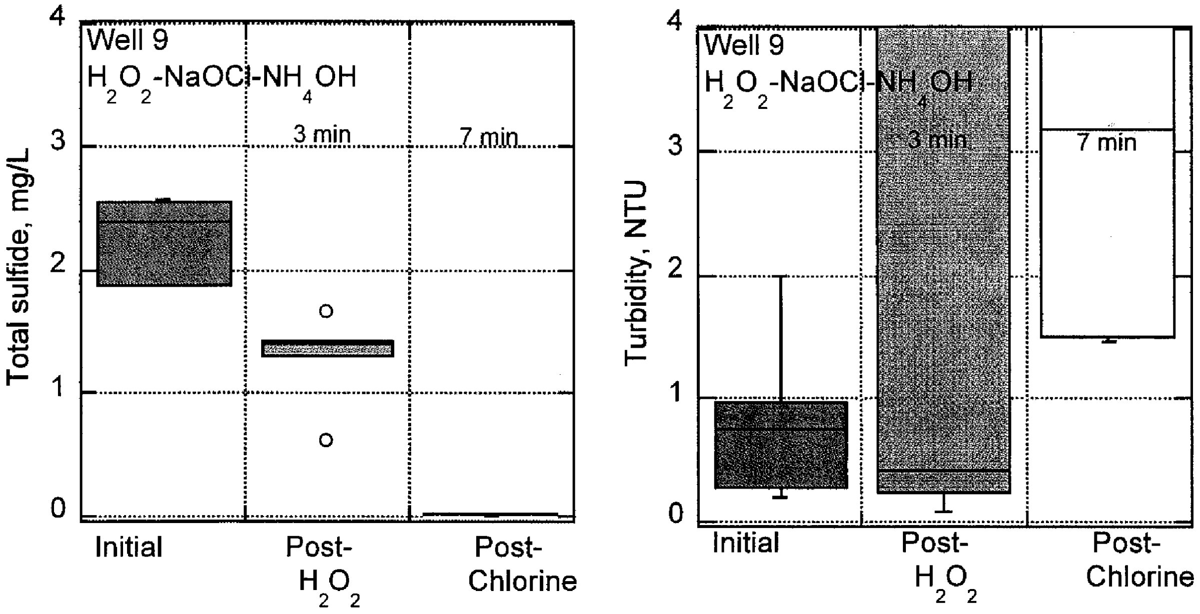


Figure 42. Impact of hydrogen peroxide and chlorine oxidation of hydrogen sulfide on levels of total sulfide and turbidity in water from well 9 at ambient pH.

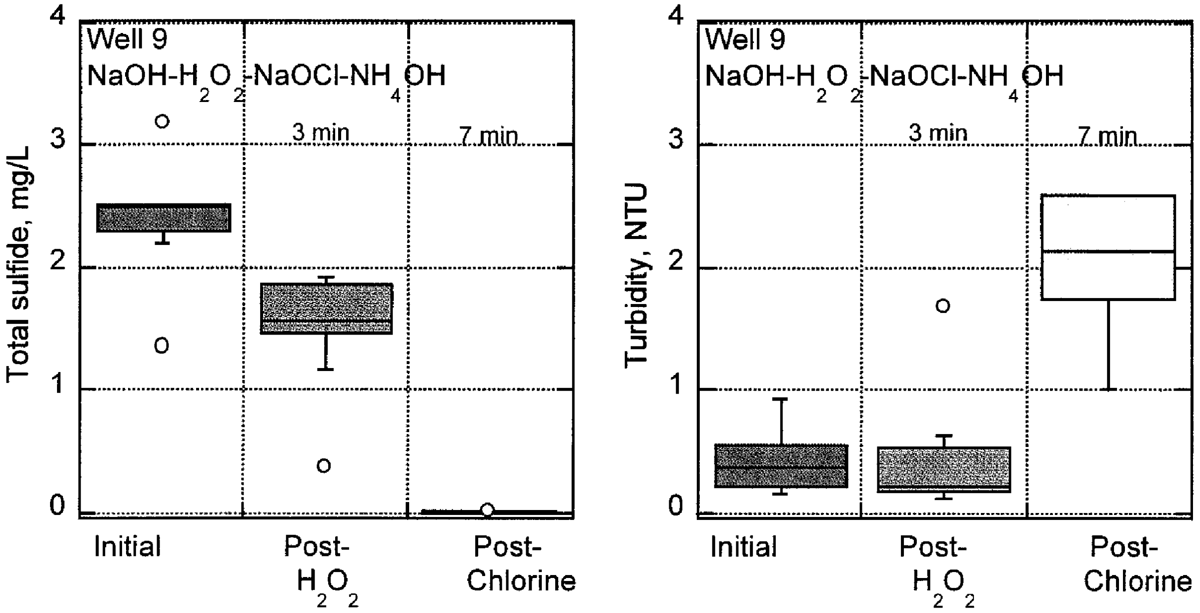


Figure 43. Impact of hydrogen peroxide and chlorine oxidation of hydrogen sulfide on levels of total sulfide and turbidity in water from well 9 at elevated pH (~ pH 8.3).

A final iteration on pH control is to increase the pH after hydrogen peroxide addition. This approach would allow for more conversion of sulfide by hydrogen peroxide due to the faster reaction rates associated with the lower pH. However, chlorination at a higher pH can result in increased turbidity. A comparison of sulfide removal and turbidity patterns associated with initial oxidation using hydrogen peroxide followed by addition of caustic soda and sodium hypochlorite is shown in Figure 44. Oxidation of hydrogen sulfide by hydrogen peroxide was highly variable as can be seen by the height of the box-plot. Significant turbidity (> 4 NTU) was formed as a result of chlorination following hydrogen peroxide oxidation.

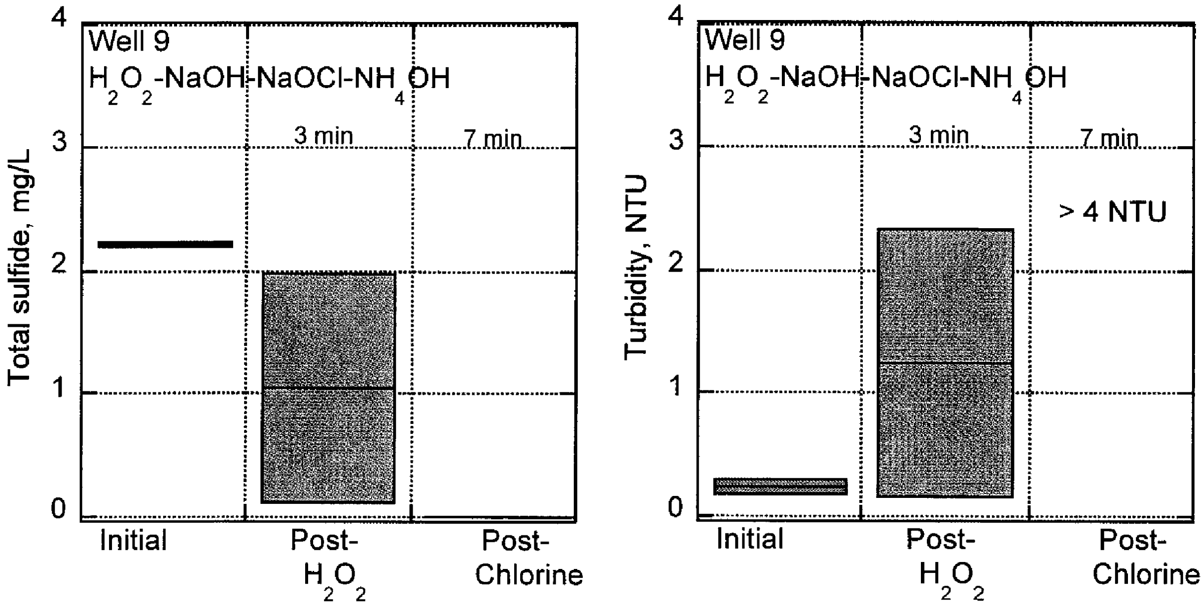


Figure 44. Impact of adding caustic soda downstream of hydrogen peroxide oxidation coupled with chlorine oxidation of hydrogen sulfide on levels of total sulfide and turbidity in water from well 9.

Based on these results, the optimum approach for applying this two-stage oxidation treatment is to elevate the pH prior to hydrogen peroxide addition. The main advantage of using the two-stage oxidation is that it reduces the net chlorine demand of the water and could potentially form more stable reaction products. Turbidity levels associated with the two-stage oxidation were lower than levels associated with the use of sodium hypochlorite alone. Even though turbidity is not currently regulated in groundwater systems, it would be advantageous to minimize the amount of particulate matter introduced into the water distribution system.

Follow-up testing was conducted at other well sites to determine if the results observed at well 9 could be extrapolated to water from other wells. A comparison of sulfide removal and turbidity patterns associated with two-stage oxidation at elevated pH is shown in Figure 45 for water from wells 2,6,8, and 9. As shown, hydrogen peroxide was effective at removing a portion of the sulfides from each well under elevated pH conditions. Turbidity generation patterns varied among the wells with the similar turbidity levels associated with wells 6 and 9 even though the sulfide levels differed by a factor of 4 between the two water sources.

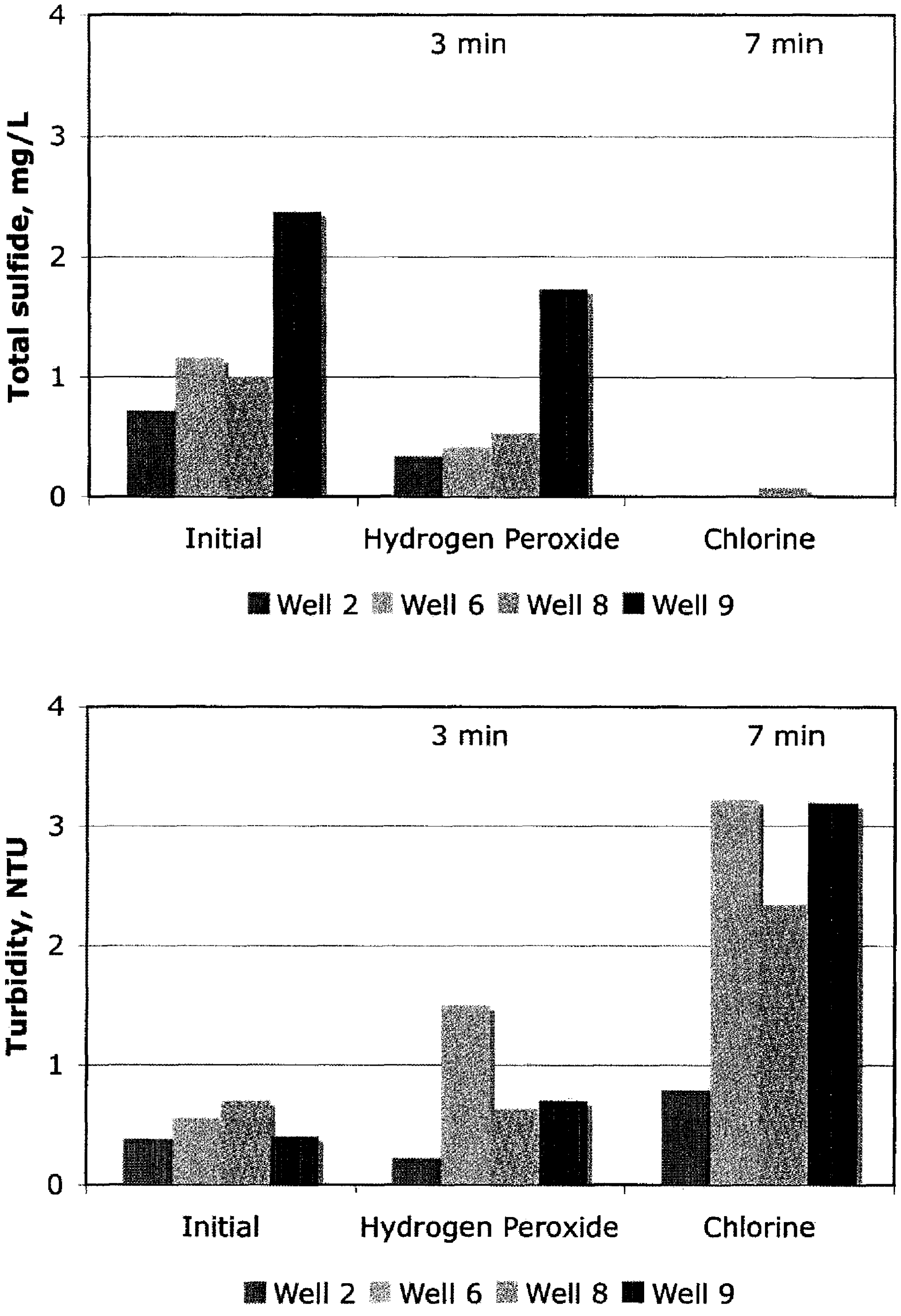


Figure 45. Comparison of a) sulfide and b) turbidity levels associated with two-stage oxidation of hydrogen sulfide using hydrogen peroxide and sodium hypochlorite at pH over 7.8 at wells 2, 6, 8, and 9.

An additional comparison of the oxidation reactions from wells 2, 6, 8, and 9 is given in Figure 46. The fraction of hydrogen sulfide oxidized by each oxidant is shown as a percent of the total sulfide oxidized and as a mass relationship. As shown, a similar amount of hydrogen sulfide was oxidized from each source water by hydrogen peroxide, even though the initial hydrogen sulfide levels varied from below 1 mg/L to over 2 mg/L. The levels of hydrogen sulfide in untreated water from wells 2,6,and 8 were similar, however the turbidity generated from chlorine addition differed among the wells.

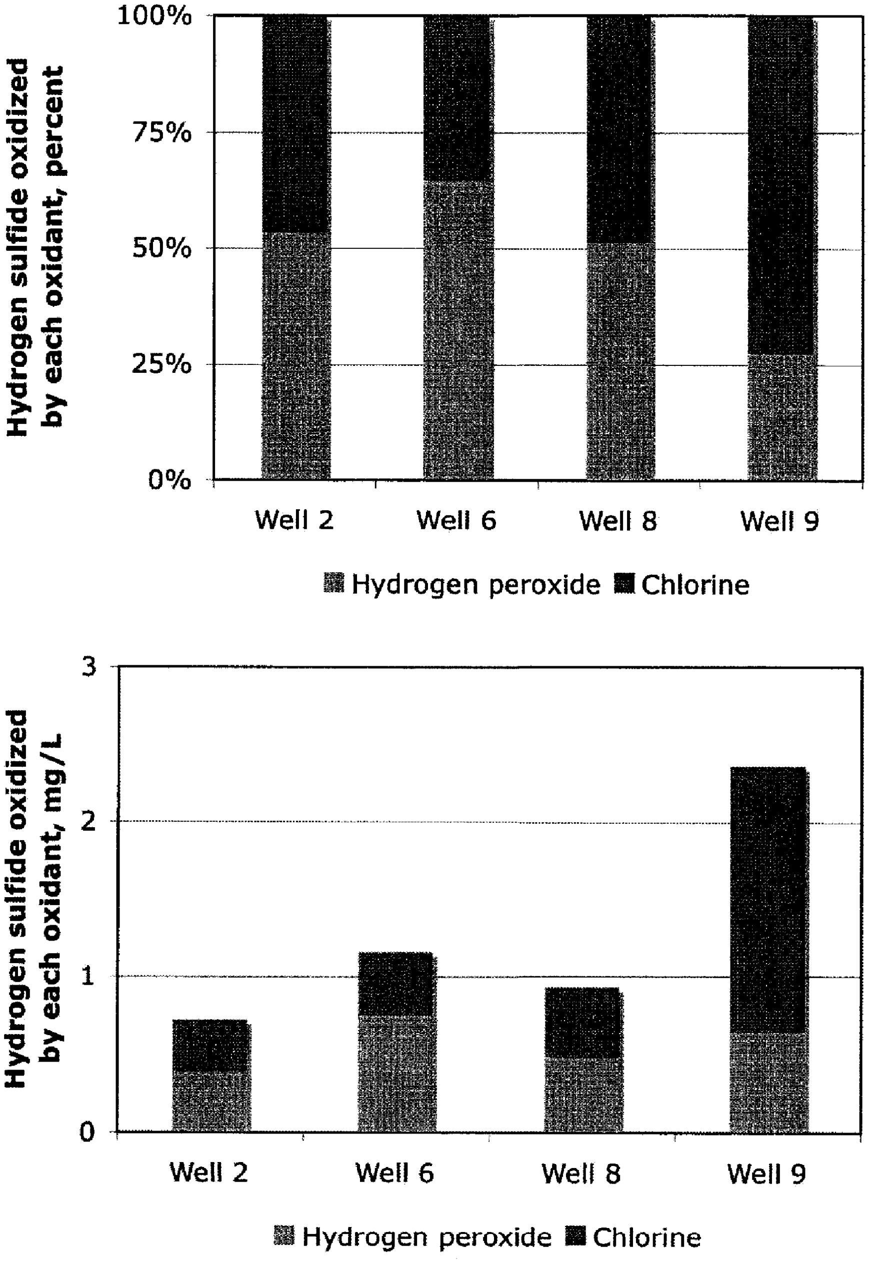


Figure 46. Comparison of the relative amount of hydrogen sulfide oxidized by hydrogen peroxide and chlorine in water from wells 2,6,8, and 9 at pH over 7.8.

Ultraviolet irradiation-chlorine oxidation

As an alternative to the use of hydrogen peroxide as a primary oxidant, the potential for using UV irradiation was evaluated as a candidate hydrogen sulfide control technology. An advantage of the use of UV is that it can serve to provide some degree of primary disinfection. In addition, the use of UV does not require supplemental chemical storage on-site. A UV unit from Trojan technologies was installed in-line in the pilot plant and operated at a flowrate of 1 gpm (model 02AM15, 3 amps,30 mJ/cm^2 @95% UV transmittance). Hydrogen sulfide levels were evaluated before and after UV oxidation.

Results from pilot testing conducted at well 9 are shown in Figure 47. As shown, the decrease in hydrogen sulfide levels associated with UV irradiation surpassed oxidation efficiencies associated with hydrogen peroxide. However, turbidity levels formed through the UV reactor and from chlorination were higher than turbidity associated with the other treatment scenarios evaluated.

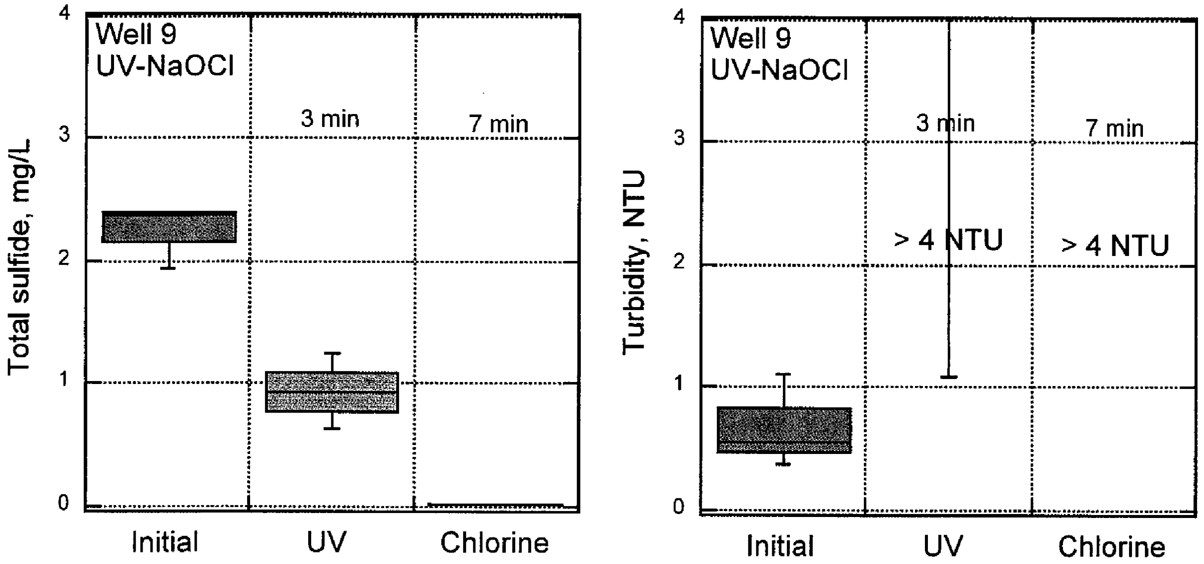


Figure 47. Impact of using ultraviolet (UV) irradiation coupled with chlorine oxidation of hydrogen sulfide on levels of total sulfide and turbidity in water from well 9.

Hydrogen Peroxide-UV

As a final oxidation combination, the use of hydrogen peroxide in conjunction with ultraviolet radiation was tested. This photochemical oxidation is widely used for groundwater remediation and is effective for oxidizing organic contaminants in water. The combination of hydrogen peroxide and UV generates hydroxyl radicals which serve as advanced oxidants. A pathway that has been suggested to describe the formation of hydroxyl radicals is (Lee et al. 2004 and others):

$$H_2O_2 + h\nu \rightarrow 2{\bullet}OH$$
$${\bullet}OH + H_2O_2 \rightarrow HO_2{\bullet} + H_2O$$
$${\bullet}OH + {\bullet}OH \rightarrow H_2O_2$$
$$HO_2{\bullet} + HO_2{\bullet} \rightarrow H_2O_2 + O_2$$
$$HO_2{\bullet} + H_2O_2 \rightarrow {\bullet}OH + O_2 + H_2O$$
$$HO_2{\bullet} + {\bullet}OH \rightarrow O_2 + H_2O$$

Similar reactants can be formed from ozone and UV or other mixed oxidants including Fenton's reagent. Hydroxyl radicals have a higher oxidation potential (see Figure 31) than any of the other oxidants used for hydrogen sulfide oxidation. In addition, by coupling the two processes, a lower net dose of hydrogen peroxide would be needed, saving on chemical costs. Many researchers have reported that H_2O_2/UV oxidation is effective for oxidizing organic compounds in groundwater (Acero and Von Gunten 2001, Duquget et al 1989, Lee et al. 2004, Wang et al. 2000, 2001).

In this project the combination of hydrogen peroxide with UV was tested under different pH conditions. Results from hydrogen peroxide-UV oxidation followed by chlorination and ammonia addition are summarized in Figure 48. As shown, the combination of hydrogen peroxide and UV was effective at reducing the concentration of hydrogen sulfide. However, significant turbidity was generated through the process.

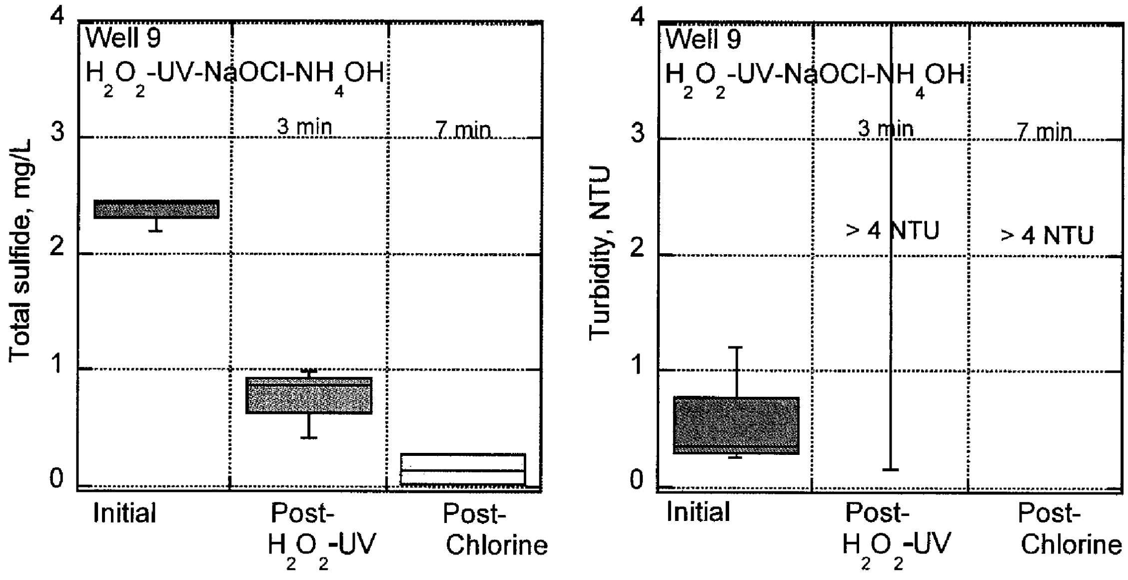


Figure 48. Impact of using hydrogen peroxide coupled with ultraviolet (UV) irradiation followed by chlorine oxidation on levels of total sulfide and turbidity in water from well 9.

Characterization of turbidity generated through oxidation reactions

While oxidation technology was effective for control of hydrogen sulfide, the generation of varying amounts of turbidity during oxidation renders this treatment impractical without some type of downstream liquid/solid separation process. To evaluate potential methods of preventing turbidity formation, particles generated through different treatment scenarios were characterized using scanning electron microscopy coupled with energy dispersive spectroscopy (SEM/EDS). This approach provides a means of qualitatively determining the particle size and dominant elemental composition of the particles and may help to explain the genesis of the particles.

Example electron micrographs are shown in Figure 49. As shown, the turbidity is dominated by micron-sized or submicron-sized particles. Mineral precipitates are also present. Energy dispersive spectroscopy was used to evaluate the elemental composition of the precipitates. The sub-micron particles were primarily organic in nature and were most likely formed from reactions between oxidant chemicals and dissolved organic material. The inorganic constituents consisted of calcium, silica, and iron. Minor amounts of sulfur, aluminum, and potassium were observed in some samples. In general, the dominant contributor to the turbidity was organic particles and higher concentrations of organic particles seemed to be associated with the use of UV or hydrogen peroxide coupled with UV.

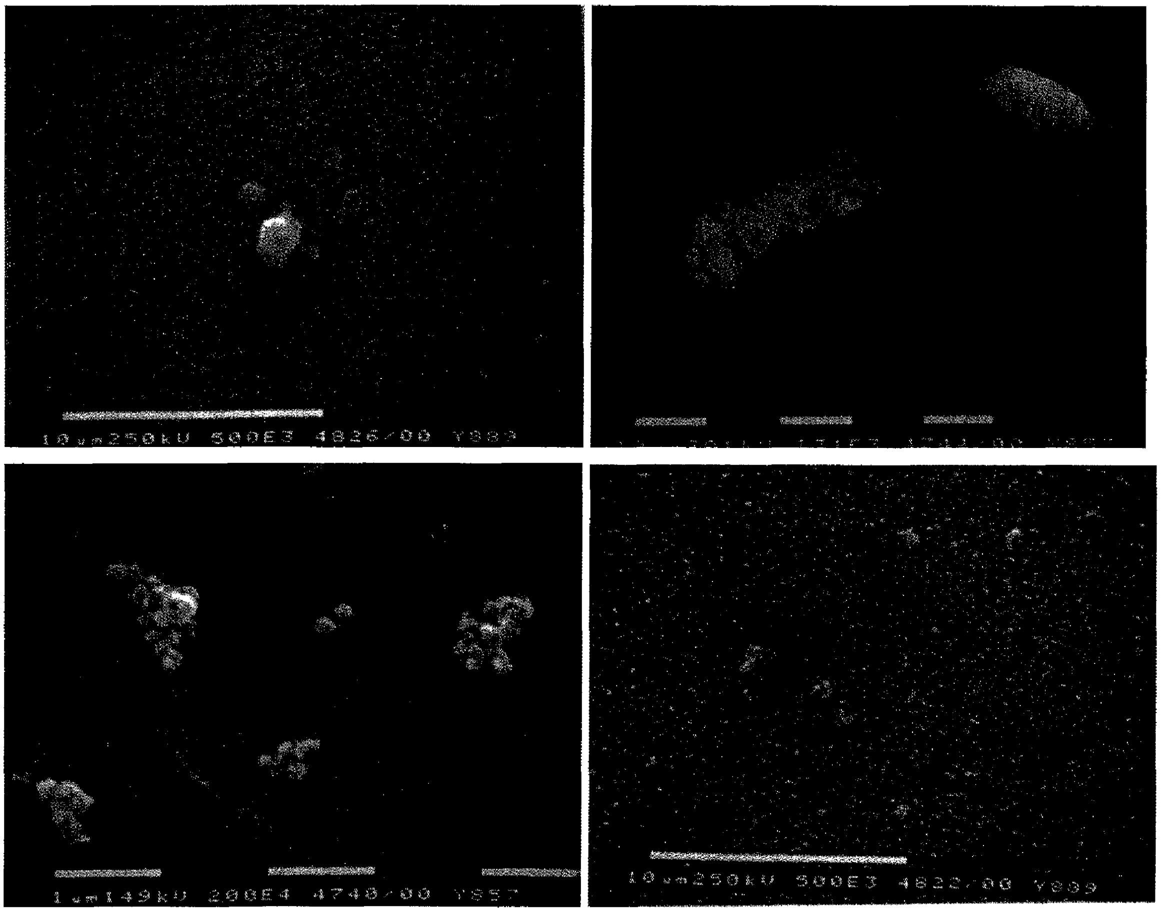


Figure 49. Comparison of characteristics of particles concentrated from pilot-plant testing of water from well 9. The white bar in each micrograph represents either 1 or 10 micrometers.

Role of turbidity in candidate treatment technologies

While the primary focus of this project was to evaluate technologies for control of hydrogen sulfide, it is evident that other water quality parameters need to be considered in the overall analysis. Control of particles that are either in the untreated water or generated through the treatment technology is an important issue. The presence of particles in water can interfere with disinfection effectiveness by shielding microorganisms from the action of disinfection. Turbidity is used as an indirect measure of the quantity of particles in water. The technologies evaluated in this project include aeration, anion exchange, and oxidation technologies. A summary of the issues related to turbidity generation and/or removal through each technology is provided in this section.

Aeration

Pilot testing of aeration was not conducted through this project, however information on turbidity generation has been observed in groundwater aeration systems. Sources of turbidity include microbial growth, oxidized iron and manganese, elemental sulfur and metallo-sulfide complexes. There is no direct mechanism for removal of turbidity through aeration. Thus the turbidity in the treated water consists of particles in the untreated water plus additional particles formed through aeration and oxidation. Turbidity levels reported in other water systems are similar to the levels observed in this project for oxidation technologies.

Examples of turbidity formation from biomass generation through groundwater aeration are shown in Figure 50. Exposure of groundwater containing hydrogen sulfide and organics to air promotes the growth of sulfur oxidizing bacteria. Bacterial growth rates are impacted by temperature. Turbidity generated by biological growth has been reported in aeration systems used to treat Florida groundwater (Duranceau et al. 2003, Levine et al. 2004,).

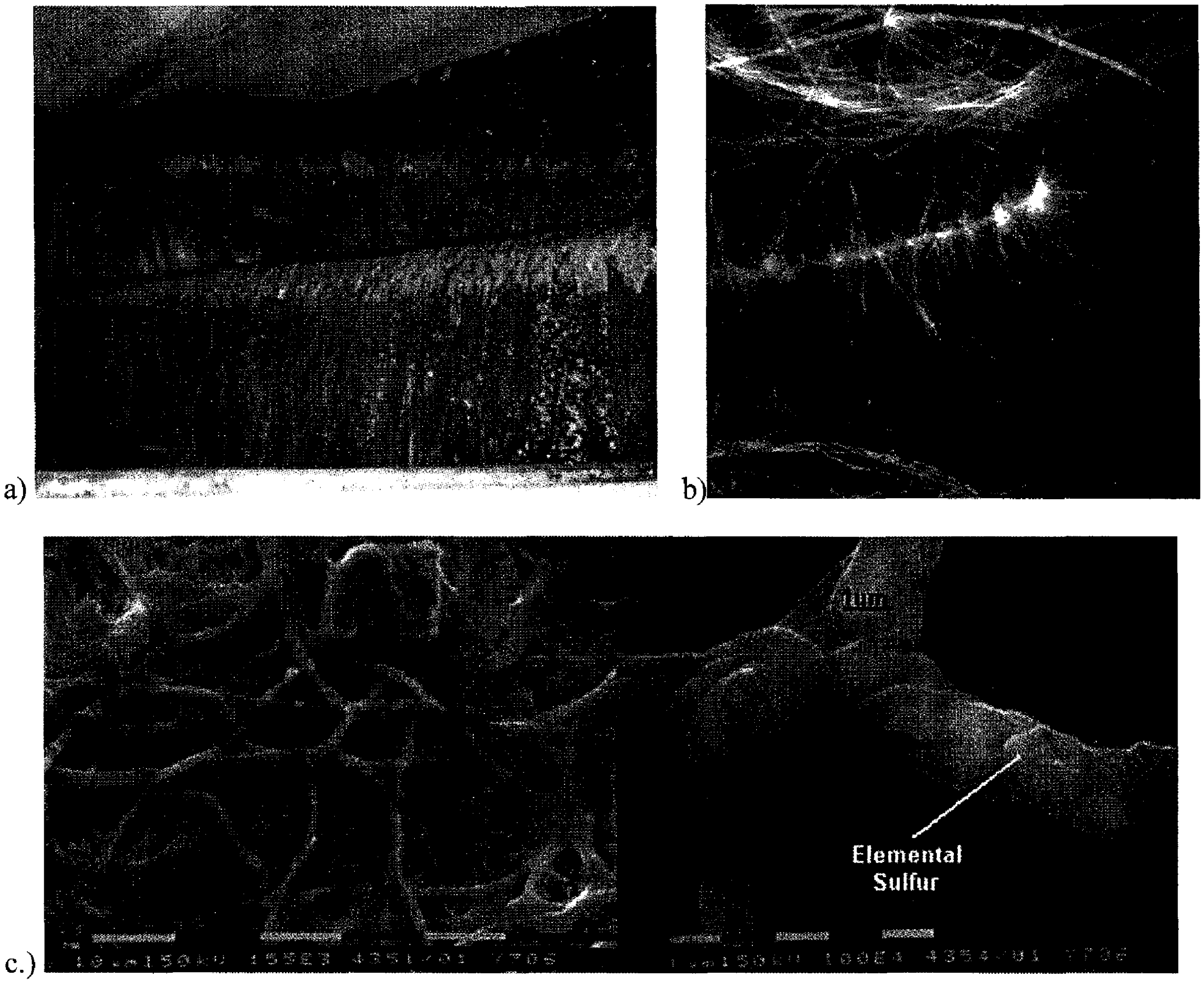


Figure 50. Examples of particles in aeration systems: a) Photograph of inside of tower aeration system , b) light micrograph, and c) electron micrograph of biological growth and associated turbidity in an aeration system treating a Florida groundwater (Excerpted from Levine 2004b)

<u>Anion exchange</u>

Anion exchange has a unique ability to remove negatively charged constituents from water in exchange for chloride ions. Most naturally occurring particles in water are negatively charged and, therefore, are amenable to removal through anion exchange resins depending on the particle size, surface charge, and hydraulics. In addition, unlike the other technologies tested in this project, there are relatively few mechanisms for formation of particles through anion exchange. Thus, it is anticipated that turbidity levels following anion exchange will be similar or lower than turbidity levels associated with the untreated water. A summary of the net reduction in turbidity observed through preliminary pilot tests is shown in Figure 51. While turbidity reduction is not a goal of the treatment system, anion exchange is effective for removing some of the particles associated with the untreated water.

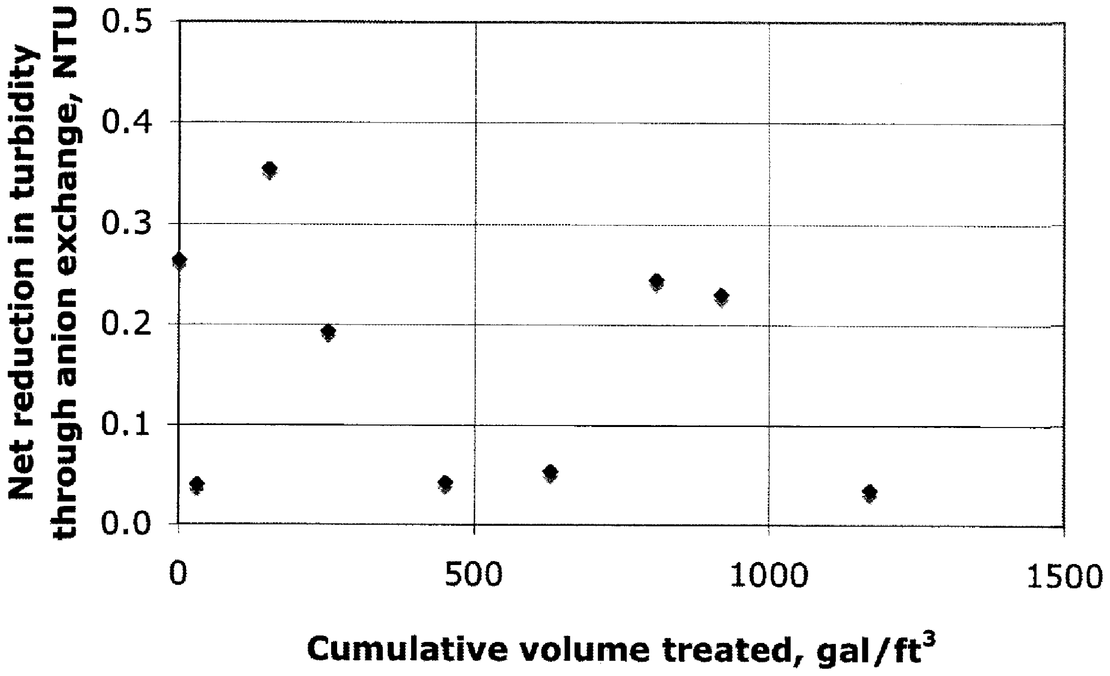


Figure 51. Reduction in turbidity associated with treating water from well 9 through anion exchange.

Oxidation technologies

Turbidity generated through oxidation technologies appears to result from minerals and organics in the water reacting with oxidants. In addition, turbidity in the untreated water may serve as a reaction site or nucleus for the formation of other particles. The extent of turbidity generation is impacted by pH, oxidation conditions, and water quality variables including iron, calcium, silica, sulfur, and organics.

SUMMARY OF TECHNOLOGY EVALUATION

Technologies evaluated for control of hydrogen sulfide in the Seven Springs water system include removal technologies and oxidation technologies. Each of the technologies is effective for control of hydrogen sulfide. Other water quality variables and factors that influence the efficacy of each technology are discussed in this section.

Water quality comparison of technologies

A comparison of the impact of each of the candidate technologies on hydrogen sulfide, organic carbon, sulfate, turbidity, and chloride is given in Figures 52-53. For purposes of comparison, water quality parameters are compared to untreated water quality from well 9. While the trends are likely to be similar, water from other wells may not reflect the exact same relationships.

Each of the technologies is effective for reduction of hydrogen sulfide. In addition, the use of chlorine disinfection downstream of hydrogen sulfide control provides supplemental treatment capacity by reacting with residual hydrogen sulfide as needed, providing an additional hydrogen sulfide control measure. In consort with control of hydrogen sulfide, the chlorine demand of the water is reduced by all of the technologies (except chlorine oxidation). The extent of the chlorine demand reduction depends on the amount of residual hydrogen sulfide associated with each technology. Data shown in Figures 52 and 53 are derived from pilot-scale and bench-scale tests conducted during this project.

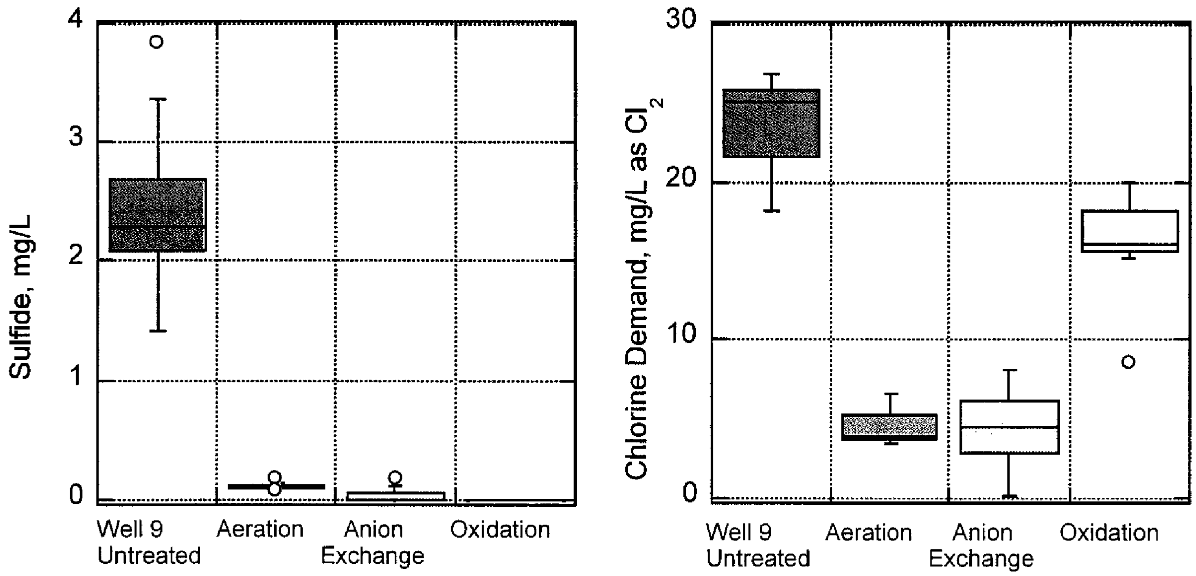


Figure 52. Effectiveness of aeration, anion exchange, and oxidation for reduction of hydrogen sulfide and chlorine demand associated with water from the Seven Springs system.

Anion exchange is the only one of the candidate technologies that is effective for reduction of sulfate and organic carbon. The levels of rsulfate and organic carbon shown in Figure 53 are derived from preliminary pilot-scale tests conducted on water from well 9. Aeration and oxidation are not expected to impact sulfate or organic carbon levels.

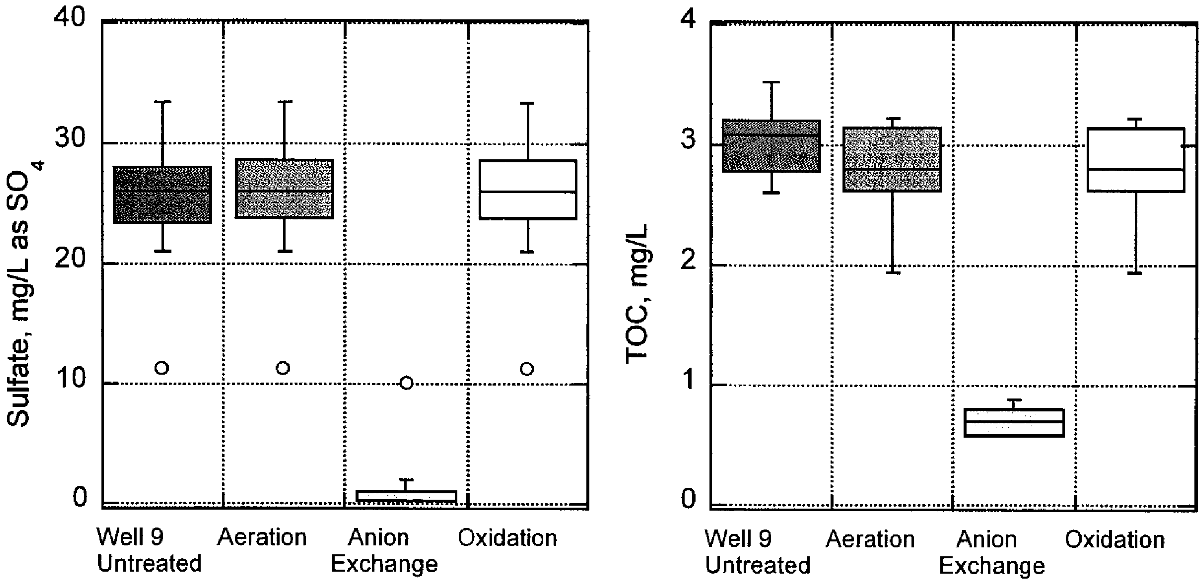


Figure 53. Impact of aeration, anion exchange, and oxidation on organic carbon (TOC) and sulfate levels in treated water from the Seven Springs water system.

The impacts of each technology on turbidity are variable depending on the turbidity characteristics associated with the untreated water. Aeration and oxidation technologies do not have any mechanism for removal of turbidity, thus it is anticipated that turbidity levels will not decrease using these technologies. Turbidity may increase through treatment due to the formation of mineral precipitates and organic particles. Biological growth within the aeration tower may also contribute intermittent turbidity to aerated water. Anion exchange has the capacity to remove particles depending on their size, surface charge, and physical properties.

A qualitative comparison of the water quality impacts of the candidate hydrogen sulfide control technologies is given in Table 16. As shown, while all technologies are effective at controlling hydrogen sulfide levels, anion exchange offers additional water quality advantages for reduction of sulfates, organic carbon, and turbidity.

Table 16. Qualitative comparison of impacts of treatment technologies on water quality

Water Quality Parameter	Packed-Tower[a] Aeration with pH control	Fixed-Bed Anion Exchange	Oxidation
Sulfide	>90% removal/conversion	>90% removal	>90% conversion
Sulfate	No impact	>90 % removal	No impact, minor increase due to sulfate formation (2.8 mg sulfate /mg sulfide oxidized
Organic Carbon	No impact	60-80% removal	No impact
Turbidity	No removal mechanism; potential increase due to sloughing of biomass and chemical precipitates from oxidation/precipitation reactions that occur in the aeration tower	Removal of negatively charged colloidal particles; no mechanism for turbidity formation	No removal mechanisms; potential formation due to mineral and organic oxidation (iron, sulfur, organic colloids, etc.)
Chloride	No impact	Increases 1 mg/mg sulfide removed and 0.7 mg/mg sulfate removed	Chlorine oxidation results in 5-8 mg of chloride per mg of sulfide converted; Other oxidants have no impact on chloride levels
pH	Controlled upstream and downstream of process	No impact	Upstream control
Dissolved oxygen	Increase up to oxygen saturation	No impact	Slight increase
Chlorine demand	Reduction proportional to sulfide removal	Reduction proportional to sulfide removal	Reduction proportional to sulfide oxidation. Supplemental chlorine demand due to partially oxidized organics and presence of residual oxidant
Potential for hydrogen sulfide reformation	Minor impact because only one form of sulfur is removed: nonionized hydrogen sulfide	Major impact because most forms of sulfur are removed	Minor impact; Hydrogen sulfide is converted to more stable form, but not removed.

[a] Packed tower aeration includes supplying air through forced draft (or induced draft)

A summary of critical factors to be considered in technology selection is given in Table 17. Key issues relate to process performance, water quality impacts, waste generation, operations, and costs. A matrix comparing the technologies evaluated in this project is given in Table 18 based on the criteria identified in Table 17. For this initial evaluation, each of the factors was ranked on a score of 1 (lowest) to 10 (highest). The maximum possible score is 110 points.

Table 17. Factors used to compare technologies evaluated for control of hydrogen sulfide in the Seven Springs system

Factor	Rationale
Efficiency	To reduce water quality concerns associated with hydrogen sulfide, the efficiency of hydrogen sulfide removal is a critical factor
Water quality impacts	Other water quality factors that are of significance include sulfates, organic carbon, dissolved oxygen, corrosivity, turbidity, and the potential for reformation of sulfides
Waste generation	A method for disposing of wastes generated by the technology will need to be incorporated into the overall treatment system
Operations	
Ease of operation	To develop a reliable treatment system, it is necessary that the system is compatible with existing technology and can be operated reliably with minimal oversight.
Amenability to on/off operation	It is critical that the on/off cycling of wells does not interfere with process performance and reliability
Need for repressurization	If water is exposed to the atmosphere during treatment, repressurization (re-pumping) will be needed thus requiring balancing the operation of two sets of pumps at each site
Site considerations	
Space requirements	Four of the five sites are in residential neighborhoods with limited space availability; The footprint of the control technology is an important consideration
Odor	The proximity of residential neighborhoods necessitates effective odor control
Noise	The proximity of residential neighborhoods necessitates minimal generation of noise and other nuisances
Capital and Operating Costs	Costs are an important consideration to control impacts on customer's water rates

Table 18. Comparison of technologies evaluated based on criteria defined in Table 15

Factor	Aeration[a] at well sites (pH adjust)	Centralized aeration[a] (pH adjust)	Fixed-Bed Anion Exchange	Hydrogen peroxide oxidation	UV/H_2O_2 oxidation	Chlorination
Efficiency	10	10	10	10	10	10
Water quality impacts	7 Turbidity generation; biofilms	7 Turbidity generation; biofilms	10 Removal of Sulfate, Turbidity, TOC	5 Turbidity generation	3 Turbidity generation	5 Turbidity generation
Potential for sulfide reversion	7	7	10	2	2	2
Waste generation	6 Routine maintenance for control of fouling	8 Routine maintenance for control of fouling	5 Brine	10	10	10
Operations						
Ease of operation	6 Chemical dose management, maintenance	7 Chemical dose management, maintenance	10	3 Chemical dose management, pH control	3 Chemical dose management	3 Chemical dose management, pH control
Amenability to on/off operation	4	9	10	10	10	10
Need for supplemental pumping	2	8 Centralized	10	10	10	10
Design and Site considerations						
Space availability	2	8 Need site	10	10	10	10
Odor	3	8 Scrubber	10	10	10	10
Noise and excess traffic	2 Blowers; chemical delivery	7 Blowers; chemical delivery	8 Chemical delivery	4 Chemical delivery	5 Chemical delivery	3 Chemical delivery
Need for repumping	2	6 Centralized	10	10	10	10
Score excluding cost information	46% (51)	77% (85)	93% (103)	76% (84)	75% (82)	75% (83)

[a] Assumes Packed Tower Aeration with air supplied through forced draft (or induced draft)

Ranking of technologies

A comprehensive review of sulfide control technologies has been conducted in this project through literature surveys, bench-scale testing, and field testing. Control of hydrogen sulfide can be accomplished through **removal technologies** such as aeration or anion exchange or **conversion technologies** such as oxidation.

Based on the evaluation conducted in this project and the history of water quality concerns associated with the Seven Springs water system, the use of a technology that removes sulfide is preferred over technologies that convert sulfides if the costs are reasonable. In light of the technology ranking results in Table 18, fixed-bed anion exchange (highest ranking) and centralized forced-draft-packed-tower aeration with pH control (second highest ranking) are the available treatment options that warrant further consideration for the Seven Springs System.

The use of fixed-bed anion exchange has compelling advantages over the other technologies evaluated for several reasons:

- Multiple forms of sulfur are removed providing a mechanism for reducing the total mass of sulfur in the treated water and minimizing the potential for sulfide reformation in residential plumbing.
- Organic carbon levels are reduced, thereby alleviating concerns associated with disinfection byproduct formation if free chlorine is to be used for disinfection or if the chloraminated system is to be periodically treated by free chlorine as part of system-wide "chlorine burn" procedures.
- There is no mechanism for generation of turbidity within the anion exchange system. In addition, there is potential for removal of negatively charged colloidal particles through anion exchange, resulting in a net decrease in turbidity.

While the use of aeration is widely promoted throughout the State of Florida, it does not have the water quality and operational advantages associated with packed-bed anion exchange. In addition, it is impractical to implement aeration systems at the existing Seven Springs treatment sites due to several constraints including: space limitations, the likelihood of generating nuisance odors and noise that would impact adjacent residential neighborhoods, the on/off cycling of pumps at each well site, and the need for supplemental pumping to repressurize the system. If forced-draft-packed-tower aeration is to be adopted for the Seven Springs system, it is suggested that a centralized facility be designed to overcome the limitations associated with direct treatment at the well-sites. However, it is important that a location suitable for centralized treatment is identified if this option is to be further considered.

Oxidation technologies are effective for control of hydrogen sulfide, but it is important to optimize chemical addition approaches to minimize turbidity formation. In addition, due to the potential for sulfide reformation the use of conversion technologies are less desirable than the removal technologies.

CONCLUSIONS AND RECOMMENDATIONS

Alternative technologies for control of hydrogen sulfide in water from wells that serve the Seven Springs water system were assessed and bench-scale and pilot-scale testing was conducted to generate relevant field data as part of this project.

The major conclusions from this study are:

1. Water quality varies among the wells that serve the Seven Springs system. In addition to control of hydrogen sulfide, it is important to consider the co-occurrence of other water quality constituents, particularly organic carbon and turbidity, in assessing the efficacy of various control technologies.

2. Aeration technology provides an effective approach for removing and oxidizing hydrogen sulfide. Air stripping serves to remove nonionized hydrogen sulfide. The oxygen introduced through aeration serves as an oxidant that can react with hydrogen sulfide and other reduced minerals. Biological oxidation of hydrogen sulfide can also occur within aeration systems. There is potential for turbidity to be generated through the aeration process due to biological activity coupled with chemical oxidation of sulfur and other minerals. The use of aeration also requires on-site storage of chemicals for pH control and repressurization of the water prior to disinfection and introduction of the treated water into the distribution system.

3. The implementation of aeration at individual well sites is likely to be problematic due to current method of system operation and space limitations at each treatment facility. Because most of the well-sites are located in residential neighborhoods, effective control of nuisance odors and noise generated by the aeration systems is essential. In addition, the on/off cycling of pumps at each well site is likely to compromise process performance.

4. Fixed-bed anion exchange technology is effective for removing hydrogen sulfide from the Seven Springs source water. Additional benefits of anion exchange technology include coincident removal of other forms of sulfur including sulfates, polysulfides, thiosulfates, and sulfites. In addition, negatively charged (anionic) forms of organic carbon, color-compounds, and turbidity are removed through treatment. Anion exchange technology does not generate nuisance odors or noise, thus imposing minimal impact to neighboring property owners. Another advantage of fixed-bed anion exchange is that treatment systems can be designed to be compatible with existing site constraints, thus reducing the costs and time needed for implementation. Because the water is treated directly from the wells, the implementation of anion exchange technology would not require repressurization.

5. Oxidation technology is effective for control of hydrogen sulfide through conversion reactions, however the presence of organics in the untreated water poses water quality complications that result in the generation of turbidity upon the addition of chlorine for disinfection. Oxidation technology requires additional on-site storage of chemicals and process controls for chemical dosing and water quality monitoring. Oxidation technology is essentially an "in-pipe" treatment and does not require repressurization prior to introduction of the treated water into the distribution system.

6. In the context of the FDEP rule pertaining to hydrogen sulfide removal (Chapter 62-555.315(5), fixed-bed anion exchange technology surpasses the effectiveness of forced-draft-packed-tower aeration with pH control by removing the dominant forms of reduced sulfur without requiring pH adjustment or repressurization. In addition, other anionic forms of sulfur including sulfate, polysulfides, thiosulfate, and sulfite are removed through fixed-bed anionic exchange treatment thus yielding water with a lower total mass of sulfur than aeration technology and reducing the potential for sulfide reformation. Co-incident benefits of anion exchange include reduction of organic carbon and turbidity, thereby decreasing the potential for formation of disinfection byproducts and improving the effectiveness of secondary disinfection.

7. Barring unforeseen issues arising from additional testing and permitting, it is anticipated that fixed-bed anion exchange will be effective for addressing water quality concerns associated with the Seven Springs water system.

Recommendations and follow-up

All of the technologies evaluated in this study are capable of controlling hydrogen sulfide, however it is important that the hydrogen sulfide control approach adopted for the Seven Springs system is compatible with site constraints and system limitations. Fixed-bed anion exchange is the only technology evaluated that is practicable for removing hydrogen sulfide and other forms of sulfur and can be readily implemented at the well-sites. Fixed-bed anion exchange has ancillary benefits of removal of organic carbon, color compounds, and turbidity.

While this project addressed technical feasibility and water quality impacts, it is important to develop accurate cost-estimates for the candidate technologies prior to final process selection. Because the desired treatment focuses on removal of hydrogen sulfide versus conversion, the cost of fixed-bed anion exchange should be compared to the cost of centralized aeration.

Based on the pilot-scale data generated through this study, it is recommended that detailed designs be developed for implementing fixed-bed anion exchange at five sites within the Seven Springs water system (wells 2,6,8,9, and the Mitchell site that treats wells 3 and 4). The permitting process should also be initiated. As part of detailed design and permitting of fixed-bed anion exchange for the Seven Springs system, it is important to quantify the exchange capacity and service-cycle duration of the resins, characterize regenerant quality and volume, and ensure that regenerant disposal practices are compatible with reclaimed water requirements. It is also suggested that corrosion control be re-optimized to ensure compatibility with the new treatment system.

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APPENDIX
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Water Quality Summary, Well 9

Well # 9

Parameter	pH	Temperature, °C	Conductivity uS/cm	Sulfide, mg/L S^{2-}	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfate, mg/L SO_4^{2-}	Ferrous Iron, mg/L	TOC, mg/L	Apparent Color, PtCo	UV-254	Cl^-
Min	6.16	25.00	479.00	0.78	0.10	130.00	11.28	0.00	2.56	7.00	-0.01	20.99
Max	7.77	31.30	661.00	3.65	5.10	240.00	43.00	0.47	3.51	42.00	0.18	26.00
Avg	7.43	26.53	529.46	2.30	0.73	199.22	27.31	0.10	3.07	16.64	0.10	23.50
std. dev	0.21	1.47	36.10	0.51	1.12	18.85	5.56	0.12	0.31	9.44	0.08	3.54
# of samples	47	23	41	47	44	32	25	21	9	11	7	2

Water Quality Summary, Well 8

Well # 8

Parameter	pH	Temperature, °C	Conductivity uS/cm	Sulfide, mg/L S^{2-}	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfate, mg/L SO_4^{2-}	Ferrous Iron, mg/L	TOC, mg/L	Apparent Color, PtCo	UV-254	Cl^-
Min	6.64	25.30	420.00	0.33	0.13	200.00	11.28	0.04	3.01			
Max	7.47	27.40	506.00	1.32	6.00	200.00	11.28	0.14	3.01			
Avg	7.24	26.35	478.25	1.01	1.45	200.00	11.28	0.09	3.01			
std. dev	0.31	1.48	39.28	0.32	2.20			0.07				
# of samples	9	2	4	7	8	1	1	2	1			

Water Quality Summary, Well 7

Well # 7

Parameter	pH	Temperature, °C	Conductivity uS/cm	Sulfide, mg/L S^{2-}	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfate, mg/L SO_4^{2-}	Ferrous Iron, mg/L	TOC, mg/L	Apparent Color, PtCo	UV-254	Cl^-
Min	7.45	24.80		< 0.1	2.70							
Max	7.45	24.80		< 0.1	2.70							
Avg	7.45	24.80		< 0.1	2.70							
std. dev												
# of samples	1	1			1							

Water Quality Summary, Well 6

Well # 6

Parameter	pH	Temperature, °C	Conductivity uS/cm	Sulfide, mg/L S^{2-}	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfate, mg/L SO_4^{2-}	Ferrous Iron, mg/L	TOC, mg/L	Apparent Color, PtCo	UV-254	Cl^-
Min	7.33	25.10	392.00	1.41	0.19							
Max	7.46	25.10	392.00	1.41	0.20							
Avg	7.40	25.10	392.00	1.41	0.19							
std. dev	0.09											
# of samples	2	1	1	1	2							

Water Quality Summary, Well 4

Well # 4

Parameter	pH	Temperature, °C	Conductivity uS/cm	Sulfide, mg/L S^{2-}	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfate, mg/L SO_4^{2-}	Ferrous Iron, mg/L	TOC, mg/L	Apparent Color, PtCo	UV-254	Cl^-
Min	7.41	25.80		0.65	0.15							
Max	7.44	25.80		0.65	0.84							
Avg	7.43	25.80		0.65	0.50							
std. dev	0.02				0.49							
# of samples	2.00	1.00		1.00	2.00							

Water Quality Summary, Well 3

Well # 3

Parameter	pH	Temperature, °C	Conductivity uS/cm	Sulfide, mg/L S^{2-}	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfate, mg/L SO_4^{2-}	Ferrous Iron, mg/L	TOC, mg/L	Apparent Color, PtCo	UV-254	Cl^-
Min	7.50	25.60		0.85	0.11							
Max	7.54	25.60		0.85	0.18							
Avg	7.52	25.60		0.85	0.15							
std. dev	0.03				0.05							
# of samples	2.00	1.00		1.00	2.00							

Water Quality Summary, Well 2

Well # 2

Parameter	pH	Temperature, °C	Conductivity uS/cm	Sulfide, mg/L S^{2-}	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfate, mg/L SO_4^{2-}	Ferrous Iron, mg/L	TOC, mg/L	Apparent Color, PtCo	UV-254	Cl^-
Min	7.50	25.60		0.69	0.02							
Max	7.58	25.60		0.69	0.28							
Avg	7.54	25.60		0.69	0.15							
std. dev	0.06				0.18							
# of samples	2.00	1.00		1.00	2.00							

Water Quality Summary, Aloha Gardens

Well # Aloha Gardens

Parameter	pH	Temperature, °C	Conductivity uS/cm	Sulfide, mg/L S^{2-}	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfate, mg/L SO_4^{2-}	Ferrous Iron, mg/L	TOC, mg/L	Apparent Color, PtCo	UV-254	Cl^-
Min	7.43	26.20		< 0.1	0.77							
Max	7.43	26.20		< 0.1	0.77							
Avg	7.43	26.20		< 0.1	0.77							
std. dev												
# of samples	1.00	1.00		1.00	1.00							

CO2 Injection Tests Well 9

6/9/2005

CO_2 Injection Tests
Well#9

CO_2 Injection to lower pH to 6.00, followed by air injection to raise pH to 7.5, followed by chlorine addition.

No chemicals were needed.

Initial Volume of water = 2L

Initial Parameters:

Temperature, °C	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfide, mg/L S^{2-}	Conductivity, µS/cm	pH	Dissolved Oxygen, mg/L O_2	ORP, mV
23.9	0.165	200	1.605	493	7.12	1.78	-170
Batch Test		CO_2 flowrate=	3.6 mL/sec				

Speed=200rpm

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	7.12	0.165	493	1.78
0.5	7.88		491	2.68
1	6.44		491	2.66
1.5	6.21		494	2.58
2	6.05		494	2.64
2.5	5.88		494	2.6
3	5.75		494	2.44
3.5	5.75		495	2.42
4	5.64		495	2.3
4.5	5.6		496	2.43
5	5.57	0.155	495	2.3
6	5.49		496	2.43
7	5.46		494	2.41
8	5.44		497	2.41
9	5.35		496	2.33
10	5.33	0.122	496	2.29
11	5.34		497	2.18
12	5.32		496	2.27
13	5.38		498	2.16
14	5.28		498	2.2
15	5.3	0.164	498	2.08
16	5.25		499	2.05
17	5.28		499	2.12
18	5.25		499	1.93
19	5.29		498	2.06
20	5.32	0.123	499	2.08

Aeration following CO2 injection, well 9

Air flowrate= 11.49mL/sec

Air Injection

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	5.5	0.123	501	2.31
0.5	5.66		498	3.6
1	5.6		492	4.49
1.5	5.66		498	4.77
2	5.73		499	4.62
2.5	5.78		497	5.13
3	5.83		500	5.6
3.5	5.88		496	5.92
4	5.93		500	5.92
4.5	5.98		499	6.42
5	6.02	0.14	501	6.63
6	6.13		499	6.87
7	6.23		499	7.05
8	6.33		494	7.15
9	6.42		489	7
10	6.52	0.161	501	7.2
11	6.61		500	7.21
12	6.7		489	7.15
13	6.8		500	7.28
14	6.9		499	6.28
15	6.99	0.165	500	7.07
16	7.09		499	6.9
17	7.19		498	6.94
18	7.29		499	6.65
19	7.41		496	6.6
20	7.52	0.162	499	6.6

Final Alkalinity=200mg/L $CaCO_3$

Chlorination following CO2 injection and aeration, well 9

Volume of water = 1.5L

NaOCl Addition

Volume (µL)	Cumulative NaOCl (µL)	Cumulative NaOCl, mg/L	Chlorine Residual, mg/L Cl_2	Chlorine Demand, mg/L Cl_2	ORP, mV
20	20	0.794	0	0.794	
20	40	1.588	0.2	1.388	
20	60	2.382	0.2	2.182	
20	80	3.175	1	2.175	
20	100	3.969	1	2.969	
20	120	4.763	1.4	3.363	571
20	140	5.557	2.2	3.357	619
20	160	6.351	2.9	3.451	644
20	180	7.145	3.9	3.245	659
20	200	7.939	4.6	3.339	673

Final Parameters:

pH	Alkalinity, mg/L $CaCO_3$	Conductivity, µS/cm	Turbidity, NTU	Dissolved Oxygen, mg/L O_2
8.18	200	549	0.275	5.02

Sulfuric acid injection, Well 9

6/9/2005

H_2SO_4 Injection
Well#9
H_2SO_4 Injection to lower pH to 6.00, followed by air injection to raise pH to 7.5, followed by chlorine addition.
Initial Volume of water = 2L
Initial Parameters:

Temperature, °C	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfide, mg/L S^{2-}	Conductivity, μS/cm	pH	Dissolved Oxygen, mg/L O_2	ORP, mV	Ferrous Iron, mg/L Fe^{2+}	UV-254, cm^{-1}	Color, Pt-Co Units
23.7	0.141	200	0.851	549	7.54	1.89	-134	0.014	-0.01	7

Batch Test
Speed=200rpm

0.1 N H_2SO_4 Titration

Volume Added, μL	Cumulative Volume Added, μL	Cumulative Volume Added, mg/L	pH	Conductivity, μS/cm	DO, mg/L O_2
100	100	245	7.55	490	2.44
100	200	490	7.55	490	
100	300	735	7.54	490	
100	400	980	7.53	490	
100	500	1225	7.52	490	
200	700	1715	7.51	490	
200	900	2205	7.48	490	
400	1300	3185	7.44	491	
400	1700	4165	7.41	492	
500	2200	5390	7.36	492	
500	2700	6615	7.31	493	
500	3200	7840	7.28	493	
500	3700	9065	7.25	493	
500	4200	10290	7.22	494	
500	4700	11515	7.18	494	
500	5200	12740	7.16	494	
500	5700	13965	7.12	494	
500	6200	15190	7.09	495	
500	6700	16415	7.06	496	
500	7200	17640	7.04	496	
500	7700	18865	7.02	496	
500	8200	20090	6.99	497	
500	8700	21315	6.97	497	
1000	9700	23765	6.93	498	
1000	10700	26215	6.89	498	
1000	11700	28665	6.84	499	
1000	12700	31115	6.8	500	
1000	13700	33565	6.75	500	

Aeration and chlorination following sulfuric acid addition, Well 9

Air flowrate= 17.22 mL/sec

Volume of water: 1.5L

Air Injection

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	5.98	0.356	517	6.29
1	6.04		507	7.32
2	6.13		513	7.77
3	6.14		504	5.92
4	6.32		518	5.66
5	6.4	0.276	518	5.64
6	6.5		518	5.6
7	6.59		518	5.47
8	6.67		514	5.43
9	6.76		518	5.37
10	6.84	0.276	518	5.35
11	6.92		517	5.21
12	7		515	5.09
13	7.09		518	5.07
14	7.18		518	5.04
15	7.26	0.246	513	5.01
16	7.37		518	4.82
17	7.43		507	4.81
18	7.51		518	4.78
19	7.57		516	4.74
20	7.65	0.266	517	4.74

Final Alkalinity=40mg/L $CaCO_3$

NaOCl Addition

Volume (µL)	Cumulative NaOCl (µL)	Cumulative NaOCl, mg/L	Chlorine Residual, mg/L Cl_2	Chlorine Demand, mg/L Cl_2	ORP, mV
0	0	0.000	0	0.000	-58
20	20	0.794	0	0.794	-49
20	40	1.588	0	1.588	-33
20	60	2.382	0.3	2.082	-8
20	80	3.175	0.2	2.975	88
20	100	3.969	0.3	3.669	340
20	120	4.763	0.7	4.063	541
20	140	5.557	1.3	4.257	604
20	160	6.351	1.8	4.551	639
20	180	7.145	2.1	5.045	658
20	200	7.939	2.8	5.139	679
20	220	8.733	4.5	4.233	691
20	240	9.526	4.3	5.226	707
20	260	10.320	3.7	6.620	718

Final Parameters:

pH	Alkalinity, mg/L $CaCO_3$	Conductivity, µS/cm	Turbidity, NTU	Dissolved Oxygen, mg/L O_2
	40		0.362	

CO2 injection well 9

6/10/2005

CO_2 Injection Tests
Well#9

CO_2 Injection to lower pH to 6.00, followed by air injection to raise pH to 7.5, followed by chlorine addition.
No chemicals were needed.
Initial Volume of water = 2L
Initial Parameters:

Temperature, °C	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfide, mg/L S^{2-}	Conductivity, µS/cm	pH	Dissolved Oxygen, mg/L O_2	ORP, mV
18.3	0.197	170	1.194	436	7.36	4.43	-135

Batch Test
Speed=200rpm
CO_2 flowrate= 4.94 mL/sec

Ferrous Iron, mg/L Fe^{2+}	UV-254, cm^{-1}
0.007	0.428

CO_2 Injection

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	7.36	0.197	436	3.51
1	6.62		441	4.4
2	6.14		442	4.17
3	5.94		442	3.75
4	5.81		443	3.4
5	5.73	0.17	444	3.32

Final Alkalinity=170 mg/L $CaCO_3$

Aeration following CO2 injection, well 9

Air flowrate= 17.22 mL/sec

Air Injection

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	5.73	0.17	444	3.32
1	5.78		446	7.34
2	5.88		445	8.03
3	5.99		424	8.41
4	6.08		444	8.99
5	6.19	0.197	446	9.39
6	6.29		446	9.68
7	6.38		448	10.3
8	6.48		444	
9	6.59		426	10.69
10	6.69	0.215	449	10.82
11	6.79		442	10.53
12	6.88		437	10.46
13	6.98		450	10.48
14	7.08		450	10.55
15	7.19	0.187	437	10.49
16	7.3		440	10.83
17	7.41		450	10.66
18	7.51		450	10.75
19	7.63		441	10.56
20	7.73	0.185	445	10.69

Chlorination following CO2 injection and aeration, well 9

Volume of water = 1.5L

NaOCl Addition

Volume (µL)	Cumulative NaOCl (µL)	Cumulative NaOCl, mg/L	Chlorine Residual, mg/L Cl_2	Chlorine Demand, mg/L Cl_2	ORP, mV
0	0	0.000	0	0.000	-35
20	20	0.794	0.2	0.594	-17
20	40	1.588	0.3	1.288	50
20	60	2.382	1.5	0.882	121
20	80	3.175	1.3	1.875	294
20	100	3.969	1.3	2.669	508
20	120	4.763	2.9	1.863	565
20	140	5.557	1.6	3.957	601
20	160	6.351	2.8	3.551	621
20	180	7.145	3.4	3.745	639
20	200	7.939	4.9	3.039	653
20	220	8.733	6	2.733	668

Final Parameters:

pH	Alkalinity, mg/L $CaCO_3$	Conductivity, µS/cm	Turbidity, NTU	Dissolved Oxygen, mg/L O_2
8.35	200	503	0.218	8.1

CO2 injection well 8

6/13/2005

CO_2 Injection Tests
Well#8
No chemicals were needed.
Initial Volume of water = 2L
Initial Parameters:

Temperature, °C	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfide, mg/L S^{2-}	Conductivity, µS/cm	pH	Dissolved Oxygen, mg/L O_2	ORP, mV	Ferrous Iron, mg/L Fe^{2+}	UV-254, cm^{-1}
26.3	4.13	180	< 0.1	500	7.43	1.96	87	0.055	0.109

Batch Test
Speed=200rpm
CO_2 flowrate= 4.93 mL/sec

CO_2 Injection

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	7.33	4.13	493	1.96
0.5	6.7		465	1.79
1	6.52		495	1.83
1.5	6.14		494	1.84
2	5.98		488	2.2
2.5	5.86		490	2.24
3	5.84		495	2.26
3.5	5.73		494	1.87

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm
4	5.71		494
4.5	5.61		489
5	5.6	3.87	492
6	5.52		490
7	5.46		493
8	5.47		492
9	5.41		483
10	5.41	3.86	493

Final Alkalinity=190 mg/L $CaCO_3$

Aeration following CO2 injection, well 8

Air flowrate= 17.25 mL/sec

Air Injection

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen mg/L O_2
0	5.43	3.86	492	1.45
1	5.57		463	1.94
2	5.73		490	2.49
3	5.88		484	2.74
4	6.02		488	2.81
5	6.05	3.76	478	3.08
6	6.32		482	3.01
7	6.44		480	2.99
8	6.57		474	2.28
9	6.7		467	1.84
10	6.84	3.5	487	2.92
11	6.97		484	2.91
12	7.11		481	2.88
13	7.25		481	2.77
14	7.4		461	2.75
15	7.53	3.36	480	2.62

Final Alkalinity=220mg/L $CaCO_3$

NaOCl Addition

Volume of water=500mL

Volume (µL)	Cumulative NaOCl (µL)	Cumulative NaOCl mg/L	Chlorine Residual mg/L Cl_2	Chlorine Demand mg/L Cl_2
0	0	0.000	0	0.000
20	20	2.382	0.5	1.882
20	40	4.763	1.4	3.363
20	60	7.145	3.9	3.245
20	80	9.526	5.6	3.926

Final Parameters:

pH	Alkalinity, mg/L $CaCO_3$	Conductivity, µS/cm	Turbidity, NTU	Dissolved Oxygen, mg/L O_2
7.89	210	546	3.05	6.05

CO2 injection well 8

6/14/2005

CO_2 Injection Tests
Well#8

CO_2 Injection to lower pH to 6.00, followed by air injection to raise pH to 7.5, followed by chlorine addition.
No chemicals were needed.
Initial Volume of water = 2L
Initial Parameters:

Temperature, °C	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfide, mg/L S^{2-}	Conductivity, µS/cm	pH	Dissolved Oxygen, mg/L O_2	ORP, mV
13.8	2.51	210	< 0.1	362	7.6	4.73	220

Batch Test
Speed=200rpm

CO_2 flowrate= 4.03 mL/sec

Pressure, psi=16

Ferrous Iron, mg/L Fe^{2+}	UV-254, cm^{-1}	Sulfate, mg/L SO_4^{2-}
0.006	0.118	12.6

CO_2 Injection

Time, min	pH	Turbidity, NTU	Conductivity µS/cm	Dissolved Oxygen, mg/L O_2
0	7.6	2.51	220	4.73
0.5	7.32		367	5.68
1	6.96		368	5.74
1.5	9.65		369	5.55
2	9.38		368	5.48
2.5	6.14		370	5.29
3	6.06		370	5.55
3.5	5.97		370	5.06
4	5.9		371	4.94
4.5	5.84		371	4.75
5	5.8	2.03	371	4.73

Final Alkalinity=170 mg/L $CaCO_3$

Final Sulfate=10.8 mg/L SO_4^{2-}

Aeration and chlorination following CO2 injection, well 8

Air flowrate= 18.27 mL/sec

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	5.8	2.03	371	4.73
1	5.86		368	6.33
2	5.96		377	8.68
3	6.06		372	8.55
4	6.16		376	9.35
5	6.28	1.75	377	9.63
6	6.36		373	9.77
7	6.44		376	10.18
8	6.54		379	10.2
9	6.63		383	10.25
10	6.73	1.69	381	10.21
11	6.82		384	10.06
12	6.93		384	10.05
13	7.02		368	9.91
14	7.13		382	9.9
15	7.24	1.63	385	9.87
16	7.35		381	9.65
17	7.46		386	9.76
18	7.56		386	9.68
19	7.67		386	9.93
20	7.74	1.43	386	9.79

Final Alkalinity=200mg/L $CaCO_3$

NaOCl Addition

Volume of water=500mL

Volume (µL)	Cumulative NaOCl (µL)	Cumulative NaOCl mg/L	Chlorine Residual, mg/L Cl_2	Chlorine Demand, mg/L Cl_2	ORP, mV
0	0	0.000	0	0.000	212
20	20	2.382	0.7	1.682	458
20	40	4.763	3.2	1.563	670
20	60	7.145	6.1	1.045	738

Final Parameters

pH	Alkalinity mg/L $CaCO_3$	Conductivity, µS/cm	Turbidity, NTU	Dissolved Oxygen, mg/L O_2
7.93	220	470	1.19	8.11

Sulfuric acid injection, well 8

6/14/2005

H_2SO_4 Injection

Well#8	Batch test	200 rpm	0.1 N H2SO4

H_2SO_4 Injection to lower pH to 6.00, followed by air injection to raise pH to 7.5, followed by chlorine addition.
Initial Volume of water = 2L

Temperature, °C	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfide, mg/L S^{2-}	Conductivity, µS/cm	pH	Dissolved Oxygen, mg/L O_2	ORP, mV
15.1	0.783	180	< 0.1	374	7.54	4.14	400

Volume Added, µL	Cumulative Volume Added, µL	Cumulative Volume Added, mg/L	pH	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2	Final Alkalinity=40 mg/L $CaCO_3$	
0	0	0	7.54	374	4.14		
2000	2000	4900	7.35	378			
2000	4000	9800	7.24	380			
2000	6000	14700	7.1	382	Final Turbidity=0.607 NTU	Final Sulfate=194 mg/L SO_4^{2-}	
2000	8000	19600	6.93	384			
2000	10000	24500	6.9	387	Ferrous Iron, mg/L Fe^{2+}	UV-254, cm^{-1}	Sulfate, mg/L SO_4^{2-}
2000	12000	29400	6.86	389	0.007	0.078	13.1
2000	14000	34300	6.77	391			
2000	16000	39200	6.67	393			
2000	18000	44100	6.62	396			
2000	20000	49000	6.56	398			
2000	22000	53900	6.47	400			
2000	24000	58800	6.37	402			
2000	26000	63700	6.28	405			
2000	28000	68600	6.2	408			
2000	30000	73500	6.11	411	7.83		

Aeration following sulfuric acid injection, well 8

Air Injection Air flowrate= 17.22 mL/sec

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	6	0.607	420	6.64
1	6.03		419	8.39
2	6.02		423	9.39
3	6.03		420	9.87
4	6.24		423	9.32
5	6.33	0.63	420	9.33
6	6.39		424	9.42
7	6.44		419	9.42
8	6.55		424	9.4
9	6.63		403	9.4
10	6.71	0.655	426	9.43
11	6.83		426	9.63
12	6.91		423	9.76
13	7		423	9.77
14	7.08		422	9.83
15	7.16	0.616	420	9.86
16	7.25		419	9.84
17	7.34		399	9.87
18	7.42		426	9.85
19	7.48		423	9.86
20	7.56	0.617	426	9.72

Final Alkalinity=50 mg/L $CaCO_3$

Final Sulfate=220 mg/L SO_4^{2-}

Chlorination following sulfuric acid injection and aeration, well 8

NaOCl Addition
Volume of water =500mL

Volume (µL)	Cumulative NaOCl (µL)	Cumulative NaOCl, mg/L	Chlorine Residual, mg/L Cl_2	Chlorine Demand, mg/L Cl_2	ORP, mV
0	0	0.000	0	0.000	279
10	10	1.191	0.3	0.891	290
10	20	2.382	1.5	0.882	518
10	30	3.572	3.1	0.472	687
10	40	4.763	5.9	-1.137	736

Final Parameters:

pH	Alkalinity, mg/L $CaCO_3$	Conductivity, µS/cm	Turbidity, NTU	Dissolved Oxygen, mg/L O_2	Sulfate, mg/L SO_4^{2-}
7.72	50	506	0.454	6.8	195

Sulfuric acid injection, well 8

6/14/2005

H_2SO_4 Injection
Well#8

H_2SO_4 Injection to lower pH to 6.00, followed by air injection to raise pH to 7.5, followed by chlorine addition.
Initial Volume of water = 2L
Initial Parameters:

Temperature, °C	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfide, mg/L S^{2-}	Conductivity, µS/cm	pH	Dissolved Oxygen, mg/L O_2	ORP, mV	Ferrous Iron, mg/L Fe^{2+}	UV-254, cm^{-1}	Sulfate, mg/L SO_4^{2-}
13.5	3.06	190	< 0.1	357	7.5	3.66	426	0.015	0.115	8.3

Batch Test
Speed=200rpm

0.1 N H_2SO_4 Titration

Volume Added, µL	Cumulative Volume Added, µL	Cumulative Volume Added, mg/L	pH	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	0	0	7.5	357	3.66
5000	5000	12250	7.27	363	4.78
5000	10000	24500	7.03	368	5.17
5000	15000	36750	6.79	372	5.5
5000	20000	49000	6.55	377	6.05
5000	25000	61250	6.31	384	6.49
2000	27000	66150	6.2	387	6.85
2000	29000	71050	6.11	390	7.21
2000	31000	75950	6.03	393	7.57

Final Alkalinity=40 mg/L $CaCO_3$
Final Turbidity=2.74 NTU
Final Sulfate=146 mg/L SO_4^{2-}

Aeration following sulfuric acid injection, well 8

Air flowrate= 17.22 mL/sec

Air Injection

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	6.02	2.74	397	7.57
1	6.07		399	8.99
2	6.17		398	9.17
3	6.24		400	10.19
4	6.3		401	10.19
5	6.38	2.7	401	10.13
6	6.46		402	10.01
7	6.53		400	9.92
8	6.61		402	9.61
9	6.69		403	9.8
10	6.76	2.68	404	9.67
11	6.84		404	9.55
12	6.93		405	9.47
13	6.99		405	9.43
14	7.08		406	9.45
15	7.18		405	9.33
16	7.24		407	9.47
17	7.33		407	9.54
18	7.4		408	9.67
19	7.48		408	9.75
20	7.55		409	9.77

CO_2 injection and aeration, well 7

6/16/2005

CO_2 Injection Tests
Well#7

CO_2 Injection to lower pH to 6.00, followed by air injection to raise pH to 7.5, followed by chlorine addition.
Initial Volume of water = 2L
Initial Parameters:

Temperature, °C	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfide, mg/L S^{2-}	Conductivity, µS/cm	pH	Dissolved Oxygen, mg/L O_2	ORP, mV	Ferrous Iron, mg/L Fe^{2+}	UV-254, cm^{-1}	Sulfate, mg/L SO_4^{2-}
11.5	4.39	150	< 0.1	329	7.46	6.15	220	0.011	0.061	26.6

Batch Test
Speed=200rpm
CO_2 flowrate= 5.05 mL/sec
Presure=17 psi

CO_2 Injection

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	7.46	4.39	329	6.15
1	6.8		335	7.32
2	6.08		335	7.7
3	5.82		334	6.42
4	5.67		337	6.19
5	5.56	4.16	338	5.31
6	5.5		339	5.09
7	5.45		340	4.65
8	5.41		340	4.44
9	5.38		341	4.15
10	5.36	4.13	341	3.95

Final Alkalinity=60 mg/L $CaCO_3$
Final Sulfate=23.7mg/L SO_4^{2-}

Air flowrate= 17.25 mL/sec

Air Injection

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	5.36	4.13	341	3.95
1	5.48		342	6.51
2	5.58		347	7.96
3	5.67		348	8.76
4	5.78		348	9.36
5	5.87	3.89	348	9.87
6	5.99		339	10.44
7	6.06		350	10.71
8	6.15		350	10.96
9	6.24		349	11.12
10	6.31	4.03	342	11.27
11	6.42		349	11.36
12	6.51		351	11.44
13	6.6		350	11.47
14	6.7		351	11.49

Chlorination following CO2 injection and aeration, well 8

NaOCl Addition

Volume of water=500mL

Volume (μL)	Cumulative NaOCl (μL)	Cumulative NaOCl, mg/L	Chlorine Residual, mg/L Cl_2	Chlorine Demand, mg/L Cl_2	ORP, mV
0	0	0.000			231
10	10	1.191			632
10	20	2.382			690

CO2 injection well 7

6/16/2005

CO_2 Injection Tests

Well#7

CO_2 Injection to lower pH to 6.00, followed by air injection to raise pH to 7.5, followed by chlorine addition.

Initial Volume of water = 2L

Initial Parameters:

Temperature, °C	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfide, mg/L S^{2-}	Conductivity, μS/cm	pH	Dissolved Oxygen, mg/L O_2	ORP, mV	Ferrous Iron, mg/L Fe^{2+}	UV-254, cm^{-1}	Sulfate, mg/L SO_4^{2-}
12.8	4.19	180	< 0.1	335	7.65	6.46	481	0.013	0.069	23.7

Batch Test

Speed=200rpm

CO_2 flowrate= 9.21 mL/sec

Pressure =2psi

CO_2 Injection

Final Turbidity=4.27NTU

Final Sulfate=23.2mg/L SO_4^{2-}

Time, min	pH	Turbidity, NTU	Conductivity, μS/cm	Dissolved Oxygen, mg/L O_2
0	7.65	4.14	335	6.46
1	6.92		340	8.56
2	6.15		341	10.12
3	5.74		343	6.37

Aeration and chlorination after CO2 injection, well 7

Air flowrate= 17.25 mL/sec

Air Injection

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	5.52	4.2	344	5.61
1	5.6		342	7.38
2	5.7		341	8.56
3	5.8		345	9.28
4	5.89		347	9.62
5	5.99	4.28	334	10.09
6	6.1		345	10.31
7	6.17		352	10.57
8	6.26		352	10.79
9	6.36		347	10.94
10	6.44	4.23	311	11.02
11	6.5		352	11.05
12	6.62		352	11.09
13	6.71		352	11.1
14	6.8		355	11.07
15	6.9	4.11	355	11.1
16	7		349	11.22
17	7.11		338	11.16
18	7.23		355	11.31
19	7.34		356	11.25

Final Alkalinity=160mg/L $CaCO_3$

Final Sulfate=23.4 mg/L SO_4^{2-}

NaOCl Addition

Volume of water=500mL

Volume (µL)	Cumulative NaOCl (µL)	Cumulative NaOCl, mg/L	Chlorine Residual, mg/L Cl_2	Chlorine Demand, mg/L Cl_2	ORP, mV
0	0	0.000			234
20	20	2.382			613
20	40	4.763			703

Sulfuric acid injection, well 7

6/17/2005

H_2SO_4 Injection
Well#7

H_2SO_4 Injection to lower pH to 6.00, followed by air injection to raise pH to 7.5, followed by chlorine addition.
Initial Volume of water = 2L
Initial Parameters:

Temperature, °C	Turbidity, NTU	Alkalinity, mg/L $CaCO_3$	Sulfide, mg/L S^{2-}	Conductivity, μS/cm	pH	Dissolved Oxygen, mg/L O_2	ORP, mV	Ferrous Iron, mg/L Fe^{2+}	UV-254, cm^{-1}	Sulfate, mg/L SO_4^{2-}
12.6	1.89	190	< 0.1	350	7.28	5.15	225	0.03	0.048	28

Batch Test
Speed=200rpm

0.1 N H_2SO_4 Titration

Volume Added, μL	Cumulative Volume Added, μL	Cumulative Volume Added, mg/L	pH	Conductivity, μS/cm	Dissolved Oxygen, mg/L O_2
0	0	0	7.28	350	5.15
2000	2000	4900	7.29	350	7.34
2000	4000	9800	7.13	352	7.78
2000	6000	14700	6.97	356	8.19
2000	8000	19600	6.84	359	8.54
2000	10000	24500	6.77	363	8.71
2000	12000	29400	6.66	365	8.89
2000	14000	34300	6.56	368	9.01
2000	16000	39200	6.44	371	9.16
2000	18000	44100	6.34	373	9.22
2000	20000	49000	6.24	375	9.31
2000	22000	53900	6.02	378	9.33

Final Alkalinity=30 mg/L $CaCO_3$
Final Turbidity=1.74 NTU
Final Sulfate=12.9 mg/L SO_4^{2-}

Aeration after sulfuric acid injection, well 7

Air flowrate= 17.22 mL/sec

Air Injection

Time, min	pH	Turbidity, NTU	Conductivity, µS/cm	Dissolved Oxygen, mg/L O_2
0	5.93	1.74	382	5.83
1	5.93		383	9.98
2	6.07		372	10.02
3	6.08		375	10.68
4	6.22		386	10.7
5	6.29	1.69	380	10.88
6	6.36		387	10.94
7	6.41		387	11.15
8	6.48		344	11.2
9	6.54		387	11.25
10	6.6	1.66	389	11.28
11	6.66		390	11.31
12	6.72		390	11.25
13	6.78		390	11.27
14	6.85		391	11.3
15	6.91	1.61	391	11.26
16	6.97		392	11.34
17	7.03		393	11.23
18	7.1		394	11.25
19	7.17		394	11.23
20	7.25	1.52	394	10.94

Added 0.5mL of 0.1 N Na2CO3 to bring the pH up to 7.72 = 1325 mg/L Na2CO3

Final Alkalinity=50 mg/L $CaCO_3$
Final Turbidity=1.55 NTU

Final Sulfate=14.7 mg/L SO_4^{2-}

Well 9, H2O2-NaOCl-NH4OH, pH 8.3

Initial Conditions: 10-18-04

N.B. The initial sulfide concentration was measured using the spectrophotometer

Temp. (°C)	Conductivity (µS/cm)	ORP (mV)	pH	Turbidity (NTU)	DO (mg/L)	Sulfide (mg/L)
24.9	479	-126	7.34	0.181	0.71	2.77

Set Parameters:

pH	**Volume (L)**	**Peroxide ratio**
8.3	**2**	**0.5:1**

Temp. (°C)	Time (min)	H2S (mg/L) measured by probe	pH	H2O2 added (µL)	Cl2 Added (µL)	Residual Cl2 (mg/L)	Turbidity (NTU)	NH3 Added (µL)	Chloramine formed (mg/L as Cl2)	Free NH3 (mg/L as N)
25.1	0	–	8.3	0	0	0	–	0	0	0
25.2	0	2.77	8.3	100	0	0	–	0	0	0
25.2	1	2.106	8.3	0	0	0	–	0	0	0
25.3	2	1.722	8.31	0	0	0	–	0	0	0
25.4	4	1.15	8.33	0	0	0	–	0	0	0
25.6	6	0.89	8.33	0	0	0	–	0	0	0
25.7	8	0.881	8.32	0	0	0	–	0	0	0
25.9	9	–	8.34	0	320	3	0.94	0	0	0
26	–	–	8.32	0	20	2.6	–	0	0	0
26.6	–	–	8.3	0	20	2.4	4.31	0	0	0
26.8	–	–	8.29	0	20	3.1	–	0	0	0
27	–	–	8.29	0	20	3.8	5.67	0	0	0
27.2	–	–	8.28	0	20	3.6	–	0	0	0
27.6	–	–	8.27	0	20	3.8	–	0	0	0
–	–	–		0	20	3.9	7.11	0	0	0
–	–	–		0	40	5.1(t)/ 4.7 (f)	–	0	0	0
28.3	–	–	8.36	0	0	0	–	14.1	0	0
–	–	–	8.36	0	0	0	8.2	0	3.69	0.05 (lower limit)

Well # _9_ Field Measurement data		**Date:**	7/13/2004
		Time	13:00
<u>Phase 1</u>	**<u>Initial Conditions</u>**	**Examiners:**	Salah Albustami Allen Hunter

	Raw water	Tank out
Temperature	26.5	26
Conductivity	507 µS	524 µS
ORP	-204	550
pH	7.44	6.87
Turbidity	–	–
DO	.21 mg/L	

Set parameters						Volume reqd
pH	7.80	Vol Reqd.	0.5 mL 1.0N NaOH	$H_2O_2 : S^{2-}$	1 to 1	0.2 mL
UV dosage			1.0 mL 0.1N HCl	Chlorine ratio		
				Chlorine Intro time		

Temperature:		50 mL sample				Res. Oxi.		
sample #	Time	H2S (DTU)	pH	ORP	Turbidity NTU		Time	H2S (mg/l)
1	0	19	7.79	-213	At end		0	3.04
2	1	19	7.78				1	3.04
3	2	8	7.8				2	1.28
4	3	10	7.81				3	1.60
5	4	13	7.8		time:		4	2.08
6	5	9	7.81		30 min dark		5	1.44
7	6	4	7.81				6	0.64
8	7	17	7.81				7	2.72
9	8	6	7.81	-56			8	0.96
10					Time:	.3 mg/L		

Well # _9_ Field Measurement data

Date: 7/13/2004
Time 15:10
Examiners: Salah Albustami
Allen Hunter

Phase 1 **Initial Conditions**

	Raw water	Tank out
Temperature	26.5	26
Conductivity	507 µS	524 µS
ORP	-204	550
pH	7.44	6.87
Turbidity	–	–
DO	0.21 mg/L	

Phase 3 **Sulfide kinetics**

Set parameters

pH	7.93	Vol Reqd.	0.55 mL 1.0N NaOH	$H_2O_2:S^{2-}$	1 to 1	3% H_2O_2 Volume reqd 0.2 mL
UV dosage				Chlorine ratio		
				Chlorine Intro time		
Temperature:		50 mL sample				Res. Oxi.

sample #	Time: min	H2S (DTU)	pH	ORP	Turbidity NTU		Time: min	H2S (mg/l)
1	0	17	7.93	-208	At end		0	2.72
2	1	14	7.92				1	2.24
3	2	15	7.94				2	2.40
4	3	8	7.95				3	1.28
5	4	8	7.96		time:		4	1.28
6	5	6	7.96		30 min dark		5	0.96
7	6	10	7.97				6	1.60
8	7	5	7.97				7	0.80
9	8	9	7.97	-62			8	1.44
10					Time:	.6 mg/L		

Well # _9_ Field Measurement data

Date: 7/14/2004
Time 11:00
Examiners: Salah Albustami
Allen Hunter

Phase 1 **Initial Conditions**

	Raw water	Tank out
Temperature	25.7	25.7
Conductivity	508 µS	572 µS
ORP	-203	709
pH	7.42	6.79
Turbidity	0.303	0.908
DO	.40 mg/L	1.09

Phase 3 **Sulfide kinetics**

Set parameters						3% H_2O_2 Volume reqd
pH	8.00	Vol Reqd.	0.75 mL 1.0N NaOH	H_2O_2 :S^{2-}	1 to 1	0.2 mL
UV dosage				Chlorine ratio		
				Chlorine Intro time		
Temperature:		50 mL sample				Res. Oxi.

sample #	Time: min	H2S (DTU)	pH	ORP	Turbidity NTU	Time: min	H2S (mg/l)
1	0	24	8.00	-244	At end	0	3.85
2	1	23	8.00		0.31	1	3.69
3	2	14	7.99			2	2.24
4	3	12	7.99			3	1.92
5	4	12	7.99		time: 10 min	4	1.92
6	5	13	7.99		30 min dark	5	2.08
7	6	13	7.99		0.17	6	2.08
8	7	11	7.99			7	1.76
9	8	10	7.99	—		8	1.60
10					Time:15 min		

Well # _9_ Field Measurement data

Date: 7/13/2004

Time 16:00

Examiners: Salah Albustami
Allen Hunter

Phase 1 **Initial Conditions**

	Raw water	Tank out
Temperature	26.5	26
Conductivity	507 µS	524 µS
ORP	-204	550
pH	7.44	6.87
Turbidity	–	–
DO	.21 mg/L	

Phase 3 **Sulfide kinetics**

Set parameters

						3% H_2O_2 Volume reqd
pH	8.1	Vol Reqd.	0.90 mL 1.0N NaOH	$H_2O_2 : S^{2-}$	1 to 1	0.2 mL
UV dosage				Chlorine ratio		
				Chlorine Intro time		

Temperature:		50 mL sample				Res. Oxi.		
sample #	Time: min	H2S (DTU)	pH	ORP	Turbidity NTU		Time: min	H2S (mg/l)
1	0	23	8.1	-206	At end		0	3.69
2	1	17	8.09				1	2.72
3	2	16	8.08				2	2.56
4	3	11	8.07				3	1.76
5	4	12	8.06		time:		4	1.92
6	5	12	8.07		30 min dark		5	1.92
7	6	12	8.08				6	1.92
8	7	14	8.08				7	2.24
9	8	10	8.08	-76			8	1.60
10					Time:	1.0 mg/L		

Well # _9_ Field Measurement data

Date: 7/14/2004
Time 12:45
Examiners: Salah Albustami
Allen Hunter

Phase 1 **Initial Conditions**

	Raw water	Tank out
Temperature	25.7	25.7
Conductivity	508 µS	572 µS
ORP	-203	709
pH	7.42	6.79
Turbidity	0.303	0.908
DO	.40 mg/L	1.09

Phase 3 **Sulfide kinetics**

						3% H_2O_2 Volume reqd
Set parameters						
pH	8.20	Vol Reqd.	0.90 mL 1.0N NaOH	$H_2O_2:S^{2-}$	1 to 1	0.2 mL
UV dosage				Chlorine ratio		
				Chlorine Intro time		

Temperature:		50 mL sample				Res. Oxi.		
sample #	Time: min	H2S (DTU)	pH	ORP	Turbidity NTU		Time: min	H2S (mg/l)
1	0	16	8.20	-231	At end		0	2.56
2	1	15	8.19		.404 @ t0		1	2.40
3	2	15	8.19				2	2.40
4	3	11	8.20		.390 @t 8.5		3	1.76
5	4	13	8.20		time: 10 min		4	2.08
6	5	11	8.20				5	1.76
7	6	9	8.20				6	1.44
8	7	10	8.20				7	1.60
9	8	7	8.20	-109	0.338		8	1.12
10	9	8	8.2		Time:15 min		9	1.28

Well # _9_ Field Measurement data

Date: 7/14/2004

Time 12:45

Examiners: Salah Albustami
Allen Hunter

Phase 1 **Initial Conditions**

	Raw water	Tank out
Temperature	25.7	25.7
Conductivity	508 µS	572 µS
ORP	-203	709
pH	7.42	6.79
Turbidity	0.303	0.908
DO	.40 mg/L	1.09

Phase 3 **Sulfide kinetics**

Set parameters

						3% H_2O_2 Volume reqd
pH	8.30	Vol Reqd.	1.00 mL 1.0N NaOH	$H_2O_2:S^{2-}$	1 to 1	0.2 mL
UV dosage			0.5 mL 0.1N HCl	Chlorine ratio	xxxxxx	xxxxxx
				Chlorine Intro time	xxxxxx	xxxxxx

Temperature:

50 mL sample

sample #	Time: min	H2S (DTU)	pH	ORP	Turbidity NTU	Res. Oxi.	Time: min	H2S (mg/l)
1	0	20	8.28	-228	At end		0	3.20
2	1	15	8.28		.183 @ t0		1	2.40
3	2	13	8.29				2	2.08
4	3	14	8.29				3	2.24
5	4	13	8.29		time: 10 min		4	2.08
6	5	13	8.29				5	2.08
7	6		8.29					
8	7		8.28					
9	8		8.29	-137	0.276	1.0 mg/L		
10					Time:13 min			

Well # _9_ Field Measurement data

Date: 7/21/2004

Time 11:00

Examiners: SA AH

Phase 1 **Initial Conditions**

	Raw water	Tank out
Temperature	25.9	25.9
Conductivity	512 µS	527 µS
ORP	-215	650
pH	7.43	6.78
Turbidity	0.14	1.21
DO	.45 mg/L	.97 mg/L

Phase 3 **Sulfide kinetics**

Set parameters						Volume reqd
pH	8.40	Vol Reqd.	1.10 mL 1.0N NaOH	$H_2O_2 : S^{2-}$	1 to 1	0.2 mL
UV dosage			0.4 mL 0.1N HCl	Chlorine ratio		
				Chlorine Intro time		

Temperature:

sample #	Time	H2S (u?)	pH	ORP	Turbidity NTU	Res. Oxi.	Time	H2S (mg/l)
1	0	17	8.38	-230	.71 NTU ; t=0		0	2.72
2	1.0	16	8.38				1.0	2.56
3	2.0	16	8.38				2.0	2.56
4	3.0	14	8.38				3.0	2.24
5	4.0	19	8.37		.44 NTU ;t= 9		4.0	3.04
6	5.0	12	8.37				5.0	1.92
7	6.0	13	8.37				6.0	2.08
8	7.0	10	8.36				7.0	1.60
9	8.0	12		-100	30 min dark		8.0	1.92
10	9.0				.310 NTU			

Well # _9_ Field Measurement data

Date: 7/21/2004
Time 13:00
Examiners: SAL AH

Phase 1 **Initial Conditions**

	Raw water	Tank out
Temperature	25.9	25.9
Conductivity	512 µS	527 µS
ORP	-215	650
pH	7.43	6.78
Turbidity	0.14	1.21
DO	.45 mg/L	.97 mg/L

Phase 3 **Sulfide kinetics**

Set parameters

pH 8.51 Vol Reqd. 1.15 mL 1.0N NaOH

H_2O_2 :S^{2-} 1 to 1

Volume reqd 0.2 mL

UV dosage

Chlorine ratio

Chlorine Intro time

Temperature:

sample #	Time	H2S (u?)	pH	ORP	Turbidity NTU	Res. Oxi.	Time	H2S (mg/l)
1	0	16	8.51	-244	.69 NTU ; t=0		0	2.56
2	1.0	17	8.49				1.0	2.72
3	2.0	12	8.49				2.0	1.92
4	3.0	12	8.5				3.0	1.92
5	4.0	9	8.5		.64 NTU ;t= 11		4.0	1.44
6	5.0	10	8.5				5.0	1.60
7	6.0	9	8.49				6.0	1.44
8	7.0	11	8.5				7.0	1.76
9	8.0	10	8.49	-118	30 min dark		8.0	1.60
10	9.0				.60 NTU			

2 to 1 ratio
0.4 ml H_2O_2 Added (3%)

pH	Sulfide conc, @ T=0(min)	Sulfide conc, @ T=(min)	Temp.C(@ the beginning of the run)	Time(min)	Sulfide percent removal
7.8	2.56	0.8	25.9	5	68.75
8	2.88	1.12	25.9	6	61.11
8.2	2.72	1.6	25.9	10	41.18
8.3	3.36	1.6	25.9	10	52.38
8.4	2.88	1.44	25.9	10	50.00
8.5	3.36	1.44	25.7	10	57.14

3 to 1 ratio
0.6 ml H_2O_2 Added (3%)

pH	Sulfide conc, @ T=0(min)	Sulfide conc, @ T=(min)	Temp.C(@ the beginning of the run)	Time(min)	Sulfide percent removal
8	2.72	0.96	25.7	5	64.71
8.2	2.88	1.28	25.7	6	55.56
8.4	2.72	1.92	25.7	10	29.41
8.6	3.2	1.92	25.7	10	40.00

4 to 1 ratio
0.8 ml H_2O_2 Added (3%)

pH	Sulfide conc, @ T=0(min)	Sulfide conc, @ T=(min)	Temp.C(@ the beginning of the run)	Time(min)	Sulfide percent removal
8	2.88	0.96	25.7	8	66.67
8.2	2.72	1.92	25.7	8	29.41
8.4	2.88	1.76	25.7	9	38.89
8.6	3.36	1.76	25.7	9	47.62

5 to 1 ratio
1.0 ml H_2O_2 Added (3%)

pH	Sulfide conc, @ T=0(min)	Sulfide conc, @ T=(min)	Temp.C(@ the beginning of the run)	Time(min)	Sulfide percent removal
8	2.56	1.6	25	9	37.50
8.2	3.36	2.08	25	9	38.10
8.4	2.88	1.92	25	9	33.33
8.6	3.2	2.24	25	9	30.00

Summary of pilot plant tests

Date	12/9/2004	12/16/2004	12/17/2004	12/17/2004	12/17/2004	12/20/2004	12/21/2004	12/21/2004
Field Data	UV test varying flowrate	peroxide & NaOH	peroxide & chlorine	peroxide only	UV/ Peroxide	UV/ Chlorine	peroxide-chlorine	peroxide-UV-chlorine
Test Description	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant
Number of tests run	2	2	1	1	1	1	1	1
Key findings	Improved removal at lower flowrates	Turbidity > 10 NTU at pH 7.8	About 50% sulfide oxidized with hydrogen peroxide; sulfide < 0.1 mg/L following chlorine addition	Sulfide < 0.1 mg/L following 25 minute reaction time	Sulfide < 0.1 mg/L following UV/Peroxide	Sulfide < 0.1 mg/L following UV/Chlorine	About 62% sulfide oxidized with hydrogen peroxide; sulfide < 0.1 mg/L following chlorine addition	About 60% sulfide oxidized with hydrogen peroxide, 72% of remaining sulfide oxidized by UV; sulfide < 0.1 mg/L following chlorine addition.
H_2O_2:S^{2-} ratio							0.5:1	0.5:1
Cl2:S2- ratio								
H2O2 concentration, mg/L			1.08	1.08	1.08		1.08	1.08
UV on/off	ON	OFF	OFF	OFF	ON	ON	OFF	ON
Cl2 concentration, mg/L Cl_2			2.83			21.83	21.83	21.83
Total Cl_2 residual at Tap 7, mg/L Cl_2						3.9	3.9	3.9
Free Cl_2 residual at Tap 7, mg/L Cl_2			3.3			1	3.7	8.1
Actual Chlorine Demand, mg/L Cl_2						20.83	18.13	13.73
Total Chloramine residual at Tap 7, mg/L Cl_2								
NH3 concentration, mg/L NH_3-N								
Free NH_3 residual at Tap 7, mg/L NH_3-N								

Date	12/27/2004	12/28/2004	12/28/2004	12/29/2004	12/29/2004	12/29/2004	12/29/2004
Field Data	pH8.0/peroxide	pH9-peroxide-chlorine	pH9/chlorine	pH9-peroxide-UV-chlorine	pH9/peroxide/chlorine	pH9/chlorine	pH9/UV/Chlorine
Test Description	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant
Number of tests run	1	3	1	1	1	1	1
Key findings	About 40% sulfide removal with hydrogen peroxide	About 83% sulfide oxidized with hydrogen peroxide; sulfide < 0.1 mg/L following chlorine reaction	Sulfide < 0.1 mg/L following chlorine addition	About 12% sulfide oxidized with hydrogen peroxide; 70% of remaining sulfide oxidized by UV; sulfide < 0.1 mg/L following chlorine reaction	About 23% sulfide oxidized with hydrogen peroxide; sulfide < 0.1 mg/L following chlorine reaction	T Sulfide < 0.1 mg/L following chlorine reaction	About 62% sulfide oxidized with UV; sulfide < 0.1 mg/L following chlorine reaction
H_2O_2:S^{2-} ratio	0.5:1	0.5:1		0.5:1	0.5:1		
Cl2:S2- ratio							
H2O2 concentration, mg/L	1.08	1.08		1.08	1.08		
UV on/off	OFF	OFF	OFF	ON	OFF	OFF	ON
Cl2 concentration, mg/L Cl_2		21.83	21.83	21.83	21.83	21.83	21.83
Total Cl_2 residual at Tap 7, mg/L Cl_2		3.9	3.9	3.9	3.9	3.9	3.9
Free Cl_2 residual at Tap 7, mg/L Cl_2		6.3	3.1	6.1	6.1	3.7	4.1
Actual Chlorine Demand, mg/L Cl_2		15.53	18.73	15.73	15.73	18.13	17.73
Total Chloramine residual at Tap 7, mg/L Cl_2							
NH3 concentration, mg/L NH_3-N							
Free NH_3 residual at Tap 7, mg/L NH_3-N							

Date	1/3/2005	1/6/2005	1/18/2005	1/21/2005
Field Data	pH8/Chlorine	pH8/peroxide/Chlorine	pH8/peroxide/Chlorine	pH8/peroxide/Chlorine
Test Description	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant
Number of tests run	1	1	1	1
Key findings	Sulfide < 0.1 mg/L following chlorine reaction	About 23% sulfide oxidized with hydrogen peroxide; sulfide < 0.1 mg/L following chlorine reaction	About 17% sulfide oxidized with hydrogen peroxide; sulfide < 0.1 mg/L following chlorine reaction	About 93% sulfide oxidized with hydrogen peroxide; sulfide < 0.1 mg/L following chlorine reaction
H_2O_2:S^{2-} ratio				2:1
Cl2:S2- ratio				
H2O2 concentration, mg/L		1.08	1.08	5.07
UV on/off	OFF	OFF	OFF	OFF
Cl2 concentration, mg/L Cl_2	21.83	19.6	23.67	46.19
Total Cl_2 residual at Tap 7, mg/L Cl_2	3.9			
Free Cl_2 residual at Tap 7, mg/L Cl_2	0.2	3.7	5.4	4
Actual Chlorine Demand, mg/L Cl_2	21.63	15.9	18.27	42.19
Total Chloramine residual at Tap 7, mg/L Cl_2				
NH3 concentration, mg/L NH_3-N				
Free NH_3 residual at Tap 7, mg/L NH_3-N				

Date	4/5/2005	4/6/2005	4/6/2005	4/11/2005	4/12/2005	4/16/2005
Field Data	Anion Exchanger Resin B/ chloramine	Anion Exchanger Resin B/ chloramine	Anion Exchanger Resin B/ chloramine	Anion Exchanger Resin B/ chloramine	Anion Exchanger Resin B/ chloramine	Anion Exchanger Resin A/ chloramine
Test Description	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant	Pilot Plant
Number of tests run	1	1	1	1	1	1
Key findings	Sulfide < 0.1 mg/L following reaction	Sulfide < 0.1 mg/L following reaction	Sulfide < 0.1 mg/L following reaction	Sulfide < 0.1 mg/L following reaction	Sulfide < 0.1 mg/L following reaction	Sulfide < 0.1 mg/L following reaction
H_2O_2:S^{2-} ratio						
Cl2:S2- ratio						
H2O2 concentration, mg/L						
UV on/off	OFF	OFF	OFF	OFF	OFF	OFF
Cl2 concentration, mg/L Cl_2	6.93	10.57	6.93	6.93	6.93	7.27
Total Cl_2 residual at Tap 7, mg/L Cl_2	4.6	3	1.9	4.2	2.6	6.6
Free Cl_2 residual at Tap 7, mg/L Cl_2	4.6	0.9	0.3	3.9	2.1	3.6
Actual Chlorine Demand, mg/L Cl_2	-1.63	7.07	4.84	-0.49	2.42	-0.76
Total Chloramine residual at Tap 7, mg/L Cl_2	3.96	2.6	1.79	3.52	2.41	4.43
NH3 concentration, mg/L NH_3-N	1.25	1.81	1.25	1.25	1.25	1.27
Free NH_3 residual at Tap 7, mg/L NH_3-N	0.96	0.49	0.31	0.27	0.55	0.53

Date	4/17/2005	4/18/2005	4/24/2005
Field Data	Anion Exchanger Resin A/ chloramine	Anion Exchanger Resin A/ chloramine	Anion Exchanger Resin A/ chloramine
Test Description	Pilot Plant	Pilot Plant	Pilot Plant
Number of tests run	1	1	1
Key findings	Sulfide < 0.1 mg/L following reaction	Sulfide < 0.1 mg/L following reaction	Sulfide < 0.1 mg/L following reaction
H_2O_2:S^{2-} ratio			
Cl2:S2- ratio			
H2O2 concentration, mg/L			
UV on/off	OFF	OFF	OFF
Cl2 concentration, mg/L Cl_2	9.24	8.41	7.24
Total Cl_2 residual at Tap 7, mg/L Cl_2	5.4	3.4	4.4
Free Cl_2 residual at Tap 7, mg/L Cl_2	3.3	2	2.4
Actual Chlorine Demand, mg/L Cl_2	3.11	3.91	0.75
Total Chloramine residual at Tap 7, mg/L Cl_2	2.83	2.5	4.09
NH3 concentration, mg/L NH_3-N	1.14	1.14	0.73
Free NH_3 residual at Tap 7, mg/L NH_3-N	0	0.3	0

Tracer test data

Conductivity Tracer Test: Dec. 6, 2004

50 mL of saturated NaCl solution injected using the pH injection pump.

	after UV		
Time (sec)	Conductivity (mS/cm)	Conductivity (mS/cm)	
0	0.59	0.52	0.6
20	0.58	0.52	0.58
40	0.58	0.52	0.57
60	0.57	0.52	0.56
80	0.56	0.52	0.56
100	0.56	0.52	0.55
120	0.56	0.52	0.55
140	0.63	0.52	0.55
160	1.06	0.52	0.54
180	2.16	0.52	0.54
200	1.88	0.52	0.54
220	1.71	0.52	0.53
240	1.69	0.52	0.53
260	1.67	0.52	0.53
280	1.64	0.52	0.52
300	1.6	0.52	0.52
320	1.48	0.52	0.52
340	1.33	0.52	0.52
360	1.19	0.52	0.52
380	1.07	0.52	0.52
400	0.99	0.52	0.52
420	0.92	0.54	0.52
440	0.8	0.58	0.52
460	0.83	0.67	0.52
480	0.81	0.84	0.52
500	0.77	1.03	0.52
520		1.21	0.52

Color Tracer Test: Dec. 7, 2004 and Dec. 9, 2004

50 mL of food coloring injected using pH pump

	at effluent		at effluent
Time (min)	Color (Blue)	Time (min)	Color (Green)
0		0	
5		5	
10		10	
15		15	
20		19.85	16
20.5	179	20.35	15
21	314	20.85	48
21.5	446	21.35	139
22	536	21.85	212
22.5	576	22.35	308
23	560	22.85	386
23.5	500	23.35	432
24	430	23.85	450
24.5	362	24.35	442
25	294	24.85	414
25.5	230	25.35	370
26	183	25.85	322
26.5	150	26.35	290
27	116	26.85	252
27.5	95	27.35	219
28	72	27.85	193
28.5	58	28.35	160
29	47	28.85	135
29.5	38	29.35	115
30	31	29.85	100
30.5	26	30.35	86
31	24	30.85	74

pH Adjust-H2O2-Chlorine

Date	well	dose ratio H2O2: H2S	pH	turbidity initial, NTU	sulfide initial, mg/L	turbidity, NTU post-peroxide 3 min	sulfide, mg/L post-peroxide	turbidity, NTU post-chlorine	sulfide, mg/L post-chlorine	TOC, mg/L	Ca, mg/L	Mg, mg/L	Fe, dissolved, mg/L	Fe (total) mg/L
12/16/2004	9		7.46	2.000	2.42		0.62			3.02	85.06	6.13	0.122	0.431
12/17/2004	9		7.47	0.270	2.58		1.31	4.84	< 0.1					
12/17/2004	9		7.49	0.510	2.56	0.570	1.66							
12/21/2004	9	0.5	7.46	0.976	1.89	0.244	1.42	1.53	0.720					
12/21/2004	9		7.46	0.976	1.89	0.244	1.42		0.120					
12/21/2004	9	0.5	8.20	0.236	2.39	0.153	1.54	1.00	< 0.1					
12/27/2004	9	0.5	7.84	0.481	2.50	0.217	1.66	1.20	< 0.1					
12/27/2004	9	0.5	7.87	0.186	2.51	0.163	1.45							
12/27/2004	9	0.5	7.97	0.152	3.19	0.117	1.57		< 0.1					
12/28/2004	9	0.5	8.57	0.300	1.36	0.428	1.16	2.13	< 0.1					
12/28/2004	9	0.5	8.68	0.923	2.51	0.207	1.48	2.02	< 0.1					
12/28/2004	9	0.5	8.75	0.385	2.36	0.198	1.87	1.74	< 0.1					
12/29/2004	9	0.5	9.27	0.604	2.24	1.690	1.84	5.81	< 0.1					
1/3/2005	9	0.5	7.88	0.520	2.20	0.384	1.89	2.60	< 0.1	2.98	84.28	6.07	0.131	0.600
1/6/2005	9		7.92	0.215	2.51	0.639	1.92	2.26	< 0.1	3.13	86.31	6.22	0.13	0.538

H2O2/UV-Chlorine

Date	well	dose ratio H2O2:H2S	pH	Initial Turbidity, NTU	Initial Sulfide, mg/L	Turbidity, NTU Post-Peroxide-UV	Sulfide, mg/L Post-Peroxide-UV	Turbidity, NTU Post-Chlorine	Sulfide, mg/L post-Chlorine
12/17/2004	9		7.59	1.20	2.46	14.10	0.41		
12/21/2004	9	0.5	7.51	0.25	2.44	0.15	0.99	>10	0.274
1/3/2005	9	0.5	7.77	0.36	2.20	21.70	0.87	>10	< 0.1

UV-Chlorine

Date	well	UV	pH	Initial Turbidity, NTU	Initial Sulfide, mg/:	Turbidity, NTU Post-UV	Sulfide, mg/L post-UV	Turbidity, NTU Post-Chlorine	Sulfide, mg/L post-Chlorine
12/20/2004	9		7.42	0.37	1.95	>10	0.910	>10	< 0.1
12/29/2004	9		8.92	1.10	2.37	1.09	0.643	4.74	< 0.1
1/3/2005	9		7.85	0.56	2.40	8.60	1.240		
1/3/2005			7.85	0.56	2.40	9.08	0.945	>10	< 0.1

Well 9; Anion Exchange; Resin A;

Date	Raw pH	Temp, C	Raw Sulfide mg/L	Raw Sulfate mg/L	Raw Iron mg/L	Raw Chloride	Raw Turbidity	Raw Alkalinity	TOC
5/16/2005	7.77		2.080	28.0			1.010	200	
5/17/2005			2.110	43.0			0.262	230	
5/18/2005	7.22		2.420	25.0			0.165	190	
5/24/2005	7.70	26.1	2.610	32.0	0.149		0.312	210	
5/30/2005	7.44	27.5	1.960	33.4	0.038		0.412	190	1.94
7/19/2005	7.36	26.9	3.650	31.0	<0.001		0.741	210	2.63
7/19/2005	7.36	26.9	3.650	31.0	<0.001		0.741	210	2.63
7/20/2005	7.43	26.4	2.300	26.0	0.020	19.0	0.330	200	2.80

Date	AE pH	Temp, C	AE Sulfide, mg/L	AE Sulfate, mg/L	AE Iron	AE chloride	AE Turbidity	AE Alkalinity	TOC	Gallons
5/16/2005			< 0.1	<1			0.655			150
5/17/2005			< 0.1	2.0			0.068			250
5/18/2005			< 0.1	10.0			0.122			450
5/24/2005	7.17	25.8	< 0.1		0.160		0.258	180		630
5/30/2005	7.21	28.1	< 0.1	0.9	0.043		0.167		0.57	810
7/19/2005	7.46	26.2	< 0.1	< 1	0.030	27.0	0.276	230	0.89	regen
7/19/2005	7.56	26.8	< 0.1	< 1	0.030	28.0	0.109	210		500
7/20/2005	7.63	26.9	< 0.1	< 1	0.090	26.0	0.100	240	0.80	920

Well monitoring data (untreated water)

Date	Well	Chloride, mg/L	Sulfate, mg/L	TDS, mg/L	pH	Conductivity, microS/cm	Alkalinity, mg/L as $CaCO_3$	Calcium, mg/L	Total hardness, mg/L as $CaCO_3$	Ortho p, mg/L as PO_4
2/12/2003	1	10	1	254						
5/31/2003	1	13	1	280						
6/10/2003	1			288	7.19	459	259	82	230	0.23
8/6/2003	1	11	1.3	225						
11/12/2003	1	1.8	1	260						
2/17/2004	1	11	1	296						
5/12/2004	1	16	1	270						
5/26/2004	1			258	7.62	451	219	79	236	0.2
8/4/2004	1	13	1	253						
9/27/2004	1			260	6.94	461	224	82	227	0.28
11/3/2004	1	10	1	279						
2/8/2005	1	11	1	270						
2/12/2003	2	10	3.5	222						
5/31/2003	2	9.9	3.6	228						
6/10/2003	2			246	7.4	397	209	72	190	0.4
8/6/2003	2	11	1	250						
11/12/2003	2	2.3	1	230						
2/17/2004	2	9.9	1	254						
5/12/2004	2	22	1	248						
5/26/2004	2			222	7.52	393	177	76	191	0.31
8/4/2004	2	10	1	208						
9/27/2004	2			216	6.96	401	182	72	191	0.4
11/3/2004	2	10	1.4	218						
2/8/2005	2	9.7	3.5	230						

Date	Well	Chloride, mg/L	Sulfate, mg/L	TDS, mg/L	pH	Conductivity, microS/cm	Alkalinity, mg/L as $CaCO_3$	Calcium, mg/L	Total hardness, mg/L as $CaCO_3$	Ortho p, mg/L as PO_4
2/12/2003	3	11	13	216						
5/31/2003	3	10	14	254						
6/10/2003	3			288	7.21	458	259	82	225	0.25
8/6/2003	3	14	14	268						
11/12/2003	3	3.6	22	174						
2/17/2004	3	9	15	242						
5/12/2004	3	22	6.7	24						
5/26/2004	3			230	7.55	390	163	70	193	0.27
8/4/2004	3	10	10	212						
9/27/2004	3			250	6.96	400	165	67	185	0.31
11/10/2004	3	9.3	13	218						
2/8/2005	3	9.7	12	232						
2/12/2003	4	11	2.6	238						
5/31/2003	4	9.4	13	240						
6/10/2003	4			260	7.32	429	218	72	200	0.35
8/6/2003	4	11	7.2	234						
11/12/2003	4	8.6	5.6	238						
2/17/2004	4	9.4	7	252						
5/12/2004	4	18	6.4	252						
5/26/2004	4			252	7.1	437	210	79	228	0.25
8/4/2004	4	29	8.8	248						
9/27/2004	4			222	6.81	418	184	75	207	0.34
11/10/2004	4	11	6.9	222						
2/9/2005	4	11	7.7	242						

Date	Well	Chloride, mg/L	Sulfate, mg/L	TDS, mg/L	pH	Conductivity, microS/cm	Alkalinity, mg/L as $CaCO_3$	Calcium, mg/L	Total hardness, mg/L as $CaCO_3$	Ortho p, mg/L as PO_4
2/12/2003	6	18	6.3	218						
5/31/2003	6	15	7.4	220						
6/10/2003	6			258	7.23	396	180	70	185	0.36
8/6/2003	6	12	7.7	236						
11/12/2003	6	15	1	2144						
2/17/2004	6	15	6.7	236						
5/12/2004	6	30	3.5	240						
5/26/2004	6			240	6.98	394	158	68	233	0.33
8/4/2004	6	20	7.2	218						
9/27/2004	6			216	6.76	398	158	69	184	0.36
11/3/2004	6	18	8.2	230						
2/8/2005	6	17	7.6	230						
5/31/2003	7	130	7.5	434						
6/10/2003	7			276	7.27	434	164	66	175	0.36
8/6/2003	7	31	15	242						
11/12/2003	7	28	16	240						
2/17/2004	7	12	13	256						
5/12/2004	7	35	5.5	254						
5/26/2004	7			238	7.48	402	142	80	215	0.46
8/4/2004	7	27	16	234						
9/27/2004	7			228	7.13	425	173	69	176	0.42
11/3/2004	7	32	20	250						
2/8/2005	7	17	8.3	220						

Date	Well	Chloride, mg/L	Sulfate, mg/L	TDS, mg/L	pH	Conductivity, microS/cm	Alkalinity, mg/L as $CaCO_3$	Calcium, mg/L	Total hardness, mg/L as $CaCO_3$	Ortho p, mg/L as PO_4
2/12/2003	8	12	12	258						
5/31/2003	8	12	12	284						
6/10/2003	8			284	7.26	461	218	82	220	0.34
8/6/2003	8	20	11	288						
11/12/2003	8	9.6	9.8	262						
2/17/2004	8	12	13	268						
5/12/2004	8	31	6.6	280						
5/26/2004	8			272	7.15	456	190	72	168	0.2
8/4/2004	8	14	8.8	262						
9/27/2004	8			262	6.79	459	191	78	221	0.37
11/3/2004	8	28	12	268						
2/9/2005	8	9.7	11	250						
2/12/2003	9	14	22	282						
5/31/2003	9	13	23	284						
6/10/2003	9			318	7.12	485	194	85	230	0.37
8/6/2003	9	18	25	308						
11/12/2003	9	13	24	276						
2/17/2004	9	25	22	282						
5/12/2004	9	39	26	290						
5/26/2004	9			386	7.25	489	175	80	237	0.32
8/4/2004	9	15	21	270						
9/27/2004	9			288	6.86	487	170	80	231	0.27
11/3/2004	9	14	29	280						
2/9/2005	9	15	25	280						

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December 21, 2005

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Re: Aloha Utilities, Inc.
Our File No. 26038.01

Dear Steve and Rick:

Attached is a copy of the non-binding conceptual capital cost estimate for the implementation of the anion exchange treatment system at Aloha Utilities' five treatment plants. In addition to the conceptual nature and the +/- 30% estimated potential variability and the contingencies contained therein; it is important to keep in mind the purpose for which this estimate has been prepared. It is very unusual to attempt to prepare an estimate of cost in advance of even performing preliminary design. Therefore, this estimate is subject to some significant qualification. We are hopeful that actual cost will come in at or near the estimate, however, there is certainly no incentive for the Utility to attempt to over or underestimate the cost of these facilities. To the extent settlement is attained and we begin moving forward with implementation as we become aware of any factors that would substantially impact this estimate as we move forward in this process and in the construction of the facilities, we will certainly let the Commission and the Office of Public Counsel know.

This estimate has been prepared solely for the purpose of allowing a review of the conceptual costs of implementation of the anion exchange treatment option selected by the parties at five locations within Aloha's system. It should be used for no other purposes other than as stated herein.

If you have any questions or if I can provide any further information, please do not hesitate to contact me.

Sincerely,
ROSE, SUNDSTROM & BENTLEY
F. Marshall Deterding
For The Firm

FMD/tms
cc: Marshall Willis
Troy Rendell
Wayne Forehand
John H. Gaul, Ph.D.

MEMO

To:	Stephen G. Watford, President
From:	David W. Porter, P.E.
Subject:	Non-Binding Conceptual Capital Cost Estimate Modifications to Existing Seven Springs Water Plants 2, 6, 8, 9 and Mitchell to add Anion Exchange Pretreatment Process
Date:	December 20, 2005

At your direction, a non-binding conceptual capital cost estimate has been completed for those modifications that would be required to the existing Seven Springs Water Plants 2, 6, 8, 9 and Mitchell to add an anion exchange pretreatment step to each plant to remove hydrogen sulfide from the raw water which feeds each plant. The estimated costs were developed based on the treatment requirements known at this time which were obtained from the work undertaken by the University of South Florida by contract with Aloha.

Understanding the limitations and additional factors outlined herein (Page 8) that may cause the cost of the estimate to change, our team has developed the following non-binding conceptual capital cost estimates to add anion exchange pretreatment to remove hydrogen sulfide at the existing Seven Springs Water Plants 2, 6, 8, 9, and Mitchell:

Major Equipment	$3.94M
Construction	1.63M
Engineering/Permitting/Bidding/Construction Observation/Etc.	0.56M
Total:	**6.13M (+/- 30%)**

ALOHA ANION EXCHANGE SYSTEM
NON-BINDING CAPITAL COST ESTIMATE

Date: 12/19/05

DESCRIPTION	WTP #2	WTP #6	WTP #8	WTP #9	MITCHELL	WTP #3 & #4	TOTAL
MOBILIZATION, BONDS, & INSURANCE	$17,000.00	$17,000.00	$17,000.00	$17,000.00	$17,000.00		$85,000.00
SITE WORK	$60,000.00	$60,000.00	$65,000.00	$65,000.00	$60,000.00		$310,000.00
STRUCTURAL CONCRETE	$38,000.00	$38,000.00	$38,000.00	$38,000.00	$38,000.00		$190,000.00
MECHANICAL & PIPING	$112,000.00	$112,000.00	$112,000.00	$112,000.00	$112,000.00		$560,000.00
INSTRUMENTATION, CONTROLS & ELECTRICAL	$36,000.00	$36,000.00	$36,000.00	$36,000.00	$36,000.00		$180,000.00
START-UP BRINE/BACKWASH WATER DISPOSAL	$31,000.00	$31,000.00	$31,000.00	$31,000.00	$31,000.00		$155,000.00
WTP #3 & #4 ELECTRICAL AND I & C UPGRADE						$78,000.00	$78,000.00
ALLOWANCE FOR WELL PUMPS UPGRADE							$75,000.00
CONSTRUCTION SUB-TOTALS	**$294,000.00**	**$294,000.00**	**$299,000.00**	**$299,000.00**	**$294,000.00**	**$78,000.00**	**$ 1,633,000.00**
MAJOR EQUIPMENT(Includes 7% Sales tax)							**$ 3,938,000.00**

EQUIPMENT AND CONSTRUCTION SUB-TOTAL : $ 5,571,000.00

ENGINEERING, PERMITTING, BIDDING & CONSTRUCTION SERVICES (10%) **$ 558,000.00**

TOTAL ESTIMATED COST: $ 6,129,000.00

RANGE OF ESTIMATED COST +/- 30%

ALOHA ANION EXCHANGE - NON-BINDING CAPITAL COST EST. Date: 12/19/05
TYPICAL FOR WELL # 8 & 9

DESCRIPTION	QUANTITY		UNIT PRICE	ESTIMATED COST
MOBILIZATION BONDS & INSURANCE				
MOBILIZATION	1	LS	5,000.00	5,000.00
BONDS & INSURANCE	1	LS		12,000.00
TOTAL MOBILIZATION BONDS & INSURANCE				**$ 17,000.00**
SITE WORK				
PERMIT FEES	1	LS	5,000.00	5,000.00
GEO TECH & TESTING	1	LS	2,000.00	3,500.00
CLEARING & GRUBBING	0.5	AC	15,000.00	7,500.00
PROOF ROLL	0.5	AC	1,000.00	500.00
EROSION CONTROL - SILT FENCE	300	LF	4.00	1,200.00
SOD	600	SY	4.25	2,550.00
IMPORT & PLACE FILL	1,400	CY	25.00	35,000.00
FENCING 6' CHAIN LINK	200	LF	25.00	5,000.00
SITE GRADING	2	DAY	2,000.00	4,000.00
TOTAL SITE WORK				**$ 64,250.00**
STRUCTURAL CONCRETE				
12" CONCRETE - FILTER Pad	525	SF	35.00	18,375.00
12" CONCRETE - BACKWASH STORAGE PAD	256	SF	35.00	8,960.00
6" CONCRETE PUMP PAD	1	LS	1,500.00	1,500.00
12" CONCRETE SILO PAD	256	SF	35.00	8,960.00
TOTAL STRUCTURAL CONCRETE				**$ 37,795.00**
MECHANICAL & PIPING				
1 HP BACKWASH WATER TRANSFER PUMPS	2	EA	500.00	1,000.00
SCH-80 PVC PIPING PUMPS	1	LS	1,000.00	1,000.00
FORCE MAIN 2" SCH 80 PVC PIPING	200	LF	40.00	8,000.00
6" SCH-80 PVC BACKWASH PIPING	60	LF	50.00	3,000.00
6" DIP BACKWASH SUPPLY	100	LF	80.00	8,000.00
6" DOUBLE CHECK ASSEMBLY/W ARV & PAD	1	EA	5,000.00	5,000.00
8" DIP RAW INFLUENT	100	FT	150.00	15,000.00
8" DIP TREATED EFFLUENT	100	LF	150.00	15,000.00
TESTING	1	LS	1,000.00	1,000.00
CHLORINATION	1	LS	2,000.00	2,000.00
PAINTING	1	LS	10,000.00	10,000.00
2" WATER SUPPLY TO SILO	100	LF	45.00	4,500.00
CRANE TO SET EQUIPMENT	1	LS	5,000.00	5,000.00
LABOR FOR TONKA PIPING, VALVES, FITTINGS	1	LS	15,000.00	15,000.00
LABOR SET EQUIPMENT	1	LS	3,500.00	3,500.00
LABOR START -UP	1	LS	5,000.00	5,000.00
PROJECT MANAGEMENT	1	LS	10,000.00	10,000.00
TOTAL MECHANICAL & PIPING				**$ 112,000.00**

ALOHA ANION EXCHANGE - NON-BINDING CAPITAL COST EST. Date: 12/19/05
TYPICAL FOR WELL # 8 & 9

DESCRIPTION	QUANTITY		UNIT PRICE	ESTIMATED COST
INSTRUMENTATION, CONTROLS, & ELECTRICAL	1	LS	36,000.00	**$ 36,000.00**
BRINE AND BACKWASH WATER DISPOSAL AT START-UP	1	LS	31,000.00	**$ 31,000.00**
TOTAL BID PROPOSAL - WTP #8 & #9				**$ 298,045.00**

NOTES:

1. Piping prices include all labor, materials, fittings, valves, accessories, and appurtenances.

ALOHA ANION EXCHANGE - NON-BINDING CAPITAL COST EST. Date: 12/19/05
TYPICAL FOR MITCHELL, #2, & #6

DESCRIPTION	QUANTITY		UNIT PRICE	PROBABLE COST
MOBILIZATION, BONDS & INSURANCE				
MOBILIZATION	1	LS	5,000.00	5,000.00
BONDS & INSURANCE	1	LS		12,000.00
TOTAL MOBILIZATIOM, BONDS & INSURANCE				**$ 17,000.00**
SITE WORK				
PERMIT FEES	1	LS	5,000.00	5,000.00
GEO TECH & TESTING	1	LS	2,000.00	3,500.00
CLEARING & GRUBBING	0.5	AC	2,000.00	1,000.00
PROOF ROLL	0.5	AC	1,000.00	500.00
EROSION CONTROL - SILT FENCE	300	LF	4.00	1,200.00
SOD	600	SY	4.25	2,550.00
IMPORT & PLACE FILL	100	CY	25.00	2,500.00
FENCING 6' CHAIN LINK	200	LF	25.00	5,000.00
SITE GRADING	2	DAY	2,000.00	4,000.00
TOTAL SITE WORK				**$ 59,250.00**
STRUCTURAL CONCRETE				
12" CONCRETE - FILTER Pad	525	SF	35.00	18,375.00
12" CONCRETE - BACKWASH STORAGE PAD	256	SF	35.00	8,960.00
6" CONCRETE PUMP PAD	1	LS	1,500.00	1,500.00
12" CONCRETE SILO PAD	256	SF	35.00	8,960.00
TOTAL STRUCTURAL CONCRETE				**$ 37,795.00**
MECHANICAL & PIPING				
1 HP BACKWASH WATER TRANSFER PUMPS	2	EA	500.00	1,000.00
SCH-80 PVC PIPING PUMPS	1	LS	1,000.00	1,000.00
FORCE MAIN 2" SCH 80 PVC PIPING	200	LF	40.00	8,000.00
6" SCH-80 PVC BACKWASH PIPING	60	LF	50.00	3,000.00
6" DIP BACKWASH SUPPLY	100	LF	80.00	8,000.00
6" DOUBLE CHECK ASSEMBLY/W ARV & PAD	1	EA	5,000.00	5,000.00
8" DIP RAW INFLUENT	100	FT	150.00	15,000.00
8" DIP TREATED EFFLUENT	100	LF	150.00	15,000.00
TESTING	1	LS	1,000.00	1,000.00
CHLORINATION	1	LS	2,000.00	2,000.00
PAINTING	1	LS	10,000.00	10,000.00
2" WATER SUPPLY TO SILO	100	LF	45.00	4,500.00
CRANE TO SET EQUIPMENT	1	LS	5,000.00	5,000.00
LABOR FOR TONKA PIPING, VALVES, FITTINGS	1	LS	15,000.00	15,000.00
LABOR SET EQUIPMENT	1	LS	3,500.00	3,500.00
LABOR START -UP	1	LS	5,000.00	5,000.00
PROJECT MANAGEMENT	1	LS	10,000.00	10,000.00
TOTAL MECHANICAL & PIPING				**$ 112,000.00**

ALOHA ANION EXCHANGE - NON-BINDING CAPITAL COST EST. Date: 12/19/05
TYPICAL FOR MITCHELL, #2, & #6

DESCRIPTION	QUANTITY		UNIT PRICE	PROBABLE COST
INSTRUMENTATION, CONTROLS & ELECTRICAL	1	LS	36,000.00	$ **36,000.00**
BRINE AND BACKWASH WATER DISPOSAL AT START-UP	1	LS	31,000.00	$ **31,000.00**
TOTAL BID PROPOSAL - MITCHELL, WTP#2, & WTP #6				$ **293,045.00**
UPGRADE ELECTRICAL, INSTRUMENTATION, & CONTROL AT WTP #3 & #4	1	LS	78,000.00	$ **78,000.00**

NOTES:

1. Piping prices include all labor, materials, fittings, valves, accessories, and appurtenances.

ALOHA ANION EXCHANGE - NON-BINDING CAPITAL COST EST. Date: 12/19/05

DESCRIPTION	QUANTITY		UNIT PRICE	ESTIMATED COST
MAJOR EQUIPMENT (INCLUDES 7% TAX)				
ANION EXCHANGE FILTER SYSTEM, 16,000 GAL.BACKWASH WATER STORAGE TANK, SALT SILO AND BRINE SOLUTION EQUIPMENT INCLUDING PIPING, FITTINGS, VALVES, ETC.	1	LS		3,680,000.00
7% SALES TAX	1	LS		257,600.00
TOTAL MAJOR EQUIPMENT				**$ 3,937,600.00**

As you are aware, this estimate has been prepared in a very short time to accommodate the request of PSC staff, customer representatives and OPC. All parties agreed at the time that Aloha agreed to have this estimate prepared that it would be understood that this estimate would be non-binding and subject to change when more detailed design, permitting and construction bidding were undertaken in the future. Those factors that may cause the actual capital costs to change include, but are not limited to, the following:

1. The estimate is based on the costs for materials and services known on this date (December 19, 2005). Future costs may be different. The volatility of construction costs and/or services are considerable and can not be projected at this time.
2. No detailed design (process, site construction, mechanical, electrical, etc.) has been completed at this time. The estimate is based solely on conceptual information. When final design is undertaken, factors not known at this time may be discovered.
3. No regulatory agency permitting (FDEP, Pasco County, etc.) has been undertaken at this time, therefore, as the permitting processes are undertaken after final design is underway, the regulatory agencies may require design and/or construction changes not anticipated in the conceptual design used to form this estimate.
4. Compliance with an existing Pasco County ordinance requiring aeration treatment to control hydrogen sulfide at these facilities allows for the substitution of alternative technology by variance. This variance has not been obtained as of this date, therefore, there may be cost changes caused due to complying with this Pasco County Order which were not included in this estimate.
5. The cost data used to prepare this cost estimate was obtained from a number of different equipment manufacturers, manufacturers representatives, construction companies, engineers of various specialties (Civil, Electrical, Instrumentation, Mechanical, Process, etc.) and others. The data provided by these sources were of the type that they normally supply at the conceptual phase of a project and are subject to change as the project requirements become more defined.
6. It is assumed that there is sufficient land area available to accommodate the installation of the new equipment and appurtenances at each of the existing plant sites.
7. It is assumed that the regeneration waste may be disposed of by discharge into the existing Seven Springs Wastewater Collection System.

Although too numerous to list here, I wish to thank the many companies and individuals that put forth considerable effort in a very short time frame to assist in the preparation of this estimate.

If you have any questions, please call me.

UNIVERSITY OF CENTRAL FLORIDA
CIVIL AND ENVIRONMENTAL ENGINEERING COLLEGE OF ENGINEERING
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February 20, 2006

Rick Melson, General Counsel
Florida Public Service Commission
Office of the General Counsel
2540 Shumard Oak Blvd.
Tallahassee, FL 32399-0863

RECEIVED
FEB 23 2006
FLORIDA PUBLIC SERVICE COMMISSION
OFFICE OF THE GENERAL COUNSEL

Ref: Review of Conceptual Cost Estimate

Dear Rick,

This is a letter of transmittal of my review of Aloha Utilities Conceptual Cost Estimate for installation of the ion exchange facilities at each of five locations within their service area. Each of the installations will have a capacity of 500 gpm for a total capacity of 2500 gpm.

All assumed details are described in the report that is included in this mailing. Please contact me at your convenience if you have any questions.

Sincerely,

James S. Taylor

Review of Conceptual Cost for Incorporation of Ion Exchange into AU Existing Water Treatment Facilities.

James S. Taylor, Ph.D., P.E. 2/29/06
Environmental Resources Inc.
1630 Wood Duck Drive
Winter Springs, FL 32708

Introduction

This document is a review of the Conceptual Cost Estimate for incorporation of sulfide removal ion exchange facilities into Aloha Utilities (AU's) existing water treatment facilities.

There are several categories of cost estimates. The most general cost estimate is a Systems Cost Estimate, which can be made solely on the basis of capacity. Typical units for Systems Cost Estimates are $/gallon of capacity. A Conceptual Cost Estimate is a more detailed cost estimate, is not constrained by the Systems Cost Estimate, and requires significant time, effort and expense to secure engineering, vendor and construction cost estimates. Depending on the stage at which a cost estimate is prepared, detailed engineering design work may or may not have been performed; however, typically detailed engineering design is not done for a Conceptual Cost Estimate. A Conceptual Cost Estimate can be used to secure buyer approval and also approval of financing agency. Finally, there is an actual cost, which is not an estimate but the Actual Cost the contractors will charge to build the facilities. The Actual Cost is in no way constrained to conform to either the Systems Cost Estimate or the Conceptual Cost Estimate. The Actual Cost is determined through a competitive bidding process in which contractors prepare bids based on their review of detailed design information included in the buyer's invitation to bid. A contractor's bid will be selected from all contractors who have responded to the buyer's announcement for bid. The Actual Cost can be more or less the Conceptual Cost Estimate, and will be what it will cost to build. Typically, the Actual Cost will be acceptable to the buyer, and contracts can be let for construction. On occasion, modifications have to be made in design and new bids have to be submitted to secure an Actual Cost that conforms to existing budgets.

Conceptual Cost Estimate

The basic conceptual design parameters used in the preparation of the non-binding conceptual capital cost estimate for the proposed ion exchange facilities are identified by Aloha Utilities and David Porter, P.E. in the following text (Porter, 2005). In addition, the estimate provides detailed costs for (a) Mobilization, bonds and insurance, (b) Site work, (c) Structural concrete, (d) Mechanical & piping, (e) Instrumentation, controls and electrical, (f) Start-up brine/backwash water disposal, (g) WTP 3 & 4 electrical and I&C upgrade and (h) allowance for well pumps upgrade. Items (a) through (e) will be referred to as construction.

1. Five existing water treatment plants (WTP) known as WTPs 2, 6, 8, 9 and Mitchell will be upgraded to include the anion exchange pre-treatment process. WTPs 1 and 7 will not

require the sulfide removal because the sulfide levels are too low, (< 0.3mg/L). The nominal pumping rate for each of the raw water wells which provide raw water to plants 2, 6, 8 and 9 are 500 GPM each. Wells 3 and 4 together pump 500 GPM and feed the Mitchell plant. Therefore, the anion exchange pretreatment units to be installed are rated for 500 GPM at WTPs 2, 6, 8 and 9, and the Mitchell WTP.

2. Each plant will have three contact vessels. This will allow for one vessel to be taken out of service for regeneration at any time without loss of total flow capacity for the plant. For plants 2, 6, and Mitchell the vessel sizes are 8' diameter by 12' shell height. For Plants 8 and 9 the vessel sizes are 9' diameter by 12' shell height. The 8' diameter vessels will be filled with 175 cubic feet of Thermax type AP 72 strong base ion-exchange resin. The 9' diameter vessels will be filled with 225 cubic feet of the same resin.

3. For the purposes of developing this cost estimate, it was assumed, based on pilot work performed by Dr. Levine at the University of South Florida and on discussions with Tonka, the manufacturer of the Thermax resin, regarding other facility experience, that regeneration will be required for all three vessels each day at Plants 8 and 9. For Plants 2, 6 and Mitchell the contact vessels will be regenerated on a recurring two day cycle of two columns the first day and one the second day.

4. Each plant will also have a brine maker that will be capable of making the quantity of brine needed for regeneration at each plant. The original concept was to install a central brine making facility and transport brine to each plant by truck when needed. However, based on further review by Dr. Levine and Tonka, the logistics were not practical, and therefore smaller brine makers will be required at each plant.

5. Each plant will include the vessels, vessel internals, piping, valves, access platform, accessories, process control metering and instrumentation, brine dilution feed systems, automatic controls, and material coatings. This is the equipment shown on Mr. Porter's conceptual cost estimate as the "Major Equipment." The other items on the estimate are those needed to tie in the new equipment hydraulically, electrically and to the SCADA system, to ready the sites to construct the new facilities and the other related construction costs

In addition Construction costs, costs were also provided for Major Equipment as described in the following text, and for Engineering, Permitting, Bidding & Construction Services identified as Services as shown in Table 1. It should be noted that the variability of the Conceptual Cost Estimate is ± 30%, which is reasonable. The Conceptual Cost Estimates are \$4,290,300 (-30%), \$6,129,000, and \$7,967,700 (+30%).

Table 1. Conceptual Cost Estimate for Installation of AU IX Facilities at No. 2, 6, 8, 9 and Mitchell WTPs

Item	(-30%)	Conceptual Cost	(+30%)
Construction	$1,143,100	$1,633,000	$2,122,900
Major Equipment	$2,756,600	$3,938,000	$5,119,400
Services	$390,600	$558,000	$725,400
Total	$4,290,300	$6,129,000	$7,967,700

Systems Cost Estimate

A Systems Cost Estimate (SCE) was prepared to provide a benchmark for judging the reasonability of Aloha's Conceptual Cost Estimate. The SCE resulted in a gross estimation of the cost of ion exchange (IX) facilities ranging from $0.75/gallon to $2.00/gallon of installed daily capacity. The range of capital cost depends on the following (USEPA, 1998, USEPA 2003):

- Size: Size of plant is typically the major factor affecting cost. Total cost increases as plant capacity increases, but unit cost decreases as plant capacity increases. Installing several smaller plants therefore costs more than installing a single larger plant with the same total capacity.
- Site: The sites for the AU IX facilities are fixed and small, relative to installation of IX facilities in existing sites. This factor tends to result in higher costs on a per-gallon basis.
- System: There are different types of IX systems. There are general IX facilities that can be used to completely deionize water, and there are rather newly developed IX systems that offer unique capabilities for removal of specific ions and are selective for those ions. Thermax is a selective resin as it essentially removes only sulfides and sulfates, leaving alkalinity in the finished water. Thermax is a proprietary resin; however the associated equipment can be secured from several suppliers (including Tonka, US Filter and Hungerford & Terry), which creates a competitive bidding environment and typically decreases cost.
- Operation: Operation of the AU IX facilities operation will be essentially automatic, which will reduce cost of operation but increase capital cost; hence, increasing the SCE.
- Financial Trends: Financial trends have been inflationary in the last five to six years. This trend increases the SCE and the range of the SCE.

Given the specific configuration of AU's system, one would expect the installation of IX facilities in the existing AU WTPs to trend toward the higher end of the SCE range. The IX facilities at AU are small (five each @ 0.72 MGD), the sites are existing and offer little space or flexibility, the resin is proprietary, the operation is remote and needs to be automated, and inflation has been ongoing. All of these factor will push the SCE to the high end of the range.

For example, the total cost for 50 and 500 gpm IX facilities is quoted at $320,000 and $630,000 based on arsenic removal IX facilities in a USEPA, Aug. 2001 publication, (USEPA, 2001). Using the Engineering New Record Construction Cost Index (CCI) to update that to present cost, results in 20 % increase to $384,000 and $816,000 for 50 and 500 gpm facilities, respectively. The order of the unit costs for 50 and 500 gpm are reversed, and are $8.74/gallon and $1.13/gallon, respectively. Arsenic and sulfides are both anions, removed by strong base anion resins that are recharged with NaCl, and low finished water concentrations are required for both. The CCE of $6,129,000 for 2500 gpm at five installations is $1.70/gallon, which is within the SSE range of $0.75/gallon to $2.00/gallon. Other cost estimates for specific ion removal are even higher at flows less than 50 gpm when updated to present day costs, (Edmonds and Salem, 1998, USEPA, 1998)

Other Reviews

Construction Costs

Dr. Taylor, in conjunction with other water treatment professionals who have first hand knowledge of costs associated with the design and build of water treatment facilities, conducted a general review of the construction costs detailed in Aloha's Conceptual Cost Estimate. The eight pages of specific costs were reviewed on a line-item basis were found acceptable in all cases.

Major Equipment Cost

The review of the major equipment cost included consideration of the cost for tanks and brine tanks installed at the Lantana system several years ago. This cost was $700,000, which represents a cost of approximately $812,000 in present dollars. Although the Lantana IX system in 3 MGD, the cost for tanks and associated equipment does not vary significantly based on the size of the plant. Assuming a present day tank cost of approximately $800,000 per system, the cost for AU's five systems would be approximately $4,000,000, which supports the reasonability of Aloha's estimate.

The quoted 2006 cost for installation of a 1 MGD Miex IX facility at Wedgefield, FL was $900,000. Miex IX operates as a fluidized bed as opposed to a fixed bed, which is utilized by Thermax. However both systems use three tanks and similar recharge and inter-stage piping. The Wedgefield site is open and unconstrained; hence this cost is also within the range of the CCE for AU and makes the choice of Thermax resin look economically favorable to Miex.

The information in the Conceptual Cost Estimate regarding the capital cost of equipment could be more detailed. However, given the short time frame in which the CCE was prepared, this lack of detail is not a cause for concern. Consideration of the actual costs for other IX facilities in Florida indicates that the major equipment cost included in the CCE is reasonable for this type of estimate.

Services

The cost for services was found to be reasonable by all professional reviews.

Conclusions

The CEE of $6.13 million (+/- 30%) for installation of IX facilities at the AU five WTPs is satisfactory for a Conceptual Cost Estimate based on the cost review conducted by J. S. Taylor.

The Actual Cost of the facilities could ultimately fall outside the range of the CCE based on changes that result from detailed design, changes in prices of labor and materials, actual equipment bids, and a host of other factors. The CCE nevertheless appears to be a good faith estimate based on reasonable assumptions at the time it was prepared.

Delaying construction of the ion exchange facilities would almost certainly result in increased costs at a later date, and would delay any improvement in finished water quality for a prolonged period.

References:

Design Manual: Removal of As for Drinking Water Utilities, USEPA/600/R-03/080, Cincinnati, OH, June 2003

Edmonds, C., E. Salem, Comparison of EDE and IX Costs, Ultrapure Water, UP150943, November 1998

Guide to Documenting and Managing Cost and Performance Information for Remediation Projects - Revised Version, October, 1998, EPA 542-B-98-007

Innovative Remediation Technologies: Field Scale Demonstration Project in North America, USEPA, 2nd Edition August, 2001

Porter, D. E., Information for Conceptual Cost Estimate, Dec. 19, 2005