ESTCP
Cost and Performance Report

(ER-0544)

Direct Fixed-Bed Biological Perchlorate Destruction Demonstration

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ACRONYMS AND ABBREVIATIONS

[D/A]	electron donor to electron acceptor ratio
BAC	biologically active carbon
BDOC	biodegradable dissolved organic carbon
BOD	biochemical oxygen demand
BW	backwash
C	concentration
CA DHS	California Department of Health Services
CDPH	California Department of Public Health
CFU	colony forming unit
COD	chemical oxygen demand
CT	concentration x contact time
DBP	disinfection by-product
DBPFP	disinfection by-product formation potential
DNA	deoxyribonucleic acid
DO	dissolved oxygen
DOC	dissolved organic carbon
DPH	Department of Public Health
DWEL	Drinking Water Equivalent Level
EBCT	empty-bed contact time
FXB	fixed-bed
GAC	granular activated carbon
gpm	gallons per minute
HAA_5	haloacetic $acid_5$
HPC	heterotrophic plate count
IX	ion exchange
LB	lysogeny broth
LOD	limit of detection
MCL	maximum contaminant level
MWH	Montgomery Watson Harza
NPDES	National Pollutant Discharge Elimination System
NTU	nephelometric turbidity unit

O&M	operations and maintenance
PCB	polychlorinated biphenyl
PCR	polymerase chain reaction
PRB	perchlorate-reducing bacteria
PVC	polyvinyl chloride
RDP	Ribosomal Database Project
SIC	Standard Industrial Classification
TCLP	toxicity characteristic leaching procedure
TDS	total dissolved solids
TOC	total organic carbon
TSS	total suspended solids
TTHM	total trihalomethane
TTLC	total threshold limit concentration
USEPA	U.S. Environmental Protection Agency
VSS	volatile suspended solids
WET	waste extraction tests

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Technical material contained in this report has been approved for public release.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Perchlorate is a groundwater contaminant that has recently received heightened attention. Its presence is often associated with facilities that once manufactured, handled, or stored ammonium perchlorate, a solid-rocket fuel oxidant. The severity and extent of perchlorate contamination was difficult to assess until 1997, when a new ion chromatographic method was developed to decrease the limit of detection (LOD) for perchlorate from 400 micrograms per liter (µg/L) to 4 µg/L (CDHS, 1997). Since then, perchlorate has been detected in drinking water sources in 25 states (Brandehuber and Clark, 2004).

Both abiotic and biotic processes have been developed and evaluated for treating perchlorate-contaminated drinking water. Typical abiotic perchlorate treatment processes include ion exchange (IX) (Tripp et al., 2003; Gu et al., 2001), reverse osmosis/nanofiltration (Amy et al., 2003), electrodialysis reversal (Booth et al., 2000), and tailored granular activated carbon (GAC) (Na et al., 2002). These processes separate perchlorate from the bulk solution by adsorption or diffusion-limited filtration.

The main drawback with abiotic approaches is that they each create a concentrated perchlorate waste stream that must be further treated or disposed. On the other hand, biological processes convert perchlorate to innocuous chloride and oxygen (Coates et al., 1999; Rikken et al., 1996), thereby eliminating perchlorate from the environment. Of the various available biological perchlorate treatment technologies, none has been tested more extensively on drinking water and been demonstrated to be as simple, efficient, robust, and cost-effective as GAC-based heterotrophic (i.e., uses organic carbon sources) fixed-bed (FXB) bioreactors. The main advantages of FXB biological processes relative to conventional perchlorate treatment processes include:

- Perchlorate is not concentrated, but rather is converted to innocuous chloride and oxygen.
- Multiple contaminants can be removed in a single reactor (e.g., perchlorate and nitrate).
- Design and operation of FXB bioreactors is comparable to the design and operation of conventional granular media filters.
- Associated costs can be low.

1.2 OBJECTIVES OF THE DEMONSTRATION

The overall objective of this work was to evaluate the efficacy of using FXB bioreactors and post-treatment to remove perchlorate from drinking water and to produce water that meets all regulations. Specific project emphases included the demonstration of sustained perchlorate removal capabilities; the identification and evaluation of process limitations and potential failure scenarios; and the development of realistic designs and cost estimates for full-scale, potable FXB biological perchlorate treatment.

1.3 DEMONSTRATION RESULTS

In February 2007, a 10-month demonstration study was initiated in Rialto, California, to treat perchlorate-contaminated groundwater using FXB bioreactor technology. Two first-stage, parallel FXB bioreactors (F120 with a 3.9-ft bed depth and a 2-ft diameter, and F130 with a 4.7-ft bed depth and a 2-ft diameter) treated groundwater to remove perchlorate. Effluent from these reactors was dosed with hydrogen peroxide (i.e., reoxygenate + oxidize residual organics and hydrogen sulfide). The reoxygenated water was then passed through an FXB biofilter (F150) to oxidize any remaining organics and sulfide and to remove turbidity. Chlorine was then dosed to the effluent of the biofilter as a final disinfection step. In parallel with the pilot testing, a mathematical model was developed and calibrated, which can be used to elucidate observed phenomena during pilot testing and to predict the perchlorate removal performance of an FXB bioreactor system at other sites. Additionally, molecular microbiological analyses were performed to quantify the relative abundance of specific bacteria within the mixed microbial community in the bioreactor bed. A bench-scale FXB bioreactor was also constructed to test how nutrient addition and intermittent electron donor addition patterns affect the performance and microbial community of a bioreactor. Tests were run using the bench-scale bioreactor that could not be easily conducted using the demonstration-scale system. The bench-scale system also provided "replicates" for the tests that were performed with both systems.

The results of this study showed that 1) as FXB bioreactor treatment systems scale up, process efficiencies also go up (i.e., the required contact time to achieve sustained, robust perchlorate removal to below detection was one-third the contact time required during previous, smaller scale studies); 2) hydrogen peroxide reoxygenation, polishing filtration, and chlorination provide effective post-treatment; 3) system operation is straightforward, requiring no specialized training or extraordinary maintenance procedures; 4) the bacterial communities in these systems are largely gram-negative *Proteobacteria*;5) site-specific performance of these systems can be predicted using a mathematical model developed as part of this demonstration; and 6) costs for FXB biological perchlorate treatment systems can be low.

1.4 IMPLEMENTATION ISSUES

Any full-scale, potable FXB biological perchlorate treatment process would be subject to all federal and state drinking water regulations. In addition to these established and emerging drinking regulations, which primarily apply to distributed water quality, utilities will also have to consider how to handle the backwash (BW) wastewater. This waste stream should be $\leq$3% of the total water treated and have BW wastewater of low strength. Therefore, it is expected that it can be discharged to the local sewer in many instances, though this would have to be confirmed on a site-specific basis. If no sewer discharge is allowable at a given site, a wastewater clarification and recycle process would need to be considered.

Lastly, a permit for full-scale installation and operation of a potable, FXB biological perchlorate treatment system must be applied for and received from the California Department of Public Health (CDPH). Conditional CDPH approval for full-scale implementation of the FXB process was granted to Carollo Engineers in 2004, and discussions with CDPH in February 2008 indicated that, based on the performance data from various FXB biological perchlorate and nitrate treatment pilot studies, full-scale FXB biological treatment facility permitting should follow the standard schedule and protocol for any new water treatment facility in California.

2.0 INTRODUCTION

2.1 BACKGROUND

Perchlorate is a groundwater contaminant that has recently received heightened attention. Its presence is often associated with facilities that once manufactured, handled, or stored ammonium perchlorate, a solid-rocket fuel oxidant. The severity and extent of perchlorate contamination was difficult to assess until 1997, when a new ion chromatographic method was developed to decrease the LOD for perchlorate from 400 µg/L to 4 µg/L (CDHS, 1997). Since then, perchlorate has been detected in drinking water sources in 25 states (Brandehuber and Clark, 2004).

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The main drawback with abiotic approaches is that they each create a concentrated perchlorate waste stream that must be further treated or disposed. On the other hand, biological processes convert perchlorate to innocuous chloride and oxygen (Coates et al., 1999; Rikken et al., 1996), thereby eliminating perchlorate from the environment. Of the various available biological perchlorate treatment technologies, none has been tested more extensively on drinking water and been demonstrated to be as simple, efficient, robust, and cost-effective as GAC-based heterotrophic (i.e., uses organic carbon sources) FXB bioreactors.

This demonstration project confirmed the advantages of biological perchlorate-reducing processes that have been identified through bench- and pilot-scale testing. These advantages include:

- Perchlorate is not concentrated, but rather is converted to innocuous chloride and oxygen.
- Multiple contaminants can be removed in a single reactor (e.g., perchlorate and nitrate).
- Design and operation of FXB bioreactors are comparable to the design and operation of conventional granular media filters.
- Associated costs can be low.

2.2 OBJECTIVES OF THE DEMONSTRATION

The objective of this work was to evaluate the efficacy of using 1) FXB bioreactors to remove perchlorate from raw groundwater and 2) a post-treatment reoxygenation, biofiltration, and final disinfection process to condition the water to potable standards. Using 10 years of bench- and pilot-scale experience as a foundation, scale-up issues were identified by evaluating a demonstration-scale FXB bioreactor system treating water from Rialto, California, Well #2.

Specific project emphases included the demonstration of sustained perchlorate removal capabilities; the identification and evaluation of process limitations and potential failure scenarios; and the development of realistic designs and cost estimates for full-scale, potable FXB biological perchlorate treatment.

2.3 REGULATORY DRIVERS

There is no federal maximum contaminant level (MCL) for perchlorate. In February 2005, the U.S. Environmental Protection Agency (USEPA) adopted the National Academy of Science's recommended perchlorate reference dose of 0.007 milligrams per kilogram per day, which correlates to a Drinking Water Equivalent Level (DWEL) of 24.5 µg/L. Individual states have established provisional perchlorate action levels ranging from 1 to 18 µg/L, while Massachusetts has set a primary drinking water MCL of 2 µg/L. California's 6 µg/L MCL went into effect on October 19, 2007.

2.4 STAKEHOLDER/END-USER ISSUES

There were a few overarching questions about FXB biological perchlorate treatment that were addressed by this demonstration project:

- Is the process robust, or is it susceptible to fluctuations in feed water quality or operating conditions?
- How well can the system handle relatively high concentrations of perchlorate in the raw water (e.g., ~1 mg/L)? This issue targets the question of whether the FXB bioreactor system can be applied at a remediation site (i.e., a nonpotable application).
- What post-treatment is necessary to produce safe, aesthetically acceptable water?
- What are the associated treatment costs?
- What bacterial communities comprise the bioreactor beds?
- How well can the process be modeled?

3.0 TECHNOLOGY

3.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Technology Description. The technology relies on the premise that bacteria can gain substantial energy by mediating the transfer of electrons from an electron donor (such as acetic acid) to perchlorate. Thermodynamic data indicate that perchlorate is a strong oxidant (i.e., accepts electrons readily). Rikken et al. (1996) provided the free energies (at standard conditions and pH = 7) for the stoichiometric reactions between acetate and dissolved oxygen (DO), acetate and nitrate, and acetate and perchlorate:

(1) $CH_3COO^- + 2O_2 \rightarrow 2HCO_3^- + H^+$; $\Delta G^{o\prime} = -844$ KJ/mol acetate
(2) $CH_3COO^- + {}^3/_5NO_3^- + {}^{13}/_5H^+ \rightarrow 2HCO_3^- + {}^4/_5H_20 + {}^4/_5N_2$; $\Delta G^{o\prime} = -792$ KJ/mol acetate
(3) ${}^1/_2CH_3COO^- + ClO_4^- \rightarrow HCO_3^- + {}^1/_2H^+ + ClO_2^-$; $\Delta G^{o\prime} = -801$ KJ/mol acetate[1]

Biological perchlorate treatment processes capitalize on this principle by maintaining an environment that fosters the growth of perchlorate-reducing bacteria (PRB). FXB biological processes utilize a stationary bed of media such as sand, plastic, or GAC on which biofilms containing PRB develop. Water is drawn from a well, amended with an electron donor and then pumped across the media bed. Bacteria in the bed reduce DO, nitrate, and perchlorate. For convention during this project, electron donor (i.e., acetic acid) addition was dosed and adjusted in terms of a stoichiometric electron donor to electron acceptor ratio ([D/A]). [D/A] represents the stoichiometric acetic acid demand exerted by the raw water DO and nitrate concentration according to Equations (1) and (2) above. For simplicity only, the [D/A] calculation assumes that the fraction of electrons used for energy is 1 (i.e., $f_e = 1$). The cell synthesis half-reactions are ignored to simplify the calculation.

Post-Treatment. For remediation applications, it is unlikely that a perchlorate-reducing FXB bioreactor process would require substantial post-treatment (possibly reaeration and disinfection only). On the other hand, for drinking water treatment applications, treatment downstream of a FXB bioreactor process needs to have the ability to achieve the following treatment goals:

- Reoxygenation: Since biological perchlorate reduction requires near anaerobic conditions, DO must be supplied during the post-treatment process.
- Residual Organic Carbon Removal: The addition of an easily assimilable organic substrate can lead to the production of biologically unstable product water.
- Sulfide and Turbidity Removal: Under anaerobic conditions, sulfate can be reduced to sulfide, which is odorous. Biomass that sloughs from the FXB reactor during production may produce turbidity.
- Disinfection: As with any drinking water treatment process, a disinfection step must be included in the FXB biological perchlorate treatment train.

For this project, post-FXB bioreactor treatment included in-line reoxygenation (i.e, dosing of hydrogen peroxide), second stage biologically active filtration, and chlorination. A schematic of

[1] Perchlorate-reducing bacteria reduce perchlorate to chlorite and then convert chlorite to chloride and oxygen during a dismutation reaction that yields no energy (Coates et al., 1999).

the demonstration treatment train is provided in Figure 1, and a 3-D model of the pilot system is provided in Figure 2.

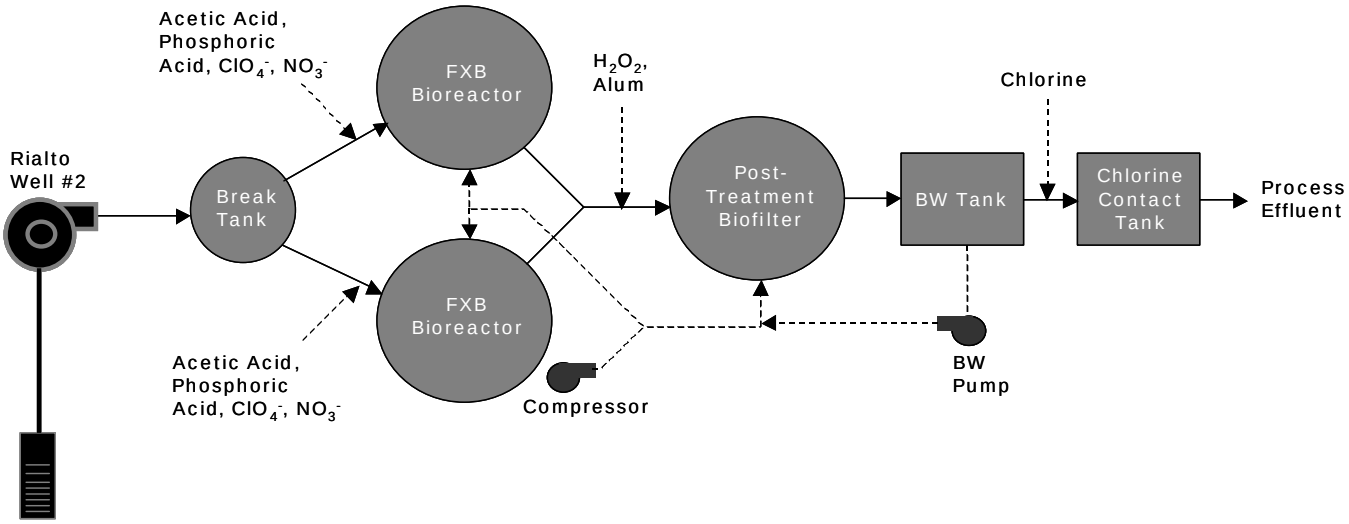

Figure 1. Fixed-bed bioreactor treatment train.

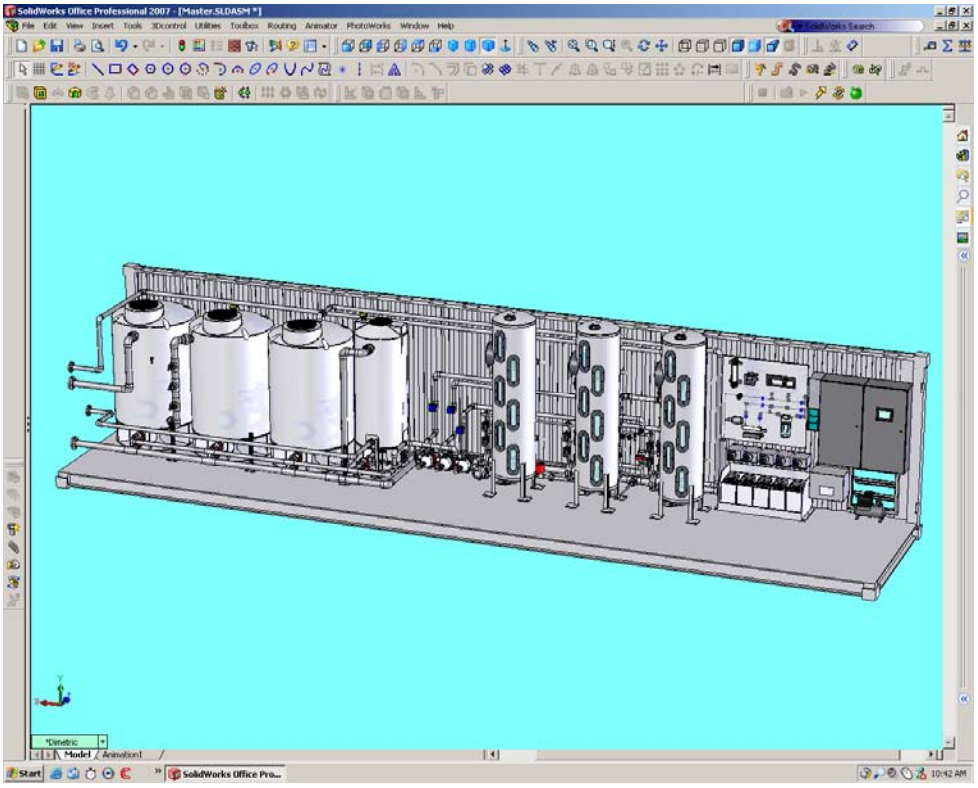

Figure 2. Three-dimensional model of the FXB demonstration system.

Design Parameters. Design parameters were developed during demonstration testing that were used to construct preliminary process flow diagrams, facility layouts, and cost estimates. The critical design parameters for the FXB bioreactors included:

- Biogrowth support media selection
- Empty-bed contact time (EBCT)/surface loading rate/bed depth
- Efficiency/recovery
- Acetic acid dosing requirements
- Nutrient dosing requirements
- Headloss trends/pumping requirements
- Backwash protocol (frequency, air scour rate and duration, fluidization rate and duration)
- Backwash wastewater quality, including volatile suspended solids (VSS), total suspended solids (TSS), biochemical oxygen demand (BOD), and total dissolved solids (TDS).

The critical post-treatment design parameters included:

- Hydrogen peroxide dosing requirements
- Coagulant dosing requirements
- EBCT
- Headloss trends/pumping requirements
- Backwash protocol (frequency, air scour rate and duration, fluidization rate and duration)
- Chlorine dosing requirements.

3.2 PREVIOUS TESTING OF THE TECHNOLOGY

3.2.1 Bench-Scale Testing

Since 1998, numerous bench-scale FXB bioreactors have been tested at the University of Illinois at Urbana-Champaign (Choi, 2005; Choi et al., 2003; Brown et al., 2003; Brown et al., 2002; Brown, 2002). This work has demonstrated that FXB bioreactors:

- Can achieve and sustain perchlorate removal to below detection (2 µg/L) using bacteria present in groundwater or dechlorinated tap water.
- Require the addition of only an electron donor (i.e., background nutrient concentrations are generally sufficient to sustain efficient perchlorate-reducing bioactivity).
- Require EBCTs ranging from <1 to 25 minutes, depending on the concentration of DO and nitrate in the raw water. As raw water DO and nitrate concentrations

increase, the required EBCT to remove perchlorate to below detection also increases. This is because biological perchlorate degradation is inhibited by the presence of DO and nitrate (i.e., bacteria typically utilize DO and nitrate as terminal electron acceptors before they utilize perchlorate as a terminal electron acceptor) This impact is especially pronounced in groundwater systems where perchlorate is typically an order-of-magnitude lower in concentration than DO or nitrate.

- Are robust with respect to fluctuations in raw water pH (6.5-9.0 tested), temperature (as low as 5°C tested), perchlorate concentration (10-300 µg/L tested), and sulfate concentration (0-100 mg/L tested).
- Are robust with respect to electron donor feed system failures and filter bed cleaning events (comparable to backwashing events).

3.2.2 Pilot-Scale Testing

In January 2004, a 6-month study in southern California was completed that was designed to evaluate various technologies for removing perchlorate from groundwater. Pilot-scale FXB and fluidized-bed bioreactors were tested in parallel along with three single-pass, perchlorate-specific IX resins (bench-scale). FXB bioreactor performance can be summarized as follows (Brown et al., 2005):

- Consistent perchlorate removal to below detection was achieved in the reactor using only organisms indigenous to the Saugus aquifer. With influent DO and nitrate concentrations of 7 and 15 mg/L (as NO_3^-), respectively, the lowest EBCT and acetic acid concentration that allowed consistent perchlorate removal to below detection were 15 minutes and 7.8 mg/L as carbon, respectively. Twenty-four-hour run times (i.e., length of production times between two backwashes) were used under these conditions, as headloss built up and had to be removed. For this pilot, the headloss value that triggered a backwash was 30 ft (13.0 psig), which was driven by feed pump capacity. A design EBCT of 25 minutes was chosen to allow for 48-hour run times.
- Effluent total organic carbon (TOC) and biodegradable dissolved organic carbon (BDOC) concentrations were generally below the detection limit of 0.1 mg/L.
- No fecal coliforms were detected in the feed or effluent of the reactor.
- Average feed and effluent turbidities were 0.5 and 0.6 nephelometric turbidity unit (NTU), respectively.
- Headloss across the reactor ranged from <2 to 30 ft (0.9-13.0 psig) but was typically between 5 and 10 ft (2.2-4.3 psig).
- Backwashing with water containing 6-8 mg/L DO concentrations did not impact perchlorate removal performance.
- Fluctuations in feed perchlorate concentrations (5 µg/L to 300 µg/L) did not impact perchlorate removal performance.
- Gradual changes in feed DO and nitrate concentrations did not impact perchlorate removal performance.

- Periods of extended system shutdown (up to 2 weeks) did not impact perchlorate removal performance.
- A 24-hour acetic acid feed failure simulation did not impact perchlorate removal performance.
- Seven-day total trihalomethane (TTHM) formation potentials of FXB bioreactor effluent using 3-5 mg/L free chlorine residual or 3-5 mg/L combined chlorine residual incubated for 7 days at 70-80°F were 20 µg/L and <1 µg/L, respectively.
- Seven-day haloacetic acid$_5$ (HAA_5) formation potentials of FXB bioreactor effluent using 3-5 mg/L free chlorine residual or 3-5 mg/L combined chlorine residual incubated for 7 days at 70-80°F were 26 µg/L and 17 µg/L, respectively.

Based on the results of this pilot-scale work, Carollo Engineers submitted a comprehensive FXB biological perchlorate treatment engineering report to the California Department of Health Services (CA DHS); now called the CDPH technology acceptance application program (Brown et al., 2004). On November 15, 2004, CA DHS granted Carollo Engineers "Conditional Acceptance of Fixed-Bed Biological Treatment for the Production of Drinking Water from Perchlorate Contaminated Water" (Sakaji, 2004).

3.2.3 Demonstration Testing: ER-0544

In February 2007, a 10-month demonstration study was initiated in Rialto, California, to treat perchlorate-contaminated groundwater using FXB bioreactor technology. Two first-stage, parallel FXB bioreactors (F120 with a 3.9-ft bed depth and a 2-ft diameter, and F130 with a 4.7-ft bed depth and a 2-ft diameter) treated groundwater to remove perchlorate. Effluent from these reactors was dosed with hydrogen peroxide (i.e., reoxygenate + oxidize residual organics and hydrogen sulfide). The reoxygenated water was then passed through an FXB biofilter (F150) to oxidize any remaining organics and sulfide and to remove turbidity. Chlorine was then dosed to the effluent of the biofilter as a final disinfection step. In parallel with the pilot testing, a mathematical model was developed and calibrated, which can be used to elucidate observed phenomena during pilot testing and to predict the perchlorate removal performance of an FXB bioreactor system at other sites. Additionally, molecular microbiological analyses were performed to quantify the relative abundance of specific bacteria within the mixed microbial community in the bioreactor bed. A bench-scale FXB bioreactor was also constructed to test how nutrient addition and intermittent electron donor addition patterns affect the performance and microbial community of a bioreactor. Tests were run using the bench-scale bioreactor that could not be easily conducted using the demonstration-scale system. The bench-scale system also provided "replicates" for the tests that were performed with both systems.

The results of this study showed that 1) as FXB bioreactor treatment systems scale up, process efficiencies also go up (i.e., the required contact time to achieve sustained, robust perchlorate removal to below detection was one-third the contact time required during previous, smaller scale studies); 2) hydrogen peroxide reoxygenation, polishing filtration, and chlorination provide effective post-treatment; 3) system operation is straightforward, requiring no specialized training or extraordinary maintenance procedures; 4) the bacterial communities in these systems are largely gram-negative *Proteobacteria*; 5) site-specific performance of these systems can be

predicted using a mathematical model developed as part of this demonstration; and 6) costs for FXB biological perchlorate treatment systems can be low.

3.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Three processes that have received considerable attention for treating perchlorate include FXB bioreactors, fluidized-bed bioreactors, and single-pass IX. FXB bioreactors use a stationary bed of granular media for biogrowth support to which an organic electron donor is added. Contaminated water is passed through the bed and excessive biogrowth is removed during backwashing, which occurs approximately every 24 hours. Fluidized-bed bioreactors[2] are completely mixed systems that use recycle lines and high feed pumping rates to maintain a suspended bed of granular media for biogrowth support. An organic electron donor is added to the bioreactor, and biomass control is maintained using an off-line biomass/GAC separator (i.e., backwashing is not required). Single pass IX uses perchlorate-selective resins to remove perchlorate from contaminated water. During this process, contaminants are adsorbed to the resin, and once exhausted, the resin is removed and transported for incineration. A general comparison of the strengths and weaknesses of each process is provided in Table 1.

Table 1. Advantages and limitations of various oxidant-reducing bioreactor technologies based on available data.

Configuration	Strengths	Weaknesses
Fixed-bed	• Can remove multiple contaminants in a single reactor (e.g., nitrate, perchlorate, volatile organic compounds) • Short EBCTs required (redox gradients allow efficient use of specific microbial metabolisms) • Simple design and operation • Robust with respect to operational and water quality upsets • Low costs; costs not highly sensitive to raw water quality or perchlorate treatment goals • Received conditional CDPH certification for treating perchlorate-contaminated drinking water • Green technology (i.e., contaminants are degraded instead of concentrated) • High recoveries	• Backwash required • Electron donor required and nutrient dose may be required • Post-treatment reoxygenation and filtration required • No full-scale potable installations in operation for perchlorate removal (20+ full-scale potable installations in operation for nitrate removal in Europe)

[2] The fluidized-bed reactor that has received CA DHS conditional approval for perchlorate treatment is a proprietary process developed by Shaw Environmental, Inc.

Table 1. Advantages and limitations of various oxidant-reducing bioreactor technologies based on available data. (continued)

Configuration	Strengths	Weaknesses
Fluidized-bed	• Full-scale installations for remediation applications (i.e., nonpotable) • No off-line backwash required • Low operations and maintenance (O&M) costs • Received conditional CDPH certification for treating perchlorate-contaminated drinking water • Green technology (i.e., contaminants are degraded instead of concentrated) • High recoveries	• High feed pumping rates • Electron donor required and nutrient dose may be required • Recycle required • Post-treatment reoxygenation and filtration required
Single-pass ion exchange	• Full-scale installations in operation • Simple design and operation • High recoveries • Low cost	• Only targets perchlorate • Not a green technology (i.e., contaminants are concentrated, then exhausted IX resin removed and transported for incineration)

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4.0 PERFORMANCE OBJECTIVES

4.1 SUMMARY

Performance objectives listed in Table 2 apply to the complete FXB bioreactor and post-treatment process train.

Table 2. Performance objectives.

Type of Performance Objective	Primary Performance Criteria	Success Criteria	Actual Performance Success Criteria Met?
Qualitative	Confidence in viability of the process	Utility/operator/Department of Public Health (DPH) acceptance	Yes
	Ease of use	Operator acceptance	Yes
Quantitative	Sustained removal of raw water perchlorate to below detection under steady-state optimized conditions (Phase 3 testing)	≥95% of effluent perchlorate concentrations below 2 µg/L over 6-week testing period	Yes
	Sustained removal of raw water perchlorate to below detection during periods of transient system upsets (Phase 4 testing)	≥95% of effluent perchlorate concentrations below 2 µg/L during each robustness test (includes high resolution sampling)	Yes
	High process efficiency	≥95% of raw water recovered for distribution	Yes
	Effluent DO levels	Effluent DO concentration = raw water DO concentration ± 1 mg/L	Yes
	Biological stability of effluent	≥90% of effluent BDOC concentrations below detection (<0.1 mg/L) during 6-week Phase 3 testing period	
	Aesthetic quality of effluent	No olfactory hydrogen sulfide detection in ≥95% of effluent samples during 6-week Phase 3 testing period	
	Disinfection by-product formation potential (DBPFP) of effluent	<60 µg/L TTHMs and <40 µg/L HAA_5 in all DBPFP tests during 6-week Phase 3 testing period	
	Microbial quality of effluent	≥90% of effluent heterotrophic plate counts (HPC) ≤500 counts/mL during 6-week Phase 3 testing period	

4.2 PERFORMANCE OBJECTIVES

- **Confidence in the Viability of the Process.** It is important to demonstrate robust performance with any water treatment process so that utility managers, utility operators, regulators, and consumers can be confident that all water quality standards will be met regardless of raw water quality or operating conditions. For innovative processes with no full-scale track record, performance demonstration is particularly critical for establishing

the viability of the process. Essentially, this objective reflects the cumulative demonstration of all other objectives listed in Table 2. If all other performance objectives are met, then utility, operator, and regulatory acceptance should follow.

- **Ease of Use.** Operators must be comfortable with the operation and maintenance of a treatment facility. The more complicated a process, the more opportunities for system failure, and the more time required to maintain the system. If a treatment process is simple, robust, and fully automated, operator attention requirements should be minimal. The FXB biological pilot is fully automated. Operator attention requirements were monitored through the demonstration to assess the ease-of-use performance criterion.

- **Sustained Perchlorate Removal.** Perchlorate concentrations in the effluent of the bioreactor were measured approximately every hour by an in-line ion chromatograph. Grab samples were also taken daily for duplicate analysis at a University of Michigan laboratory. Sustained removal was defined as detecting no perchlorate (<2 µg/L) in ≥95% of bioreactor effluent samples over the 6-week Optimal Operation testing phase (Phase 3 testing).

- **High Process Efficiency.** The availability of usable water supplies is diminishing, making it vital that water treatment facilities deliver as much as possible of the water they treat (i.e., minimize losses). Backwash frequencies and flow rates were logged daily. This information was combined with production rates to calculate process efficiencies throughout each phase of pilot testing.

- **Dissolved Oxygen.** Fluctuating or very low DO concentration in drinking water distribution systems can cause corrosion and taste and odor problems. To avoid these issues, a performance objective was established for the FXB bioreactor and post-treatment system to produce water with a DO concentration that was within 1 mg/L of the raw water DO concentration. Raw water and effluent DO concentrations were monitored continuously during the demonstration to evaluate this performance objective.

- **Biological Stability.** Biodegradable compounds in treated water promote biological growth in a distribution system, which could lead to corrosion and/or the generation of offensive tastes and odors. The related performance objective states that ≥90% of system effluent BDOC concentrations should be below the 0.1 mg/L detection limit. BDOC samples across the treatment system were collected once per week for analysis at a local laboratory.

- **Aesthetic Quality.** Consumers judge the health and safety of their drinking water based on aesthetics (taste, odor, clarity, etc.). To evaluate clarity, turbidity (i.e., a measure of cloudiness) was monitored and recorded daily. To evaluate odors, hydrogen sulfide, which confers a rotten-egg odor, was monitored daily as well. Occasionally, analytical hydrogen sulfide measurements were taken. However, since the human olfactory system has a lower limit of hydrogen sulfide detection (~0.5 µg/L) than field-based analytical techniques (~10-20 µg/L), an olfactory-based presence/absence data point was recorded each day for all sample locations throughout demonstration testing.

- **Disinfection By-Product Formation Potential.** Disinfection by-product (DBP) regulations limit the concentration of TTHMs and the HAA_5s to <0.080 µg/L and <0.060 µg/L, respectively, measured as running annual averages of quarterly samples at four distribution system sites per treatment facility or entry point. Therefore, it is critical that

water produced from an FXB bioreactor treatment plant have low potential to form DBPs. To quantify DBPFP, three 7-day DBPFP tests were conducted using raw water, effluent from the FXB bioreactor, and effluent from the polishing biofilter.

- **Microbial Quality.** Per USEPA regulations, utilities that have no detectable disinfectant in their distribution systems can meet the residual disinfectant requirement if they can show HPCs below 500 counts/mL coming out of their treatment plant. Thus, to demonstrate the microbial quality of product water from the FXB bioreactor system, a performance objective was established that required ≥90% of effluent HPC samples to show ≤500 counts/mL during the Optimal Operation testing phase.

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5.0 SITE DESCRIPTION

5.1 TEST SITE DESCRIPTION AND HISTORY

Well #2 at the City of Rialto, California, served as the demonstration site for this project. This well, which has been removed from production due to perchlorate contamination, has a capacity of 2,045 gallons per minute (gpm) and is not equipped with any form of treatment presently. Table 3 provides the available historical water quality data for Rialto Well #2 as well as perchlorate and nitrate data collected during demonstration testing.

Table 3. Rialto Well #2 water quality.

Historical Raw Water Quality				
Raw Water Quality Parameter	**Average**	**Minimum**	**Maximum**	
Perchlorate (μg/L)	74	34	88	
Nitrate (mg/L as NO_3^-)	26	23	28	
Chloride (mg/L)	13	12	13	
Sulfate(mg/L)	12	11	12	
Carbonate/bicarbonate (mg/L)	<3/210	<3/210	<3/210	
pH	7.8	7.7	7.9	
Total dissolved solids (mg/L)	260	260	260	
Volatile organic compounds (μg/L)	Not detected	Not detected	Not detected	
Raw Water Quality Collected During Demonstration Testing				
Raw Water Quality Parameter	**Average**	**Minimum**	**Maximum**	**95th Percentile**
Perchlorate (μg/L)	53.5	37.0	61.0	57.8
Nitrate (mg/L)	27.8	24.9	38.6	30.2

Typical raw water DO concentrations were 8-10 mg/L. The high raw water DO and nitrate concentrations made Rialto Well #2 a challenging test site, as DO and nitrate can inhibit biological perchlorate degradation.

The area surrounding Well #2 has hosted several potential sources of perchlorate contamination over the last century. The Rialto Ammunition Storage Point, a ~2,800-acre area used during the 1940s for the storage of ordnance and explosives for World War II included the site of the present-day Well #2. The "160-acre parcel," located approximately 2 miles to the northwest of Well #2 has been used for many industrial purposes, including fireworks manufacturing and large-scale explosives disposal, both potential sources of perchlorate. Other areas near Well #2 have been used by a multitude of companies for ordnance and pyrotechnics manufacturing and for the treatment, storage, and disposal of explosive waste. The area was formerly used as a citrus grove, and those groves are believed to have used large qualities of Chilean sodium nitrate containing perchlorate. Table 4 details the Standard Industrial Classification (SIC) codes for the former manufacturing activities that have occurred near Well #2 (Geosyntec, 2006).

Table 4. SIC codes for former manufacturing activities (OSHA, 2008).

Activity	Description	SIC Code
Explosives manufacturing	Establishments primarily engaged in manufacturing explosives	2892
Fireworks manufacturing	Chemicals and chemical preparations, not elsewhere classified	2899
Ammunition manufacturing	Ammunition manufacturing, except for small arms	3483

Well #2 is located in the Rialto-Colton Basin (Basin). Groundwater in the Basin occurs in alluvial sediments at depths usually below 450 ft, and groundwater flow is generally to the southeast. This groundwater flow is controlled by several barriers and faults in the vicinity. There are four hydrostratigraphic units in the Basin: river channel deposits and the upper, middle, and lower water-bearing units. The middle water-bearing unit is the most relevant for Well #2 as it provides much of the water that is pumped by the well. It consists primarily of coarse to medium sand and interbedded silt and clay. The middle water-bearing unit ranges in thickness from about 240 to 600 ft. There are three laterally continuous aquifers in the middle water-bearing unit: the upper, the intermediate, and the deep regional aquifers. The deep regional aquifer provides much of the groundwater that is pumped by municipal supply wells such as Well #2. The three aquifers are separated by aquitards that range from a thickness of a few feet to more than 30 ft. Some surficial soil borings in the area have revealed soil concentrations of perchlorate as high as 205 mg/kg near former pyrotechnics disposal ponds (Geosyntec, 2006).

5.2 PRE-DEMONSTRATION TESTING AND ANALYSIS

Prior to the start of demonstration testing, the City of Rialto provided historical mean, maximum, and minimum Well #2 raw water quality, including perchlorate, nitrate, chloride, sulfate, carbonate, bicarbonate, pH, TDSs, specific conductance, and volatile organics. Once Well #2 was started for demonstration testing, the DO, nitrate, and perchlorate concentrations were measured and used to establish initial operating conditions (EBCT and acetic acid dose) for the FXB biological pilot. No additional pre-demonstration testing or analyses were performed.

6.0 TEST DESIGN

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

In February 2007, a 10-month demonstration study was initiated to treat perchlorate-contaminated groundwater from Rialto Well #2 using FXB bioreactor technology. Two first-stage, parallel FXB bioreactors (F120 and F130) treated groundwater to remove perchlorate. Acetic acid (electron donor) and phosphoric acid (nutrient) were fed to the process flow upstream of the bioreactors. See Figure 1 for a detailed process flow diagram. Effluent from these reactors was dosed with hydrogen peroxide to reoxygenate and oxidize residual organics and hydrogen sulfide. The reoxygenated water was then passed through a second stage FXB biofilter (F150) to oxidize any remaining organics and sulfide and to remove turbidity. The bioreactors and the biofilter had six 12-inch windows that ran the length of each pressure vessel, which allowed for visual observation of bed depth, biogrowth, and mixing during backwash events. Effluent from the biofilter was discharged to a backwash tank and therefore served as the source water for backwashing the bioreactors and biofilter. Overflow from the backwash tanks was dosed with chlorine and flowed into the chlorine contact tank. A detailed description of the pilot testing phases is provided in Section 6.4.5.

In parallel with the demonstration testing, a bench-scale FXB bioreactor was constructed to serve as a rapid screening process for identifying the effects of nutrient addition and acetic acid dosing patterns on perchlorate removal performance. A mathematical model was developed and calibrated, which could be used to elucidate observed phenomena during pilot testing and to predict the perchlorate removal performance of an FXB bioreactor system at other sites. Additionally, molecular microbiological analyses were performed to quantify the relative abundance of specific bacteria within the mixed microbial community in the bioreactor bed.

6.2 BASELINE CHARACTERIZATION

Baseline characterization for Well #2 consisted only of gathering historical raw water quality data and measuring current raw water concentrations of DO, nitrate, and perchlorate. See Sections 5.1 and 5.2 for additional details.

6.3 TREATABILITY RESULTS

During the 10-year period preceding this demonstration, numerous bench- and pilot-scale studies were completed that showed the treatability of perchlorate-contaminated groundwater using the FXB biological process. See Section 3.2 for additional details.

6.4 FIELD TESTING

6.4.1 Demonstration Installation and Start-Up

The following site preparations were made at Rialto Well #2 (Shaw Environmental, Inc. coordinated these efforts):

- Well #2 pump motor was refurbished and the casing inspected.
- Power was expanded to handle multiple pilot systems.

- A National Pollutant Discharge Elimination System (NPDES) permit modification was acquired through the Santa Ana Regional Water Quality Control Board to allow for the discharge of raw and treated Well #2 water to an adjacent catch/percolation basin.
- A waste discharge line from the site to the adjacent catch/percolation basin was installed.
- Lighting and a new security gate were installed.
- Site was graded.

A new demonstration-scale FXB bioreactor skid was constructed for this project. A basic schematic of the process is provided in Figure 1. The skid was contained in a 40-ft x 8-ft x 8-ft trailer. The 2-ft diameter parallel bioreactors and the 2-ft diameter biofilter were filled with virgin Calgon F-816 GAC, with an effective size of approximately 1.4 mm. One bioreactor and the biofilter were filled to a depth of 4.7 ft, and the other bioreactor was filled to a depth of 3.9 ft. All three pressure vessels included depthwise sample ports, spaced 6 inches apart, which allowed for depthwise evaluation of DO, nitrate, and perchlorate profiles across the biological beds.

Once the skid was positioned on site, Schedule 80 polyvinyl chloride (PVC) piping was installed to connect Well #2 with the raw water line on the outside of the trailer. Raw water was pumped from Rialto Well #2 into the bottom of a break tank at the head of the FXB bioreactor treatment train. However, the well water was supersaturated with gas, and gas bubbles formed in the bioreactor beds, causing rapid headloss build-up. To eliminate this problem, the well water was redirected to the top of the break tank and a spray nozzle was added to the pipe discharging into the break tank. This allowed supersaturated gas to come out of solution before reaching the bioreactor beds. Excess water overflowed from the break tank to a discharge line flowing to the adjacent catch/percolation basin. Treated effluent and backwash wastewater also discharged to this basin.

6.4.2 Period of Operation

Dates and durations for each component of the FXB biological perchlorate destruction demonstration project are listed in Table 5.

Table 5. FXB biological perchlorate destruction demonstration schedule.

Tasks	Start	Finish	Duration	2007												2008	
				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb
1. Site mobilization	1/22/2007	2/20/2007	29 days														
2. Demonstration testing	2/28/2007	2/5/2008	342 days														
Phase 1: Bioacclimation	2/282/007	3/20/2007	20 days														
Phase 2: Optimization	3/21/2007	7/30/2007	133 days														
Phase 3: Sustained Optimal Operation	7/31/2007	9/8/2007	39 days														
Phase 4: Robustness Characterization	9/9/2007	12/20/2007	102 days														
Bench-Scale Bioreactor Operation	1/3/2007	11/27/2007	328 days														
Modeling	2/28/2007	12/20/2007	294 days														
Microbiological Analyses	4/17/2007	1/19/2008	276 days														
Media characterization	12/20/2007	2/5/2008	16 days														
3. a. Preliminary designs and conceptual layouts	8/15/2007	11/14/2007	91 days														
b. Cost model development	10/15/2007	11/27/2007	43 days														
4. Demonstration complete	2/5/2008	2/5/2008	0 days														★

6.4.3 Amount/Treatment Rate of Material Treated

Two FXB bioreactors were operated in parallel. EBCTs, associated flow rates and hydraulic loading rates tested for the two bioreactors and the biofilter are listed in Table 6.

Table 6. Hydraulic conditions tested during the FXB demonstration study.

Parameter	Bioreactor F120				Bioreactor F130					Biofilter F150		
EBCT (min)	7	8	10	15	5	10	12	15	18	7	7.5	10
Flow (gpm)	13.1	11.5	9.2	6.1	22.1	11.0	9.2	7.4	6.1	15.8	14.7	11.0
Loading rate (gpm/ft^2)	4.2	3.7	2.9	1.9	7.0	3.5	2.9	2.3	1.9	5.0	4.7	3.5

The F130 Bioreactor operated at an average production rate of 11.0 gal/min (660 gal/hr, 15,840 gal/day) for 294 days, and the F120 Bioreactor operated at an average production rate of 9.2 gal/min (552 gal/hour, 13,248 gal/day) for 190 days. Therefore, the total volume of Rialto Well #2 raw water treated was approximately 7.2 million gallons.

6.4.4 Residuals Handling

Treated water and backwash wastewater were discharged to an adjacent catch/percolation basin per an NPDES permit modification.

6.4.5 Experimental Design

A 10-month FXB bioreactor demonstration program was conducted. The overall objective of this study was to refine design parameters for the full-scale implementation of FXB biological perchlorate removal from groundwater to identify any process limitations or failure scenarios and to develop operating and design parameters for a complete FXB biological treatment train.

Demonstration Testing Phase 1 (Biological Acclimation): The purpose of this phase was to develop efficient perchlorate-reducing biological activity in the filters using microorganisms indigenous to the local groundwater. One FXB bioreactor had a bed depth of 3.9 ft, and the other

FXB bioreactor had a bed depth of 4.7 ft. An EBCT of 15 minutes was used and acetic acid (technical grade) was dosed at a concentration 50% above that required to stoichiometrically reduce all raw water DO and nitrate ([D/A]=1.5; $O_2 \Rightarrow H_2O$, $NO_3^- \Rightarrow N2$; for simplicity only, the [D/A] calculation assumes that the fraction of electrons used for energy is 1 [i.e., f_e=1]. The cell synthesis half-reactions are ignored to simplify the calculation). This ensured that electron donor is not limiting. No phosphoric acid was added initially. However, only partial perchlorate removal was observed during the first few months of testing. Therefore, 96 days into demonstration testing, phosphoric acid dosing commenced at approximately 0.1 mg/L as PO_4-P.

Demonstration Testing Phase 2 (EBCT, Surface Loading Rate, Acetic Acid, and Backwash Optimization): The purpose of this phase was to determine the minimum EBCT ($EBCT_{critical}$) and minimum acetic acid dose ($AA_{critical}$) required to achieve perchlorate removal to below the 2 µg/L detection limit while maintaining process efficiencies of 95% or greater. Depth-wise sampling ports allowed for the simultaneous evaluation of multiple EBCTs. Thus, it was possible to maintain a constant EBCT while varying the surface loading rate (i.e., effective bed depth changed by using different sample ports). This information was used to determine whether a design EBCT is independent of bed depth or surface loading rate.

Using the $EBCT_{critical}$, the acetic acid dose was incrementally decreased from [D/A]=1.5 until perchlorate breakthrough was observed. An optimized backwashing protocol was also developed during this phase (e.g., frequency, air scour rate and duration, fluidization rate, and duration).

Demonstration Testing Phase 3 (Optimal Operation): The purpose of this phase was to demonstrate sustained (6 weeks) perchlorate removal to below detection using the critical (or just above the critical) EBCT, acetic acid dose, and backwashing protocol determined during Phase 2. Six weeks provided sufficient time to evaluate the sustainability of the FXB biological perchlorate removal process under steady conditions.

Demonstration Testing Phase 4 (Robustness Characterization): The purpose of this phase was to determine how the FXB bioreactor responds to various process disturbances. The $EBCT_{critical}$ and $AA_{critical}$ remained fixed as operating parameters throughout most of this phase. Perchlorate removal performance during each disturbance was monitored, and required perchlorate removal performance recovery periods were measured. Five disturbances were tested:

1. Backwashing: Perchlorate concentrations were monitored in the backwash wastewater and were also measured in the effluent of the FXB bioreactors immediately following a backwash event.
2. Perchlorate feed fluctuation: The impact of step changes in feed perchlorate concentration were evaluated. Step feed perchlorate spikes to 100, 400, 600, 800, and 930 mg/L were tested. Each dose was spiked for 1 to 4 days, and the EBCT and [D/A] were constant at 10 minutes and 1.7, respectively.
3. Nitrate feed fluctuation: The impact step changes in feed nitrate concentration were evaluated. Step feed nitrate spikes to 38 mg/L and 45 mg/L (as NO_3^-) were tested. Each spike was tested for 1-2 days, and the EBCT remained unchanged at

10 minutes. The acetic acid dose was increased to account for the additional nitrate, but remained at a 1.7 [D/A].

4. Electron donor feed failure simulation: The acetic acid feed system was turned off for up to a 24-hour period to simulate a full-scale chemical dosing system failure. Five different shutdown scenarios were tested, which varied backwash frequency, length of acetic acid shutdown, and acetic acid dose.

5. Temporary system shutdown: The demonstration system was completely powered down for a 24-hour period and a 2-week period. These shutdown tests simulated an inadvertent full-scale system shutdown, but also helped elucidate an appropriate stand-by bioreactor rotation strategy.

Backwash Wastewater Characterization: Backwash wastewater composite samples were analyzed for TDS, VSS, TSS, and BOD. These analyses were performed three times throughout demonstration testing and were used to determine an appropriate handling/discharge strategy for backwash wastewater.

Post-Treatment: There were four main post-treatment goals: 1) reoxygenate, 2) remove residual BDOC, 3) remove sulfide, and 4) disinfect. Specific post-treatment performance targets associated with these goals are listed in Table 2. A short-term coagulant dosing test was also performed to see if alum could improve turbidity removal across the biofilter. Since the average biofilter effluent turbidity (0.35) was only 0.05 NTU higher than the average raw water turbidity (0.30 NTU), post-treatment testing did not include a turbidity removal optimization phase. The following post-treatment parameters were varied during demonstration testing to determine post-treatment requirements:

- Hydrogen peroxide dose.
- Alum dose.
- EBCT across Biofilter F150.
- Filter backwash protocol for Biofilter F150 (frequency, air scour rate and duration, fluidization rate and duration).
- Chlorine dose and contact time (concentration multiplied by time [CT]).

Modeling: As part of the demonstration, a mathematical model was developed that is capable of simulating all test phases proposed, including the effects of influent characteristics, EBCT, and backwashing. The purpose of the mathematical modeling was to make use of the experimental results from the demonstration scale reactors and to evaluate to what extent system performance can be extrapolated from the available results. The mathematical model had to be developed mainly based on bulk phase measurements of perchlorate, nitrate, oxygen, and acetate. These empirical observations were combined with well-studied diffusion-reaction descriptions of processes in the biofilm (Morgenroth, 2008). While the model structure for biofilm systems (i.e., the one-dimensional diffusion-reaction modeling approach) is well established (Wanner et al., 2006), the values of model parameters are not. In the current study, most of the model parameters are based on literature information and some are estimated based on observed reactor performance. To take into account the uncertainty of kinetic parameters, a range of reasonable

parameter combinations is simulated to evaluate the sensitivity of model predictions to specific parameter values.

The mathematical modeling followed these steps:

- Defining of model structure
- Selection of standard model parameters from the literature and from calibrating against reactor performance
- Use of calibrated model to evaluate the influence of operating conditions on reactor performance
- Influence of EBCT and electron donor addition.
- Influence of biofilm thickness and backwashing.
- Influence of influent perchlorate concentrations.
- Influence of influent nitrate concentrations.

The modeling can be used to elucidate phenomena observed during demonstration testing and predict perchlorate removal performance at other sites to facilitate a rapid preliminary design analysis (and economic analysis when combined with the cost model).

Bench-Scale System: A bench-scale FXB bioreactor was constructed to test how nutrient addition and intermittent electron donor addition patterns affect the microbial community and performance of a bioreactor. Tests were run using the bench-scale bioreactor that could not be easily conducted using the demonstration-scale system. The bench-scale system also provided "replicates" for the tests that were performed with both systems. The bench-scale FXB bioreactor system started in September 2006 and continued to operate under conditions closely matching the demonstration-scale operating conditions until September 2008 when the operating conditions were changed to suit a different research project.

The bench-scale FXB bioreactor was constructed with a GAC bed volume of 200 mm^3 (Calgon F-816 was used, which was also used for the demonstration-scale system). Synthetic groundwater was used as influent and pumped into the reactor in a down flow mode at the flow rate of 10 mL/min. The concentrations of DO, nitrate, and perchlorate in the influent were between 6 and 7 mg/L, 25 mg/L (as NO_3^-), and 75 µg/L, respectively. Based on stoichiometric calculation with an assumed net yield value of 0.4 g chemical oxygen demand $(COD)_{biomass}$/ g $COD_{acetate}$, 13 mg/L as concentration (C) of acetic acid was needed to completely remove all three electron acceptors. With a safety factor of 1.5 applied, 20 mg/L as C of acetic acid was added to the reactor. These operating conditions were defined as the baseline for this system.

Intermittent addition of acetic acid to the BAC reactor was tested by dividing one backwash cycle (i.e., 48 hours) into four cycles. Each 12-hour cycle consisted of a 6-hour acetic acid addition at a concentration twice the stoichiometric requirement (i.e., 26 mg/L as C) followed by addition at a concentration half of the stoichiometric requirement (i.e., 6.5 mg/L as C) for 6 hours.

Microbial Characterization: Biologically active carbon (BAC) samples were taken from the FXB Bioreactor F130 in May 2007 (~ one month before phosphorus addition was initiated) and again in September 2007 (a few months after phosphorus addition was initiated). A vertical core of the BAC bed was taken using a 1-inch PVC pipe. The core was placed in a 1-liter sample bottle and shipped to the University of Michigan for clone library analysis. Pre- and post-phosphorous BAC samples were also collected from the bench-scale BAC reactor.

By conducting clone library analyses on both biomass samples, the effects of phosphorus on the microbial community inside the bioreactor were elucidated, and the correlation between microbial composition and reactor performance was established. Similarly, biomass samples were also collected from the bench-scale BAC reactor, both before and after phosphorus addition. The microbial analyses for the bench-scale BAC reactor were compared with those for the bioreactor F130. Finally, along with the biomass samples from F130, a biomass sample from the bioreactor F120 was also collected in May 2007, and analyzed to determine the similarity between the microbial communities in the two demonstration-scale BAC reactors.

Deoxyribonucleic acid (DNA) samples were extracted from the BAC samples using FastDNA SPIN Kit by Qbiogene (Irvine, California). The DNA concentration of each sample was measured using a NanoDrop 1000 (NanoDrop Technology, Wilmington, Delaware), and DNA quality was evaluated by running a 1% agarose gel. DNA extracts were amplified in triplicates using the polymerase chain reaction (PCR) with the forward primer 8F (AGA-GTT-TGA-TCC-TGG-CTC-AG) and the reverse primer 1387R (GGG-CGG-[A/T]GT-GTA-CAA-GGC). The composition of the PCR reactions was adopted from the work by Briones and coworkers (2007). The PCR reaction involved 30 cycles and started with 5 min of denaturation at 95˚C and ended with a final extension at 72˚C for 18 min. Each cycle consisted of denaturation at 95˚C for 30 s, annealing at 50˚C for 45 s, and extension at 72˚C for 2 min. Pooled PCR products were purified by running agarose gel electrophoresis and extracted using the MinElute Gel Extraction Kit (QIAGEN Inc, Valencia, California). Purified PCR products were cloned into TOPO vector (Invitrogen, Carlsbad, California), and transformed into chemically competent *Escherichia coli*. The transformed *E. coli* were plated on lysogeny broth (LB) agar and incubated at 37˚C overnight. Colonies were picked and used to inoculate three 96-well microplates. Two of the three 96-well microplates were sent to the Genomic Center at Washington University (St. Louis, Missouri) for DNA sequencing.

Raw sequence readings obtained from the Genomic Center were entered into the Ribosomal Database Project (RDP) maintained by Michigan State University (East Lansing, Michigan). The raw DNA sequences were classified into various bacterial populations, and the relative abundance of identified populations was quantified.

Media Characterization: Based on full-scale European biodenitrification experience, it is anticipated that the GAC would have to be replaced about every 10 years. To identify appropriate disposal procedures for the spent GAC, toxicity characteristics leaching procedure (TCLP), total threshold limit concentration (TTLC), and waste extraction tests (WET) leaching procedure tests were performed on a mixed sample of GAC from both bioreactors at the end of demonstration testing. These tests, which simulate conditions that may be present in a landfill, are designed to extract constituents that are sorbed to the GAC media. Extraction fluids (e.g., citrate, sodium acetate) are added to a batch of BAC media and tumbled for up to 48 hours to extract any sorbed constituents that may ultimately leach during long-term storage in a landfill.

Extracted metals, volatiles, semivolatiles, pesticides, polychlorinated biphenyls (PCB), herbicides, and perchlorate were quantified.

6.5 SAMPLING METHODS

Figure 3 illustrates the various sampling locations and Table 7 lists the various water quality parameters that were measured, sampling location and frequency, and the associated laboratory responsible for the analysis. Increased perchlorate sampling frequencies during the robustness tests are described in Section 6.4.5.

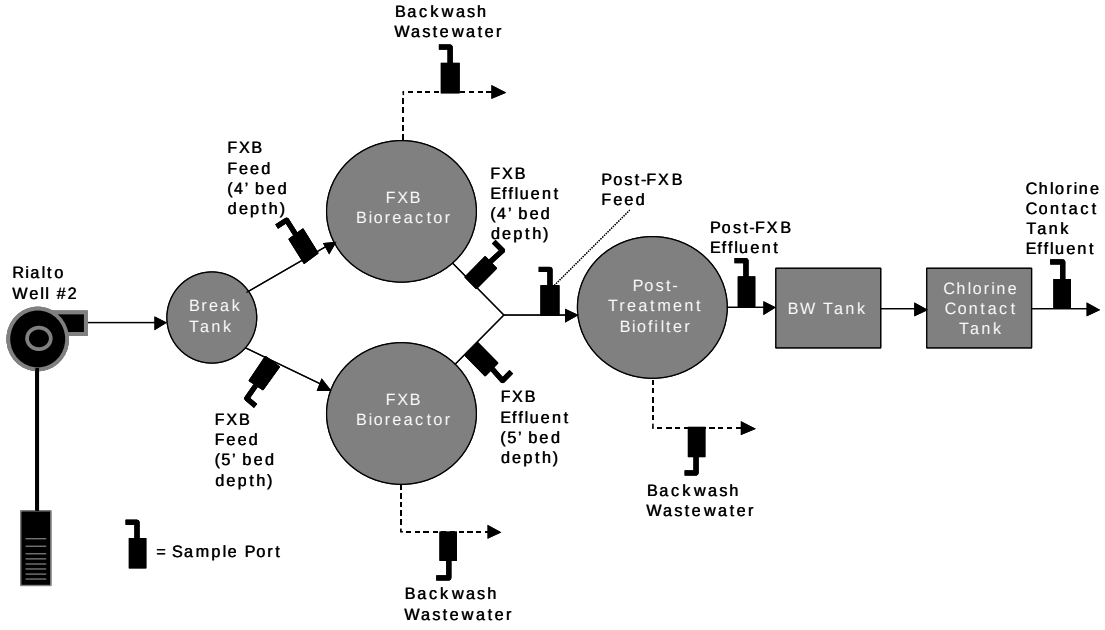

Figure 3. Water quality sampling points.

Table 7. Testing matrix for the FXB bioreactor and post-treatment demonstration.

Parameter	Sampling Location	Sampling Frequency	Lab
Perchlorate	FXB[1] feed	3/week	University of Michigan and occasional checks with MWH[2] laboratories
	2 FXB effluent	3/week	
	FXB feed	1/2 hours	On-site: In-line Dionex ion chromatograph
	2 FXB effluent	1/2 hours	
	Depth wise sample ports	1/week	
Nitrate	FXB feed	3/week	University of Michigan and occasional checks with MWH
	2 FXB effluent	3/week	
	FXB feed	1/2 hours	On-site: In-line Hach NITRATAX nitrate probe daily using a Hach DR 890 colorimeter
	2 FXB effluent	1/2 hours	
	Depth wise sample ports	1/week	
DO	FXB feed	1/2 hours	On-site: In-line Hach sc100™ LDO™ probe
	2 FXB effluent	1/2 hours	
	Post-FXB[3] feed	1/2 hours	
	Post-FXB effluent	1/2 hours	
	Chlorine contact tank effluent	1/2 hours	
	Depth wise sample ports	1/week	
Chlorate	FXB effluent	1/week	University of Michigan
Chlorite	FXB effluent	1/week	University of Michigan
Nitrite	FXB feed	1/week	University of Michigan and occasional checks with MWH
	2 FXB effluent	1/week	
Sulfate	FXB feed	1/week	University of Michigan
	2 FXB effluent	1/week	
Phosphate	FXB feed	1/ 2 weeks	University of Michigan
	2 FXB effluent	1/2 weeks	
Ammonia	FXB feed	1/2 weeks	University of Michigan
	2 FXB effluent	1/2 weeks	
Iron & manganese	FXB feed	1/month	University of Michigan
	2 FXB effluent	1/month	
	Post-FXB effluent	1/month	
H_2S	Post-FXB feed	1/week	On-site colorimetric method based on USEPA 376.2
	Post-FXB effluent	1/week	
DOC[4]	FXB feed	2/week	University of Michigan and occasional checks with MWH
	2 FXB effluent	2/week	
	Post-FXB effluent	2/week	
	Chlorine contact tank effluent	2/week	
Biodegradable organic carbon	FXB feed	1/2 weeks	MWH
	2 FXB effluent	1/week	
	Post-FXB effluent	1/week	
Free chlorine	Chlorine contact tank effluent	3/week	On-site: Hach DR 890 Colorimeter
TTHMs	DBPFP[5] tests	10 total DBPFP tests	MWH
HAA_5	DBPFP tests	10 total DBPFP tests	MWH
Heterotrophic plate counts	FXB feed	1/week	MWH
	2 FXB effluent	1/week	

Table 7. Testing matrix for the FXB bioreactor and post-treatment demonstration.
(continued)

Parameter	Sampling Location	Sampling Frequency	Lab
	Post-FXB effluent	1/week	
	Chlorine contact tank effluent	1/week	
Total & fecal coliforms	FXB feed	1/week	MWH
	2 FXB effluent	1/week	
	Post-FXB effluent	1/week	
	Chlorine contact tank effluent	1/week	
	Backwash wastewater	4 total BW samples per each of 3 FXB reactors	
Turbidity	FXB feed	Daily	On-site: Hach DR 890 Colorimeter
	2 FXB effluent	Daily	
	Post-FXB effluent	Daily	
pH	FXB feed	Daily	On-site: Hach pH probe
	2 FXB effluent	Daily	
	Post-FXB effluent	Daily	
	Chlorine contact tank effluent	Daily	
Temperature	FXB feed	1/2 hours	On-site: In-line Hach sc100™ LDO™ probe
Head loss	Across all 3 FXB reactors	Continuous	On-site: In-line pressure transducer
Flowrate	Across all 3 FXB reactors	Continuous	On-site: In-line Magflow meter
Volatile suspended solids	Backwash wastewater	3 total BW samples per each of 3 FXB reactors	MWH
Total suspended solids	Backwash wastewater	3 total BW samples per each of 3 FXB reactors	MWH
Total dissolved solids	Backwash wastewater	3 total BW samples per each of 3 FXB reactors	MWH
Biochemical oxygen demand	Backwash wastewater	3 total BW samples per each of 3 FXB reactors	MWH

[1]FXB: F120 and F130 Bioreactors
[2]MWH: Montgomery Watson Harza
[3]Post-FXB: F150 Biofilter reactor
[4]DOC: dissolved organic carbon
[5]DBPFP: disinfection by-product formation potential (See Standard Method 5701B)

6.6 DATA ANALYSIS, INTERPRETATION, AND EVALUATION

Water quality and operational data were compiled, tabulated, and plotted daily so that trends and instantaneous performance could be rapidly analyzed to determine appropriate system modifications. Optimal operating conditions established during Phase 2 Optimization testing were used during the Phase 3 Sustained Removal testing and Phase 4 Robustness testing. This ensured that design parameters were selected so that treatment objectives would be met and sustained during periods of constant (i.e., varying by less than 10%) and unsteady (i.e., varying by greater than 10%) water quality and operational conditions.

7.0 PERFORMANCE ASSESSMENT

7.1 PERFORMANCE CRITERIA AND CONFIRMATION METHODS

A detailed listing of the criteria and confirmation methods that were used to determine the effectiveness of FXB demonstration testing is provided in Table 8. Essentially, the effectiveness of the demonstration was defined by how efficiently the FXB biological treatment train (FXB bioreactor and post-treatment) produced perchlorate-free (i.e., perchlorate concentrations below 2 µg/L) potable water during steady and unsteady conditions. It was also important that the process train maintain an overall efficiency of ≥95% (i.e., raw water recovered for distribution). Water quality and operation performance parameters were selected to provide a comprehensive and, in many cases, continuous evaluation of treatment system performance. Details on sampling location, frequency, and associated analysis for these parameters are provided in Figure 3 and Table 7.

Table 8. Performance criteria and performance confirmation methods.

Performance Criteria	Expected Performance Metric (pre demo)	Performance Confirmation Methods	Actual (post demo)
PRIMARY CRITERIA (**Performance Objectives**) (**Qualitative**)			
Ease of Use 1. Operator training requirements 2. System maintenance requirements	1. Standard 2. Minor	Experience from demonstration operation	Monitored labor demand associated with system operation and maintenance
PRIMARY CRITERIA (Performance Objectives) (Quantitative)			
Contaminant Reduction 1. Perchlorate 2. Nitrate 3. BDOC	1. ≥95% effluent perchlorate below 2 µg/L during 6-week optimal operation testing period (Phase 3) 2. ≥95% effluent nitrate below 1 mg/L (as NO_3^-) during same period 3. ≥95% effluent BDOC below 0.1 mg/L during same period	Analysis of water quality samples taken during demonstration testing; duplicate and triplicate analyses of perchlorate and nitrate occasionally performed	Analysis of water quality samples taken during demonstration testing
Factors Affecting Technology Performance 1. EBCT 2. Acetic acid dose 3. Nutrient dose 4. Raw water DO and nitrate concentrations 5. Backwash effectiveness 6. Process upsets	1. ≤25 minutes 2. ≤50% above the stoichimetric raw water acetic acid demand based DO and nitrate concentrations 3. None required 4. No limit 5. 24-48-hour run time; ≤5	1. Continuous Magflow meter and occasional manual calibration checks 2. Mass balance and regular DOC measurements 3. Experience from demonstration	1. Continuous Magflow meter and occasional manual calibration checks 2. Mass balance and regular DOC measurements 3. Experience from demonstration

Table 8. Performance criteria and performance confirmation methods. (continued)

Performance Criteria	Expected Performance Metric (pre demo)	Performance Confirmation Methods	Actual (post demo)
	minutes air scour at ≤5 ACFM and ≤10 minutes fluidization at 10 gpm/ft^2 loading rate 6. No measurable performance impact (see robustness)	operation 4. Experience from demonstration operation 5. Experience from demonstration operation; air flow meter; Magflow meter 6. Experience from demonstration operation	operation 4. Experience from demonstration operation 5. Experience from demonstration operation; air flow meter; Magflow meter 6. Experience from demonstration operation
Process Waste 1. Process efficiency 2. Used media	1. ≥95% of raw water recovered for distribution 2. Nonhazardous characterization of used GAC at end of demonstration testing	1. Calculation using throughput volumes and backwash waste volumes 2. TCLP test	1. Calculation using throughput volumes and backwash waste volumes 2. TCLP, TTLC, and WET tests
Robustness/Reliability 1. Sustained removal 2. Performance during and after process upsets • Backwashing • Raw water quality fluctuation • System shut-down periods • Acetic acid feed failure	1. ≥95% effluent perchlorate below 4 µg/L during 6-week "steady state testing period" (Phase 3) 2. ≥95% effluent perchlorate below 4 µg/L during each robustness test (Phase 4); includes high-resolution sampling	Analysis of water quality samples taken during demonstration testing; duplicate and triplicate analyses of perchlorate and nitrate occasionally performed	Analysis of water quality samples taken during demonstration testing
Effluent Quality 1. DO 2. BDOC 3. H_2S 4. DBPs 5. HPCs	1. Effluent DO concentration = raw water DO concentration ± 1 mg/L 2. ≥90% of effluent BDOC concentrations below detection (<0.1 mg/L) during 6-week Phase 3 testing period 3. No olfactory hydrogen sulfide detection in ≥95% of effluent samples during 6-week Phase 3 testing period 4. <60 µg/L TTHMs and <40 µg/L HAA_5 in all DBPFP tests during 6-week Phase 3 testing period	Analysis of water quality samples taken during demonstration testing; duplicate and triplicate analyses of perchlorate and nitrate occasionally performed	Analysis of water quality samples taken during demonstration testing

Table 8. Performance criteria and performance confirmation methods. (continued)

Performance Criteria	Expected Performance Metric (pre demo)	Performance Confirmation Methods	Actual (post demo)
	5. ≥90% of effluent HPCs ≤500 counts/mL during 6-week Phase 3 testing period		
SECONDARY PERFORMANCE CRITERIA (Qualitative)			
Safety 1. Hazards	1. Acetic acid; chlorine	Experience from demonstration operation	Experience from demonstration operation and knowledge of standard chemical storage and handling protocols
Scale-Up Constraints 1. Heterogeneity of biological growth 2. Backwash effectiveness	1. Uniform head loss build-up 2. Consistent "clean-bed" head loss	Continuous monitoring of head loss during demonstration operation	Head loss monitoring and visual inspection of biogrowth in the bioreactors
SECONDARY PERFORMANCE CRITERIA (Quantitative)			
Hazardous Materials 1. Accumulated GAC adsorbates	1. "Nonhazardous" rating for used GAC	TCLP test	TCLP, TTLC, and WET tests

7.2 DEMONSTRATION PERFORMANCE

Detailed demonstration data and figures are provided in Appendix B of the ER-0544 Final Report. A summary of the data as they relate to the performance criteria listed in Table 8 is provided above. To simplify this section, the text will focus on Bioreactor F130, which contained 4.7 ft of GAC media. Bioreactor F120 (3.9-ft bed depth) performed well, but a full-scale system would be designed around the deeper bed depth to reduce the number of reactor vessels required.

7.2.1 Ease of Use

Ease of use relates to the complexity of system operation and addresses the issues of how much specialized training and operator attention are required. The demonstration pilot was automated with respect to production, backwashes, chemical dosing, and sampling (DO, nitrate, and perchlorate). The pilot operator was required only to maintain stock solutions of chemicals and sample for water quality parameters that were not measured in-line. Though some troubleshooting was also required during demonstration testing, it was minimal and was mostly associated with limitations of the piloting equipment. For example, one bioreactor underdrain lateral had to be repaired on several occasions. This would not be an issue with a full-scale system as the underdrain would be a nozzle-based system and would not be removable. Further,

more automation would be included in a full-scale system (e.g., feed-forward control logic that would allow the acetic acid and phosphoric acid dosing to pace off of the raw water DO and nitrate concentrations automatically), so it is anticipated that full-scale operation would be even less complex than the pilot-scale demonstration proved to be. No specialized operator training requirements and minimal system maintenance requirements are anticipated for full-scale operation.

7.2.2 Contaminant Reduction

Perchlorate: Using an EBCT of 10-12 min, a phosphoric acid dose of 150 µg/L, and a [D/A] of 1.70, perchlorate was removed from 53.5 µg/L to <2 µg/L throughout the Optimal Operation testing phase. EBCTs as low as 5 min also resulted in steady removal of perchlorate to below detection. The detection limit for most perchlorate samples was 2 µg/L. However, numerous perchlorate samples were analyzed at a 0.5 µg/L reporting limit, and perchlorate was not detected.

Nitrate: To achieve biological perchlorate removal, nitrate must first be removed to low levels, so it was not surprising to see that effluent nitrate concentrations were low. Effluent nitrate concentrations were typically 1 mg/L (as NO_3^-) or less during this phase.

Biodegradable Organic Carbon: Except for one outlier, BDOC concentrations coming out of Bioreactor F130 were very low, often non-detect (<0.1 mg/L). BDOC concentrations increased slightly across F150. During the Optimal Operation testing phase (Days 154-192), all BDOC measurements in the effluent of F150 were below 0.5 mg/L.

7.2.3 Factors Affecting Technology Performance

Empty-Bed Contact Time: With raw water DO and nitrate concentrations of 10 mg/L and 30 mg/L, respectively, it was anticipated that an EBCT of ~20 min would be required to achieve sustained perchlorate removal to below detection across F130. As indicated above, sustained perchlorate removal to below detection was achieved at EBCTs as low as 5 min. A design EBCT of 10 min was selected for the cost estimates and facility lay-outs generated during this project.

Acetic Acid Dose: Sustained perchlorate removal was achievable when the [D/A] was 1.6 or greater (i.e., 60% above stoichiometric raw water acetic acid demand based on DO and nitrate concentrations). When [D/A] was 1.5 and 1.4, 20% and 40% perchlorate breakthrough was observed, respectively. A design [D/A] of 1.7 was selected for the cost estimates generated during this project.

Nutrient Dose: A phosphoric acid dose of ≥100 µg/L as PO_4-P was required to achieve sustained perchlorate removal to below detection. When no phosphoric acid was added, 40-60% perchlorate breakthrough was observed. A design phosphoric acid dose of 150 µg/L as PO4-P was selected for the cost estimates generated during this project.

Raw Water Dissolved Oxygen and Nitrate Concentrations: Raw water nitrate concentrations matched the historical raw water quality data provided by the City of Rialto. No historical raw

water DO concentrations were available, and start-up revealed that the raw water was supersaturated with gas. A spray nozzle was added to the raw water break tank to remove dissolved gas, and resulting feed DO concentrations were 8-10 mg/L.

Backwash Effectiveness: The ability of pilot-scale filters to effectively simulate a full-scale backwash system is severely limited for two reasons: 1) Uniformity of backwash and air scour flow is difficult to control at the pilot scale due to limitations in the underdrain system, and 2) It is difficult to control media loss during a pilot-scale backwash, which means that a simultaneous air scour/fluidization step must be very short. To get around these limitations, a 28-step backwash procedure was utilized that summed to fluidization (with surface wash) for 69 sec at 4.8 gpm/ft^2, 12.7 gpm/ft^2 for 180 sec, 3.2 gpm/ft^2 for 120 sec, 6.7 gpm/ft^2 for 480 sec, and 1.3 gpm/ft^2 for 30 sec. 2-3.2 SCFM/ft^2 air scour was pulsed during the fluidization steps for a total of 24 sec. Run times varied between 17 and 24 hours. It should be noted that a full-scale backwash procedure would likely include four steps: 1) drain, 2) air scour (one loading rate), 3) combined air scour/fluidization (one loading rate for air scour and one loading rate for fluidization), and 4) fluidization (one loading rate).

A good metric for backwash effectiveness is low, consistent clean-bed headlosses. Clean-bed headlosses were typically ~0.5 psig (1.2 ft), while the headloss at the end of a 17-24-hour run was typically just above 1 psig (2.3 ft).

Process Upsets: Several robustness tests were run using Bioreactor F130. These tests included backwash testing, system shutdowns, acetic acid shutdowns, perchlorate spiking, and nitrate spiking.

- ***Backwashing.*** For the high-resolution backwashing test, a backwash was performed, and the pilot was then returned to production mode. Perchlorate samples were taken immediately after the backwash and at 15-min intervals for 120 min. No perchlorate was detected.
- ***Perchlorate Spiking.*** Step changes in perchlorate simulate actual well field operations where pumps with differing water qualities come on line and off line at different times and at varying intervals. Transient perchlorate loading episodes had very little impact on perchlorate removal performance in Bioreactor F130. Over an 11-day period, the feed perchlorate concentration was varied in step changes from 100 μg/L to 400 μg/L to 600 μg/L to 800-930 μg/L and back to the background concentration of 55 μg/L while the EBCT and the feed [D/A] ratio were maintained at 10 min and 1.70, respectively. For the majority of the test, the perchlorate concentration was at or below the LOD.
- ***Nitrate Spiking.*** Step changes in nitrate simulate actual well field operations where pumps with differing water qualities come on line and off line at different times and at varying intervals. During the nitrate spiking tests, nitrate feed concentrations to the reactor were step-increased from 30 mg/L (background) to 38 mg/L and then to 45 mg/L (all as NO_3^-). During this test, the EBCT was constant at 10 min, and a [D/A] ratio of 1.70 was maintained. No perchlorate or nitrate breakthrough was observed.

- ***System Shutdown Periods.*** F130 was shut down for 24-hour and 1-week periods. After each shutdown period, the pilot was put back into production and high-resolution samples were taken over the next 24-hour period. No perchlorate breakthrough was observed during either test.
- ***Acetic Acid Feed Failures.*** Simulated acetic acid feed failure experiments demonstrated that up to 10 hours are available after an acetic acid feed pump failure before perchlorate breakthrough occurs. The maximum perchlorate breakthrough after a 24-hour acetic acid feed pump shut-off was 11 µg/L. After the pump was restarted at Hour 24, perchlorate removal to below detection was again achieved after approximately 4 hours.

7.2.4 Process Waste

Process Efficiency: System recovery is defined as the volume of treated raw water recovered for distribution, or [(total volume of water treated minus total losses)/(total volume of water treated)] x 100. During the Optimal Operation testing phase, system recoveries were 93-96%. Higher recoveries are anticipated for a full-scale system, as air scour and backwash fluidization steps will likely be more efficient.

Used Media: Minimal metals accumulation occurred on the GAC, and all metals detected were detected below their hazardous waste threshold values. Uranium detected on the media was well below the hazardous waste threshold value. No trace organics were detected on the media. Media disposal is expected to occur approximately every 10 years, at which point media characterization tests would need to be performed to identify appropriate disposal options.

7.2.5 Robustness/Reliability

Sustained Removal: See the Perchlorate subsection of Section 7.2.2.

Performance During and After Upsets: See the Process Upsets subsection of Section 7.2.3.

7.2.6 Effluent Quality

Dissolved Oxygen: DO going into Biofilter F150 was typically <1 mg/L, and hydrogen peroxide was dosed to F150 at between 8 and 12 mg/L. The F150 effluent DO concentration averaged 5.3 mg/L and ranged from 1-12 mg/L.

Biodegradable Organic Carbon: See the Biodegradable Organic Carbon subsection of Section 7.2.2.

Hydrogen Sulfide: Hydrogen sulfide was monitored daily. Occasionally, analytical hydrogen sulfide measurements were taken. However, since the human olfactory system has a lower hydrogen sulfide detection limit (~0.5 µg/L) than field-based analytical techniques (~10-20 µg/L), an olfactory-based presence/absence data point was recorded each day for all sample locations throughout demonstration testing. No hydrogen sulfide was detected analytically. A slight hydrogen sulfide smell was detected in the effluent of F130 daily, but none was detected in the effluent of F150.

Disinfection By-Products: Each of the raw samples produced no appreciable HAAs or TTHMs. DBPFP was low coming out of Bioreactor F130 (21-42 µg/L HAA_5 and 22-34 µg/L TTHMs) and decreased across Biofilter F150 (6-15 µg/L HAA_5 and 8-15 µg/L TTHMs). Thus, all DBP measurements were well below federal MCLs.

Heterotrophic Plate Counts: HPCs coming out of F130 and F150 were too numerous to count (>5,700 counts/mL) Throughout the majority of pilot testing, free chlorine doses of 1-2 mg/L as Cl_2 were used for the final disinfection step, leaving residuals of approximately 0.5-1.2 mg/L as Cl_2. Based on a tracer test, the t10 through the chlorine contact tank was 17 min (i.e., CT = 8.5-20.4 mg-min/L) when an EBCT of 10 min was used through the post-treatment biofilter. Typical resultant HPCs in the effluent of the chlorine contact tank were 1-35 colony forming unit (CFU)/mL.

A CT of 2 mg-min/L was also tested. This CT was achieved through two conditions: 1) a chlorine residual of 0.l2 mg/L as Cl_2 + a t_{10} of 17 min, and 2) a chlorine residual of 0.20 mg/L as Cl_2 + a t_{10} of approximately 10 min. Resultant HPCs in the effluent of the chlorine contact tank were 44-430 CFU/mL.

7.2.7 Hazards

The primary hazards associated with FXB biological perchlorate treatment are associated with chemicals such as acetic acid, phosphoric acid, hydrogen peroxide, and chlorine. All these chemicals are NSF-60-certified for drinking water applications, and standard protocols can be followed when they are stored and handled.

7.2.8 Scale-Up Constraints

Heterogeneity of Biological Growth: Meaningful depthwise pressure measurements were difficult to acquire as the depthwise sampling ports were typically blocked by biogrowth. Visual inspection showed that the heaviest biogrowth occurred in the top 12-24 inches of each bed, as expected. The biogrowth was milky white and appeared evenly distributed at a given depth. Biogrowth was also observed in the deeper portions of the beds, but it appeared much less dense. Most importantly, the observed heterogeneity in biogrowth patterns did not appear to cause any short-circuiting through the bioreactors.

Backwash Effectiveness: See the Backwash Effectiveness subsection of Section 7.2.3.

7.2.9 Hazardous Material

See the Used Media subsection of Section 7.2.4.

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8.0 COST ASSESSMENT

8.1 COST DRIVERS

The main cost driver for FXB biological perchlorate removal systems is the concentration of DO and nitrate in the raw water. Because the presence of DO and nitrate inhibits biological perchlorate reduction, raw water DO and nitrate must be removed before perchlorate reduction to below detection is achieved. Therefore, the bioreactor system must be sized so that sufficient contact time (i.e., EBCT) is provided for the bacteria to reduce DO and nitrate. Perchlorate concentrations in groundwater are typically several orders of magnitude lower than DO and nitrate concentrations in groundwater. Therefore, no contact time beyond that provided for DO and nitrate reduction is necessary, regardless of raw water perchlorate concentration or target effluent perchlorate concentration. During this demonstration, feed water perchlorate concentrations were spiked all the way up to ~1 mg/L, and sustained perchlorate removal to below detection was achieved using the same EBCT and acetic acid dose used to remove background concentrations of perchlorate (~54 µg/L) to below detection.

It is interesting to note that the required EBCT (i.e., reactor sizing) is not nearly as sensitive to raw water DO and nitrate concentrations as originally thought. Performance data from this demonstration study and from an FXB biodenitrification pilot study recently completed in Riverside, California, (Brown, 2008) support this assertion. During this demonstration study, with average raw water DO and nitrate (as NO_3^-) concentrations of 8 and 28 mg/L, respectively, perchlorate removal to below detection was achieved using an EBCT of 5 min (lowest EBCT tested), resulting in a design EBCT of 10 min. During the Riverside biodenitrification pilot testing, average raw water DO and nitrate (as NO_3^-) concentrations were 3 and 75 mg/L, respectively. Nitrate was removed to below 5 mg/L at the shortest EBCT tested, 4 min, suggesting that effective perchlorate removal could be achieved using very short EBCTs, even when nitrate concentrations in the raw water are very high. The design EBCT for the biodenitrification system in Riverside was also set at 10 min. *This relative insensitivity of design EBCT to raw water quality is an important aspect of the FXB bioreactor process*.

Raw water DO and nitrate concentrations directly impact O&M costs. Regardless of required EBCT, sufficient acetic acid must be dosed to the system to remove raw water DO and nitrate before achieving complete perchlorate removal. Since acetic acid dosing requirements are a function of stoichiometric oxidation, reduction, and cell synthesis reactions, the required acetic acid dose increases and decreases proportionally with increases and decreases in raw water DO and nitrate concentration. The cost model developed during this study showed that acetic acid costs account for over 80% of the total annual O&M costs of an FXB biological perchlorate treatment system. Thus, fluctuations in unit acetic acid costs or raw water DO and nitrate concentrations will have a substantial impact on O&M costs.

8.2 COST ANALYSIS

This assessment was designed to provide a complete project cost estimate, including design, construction, and annual operating and maintenance costs for the 30-year life cycle of the system. The cost model used to develop this assessment is based on data collected during the FXB biological perchlorate destruction demonstration conducted at the City of Rialto Well #2.

Optimal operating criteria were developed during the pilot demonstration for key system parameters such as:

- GAC bed depth
- Filter media depth
- Empty bed contact time
- Backwash frequency
- Chemical dosages.

The design criteria from the demonstration have been combined with our extensive knowledge of project development and construction cost components to provide this detailed assessment.

8.2.1 Treatment Capacity Assessments

A 1,000-gpm system and a 2,000-gpm system were evaluated to demonstrate economies-of-scale. A process flow diagram and conceptual facility layouts for the 1,000-gpm system and the 2,000-gpm system are provided in Figures 4, 5, and 6, respectively.

8.2.2 Basis of Design

The cost assessment includes redundant equipment for critical subsystems to provide reliability and to meet regulatory requirements. A standby bioreactor vessel and a standby biofilter vessel are included in the basis of design for use during backwash periods or media replacement maintenance to allow for uninterrupted operation per regulatory requirements. Similarly, standby chemical metering pumps, back wash water pumps, and backwash air scour blowers are included to ensure system reliability. Chemical bulk storage is provided for 30 days of operation between product deliveries as required by Ten States Standards.

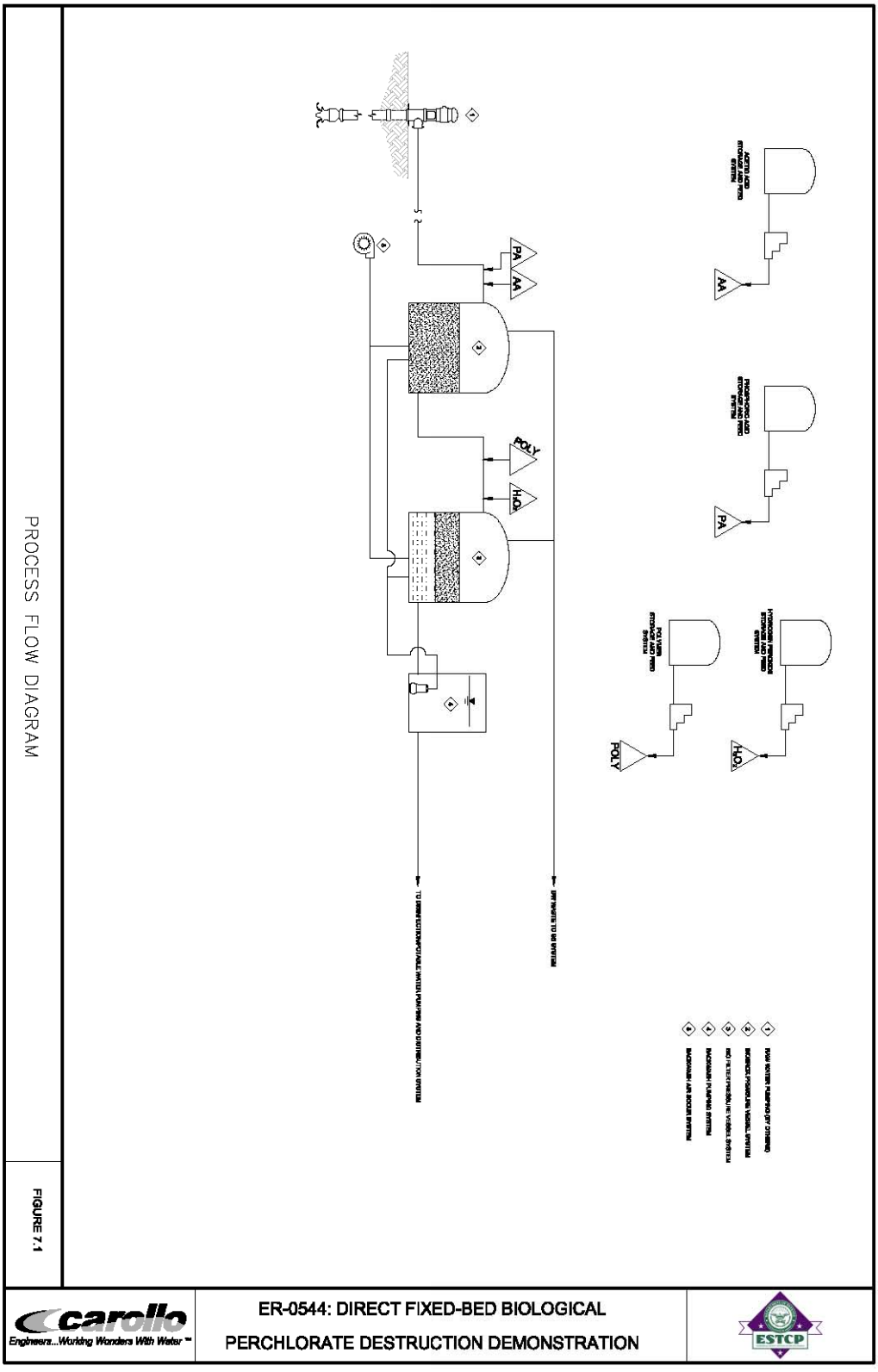

Figure 4. Process flow diagram.

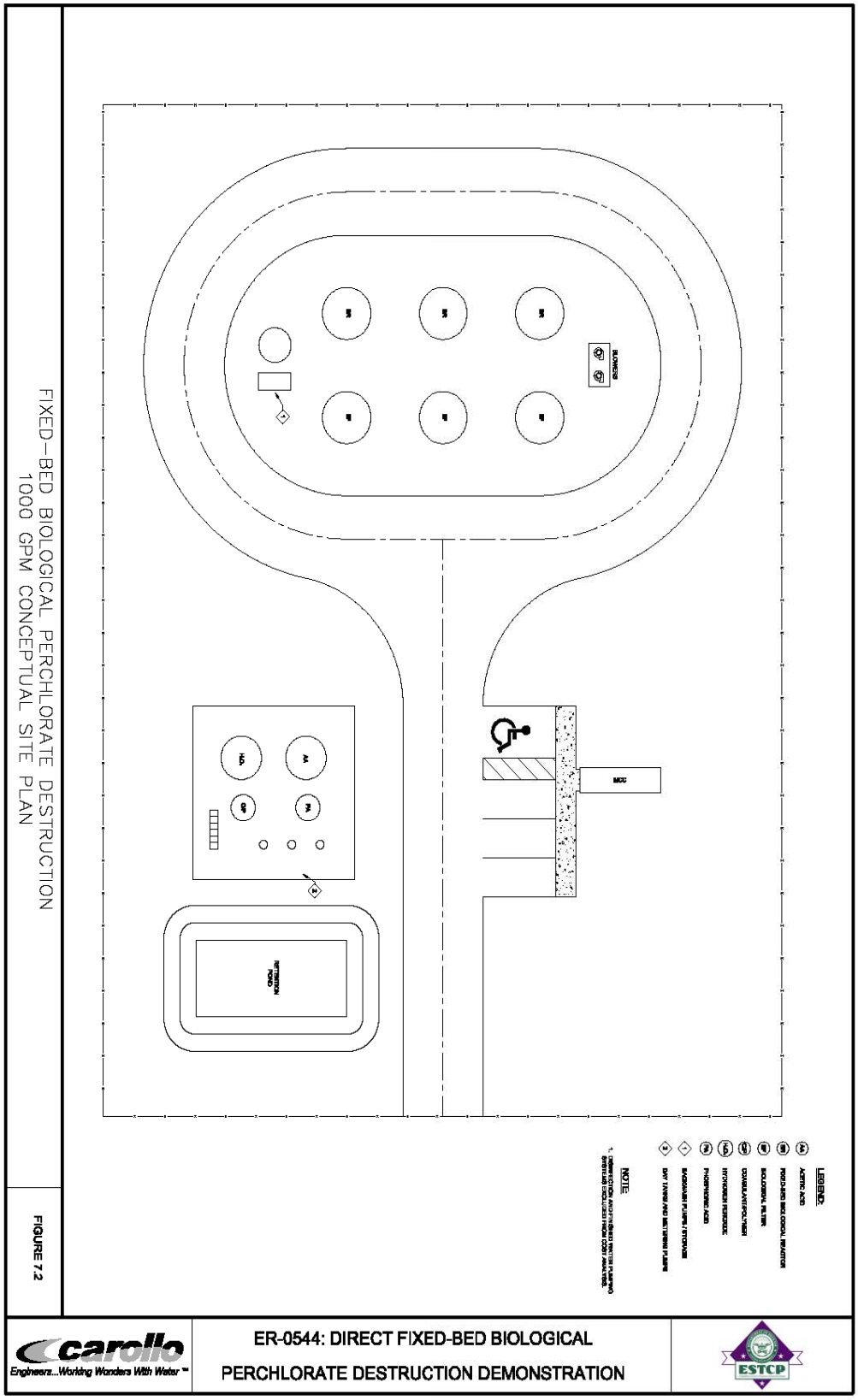

Figure 5. 1,000-gpm Conceptual Site Plan.

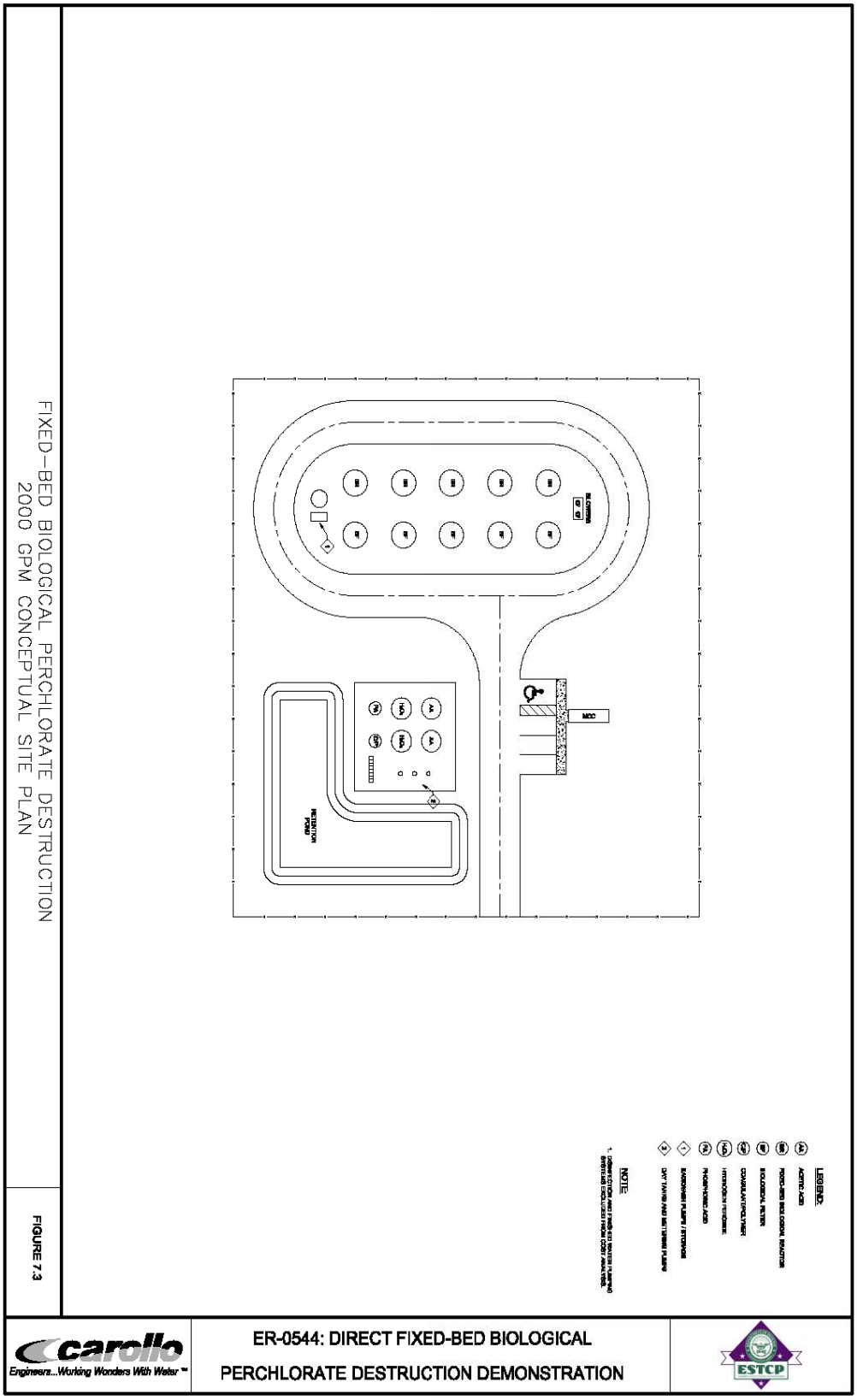

Figure 6. 2,000-gpm Conceptual Site Plan.

The demonstration study showed that perchlorate removal to below detection was achieved and sustained at EBCTs as low as 5 min, which was the lowest EBCT tested. The resultant EBCTs in the 1,000- and 2,000-gpm system cost estimates below are 8.5 min and 10.6 min, respectively, thereby providing considerable flexibility in capacity/contact time for each system. This assessment assumes that an in-line perchlorate ion chromatograph, which carries a sizable price tag, will always be required during full-scale operation. Table 9 provides details of the basis of design system components.

Table 9. Basis of design criteria.

Description	Finished Water Flowrate		
	Units	1,000 gpm	2,000 gpm
Biological Reactor System			
Number of vessels (total)	Number (No.)	3	5
Redundant vessels	No.	1	1
Flow per vessel	gpm (mgd)	500 (0.72)	500 (0.72)
Perchlorate levels influent/effluent	µg/L	5-1,000/Nondetect	
Biological Filtration System			
Number of vessels (total)	No.	3	5
Redundant vessels	No.	1	1
Flow per vessel	gpm (mgd)	500 (0.72)	500 (0.72)
Turbidity[1] (effluent)	NTU	0.2	0.2
Acetic Acid System			
Metering pumps (total)	No.	2	2
Redundant metering pumps	No.	1	1
Bulk storage (30-day supply)	gal	4,100	8,100
Phosphoric Acid System			
Metering pumps (total)	No.	2	2
Redundant metering pumps	No.	1	1
Bulk storage (30-day supply)	gal	30	60
Coagulant System			
Metering pumps (total)	No.	2	2
Redundant metering pumps	No.	1	1
Bulk storage (30-day supply)	gal	130	260
Back Wash System			
Number of BW water pumps (total)	No.	2	2
Redundant BW water pumps	No.	1	1
Number of BW air scour blowers	No.	2	2
Redundant BW air scour blowers	No.	1	1
Number BW water holding tank	No.	1	1
Volume BW water holding tank	gal	1,000	2,000
Inline Perchlorate Analyzer			
Number of perchlorate analyzers	No.	1	1
Manufacturer/model/type	DIONEX /DX900/Ion Chromatograph		
Raw Water Quality	DO = 6 mg/L, NO_3 = 28 mg/L as NO_3^-, Sulfate = 12 mg/L, TDS = 260 mg/L		

[1] Less than or equal to 0.2 NTU in 95% of samples, never to exceed 1.0 NTU per CDPH regulations.

8.2.3 Project Costs

Project costs include capital costs for system equipment and installation, along with standard project line item costs, including:

- Contractor mobilization/demobilization (1.5% of installed equipment costs)
- Site civil work
- Yard piping
- Electrical/I&C (30% of installed equipment costs)
- General conditions (10% of installed equipment costs)
- Contractor overhead and profit (10% of installed equipment costs)
- Sales tax (7.75% of equipment material costs)
- Engineering design services (12% of project costs)
- Engineering construction phase services (4% of project costs)
- Owner's reserve for change orders (5% of project costs).

Excluded from the project cost assessment are:

- Land acquisition costs
- Major site improvement work, such as fill material or substantial clearing
- Raw water resource development and pumping/piping system
- Disinfection system
- Finished water storage
- High service pumping system
- Laboratory or staff office space
- Bringing utilities to/from the site (water, wastewater, power, communications)
- Environmental assessment of site
- Architectural accents to structures
- Owner administration and legal fees.

Table 10 lists the detailed line items and estimated project costs for each of the two system capacities in the cost assessment.

Table 10. Project cost estimate.

No.	Description	Finished Water Flowrate	
		1,000 gpm	2,000 gpm
1	Mobilization/demobilization	$ 60,000	$ 107,000
2	Site civil installed cost	$ 23,000	$ 46,000
3	Yard piping installed cost	$ 60,000	$ 90,000
4	Biological reactor system installed cost	$ 808,000	$ 1,511,000
5	Biological filtration system installed cost	$588,000	$ 1,095,000
6	In-line perchlorate analyzer installed cost	$ 165,000	$ 154,000
7	Equipment structures installed cost	$ 121,000	$ 238,000
8	Electrical/I&C installed cost	$ 548,000	$ 959,000
TOTAL DIRECT INSTALLED COST		$2,373,000	$4,200,000
CONTINGENCY		$ 366,000	$ 640,000
GENERAL CONDITIONS		$ 281,000	$ 491,000
CONTRACTOR OVERHEAD & PROFIT		$ 309,000	$ 540,000
SALES TAX		$ 125,000	$ 229,000
ENGINEERING		$ 563,000	$ 986,000
OWNER'S RESERVE FOR CHANGE ORDERS		$ 176,000	$ 309,000
ESTIMATED TOTAL COST		$4,193,000	$7,395,000

8.2.4 Operation and Maintenance Costs

Annualized costs for operation and maintenance are estimated for the major equipment and system consumables based on a 30-year life cycle. Costs for infrequent consumables, such as the filter sand media with an estimated 10-year life, are adjusted for inflation at 3% and distributed over the system life cycle for inclusion with the annual operation and maintenance costs.

- Consumables:
  - Hydrogen peroxide 25% ($0.43/lb)
  - Acetic acid 50% ($0.86/lb)
  - Phosphoric acid 85% ($0.35/lb)
  - Polymer 49% ($0.13/lb)
- Media Replacement:
  - GAC 10-year life ($25/cf)
  - Filter anthracite 10-year life ($10/cf)
  - Filter sand 10-year life ($7/cf)
- Power ($0.12/kW-hr)

Excluded from the annual operation and maintenance cost estimate:

- Operations labor (no significant increase to a given utility's workload anticipated)
- Raw water pumping power
- Disinfection chemicals
- Finished water pumping power
- Minor equipment and lighting power.

Table 11 provides estimated line item costs for the operations and maintenance.

Table 11. Annual operations and maintenance costs.

No.	Description	Finished Water Flowrate	
		1,000 gpm	2,000 gpm
1	Acetic acid	$ 144,000	$ 289,000
2	Phosphoric acid	$ 1,000	$ 2,000
3	Hydrogen peroxide	$ 15,000	$ 30,000
4	Polymer	$ 1,000	$ 2,000
5	GAC	$6,000	$ 11,000
6	Filter sand/anthracite	$ 3,000	$ 6,000
7	Power	$ 5,000	$ 8,000
	ESTIMATED ANNUAL O&M COST	**$ 175,000**	**$ 348,000**

8.2.5 Treatment Costs

Per ESTCP requirements, the project costs were amortized utilizing the current Office of Management and Budget Real Discount Rate of 2.8% for the 30-year life-cycle assessment to obtain an annual budget estimate. Table 12 summarizes the amortized project costs, the O&M costs, and treatment costs.

Table 12. Treatment costs.

No.	Description	Finished Water Flowrate	
		1,000 gpm	2,000 gpm
1	Amortized[1] project costs	$ 209,000	$ 368,000
2	Annual O&M costs	$ 175,000	$ 348,000
	ESTIMATED ANNUAL BUDGET	**$ 384,000**	**$ 716,000**
	TREATMENT COSTS $/1,000-GAL	**$ 0.73**	**$ 0.68**
	TREATMENT COSTS $/AC-FT	**$ 238**	**$ 222**

[1] Amortized at the current Real Discount Rate of 2.8% and a 30-year life cycle.

8.2.6 Economy of Scale

The cost assessment indicates a 6.7% reduction in treatment costs due to economy of scale as the system finished water capacity is increased from 1,000 gpm to 2,000 gpm. Many of the process subsystems, such as air scour blowers, backwash pumps, and metering pumps require no additional equipment to process the increased treatment flowrate due to their flexible range of operation.

In each of the two flow rates assessed, a single standby biological reactor and a single standby biological filter pressure vessel is required to allow a duty vessel to enter a backwash cycle or for periodic maintenance of the media. Increased costs for the 2,000-gpm system include only those costs for duty vessels for the increased treatment capacity without the added cost of additional standby vessels, thus providing significant economy of scale.

8.3 COST COMPARISON WITH SINGLE-PASS ION EXCHANGE

The only process currently operating at full scale for removing perchlorate from drinking water is IX. IX systems concentrate perchlorate onto a resin, which is removed and regenerated or incinerated (i.e., single-pass IX) once the resin is exhausted. IX systems are proprietary in nature and therefore cost and system data are not readily available.

Equipment and operational cost data for a 1,000 gpm single-pass IX perchlorate selective system was obtained from Siemens Water Technologies Corporation for influent perchlorate concentrations of 50 µg/L and 270 µg/L. The supplier does not recommend the IX system for perchlorate concentrations of 1,000 µg/L. The IX cost data were provided in operating terms of 18 hrs/day, 300 days/year and were proportionally adjusted to operating terms of 24 hrs/day and 365 days/year for comparative purposes in this analysis.

8.3.1 IX Basis of Design

The IX system consists of a lead vessel followed by a polishing lag vessel that constitute a single treatment train. Each treatment train has an operating capacity of 1,000 gpm of finished water. As with the FXB biological system, the cost analysis provided for a redundant train to permit continuous operations during maintenance and resin change-out and to meet regulatory requirements for reliability. Table 13 lists the IX basis of design criteria.

Table 13. IX basis of design criteria.

Description	Units	1,000-gpm Finished Water Facility Influent Perchlorate Level[1]		
		50 µg/L	270 µg/L	1,000 µg/L
Total number of IX lead-lag vessel pairs[2]	No.	2	2	N/A
Redundant IX lead-lag vessel pairs[2]	No.	1	1	N/A
Effluent perchlorate level	µg/L	<4 µg/L		N/A

[1] Other raw water quality: DO = 6 mg/L, NO_3 = 28 mg/L as NO_3^-, Sulfate = 12 mg/L, TDS = 260 mg/L
[2] One lead-lag vessel pair constitutes a single 1,000 gpm finished water treatment system.

8.3.2 IX Project Costs

IX project costs include capital costs for system equipment and installation, along with standard project line item costs, including:

- Contractor mobilization/demobilization (1.5% of installed equipment costs)
- Site civil work
- Yard piping
- Electrical/I&C (30% of installed equipment costs)
- General conditions (10% of installed equipment costs)
- Contractor overhead and profit (10% of installed equipment costs)
- Sales tax (7.75% of equipment material costs)
- Engineering design services (12% of project costs)

- Engineering construction phase services (4% of project costs)
- Owner's reserve for change orders (5% of project costs).

Excluded from the project cost assessment are:

- Land acquisition costs
- Major site improvement work, such as fill material or substantial clearing
- Raw water resource development and pumping/piping system
- Disinfection system
- Finished water storage
- High service pumping system
- Laboratory or staff office space
- Bringing utilities to/from the site (water, wastewater, power, communications)
- Environmental assessment of site
- Architectural accents to structures
- Owner administration and legal fees.

Table 14 summarizes the project cost data for 1,000-gpm IX facilities at varying influent perchlorate levels.

Table 14. IX project cost estimate.

No.	Description	1,000-gpm Finished Water Facility Influent Perchlorate Level[1]		
		50 µg/L	270 µg/L	1,000 µg/L
1	Mobilization/demobilization	$ 53,000	$ 53,000	N/A
2	Site civil installed cost	$ 23,000	$ 23,000	N/A
3	Yard piping installed cost	$ 60,000	$ 60,000	N/A
4	IX system installed cost	$ 1,544,000	$ 1,544,000	N/A
5	Electrical/I&C installed cost	$ 489,000	$ 489,000	N/A
TOTAL DIRECT INSTALLED COST		$ 2,169,000	$ 2,169,000	N/A[1]
CONTINGENCY		$ 326,000	$ 326,000	N/A[1]
GENERAL CONDITIONS		$ 250,000	$ 250,000	N/A[1]
CONTRACTOR OVERHEAD & PROFIT		$ 275,000	$ 275,000	N/A[1]
SALES TAX		$ 110,000	$ 110,000	N/A[1]
ENGINEERING		$ 501,000	$ 501,000	N/A[1]
OWNER'S RESERVE FOR CHANGE ORDERS		$ 157,000	$ 157,000	N/A[1]
ESTIMATED TOTAL COST		$ 3,788,000	$ 3,788,000	N/A[1]

[1] Other raw water quality: DO = 6 mg/L, NO_3 = 28 mg/L as NO_3^-, Sulfate = 12 mg/L, TDS = 260 mg/L

Annualized costs for operation and maintenance are estimated for the major equipment and system consumables based on a 30-year life cycle.

- Consumables:
  - IX Resin
    - Influent perchlorate = 50 µg/L ($219,000 per year)
    - Influent perchlorate = 270 µg/L ($412,000 per year)

- Influent perchlorate = 1,000 µg/L (NA)

- Power ($0.12/kW-hr).

Excluded from the annual operation and maintenance cost estimate:

- Operations labor (no significant increase to a given utility's workload anticipated)
- Raw water pumping power
- Disinfection chemicals
- Finished water pumping power.

Table 15. IX annual operations and maintenance costs.

No.	Description	1,000-gpm Finished Water Facility Influent Perchlorate Level[2]		
		50 µg/L	270 µg/L	1,000 µg/L
1	Power (<100 kW/yr)	-	-	N/A[1]
2	IX resin replacement & disposal	$ 219,000	$ 412,000	N/A[1]
	ESTIMATED ANNUAL O&M COST	**$ 219,000**	**$ 412,000**	N/A[1]

[1] Treatment of perchlorate at 1,000 µg/L is not recommended by the IX supplier.
[2] Other raw water quality: DO = 6 mg/L, NO_3 = 28 mg/L as NO_3^-, Sulfate = 12 mg/L, TDS = 260 mg/L

8.3.3 IX Treatment Costs

The IX project costs are amortized utilizing the current Office of Management and Budget Real Discount Rate of 2.8% for the 30-year life-cycle assessment to obtain an annual budget estimate. Table 16 summarizes the amortized project costs, the O&M costs, and treatment costs.

Table 16. Summarized IX treatment costs.

No.	Description	1,000-gpm Finished Water Facility Influent Perchlorate Level[1]		
		50 µg/L	270 µg/L	1,000 µg/L
1	Amortized[2] project costs	$ 189,000	$ 189,000	N/A
2	Annual O&M costs	$ 219,000	$ 412,000	N/A
	ESTIMATED ANNUAL BUDGET	**$ 408,000**	**$ 601,000**	N/A
	TREATMENT COSTS $/1,000-GAL	**$ 0.78**	**$ 1.14**	N/A
	TREATMENT COSTS $/AC-FT	**$ 254**	**$ 372**	N/A

[1] Treatment of perchlorate at 1,000 µg/L is not recommended by the IX supplier.
[2] Amortized at the current Real Discount Rate of 2.8% and a 30-year lifecycle.

8.3.4 Treatment Cost Comparison

When the raw water perchlorate concentration is approximately 50 µg/L, total treatment costs for the FXB biological system and the single-pass IX system are comparable (approximately $240-$250/AF for a 1,000-gpm system). As raw water perchlorate concentrations increase, the cost of the FXB biological system does not change, while the cost of the single-pass IX system increases

(see Figure 7). The relative insensitivity of the FXB biological process to raw water perchlorate (and nitrate concentration – See Section 8.1) provides confidence that an FXB biological system installed today will be effective in the future without the need for additional treatment capacity even if raw water perchlorate (or nitrate) levels increase. Perhaps the most important difference between the two treatment approaches is that, while the single-pass IX system removes only perchlorate, the FXB biological process removes nitrate and perchlorate in a single bioreactor. Other contaminants, such as halogenated organics, can be removed simultaneously in the FXB bioreactor as well (Brown, 2008), making the FXB biological system particularly well suited for multiple-contaminant treatment applications.

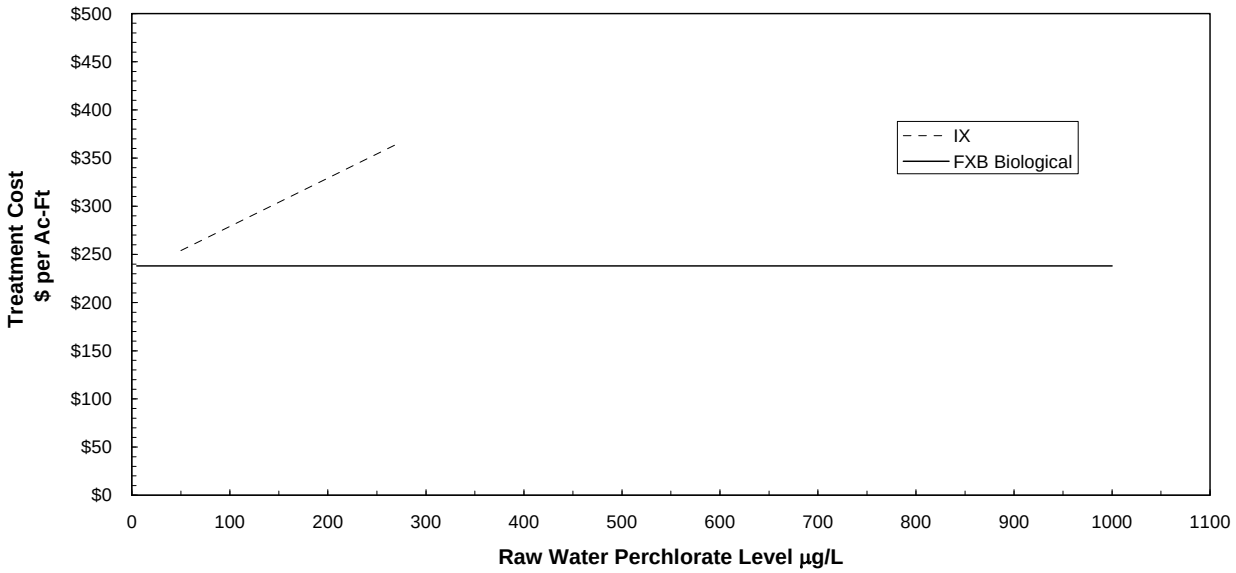

Figure 7. FXB biological and single-pass IX treatment costs as a function of raw water perchlorate concentration.

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9.0 IMPLEMENTATION ISSUES

9.1 REGULATORY CONSIDERATIONS

Any full-scale, potable FXB biological perchlorate treatment process would be subject to all federal and state drinking water regulations. The majority of applicable drinking water regulations are established and well known. However, regulations associated specifically with potable biological perchlorate and nitrate treatment facilities have not been finalized. The CDPH is in the process of finalizing these regulations, which will deal with issues such as inactivation requirements, turbidity limits, and water quality monitoring requirements.

In addition to these established and emerging drinking regulations, which primarily apply to distributed water quality, utilities will also have to consider how to handle the BW wastewater. This waste stream should be $\leq$3% of the total water treated, and have BW wastewater of low strength. Therefore, it is expected that it can be discharged to the local sewer in many instances, though this would have to be confirmed on a site-specific basis. If no sewer discharge is allowable at a given site, a wastewater clarification and recycle process would need to be considered.

Lastly, a permit for full-scale installation and operation of a potable, FXB biological perchlorate treatment system must be applied for and received from the CDPH. Conditional CDPH approval for full-scale implementation of the FXB process was granted to Carollo Engineers in 2004 and discussions with CDPH in February 2008 indicated that, based on the performance data from various FXB biological perchlorate and nitrate treatment pilot studies, full-scale FXB biological treatment facility permitting should follow the standard schedule and protocol for any new water treatment facility in California.

9.2 END-USER ISSUES

Previous bench- and pilot-scale testing showed that FXB biological perchlorate treatment is promising, and it led to the CDPH Conditional Approval for full-scale process implementation. The results of this ESTCP demonstration study showed that 1) as FXB bioreactor treatment systems scale up, process efficiencies also go up (i.e., required contact times to achieve sustained, robust perchlorate removal decreased substantially relative to contact time requirements established during previous, smaller scale studies); 2) hydrogen peroxide reoxygenation, polishing filtration, and chlorination provide effective post-treatment; 3) system operation is straightforward, requiring no specialized training; 4) the bacterial communities in these systems are largely gram-negative Proteobacteria; 5) site-specific performance of these systems can be predicted using a mathematical model developed as part of this demonstration; and 6) total water production costs for an FXB system can be low.

In spite of the numerous strengths of FXB systems demonstrated during this project, one significant obstacle still hinders the widespread realization of these systems at full-scale: the lack of the first full-scale, potable FXB biological perchlorate treatment facility. Though full-scale, anoxic/anaerobic FXB biological treatment processes have been used in Europe for over 20 years to remove nitrate from drinking water, no such facilities exist in the United States for perchlorate or nitrate treatment. Since it is more comfortable to select a process for full-scale treatment

when there is a full-scale track record to affirm the selection, it is not easy for stakeholders to choose a novel process for their treatment system. In other words, the primary end user issue relates to the willingness to design, install, and operate a process with no full-scale track record. The most important outcome of this demonstration is that the results strongly suggest that this risk is small, while the potential benefits are considerable.

9.3 PROCUREMENT

While the expertise to design and operate an FXB biological perchlorate treatment system is not common in the drinking water industry, the process itself is not proprietary. FXB biotreatment is a modified form of standard granular media filtration and therefore would be procured through a typical bidding process. Specifications for the FXB bioreactor vessel have been developed based on 1) the performance observed during demonstration testing, 2) the Project Team's experience with two full-scale FXB bioreactor projects (different applications but similar characteristics), and 3) full-scale European biodenitrification experience.

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