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FOSTER WHEELER ENVIRONMENTAL CORPORATION

REPORT

PERCHLORATE TREATABILITY STUDIES: USE OF REVERSE OSMOSIS AND BIOTREATMENT FOR REMOVAL OF PERCHLORATE FROM JPL GROUNDWATER

Prepared for the:

National Aeronautics and Space Administration
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109

December, 1999

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AT THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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EXECUTIVE SUMMARY

Perchlorate (ClO_4^-) has been detected in groundwater at the Jet Propulsion Laboratory (JPL) and in downgradient municipal production wells, and is a major factor with regard to the groundwater Feasibility Study (FS) (Foster Wheeler, 1999). Because the identification of ClO_4^- as an environmental contaminant has occurred relatively recently, cost-effective technologies for treating ClO_4^--impacted water are still undergoing development. Currently, there are three basic *ex-situ* treatment technologies with potential applicability for treating JPL groundwater: ion exchange (IE), reverse osmosis (RO), and biological treatment. Each of these technologies was tested for the JPL groundwater FS. IE was previously tested at the bench- and pilot-scales at JPL. This report describes results of initial bench-scale experiments in which the feasibility of RO and biotreatment was investigated to determine their feasibility for treating JPL groundwater.

United States Filter Corporation (US Filter) was selected to conduct RO and biotreatment studies. The main objective of the RO experiments was to establish process feasibility of RO to treat JPL groundwater to non-detectable ClO_4^- levels [<4 micrograms per liter (μg/L)]. RO does not destroy ClO_4^-, rather it is collected in a concentrated waste stream (rejectate), which must be treated or disposed of appropriately. In an effort to minimize production of wastes, RO was also evaluated to further concentrate the rejectate produced from initial RO treatment of groundwater. Two membranes, including cellulose acetate and thin film composite were evaluated, and achievable rejection rates were estimated.

Biotreatability studies were conducted through both US Filter and the University of California, Riverside (UCR). The US Filter studies were intended to confirm process feasibility of their fluidized bed reactor (FBR) technology to treat JPL groundwater and simulated RO rejectate to non-detect ClO_4^- levels (<4 μg/L). US Filter also carried out several additional experiments to evaluate RO permeate polishing, including evaluation of treatment using a second RO pass and ion exchange resins.

The set of biotreatability experiments conducted through UCR was performed at Professor W. T. Frankenberger's laboratory, the Center for Environmental Microbiology (CEM). The objective of these experiments was to demonstrate process feasibility of a packed bed reactor (PBR) for treatment of JPL groundwater and to preliminarily assess, through laboratory flask studies, the potential for biological treatment of RO rejectates.

Results from the RO tests indicated that, at the recovery rate of 80%, the ClO_4^- was reduced from approximately 800 μg/L to 12-16 μg/L in the first stage, which is below the California Department of Health Services Interim Action Level of 18 μg/L. In the second stage RO (treatment of the rejectate generated in the initial groundwater treatment), the recovery rate was 50% and the ClO_4^- concentration was reduced from approximately 3,600 μg/L to 17-18 μg/L.

When considering these results, it is important to note that while RO systems consist of multiple membranes in multiple elements (arrays), this test was conducted using only one membrane in one element. This is consistent with US Filter's approach to this type of testing, which is to obtain the worst case conditions for scale-up. This is done to insure that the results from the large-scale system will generally be better than the test results because the permeate from one element will be diluted by the permeates from the other elements. Therefore, it is believed that with a full size RO system, non-detectable ClO_4^- concentrations in treated water are readily achievable. Experiments to assess further treatment (polishing) of the permeate using second pass RO and IE demonstrated the capability of these techniques to reduce permeate ClO_4^- concentrations to non-detect levels.

With regard to US Filter's biotreatment tests, ClO_4^- concentrations in simulated feed were lowered from 1.5 milligrams per liter (mg/L) to less than 0.5 mg/L, and in many cases to less than 0.1 mg/L. However, the small bench scale FBR was not able to meet non-detect ClO_4^- levels. This resulted from a variety of upset conditions, and it is believed, from difficulties in testing FBR technology at this small scale.

US Filter notes that documented historical data indicate that non-detect effluent ClO_4^- levels would easily be achieved using larger scale equipment. The process is well understood, and is essentially identical to the denitrification process. US Filter has over 70,000,000 gallons of water being denitrified every day with FBR technology, and thus have a proven track record of years of field operation with proven robustness.

Results From the UCR effort suggest that JPL groundwater is treatable to non-detect ClO_4^- concentrations in the PBR system with a residence time as low as 0.4 hours. In addition, results preliminarily suggest that ClO_4^- can be destroyed in primary and secondary RO rejectates by various inocula, and therefore, biological treatment of RO rejectates appears feasible.

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ACRONYMS AND ABBREVIATIONS

ARA	Applied Research Associates
CEM	Center for Environmental Microbiology
cm	Centimeter
Cl^-	Chloride
ClO_4^-	Perchlorate
FBR	Fluidized Bed Reactor
FS	Feasibility Study
IE	Ion Exchange
JPL	Jet Propulsion Laboratory
mg/L	Milligram per liter
mL	Milliliter
OU-1	Operable Unit 1 (On-Site Groundwater)
OU-3	Operable Unit 3 (Off-Site Groundwater)
PBR	Packed Bed Reactor
RO	Reverse Osmosis
SO_4^{2-}	Sulfate
TFC	Thin Film Composite
UCR	University of California, Riverside
µg/L	Microgram per liter
US Filter	United States Filter Corporation
VOC	Volatile Organic Compound

1.0 INTRODUCTION

Perchlorate (ClO_4^-) was detected in groundwater at the Jet Propulsion Laboratory (JPL) and in downgradient municipal production wells during the Operable Unit 1/Operable Unit 3 (OU-1/OU-3) Remedial Investigation, and is a major factor with regard to the OU-1/OU-3 Feasibility Study (FS). The identification of ClO_4^- as an environmental contaminant has occurred relatively recently (due to refinements in analytical methodology), and although considerable progress has been made, reliable, cost-effective technologies for treating ClO_4^--impacted water are still under investigation.

Because the depth and extensiveness of impacted groundwater at JPL precludes *in-situ* treatment techniques, it appears at this time that pump-and-treat technology is the only workable option for remediation of ClO_4^--impacted groundwater at JPL. Unlike the volatile organic compounds (VOCs) detected in JPL groundwater, ClO_4^- is not volatile, and therefore cannot be removed by VOC treatment processes. However, several processes that are amenable to pump-and-treat systems have been identified for removing ClO_4^- from water, and/or converting it to less toxic forms.

There are three basic removal technologies that are currently considered to be applicable: ion exchange (IE), reverse osmosis (RO), and biological treatment. Of these, biological treatment is generally considered to be the most economical technique (Urbanski, 1998), largely because, unlike IE and RO, biotreatment destroys ClO_4^- by converting it to chloride (Cl^-), which is innocuous. There are, however, unresolved regulatory and public perception issues with regard to the ultimate fate of effluent from biological treatment systems. Both IE and RO appear to be less feasible than biotreatment in terms of economics, but may be more favorable in terms of issues regarding the disposition of effluent, which is of major importance at JPL. A key disadvantage of IE and RO, however, is that with these techniques, ClO_4^- is not destroyed, and a concentrated waste stream is generated. Hence, in light of what is presently known, a combination of removal and destruction techniques will most likely be needed to provide a solution that is both technically and economically feasible.

2.0 RATIONALE

As noted above, there is a general lack of verifiable information regarding technical and economic aspects of ClO_4^- treatment technologies, which have only recently been developed, and are still undergoing testing. In addition, uncertainties exist at JPL regarding the final disposition of treated water, which is crucial in selecting an appropriate treatment technology. For these reasons, each of the three removal technologies mentioned above were tested (to varying degrees) for the JPL FS.

IE was previously tested at the bench- and pilot-scales at JPL (Foster Wheeler, 1999-Appendices B-2 and C). The pilot-scale IE test was conducted by Calgon Carbon Corporation, and included a proprietary catalytic treatment system to destroy ClO_4^- in the process waste. The process waste (regenerant, or "brine") consists of an aqueous solution containing 7% sodium chloride. The catalytic treatment system allows for recycling of the brine, thereby greatly minimizing the production of process wastes. Overall, the test was successful, and there is little doubt that IE is capable of removing ClO_4^- from JPL groundwater to non-detect levels.

However, the catalytic destruction system, which is still undergoing development (refinement), was only tested for 10 days, and therefore long-term evaluation of the process was not possible. This is significant, as there are presently no other methods for removing ClO_4^- from the IE brine (some evidence suggests that more dilute IE brines may be treated biologically, but this has not yet been demonstrated for the 7% NaCl solution used by Calgon). Without the catalytic system, the economic feasibility of IE at JPL is questionable, because the brine (or spent resins) would have to be transported and treated off-site. For this reason, it was deemed prudent to study the feasibility of the other potential options, including RO and biotreatment, to determine their applicability for treating JPL groundwater.

3.0 APPROACH

The approach used in preliminary technology evaluation and vendor selection is outlined below.

Reverse Osmosis

Reverse osmosis is a membrane process in which dissolved salts are separated from water by filtering through a semi-permeable membrane at a pressure greater than the osmotic pressure caused by the dissolved species in the water. RO also coincidentally removes a high percentage of other dissolved ionic and organic species (including hexavalent chromium). As with IE, RO does not destroy ClO_4^-, rather it is collected in a concentrate (rejectate), which must be treated or disposed of appropriately.

At the outset of this study, numerous RO vendors were contacted, and none were able to provide any information on removal of ClO_4^- at low concentrations from groundwater. US Filter, which is a world leader in RO technology and is involved in various aspects of ClO_4^- treatment research, was selected to perform the RO testing.

Biotreatment of Groundwater

Because pump-and-treat has been identified as the preferred approach at JPL, appropriate biological process options for *ex-situ* treatment of groundwater at JPL involve bioreactors. In this process, groundwater is extracted and pumped through vessels containing microbes that are attached to, or suspended within various matrices in the vessels. Within the reactor, ClO_4^- serves as a terminal electron acceptor in microbial respiration as oxygen becomes limiting, analogous to nitrate and sulfate (SO_4^{2-}) reduction in soils and water. In this process, ClO_4^- is converted to the chloride ion (Cl^-), which is innocuous. Because many of these mechanisms are enzymatic in nature, reaction rates can be rapid.

At the time of these experiments, very few vendors were capable of providing bioreactors to remove ClO_4^- from groundwater. A fluidized bed reactor (FBR) process developed through Envirogen/Envirex (Envirex is owned by US Filter) for the Rancho Cordova Aerojet site was initially identified as being the furthest along in terms of development. US Filter was therefore selected to conduct the initial biotreatability studies.

It is noted that Applied Research Associates (ARA), Ft. Lauderdale, FL., has since been identified as another leader in the field. However to our knowledge, their process is more amenable to treating more concentrated streams than the JPL groundwater (process wastes, potentially including RO rejectates and IE brines). ARA was subsequently contracted for the JPL FS to conduct treatability studies to assess removal of ClO_4^- from RO rejectates (Foster Wheeler, 1999-Appendix F).

In addition, Professor W. T. Frankenberger of UCR, had reported preliminary success in removing ClO_4^- from groundwater using a recently isolated ClO_4^--reducing organism, *perc1ace*, in a packed bed reactor system (PBR). PBR systems are generally viewed as having potential advantages over FBR systems in terms of ease in operation in cases where influent feeds contain little organic carbon, such that clogging is minimized. With regard to the JPL application, groundwater extracted from the Raymond Basin contains essentially no organic carbon, and in fact, a carbon source must be added to the water for the reduction of ClO_4^- to occur. Because the additions of organic carbon can be optimized such that clogging would minimized, and because the UCR reactor had been successful in treating JPL groundwater in preliminary laboratory tests, the UCR PBR was further evaluated for its ability to treat the JPL groundwater.

Biotreatment of RO Rejectates

Finally, because the feasibility of RO at JPL rests largely on treatment of waste streams (rejectates), biological removal of ClO_4^- from saline environments simulating RO rejectates was also preliminarily assessed in a laboratory flask experiment. In addition, it was also originally planned that, pending results of the FBR tests for groundwater, US Filter would also test for biotreatability of the RO rejectate using the bench-scale FBR. As will be explained below, this US Filter test was ultimately not carried out.

4.0 OBJECTIVES

Specific objectives of the treatability studies were as follows:

US Filter Study

- Establish process feasibility of RO to treat JPL groundwater to non-detect ClO_4^- levels (<4 μg/L).
- Establish process feasibility of second pass RO to treat the initial RO rejectate from treatment of JPL groundwater to non-detect ClO_4^- levels (<4 μg/L).
- Evaluate two RO membranes, including cellulose acetate and thin film composite (TFC).
- Estimate achievable rejection rates.
- Confirm process feasibility of US Filter's FBR technology to treat JPL groundwater to non-detect ClO_4^- levels (<4 μg/L) and estimate the required residence time.
- Establish process feasibility of the FBR to treat simulated RO rejectate from the treatment of JPL groundwater to non-detect ClO_4^- levels (<4 μg/L).

UCR Study

- Demonstrate process feasibility of the PBR for treatment of JPL groundwater and estimate initial scale-up parameters (required residence time and energy/nutrient additions).
- Screen inocula with potential for reducing ClO_4^- in RO rejectates. If salt-tolerant (halotolerant) microorganisms capable of carrying out reduction of ClO_4^- in saline environments can be isolated, this will provide a good indication that the RO rejectate is biologically treatable [biological treatment of IE regenerant (7% NaCl) has not been demonstrated to date due to extreme salt content].

It is noted that US Filter also carried out several experiments to evaluate RO permeate polishing which were not part of the initial scope. These included evaluation of treatment using a second RO pass, and ion exchange resins.

5.0 SUMMARY OF EXPERIMENTAL METHODOLOGY

Brief descriptions of the experiments are included below. The complete respective reports, which discuss in detail all aspects of the testing, are included in Appendices A (US Filter) and B (UC Riverside).

US Filter Study

Two stages of RO testing were initially conducted. The first stage RO was performed on raw JPL groundwater as the influent source. The second stage RO was used to treat the rejectate stream from the first stage RO. Two separate RO membranes (cellulose acetate and TFC) were evaluated during the first stage tests, and a TFC seawater membrane was used for the second stage test. Permeate recoveries were 80% for the first stage tests, and 50% for the second stage tests. To assure that the ClO_4^- concentration could be reduced to below the detection limit of 4 μg/L, testing was performed using a second pass RO as a polish for the primary stage RO permeate. In addition, ion exchange was also evaluated as a polish for the RO permeate.

With regard to the bioreactor (FBR) test, a synthetic waste stream having characteristics similar to JPL groundwater was used to acclimate the reactor. Acclimation was expected to take several weeks, following which, actual JPL groundwater would be used as the feed. Unfortunately, due to test equipment malfunctions with the small-scale bench system, US Filter was unable to produce the consistent high quality effluent (<4 μg/L ClO_4^-) as has been demonstrated in other projects, and actual JPL groundwater was therefore never used (this is explained further below and in Appendix A).

UCR Study

A bench-scale bioreactor (PBR), consisting of a cylindrical plexiglass column was set up and operated in an up-ward flow mode. The column specifications were as follows: total height: 21.4 centimeters (cm); inside diameter: 13.5 cm; bed height: 12.5 cm; total volume: 3062 milliliters (mL); total bed volume: 1789 mL; pore volume: 1236 mL. Celite (a pelletized diatomaceous earth preparation), which has been used in a similar bioreactor study at Tyndall AFB, was used as the packing material for this study. The column was colonized with a perchlorate/ nutrient/inoculum rich stream for approximately 3 weeks. The inoculum previously identified by Dr. Frankenberger, *perclace* (Herman and Frankenberger, 1999), was used.

Once the column was effectively colonized, actual JPL groundwater, collected from JPL monitoring well MW-16, was amended with nitrogen and phosphorous. The water was supplemented with sodium acetate as the energy source via an in-line feed pump, as determined in previous work (Herman and Frankenberger, 1999), and fed into the reactor. Influent and effluent samples were collected and subsequently analyzed for ClO_4^- (and other parameters) in-house, in accordance with U.S. Environmental Protection Agency Method 300.0.

The general approach was to begin with a residence time that yielded non-detectable effluent ClO_4^- concentrations (based on prior experimentation), and incrementally increase the flow rate, thereby decreasing the residence time until breakthrough occurred.

A screening level experiment was also conducted to identify inocula capable of reducing ClO_4^- in liquid medium approximating the salt content of RO rejectates. This experiment was designed to provide an indication of the feasibility of biologically reducing ClO_4^- in secondary RO rejectates. This included testing the bacterium previously isolated by Dr. Frankenberger (*perc1ace*), and several new sources of inoculum collected from saline environments. Flasks containing aliquots of simulated RO rejectates were inoculated, provided with a carbon source, and tested for a decrease in ClO_4^- concentrations.

6.0 SUMMARY OF FINDINGS

The major findings and conclusions of the studies are described in detail in the respective appendices, and are summarized here are as follows:

US Filter Study-Reverse Osmosis

1. Results indicate that the TFC membrane is highly effective in removing ClO_4^- from JPL groundwater and from RO rejectate.

2. Using RO to treat JPL groundwater, at the recovery rate of 80% the ClO_4^- concentration was reduced from approximately 800 μg/L in the feed to 12-16 μg/L in the permeate.

3. Using RO to treat the rejectate from the initial groundwater RO treatment experiment, at a recovery rate of 50% the ClO_4^- concentration was reduced from approximately 3,600 μg/L in the feed to 17-18 μg/L in the permeate.

4. When considering these results, it is important to note that while RO systems consist of multiple membranes in multiple elements (arrays), this test was conducted using only one membrane in one element. This is consistent with US Filter's approach to this type of testing, which is to obtain the worst case conditions for scale-up. This is done to insure that the results from the large-scale system will generally be better than the test results because the permeate from one element will be diluted by the permeates from the other elements. Therefore, it is believed that with a full scale RO system, non-detectable ClO_4^- concentrations in treated water are readily achievable.

5. Further treatment of the permeate using second pass RO as a polishing technique lowered permeate ClO_4^- concentrations to non-detect levels.

6. Further treatment of the permeate using ion exchange (strong and weak base anion exchange resins) lowered permeate ClO_4^- levels to non-detect levels. Because the total dissolved solids of the permeate is very low, resin regeneration is greatly minimized.

US Filter Study-Biological Treatment

1. ClO_4^- concentrations in simulated feed were lowered from 1.5 milligrams per liter (mg/L) to less than 0.5 mg/L, and in many cases to less than 0.1 mg/L.

2. Unfortunately, the FBR was not able to meet non-detect ClO_4^- levels at the small bench scale. This resulted from a variety of upset conditions, and it is believed, from difficulties in testing FBR technology at this small scale.

3. However, US Filter notes that documented historical data indicate that non-detect effluent ClO_4^- levels would easily be achieved using larger scale equipment.

4. The biological treatment process for ClO_4^- is well understood, and is essentially identical to the denitrification process. US Filter has over 70,000,000 gallons of water being denitrified every day with FBR technology, and thus have a proven track record of years of field operation with proven robustness.

UCR Studies

1. Results suggest that JPL groundwater is treatable to non-detect ClO_4^- concentrations in the PBR/*perc1ace* system with a residence time as low as 0.4 hours.

2. Influent acetate (energy source) concentrations of less that 500 mg/L and potentially less than 250 mg/L yielded non-detect effluent ClO_4^- levels, and relatively low acetate concentrations (in many cases less than 50 mg/L) were present in the effluent.

3. Nitrate is also removed in this system, and pH remains relatively constant during the process.

4. The need for addition of nitrogen as a nutrient is minimal.

5. Reduction of SO_4^2 was not observed.

6. Results preliminarily suggest that ClO_4^- and nitrate can be destroyed in primary and secondary RO rejectates by various inocula, and therefore, biological treatment of RO rejectates appears feasible.

7.0 REFERENCES

Foster Wheeler. 1999. Draft Feasibility Study Report for Operable Units 1 and 3: On-site and Off-Site Groundwater. Jet Propulsion Laboratory.

Herman, D. C. and W. T. Frankenberger, Jr. 1999. Microbial-Mediated Reduction of Perchlorate in Groundwater. J. Env. Qual. 27(4):750-754.

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APPENDIX A

US FILTER REPORT

U.S. FILTER WASTEWATER GROUP

Treatability Study
Conducted For

Foster Wheeler Environmental Corporation
611 Anton Boulevard, Suite 800
Costa Mesa, CA 92626

(Removal of Perchlorate from Groundwater using Reverse Osmosis and Biological Treatment)

August 11, 1999
Revised October 29, 1999
Report No. 53016

Submitted by:

U.S. Filter
1100 East Willow Street
Signal Hill, CA 90806

1.0 Introduction

USFilter Corporation (USFilter) was contracted by Foster Wheeler Environmental Corporation (Foster Wheeler) to conduct a laboratory treatability study on a representative groundwater sample from the Jet Propulsion Laboratory (JPL) site located in Pasadena, CA. The purpose of the study was to evaluate the feasibility of reverse osmosis (RO) and fluidized bed reactor (FBR) technologies in reducing the perchlorate (ClO_4^-) concentration in the groundwater to less than 4 micrograms per liter (ug/l). Perchlorate contamination is generally the result of the dissociation of ammonium perchlorate (in water), which is an oxidizer used in rocket fuels. The scope of evaluation included treatment of the groundwater with RO alone, with FBR alone and a scenario whereby the RO reject was treated by the FBR. The treatment approach involved using an RO at 80% recovery and treating the reject with a seawater RO to achieve a total of 90% recovery. However, due to the silica concentration in the sample, the recovery was reduced to 75% in the design to avoid a softening pretreatment requirement. All tests were performed at USFilter's laboratory located in Warrendale, PA. In-house performance was tracked using an ion-specific probe. All reported analyses were performed by Del Mar Analytical of Irvine, CA using EPA method 300.

2.0 Technology Descriptions

This section provides descriptions of the technologies applied during the treatability study.

2.1 Reverse Osmosis

Reverse osmosis was selected for evaluation due to anticipated economic feasibility, simplicity of operation, modular design flexibility, and robustness in removing not just the perchlorate, but other potential contaminants. RO filtration typically removes constituents down to less than 0.0001 microns in size. This makes it highly applicable for the removal of perchlorate. The RO technology involves forcing water, under greater than osmotic pressure, through a semi-permeable membrane from a solution of greater concentration to a lower concentration solution. Both cellulose acetate (CA) and thin film composite (TFC) membranes were evaluated.

2.2 Fluidized Bed Reactor

USFilter's fluidized bed reactor technology is an anoxic biological treatment process, which consists of a columnar reactor that optimizes biological treatment by employment of a bed media such as sand or granular activated carbon (GAC). The bed media serves as support material for biological growth. Water flows upward through the reactor at a sufficient velocity to expand and fluidize the bed. The design allows a large inventory of biomass to be maintained within the reactor while maximizing the contact between the microorganisms and the target contaminants. For perchlorate treatment, a carbon substrate and nutrients are added to the influent of the reactor.

3.0 Sample Description

Four hundred (400) gallons of samples was received on March 10, 1999. The sample was clear, colorless, and contained a few suspended fines.

A complete analysis of the as received sample is presented in Table 1

Table 1- "As Received" Sample

Parameter	Units	Results
Aluminum	(mg/l)	<0.008
Barium	(mg/l)	0.071
Calcium	(mg/l)	57.1
Iron	(mg/l)	0.01
Magnesium	(mg/l)	21.4
Manganese	(mg/l)	0.002
Potassium	(mg/l)	1.61
Silica	(mg/l)	33.1
Sodium	(mg/l)	25.3
Strontium	(mg/l)	0.401
pH		6.97
Conductance	um/cm	567
Ammonia	(mg/l)	<0.08
COD	(mg/l)	<10
Solids - Dissolved	(mg/l)	375
TOC	(mg/l)	<1.3
Turbidity	NTU	1
Alkalinity	(mg/l)	149
Chloride	(mg/l)	25.6
Nitrogen - nitrate	(mg/l)	14.8
Phosphate -0	(mg/l)	0.052
Sulfate	(mg/l)	50.1

4.0 Test Procedures

4.1 Reverse Osmosis Testing

Two stages of RO testing were performed in the initial testing phase. The first stage RO received untreated sample as a feed source. The second stage RO treated the reject stream from the first stage RO. Two separate reverse osmosis membranes were evaluated. Cellulose acetate (CA) and thin film composite (TFC). The cellulose acetate membranes are generally more stable in oxidizing environments, while the thin film composite membranes generally allow for lower levels of contaminant leakage. However, consultation with membrane suppliers indicates that the oxidation reduction potential (ORP) of the JPL sample is not considered sufficient to create problems with the membranes.

4.1.1 First Stage RO Tests

A single element 2.5" spiral wound membrane was used for testing. The RO module was a 2.5" diameter x 40" long element, fed by a centrifugal pump. A schematic of the system used for testing is presented in Figure 1. The following conditions apply to both tests:

Permeate recovery.....80%
Membrane flux.....13 GFD (gallons/day/sq. ft.)
Pretreatment.....none
Membrane surface area.....23 ft^2

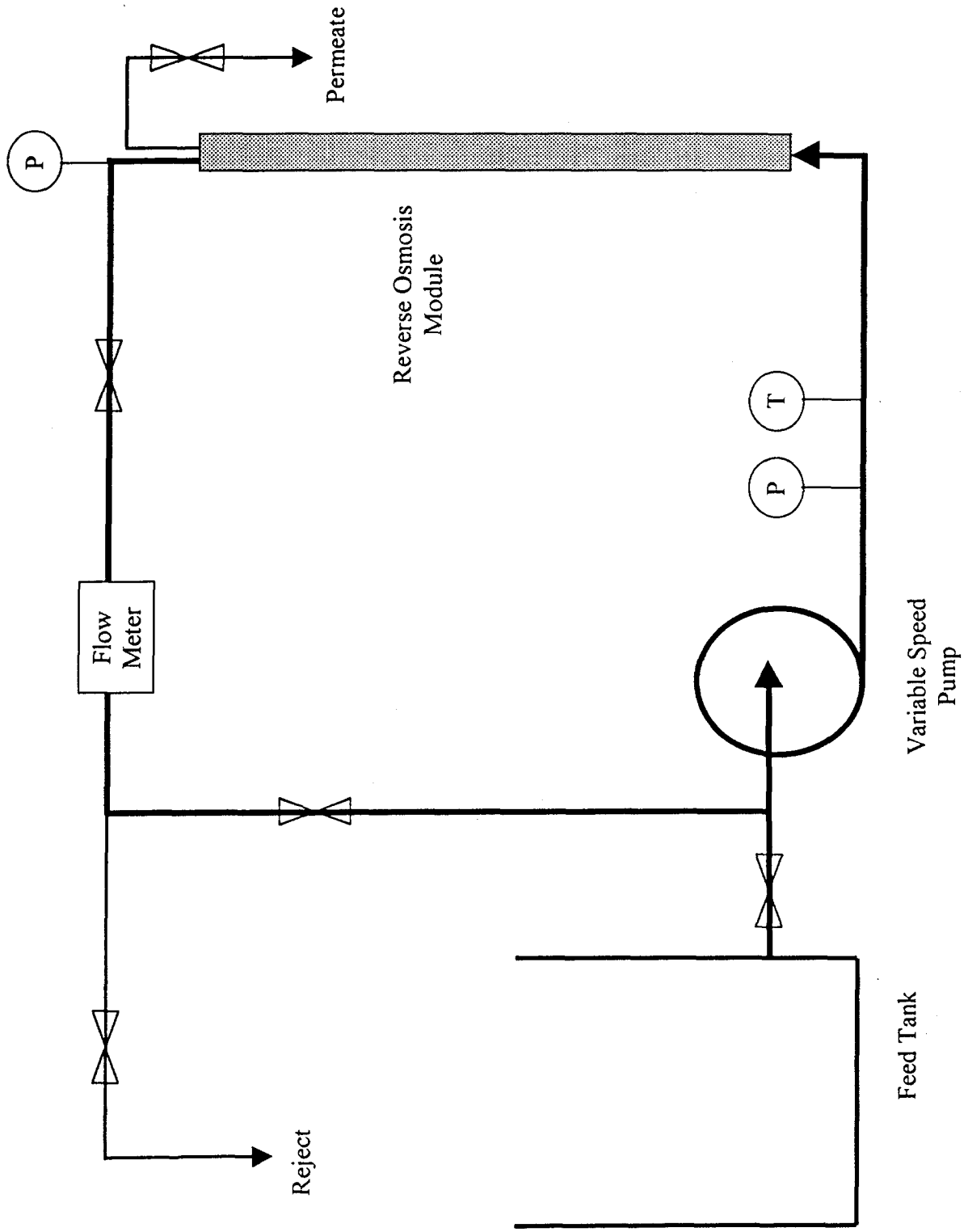
The permeate recovery and membrane flux were selected based upon historical experiences in treating similar wastewater samples. Both tests ran very well with respect to flux rates and pressure. Effluent quality from the TFC membrane was significantly superior to that obtained with the CA membrane. Data collected during these tests is presented in Table 2 (TFC) and Table 3 (CA).

4.1.2 Secondary Stage Tests (RO treatment of the First Stage Reject Stream)

The reject from each of the initial runs was further concentrated with a secondary stage RO. Because the samples were already concentrated once, a TFC seawater membrane was used for both tests. Both secondary concentration tests were conducted using the following conditions:

Membrane type .....2.5 inch seawater
Permeate recovery.....50%
Membrane flux.....10 GFD (gallons/day/sq. ft.)
Pretreatment.....none
Membrane surface area.....23 ft^2

Figure 1
Reverse Osmosis Schematic



It should also be noted that the volume of sample available for this test was relatively small, therefore making for a short run time (20 minutes).

Once again, both tests ran very well with respect to flux rates and pressure. The effluent quality for both runs was good. Data collected during these tests is presented in Table 4 (TFC) and Table 5 (CA).

4.1.3 Permeate Polish Using 2nd Pass RO

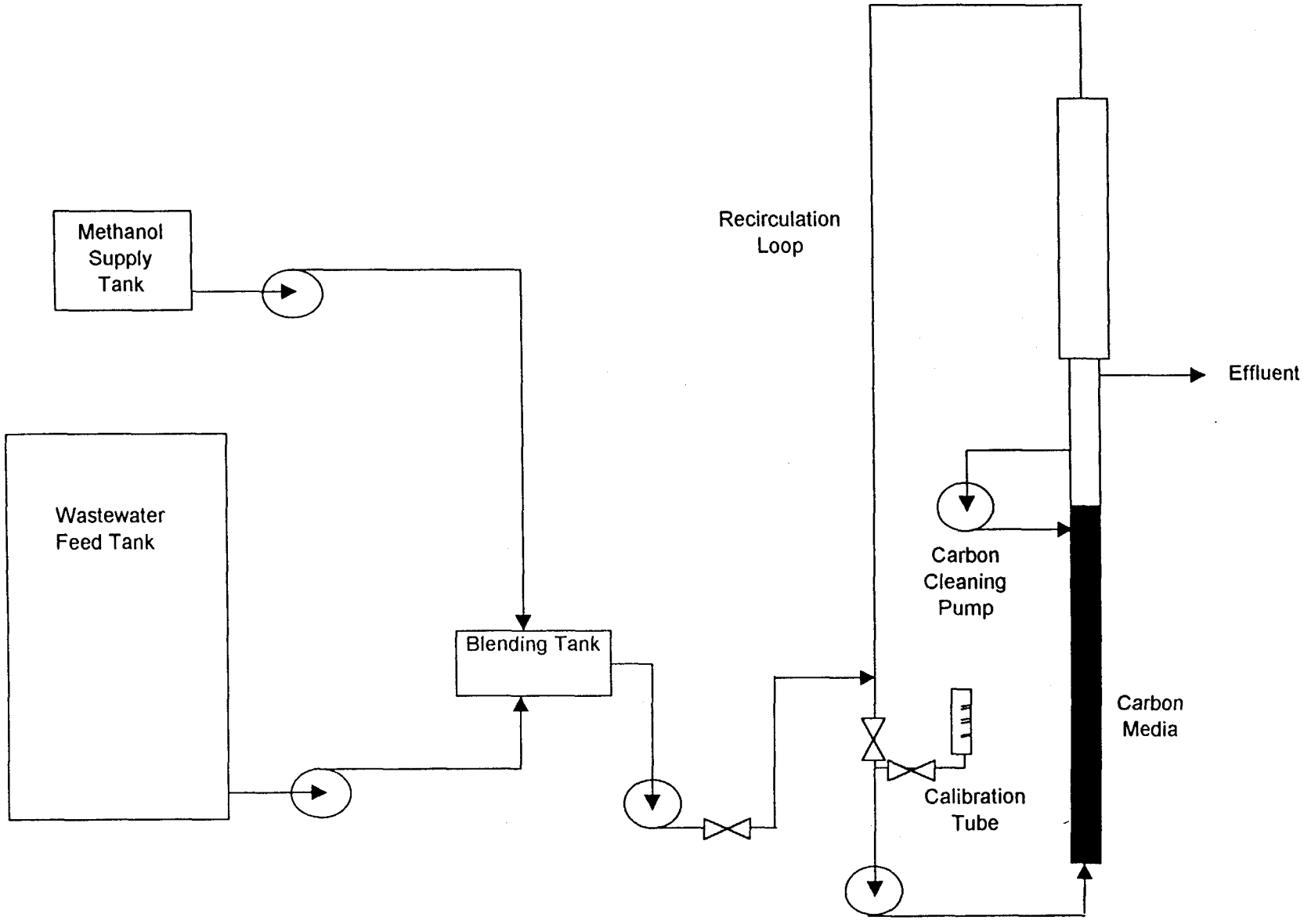
To assure that the perchlorate concentration could be reduced to below the detection limit of 4 ug/l, testing was performed using a second pass RO to treat the primary stage RO permeate. A RO permeate with perchlorate concentrations of 27 ug/l, 30 ug/l and 38 ug/l was fed to a TFC RO membrane in a 2.5" diameter x 40" long module. Three separate tests were performed with a 13 GFD flux rate and recovery rates of 80%, 85%, and 90% respectively.

4.2 Fluidized Bed Reactor Treatment

Biological studies require a relatively large volume of sample (20 gallons/day). To reduce shipping charges, the plan at the onset of the study was to prepare a synthetic waste stream having the same characteristics as the groundwater. This synthetic solution would be used to acclimate the fluidized bed reactor (FBR). Acclimation was expected to take several weeks. Once the system was fully acclimated and producing an acceptable quality effluent, actual feed would be used.

Unfortunately, due to test equipment malfunctions small-scale bench system, we were unable to produce the consistent high quality effluent (<4 ppb perchlorate) as has been demonstrated in other projects. These malfunctions are more an issue with small-bench scale biological systems that pilot plant or full-scale systems. However, it is important to note that treatment of perchlorate to the required levels using the FBR is easily achievable and well documented. This can easily be verified in a pilot test. Data is readily available that supports the applicability of the FBR system in reducing perchlorate in the groundwater sample.

Figure 2
Fluidized Bed Reactor Schematic



USFilter
UNITED STATES FILTER CORPORATION

4.3 Ion Exchange Polish of RO Permeate

As part of the assurance that the perchlorate concentration could be consistently reduced to below detection, ion exchange was used to polish the RO permeate. Two separate tests were performed. The first test was performed by running 180 bed volumes (BV) through a weak base anion resin. The second test was performed by running 180 BV through a strong base anion resin. The permeate for these tests contained 30 ug/l of perchlorate.

5.0 Results

5.1 Reverse Osmosis Results

Results of both the primary RO system and secondary RO membrane tests indicate that the TFC membrane is highly effective in removing perchlorate from the JPL sample. At the high recovery rate of 80%, the perchlorate was reduced to 12-16 ug/l in the first stage RO. In the second stage RO, the recovery rate was 50% and the perchlorate leakage was only 17 – 18 ug/l. This was especially encouraging since the RO testing approach US Filter takes on this type of bench scale work is to focus on the last element in the last stage of the RO train. This gives the worst case conditions for scaling and rejection, since the feed leaving the last element will be the most concentrated. In full-scale design, the product results will almost always be better than our test results because the permeate from the last element will be diluted by the permeate from the preceding elements. For example, typically a single stage RO with 6 elements in series would concentrate a feed by 50 %. Therefore, the permeate from the first element is seeing a feed 1/2 the strength of the permeate from the 6th element. The actual combined permeate quality is sum of the 6 elements. This becomes clear with the RO projection. The TDS out of the 6th element in the first stage of one our projections for this project was projected at 11 ppm TDS. The TDS out of the first element was projected at 5ppm TDS. The composite for all 6 elements was 8 ppm TDS. The perchlorate projections for a full scale unit would be directly analogous to this. This of course is impacted by the RO configuration.

Leakage was unacceptably high in the test using cellulose acetate (CA) membranes (~600 ppb). While analytical results of the second RO permeate indicate that the perchlorate concentration was reduced to below the detection limit of 4 ppb, this result does not correlate with the reject and feed results. Therefore, it is likely that these results are analytical anomalies.

To assure that the objective 4 ug/l concentration could be consistently be achieved, analyses were performed using a second pass RO membrane and ion exchange (anion) resin system to polish the RO permeate. For this test, a higher concentration permeate was used (30 ug/l of perchlorate) than was detected in our RO testing. Analytical results indicate that at 80% recovery, the perchlorate concentration was reduced to

below the detection limit of 4 ug/l. At 85% recovery, 4.2 ug/l of perchlorate was detected. At 90% recovery, only 4.3 ug/l was detected. While this indicates that perchlorate can easily be reduced to below detection with RO membranes, polishing the permeate with ion exchange was also evaluated and results are provided in Section 5.3 of this report.

Table 2
Primary ROTest - Thin Film Composite Membrane

Time (min)	Influent Pressure (psi)	Effluent Pressure (psi)	Reject Flow (ml/min)	Permeate Flow (ml/min)	Temp (F)	Permeate pH	Reject pH	Permeate Conductivity (uS)	Reject Conductivity (uS)	Permeate TDS (mg/l)	Reject TDS (mg/l)	Permeate Perchlorate (ug/l)	Reject Perchlorate (ug/l)
0	190	170	197	786	82	---	---	0	---	---	---	---	---
30	190	170	204	782	82	6.59	---	18.44	---	13	---	12	---
60	190	170	238	790	82	6.41	7.78	19.51	2123	41	1574	12	3400
90	190	170	200	780	82	6.21	---	22.17	---	32	---	15	---
120	190	170	186	780	82	6.13	7.88	20.52	2231	22	1618	14	3200
150	190	170	188	780	82	6.13	---	21.45	---	7	---	15	---
180	190	170	195	780	82	6.2	7.85	21.67	2242	34	1668	14	3700
210	190	170	200	780	82	5.79	---	22	---	6	---	15	---
240	190	170	200	780	82	5.86	7.71	22.79	2304	16	1719	16	4000
270	190	170	194	780	82	5.73	---	23.35	---	---	---	16	---
280	190	170	192	780	82	---	---	---	---	---	---	---	---

Thin film composite membrane
Membrane surface area = 23 ft^2
80% recovery
13 GFD (gallons / day / ft^2)

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Table 3
Primary RO Test - Cellulose Acetate Membrane

Time (min.)	Infuent Pressure (psi)	Effluent Pressure (psi)	Reject Flow (ml/min)	Permeate Flow (ml/min)	Temp (F)	Permeate pH	Reject pH	Permeate Conductivity (uS)	Reject Conductivity (uS)	Permeate TDS (mg/l)	Reject TDS (mg/l)	Permeate Perchlorate (ug/)	Reject Perchlorate (ug/l)
0	210	180	198	790	80	---	---	---	---	---	---	---	---
30	200	175	250	800	82	5.64	---	104.3	---	92	---	650	---
60	200	175	197	790	82	5.73	7.29	114.4	1926	118	1424	670	1600
90	200	175	186	786	84	5.78	---	134	---	123	---	680	---
120	200	175	210	780	84	5.86	7.59	129	1990	109	1347	660	---
150	205	180	186	775	84	5.86	---	137	---	120	---	650	---
180	205	180	188	790	84	5.74	7.45	137.4	2084	109	1518	640	1600
210	205	180	188	790	84	5.7	---	137.5	---	117	---	650	---
240	205	180	190	788	84	5.91	7.41	137.2	2093	125	1526	650	1600
270	205	180	188	785	84	5.87	---	135.2	---	127	---	650	---

Cellulose acetate membrane
Membrane surface area = 23 ft^2
80% recovery
13 GFD (gallons/day/ft^2)

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Table 4
Secondary RO Test - TFC Reject

Time (min)	Influent Pressure (psi)	Effluent Pressure (psi)	Reject Flow (ml/min)	Permeate Flow (ml/min)	Temp (F)	Permeate pH	Reject pH	Permeate Conductivity (uS)	Reject Conductivity (uS)	Permeate TDS (mg/l)	Reject TDS (mg/l)	Permeate Perchlorate (ug/l)	Reject Perchlorate (ug/l)
0	230	200	600	620	85	--	--	--	--	--	--	--	--
5	230	200	630	630	84	--	--	--	--	--	--	--	--
10	230	200	610	610	85	6.29	7.67	17.58	3,072	5	2,795	17	7,900
15	230	200	620	610	85	--	--	--	--	--	--	--	--
20	230	200	610	610	85	6.2	7.74	16.84	3,110	<5	2,901	18	7,800
25	230	200	610	620	85	6.14	6.14	18.08	--	37	--	17	--

Thin film composite membrane (seawater)
Membrane surface area = 23 ft^2
50% recovery
10 GFD (gallons / day / ft^2)

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Table 5
Secondary RO Test - CA Reject

Time (min.)	Influent Pressure (psi)	Effluent Pressure (psi)	Reject Flow (ml/min)	Permeate Flow (ml/min)	Temp (F)	Permeate pH	Reject pH	Permeate Conductivity (uS)	Reject Conductivity (uS)	Permeate TDS (mg/l)	Reject TDS (mg/l)	Permeate Perchlorate (ug/)	Reject Perchlorate (ug/l)
0	230	200	605	605	80	--	--	--	--	--	--	--	--
5	230	200	630	620	83	--	--	--	--	--	--	--	--
10	220	195	620	630	83	5.95	7.91	12.1	2303	29	1,897	<4	390
15	220	195	630	610	83	--	--	--	--	--	--	--	--
20	220	195	620	610	83	5.91	7.87	12.3	2345	21	1,885	<4	380
25	220	195	620	610	83	6.12	--	13.3	--	--	--	<4	--

Thin film composite membrane (seawater)
Membrane surface area = 23 ft^2
50% recovery
10 GFD (gallons / day / ft^2)

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5.2 Fluidized Bed Reactor Results

The FBR was able to produce an effluent containing less than 100 ppb of perchlorate for several days at a time. Unfortunately this high quality effluent was not sustainable for longer periods of time. This was due to mechanical and operational problems related to the scale of the laboratory study (pump failures, plumbing leaks, and accidental chemical overdose). This is not due to the applicability of the technology.

Documented historical data indicates that consistent effluent would be achieved using larger scale equipment and more continuous monitoring (the lab system was monitored only during the day shift).

A bench study currently underway is running on actual site water. The raw feed has between 300 and 400 mg/l of perchlorate, 25 mg/l of nitrate nitrogen, and a TDS of 11,000 mg/l. Two reactors are operating, FBR #1 is at a loading of 600 lbs COD/D/1000cu.ft. This is equivalent to 130 lbs NO3-N/D/1000 cu.ft. FBR #2 is at a loading of 440 lbs COD/D/1000 cu. ft. COD and NO3-N loading rates are on the design summaries. We operate denitrification systems at two to three times these loading rates. Additional IC data is pending, however, using a specific ion electrode, we are maintaining very low perchlorate levels out of the stage 1 reactor.

5.3 Permeate Polish

After initial testing, RO permeate samples containing perchlorate concentrations of 27 ug/l, 30 ug/l and 38 ug/l were treated with ion exchange. Each of these three samples were split and half was treated with a weak base resin and the other half with a strong base resin. Results indicate that for each sample, the perchlorate was reduced to below the detection limit of 4 ug/l for both the weak base and for the strong base resins.

Table 6
FBR - Influent and Effluent Analysis

Date	Influent Nitrate (mg/l)	Effluent Nitrate (mg/l)	Influent Nitrite (mg/l)	Effluent Nitrite (mg/l)	Influent P (mg/l)	Effluent P (mg/l)	Influent COD (mg/l)	Effluent COD (mg/l)	Influent ClO4 (mg/l)	Effluent ClO4 (mg/l)	Influent Sulfate (mg/l)	Effluent Sulfate (mg/l)	Comments (see last pg)
03/03/99	---	---	---	---	---	---	---	---	1.2	0.5	---	---	
03/05/99	---	---	---	---	---	---	62	26	1	0.4	---	---	
03/06/99	---	---	---	---	---	---	52	19	0.8	0.5	---	---	
03/07/99	---	---	---	---	---	---	47	15	0.9	0.35	---	---	
03/08/99	---	---	---	---	---	---	67	13	0.8	0.4	---	---	
03/09/99	---	---	---	---	---	---	44	14	---	---	---	---	
03/10/99	---	---	---	---	---	---	60	13	0.7	0.4	---	---	
03/11/99	---	---	---	---	---	---	49	12	0.6	0.3	---	---	
03/12/99	---	---	---	---	---	---	47	14	0.9	0.5	---	---	
03/13/99	---	---	---	---	---	---	52	8	1	0.5	---	---	
03/14/99	---	---	---	---	---	---	48	11	1.1	0.4	---	---	
03/15/99	22	0.22	0.9	0.3	0.62	0.48	---	---	1.1	0.45	---	---	
03/16/99	24	0.2	---	---	---	---	40	11	1	0.3	---	---	
03/17/99	27	0.2	0.9	0.2	0.7	0.4	37	8	1	0.3	---	---	
03/18/99	---	---	---	---	---	---	---	---	---	---	---	---	
03/19/99	25.0	0.2	0.3	0.1	0.5	0.3	42	9	1.1	0.25	---	---	
03/24/99	37.4	5.6	11	4	0.92	0.70	37	7	1.2	1.0	85	78	(1)
03/25/99	---	---	---	---	---	---	47	8	---	---	---	---	
03/26/99	26.5	0.4	6	< 1	0.75	0.35	42	6	1	0.4	80	68	
03/29/99	---	19.8	---	18	---	1.83	24	< 1	2.4	0.5	---	100	
03/30/99	---	---	---	---	---	---	---	< 1	---	---	---	---	
03/31/99	---	15.8	---	35	---	2.22	---	< 1	---	0.4	---	116	
04/01/99	---	---	---	---	---	---	---	< 1	---	---	---	---	
04/02/99	35.6	2.9	22	13	---	1.00	---	< 1	1.1	0.20	---	92	
04/03/99	---	---	---	---	---	---	---	< 1	1.1	0.19	---	---	
04/05/99	25.5	0.4	15	8	1.40	1.20	---	< 1	1.3	0.14	---	98	
04/06/99	---	---	---	---	---	---	---	---	---	---	---	---	
04/07/99	---	0.4	12	5	---	0.9	29	< 1	1.2	0.18	---	105	
04/09/99	22.0	< 0.2	12	10	1.2	0.4	39	<1	1.2	0.1	118	96	
							Del Mar Labs (4-9-99):			0.023			
04/10/99	---	---	---	---	---	---	---	---	---	---	---	---	
04/12/99	30.8	0.9	---	---	1	0.6	37	< 1	1.4	0.1	140	110	(2)
04/13/99	---	---	---	---	---	---	---	---	1.6	0.09	---	---	(3)

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Table 6
FBR - Influent and Effluent Analysis

Date	Influent Nitrate (mg/l)	Effluent Nitrate (mg/l)	Influent Nitrite (mg/l)	Effluent Nitrite (mg/l)	Influent P (mg/l)	Effluent P (mg/l)	Influent COD (mg/l)	Effluent COD (mg/l)	Influent ClO4 (mg/l)	Effluent ClO4 (mg/l)	Influent Sulfate (mg/l)	Effluent Sulfate (mg/l)	Comments (see last pg)
04/14/99	18.5	0.9	---	---	0.8	0.55	52	12	1.2	0.1	122	108	
04/15/99	---	---	---	---	---	---	---	---	0.9	0.1	---	---	
04/16/99	21.1	1.3	---	---	0.87	0.55	58	10	1.1	0.11	140	128	
						Del Mar Labs (4-16-99):			1.8	0.17			
04/18/99	18.5	< 1	---	---	0.80	0.6	---	---	1.2	< 0.10	140	128	
04/19/99	19.3	< 1	---	---	0.87	0.55	59	12	1.2	< 0.10	140	136	
04/21/99	27.3	0.9	---	---	0.87	0.55	62	8	1.35	0.1	160	140	
04/22/99	---	---	---	---	---	---	---	---	1.3	0.2	---	---	
04/23/99	19.3	< 1	---	---	0.90	0.6	55	13	1	< 0.1	155	135	
						Del Mar Labs (4-23-99):				0.19			
04/24/99	---	---	---	---	---	---	---	---	0.9	< 0.1	---	---	
04/25/99	---	---	---	---	---	---	---	---	1.4	0.13	---	---	
04/26/99	18.9	1.2	---	---	0.75	0.5	60	18	0.9	< 0.1	130	120	
04/27/99	---	---	---	---	---	---	---	---	0.8	< 0.1	---	---	
04/28/99	18.9	0.2	---	---	0.80	0.65	62	12	0.9	< 0.1	130	120	
04/29/99	---	---	---	---	---	---	---	---	0.9	< 0.1	---	---	
						Del Mar Labs (4-29-99):				0.23			
04/30/99	18.5	0.9	---	---	0.80	0.6	63	14	1.1	0.1	130	110	
05/01/99	---	---	---	---	---	---	56	13	1.1	< 0.1	---	---	
05/02/99	---	---	---	---	---	---	58	12	1	< 0.1	---	---	
05/03/99	17.6	1.0	---	---	0.80	0.6	60	18	1.3	0.16	130	120	
05/04/99	---	---	---	---	---	---	65	14	1	< 0.1	---	---	
						Del Mar Labs 5-4-99):				<0.004			
05/05/99	--	0.9	--	13.0	--	1.1	62	9	1	0.5	--	< 0.1	
05/06/99	--	--	--	--	--	--	60	15	1.2	< 0.1	--	--	
05/07/99	--	0.6	--	14.0	--	0.96	60	6	--	< 0.1	--	< 0.1	
05/10/99	--	< 0.10	--	17.0	--	2.56	--	--	1.1	<0.1	--	70	
05/11/99	---	---	---	---	---	---	269	230	1.3	1.2	--	--	(4)
05/12/99	---	---	---	---	---	---	---	---	1.2	1.2	---	---	
05/13/99	---	---	---	---	---	---	---	---	1.2	1.2	---	---	
05/14/99	---	---	---	---	---	---	---	---	1.2	1.2	---	---	
05/15/99	---	---	---	---	---	---	---	---	1.2	1.2	---	---	
05/16/99	---	---	---	---	---	---	---	---	1.2	1.2	---	---	

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FBR - Influent and Effluent Analysis

Date	Influent Nitrate (mg/l)	Effluent Nitrate (mg/l)	Influent Nitrite (mg/l)	Effluent Nitrite (mg/l)	Influent P (mg/l)	Effluent P (mg/l)	Influent COD (mg/l)	Effluent COD (mg/l)	Influent ClO4 (mg/l)	Effluent ClO4 (mg/l)	Influent Sulfate (mg/l)	Effluent Sulfate (mg/l)	Comments (see last pg)
05/17/99	18.5	19.8	15	15	2.3	1.6	18	6	1.1	1.1	75	70	
05/18/99	18.5	2.6	15	14	1.7	1	24	6	1.1	0.9	---	---	
05/19/99	18.5	1.1	15	11	1.7	0.9	55	6	1.1	0.7	75	68	
05/20/99		--	--	--	--	--	--	--	--	--	--	--	
05/21/99	18.0	0.9	15	<1	1.7	0.8	63	9	1.2	0.2	70	70	
05/22/99	---	0.9	---	---	---	0.8	---	12	---	0.25	---	---	
05/23/99	---	0.9	---	---	---	0.7	180	24	---	0.3	---	---	
05/24/99	17.6	1.3	---	<1	---	0.8	40	10	1.1	0.2	---	42	
05/25/99	---	1.3	---	---	---	---	58	21	1.1	0.2	---	---	
05/26/99	18.9	0.9	---	<1	2.3	1.8	48	13	1.1	0.15	34	26	
05/27/99	---	---	---	---	---	---	40	10	1.1	0.1	---	---	
05/28/99	20.2	0.4	---	<1	1.6	1.2	42	10	1	0.1	62	60	
06/02/99	---	6.6	---	11	---	2.02	116	< 1.0	1.2	0.5	---	1	(5)
06/03/99	---	4.8	---	17	0.3	1	110	< 1	1.2	1.1	---	2	
06/04/99	17.6	12.8	18	14	---	---	110	< 1	1.2	1.1	36	3	
06/06/99	17.6	17.2	---	---	---	---	80	35	1.2	0.95	36	3	
06/07/99	18.2	13.2	3	6	1.6	1.58	90	44	1.2	0.88	44	40	
06/09/99	18.2	3.1	---	---	1.6	1.4	95	22	1.2	0.25	44	42	
06/10/99	18.2	1.32	---	---	1.6	1.2	80	18	1.2	< 0.1	44	25	
06/14/99	19.2	0.88	---	---	1.9	1.25	65	10	1	0.09	71	36	
							Del Mar Labs 6-14-99:		0.69	0.033			
06/15/99	---	0.88	---	---	---	---	60	10	1	< 0.1	---	---	
06/16/99	---	0.88	---	---	---	---	65	14	1	< 0.1	---	---	
06/17/99	---	0.66	---	---	---	---	60	18	1	< 0.1	---	---	
06/21/99	---	0.44	---	---	1.1	0.9	--	--	1.1	< 0.1	---	---	
06/22/99	---	0.44	---	---	1.1	1	--	--	1.1	< 0.1	---	---	
06/23/99	--	5.72	--	<1	--	0.22	--	---	--	0.15	--	1	(6)
06/24/99	--	---	--	---	--	---	--	---	--	0.24	--	---	
06/25/99	--	3.96	--	1	--	1.18	--	<1	--	0.38	--	<1	
06/28/99	--	9.24	--	---	--	---	--	<1	--	1	--	---	
06/29/99	--	13.2	--	---	--	---	--	8	--	1.2	--	---	
06/30/99	--	12	--	1	--	1.89	--	7	--	1.4	--	53	
07/06/99	0.1	4.1	1	0.1	0.1	2.2	111	<1	1.5	0.6	46	20	

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FBR - Influent and Effluent Analysis

Date	Influent Nitrate (mg/l)	Effluent Nitrate (mg/l)	Influent Nitrite (mg/l)	Effluent Nitrite (mg/l)	Influent P (mg/l)	Effluent P (mg/l)	Influent COD (mg/l)	Effluent COD (mg/l)	Influent ClO4 (mg/l)	Effluent ClO4 (mg/l)	Influent Sulfate (mg/l)	Effluent Sulfate (mg/l)	Comments (see last pg)
07/07/99	---	0.6	---	0.3	---	4.1	22	<1	1.5	1.1	---	---	
07/08/99	---	0.3	---	---	----	----	--	--	1.5	0.7	----	---	
07/09/99	6.1	0.2	---	0.2	---	2.9	--	--	1.3	0.5	---	10	
07/10/99	--	--	--	--	--	--	---	---	---	0.4	---	---	
07/11/99	--	--	---	---	---	3	---	---	---	0.4	---	---	
07/12/99	--	--	---	---	---	--	--	--	1.8	0.25	---	---	
07/13/99	---	---	---	---	---	---	69	<1	---	---	---	---	
07/15/99	4.9	1.8	---	---	---	2.8	94	<1	1.2	0.4	--	--	
07/16/99	4.8	1	---	---	---	2.8	56	<1	1.2	0.3	--	--	
07/18/99	--	--	---	---	---	---	55	4	1.4	0.2	--	--	
07/19/99	4.6	0.7	---	---	0.09	0.35	--	--	1.4	0.2	---	---	
07/20/99	--	1.8	--	--	--	--	--	--	--	1	--	--	
07/21/99	--	0.5	--	--	--	--	--	--	--	---	--	---	
07/23/99	--	1.3	--	--	--	0.53	--	<1	--	0.8	--	4	
07/26/99	--	4.2	--	--	--	0.4	--	<1	--	0.6	--	3.5	
07/28/99	--	2.9	--	--	--	0.45	--	<1	--	0.3	--	2.9	
07/29/99	--	3.3	--	--	--	---	--	---	--	0.2	--	---	
07/30/99	--	2.5	--	--	--	---	8	9	--	0.8	---	--	
08/02/99	2.6	2	--	--	0.45	0.41	8	2	1.05	1	<0.1	<0.1	

Notes

(1) Overnight leak in tubing
(2) Increase methanol dosage to increase COD by 5 mg/l
(3) Begin nitrogen purge of feed tank to insure low DO in system
(4) Feed was prepared using acidic water (anionic portion of mixed bed resin used to prepare feed was spent) The cannister was changed and the reactor re-seeded.
(5) Problems with MeOH feed pump. Redesigned system to ensure better blending and more consistent feed.
(6) Accidently added sodium carbonate instead of sodium bicarbonate for pH adjust

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6.0 Conclusions and Recommendations

It is well known in the industry that biological treatment of perchlorates is the most economical approach. However, when the treated water is intended for drinking water supply, acceptance of biologically treated water is currently not approved by the regulatory agencies. Therefore, US Filter has devised with Foster Wheeler the conceptual design that utilizes RO to reduce the perchlorate and act as additional barrier to other unidentified species. The approach of the testing was to be aggressive as far as achieving a high rate of recovery. It is important to note that in a full-scale system design, lower recovery rates would be recommended to assure minimal maintenance. This is especially true should the silica concentrations in the groundwater be as high as detected in the sample. In any event, the results of the testing indicate that this approach provides treated water of such high quality that numerous options for reuse are possible. These options include cooling tower makeup, boiler feed water, and drinking water.

The test results indicate that 800 ug/l of perchlorate detected in the JPL groundwater can be reduced to below the detection limit of 4 ug/l using either a two-pass RO or a RO with an anion resin ion exchange polish. Further, the TFC membrane will produce quite low perchlorate leakage as a primary RO with a recovery rate of 80% and a flux rate of 13 GFD. When the reject from the first stage RO is treated by a second stage seawater TFC RO, 50% of the first stage reject can be recovered with negligible increase in permeate perchlorate concentration. This results in approximately 90% recovery of the total groundwater flow. However, the limiting factor in RO recovery is the influent silicon concentration. Typically elevated silicon concentrations can create scaling problems unless calcium and magnesium are essentially completely removed by ion exchange or dispersants (anit-scalents) are added. Based upon our influent silica concentration of 33.1 mg/l, the silica in the reject of the primary RO at 80% recovery is approximately 165 mg/l. This concentration is greater than the solubility and would result in scaling. While dispersant manufacturers such has Argo have developed anti-scalant chemicals that can prevent scaling with silica concentrations in excess of 300 mg/l, the reject from the secondary RO system would be 330 mg/l (based upon a 50% recovery). Certainly the desired recovery should be taken into consideration vs. pretreatment and maintenance requirements in the full-scale system design.

The final RO reject would then be treated by the FBR, which would reduce the perchlorate to below the sewer discharge limit. It is important to note that our approach to the overall treatment of the RO reject is anoxic and denitrification is required because of the 260 ppm of nitrate nitrogen detected and only 8 mg/l of perchlorate detected in the RO reject. This level of nitrate will create a significant design challenge should an anaerobic reactor be applied. The organic carbon addition required for treating 8 mg/l of perchlorate is highly insufficient to sustain the required anaerobic reaction, meaning that significant excesses will need to be wasted and later treated in order to sustain the reaction. The large levels of nitrate nitrogen actually drive the reactor ORP or reductive environment the wrong direction for true anaerobes.

USFilter has over 70,000,000 gallons of water being denitrified every day with FBR technology and our experience and reliability is unsurpassed on large scale. The two largest plants include Reno/Sparks NV (over ten years of continuous operation), and Stockholm Sweden. Both of these are good references and welcome visitors. There is also a very large system in a Dupont facility in Singapore.

USFilter's FBR system offers many significant advantages over alternative biological systems. These advantages are provided below:

- First, we have years of experience providing large-scale reliable systems. There is nothing in our conceptual design that does not exist on the denitrification process, thus the system we are offering has a proven track record of years of field operation with proven robustness.
- The biology is a consortium of microorganisms that want to grow in this type of environment. This is not a special seed or single organism that has to be pampered to perform.
- The FBR system operates at ambient temperatures, unlike alternative anaerobic systems that must heat reactors to 25° - 35°C.
- The excess organic feed necessary to drive the perchlorate to below detection with the FBR is not as excess as is typical of an anaerobic process. BOD exiting the FBR reactors can be reduced in a simple post aeration tank. Other systems can require complete activated sludge plants to eliminate excess BOD and results in large sludge disposal costs.

The FBR systems are high rate systems and result in the smallest footprint possible.

To assure consistent supply of treated water with a concentration less than 4 ug/l, an anion ion exchange system is recommended. This is an effective resin that has been proven in these tests to reduce concentrations (greater than those detected in the test RO permeate) to less than 4 ug/l. The resin can either be regenerated on-site or collected and regenerated off-site by US Filter. If treated on-site, the regenerant would be pumped to the FBR for perchlorate destruction.

Assuming 90% recovery (80% by the first stage and 50%by the second stage) and a permeate concentration of 17 ug/l, the ion exchange resin would only have to remove less than 0.13 lbs of perchlorate per day. If the design involves a single RO stage and a 75% recovery, the ion exchange resin would treat 0.107 lbs of perchlorate per day. With the high purity of the RO permeate, very little competing ions will contribute to the IX loading. This results in significantly high efficiency. A further benefit is the variety of uses the high purity water affords. For drinking water application, the water would flow to a calcite filter to add necessary minerals.

It is important to note that these are conceptual designs. While the results of the laboratory testing and historical data indicate both performance and economic feasibility of the RO system and Ion Exchange systems, it is recommended that a pilot study be performed to confirm the design of the FBR system. US Filter can provide the equipment and personnel to perform such a verification pilot testing and provide a full-scale system economical and performance guarantee.

7.0 Conceptual Full-Scale System Design Based Upon 700 GPM

Based upon the analytical results of the groundwater sample from JPL and the results of the treatability study, a 75% recovery system is recommended to easily control scaling and reduce cleaning and maintenance. This is not to say that a higher recovery can not be achieved. However, dispersant usage, cleaning frequency and membrane life should all be factored when considering higher recovery rates. The recovery of the permeate is highly dependent upon the effectiveness of the dispersants applied and the adjustment of the pH prior to treatment.

7.1 System Description

The 75% recovery system provides a more conservative maintenance, chemical and pretreatment regimen than the 90% recovery approach that was proven achievable in the laboratory. The groundwater would be pretreated with a multimedia filter. This consists of three vessels with a capacity of 150 cubic feet each. These vessels are arranged in parallel. A chemical anti-scalant system shall be provided which includes two 100% chemical metering pumps with appropriate piping and fittings. The metering pumps are controlled by a 4-20 mA signal from a digital flow meter to pace the injection rate with the groundwater flow.

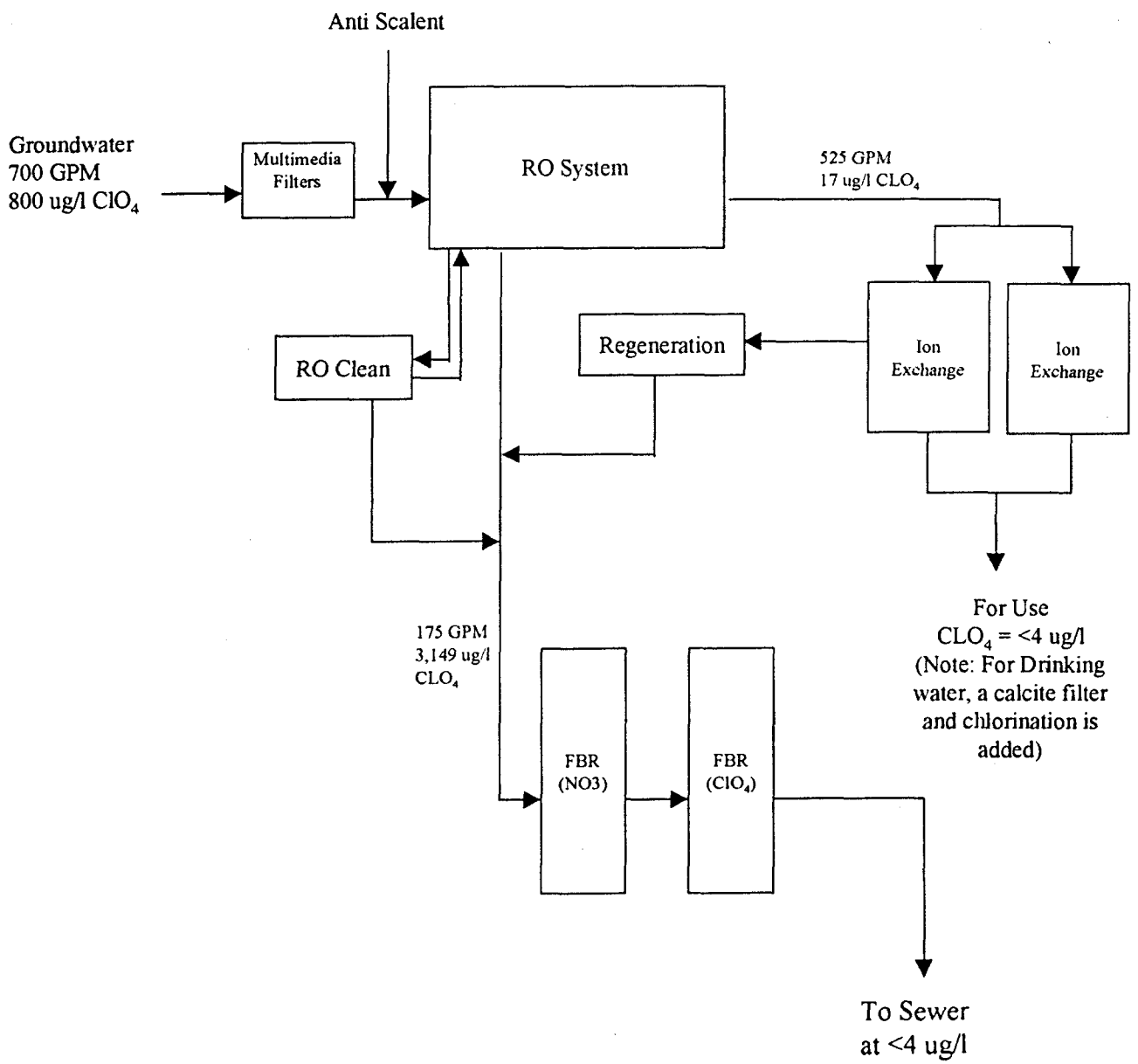
The RO system would be a single stage system consisting of two arrays. Each array shall consist of 14 pressure vessels, containing 6 membranes each for a total of 168 membranes. The permeate shall be pumped from the RO at a flow rate of 525 GPM and shall contain less than 20 ug/l of perchlorate. The permeate would then be pumped through a weak base anion resin to reduce any residual perchlorate to below the detection limit of 4 ug/l.

An RO membrane cleaning system is also included. This system includes a cleaning solution tank, pump, heater, and associated piping, valves and controls.

The ion exchange system would consist of 2 vessels (100%) with a capacity of 250 cubic feet each. The vessels would be arranged in a parallel configuration to allow for added assurance of perchlorate removal and to allow regeneration without cessation of operations. The system shall include a chemical regeneration system, pH neutralization system, and a pump skid to slowly bleed the regenerant to the reactor. Regeneration is expected to be required every 3-4 months based upon 24 hr/day operation.

The reject from the RO system shall flow at the rate of 175 gpm to the two-stage fluidized bed reactor system. As in the 90% recovery system, the FBR shall consist of a primary reactor designed to reduce the nitrates and a secondary reactor to reduce the perchlorates. It should be noted that the FBR design is based upon a Nitrate concentration of 26.7 mg/l as opposed to the concentration of 14.8 mg/l detected in the sample. The higher concentration was detected in earlier analyses by Foster Wheeler and is applied to make the design more conservative. The treated water shall contain less than 4 ug/l and flow to the sewer.

Figure 3
Jet Propulsion Laboratory
Conceptual Process Flow Diagram



8.0 Economics

This section provides a budgetary estimate of the costs of perchlorate treatment systems as described in Section 7.0 of this report. The costs are based upon a Build Own Operate Maintain (BOOM) contract whereby USFilter would install the treatment system, own the system and operate the system using USFilter employees. These cost estimates are based upon a 10 contract and assume that utilities, adequate space, any required shelter and civil engineering are provided by the client. Permits and sewer surcharges are not included.

The estimated contract price is $83,800 per month plus the variable charge of $0.24 per 1000 gallons treated.

APPENDIX B

UC RIVERSIDE REPORT

PERCHLORATE BIOTREATABILITY STUDIES: USE OF THE BACTERIAL ISOLATE "*Perc1ace*" IN A PACKED BED BIOREACTOR TO TREAT JPL GROUNDWATER AND SCREENING STUDY TO ASSESS POTENTIAL BIOTREATABILITY OF RO REJECTATES

1.0 INTRODUCTION

This report summarizes: (1) results of experiments conducted using a packed bed reactor (PBR) inoculated with a ClO_4^--reducing organism (*perc1ace*) isolated by W. T. Frankenberger Jr. of the University of California, Riverside, to treat JPL groundwater, and (2) results of the screening study to assess the potential for reducing ClO_4^- in RO rejectates.

Objectives

Experiments were conducted to address the following overall objectives:

1. Demonstrate process feasibility of the packed bed reactor/*perc1ace* for treatment of JPL groundwater and estimate several initial scale-up parameters.
2. Screen inocula with potential for reducing ClO_4^- in RO rejectates.

The objectives were addressed experimentally, as described below.

2.0 METHODOLOGY

2.1 Packed Bed Reactor Study-Treatment of Groundwater

A bench-scale PBR was set up at Dr. Frankenberger's facility [the Center for Environmental Microbiology (CEM)], with 200 gallon influent and effluent tanks. The PBR consisted of a cylindrical plexiglass column operated in an up-ward flow mode. The column specifications were as follows: total height: 21.4 cm; inside diameter: 13.5 cm; bed height: 12.5 cm; total volume: 3062 mL; total bed volume: 1789 mL; pore volume: 1236 mL. The reactor was contained in a controlled environment in which a temperature of 28°C was maintained (determined to be optimal for ClO_4^-- reduction by *perc1ace* in previous studies). A number of support media are available for PBRs, such as Celite, activated carbon, and sand. Celite (World Minerals Corporation, Lompoc, CA) was used for this study, based in part on the fact that Celite was used in Dr. Frankenberger's previous study, as well as in a PBR used to treat ClO_4^- wastewater at Tyndall AFB. A Master Flex 4S (Cole Parmer, Vernon Hills, Il.) peristaltic pump was used to deliver the influent feed to the reactor. The column was colonized with a perchlorate/nutrient/inoculum rich stream for approximately 3 weeks. The inoculum previously identified by Dr. Frankenberger, *perc1ace* (Herman and Frankenberger 1999), was used.

Once the column was effectively colonized (substantial reduction in ClO_4^- concentration demonstrated by ion-selective probe measurements of ClO_4^- in influent and effluent samples), actual JPL groundwater, collected from JPL monitoring well MW-16, was amended with nitrogen and phosphorous (as NH_4Cl and KH_2PO_4, respectively). The water was supplemented with sodium acetate as the energy source as determined in previous work (Herman and Frankenberger 1999). The acetate was delivered via an in-line feed pump, and fed into the reactor. We attempted to maintain the influent acetate concentration between 500 and 1,000 mg/L. Influent samples were collected daily, and effluent samples were collected at intervals of from 2-5 days. Samples were immediately frozen (to stop the reaction), and subsequently analyzed for ClO_4^- in-house, in accordance with (EPA Method 300.0, modified), by ion chromatography (IC) using a Dionex DX 500 instrument with an ASII column, with 100 mM NaOH eluent.

The general approach was to begin with a residence time that yielded non-detectable effluent ClO_4^- concentrations (based on prior experimentation), and incrementally increase the flow rate, thereby decreasing the residence time until breakthrough occurred. Flow rates and corresponding residence times that were ultimately evaluated are listed below:

Flow Rate, (mL/min)	Residence Time, (hr)
10	2.1
25	0.8
50	0.4
75	0.3
100	0.2

Influent and effluent samples were also periodically evaluated for other parameters, including pH (Accumet, Fisher Scientific); nitrate, sulfate, and acetate (Dionex ASII, 10 mM NaOH eluent); and ammonium-nitrogen (Technicon Auto Analyzer). A complete list of samples and analyses performed are provided in Appendix 1.

2.2 Biotreatment Laboratory Screening Study-Treatment of RO Rejectates

A screening level experiment was conducted to identify inocula capable of reducing ClO_4^- in liquid medium approximating the salt content of RO rejectates. This experiment was designed to provide an indication of the feasibility of biologically reducing ClO_4^- in primary RO rejectate (rejectate from RO treatment of groundwater) and secondary RO rejectate (rejectate from RO treatment of rejectate from groundwater treatment). This included testing the bacterium previously isolated by Dr. Frankenberger (perc1ace), and several new sources of inoculum from saline environments. Flasks containing 100 ml of simulated RO rejectates were inoculated, provided with a carbon source, and tested for a decrease in ClO_4^- concentrations as described below.

A total of twenty 250-ml Erlenmeyer flasks were set up (four different inocula, two feed concentrations, two carbon sources) at Dr. Frankenberger's facility. Inocula included *perc1ace*,

and sediments collected from saline environments including the Arroyo Seco, the Bolsa Chica Wetlands, and a water sample collected from salt evaporation ponds in Niger, Africa. The carbon sources included acetate and ethanol (0.5 g/L), and the two feed concentrations were formulated to simulate the electrical conductivity of a rejectate from RO of JPL water, and a rejectate from RO of rejectate, as described below.

It was initially estimated that the RO rejectate would contain salts elevated over the influent stream by a factor of five (20% rejection rate). Groundwater sampling results from JPL monitoring well MW-16, which is located in the contaminant source area, have shown total dissolved solids (TDS) of approximately 300 mg/L. Concentration of this water by a factor of five, would yield a rejectate with a TDS level of approximately 1500 mg/L. It was further estimated that this rejectate could be treated with RO to reject 50% of the original rejectate, yielding a secondary rejectate with a TDS concentration on the order of 3000.

The following empirical relationship can be used to estimate the electrical conductivity (EC) of a solution for which the TDS is known:

TDS (mg/L) ~ EC (dS/m) x 640 (Bohn et al., 1985).

Using this relationship, solutions with TDS levels of 1500 and 3000 mg/L would have EC values of approximately 2.3 and 4.6 dS/m, respectively. To be conservative, minimal salts medium, which contains all of the major ions present in JPL groundwater in relatively similar concentrations, was formulated to EC levels of 3.1 and 6.25 dS/m, which conservatively assumes an initial rejection rate of 15%. Following sterilization of the medium, the carbon sources were added, and ClO_4^- (as $NaClO_4$) was added at a standardized concentration of 100 mg/L. The flasks were flushed with dry N_2, capped, and incubated anaerobically for 2 weeks. ClO_4^- concentrations were measured at 1 and 2 weeks using a ClO_4^--selective probe.

It is noted that, although VOCs are present in JPL groundwater, they were not considered in this experiment (or subsequent experiments) because it is assumed that they will be removed prior to RO treatment. In addition, osmotic stress is assumed to be the major factor limiting cellular metabolism, and hence, ClO_4^--reduction. Because this was a screening level experiment to preliminarily assess ClO_4^- reduction with respect to general salt tolerance, it was not necessary to attempt to duplicate all ion concentrations in the simulated rejectates.

3.0 RESULTS AND DISCUSSION

3.1 Packed Bed Reactor Study-Treatment of Groundwater

Influent and effluent ClO_4^- and acetate concentrations for the various residence times over the duration of the groundwater experiment are shown in Figure 1. Influent ClO_4^- concentrations were generally measured between 700 and 800 μg/L, which is consistent with recent results of ClO_4^- analysis of water from MW-16, from which this water was extracted (Figure 1A). The first 15 days of the experiment evaluated residence times of 2.1 and 0.8 hours. Effluent ClO_4^-

concentrations were non-detect over this period with the exception of days 10 and 11, where the ClO_4^- levels were 13.6 and 4.25 μg/L, respectively.

Based on these results, the flow rate was increased incrementally, to evaluate residence times of 0.4 and 0.3 hours. For the remainder of the experiment, effluent ClO_4^- concentrations were below (or in a few cases, slightly above) the detection limit, with two exceptions (as noted in the following paragraphs), due to upset conditions involving dispensation of acetate.

On Day 15, the flow rate was increased such that the residence time was lowered to 0.4 hr. This necessitated changing out the acetate feed pump to accommodate the higher flow rate. Problems were initially encountered with the new pump, which interrupted the acetate flow to the column for several days. The problem was not detected until Day 19, at which time it was corrected. From Day 16 through Day 20, there was very little acetate in the system, (Figure 1B) and as a result, significant ClO_4^- breakthrough occurred over this period (Figure 1A). However, when acetate was re-supplied to the system, ClO_4^- concentrations dropped to below the detection limit for 5 of the next 6 days for which it was sampled. Although inadvertent, this upset condition verified that the observed ClO_4^--removal was coupled with utilization of acetate.

On Day 27, the flow rate was again increased, which decreased the residence time to 0.3 hr. This flow rate was maintained for only 3 days, due to the fact that the influent supply tank was nearly depleted. Over this period, ClO_4^- concentrations remained very low (non-detect or slightly above). Based on this result, a final flow rate increase was carried out on Day 31, which decreased the residence time to 0.2 hr. The ClO_4^- concentration was 18.6 μg/L, following one day at this flow rate, however, an acetate pump failure occurred on Day 32, and acetate was again absent from the system. It is therefore not clear whether the ClO_4^- breakthrough observed on Days 32, 33, and 34 would have occurred if acetate had been present in the system. At this point, the experiment was terminated due to exhaustion of the influent water supply.

Figure 2 depicts influent and effluent NO_3^- concentrations and pH values measured over the course of the experiment. Data presented in Figure 2A show that, as with as ClO_4^-, removal of NO_3^- was generally complete, with the exception of the periods where the acetate pump failed (refer to Figure 1). Influent pH values were between 7.0 and 7.6, which can generally be considered optimal for biological processes. Effluent pH values were generally between 7.0 and 8.0, indicating that the process did not appreciably influence pH.

Influent and effluent concentrations of ammonium (NH_4^+) (added as a nutrient) and sulfate (SO_4^{2-}) (naturally present in the groundwater) are presented in Figure 3. NH_4^+, which was added to the feed at a level of 20 mg/L, was consistently present in the effluent, and was therefore provided in excess (PO_4^{3-} was also added at a level of 6 mg/L, based on preliminary experiments, but was not tracked analytically in this study). This indicates that the amount of NH_4^+ can probably be reduced in future applications. Influent and effluent SO_4^{2-} concentrations were essentially the same, indicating that SO_4^{2-}-reduction did not occur in the reactor during this experiment.

3.2 Biotreatment Laboratory Screening Study-Treatment of RO Rejectates

Results of the screening study are presented in Table 1. This study was intended to provide an indication of whether ClO_4^--reduction in saline environments (approximating RO rejectates) would be feasible, with the secondary goal of obtaining a halotolerant, ClO_4^--reducing inoculum (or isolate) for potential future work in treating RO rejectates, were the need to arise. The data shown in Table 1 indicate that ClO_4^-- removal occurred in the saline solutions, to varying degrees, for all inocula tested. ClO_4^- concentrations in the control flasks remained virtually unchanged, and therefore observed removal can be attributed to the respective inoculum.

The inoculum/carbon source combination showing the most effective ClO_4^--removal in the solution where the EC was adjusted to 3.1 dS/m (simulated primary RO rejectate) were the Arroyo Seco Sediment/acetate, and *perc1ace*/acetate. In the solution where the EC was adjusted to 6.25 (simulated secondary RO rejectate), the Bolsa Chica Sediment/acetate, and *perc1ace*/acetate were the most efficient. These results indicate that ClO_4^--reducing bacteria that tolerate salinity in the range expected in RO rejectates are present in various environments, and inoculum is therefore obtainable. Importantly, this information does not allow for any conclusions regarding ClO_4^--reduction efficiency or rates in saline environments.

Based largely on these results, the *perc1ace* organism was retained for further experimentation to test the treatability of RO rejectates in the PBR (this was also based on the fact that initial characterization, including efficacy for use in the PBR system, had been carried out for this organism). It is noted, however, that the other inocula could contain organisms potentially more efficient in ClO_4^--reduction in saline environments than *perc1ace*, which could be determined in additional, shorter-term batch experiments.

4.0 CONCLUSIONS

The major conclusions of the studies described here are as follows:

Treatment of Groundwater

1. Results preliminarily suggest that JPL groundwater is treatable to non-detect ClO_4^- concentrations in the PBR/*perc1ace* system with a residence time as low as 0.4 hours.
2. Influent acetate (energy source) concentrations of less that 500 mg/L and potentially less than 250 mg/L yielded non-detect effluent ClO_4^- levels, and low acetate (in many cases less than 50 mg/L) were present in the effluent.
3. Nitrate is also removed in this system, and pH remains relatively constant during the process.
4. The need for addition of nitrogen as a nutrient is minimal.
5. Reduction of sulfate was not observed.

Potential Treatment of RO Rejectates

1. Results preliminarily suggest that ClO_4^- and nitrate can be destroyed in primary and secondary RO rejectates by various inocula, and therefore, biological treatment of RO rejectates appears feasible.

5.0 REFERENCES

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Figure 2. Influent and Effluent and Nitrate Concentration and pH, Groundwater PBR Study

Figure 3. Influent and Effluent Concentrations of Ammonium Nitrogen and Sulfate, Groundwater PBR Study

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Appendix 1. Summary of All Data Collected in PBR Groundwater Treatment Study

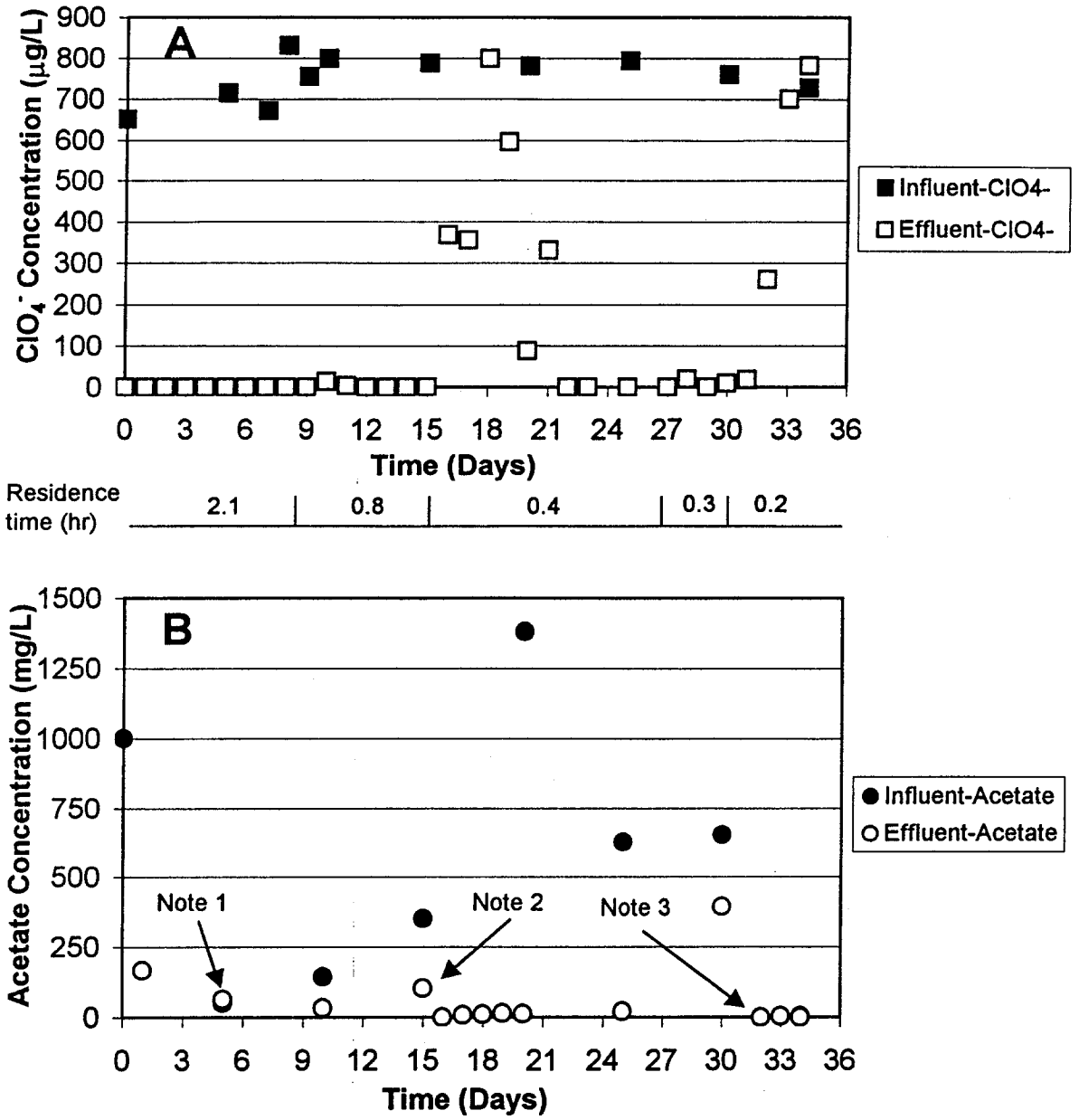
TABLE 1

REMOVAL OF ClO_4^- BY VARIOUS INOCULA IN FLASK STUDY TO PRELIMINARILY ASSESS BIOLOGICAL REDUCTION OF ClO_4^- IN AQUEOUS SALINE ENVIRONMENTS

(Initial ClO_4^- concentration was 100 mg/L)

Inoculum	Electrical conductivity of medium (dS/M)	Carbon source	ClO_4^- Removal, Day 7 (%)	ClO_4^- Removal, Day 14 (%)
Control (uninoculated)	3.1	Acetate	0	0
Control (uninoculated)	3.1	Ethanol	0	1.7
Control (uninoculated)	6.25	Acetate	1.7	1.7
Control (uninoculated)	6.25	Ethanol	0	1.7
Arroyo Seco Sediment	3.1	Acetate	99.5	98.9
Arroyo Seco Sediment	3.1	Ethanol	1.7	13.9
Arroyo Seco Sediment	6.25	Acetate	0	97.9
Arroyo Seco Sediment	6.25	Ethanol	1.7	0
Bolsa Chica Sediment	3.1	Acetate	57.6	99.1
Bolsa Chica Sediment	3.1	Ethanol	17.6	99.2
Bolsa Chica Sediment	6.25	Acetate	99.6	98.2
Bolsa Chica Sediment	6.25	Ethanol	27.9	98.8
Water, African Evaporation Ponds	3.1	Acetate	27.9	31.0
Water, African Evaporation Ponds	3.1	Ethanol	27.9	95.3
Water, African Evaporation Ponds	6.25	Acetate	10.0	21.2
Water, African Evaporation Ponds	6.25	Ethanol	10.0	17.6
Perclace	3.1	Acetate	98.9	99.6
Perclace	3.1	Ethanol	53.6	99.1
Perclace	6.25	Acetate	99.6	99.7
Perclace	6.25	Ethanol	55.6	99.4

Figure 1. Influent and effluent perchlorate (A) and acetate (B) concentrations, groundwater PBR study.



NOTES

1. Day 5: acetate feed pump failure. This was corrected shortly after influent sample was collected. Because acetate was present in the effluent samples, process efficiency was assumed to have not been effected.
2. Day 15: acetate feed pump was changed to accommodate increased reactor flow rate, problems with pump were initially encountered (see text, Sec. 3.1)
3. Day 32: acetate feed pump failure (see text, Sec.3.1).

Figure 2. Influent and effluent and nitrate concentration (A) and pH (B), groundwater PBR study.

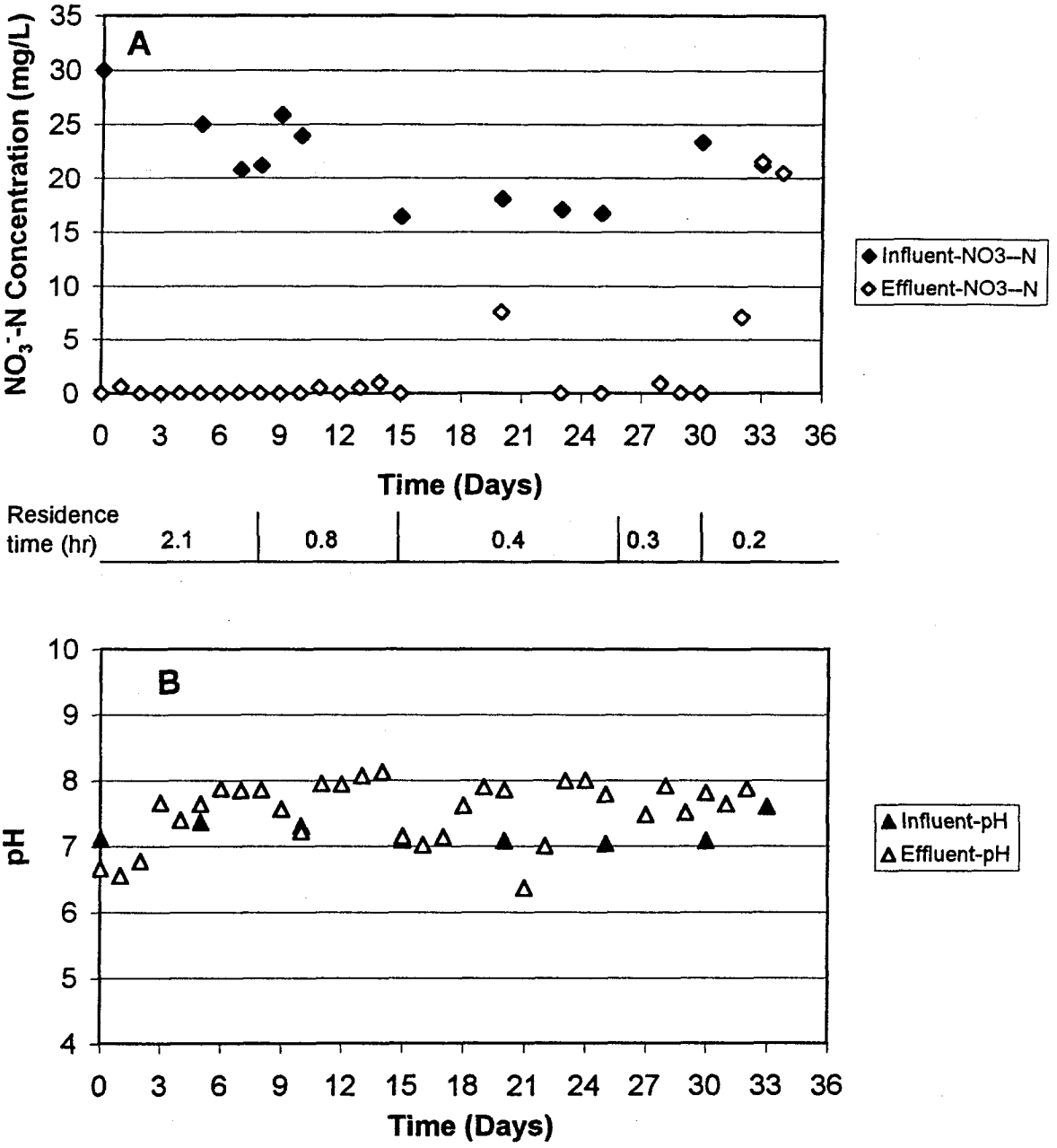
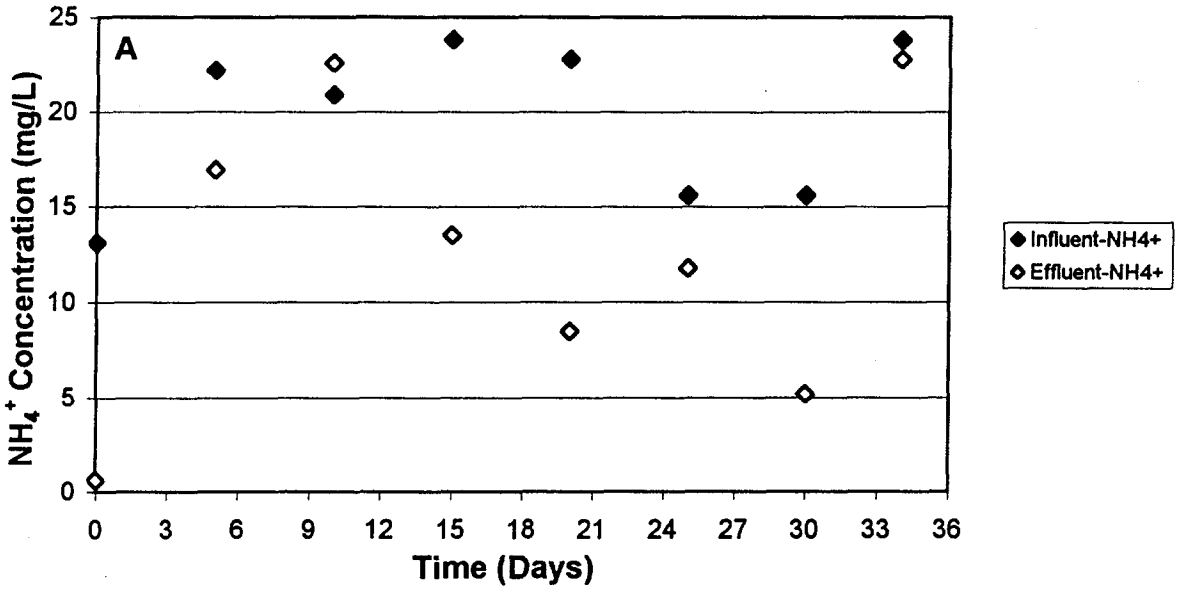
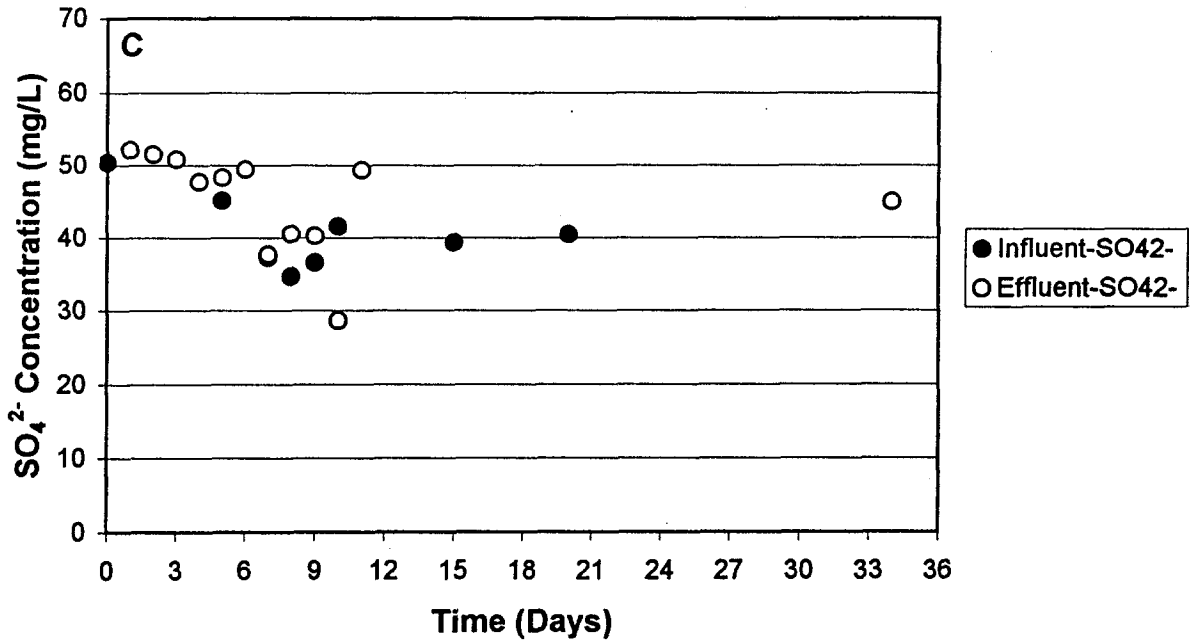


Figure 3. Influent and effluent concentrations of ammonium nitrogen (A) and sulfate (B), groundwater PBR study.





Notes:

1) Frequency of sulfate analyses was decreased after it had become apparent that sulfate reduction was not occurring to a measurable extent.

Summary of All Data Collected in PBR Groundwater Treatment Study

Sample #	Sample	Date	pH	Acetate mg/L	NO_3^--N mg/L^{-1}	SO_4^{2-} mg/L	ClO_4^- µg/L	NH_4^+-N mg/L
R1-0I	Influent	27-Apr	7.11	1.00E+03	30	50.4	650.1	13.1
R1-0E	Effluent	27-Apr	6.66	NA	ND	203.9	ND	0.62
R1-1E	Effluent	28-Apr	6.55	165.25	0.65	52.1	ND	NA
R1-2E	Effluent	29-Apr	6.77	NA	ND	51.5	ND	NA
R1-3E	Effluent	30-Apr	7.65	NA	ND	50.8	ND	NA
R1-4E	Effluent	1-May	7.39	NA	ND	47.7	ND	NA
R1-5I	Influent	2-May	7.36	51.1	25	45.1	714	22.2
R1-5E	Effluent	2-May	7.64	63.05	ND	48.3	ND	16.9
R1-6E	Effluent	3-May	7.87	NA	ND	49.4	ND	NA
R1-7I	Influent	4-May	NA	NA	20.8	37.2	671	NA
R1-7E	Effluent	4-May	7.84	NA	ND	37.6	ND	NA
R1-8I	Influent	5-May	NA	NA	21.2	34.6	830	NA
R1-8E	Influent	5-May	7.85	NA	ND	40.5	ND	NA
R1-9I	Influent	6-May	NA	NA	25.9	36.5	754	NA
R1-9E	Effluent	6-May	7.56	NA	ND	40.25	ND	NA
R1-10I	Influent	7-May	7.3	143.5	24	41.5	798	20.9
R1-10E	Effluent	7-May	7.22	32.1	ND	28.6	13.6	22.6
R1-11E	Effluent	8-May	7.95	NA	0.5	49.3	4.25	NA
R1-12E	Effluent	9-May	7.94	NA	ND	NA	ND	NA
R1-13E	Effluent	10-May	8.07	NA	0.5	NA	ND	NA
R1-14E	Effluent	11-May	8.13	NA	1	NA	ND	NA
R1-15I	Influent	12-May	7.08	350.77	16.4	39.3	787.3	23.8
R1-15E	Effluent	12-May	7.14	101.7	ND	NA	ND	13.5
R1-16E	Effluent	14-May	7.01	ND	NA	NA	368.24	NA
R1-17E	Effluent	15-May	7.13	7.5	NA	NA	355.9	NA
R1-18E	Effluent	16-May	7.61	10	NA	NA	797.64	NA
R1-19E	Effluent	17-May	7.9	13.7	NA	NA	595.9	NA
R1-20I	Influent	18-May	7.07	1381	18.1	40.4	780.6	22.8
R1-20E	Effluent	18-May	7.85	11.85	7.6	NA	88.14	8.5
R1-21E	Effluent	19-May	6.36	NA	NA	NA	330.84	NA
R1-22I	Influent	20-May	NA	NA	NA	NA	NA	NA
R1-22E	Effluent	20-May	7	NA	NA	NA	ND	NA
R1-23I	Influent	21-May	NA	NA	17.1	NA	NA	NA
R1-23E	Effluent	21-May	7.99	NA	ND	NA	ND	NA
R1-24E	Effluent	22-May	8	NA	NA	NA	NA	NA
R1-25I	Influent	23-May	7.03	625	16.7	NA	792.9	15.6
R1-25E	Effluent	23-May	7.78	19.85	ND	NA	ND	11.8
R1-26E	Effluent	24-May	NA	NA	NA	NA	NA	NA
R1-27E	Effluent	25-May	7.47	NA	NA	NA	ND	NA
R1-28E	Effluent	26-May	7.91	NA	0.95	NA	18.9	NA
R1-29E	Effluent	27-May	7.51	NA	ND	NA	ND	NA
R1-30I	Influent	28-May	7.07	652	23.4	NA	760	15.6
R1-30E	Effluent	28-May	7.81	394	ND	NA	9.26	5.2
R1-31E	Effluent	29-May	7.64	NA	NA	NA	18.6	NA
R1-32E	Effluent	30-May	7.87	ND	7.1	NA	260.7	NA
R1-33I	Influent	31-May	7.59	NA	21.2	NA	NA	NA
R1-33E	Effluent	31-May	NA	4.55	21.6	NA	700.8	NA
R1-34I	Influent	1-Jun	NA	NA	20.5	NA	728	23.8
R1-34E	Effluent	1-Jun	NA	ND	20.5	44.95	781	22.8
Detection Limit				4.0	0.47	0.75	4.0	2

NOTES:
ND: Result below detection limit
NA: Not Analyzed