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GAC-FLUIDIZED BED REACTOR PERCHLORATE TREATMENT PILOT STUDY

Prepared for

National Aeronautics and Space Administration - Jet Propulsion Laboratory

by

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USFilter

ENVIROGEN

EXECUTIVE SUMMARY

USFilter/Envirex Products and Envirogen, Incorporated (USFilter/Envirogen) have entered into an agreement to join together in the development and execution of perchlorate contaminated groundwater treatment projects using biological treatment. The most effective biological treatment process for destruction of perchlorate is the Fluidized Bed Reactor (FBR). To demonstrate the effectiveness of the FBR technology in the destruction of perchlorate in groundwater, USFilter/Envirogen performed a pilot study at the National Aeronautics and Space Administration (NASA) – Jet Propulsion Laboratory (JPL) in Pasadena, CA. Biological treatment of perchlorate and nitrate is considered a beneficial process because the only treatment byproducts are innocuous compounds and FBR operating costs are historically lower than alternative processes. Destructive technologies, such as the FBR, destroy the perchlorate and nitrate molecules resulting in chloride ions, carbon dioxide, and nitrogen gas. The purpose of this study was to demonstrate the ability of fluidized bed biological systems to consistently reduce groundwater perchlorate concentrations at JPL to below the detection limit of 4 parts per billion (ppb).

The FBR pilot demonstration was conducted in three operational modes designated as Phase 1, Phase 2, and Phase 3. Phase 1 involved forward flow operation for 27 days. The FBR operated in recycle mode during Phase 2 for 22 days and in forward flow for 52 days in Phase 3. The FBR was operated in recycle for Phase 2 because the Regional Water Quality Control Board (RWQCB) had not formally approved the discharge of the chloride concentrations that were detected in the FBR effluent, even though the FBR did not increase the chloride concentrations. The RWQCB later issued a variance and Phase 3 was started.

During Phase 1, the FBR operated with an influent flow rate of between 4.6 gallons per minute (gpm) and 5.3 gpm. These were the maximum flow rates that the well pumps would produce. The average nitrate-nitrogen (NO_3-N) feed concentration was reduced from 4.8 parts per million (ppm) to <0.1 ppm within 10 days after startup. Perchlorate was not detected in the influent to the FBR because an activated carbon filter located upstream of the FBR (to remove organic contaminants) was removing it at the time. Perchlorate concentrations are typically <4 ppb in the FBR effluent when the NO_3-N concentrations are below the detection limit. Therefore, had perchlorate been present in the FBR feed, we would have expected the concentration to be non-detectable in the FBR effluent.

During Phase 2, minimal batch doses of ethanol and nutrients were added to the FBR daily to sustain biological growth. Air was provided to supply oxygen as an electron acceptor to maintain the microflora in the reactor during this time. After 22 days without groundwater feed, the pilot FBR system returned to full treatment capacity within 3 days of receiving groundwater flow. This demonstrates the ability of the FBR to recover rapidly after system shut downs and in the event of upset conditions, such as power outages or well pump failure.

During Phase 3, the FBR reduced the average NO_3-N feed concentration from 7.5 ppm to <0.1 ppm and the average perchlorate feed concentration from 770 ppb to <4 ppb within 3 days after restart. The FBR system continued to reduce the perchlorate and nitrate concentrations to below detection limits for the duration of Phase 3.

The biological fluidized bed reactor system was demonstrated to be a reliable and effective technology for destroying perchlorate and nitrate in the groundwater at the JPL site. The system consistently reduced perchlorate levels in the JPL groundwater at site conditions to <4 ppb and NO_3-N to <0.1 ppm. FBRs provide the distinct advantage of controlling biofilm thickness and eliminating the plugging/short-circuiting that can occur in other biological configurations. When the treatment objective is to consistently achieve perchlorate concentrations <4 ppb in the effluent, no amount of short-circuiting can be tolerated.

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1.0 INTRODUCTION

USFilter/Envirex Products and Envirogen have entered into an agreement to join together in the development and execution of perchlorate contaminated groundwater treatment projects using biological treatment. To demonstrate the effectiveness of Fluidized Bed Reactor (FBR) technology in the destruction of perchlorate in groundwater, USFilter/Envirogen performed a pilot study at the National Aeronautics and Space Administration (NASA) – Jet Propulsion Laboratory (JPL) in Pasadena, CA. Operation of the FBR unit began on September 8, 2000 and was completed on December 18, 2000. This report describes the analytical results, the equipment used, the test program, and the implications for the full-scale FBR system for this application.

The purpose of the pilot FBR test was to demonstrate the ability of a fluidized bed biological system to consistently treat perchlorate extracted from the groundwater at JPL. The target effluent perchlorate concentration from the FBR was less than the current detection limit of 4 parts per billion (ppb). The proposed full-scale FBR system, discussed in Section 7.0, is also designed to consistently treat perchlorate in the groundwater at JPL to less than 4 ppb.

A USFilter/Envirex Model 30 FBR skid was selected for this demonstration. The Model 30 is the smallest scale commercial unit available. Being a commercial unit, the process control schemes are essentially the same as larger units, providing an excellent correlation to actual operating/maintenance requirements of larger systems. It also provides data that does not require scale-up adjustments for the perchlorate and nitrate loading conditions.

The design basis for the FBR pilot system and the actual operating parameters are listed below:

Parameter	Design	Actual[1]
Influent Groundwater Flow	10 gpm	5 gpm
Nitrate-Nitrogen (NO_3-N)	15 ppm	6.11 ppm
Perchlorate	800 ppb	310 ppb
Ammonia-Nitrogen	<0.05 ppm	<0.05 ppm
Total Phosphorus	<0.02 ppm	<0.02 ppm
Total Organic Carbon	<0.5 ppm	<0.5 ppm
Volatiles Detected[2]		
1,1-Dichloroethane		2.2 ppb
1,2-Dichloroethane		0.5 ppb
Carbon Tetrachloride		76 ppb
Chloroform (Trichloromethane)		8.9 ppb
Tetrachloroethylene (PCE)		1.7 ppb
Trichloroethylene (TCE)		19 ppb

[1]Concentrations based on sample collected on 10/2/00.

[2]Parameter did not affect the FBR system design.

2.0 STUDY OBJECTIVES

USFilter/Envirex Products and Envirogen intended to conduct the pilot demonstration in two phases. Phase 1 was to be performed as a high load test with an influent groundwater flow rate of 10 gpm, a NO_3-N concentration of 15 ppm, and a perchlorate concentration of approximately 800 ppb. Phase 2 was planned to be a low concentration test involving dilution of the influent stream from the wells with city water to achieve a perchlorate concentration of approximately 50 ppb.

Neither initial loading condition was tested due to the actual nitrate and perchlorate concentrations and the flow limitations of the well pump. After conversations with the Navy, USFilter/Envirogen decided that proving consistent treatment at the actual well conditions would be the most beneficial for this demonstration. Evidence from a past pilot study[1] and a bench-scale study conducted at Envirogen's laboratory have already demonstrated the ability of the FBR to treat perchlorate to <4 ppb at low influent concentrations. The pilot FBR system treated average feed concentrations of 8-16 ppm NO_3-N and 30-60 ppb perchlorate and the bench-scale FBR treated average feed concentrations of 2-4 ppm NO_3-N and 15-30 ppb perchlorate.

The pilot demonstration objectives were as follows:

- Demonstrate that the FBR can reliably treat the perchlorate-contaminated water to <4 ppb.
- Demonstrate the robustness/reliability of operation and the simplicity of the design.
- Determine optimal ethanol and nutrient dosages.
- Develop parameters required to design a full-scale FBR system to treat the groundwater at JPL.

[1]Harding Lawson Associates. 1998. *Phase 1 Treatability Study Report, Perchlorate in Groundwater, Baldwin Park Operable Unit, San Gabriel Basin.*

3.0 BACKGROUND

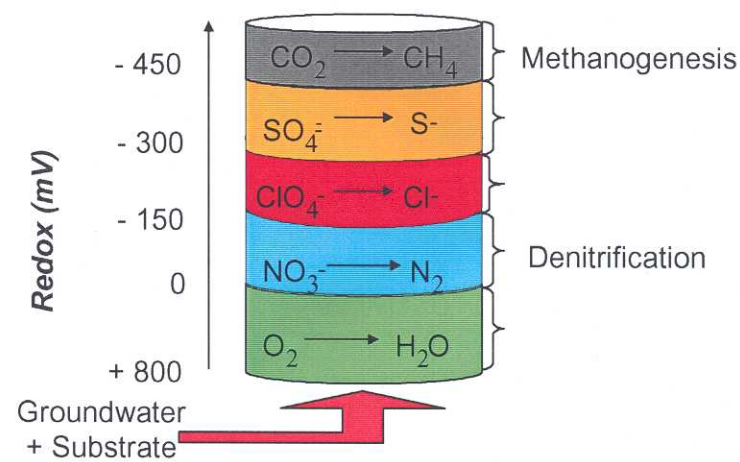
3.1 Fluidized Bed Reactor Technology

The FBR is a fixed-film reactor column that fosters the growth of microorganisms on a hydraulically fluidized bed of media, in this case activated carbon. Carbon was because it assures low-concentration perchlorate effluent, i.e., <4 ppb detection limit. The fluidized carbon selected provides an extremely large surface area on which a film of microorganisms can grow, thus producing a large inventory of biomass in a small reactor volume. The result is a system capable of high degradative performance for target contaminants, in a relatively small and economical reactor volume. The FBR can be controlled to operate under aerobic, anaerobic or anoxic conditions depending on the nature of the target compounds. For the treatment of perchlorate, the FBR is controlled to provide an anoxic environment.

Currently there are 4 full-scale FBRs at Aerojet-General Corporation in Rancho Cordova, CA treating approximately 4000 gpm and consistently reducing perchlorate to below the detection limit. A fifth FBR is under construction at Longhorn Army Ammunitions Plant in Karnack, TX, which will also be used for perchlorate treatment. The biological perchlorate reduction process can be viewed as similar to nitrate reduction (e.g., denitrification). Full-scale FBRs used for denitrification have been in operation for over 10 years. Today, over 70 million gallons of water per day is being denitrified with FBRs.

3.2 Process Microbiology

Perchlorate treatment is relatively new, but biological treatment with the FBR is a field-proven technology. The process can be viewed as similar to nitrate reduction (e.g., denitrification) where in the absence of oxygen, the nitrate anion serves as the terminal electron acceptor for microbial metabolic activity. The microorganisms in these systems are facultative aerobes, meaning they require oxygen or a suitable substitute (i.e., nitrate or perchlorate) for normal activities. Aerobic operation in the absence of oxygen is termed anoxic. For perchlorate removal, the dissolved oxygen and nitrate anions have to be removed before perchlorate can be completely removed (illustrated right). There is evidence that perchlorate reduction can occur simultaneously with nitrate reduction, but to achieve high perchlorate removal efficiencies (i.e., effluent concentrations below 4 ppb), our data suggests that all of the nitrate needs to be reduced. The same carbon source (i.e., electron donor) can be used to remove dissolved oxygen, reduce nitrate, and reduce perchlorate. A sufficient quantity has to be provided to drive these biochemical reactions.



UTILIZATION OF ELECTRON ACCEPTORS

Several microbial strains have been isolated with the ability to degrade perchlorate using the anion as a terminal electron acceptor. Many of these strains also reduce nitrate, and it is thought that the two enzyme systems may have similarities. The enzymatic pathways involved in perchlorate reduction have yet to be fully identified. However, it has been suggested that a perchlorate reductase catalyses an initial two-step reduction of perchlorate (ClO_4^-) to chlorate (ClO_3^-) and then chlorite (ClO_2^-). The chlorite is further reduced by chlorite dismutase to chloride (Cl^-) and oxygen (O_2). Thus, microbial degradation of perchlorate yields two innocuous products, chloride and oxygen. The amount of chloride released by the reduction of perchlorate is insignificant in comparison to the chloride concentration in the groundwater at JPL. At the anticipated full-scale perchlorate concentrations, approximately 0.05 ppm of chloride would be formed compared to the 25 ppm already present in the groundwater.

The reduction of perchlorate to chloride is a very favorable process from a thermodynamic perspective, yielding only slightly less energy than the reduction of oxygen to water. This indicates that bacteria capable of using perchlorate are likely to have a distinct ecological advantage in contaminated environments. All of the energy from perchlorate reduction appears to come from the perchlorate to chlorite reaction. The reduction of chlorite, while yielding no energy is necessary because chlorite is highly toxic to the microbial cell. If a bacterial strain is capable of reducing perchlorate to chlorite, but unable to degrade the chlorite further to chloride and oxygen, it is unlikely that the strain will survive in an FBR or elsewhere. For this reason, it is important to use an appropriate seed material when initiating FBR operation.

3.3 Process Description

The effectiveness of a biological system depends on maintaining a highly active biomass concentration in the bioreactor. Fixed-film bioreactors, like the FBR, cultivate organisms that prefer to grow on and attached to surfaces. The maintenance of a high biomass concentration depends on the amount of surface area available in the bioreactor environment. The FBR used for this demonstration contained granular activated carbon (GAC) to provide the large surface area. FBRs provide the distinct advantage of controlling biofilm thickness and eliminating the pluggage/short-circuiting possible in other biological configurations.

FBR reactor and cyclone separator

The basic components of an FBR system for treatment of nitrate and perchlorate include the bioreactor and cyclone separator (right), the GAC media, a fluid distribution system in to the bottom of the reactor, fluidization and influent pumps, chemical feed systems, and a bed height control component (when required). The bed of GAC media is fluidized to reduce its resistance to flow and to improve substrate/biomass contact by directing liquid flow upward into the bed. The fluidization rate is controlled to maintain a 25-30% bed expansion over the height of the bed in a resting (no flow) state. Feed flow is supplemented with recycle flow to provide the appropriate up-flow velocity for fluidization. When biofilm growth occurs on the GAC media, the particle diameter increases and the effective density of the particle decreases. This causes a further expansion in the bed height. It is necessary to manage film thickness to control or prevent bed carryover. In full-scale FBR systems, bed height is managed in the top portion of the bed

by mechanically shearing the biomass from the GAC. The "cleaned" GAC particles settle back into the bed, ready to support more biofilm growth, and the sloughed biomass is discharged. In the Model 30 FBR skid, film growth is managed manually when necessary. The top layer of media is pumped from the FBR column. This material is sheared through a valve, which separates the biomass from the media. The suspension is then discharged back into the FBR column where the "cleaned" media settles down into the bed and the sloughed biomass is carried out.

Nitrogen and phosphorus are supplied as inorganic nutrients for bacterial growth. Ethanol is supplied as an energy and carbon source to promote the reduction of oxygen, nitrate, and perchlorate in the FBR. The nutrient and ethanol were pumped continually into the reactor feed flow. The ethanol for this pilot was stored in a 55-gallon drum (right) and fed to the FBR influent line with a diaphragm metering pump. The nutrient mixture was stored in a 25-gallon tank and was also fed to the FBR influent line with a diaphragm metering pump.

55-gallon ethanol drum

In addition to the basic components of the FBR, other components were installed for the purposes of the pilot demonstration. The additional components consisted of a post aeration tank, a polypropylene filter, GAC adsorbers, and ion exchange units. Process flow diagrams for the pilot system are provided in Figures 1 and 2. Figure 1 shows how the system was installed initially, and Figure 2 represents the final configuration of the system. Modifications were made to the process trail, by moving the GAC adsorbers downstream of the FBR to prevent loading perchlorate in the adsorber beds. GAC adsorbers ahead of the FBR would have delayed the introduction of representative feed concentrations to the FBR until after the GAC reached breakthrough.

300-gallon post-aeration tank (back)

A 300-gallon post-aeration tank (left) was used to raise the effluent dissolved oxygen (DO) level and as a polishing tank for removal of excess ethanol. Fine bubble diffusers distributed a constant supply of air to the tank from the air compressor. The FBR effluent is oxygen deficient and the post aeration process elevates the oxygen concentration prior to discharge.

A 5-micron polypropylene filter was used to remove suspended solids during normal operation and bed control. This was later replaced by a 25-micron polypropylene filter to reduce maintenance requirements. The 5-micron filters became surface loaded by biological growth, resulting in reduced flux rates. This is not an issue for the full-scale system because a multi-media filter would be used. The gradient of the media contained in this type of filter enables the entire filter depth to be utilized, thus prevents surface loading. In addition, the ability to backwash prevents plugging.

The pilot system included six USFilter/Westates carbon adsorbers (below) to remove chlorinated organics (See table in Section 1). In the final configuration, two adsorbers were removed from service and four were placed upstream of the ion exchange units. This prevented fouling of the ion exchange units and provided a longer run time.

The ion exchange vessels were placed in series downstream of the carbon adsorbers and prior to discharge. The vessels were USFilter models constructed of fiberglass reinforced plastic. Each vessel contained 2 cubic feet of type II strong base resin. The ion exchange units were included as a perchlorate removal backup to the FBR prior to discharge.

Ion exchange vessels (left) and effluent GAC adsorbers (right)

4.0 PILOT STUDY PROGRAM

Regulatory issues explained later in this report caused the pilot demonstration to be performed in three operational phases: 1) initial startup and steady operation, 2) operation in recycle, and 3) restart and steady operation. The initial startup of the FBR system consisted of mechanical startup, inoculation with a biological seed material, and operation of the FBR system until the desired loading and removal capacities were achieved. Steady operation commenced when biological activity was detected by decreasing dissolved oxygen and oxidation reduction potential levels across the FBR. Mechanical startup and inoculation were completed on 9/7/00 using tap water as the initial feed. The 20 gallons of GAC media with seed material came from a full-scale operating FBR that is currently treating perchlorate at Aerojet Corporation in Rancho Cordova, CA.

Groundwater pumping began on 9/8/00 through the GAC adsorbers and into the FBR. Montgomery Watson Laboratories in Pasadena, CA analyzed water samples collected throughout the pilot study. The following sample points were established (Figure 1) and initial sampling began on 9/9/00.

- Groundwater – well pump discharge
- FBR Inf – downstream of the influent GAC adsorbers
- Ethanol tap – downstream of the ethanol addition
- FBR Eff – downstream of the cyclone separator
- Post Air Eff – downstream of the post aeration tank
- Carbon Eff – downstream of the effluent GAC adsorbers
- Ion Exchange Effluent – downstream of the ion exchange units

The system was operated using the initial flow scheme shown in Figure 1 from 9/8/00 to 10/2/00. The perchlorate removal capacity of the GAC adsorbers was not known prior to this pilot study. Perchlorate breakthrough in the GAC did not occur after operating for over three weeks. To expedite the pilot study, the four influent GAC adsorbers were placed downstream of the polypropylene filter and upstream of the ion exchange units. This was the final configuration, as shown in Figure 2, in which the groundwater was fed directly to the FBR. Operation in this flow scheme continued until 10/5/00.

Analytical results from the first chloride, sulfate, and total dissolved solids (TDS) sampling indicated that the chloride limit specified by the Regional Water Quality Control Board Basin (RWQCB) Plan was exceeded. The pilot system was placed in recycle mode, during which time, the system received no flow from the well, and did not discharge to the storm sewer. Analysis of water quality samples indicated that the chloride and sulfate concentrations in the FBR effluent were at the same level as the groundwater extracted from the aquifer. The FBR was spiked with approximately 300 grams of sodium perchlorate prior to restart, in order to saturate the FBR's GAC media and demonstrate biological treatment of the perchlorate versus adsorption. Consequently, JPL received approval from the regulators to resume forward flow from the well on 10/27/00. Additional sampling events and parameters were added to the discharge monitoring program. Steady operation and complete treatment was attained by the first sampling event on 10/30/00 according to the laboratory data and was continued until 12/18/00.

5.0 RESULTS AND DISCUSSION

The influent flow data and ethanol feed rates are compiled in Table 1 and illustrated in Figure 3. The well pump operated at maximum capacity throughout the pilot study. The maximum flow rate achieved was 5.3 gallons per minute (gpm) and the minimum flow rate was 3.6 gpm. The ethanol feed rate was varied based on the influent flow rate and the influent nitrate and perchlorate concentrations. The inconsistent ethanol flow rates in the first phase of the study were due to the lower than expected nitrate loading rate. The ethanol feed pump was designed for delivering a 40% ethanol solution to the 10 gpm design flow at 15 parts per million (ppm) of nitrate-nitrogen (NO_3-N) as discussed in Section 1.0. However, the concentration and flow rates were less than anticipated and resulted in difficulty maintaining prime at the required feed rate. The ethanol solution was diluted to approximately 20% on 9/27/00, 18% on 10/3/00, and 9% on 10/16/00. This permitted the pump to operate at its optimum rate.

The NO_3-N and perchlorate data are compiled in Table 2 and illustrated in Figures 4 and 5. Perchlorate was not detected in the feed to the FBR for most of Phase 1. However, nitrates were not adsorbed by the GAC adsorbers, and the FBR system treated NO_3-N to <0.1 ppm by the 9/18/00 sampling event, which indicates steady operation. Experience with other FBRs treating nitrate and perchlorate concentrations similar to those detected in the JPL groundwater indicates that when the electron donor is in slight excess of stiochiometric values, perchlorate concentrations are usually <4 ppb when the NO_3-N concentrations are below detection.

The system was operated in recycle for 22 days in Phase 2 while USFilter/Envirogen awaited approval from the RWQCB to discharge the chloride and sulfate levels present in the groundwater. Minimal batch doses of ethanol and nutrients were added to the FBR daily to sustain biological growth. Air was periodically added to the recycled water by pumping it through the post aeration tank and back to the FBR. This provided the microorganisms with oxygen as an alternate electron acceptor. Phase 2 lasted 22 days. The FBR was spiked with perchlorate prior to restart to saturate the GAC media. A sample collected from the FBR on 10/23/00 indicated the perchlorate concentration of the FBR effluent was 1100 ppb.

The media was saturated to assure that the only removal mechanism was biological reduction. This was necessary in the pilot demonstration because during the 22 days of Phase 2, the equilibrium level of perchlorate on the GAC media would be reduced. Therefore, some perchlorate would actually be adsorbed by the media during restart, in addition to the biological removal. In full-scale operation, this phenomenon is beneficial and allows for rapid restarts. In the pilot test we are demonstrating the biological activity and hence wanted to eliminate adsorption as a variable.

The system was restarted in the flow-through mode on 10/27/00 to begin Phase 3, which lasted for 52 days. The results of the FBR effluent analysis on 10/30/00 indicated <4 ppb of perchlorate and <0.1 ppm of NO_3-N. To demonstrate that biological treatment rather than adsorption by the GAC media was achieving these levels, the ethanol feed rate was reduced to below the required level on 11/3/00. The perchlorate in the FBR effluent increased to 15 ppb, 190 ppb, and 240 ppb, in the next three sampling events. The perchlorate concentration in the final effluent on 11/6/00 was <4 ppb. This verified that the ion exchange units used as a backup to the FBR were removing the excess perchlorate during the spike prior to restart and the ethanol feed reduction. The ethanol feed rate was increased on 11/9/00 and the FBR effluent levels of perchlorate and nitrate returned to <4 ppb and <0.1 ppm, respectively. This consistent level of treatment was maintained for the remainder of Phase 3.

As illustrated in Figure 4, the FBR received a steady increase in perchlorate concentration in the third phase of the pilot demonstration. The perchlorate concentration increased from 360 ppb to 1100 ppb and leveled off. As illustrated in Figure 5, NO_3-N concentrations in the influent water increased from 5 to 6 ppm during Phase 1 and then increased again from 7 to 8 ppm during Phase 3. The FBR consistently reduced both perchlorate and nitrate to below detection during Phase 3 (after the initial ethanol dosing test) irrespective of changes in the influent concentration of nitrate or perchlorate.

The FBR process control data are compiled in Table 3. Ethanol and nutrients are key process variables that are monitored for effective process control. The quantity of ethanol in the feed or effluent can be determined by measuring the total organic carbon (TOC), chemical oxygen demand, (COD), or biochemical oxygen demand (BOD). COD was measured daily in the field for evaluating ethanol levels because this parameter can be quantified in three hours, compared to five days for quantification of BOD. The concentrations of phosphorus and ammonia-nitrogen (NH_3-N) in the FBR effluent were monitored using Hach test kits. The results from the field test kits were verified three times per week by collecting samples and sending them to Montgomery Watson Laboratories for analysis.

According to the data collected, FBR effluent TOC should be maintained greater than 1.0 ppm for effective treatment. Recommended residual phosphorus and NH_3-N levels are 0.2 to 0.4 ppm. However, on 11/22/00 and 11/27/00, the FBR effluent NH_3-N concentration was <0.05 ppm due to a plugged feed line and the effluent levels of NO_3-N and perchlorate remained unchanged. Operating under these conditions is not recommended. However, in this case it did demonstrate the ability of the FBR to retain complete treatment through a short-term loss of the NH_3-N feed. It is possible that the perchlorate- and nitrate-reducing bacteria can utilize some of the nitrate in the feed as a source of nitrogen (rather than an electron acceptor) in the absence of ammonia. This may allow the FBR system to maintain low NH_3-N residuals when used for treatment of NO_3-N and perchlorate.

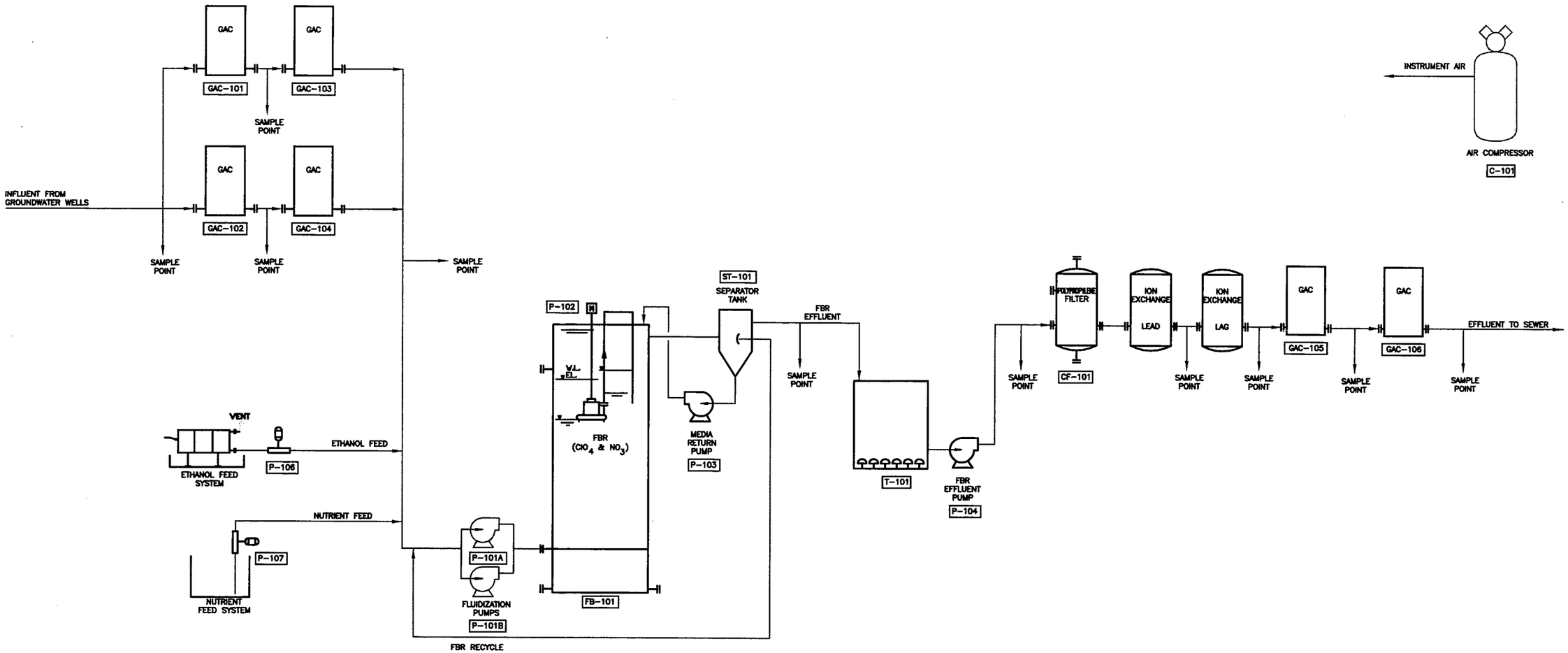
The average influent NO_3-N and perchlorate concentrations for the third phase were 7.5 ppm and 770 ppb, respectively. The average influent flow rate and ethanol feed rate over the same period were 4.1 gpm and 3.86 mL/min, respectively. The calculated ethanol feed rate of the 9% solution is 1.2 pounds per day and the NO_3-N loading rate is 0.37 pounds per day, giving a ratio of approximately 3:1. The amount of ethanol required is largely based on the nitrate loading because it is ten times greater than that of the perchlorate.

The data compiled in Table 3 was collected in accordance with the regulatory monitoring program. All regulatory limits were met with the exception of the chloride and sulfate. The chloride and sulfate concentrations in the aquifer were detected above the regulatory limits and not affected by the FBR. They were present in the FBR effluent at the same levels as found in the groundwater, with short-term changes across the ion exchange units due to the type of resin used.

BOD and total suspended solids (TSS) were analyzed in the FBR effluent. The only BOD test result was 8.4 ppm on 12/18/00. The BOD can be correlated with the COD results shown in Table 3 using on a COD:BOD ratio of 2:1, which is typical for biological treatment systems. Based on this ratio, the average BOD was <10 ppm in the FBR effluent from 11/17/00 to 12/18/00. The average TSS was <10 ppm in the FBR effluent over the same period. Both values are well below the regulatory requirements of 20 ppm BOD and 50 ppm TSS. This indicates that post-aeration or filtration may not be needed to meet these requirements for the full-scale system. If post-aeration is needed to meet

a regulatory requirement for dissolved oxygen, an air stripper could accomplish this. An air stripper could be used in the full-scale design for treatment of volatile organic contaminants and simultaneously elevate the dissolved oxygen to required concentrations.

Biomass film growth was managed in the pilot FBR manually. This procedure was sufficient to maintain a stable biomass population within the FBR. For full-scale FBRs, automatic systems are used to control bed height and biofilm growth. The pilot procedure of shearing the coated media through a pinch valve and returning the media to the FBR column was a satisfactory means of biomass control. The biofilm readily separated from the FBR media meaning that normal full-scale shearing techniques would be adequate for biofilm control.



P-105
OPTIONAL pH PUMP
TYPE: METERING
CAPACITY: 6gpd
MOTOR: 120V,60Hz,1PH

P-106
ETHANOL FEED PUMP
TYPE: METERING
CAPACITY: 6 gpd
MOTOR: 120v,60Hz,1PH

P-107
NUTRIENT ADDITION PUMP
TYPE: METERING
CAPACITY: 6gpd
MOTOR: 120V,60Hz,1PH

P-101A/B
FLUIDIZATION PUMP
TYPE: CENTRIFUGAL
CAPACITY: 36 gpm @ 35'TDH
CASE: 304 S.S.
IMPELLER: 304 S.S.
SINGLE MECHANICAL SEAL
MOTOR: 115V/230V,1PH,60Hz

FB-101
FLUIDIZED BED REACTOR
DIA: 20"
HEIGHT: 15'
MATERIAL: 304SS
MEDIA: GRANULAR ACTIVATED CARBON 10x30 MESH @ 29lbs/cuft

P-103
MEDIA RETURN PUMP
TYPE: AIR DIAPHRAGM
CAPACITY: 5 gpm @ 30'TDH
CASE: ALUM/DIE CAST
NEOPRENE ELASTOMER
AIR: 30 PSI @ 5 SCFM

ST-101
SEPARATOR TANK
DIA: 14"
HEIGHT: 61.25"
MATERIAL: 304SS

P-102
BIOMASS PUMP
TYPE: CENTRIFUGAL
CAPACITY: 12 gpm @ 13'TDH
CASE: 304 S.S.
IMPELLER: 304 S.S.
MOTOR: 1/2 HP, 1725 RPM
115V/230V,1PH,60Hz

P-104
FBR EFFLUENT PUMP
TYPE: CENTRIFUGAL

T-101
POST AERATION TANK
VOLUME: 300 GALLONS

IX-101, IX-102,
ION EXCHANGE
DIA: 10"
HEIGHT: 58"
MEDIA: ANIONIC, TYPE II STRONG BASE RESIN

C-101
AIR COMPRESSOR
TYPE: TWO STAGE TWO CYLINDER
CAPACITY: 17.68 SCFM @ 175 PSIG
MOTOR: 5HP,230V,60Hz,3PH

GAC-101, 102, 103, 104, 105 & 106
GRANULAR ACTIVATED CARBON ADSORPTION, DIAMETER: 22"
12x30 COCONUT SHELL VIRGIN CARBON

CF-101
POLYPROPYLENE FILTER
DIA: 6"
HEIGHT: 40"
5 MICRON

ECN NUMBER	REV. NO.	BY	DESCRIPTION OF REVISION	REV. BY	DATE

LOCATION OF REVISION

SCALE: NONE	DATE ISSUED: 6/12/00	CLIENT/OWNER: JET PROPULSION LAB	TITLE: FIGURE 1 PILOT DEMONSTRATION PROCESS FLOW DIAGRAM
DIMENSIONS IN INCHES UNLESS SPECIFIED		LOCATION: PASADENA, CA	
TOLERANCES UNLESS OTHERWISE SPECIFIED		ENGINEER:	
TWO (2) PLACE DEC. ±.08; THREE (3) PLACE DEC. ±.005; ANGULAR ±.50°; STRUCTURAL DIMENSIONS ±1/16; MACHINED SURFACES 250√		USFilter	
DRAWN: DJS	PROJECT ENG.:	PRODUCT CODE:	PART NUMBER:
CHECKED:	APPROVED: CW	DRAWING MADE FROM:	DRAWING NUMBER: 109

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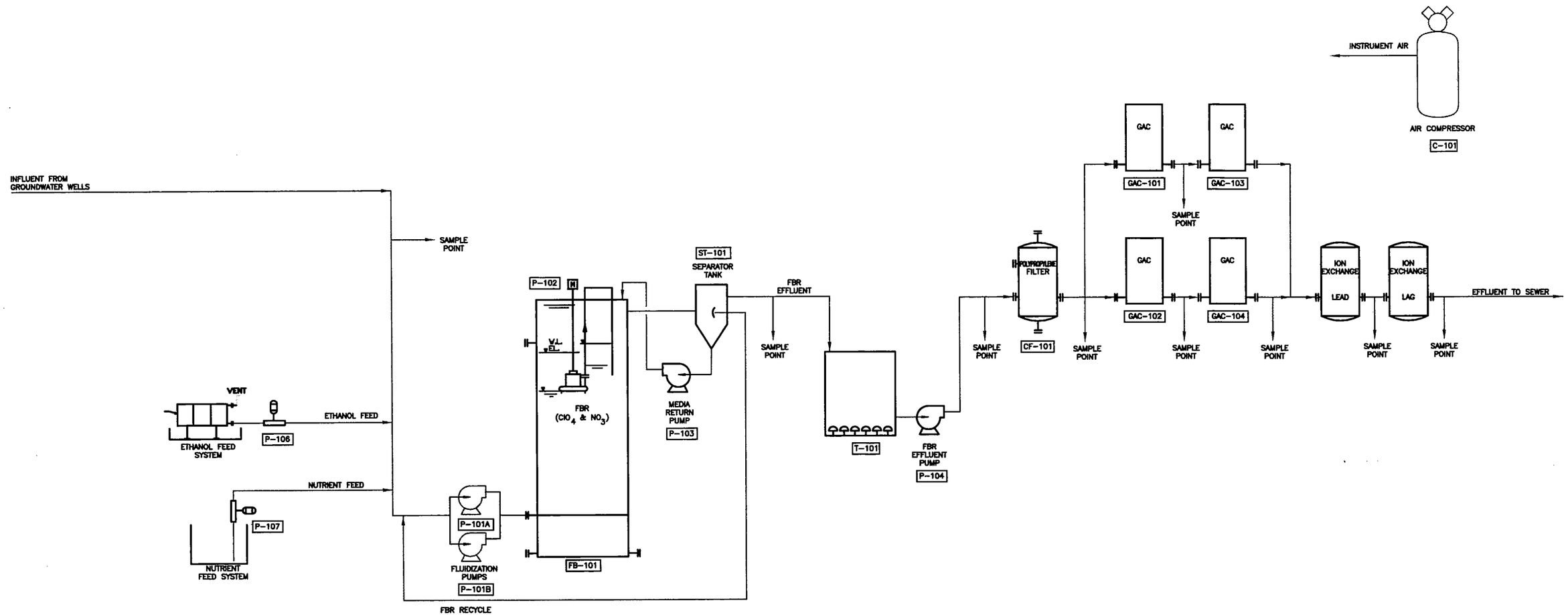

P-105
OPTIONAL pH PUMP
TYPE: METERING
CAPACITY: 6gpd
MOTOR: 120V,60Hz,1PH

P-106
ETHANOL FEED PUMP
TYPE: METERING
CAPACITY: 6 gpd
MOTOR: 120V,60Hz,1PH

P-107
NUTRIENT ADDITION PUMP
TYPE: METERING
CAPACITY: 6gpd
MOTOR: 120V,60Hz,1PH

P-101A/B
FLUIDIZATION PUMP
TYPE: CENTRIFUGAL
CAPACITY: 36 gpm @ 35'TDH
CASE: 304 S.S.
IMPELLER: 304 S.S.
SINGLE MECHANICAL SEAL
MOTOR: 115V/230V,1PH,60Hz

FB-101
FLUIDIZED BED REACTOR
DIA: 20"
HEIGHT: 15'
MATERIAL: 304SS
MEDIA: GRANULAR ACTIVATED CARBON 10x30 MESH @ 29lbs/cuft

P-103
MEDIA RETURN PUMP
TYPE: AIR DIAPHRAGM
CAPACITY: 5 gpm @ 30'TDH
CASE: ALUM/DIE CAST NEOPRENE ELASTOMER
AIR: 30 PSI @ 5 SCFM

ST-101
SEPARATOR TANK
DIA: 14"
HEIGHT: 61.25"
MATERIAL: 304SS

P-102
BIOMASS PUMP
TYPE: CENTRIFUGAL
CAPACITY: 12 gpm @ 13'TDH
CASE: 304 S.S.
IMPELLER: 304 S.S.
MOTOR: 1/2 HP, 1725 RPM 115V/230V,1PH,60Hz

P-104
FBR EFFLUENT PUMP
TYPE: CENTRIFUGAL

T-101
POST AERATION TANK
VOLUME: 300 GALLONS

IX-101, IX-102,
ION EXCHANGE
DIA: 10"
HEIGHT: 58"
MEDIA: ANIONIC, TYPE II STRONG BASE RESIN

C-101
AIR COMPRESSOR
TYPE: TWO STAGE TWO CYLINDER
CAPACITY: 17.68 SCFM @ 175 PSIG
MOTOR: 5HP,230V,60Hz,3PH

GAC-101, 102, 103, 104, 105 & 106
GRANULAR ACTIVATED CARBON ADSORPTION, DIAMETER: 22"
12x30 COCONUT SHELL VIRGIN CARBON

CF-101
POLYPRORYLENE FILTER
DIA: 6"
HEIGHT: 40"
5 MICRON

ECN NUMBER	REV. NO.	BY	DESCRIPTION OF REVISION	REV. BY	DATE

LOCATION OF REVISION

SCALE NONE	DATE ISSUED 6/12/00	CUSTOMER JET PROPULSION LAB	TITLE FIGURE 2 PILOT DEMONSTRATION PROCESS FLOW DIAGRAM
DIMENSIONS IN INCHES UNLESS SPECIFIED		LOCATION PASADENA, CA	
TOLERANCES UNLESS OTHERWISE SPECIFIED		ENGINEER	
TWO (2) PLACE DEC. ±.06; THREE (3) PLACE DEC. ±.005; ANGULAR ±.50°	STRUCTURAL DIMENSIONS ±1/16; MACHINED SURFACES 250/	USFilter	
DRAWN DJS	PROJECT ENG.	PRODUCT CODE	PART NUMBER
CHECKED	APPROVED CW	DRAWING MADE FROM	DRAWING NUMBER 109

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Figure 3
Influent Flow and Ethanol Feed Rates

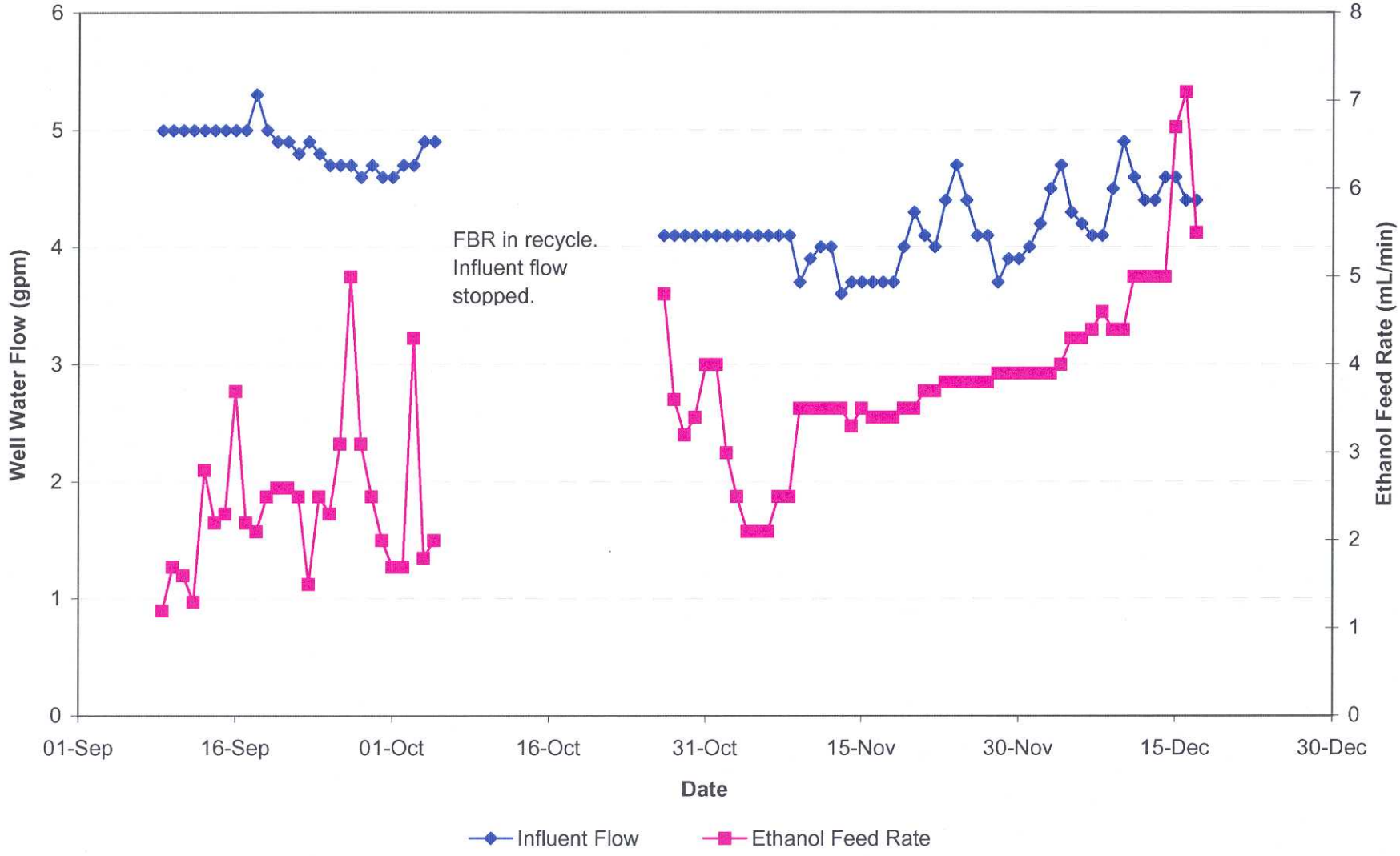


Figure 4
Perchlorate Data

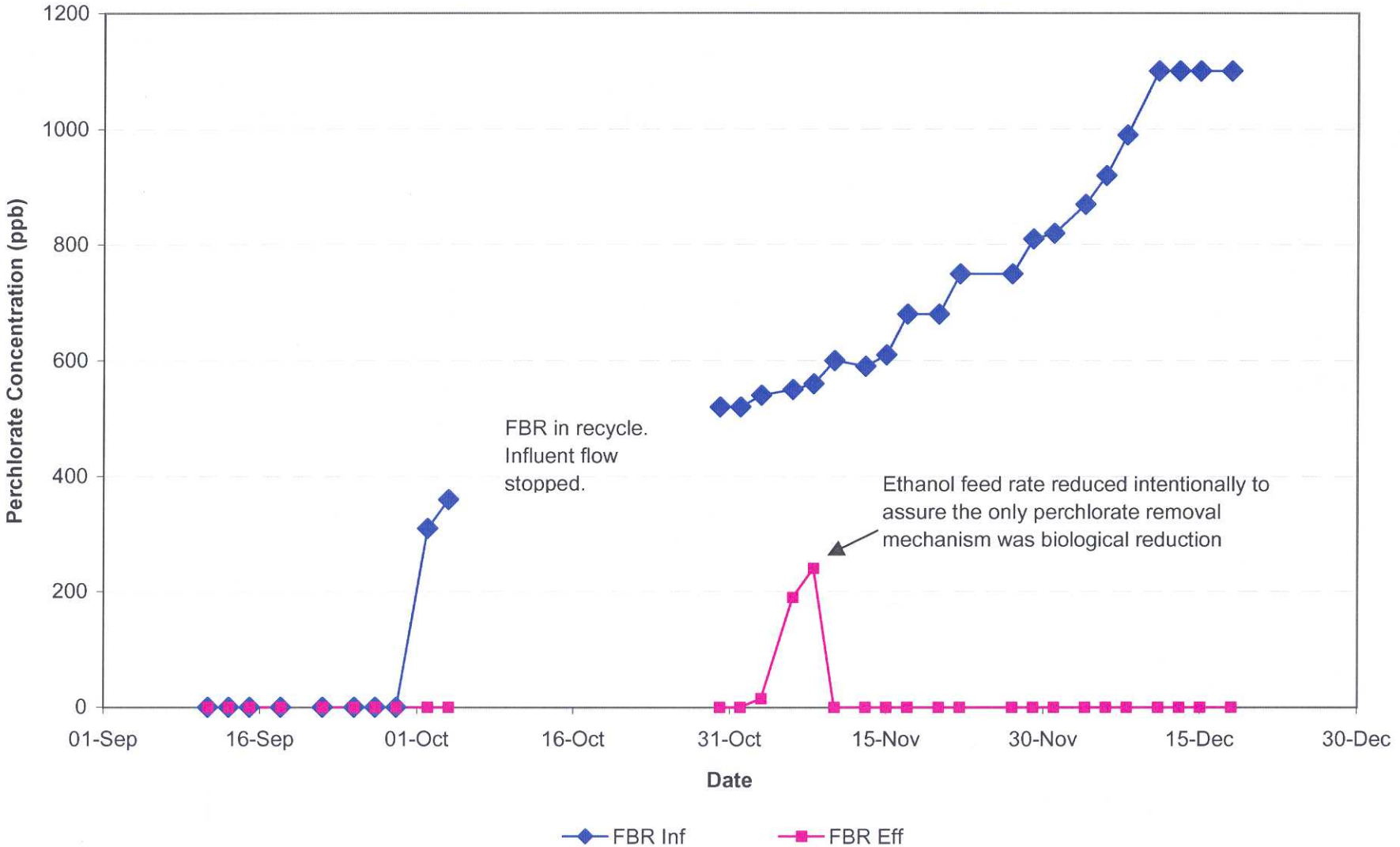
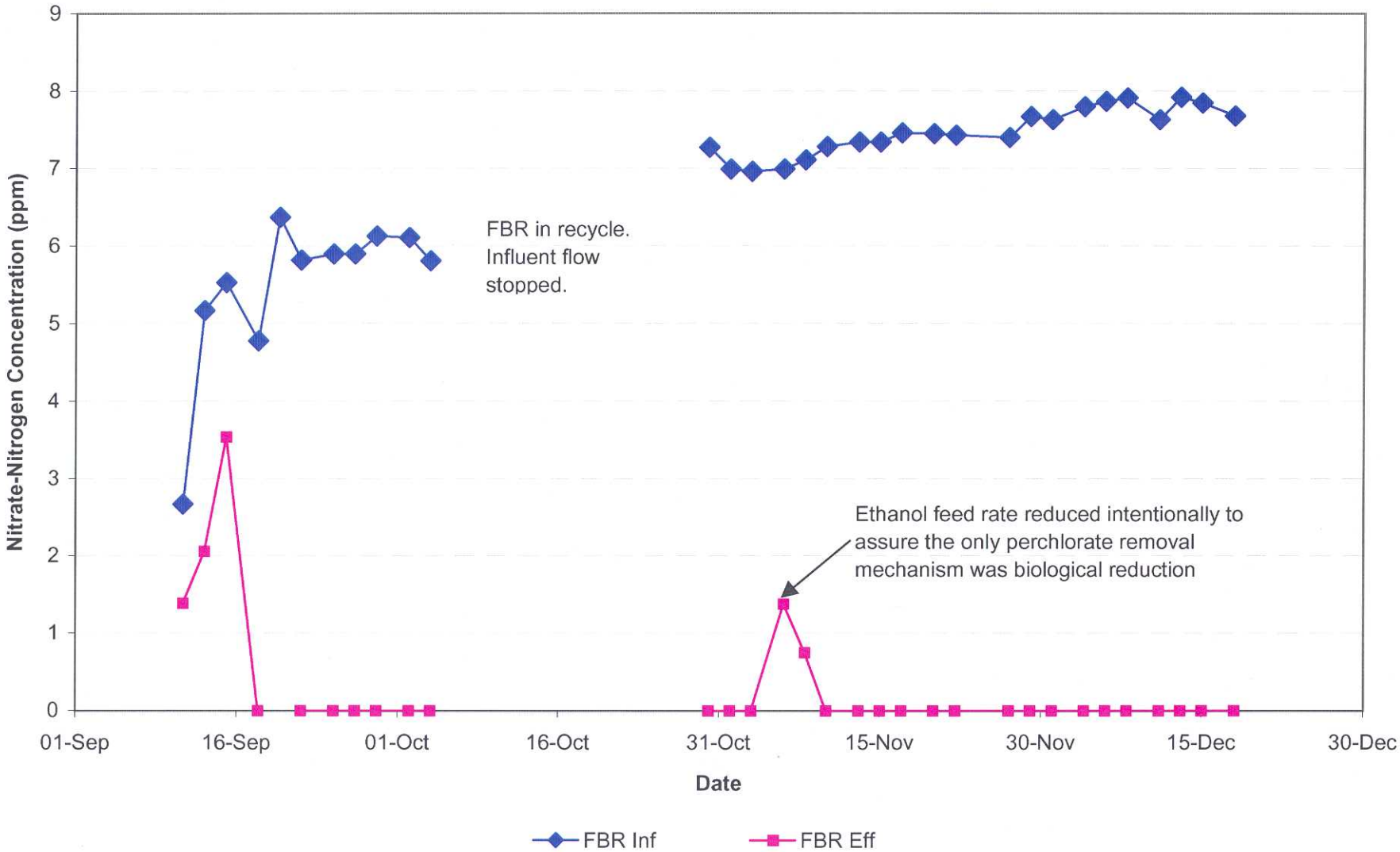


Figure 5
Nitrate-Nitrogen Data



6.0 CONCLUSION

The biological fluidized bed reactor system was demonstrated to be an effective technology for the removal of perchlorate and nitrate from groundwater in the aquifer underlying the National Aeronautics and Space Administration - Jet Propulsion Laboratory in Pasadena, California.

The key conclusions are as follows:

- The pilot FBR system consistently reduced the average NO_3-N feed concentration from 7.5 ppm to <0.1 ppm and the average perchlorate feed concentration from 770 ppb to <4 ppb.

- The pilot FBR system returned to full treatment capacity within 3 days after operation for 22 days without groundwater feed. This shows the ability of the FBR to recover rapidly after system shut downs and potential upsets.

- The data collected during this demonstration coupled with data from a past pilot study[1] and a bench-scale study conducted at Envirogen's laboratory provides a sufficient basis to design a full-scale FBR system. Scale-up adjustment is not required.

Biological treatment of perchlorate and nitrate is preferred because it is a destructive technology, resulting in only innocuous compounds (Cl^-, CO_2, and N_2). Generally biological systems are considered to have lower operating costs than other treatment alternatives. FBRs provide the distinct advantage of controlling biofilm thickness and eliminating the pluggage/short-circuiting possible in other biological configurations. When the objective is to reduce the perchlorate concentrations to <4 ppb, no amount of short circuiting can be tolerated.

[1]Harding Lawson Associates. 1998. *Phase 1 Treatability Study Report, Perchlorate in Groundwater, Baldwin Park Operable Unit, San Gabriel Basin.*

7.0 FULL SCALE RECOMMENDATIONS

This section presents the preliminary process design of a full-scale FBR system to destroy the perchlorate in the JPL groundwater. The design basis focuses on the pilot study results and previous perchlorate treatment experience with the FBR.

7.1 Process Design

7.1.1 Design Criteria

The basis for establishing the design criteria for the full-scale FBR system is the operating and analytical data collected during the pilot study. During phase 3, the average perchlorate and nitrate concentrations were 770 ppb and 7.5 ppm respectively. The anticipated perchlorate concentration at the proposed site of the full-scale system is 50 ppb rather than 770 ppb. This does not impact the FBR system design because the perchlorate concentration is much less than the nitrate concentration. The following values were used for the full-scale design based on the pilot data collected.

Parameter	Design Value
Flow (gpm)	2000
Perchlorate (ppb)	50
Nitrate as nitrogen (ppm)	7.5

7.1.2 Equipment

The key design features of the full-scale FBR system are featured on the following page. The key components of the FBR system are the reactor vessels, fluidization pumps, separation tanks for media carryover (not shown), growth control system, nutrient feed, and ethanol feed.

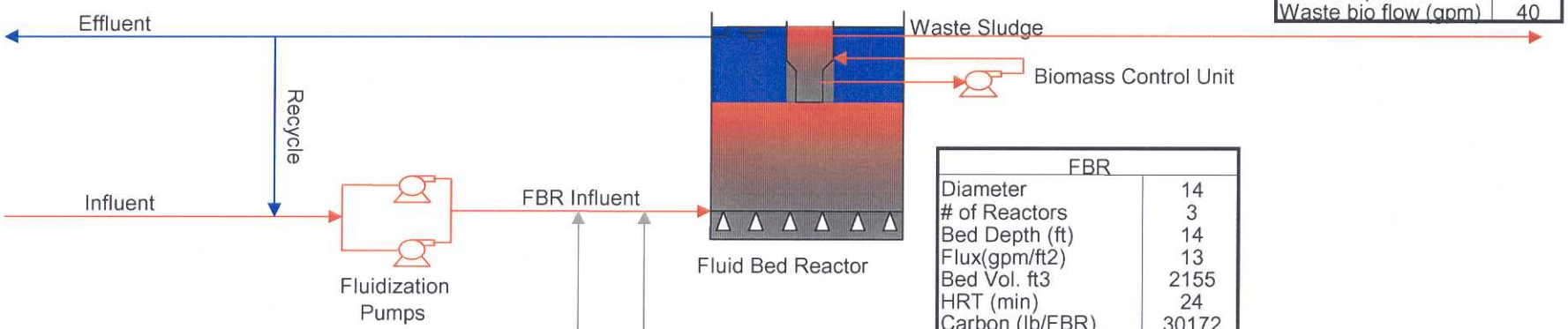
The primary difference between the full-scale FBR and the pilot-scale FBR is the growth control system. However, the control logic, media, and instrumentation are the same. The skid used a pump and valve to shear the biomass form the GAC. Residual biomass leaves the system in the effluent. The full-scale system uses a biomass cone in addition to the pump and valve. Hydraulics within the cone draws the bed into the bottom of the cone where the GAC is suctioned through the pump and valve to separate the biomass from the GAC. The pump discharges the biomass back into the cone. The clean GAC settles back into the fluidized bed, and the biomass is drawn out of the reactor through the waste biomass line. The concentrated biomass can then be disposed of separate from the treated effluent, resulting in low total suspended solids (TSS) in the effluent.

US Filter, Envirex Products
Perchlorate Fluid Bed Design

Project: JPL

Parameter	Influent		FBR Influent		Recycle		Effluent	
Flow	2000 gpm		2001 gpm		1333 gpm		2000 gpm	
Perchlorate (ClO_4)	0.05 mg/l	1.2 lb/d	0.02 mg/l	0.4 lb/d	<0.004 mg/l	0 lb/d	<0.004 mg/l	0.0 lb/d
Chlorate (ClO_3)	0.0 mg/l	0.0 lb/d	0.00 mg/l	0 lb/d	<0.1 mg/l	0 lb/d	<0.1 mg/l	0.0 lb/d
NO_3-N	7.5 mg/l	180 lb/d	2 mg/l	60 lb/d	<0.1 mg/l	0 lb/d	<0.1 mg/l	0.0 lb/d
Dissolved O_2	3.0 mg/l	72.0 lb/d	1.0 mg/l	24 lb/d	0 mg/l	0 lb/d	0.0 mg/l	0.0 lb/d
COD- Elec. Donor	50 mg/l	1189 lb/d						
Temperature	70.0 °F							

Waste Sludge	
Dry Solids (#/D)	178
TSS (mg/l) (if to eff)	7
SS in Grth Cont (mg/L)	1500
Hr/D to operate	6
Waste bio flow (gpm)	40



FBR	
Diameter	14
# of Reactors	3
Bed Depth (ft)	14
Flux(gpm/ft2)	13
Bed Vol. ft3	2155
HRT (min)	24
Carbon (lb/FBR)	30172
TCOD (lb/d/1000 ft^3)	184
NO_3-N (lb/d/1000 ft^3)	28

Electron Donor	
Type	Ethanol
Percent Weight	100%
Excess COD	40%
Stoic. COD(lb/d)	739
Cell Mass COD (lb/d)	111
Excess COD (lb/d)	340
Flow (gpd)	87

Nutrients	
Type	DAP & Urea
% Weight	39%
lb/d N	59
lb/d P	12
Flow (gpd)	29

7.2 Cost Estimate

7.2.1 Operating Cost

The operating costs were figured based on the nitrate and perchlorate concentrations listed in section 7.1. Below is a breakdown of the operating costs for the system.

7.2.2 Capital Cost

The capital cost of the full-scale FBR system is approximately $2,250,000. The design consists of three 14 foot diameter FBRs. The reactors are API 650 carbon steel tanks with plasite coating on the interior. The scope of supply includes engineering, all equipment, controls, instrumentation, media, start-up, and training. Installation of equipment, concrete pads, interconnecting pipe to and from the skid, and the MCC are not included in the budgetary price, but can be added to the scope and performed by USFilter/Envirex.

This cost estimate is for the FBR portion only. It does not include any additional equipment, such as filters, GAC adsorption, post aeration, etc., that may be required to meet the regulatory requirements. If required, USFilter/Envirex can provide this equipment.

US Filter, Envirex Products
Fluid Bed Cost Estimate

	ESTIMATED OPERATING COSTS		
Jet Propulsion Laboratory			
		Pump efficiency	0.75
ELECT COST ($/KWhr)	$0.06	Motor efficiency	0.90
FLUID PUMP BHP:	29.9	PUMP $/D	$32.15
GROWTH CONT	3.0	PUMP $/D	$0.81
		TOTAL PUMP $/D	$98.88
		Ethanol/D	$151.73
Organic carbon enter: 1 for MeOH, 2 for EtOH, 3 for Acetic Acid	2		
Methanol $/gal	$1.50		
Ethanol $/gal	$1.75		
Acetic Acid			
Nutrients $/gal	$1.65		$47.28

		TOTAL DAILY	$297.89
		TOTAL ANNUAL	$108,729

APPENDIX

Table 1
Influent Flow and Ethanol Feed Rates
Jet Propulsion Laboratory Pilot Study
Pasadena, CA
April, 2001

Date	Influent Flow (gpm)	Ethanol Feed Rate (mL/min)
09/09/00	5	1.2
09/10/00	5	1.7
09/11/00	5	1.6
09/12/00	5	1.3
09/13/00	5	2.8
09/14/00	5	2.2
09/15/00	5	2.3
09/16/00	5	3.7
09/17/00	5	2.2
09/18/00	5.3	2.1
09/19/00	5	2.5
09/20/00	4.9	2.6
09/21/00	4.9	2.6
09/22/00	4.8	2.5
09/23/00	4.9	1.5
09/24/00	4.8	2.5
09/25/00	4.7	2.3
09/26/00	4.7	3.1
09/27/00	4.7	5
09/28/00	4.6	3.1
09/29/00	4.7	2.5
09/30/00	4.6	2
10/01/00	4.6	1.7
10/02/00	4.7	1.7
10/03/00	4.7	4.3
10/04/00	4.9	1.8
10/05/00	4.9	2

Date	Influent Flow (gpm)	Ethanol Feed Rate (mL/min)
10/27/00	4.1	4.8
10/28/00	4.1	3.6
10/29/00	4.1	3.2
10/30/00	4.1	3.4
10/31/00	4.1	4
11/01/00	4.1	4
11/02/00	4.1	3
11/03/00	4.1	2.5
11/04/00	4.1	2.1*
11/05/00	4.1	2.1*
11/06/00	4.1	2.1*
11/07/00	4.1	2.5
11/08/00	4.1	2.5
11/09/00	3.7	3.5
11/10/00	3.9	3.5
11/11/00	4	3.5
11/12/00	4	3.5
11/13/00	3.6	3.5
11/14/00	3.7	3.3
11/15/00	3.7	3.5
11/16/00	3.7	3.4
11/17/00	3.7	3.4
11/18/00	3.7	3.4
11/19/00	4	3.5
11/20/00	4.3	3.5
11/21/00	4.1	3.7
11/22/00	4	3.7

Date	Influent Flow (gpm)	Ethanol Feed Rate (mL/min)
11/23/00	4.4	3.8
11/24/00	4.7	3.8
11/25/00	4.4	3.8
11/26/00	4.1	3.8
11/27/00	4.1	3.8
11/28/00	3.7	3.9
11/29/00	3.9	3.9
11/30/00	3.9	3.9
12/01/00	4	3.9
12/02/00	4.2	3.9
12/03/00	4.5	3.9
12/04/00	4.7	4
12/05/00	4.3	4.3
12/06/00	4.2	4.3
12/07/00	4.1	4.4
12/08/00	4.1	4.6
12/09/00	4.5	4.4
12/10/00	4.9	4.4
12/11/00	4.6	5
12/12/00	4.4	5
12/13/00	4.4	5
12/14/00	4.6	5
12/15/00	4.6	6.7
12/16/00	4.4	7.1
12/17/00	4.4	5.5

* The ethanol feed rate was reduced intentionally to assure the only perchlorate removal mechanism was biological reduction

Table 2
Nitrate and Pechlorate Data
Jet Propulsion Laboratory Pilot Study
Pasadena, CA
April, 2001

	Perchlorate			NO_3-N	
Date	Ground-water (ppb)	FBR Inf (ppb)	FBR Eff (ppb)	FBR Inf (ppm)	FBR Eff (ppm)
09/09/00		<4		5.53	
09/11/00		<4	<4	2.67	1.39
09/13/00		<4	<4	5.17	2.06
09/15/00		<4	<4	5.53	3.54
09/18/00		<4	<4	4.78	<0.1
09/20/00	340			6.37	
09/22/00	330		<4	5.82	<0.1
09/25/00	320		<4	5.9	<0.1
09/27/00	330	<4	<4	5.9	<0.1
09/29/00	320	<4	<4	6.13	<0.1
10/02/00		310	<4	6.11	<0.1
10/04/00		360	<4	5.81	<0.1
10/30/00		520	<4	7.27	<0.1
11/01/00		520	<4	6.99	<0.1
11/03/00		540	15*	6.96	<0.1
11/06/00		550	190*	6.99	1.38
11/08/00		560	240*	7.11	0.75
11/10/00		600	<4	7.28	<0.1
11/13/00		590	<4	7.34	<0.1
11/15/00		610	<4	7.34	<0.1
11/17/00		680	<4	7.46	<0.1
11/20/00		680	<4	7.45	<0.1
11/22/00		750	<4	7.43	<0.1
11/27/00		750	<4	7.4	<0.1
11/29/00		810	<4	7.67	<0.1
12/01/00		820	<4	7.63	<0.1
12/04/00		870	<4	7.8	<0.1
12/06/00		920	<4	7.87	<0.1
12/08/00		990	<4	7.91	<0.1
12/11/00		1100	<4	7.63	<0.1
12/13/00		1100	<4	7.92	<0.1
12/15/00		1100	<4	7.85	<0.1
12/18/00		1100	<4	7.68	<0.1

* The ethanol feed rate was reduced intentionally to assure the only perchlorate removal mechanism was biological reduction

Table 3
FBR Process Control Data (Montgomery Watson Laboratories)
Jet Propulsion Laboratory Pilot Study
Pasadena, CA
April, 2001

	TOC					COD					BOD			NH3-N		PO4-P		TSS
Date	Ethanol Tap (ppm)	FBR Eff (ppm)	FBR Eff Filtered (ppm)	Post Air Eff (ppm)	Post Air Filtered (ppm)	Ethanol Tap (ppm)	FBR Eff (ppm)	FBR Eff Filtered (ppm)	Post Air Eff (ppm)	Post Air Filtered (ppm)	FBR Eff (ppm)	Post Air Eff (ppm)	Post Air Filtered (ppm)	FBR Eff (ppm)	Post Air Eff (ppm)	FBR Eff (ppm)	Post Air Eff (ppm)	FBR Eff (ppm)
09/09/00																		
09/11/00		<0.5												1.16		0.41		
09/13/00	4.6	0.9												2.09		0.61		
09/15/00		0.5												2.03		0.56		
09/18/00		0.5												2.51		0.5		
09/22/00	5.7	1												2.36		0.75		
09/25/00		<0.5												2.21		0.51		
09/27/00	21.1	4.1												1.99		0.62		
09/29/00		1.5												2.28		0.51		
10/02/00		4.6												2.3		0.48		
10/04/00						43	14							1.15		0.43		
10/30/00		2.2												0.97		0.33		
11/01/00	15.8	3.6												0.94		0.31		
11/03/00		0.8												1.03		0.31		
11/06/00		0.5												2.14		0.78		
11/08/00	9.42	0.56												<0.05		0.15		
11/10/00		1.7												3.32		1.2		
11/13/00		2.6												1.81		0.6		
11/15/00	14.37	2.5		1.09										1.68	1.61	0.56	0.42	
11/17/00		2.1					10							1.28		0.49		<10
11/20/00		3.25												0.059		0.3		
11/22/00	17.2	3.04	2.85			49	15	7						<0.05		0.13		<10
11/27/00	14.3	2.5	2.33			50	16	9						<0.05		0.16		
11/29/00		2.97												0.264		0.39		<10
12/01/00		3	2.94				15	10						0.724		0.5		
12/04/00	15.2	1.53	1.52			52	10	<5						1.01		0.44		
12/06/00		1.44												0.98		0.52		<10
12/08/00		1.47	1.29				14	5						2.36		0.79		
12/11/00	16	2.72				57	17	10						2.31		0.69		
12/13/00		2.2					17							2.04		0.65		<10
12/15/00		3.2	3.57				15	7						1.86		0.57		
12/18/00	19.3	3.28	2.75	1.49	1.52	69	20	9	16	6	8.4	8.1	<3	1.2	1.39	0.38	0.45	10

Table 4
Discharge Monitoring Data
Jet Propulsion Laboratory Pilot Study
Pasadena, CA
April, 2001

	Ion Exchange Effluent															Carbon Eff	
Date	BOD (ppm)	TSS (ppm)	O&G (ppm)	SS (ppm)	Turb (NTU)	Sulfides (ppm)	Phenols (ppm)	ClO4 (ppb)	VOCs (ppb)	Chloride (ppm)	Sulfate (ppm)	TDS (ppm)	Cr VI (ppm)	Toxicity (survial %)	NDMA (ng/l)	VOCs (ppb)	ClO4 (ppb)
09/09/00	3	<10	<3	<0.1	0.6	<0.1	<0.01		ND					100%			
09/11/00								<4									
09/15/00										27	<2.0	260					
09/18/00	<3	<10	<3	<0.1	<0.05	<0.1	<0.01	<4	ND								
09/25/00	<3	<10	<3	<0.1	0.1	<0.1	<0.01	<4	ND								
10/02/00	<3	<10	<3	<0.1	0.15	<0.1	<0.01	<4								ND	290
10/05/00										21.7	33.5	280					
10/30/00	<3	<10	<3	<0.1	0.1	<0.1	<0.01		ND	25.5	43.3	300	<0.005				140
11/06/00	<3	<10	<3	<0.1	<0.05	<0.1	<0.01	<4	ND	24.7	43.7	300	<0.005				
11/13/00	<3	<10	<3	<0.1	<0.05	<0.1	<0.01	<4	ND	25.7	41.4	290	<0.005				
11/15/00																ND	
11/20/00	<3	<10	<3	<0.1	0.15	<0.1	<0.01	<4		170	<2.0	360	<0.005			ND	
12/01/00										25.2	47.6						
12/13/00															<2		
12/18/00		<10	<3	<0.1	0.5	<0.1		<4	ND	25.1	44	300					