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Laboratory Evaluation of Base Materials for Neutralization of the Contaminated Aquifer at the F-Area Seepage Basins

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1. Executive Summary

Laboratory studies were performed to support field-testing of base injection into the F- Area Seepage Basins groundwater. The general purpose of these experiments is to provide information to guide the test of base injection and to identify potential adverse effects. More specifically, these experiments were designed to evaluate:

- the pH response (both intensity and duration) of aquifer materials to a range of base materials and emplacement techniques;
- the impact of these base treatments on contaminant mobility; and
- the effects of base treatments on the hydraulic properties of aquifer soils.

Characterization of porewater and soils collected from the impacted plume were highly variable with respect to contaminant concentrations. It is clear, however, that U and several heavy metals are present in relatively high concentration in the porewater and are, therefore, expected to be highly mobile. Neutralization of these contaminated soils by base injection was able to reduce aqueous-phase contaminant concentrations significantly over a wide range of experimental conditions.

The results of this study showed that the aquifer response, both geochemically and hydraulically, was sensitive to the amendment chemistry. The aqueous-phase contaminant and major ion (e.g., aluminum) concentrations were generally effectively and predictably reduced as the pH of the system was raised. For the specific contaminants Tc-99 and I-129 that are expected to exist as anions in the aquifer system, enhanced mobilization during base treatment did not appear to be a problem.

NaOH (with and without carbonate) and Na_3PO_4 were evaluated over a range of pH conditions from 8.5 to 10.0. These liquid bases were generally able to reduce aqueous-phase contaminant concentrations as long as the pH of the aqueous phase was elevated, but this response was relatively short-lived. Under specific conditions (high pH and the presence of carbonate), the liquid bases evaluated in this study exhibited some increase in colloid formation and reduction in hydraulic conductivity. In one case (NaOH test at pH of 10.0 in the presence of carbonate) a significant mobilization of U from the contaminated soil was observed. Based on these findings, it has, therefore, been recommended to ERD that the initial field-testing of liquid bases be conducted at a pH of 8.5 for Na_3PO_4 and a pH of 10.0 in the absence of carbonate for NaOH.

For the solid bases evaluated in this study (lime, zero valent iron, and a mixture of zero valent iron and apatite), the aqueous-phase contaminant concentrations were effectively reduced as the solid bases increased the pH, and in the case of the zero valent iron reduced the redox potential, of the aqueous phase. Additionally, under the experimental conditions evaluated, these pH changes were relatively long-lived. The tests on solid bases, further, did not exhibit significant colloid formation or enhanced mobilization of contaminants. There is, however, a higher degree of uncertainty regarding the engineering, emplacement, cost, and reversibility of such an approach. Although solid bases (e.g., iron metal) have been emplaced at depths similar to target depths for the F-Area aquifer by hydrofracting, it is recommended that future work focus on emplacement of solid bases to evaluate engineering parameters and costs, if solid amendments are pursued. The concern regarding reversibility of solid base application could be addressed by the use of reactive well packs as an alternative emplacement.

2. Introduction

This laboratory study was an evaluation of a range of base materials for their use as neutralization agents in the aquifer system at the F-Area Seepage Basins. These data are intended to form the basis for selection of base materials for the field testing of an in situ neutralization remediation concept. A laboratory approach with actual contaminated aquifer material from the F-Area Seepage Basins has permitted a more controlled evaluation of the influences of base injection on contaminant mobility and aquifer properties. In particular, these experiments were designed to provide data on the response of aquifer materials (e.g., base consumption and soil buffer capacity) to a range of potential base materials and evaluate potential adverse impacts of this approach on contaminant mobility and aquifer hydraulic permeability.

2.1. Remediation of the F- and H-Area Seepage Basins

The objective of the current remediation project at the F- and H-Area Seepage Basins is to meet the requirements of the RCRA Part B Permit (Phase 1) between SRS and the South Carolina Department of Health and Environmental Control. This has been accomplished by building and operating a pump-and-treat system capable of maintaining hydraulic control of a specified contaminated groundwater plume, treating the extracted groundwater, and reinjecting the treated water hydraulically upgradient of the extraction system. Treatment of the extracted groundwater consists of reducing the concentrations of RCRA contaminants and radionuclides in the treated groundwater to below the established groundwater protection standards. After a major reengineering program, the WTUs have been operating effectively and have been largely successful in meeting the groundwater treatment requirements of the RCRA Part B permit.

As the project moves into the subsequent phases of remediation, more passive and less costly remediation alternatives are being investigated. A field demonstration is underway to investigate the feasibility of pH adjustment and neutralization of the aquifer system at the F Area Seepage Basins. The purposes of pH adjustment are to (1) reduce the amount of major-ion metals (e.g., aluminum and iron) being treated by the WTUs and (2) immobilize contaminants within the aquifer system (WSRC-RP-2000-4169).

3. Methods and Materials

The general approach of this study was to conduct controlled leaching experiments on base-treated soil cores from F-Area Seepage Basins. More specifically, the Environmental Restoration Department (ERD) provided contaminated soil from downgradient of the F-Area Seepage Basins. This soil was divided into smaller samples that were treated with base amendments and leached with FEX-11 groundwater, also collected downgradient from the F-Area Seepage Basins. Effluent from these experiments, as well as soil prior to and after testing, were monitored, collected, and analyzed. This section is a description of the methods and materials used to conduct this study.

3.1. Experimental Matrix

The base amendments evaluated in this study were selected based on a review of the acid-mine drainage remediation literature, recommendations contained in the base injection "White Paper" (WSRC-RP-2000-4169), and previous work conducted in our lab (McWhorter and Serkiz, 2001). Concurrence with the selection of these materials was obtained from ERD Engineering and the Environmental Sciences and Technology Department of SRTC.

Ultimately, two liquid bases, sodium hydroxide (NaOH) and trisodium phosphate (Na_3PO_4) over a pH range from 8.5 to 10.0, and three solid amendments, zero valent iron (Fe(0)), lime (CaO), and apatite ($Ca_5(PO_4)_3(OH,F,Cl)$) in combination with Fe(0), were evaluated. It is well documented that the presence of carbonate can increase the mobility of uranium by the formation of more negatively charged and, therefore, more mobile uranium-carbonate complexes (Clark et al., 1995). The presence and absence of carbonate in both NaOH and Na_3PO_4 was investigated at a pH of 8.5 and 10.0. In contrast to the liquid bases, the solid bases are expected to be more costly to emplace. Two solids emplacement techniques, reactive permeable barriers and particle slurry injection (i.e., hydrofracting), have previously been employed in remediation efforts. To examine these two emplacement techniques, several column experiments were conducted with a solid base layer on the influent side (bottom) of the column to mimic a reactive permeable barrier approach and several were conducted with the solid base intimately mixed with the whole soil to mimic solids emplacement by slurry injection, or soil mixing.

A detailed experimental matrix for this study is summarized in Table 1.

Table 1 – Experimental Matrix

Base(s)	Form of Base	pH	CO_2 Added	Wt. Soil (g)	Wt. Solid Base (g)	Wt. 2nd Solid (g)	Flowrate (mL/min)	Analyses
Series 1								
Sodium Hydroxide	Liquid	8.5	Excluded	1054.7	0	0	5	pH, Turbidity, ICP-MS, ICP-ES, Tc-99, I-129, Permeability
Sodium Hydroxide	Liquid	8.5	Yes[a]	1008.0	0	0	5	pH, Turbidity, ICP-MS, ICP-ES, Tc-99, I-129, Permeability
Trisodium Phosphate	Liquid	8.5	Yes[a]	1010.3	0	0	5	pH, Turbidity, ICP-MS, ICP-ES, Tc-99, I-129, Permeability
Lime (CaO) w/ Sand	Solid[b]	NA	NA	882.9	100.0	100.0	5	pH, Turbidity, ICP-MS, ICP-ES, Tc-99, I-129
Iron Metal (Fe(0))	Solid[b]	NA	NA	991.2	100.0	100.0	5	pH, Turbidity, ICP-MS, ICP-ES, Tc-99, I-129
Glass Wool Blank (Series 1)	NA	NA	NA	NA	NA	NA	5	pH, Turbidity, ICP-MS, ICP-ES, Tc-99, I-129
Series 2								
Sodium Hydroxide	Liquid	9.0	Yes[a]	495.6	0	0	2	pH, Turbidity, Permeability
Trisodium Phosphate	Liquid	9.0	Yes[a]	498.4	0	0	2	pH, Turbidity, Permeability
Sodium Hydroxide	Liquid	9.5	Yes[a]	495.2	0	0	2	pH, Turbidity, Permeability
Trisodium Phosphate	Liquid	9.5	Yes[a]	500.8	0	0	2	pH, Turbidity, Permeability
Influent Blank (Series 2)	NA	NA	NA	NA	NA	NA	2	pH, Turbidity
Series 3								
Sodium Hydroxide	Liquid	10.0	Excluded	505.1	0	0	2	pH, Turbidity, ICP-MS, ICP-ES, Tc-99, I-129, Permeability
Trisodium Phosphate	Liquid	10.0	Yes[a]	509.2	0	0	2	pH, Turbidity, ICP-MS, ICP-ES, Tc-99, I-129, Permeability
Sodium Carbonate	Liquid	10.0	Yes[a]	503.1	0	0	2	pH, Turbidity, ICP-MS, ICP-ES, Tc-99, I-129, Permeability
Iron Metal (Fe(0))	Solid[c]	NA	NA	365.0	212.0	0	2	pH, Eh,Turbidity, ICP-MS, ICP-ES, Tc-99, I-129, Permeability
Iron Metal (Fe(0))/Apatite	Solid[c]	NA	NA	366.2	158.0	21.6	2	pH, Turbidity, ICP-MS, ICP-ES, Tc-99, I-129, Permeability
Influent Blank (Series 3)	NA	NA	NA	NA	NA	NA	2	pH, Turbidity, ICP-MS, ICP-ES, Tc-99, I-129

[a] CO_2 Added by bubbling air into the base solution

[b] Solid base added as a solid layer in bottom of column

[c] Solid base mixed directly with the soil

NA = Not applicable

ICP/MS for trace Uranium Analysis

ICP/ES for Ag, Al, B, Ba, Cd, Co, Cr, Cu,Ca, Fe, La, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Si, Sn, Sr, Ti, U, V, Zn, Zr

3.2. Base Preparation

The composition of the liquid bases (i.e., the amount of NaOH or Na_3PO_4 needed to reach the target pH) was calculated using the USEPA's metal speciation program MINTEQA2 (Allison et al., 1991). Bases in equilibrium with atmospheric CO_2 were modeled with a constant partial pressure of CO_2 naturally found in the atmosphere (i.e., 0.03 atm). The calculated concentrations of NaOH and Na_3PO_4 required to reach the targeted pH are given in Table 2.

Table 2 – Calculated Composition of Liquid Bases

pH	CO_2 Added	Molarity NaOH	Molarity Na_2CO_3	Molarity Na_3PO_4
8.5	Excluded	3.16E-06	NA	ND
8.5	Yes[a]	1.52E-03	1.50E-03	1.70E-03
9.0	Yes[a]	5.00E-03	4.75E-03	5.70E-03
9.5	Yes[a]	2.25E-02	1.91E-02	2.82E-02
10.0	Excluded	1.00E-04	NA	ND
10.0	Yes[b]	1.92E-01	1.26E-01	2.30E-01

[a] = Equilibrated w/ CO_2 by air bubbling

[b] = Na_2CO_3 added and then equilibrated w/ CO_2 by air bubbling

NA = Not applicable

ND = Not done as part of the experimental matrix

NaOH bases, with the exception of the pH 10 base, were prepared from an approximately 0.5 M NaOH stock solution that was diluted from reagent grade 50% wt/wt carbonate-free NaOH (reagent grade Fischer SS254-500 Lot # 001755-24). The stock solution of NaOH was added dropwise to gently stirring deionized water and the pH of the solution continuously monitored until the target pH was reached. For bases with added carbonate, the samples were bubbled for several hours with air using a fritted glass diffuser and the pH of the solution adjusted using stock NaOH.

In the case of the pH 10 NaOH solution, the base was added as sodium carbonate (Na_2CO_3) solid at the concentration in Table 2. The resulting solution was bubbled with air for several hours and the final pH (10.00 ± 0.05) was adjusted with a small amount of nitric acid. In theory, the addition of Na_2CO_3 (reagent grade Fischer S-263 Lot # 850897) and equilibration with atmospheric CO_2 should result in the same composition as adding NaOH to a solution equilibrated with atmospheric CO_2 at a pH of 10. The Na_2CO_3 addition approach was done at the request of ERD Engineering to help assure that the base was saturated with respect to carbonate.

Similarly, the $Na_3PO_4 \bullet 12H_2O$(reagent grade Fischer 5377 Lot # 995953) was added based on the above described speciation calculations. The solution was bubbled for several hours with air and its final pH adjusted with a small amount of NaOH or nitric acid to $\pm$ 0.05 pH units of the target pH.

The lime (CaO) used as a solid base was a reagent grade powder (Aldrich #20, 815-19 Lot # 001755-24) and was used without further purification. The Fe(0) was an approximately 40 mesh reagent grade powder (Fischer 157-500 Lot # 004544) and was used without further purification. The apatite was a "North Carolina Natural Phosphate" Code 30 from Texas Gulf Inc. and was used without further purification.

3.3. Contaminated Soil and Water Collection and Characterization

Soil from within the contaminated plume at the F-Area Seepage Basins was collected the week of December 18, 2000 by ERD and Site Geotechnical Services personnel and delivered to STRC on December 22nd. The sample was collected from an augered boring (location FBI-1SB) using a 3-inch inner diameter split spoon sampler (24-inches long). The boring location is immediately south of Basin F-3 (SRS coordinates N74924.53 and E50098.05) and lies approximately equidistant between monitoring well clusters FSB94 and FSB95. The sampled interval was from 85 ft to 103 ft below ground surface. Stratigraphically, the soil sample was collected within the Dry Branch Formation and is also within the Upper Aquifer Zone. Thibault (2000), included as Appendix A, describes the soil collected for this work as "medium brown, fine to coarse quartz sand, moderately to poorly sorted, with varying amounts of silt/clay (generally less than 25%)."

During collection of the samples, soils were segregated into 4-ft intervals and sealed in plastic bags. The deepest two soil samples (i.e., the borings that ended at 93 and 103 feet respectively) were used in this work. To prepare these two samples (identified as FBI-1SB-93 and FBI-1SB-103) for use in the laboratory study, approximately ten pounds of each sample were air-dried. Air-drying is a common procedure used in preparing soil for use in column studies. While this air-drying may have some impact on the surface chemistry of the soil, it is necessary in order to produce uniform compacted soil columns. The two samples were composited in approximately equal volumes prior to packing into the columns. Additionally, porewater from the bottom of the sample bags was collected for analysis. Although collection of porewater in this manner is not the standard procedure used at the SRS, these samples should nevertheless provide representative data of the porewater concentrations of inorganics from these two depths.

The pH of the composite soil was measured in deionized (DI) water and in a $CaCl_2$ solution using EPA Method 9045 (US EPA, 1986). The Analytical Development Section (ADS) of SRTC digested the sample using a hydrofluoric acid/aqua regia solution and conducted elemental analyses of the total digestion solutions using ion coupled emission spectrophotometry (ICP-ES) and ion coupled mass spectrometry (ICP-MS).

Mineralogical characterization by x-ray diffraction (XRD) analysis was also conducted by the ADS. XRD data were obtained on air-dried material deposited on glass sample holders using Vaseline as a binder. The powder XRD patterns were collected at room temperature, 22 °C, using a Siemens D500 x-ray diffractometer with Bragg-Bretano geometry using Cu Kα radiation (45 kV, 40 mA) with a 1° divergence slit, 0.15° detector slit, scintillation detector, and a diffracted beam graphite monochromator. Quartz present in the samples was used as an external standard to verify instrument d-spacing calibration. Intensities were collected by step-scanning from 5° to 70° (2Θ) with a step size of 0.02° (2Θ) and a counting time of 2 seconds for each step. The goniometer was controlled by the PC package Datascan supplied by MDI, Inc. Qualitative analysis of the various phases and other data processing were performed using the computer program Jade® from MDI, Inc.

The pH and elemental composition of each of the two individual porewater samples was completed. The pH was measured using a glass electrode calibrated with NIST traceable standards and elemental analysis was conducted on samples filtered through a 0.45µm filter using ICP-ES and ICP-MS.

Environmental Restoration Department and Site Geotechnical Services Department personnel collected and delivered to SRTC approximately 250-L of groundwater from extraction well FEX-11 in individual 50-L polyethylene carboys. Groundwater from this well, which is located near the proposed field test location, was used as the column influent for this study. Because influent blanks were conducted on all sets of column experiments, these samples were extensively analyzed for the parameters in Table 1 and the results are discussed in detail below.

3.4. Column Experiments

Three series of column experiments (see Table 1) were conducted as a part of this study. The general approach for all the column studies was consistent and a general schematic is shown in Figure 1. In each study, contaminated soil was repacked into columns and the column treated with base. The treated soil cores were then leached with contaminated water and the effluent periodically collected for chemical analyses. Differences between each of the series of experiments were the columns (both geometry and materials), monitoring of the effluent (both analyses conducted and the method of analysis), and, for Series 1 and 3, the manner that the solid bases were emplaced. Photographs of the experimental setups are included as Figures 2 (Series 1) and 3 (Series 2 and 3) and specific differences are discussed below.

3.4.1. Column Packing

Contaminated soil collected from within the contaminant plume at the F-Area Seepage Basins (see Section 3.3) was used for all the column experiments. For all experiments in this study, soils were packed after air-drying to a bulk density of about 2.0 g/cm^3. This results in an initial porosity of approximately 25 percent. The columns were packed in a series of “lifts” (i.e., separate sections) and each section was compacted to the target density prior to packing the next lift. At the bottom end of all columns was a glass frit covered with approximately ¼ inch of glass wool. At the top of the soil column was a glass wool blanket of about a ½ inch thickness.

Series 1

A series of six clear-PVC columns of 7.6 cm (3") in diameter and 17.8 cm (7") in height were used in this set of experiments (Figure 2). One of the columns was filled with glass wool and served as the experimental blank. Subsequent column tests utilized collection and analysis of the column influent. This change was made due to the variability pH introduced by the use of a glass wool blank.

For the solid bases (CaO and Fe(0)), the bottom of each column was packed with a sandwich consisting of 100 grams of solid base mixed with 100 grams of washed sea sand from Fischer Scientific Co. that served to increase the hydraulic conductivity of the base layer. This sandwich configuration was designed to simulate solid base emplacement in a reactive permeable wall design.

Series 2 and 3

The columns used in Series 2 and 3 experiments were constructed of glass and were 2.5 cm in diameter and 75 cm in height (Figure 3). The column design change was made due both to difficulty in sealing the columns used in Series 1 and the commercial availability (from Kontes Glass Co.) of the glass columns. Unlike the Series 1 experiment, no column blank was employed. Rather, the influent line was sampled along with the column effluent to evaluate the impact of changes in influent quality during the experiments.

No solid base additions were made in the Series 2 experiments. In the Series 3 experiment, solid bases were intimately mixed with the soil to simulate the injection of solids into the aquifer as a slurry. Solid base concentrations were selected based on an USEPA (1994) report indicating that guar gum gel is capable of suspending approximately 1.5 kg of coarse sand per liter of gel (about 57% sand by volume). These loadings are consistent with that reported for the emplacement of Fe(0) at the Department of Defense's Massachusetts Military Reservation CS-10 Plume (Hubble, 2001). In this remediation, approximately 32% wt/wt (Fe(0)/soil) was emplaced to a depth of 120' with this technique. Because Fe(0) is more dense than sand a value of 45% by volume of pore space was arbitrarily chosen as the solids amendment concentration. In the experiment where Fe(0) and apatite were both added, approximately 75% of the total weight of the amendments was added as Fe(0) and the remaining 25% was added as apatite.

3.4.2. Soil Column Leaching

Packed soil columns used in the testing of liquid bases were saturated with at least five pore volumes of contaminated groundwater from extraction well FEX11. After saturation, five pore volumes of the liquid base was injected into the column in a reverse flow (injection in the bottom of the column) configuration.

After base addition, all soil columns were leached in a reverse flow configuration (i.e., bottom up flow) with contaminated groundwater from extraction well FEX11 at a flow rate of about 3.25 pore volumes per hour. Once started, leaching experiments were run continuously until the end of the experiment. Series 1 experiments were run to 86 pore volumes, Series 2 to 10 pore volumes, and Series 3 to 25 pore volumes. Based on calculations made by the Site Geotechnical Services Department and documented in a transmittal letter to the SCDHEC (ESH-FSS-2001-00053), one pore volume corresponds to roughly 8 days for the base injection test zone at the F-Area Seepage Basins. Based on this estimate, the total experimental runtime in Series 1 is equivalent to 16.5 years, Series 2 to 2.0 years, and Series 3 to 4.8 years of field conditions.

3.4.3. Effluent Monitoring

Samples of pore solutions from the column studies were collected at the column outlet port at specified intervals and analyzed or monitored inline for pH, Eh, turbidity, activity (Tc-99 and I-129), and elemental composition. The specific analyses for each column in this study are summarized in Table 1.

pH

pH was measured using a glass electrode calibrated with NIST traceable standards. In the Series 1 experiments, the pH of selected effluent solutions were collected in 30-mL bottles and measured within an hour of collection using a Ross™ combination glass electrode. In the Series 2 and 3 experiments, the pH was monitored inline using a flow-through glass microelectrode (Microelectrodes Inc.) with a silver/silver chloride reference electrode with 3M KCl filling solution. Electropotential data from these flow-through electrodes were downloaded once per second to a laptop computer through a GPIB interface using Labview™ software. A photograph of the inline monitoring system is included as Figure 4.

Eh

In a single soil column (Fe(0) at 11.25% solids by volume - Series 3 experiments) the redox potential (Eh) of the effluent water was monitored inline using a flow-through platinum microelectrode (Microelectrodes Inc.) with a silver/silver chloride reference electrode with 3M KCl filling solution. Electropotential data from these electrodes were downloaded once per second to a laptop computer through a GPIB interface using Labview™ software.

Tc-99 and I-129

For the Series 1 experiments, two samples from each column were collected and analyzed for Tc-99 and I-129 by the ADS of SRTC. These analyses required 2-L of sample and were replaced in subsequent column tests by the batch anion leaching experiments described in Section 3.5 . In the Series 1 experiments, this sampling approach lead to a gap in pH and turbidity data from about 0.5 to 6 pore volumes.

Turbidity

Turbidity was measured using a light scatting technique calibrated against NIST traceable standards. In all experiments, samples for turbidity analyses were collected in sealed 30-mL bottles and measured within an hour of collection.

Elemental Composition

At selected effluent volumes 30-mL aliquots were collected for elemental composition analysis by ICP-ES and ICP-MS. Samples were analyzed without filtration and were acidified to a pH of approximately 1 with ultra-pure nitric acid prior to analysis. The decision to not filter samples prior to acidification was made because the concern being addressed was mobility of contaminants and unfiltered samples should better represent the total mobile phase (both aqueous and colloidal). Additionally, analysis of both filtered and unfiltered samples would have been too costly. Given the low turbidity of most samples, this approach is probably adequate. In samples with high turbidity, the reader must recognize the elemental data represents the sum of aqueous and colloidal concentrations. ICP-ES was used to analyze for major ion chemistry (e.g., Al, Si, Fe) and ICP-MS was used exclusively to quantify low-level uranium concentration. The ADS of SRTC conducted all ICP-ES and ICP-MS analyses.

3.4.4. Post Test Analysis

Soil pH measurements were conducted on selected soil samples (CO_2-saturated NaOH at pH 8.5, 9.5, and 10.0 and CO_2-saturated Na_3PO_4 at pH 8.5 and 10.0) collected at the end of column leaching. These measurements were made in a 1:1 soil: deionized (DI) water slurry and in a 1:1 soil: $CaCl_2$ slurry using EPA Method 9045 (US EPA, 1986).

Selected samples (Series 1 liquid bases) were also collected at the end of the soil leaching for XRD analysis as described in Section 3.3 of this report.

3.5. Batch Anion Leaching Experiment

One concern raised in previous reviews of the concept of base injection into the F-Area seepage basin aquifer and identified in the base injection "White Paper" (WSRC-RP-2000-4169) is the potential for mobilization of anionic contaminant species such as Tc-99 and I-129. Conceptually, this could occur due to increased anion competition from hydroxyl anion for soil sorption binding sites and a general decrease in the electrostatic interactions between anions and the soil surface due to the increasingly negative soil surface charge associated with an increased aquifer pH.

Because of the large sample volume requirements for the analysis of Tc-99 and I-129 (2-L to achieve required detection limits) it was not practical to collect samples from the column leaching experiments for these analyses. Instead, batch-leaching experiments were conducted for each set of base conditions in Series 1 and 3. The experimental conditions for the batch leaching experiments are listed in Table 3. Additionally, an experimental blank consisting of FEX11 water and contaminated soil was also run.

The general experimental approach to this study was to mix 1000 ± 50 g of air-dried contaminated soil (the same soil used in the column experiments) with either 3-L of base solution for the liquid bases or 3-L of FEX11 water for the solid bases and the soil experimental blank. Samples were periodically agitated and the pH measured at the start of the test and after 1, 2, 3 and 5 days. At the end of five days of equilibration, the soil solids were separated by filtration and the aqueous phase analyzed for Tc-99 and I-129 activity by the ADS of SRTC.

Table 3 – Batch Anion Leaching Experimental Conditions

Base(s)	Form of Base	pH	CO_2 Added	Leaching Solution	Wt. Soil (g)	Wt. Solid Base (g)	Wt. 2nd Solid (g)
Sodium Hydroxide	Liquid	8.5	Excluded	Base	1050.0	0.0	0.0
Sodium Hydroxide	Liquid	8.5	Yes[a]	Base	1022.7	0.0	0.0
Trisodium Phosphate	Liquid	8.5	Yes[a]	Base	973.1	0.0	0.0
Sodium Hydroxide	Liquid	10.0	Excluded	Base	951.0	0.0	0.0
Sodium Carbonate	Liquid	10.0	Yes[a]	Base	1029.8	0.0	0.0
Trisodium Phosphate	Liquid	10.0	Yes[a]	Base	1036.8	0.0	0.0
Iron Metal (Fe(0))	Solid[c]	NA	NA	FEX11	1014.8	589.4	0.0
Iron Metal (Fe(0))/Apatite	Solid[c]	NA	NA	FEX11	1035.4	446.1	61.1
Soil Blank	NA	NA	NA	FEX11	1016.6	0.0	0.0

[a] CO_2 Added by bubbling air into the base solution

[c] Solid base mixed directly with the soil

NA = Not applicable

3.6. Permeability Experiment

It has been shown from studies on basin operation (Cook, 1981) and injection of treated water into the aquifer system at the F-Area seepage basins from the water treatment units (Serkiz and Thibault, 1998) that as the pH of the injectate increases the hydraulic conductivity of the aquifer decreases. This is a potential negative impact of the base injection approach because reductions in hydraulic conductivity would alter the groundwater flow field and, consequently, affect the hydraulic control of the contaminant plume being remediated by the pump-and-treat system. To assess the potential impact of base injection on the aquifer hydraulic properties, falling head permeability tests were conducted on recompacted soils prior to and after treatment with base material using the general approach in ASTM D-5084.

Considerable variability is introduced into the measurement of hydraulic conductivity by the use of recompacted soils. Therefore, the hydraulic conductivity of an individual soil column was measured both before and after base treatment. Due to the limitations of working with recompacted soils, the absolute values for hydraulic conductivity are likely not highly accurate. The relative reduction in hydraulic conductivity prior to and after base treatment, however, should provide an estimate of the relative reduction in aquifer hydraulic conductivity associated with base treatment.   The affect of base treatment on hydraulic conductivity was measured for all experimental conditions used for the column leaching tests with the exceptions of the solid base "sandwiches" of CaO and Fe(0) in Series 1 from Table 1. The experimental conditions for the permeability testing are listed in Table 4.

Table 4 – Permeability Testing Experimental Conditions

Base(s)	Form of Base	pH	CO_2 Added	Wt. Soil (g)	Wt. Solid Base (g)	Wt. 2nd Solid (g)
Sodium Hydroxide	Liquid	8.5	Excluded	72.8	0	0
Sodium Carbonate	Liquid	8.5	Yes[a]	70.4	0	0
Sodium Hydroxide	Liquid	9.0	Excluded	71.9	0	0
Sodium Hydroxide	Liquid	10.0	Excluded	77.8	0	0
Sodium Carbonate	Liquid	10.0	Yes[a]	69.8	0	0
Trisodium Phosphate	Liquid	8.5	Yes[a]	75.1	0	0
Trisodium Phosphate	Liquid	9.0	Yes[a]	73.2	0	0
Trisodium Phosphate	Liquid	9.5	Yes[a]	81.8	0	0
Trisodium Phosphate	Liquid	10.0	Yes[a]	79.3	0	0
Iron Metal (Fe(0))	Solid[c]	NA	NA	55.8	32.4	0
Iron Metal/Apatite	Solid[c]	NA	NA	58.3	25.2	3.4

[a] CO_2 Added by bubbling air into the base solution

[c] Solid base mixed directly with the soil

NA = Not applicable

The general procedure employed in this study to measure falling head hydraulic conductivity is as follows and a schematic of the experimental setup is shown in Figure 5.

Liquid Bases

- Pack approximately 70 g of air-dried contaminated soil (same as that used for column leaching study) in five lifts compacting after each lift to approximately 2.0 g/cc to a 2.5-cm diameter by 10-cm height glass column.
- Saturate with 60-mL FEX11 water from top of column by gravity feed.
- Pump 100-mL FEX11 water with peristaltic pump into bottom of column at 5 mL/min.
- Measure falling head hydraulic conductivity of FEX11 water.
    1. Measure vertical distance from the 100-mL burette mark to the outlet on the bottom of the soil column.
    2. Close three-way valve on bottom of soil column.
    3. Fill burette with FEX11 water to the 100-mL mark.
    4. Open three-way valve on bottom of soil column and time the fall of solution in the burette to the 0-mL mark and close three-way valve on bottom of soil column.
    5. Repeat Steps 3 and 4 twice.
- Pump 100-mL liquid base (approximately 3 pore volumes) with peristaltic pump into bottom of column at 2 mL/min.
- At the end of the base injection, allow the column to sit for 15 minutes.

- Measure falling head hydraulic conductivity of liquid base.
  1. Close three-way valve on bottom of soil column.
  2. Fill burette with base liquid to the 100-mL mark.
  3. Open three-way valve on bottom of soil column, time the fall of solution in the burette to the 0-mL mark, and close three-way valve on bottom of soil column.
  4. Repeat Steps 3 and 4 twice.

Solid Bases

- Mix appropriate amount of air-dried contaminated soil (same as that used for column leaching study) and solid amendments.
- Pack approximately 70 g soil/solid base mixture in five lifts compacting after each lift to approximately 2.0 g/cc to a 2.5 cm diameter by 10 cm height glass column.
- Saturate with 60-mL FEX11 water from top of column by gravity feed.
- Pump 100-mL FEX11 water with peristaltic pump into bottom of column at 5 mL/min.
- Measure falling head hydraulic conductivity of FEX11 water.
  1. Measure vertical distance from the 100-mL burette mark to the outlet on the bottom of the soil column.
  2. Close three-way valve on bottom of soil column.
  3. Fill burette with FEX11 water to the 100-mL mark.
  4. Open three-way valve on bottom of soil column and time the fall of solution in the burette to the 0-mL mark and close three-way valve on bottom of soil column.
  5. Repeat Steps 3 and 4 twice.
- Pump 100-mL FEX11 water (approximately 3 pore volumes) with peristaltic pump into bottom of column at 2 mL/min.
- At the end of FEX 11 water injection, allow the column to sit for 60 minutes.
- Measure falling head hydraulic conductivity of liquid base.
  1. Close three-way valve on bottom of soil column.
  2. Fill burette with base liquid to the 100-mL mark.
  3. Open three-way valve on bottom of soil column and time the fall of solution in the burette to the 0-mL mark and close three-way valve on bottom of soil column.
  4. Repeat Steps 3 and 4 twice.

4. Results

This section describes the results of laboratory testing of base injection to neutralize the aquifer at the F-Area Seepage Basins. Included in this section are the results from: characterization of the contaminated water and soil used in the study, column leaching of base-treated soils, batch anion leaching experiments, and hydraulic conductivity testing of base-treated soils.

4.1. Contaminated Soil and Water Collection and Characterization

The soil pH of the composite sample from the 93' and 103' (composite sample used in the column leaching studies) was acidic (3.79, 4.07 in DI water and 3.97, 3.95 in $CaCl_2$). These values are substantially lower than those reported for two background soils collected from the same lithologic unit in the F Area (5.25, 4.87 in DI water and 4.50, 4.27 in $CaCl_2$) (Johnson, 1995). The difference in soil pH values between those measured in DI water versus $CaCl_2$ has been attributed to the presence of exchangeable Al that after displacement by Ca, becomes hydrolyzed and produces protons. If this mechanism is correct, then the samples from the contaminant plume have little exchangeable Al relative to the background samples.

The individual depth-discrete samples were digested with hydrofluoric acid/aqua regia in a microwave and the results of the elemental analysis are included in Table 5. The results show similar elemental composition between the two soil samples and measurable levels of the RCRA regulated metals Ba, Cd, and Cr. The major ion chemistry of these samples is somewhat surprising with Fe representing the largest fraction of the identified elemental mass. It is expected that Si values are lower than the real composition due to the formation and loss of silica fluoride gas during sample digestion.

Consistent with previous work (Johnson, 1994), XRD mineralogical characterization of the composite soil sample indicated the presence of quartz and kaolinite with possible minor amounts of muscovite/illite. The x-ray diffraction pattern is included as Figure 6.

Porewater collected from the two soil samples collected at 103' and 93' depth was characterized for elemental composition and the data are summarized in Table 6. High concentrations of hydrogen ion (i.e., low pH), sodium, dissolved metals (Al, Fe, and Mn), and silica dominate the elemental composition of this water. This major ion chemistry is consistent with the acid-dissolution of aluminosilicates like kaolinite and metal (oxy)hydroxides like gibbsite and hydrous ferric oxide. Additionally, high concentrations of uranium (up to almost 2 mg/L) and heavy metals (Ba, Cd, Ni, and Pb) at concentrations above their primary drinking water standards were reported. Even though the samples were collected within 10' of each other, considerable variability (up to almost an order of magnitude for Co) was observed between these samples. The sample collected at 103' depth generally having higher concentrations than the sample from 93'.

Table 5 – Results of Elemental Analysis of Soil Digestion

	Sample Depth	
Analyte	103'	93'
Ag	< 0.0001%	0.0001%
Al	0.0707%	0.0732%
B	< 0.0003%	< 0.0003%
Ba	0.0015%	0.0046%
Cd	0.0001%	0.0001%
Co	< 0.0001%	< 0.0001%
Cr	0.0001%	0.0001%
Cu	0.0001%	0.0001%
Ca	0.0107%	0.0071%
Fe	0.2954%	0.2869%
La	< 0.0002%	< 0.0002%
Li	< 0.0000%	< 0.0000%
Mg	0.0026%	0.0011%
Mn	0.0021%	0.0005%
Mo	< 0.0000%	< 0.0000%
Na	0.0143%	0.0017%
Ni	0.0001%	< 0.0001%
P	0.0117%	0.0153%
Pb	< 0.0005%	< 0.0005%
Si	0.0054%	0.0049%
Sn	< 0.0003%	< 0.0003%
Sr	0.0003%	0.0009%
Ti	0.0005%	0.0004%
U	< 0.0050%	< 0.0050%
V	0.0005%	0.0006%
Zn	0.0005%	0.0007%
Zr	0.0002%	0.0001%

Table 6 – Results of Elemental Analysis of Porewater and Extraction Well Samples (all data in mg/L except pH).

		Sample Depth		FEX11
Analyte	MCL	103'	93'	
Ag	0.1	0.012	0.008	0.007
Al		102.111	29.115	18.019
B		0.032	0.098	0.384
Ba	2.000	2.145	0.561	0.376
Cd	0.005	0.031	0.021	0.005
Co		1.004	0.125	0.053
Cr	0.1	0.044	0.022	0.010
Cu		0.346	0.196	0.054
Ca		21.127	12.37	5.137
Fe		17.731	43.52	0.030
La		0.271	0.077	0.150
Li		0.023	0.016	0.011
Mg		7.774	2.239	2.187
Mn		17.398	5.368	1.412
Mo		0.047	0.016	0.012
Na		120.730	52.140	67.180
Ni	0.1	0.327	0.214	0.054
P		0.191	0.102	0.062
Pb		0.132	0.053	0.041
Si		22.072	52.331	32.943
Sn		0.117	0.058	0.033
Sr		0.132	0.071	0.024
Ti		0.259	0.011	0.023
U		1.932	1.408	1.434
V		0.008	0.01	0.005
Zn		3.823	6.805	0.075
Zr		0.317	0.016	0.032
pH		3.48	3.40	3.34

A representative result from elemental analysis of FEX11 extraction well water is also included in Table 6. Almost without exception, the dissolved concentrations from this extraction well water were lower than the porewater collected from the discrete soil samples used in this work. Care must, therefore, be exercised in the interpretation of the column leaching results (especially during the start of the experiments) due to potential non-equilibrium conditions between the extraction well water and porewater from the contaminated soil cores.

4.2. Column Experiments

The column experiments were designed to examine the pH response (both intensity and duration) of aquifer materials to a range of base materials and investigate the impact of these base treatments on contaminant mobility. The pH response was evaluated by monitoring effluent pH values after base injection and the contaminant mobility was evaluated by elemental analysis of the column effluent. Additionally, because facilitated transport of contaminants with colloidal material has been identified as a potential negative impact to the system, turbidity measurements of the effluent stream were conducted in order to evaluate the potential for colloid formation during base treatment.

Elemental analyses were conducted on selected effluent aliquots from the column leaching experiments. Samples were analyzed by ICP-ES for Ag, Al, B, Ba, Cd, Co, Cr, Cu, Ca, Fe, La, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Si, Sn, Sr, Ti, U, V, Zn, Zr and by ICP-MS for U. Because U has been identified as the major long-term risk driver (WSRC-91-1017, 1992) for this aquifer system and Al has been implicated as a significant contributor to secondary waste generation at the F-Area Water Treatment Unit (WSRC-RP-2000-4169), these two elements will be the focus of the data analysis. The remainder of the ICP-ES data are included as Appendix B.

The general approach for data analysis and presentation was to examine the changes in the effluent quality as a function of time (i.e., number of pore volumes effluent solution). For each base treatment, a graph showing the number of pore volumes of effluent versus effluent and influent quality (pH, turbidity, U, Al) has been generated. Additionally, graphs of pore volumes of effluent versus pH and turbidity for all pH values (8.5, 9.0, 9.5, and 10.0) of both NaOH saturated with CO_2 and Na_3PO_4 saturated with CO_2 are also included. These allow comparison of the influence of pH within these two bases. An index of the graphs generated for this study is included as Table 7.

Table 7 – Index of Experimental Conditions for Graphs

Base(s)	Form of Base	pH	CO_2 Added	Parameters Plotted	Figure No.
Sodium Hydroxide	Liquid	8.5	Yes	pH, Turbidity, Al, U	Figure 7
Sodium Hydroxide	Liquid	10.0	Yes	pH, Turbidity, Al, U	Figure 8
Sodium Hydroxide	Liquid	8.5, 9.0, 9.5, 10.0	Yes	pH, Turbidity	Figure 9
Sodium Hydroxide	Liquid	8.5	Excluded	pH, Turbidity, Al, U	Figure 10
Sodium Hydroxide	Liquid	10.0	Excluded	pH, Turbidity, Al, U	Figure 11
Trisodium Phosphate	Liquid	8.5	Yes	pH, Turbidity, Al, U	Figure 12
Trisodium Phosphate	Liquid	10.0	Yes	pH, Turbidity, Al, U	Figure 13
Trisodium Phosphate	Liquid	8.5, 9.0, 9.5, 10.0	Yes	pH, Turbidity	Figure 14
CaO (Sandwich)	Solid	NA	NA	pH, Turbidity, Al, U	Figure 15
Fe(0) (Sandwich)	Solid	NA	NA	pH, Turbidity, Al, U	Figure 16
Fe(0) (11.25%)	Solid	NA	NA	pH, Turbidity, Eh, Al, U	Figure 17
Fe(0) (8.20%)/Apatite (2.77%)	Solid	NA	NA	pH, Turbidity, Al, U	Figure 18

4.2.1. NaOH

pH Response

The data for the treatment of contaminated soil with NaOH are presented in Figures 7-11. The general response of the base addition is an initial increase in effluent pH that is proportional to the pH of the NaOH injection (see Figure 9). The duration of the pH response, as seen by the difference between the influent and effluent pH, however, depends on the pH of the base injection. As would be expected, the higher the pH of the base injection the longer the increased pH effect lasts. For the highest base pH values, the effect lasts between several tenths to about 10 pore volumes (equivalent approximately to between one week and two years if these lab studies can be scaled to field conditions). The effect of carbonate addition, designed to add additional buffering capacity, can be evaluated by comparing Figure 7 (pH 8.5 w/carbonate) to Figure 10 (pH 8.5 carbonate excluded) and Figure 8 (pH 10.0 w/carbonate) to Figure 11 (pH 10.0 carbonate excluded). At a pH of 8.5, the additional buffering capacity had little effect on the magnitude or duration of the pH response. At a pH of 10.0, however, the initial pH of the column effluent was almost 4 pH units greater for the CO_2 saturated base but the duration for both of these treatments was about the same (approximately 10 pore volumes).

Turbidity

The turbidity was generally low over all pH values either with or without the addition of carbonate. The one exception is the flux of a spike of large amounts of colloidal material, turbidity of about 800 NTUs, at pH 10.0 in the carbonate saturated system (see Figure 8). A photograph of the effluent is included as Figure 19. Associated with this turbidity spike is an increase in Al concentration above influent concentrations that suggests that these colloids are at least partially composed of aluminum bearing mineral phases.

U

As expected, with the exception of the pH 10.0 carbonate-saturated treatment, the uranium concentration is inversely proportional to pH (i.e., as the pH increases the U concentration decreases). For the NaOH base, the pH-U relationship appears to be relatively fast in reaching equilibrium. That is to say that there does not appear to be a time lag between the change in pH and the resulting change in U concentration. For the pH 10 treatment (both with and without carbonate), the reduction in U mobility appears to outlive the pH effect through the end of the experiment (see Figures 8 and 11). Interestingly, pH 10.0 carbonate-saturated treatment actually appears to mobilize U from the soil column (i.e., U concentrations above influent levels) as a large spike in U concentration (about 5 ppm) was observed for this experiment (see Figure 8). Because this concentration spike precedes the first increase in turbidity above influent levels, it is thought that this mobilization results from the formation of mobile aqueous specie(s), possibly carbonate complexes, and not from colloidal transport. The data indicating increased uranium mobility with increased carbonate content is consistent with data reported by Hsi and Langmuir (1985) for U sorption to the iron oxide goethite. Geothite (FeOOH) is typical of the amorphous iron coatings found on SRS soils and the Hsi and Langmuir results showed about a two-order of magnitude reduction in the Kd at a pH of 9.0 for the addition of 1×10^{-3} M total carbonate (note: 1.4×10^{-3} was used in pH 10.0 column study). For a pH of 10.0, given the slopes of the sorption edges, this reduction in Kd is expected to be even greater.

Al

The same inverse relationship between pH and Al that was observed for soluble U is generally exhibited by the Al concentrations in the column effluent. The exceptions are that no increase in Al was observed concurrent to the onset of the U spike in the pH 10 carbonate-saturated treatment and that the Al concentrations rose back to influent concentrations much more quickly with increasing pH than did the U concentrations.

4.2.2. Na_3PO_4

pH Response

The data for the treatment of contaminated soil with NaOH are presented in Figures 12-14. The general response of the base addition is an initial increase in effluent pH that is proportional to the pH of the Na_3PO_4 injection (see Figure 14). Unlike the NaOH tests, the Na_3PO_4 tests were only conducted in carbonate saturated systems. In contrast to the NaOH system (see Figure 9), the sodium phosphate treatments, with the exception of the pH 8.5 experiment, affected a greater change in the effluent pH and exhibited a longer duration of increased pH (see Figure 14). This can be explained by the additional buffering capacity of the phosphate system over that of hydroxide.

Turbidity

Unlike most of the NaOH conditions tested, all experiments at pH values greater than 8.5 resulted in the formation of large quantities of colloids (up to over 800 NTUs). This is not entirely surprising, as some of the first mechanistic-based work on the formation of colloids in aquifer systems was reported for the iron-phosphate system (Gschwend and Reynolds, 1987).

U

As was observed for the NaOH testing, U concentrations were inversely proportional to pH (see Figures 12 and 13). Like the NaOH system the pH-U relationship appears to be relatively fast to come to equilibrium but appears to have a much longer lasting effect on the suppression of U concentrations in the column effluent. This is probably due to the formation of sparing soluble uranyl-phosphate solid phases.

Al

The Al concentrations in the column effluent are, like those for the NaOH system, consistent with a pH-dependent solubility control (see Figures 12 and 13). Unlike U, however, the soluble Al concentrations rebound quickly when the pH of the column effluent become acidic.

4.2.3. Solid Bases

pH Response

Depending on the solid used and the method of placement, the pH response of the solid bases was different in magnitude and its duration relatively long-lived (see Figures 15-18). For the CaO (lime) sandwich emplacement, the effluent pH quickly rose to a pH of about 11 and remained there until the end of the test (about 90 pore volumes) (Figure 15). For the zero valent iron (Fe(0) sandwich emplacement, the pH of the effluent was increased only by 0.5 to 1 pH units (see

Figure 16). This is thought to be due to the short contact time between the influent and the Fe(0) sandwich. In contrast, when the Fe(0) was mixed directly with the soil, the effluent pH was raised to between 7 and 9 (see Figure 17) over almost all the test (14 pore volumes). In the system where Fe(0) and apatite were mixed directly with the soil, the effluent pH quickly reached a value of slightly greater than 9 and remained at that value for the majority of the test (see Figure 18). In both tests where iron was mixed directly with the soil (Figures 17 and 18) an approximately two pH unit drop was observed between 10 and 12 pore volumes. The pH, however, appears to restabilize at a pH of 7. The reason for this is not presently known, but it could be due to a reduction on the rate of Fe(0) dissolution caused by surface poisoning.

Turbidity

The turbidity in all effluent samples collected for the solid bases were low (below 10 NTU) and in the overwhelming majority of cases were equal to or less than the turbidity of the influent solution. This lack of colloid formation observed in the solid base tests may be due to the less frequent changes in the system chemistry (i.e., the system comes to steady-state conditions more quickly and remains there longer).

U

The effluent U concentrations for all solid bases evaluated were quite low (almost all at least a factor of 10 below influent U concentrations) and remained low over the entire duration of testing (see Figures 16-19).

Al

The Al concentrations in the column effluents for the solid followed those for U reductions almost exactly (see Figures 16-19) with almost all column effluent Al concentrations below 2 ppm.

Eh

The redox potential of the column with Fe(0) mixed with soil was monitored and showed the development of reducing conditions down to approximately –200 mV. (see Figure 17). The development of reducing conditions is also expected to reduce U and heavy metal mobility, although the long-term development of these reducing conditions in an aquifer can not, at present, be quantified.

4.2.4. Post-Leaching Soil Analyses

Soil pH measurements were conducted on selected soil samples after column leaching (5 pore volumes base treatment and 10 pore volumes leaching with FEX11 water) and the results are summarized in Table 8. The data for these NaOH treatments indicate that the soil pH can be raised relatively easily by a simple base injection. This is consistent with the relatively low buffering capacity associated with low-clay and kaolinite dominated soils.

Table 8 – Results of Selected Post Column Leaching Soil pH

Base	Form of Base	pH	CO_2 Added	pH DI H_20	Std Dev	pH $CaCl_2$	Std Dev
Sodium Hydroxide	Liquid	8.5	Excluded	3.56	0.13	4.23	0.13
Sodium Hydroxide	Liquid	9.5	Excluded	4.41	0.21	4.12	0.04
Sodium Hydroxide	Liquid	10.0	Excluded	4.46	0.08	4.21	0.16
None (Untreated Soil)	NA	NA	NA	3.93	0.20	3.96	0.01

XRD analyses were conducted on the same set of post-leaching soils listed in Table 8. All diffraction patterns were indistinguishable from the untreated soil with only kaolinite and quartz identified. A representative diffraction pattern is included as Figure 20.

4.3. Batch Anion Leaching Experiment

Under the solid-to-liquid-ratio of the batch leaching experiments (333g soil/L), the pH of the aqueous phase generally increases for the first 2-3 days of testing and then starts to drop (see Table 9). In the column leaching studies, the contact time for influent water was on the order of 50 min and, therefore, the full extent of reaction may not have been reached in the column leaching study.

Tc-99 and I-129 data for these batch studies are summarized in Table 10. In no case is the Tc-99 or I-129 activity greater in the base treated sample than in the soil and extraction water (FEX11) blank. This suggests that anion desorption will not be problematic under field application.

Table 9 – pH Results for Batch Leaching Studies

Base	Form of Base	pH	CO_2 Added	Leaching Solution	Elapsed Time (min) 0	385	1875	3205	4255	7110
Sodium Hydroxide	Liquid	8.5	Excluded	Base	3.42	3.90	4.78	4.63	4.01	4.31
Sodium Hydroxide	Liquid	8.5	Yes[a]	Base	6.67	4.46	6.44	6.68	6.15	6.47
Trisodium Phosphate	Liquid	8.5	Yes[a]	Base	7.52	5.81	6.50	6.91	6.37	6.78
Sodium Hydroxide	Liquid	10.0	Excluded	Base	9.08	7.67	8.73	8.84	7.84	7.91
Sodium Carbonate	Liquid	10.0	Yes[a]	Base	9.98	9.26	10.04	10.78	10.03	9.89
Trisodium Phosphate	Liquid	10.0	Yes[a]	Base	9.92	10.14	9.96	10.41	9.89	9.83
Iron Metal (Fe(0))	Solid[c]	NA	NA	FEX11	4.30	6.19	5.05	6.06	6.13	4.81
Iron Metal Fe(0))/Apatite	Solid[c]	NA	NA	FEX11	4.12	5.81	4.98	5.56	5.22	5.27
Soil Blank	NA	NA	NA	FEX11	3.85	3.61	3.74	3.63	3.44	3.54

[a] CO_2 Added by bubbling air into the base solution
[c] Solid base mixed directly with the soil

Table 10 – Tc-99 and I-129 Results for Batch Leaching Studies

Base (s)	Form of Base	pH	CO_2 Added	Leaching Solution	Tc-99 (pCi/L)	I-129 (pCi/L)
Sodium Hydroxide	Liquid	8.5	Excluded	Base	155	<5.11
Sodium Hydroxide	Liquid	8.5	Yes[a]	Base	<30.5	6.92
Trisodium Phosphate	Liquid	8.5	Yes[a]	Base	<28.2	4.99
Sodium Hydroxide	Liquid	10.0	Excluded	Base	<31.6	5.79
Sodium Carbonate	Liquid	10.0	Yes[a]	Base	<31.8	9.14
Trisodium Phosphate	Liquid	10.0	Yes[a]	Base	<42.6	9.99
Iron Metal (Fe(0))	Solid[c]	NA	NA	FEX11	<32.2	47.1
Iron Metal (Fe(0))/Apatite	Solid[c]	NA	NA	FEX11	112.0	34.5
Soil Blank	NA	NA	NA	FEX11	360.0	34.8

[a] CO_2 Added by bubbling air into the base solution

[c] Solid base mixed directly with the soil

NA = Not applicable

4.4. Permeability Results

The results for hydraulic conductivity testing of the base treatments are summarized in Table 11. The average standard deviation for the packed columns without base treatment (data not presented) was 18 percent. Given this high variability, as stated previously, the percent reduction in falling head permeability was used to evaluate the effects of base addition on hydraulic conductivity and was calculated as:

% Reduction in K = 100 x ($K_{treated}$ - K_{soil})/K_{soil}

where: $K_{treated}$ is hydraulic conductivity for the bases treated soil and base

K_{soil} is hydraulic conductivity for the untreated soil w/ FEX11 water

The results indicate that generally a significant reduction in hydraulic conductivity occurred as the pH of the system increased with the liquid bases. The magnitude of this effect was greatest for NaOH at pH 10.0 and Na_3PO_4 at pH values equal to or above 9.0. No reduction in hydraulic conductivity was observed for the solid bases tested. These systems, however, were likely not at steady-state condition and do not account for the impacts of solids emplacement. Therefore, results for solid bases may not be representative of hydraulic conductivities under field-emplacement conditions.

Table 11 – Falling Head Permeability Results

Base(s)	Form of Base	pH	CO_2 Added	% Reduction
Sodium Hydroxide	Liquid	8.5	Excluded	-3
Sodium Carbonate	Liquid	8.5	Yes[a]	19
Sodium Hydroxide	Liquid	9.0	Excluded	-2
Sodium Hydroxide	Liquid	10.0	Excluded	112
Sodium Carbonate	Liquid	10.0	Yes[a]	-3
Trisodium Phosphate	Liquid	8.5	Yes[a]	-1
Trisodium Phosphate	Liquid	9.0	Yes[a]	20
Trisodium Phosphate	Liquid	9.5	Yes[a]	45
Trisodium Phosphate	Liquid	10.0	Yes[a]	27
Iron Metal (Fe(0))	Solid[c]	NA	NA	-23
Iron Metal (Fe(0))/Apatite	Solid[c]	NA	NA	-3

[a] CO_2 Added by bubbling air into the base solution

[c] Solid base mixed directly with the soil

NA = Not applicable

5. Conclusions and Recommendations

Characterization of porewater and soils collected from the impacted plume were highly variable with respect to contaminant distributions. It is clear, however, that U and several heavy metals are present in relatively high concentration in the porewater and are, therefore, expected to be highly mobile. Partial neutralization of these contaminated soils by base injection, however, was able to reduce aqueous-phase concentrations of these contaminants over a wide range of experimental conditions. This aquifer neutralization approach should, therefore, be evaluated for passive remediation of that aquifer system. Additionally, given the high degree of vertical contaminant variability observed in samples collected for this study and in previous work (Serkiz and Johnson, 1994) suggests that depth-discrete (a.k.a., “precision”) pumping of the contaminant plume could be advantageous in reducing the volume of water treated in future phases of remediation.

The results of this study showed that the aquifer response, both geochemically and hydraulically, was sensitive to the amendment chemistry. The aqueous-phase contaminant and major ion (e.g., aluminum) concentrations were generally effectively and predictably reduced as the pH of the system was raised. For the specific contaminants that are expected to exist as anions (e.g., Tc-99 and I-129) in the aquifer system, enhanced mobilization during base treatment was not observed.

Liquid Bases

NaOH (with and without carbonate) and Na_3PO_4 were evaluated over a range of pH conditions from 8.5 to 10.0. These liquid bases were generally able to reduce aqueous-phase contaminant concentrations as long as the pH of the aqueous phase was elevated. The duration of the pH elevation, however, was relatively short-lived. Under specific conditions, the liquid bases evaluated in this laboratory study exhibited the following negative effects and, all other parameters being equal; these conditions should be avoided in field implementation of this approach.

- Large colloid fluxes were observed in this study for liquid bases (both NaOH and Na_3PO_4) saturated with carbonate at higher pH values (pH 9.0 and higher).
- A significant mobilization of U from contaminated soil, presumably due to the formation of mobile uranyl complexes (likely of a uranyl-carbonate specie(s)), was observed in the NaOH test at pH of 10.0 in the presence of carbonate.
- There was a general, although not completely systematic, reduction in hydraulic conductivity of up to 112 percent observed for liquid bases as the pH of the base increased.

Based on these findings, it has, therefore, been recommended to ERD that field-testing of liquid bases employ pH values on the low end of those tested in this study (pH of 8.5) for bases (both NaOH and Na_3PO_4) equilibrated with atmospheric CO_2. In the absence of carbonate, NaOH at higher pH values is not expected to exhibit negative impacts to contaminant mobility and, therefore, NaOH at a pH of 10.0 has been recommended to ERE for field evaluation.

Solid Bases

For the solid bases evaluated in this study (lime, zero valent iron, and a mixture of zero valent iron and apatite), the aqueous-phase contaminant concentrations were effectively reduced as the solid bases increased the pH of the aqueous phase. Additionally, under the experimental conditions evaluated, these pH changes were relatively long-lived. There is, however, a higher degree of uncertainty regarding the engineering, emplacement, cost, and reversibility of such an approach. This study looked at mimicking two types of base emplacements: a reactive permeable wall and slurry injection. Both approaches yielded positive results in reducing contaminant and major ion concentrations, with the slurry experiments resulting in a greater pH response for the Fe(0). The tests on solid bases did not exhibit significant colloid formation or enhanced mobilization of contaminants under the experimental conditions evaluated.

Although solid bases (e.g., iron metal) have been emplaced at depths similar to target depths for the F-Area aquifer by hydrofracting, it is recommended that future work focus on emplacement of solid bases in order to evaluate engineering parameters and costs, if solid amendments are pursued. The concern regarding reversibility of solid base application could be addressed by the use of reactive well packs (Gilmore et al., 1998) as an alternative, but reversible, emplacement technique. In this approach solid materials are placed in the well bore in mesh bags and, if necessary, could be removed if unanticipated negative impacts to the aquifer chemistry were observed.

6. References

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Figures

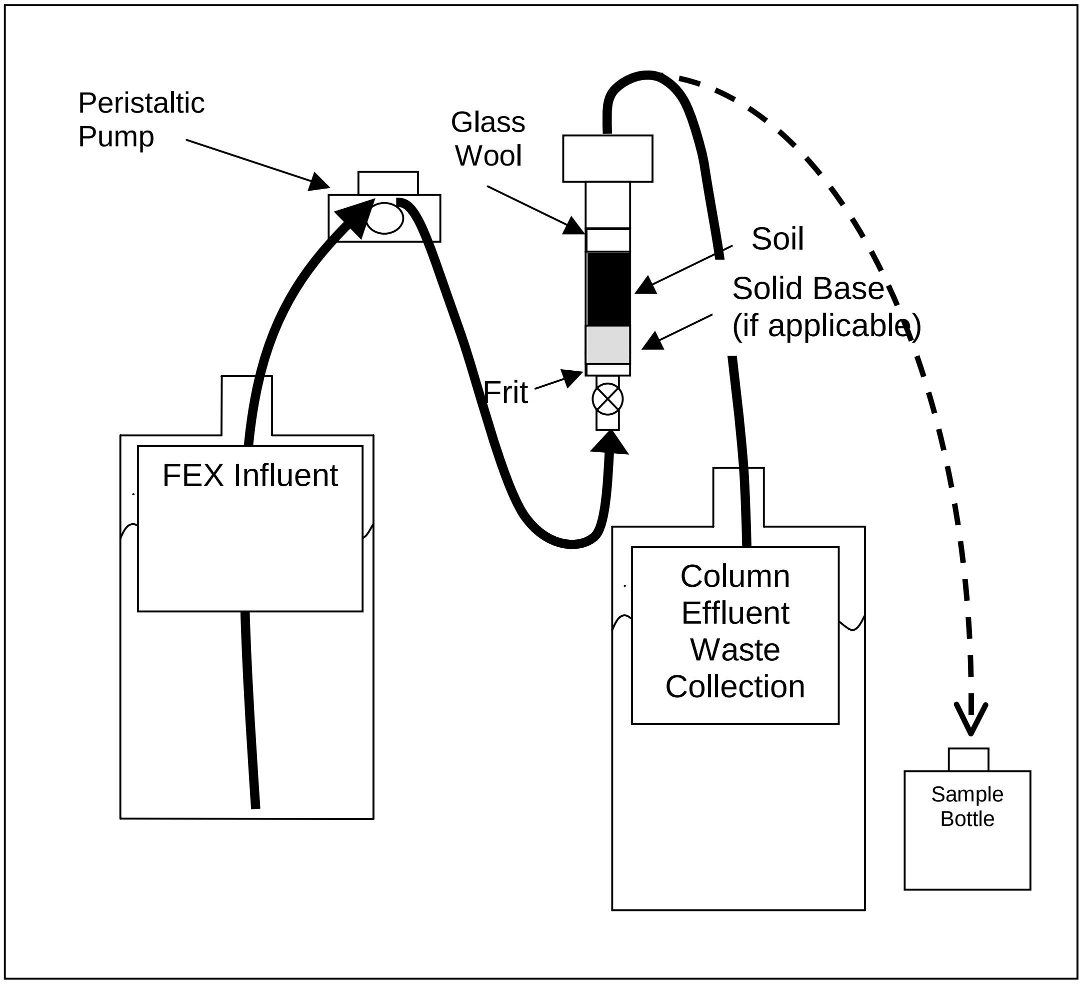
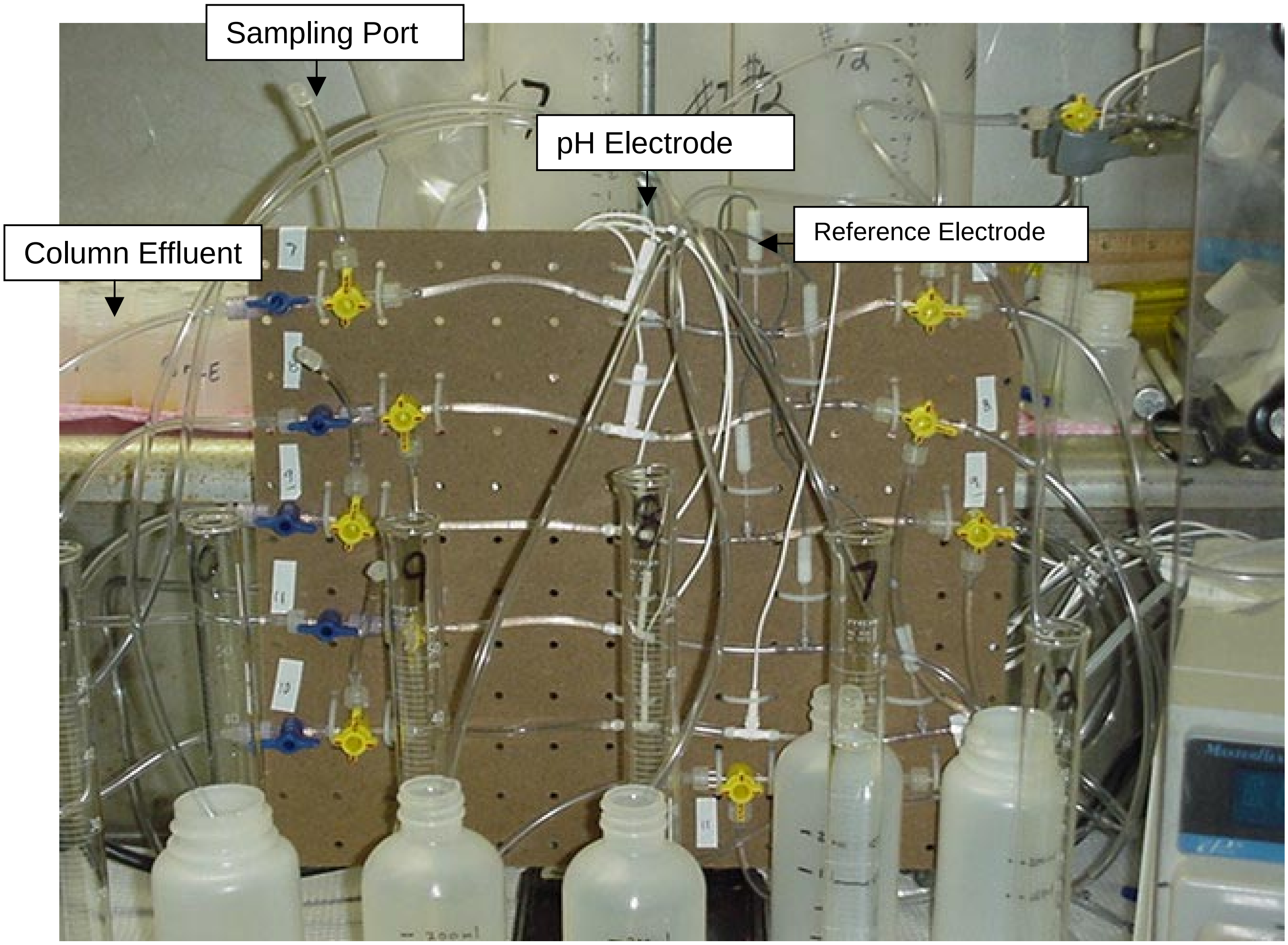


Figure 1 - Schematic of Column Leaching Experimental Setup.

Figure 2 – Photograph of Experimental Setup for Series 1.

Figure 3 – Photograph of Experimental Setup for Series 2 and 3.

Figure 4 – Photograph of Inline Monitoring System.



Note: Flow is in left to right direction.

Figure 5 - Schematic of Hydraulic Conductivity Experimental Setup.

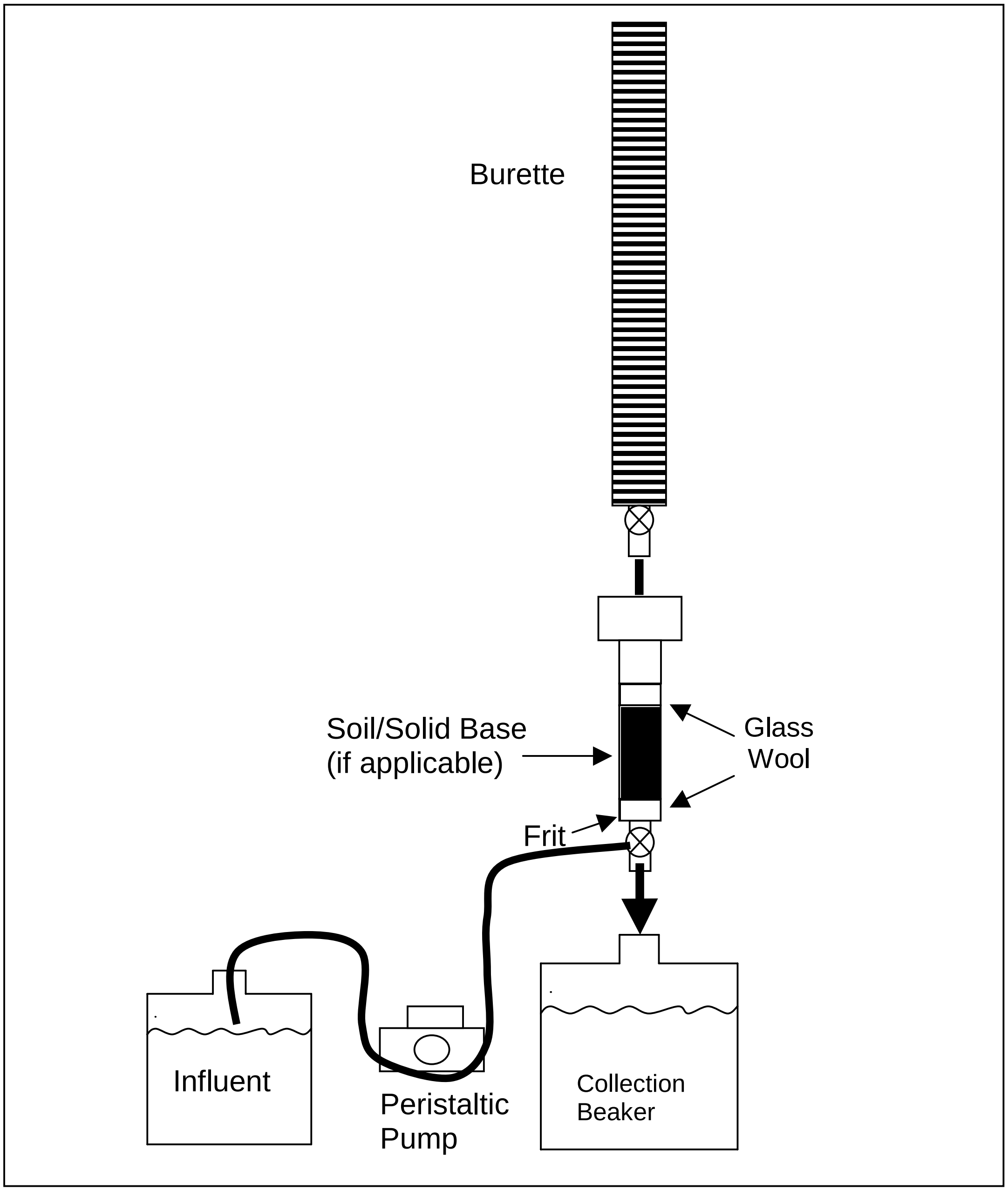


Figure 6 – XRD Diffraction Pattern for Composite Soil

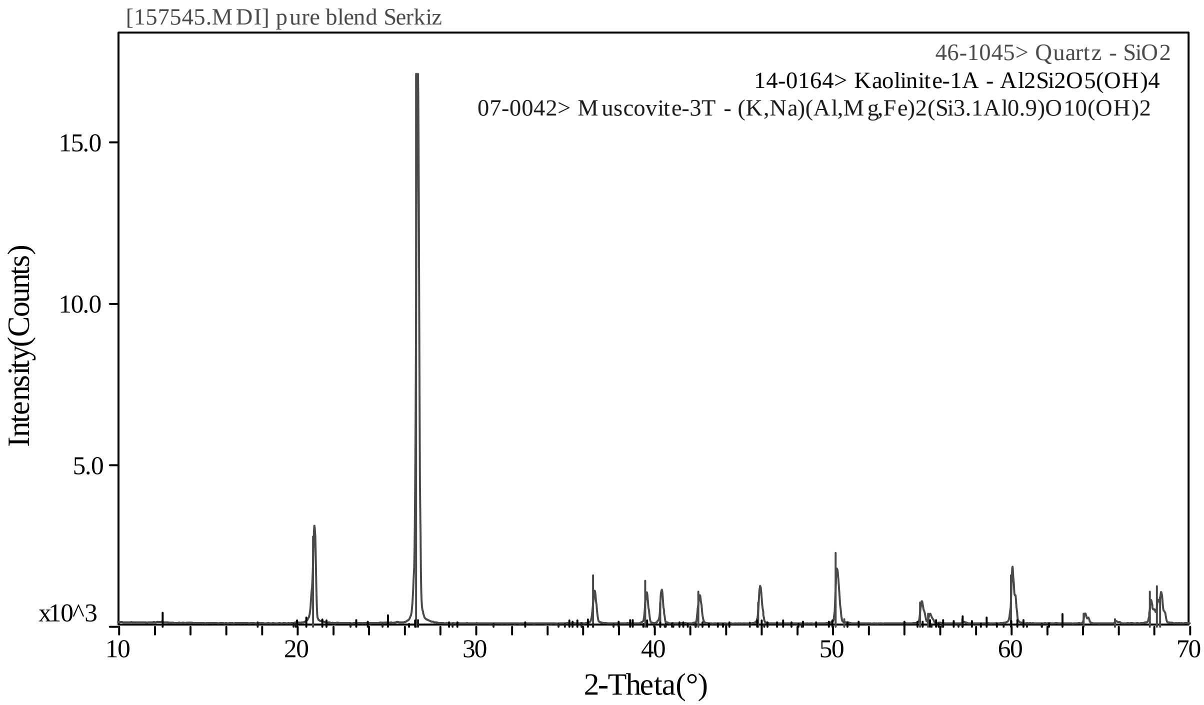


Figure 7 – Pore Volume Versus Effluent Quality NaOH; pH-8.5; Carbonate Saturated

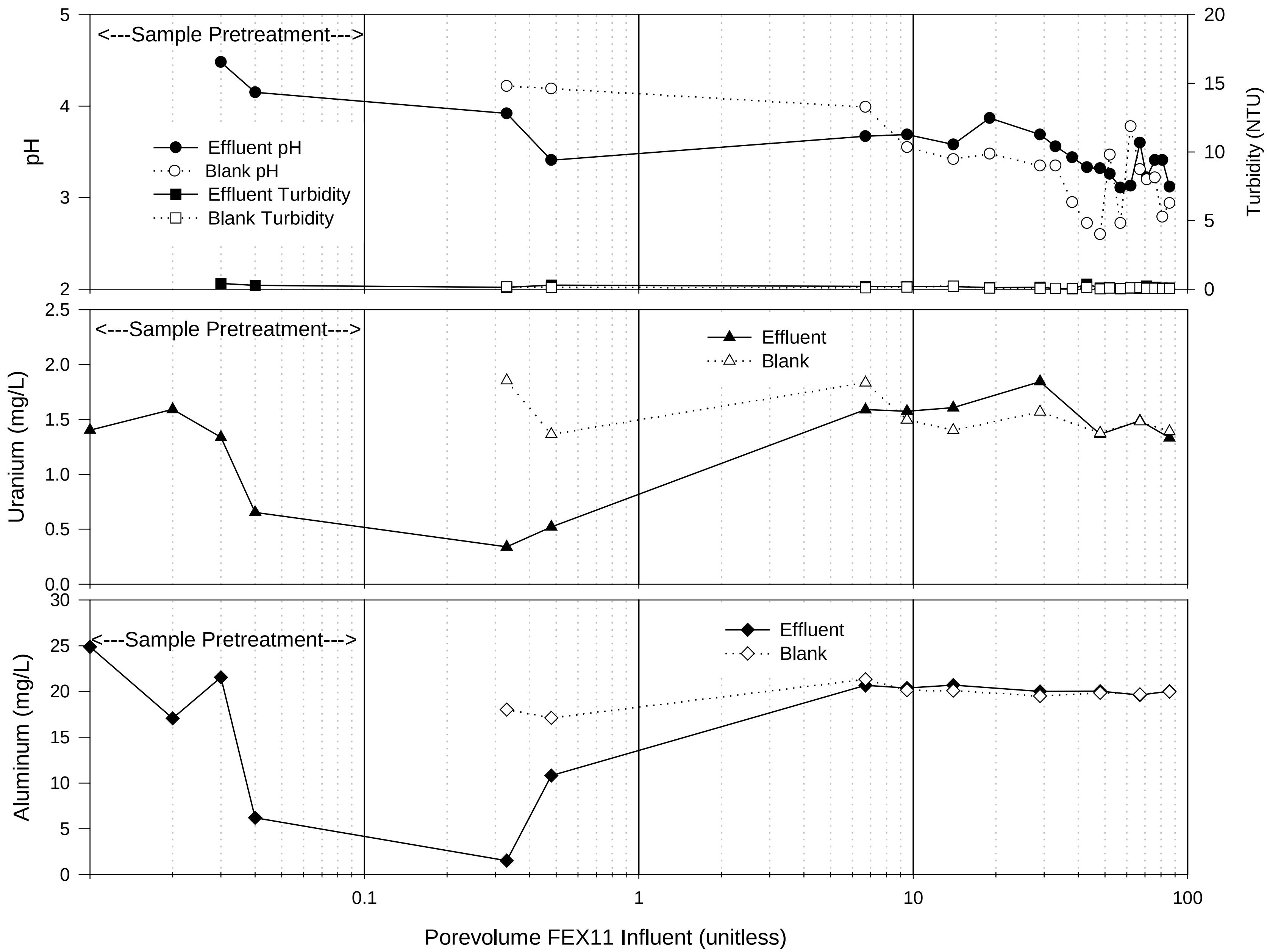
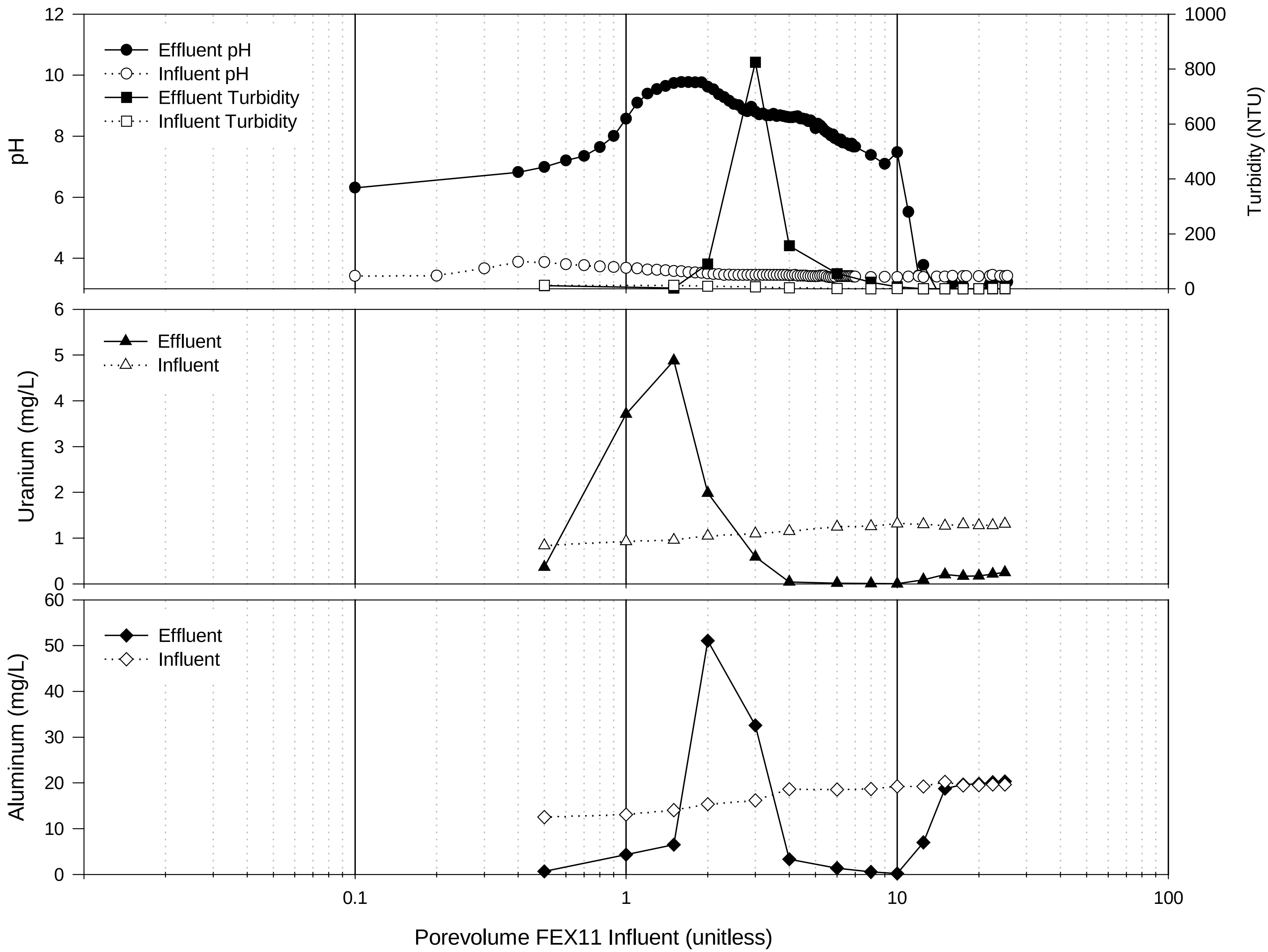


Figure 8 – Pore Volume Versus Effluent Quality NaOH; pH-10.0; Carbonate Saturated



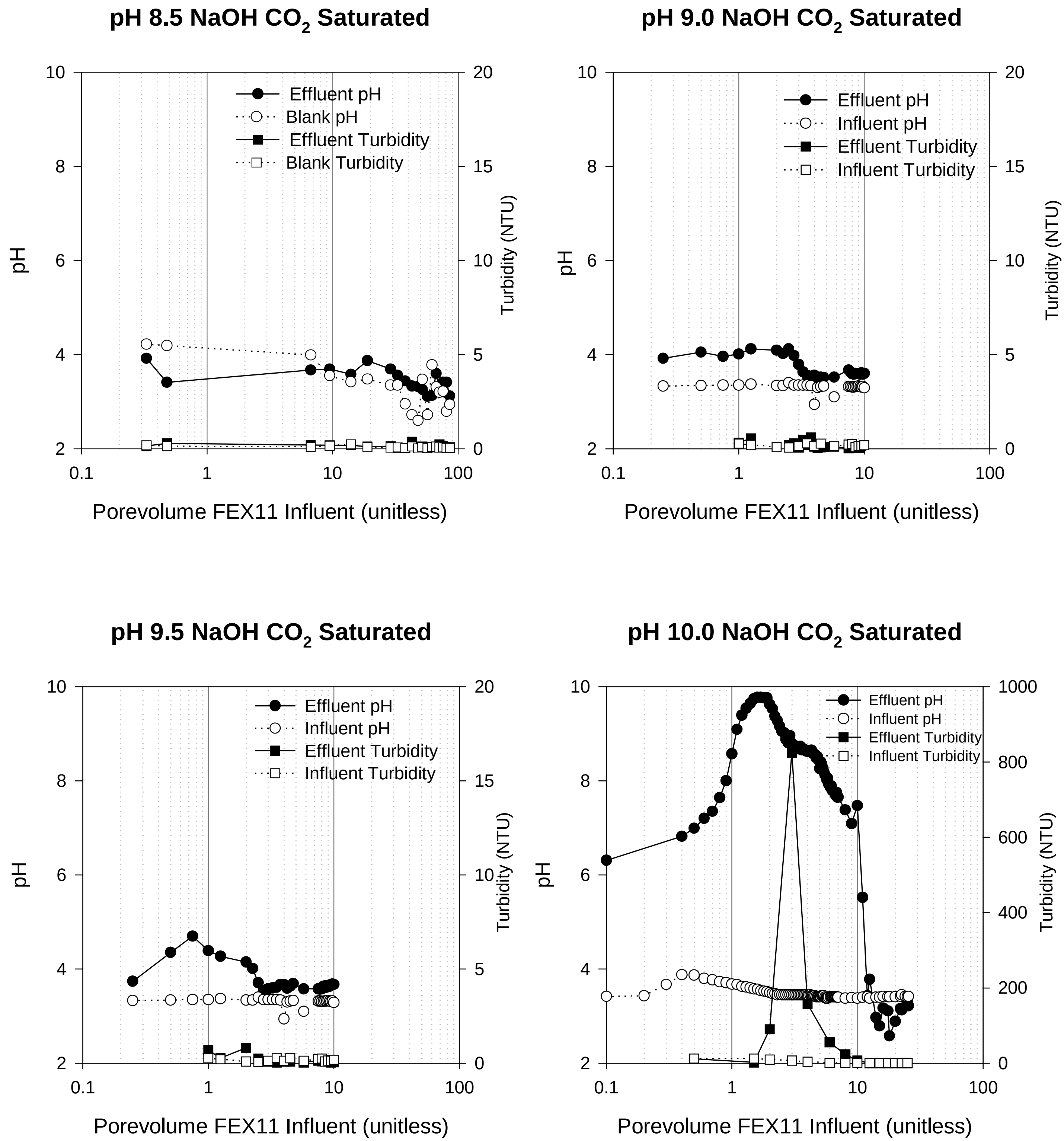


Figure 9 – Pore Volume Versus Effluent Quality NaOH; pH- All ;Carbonate Saturated

Figure 10 – Pore Volume Versus Effluent Quality NaOH; pH-8.5; Carbonate Excluded

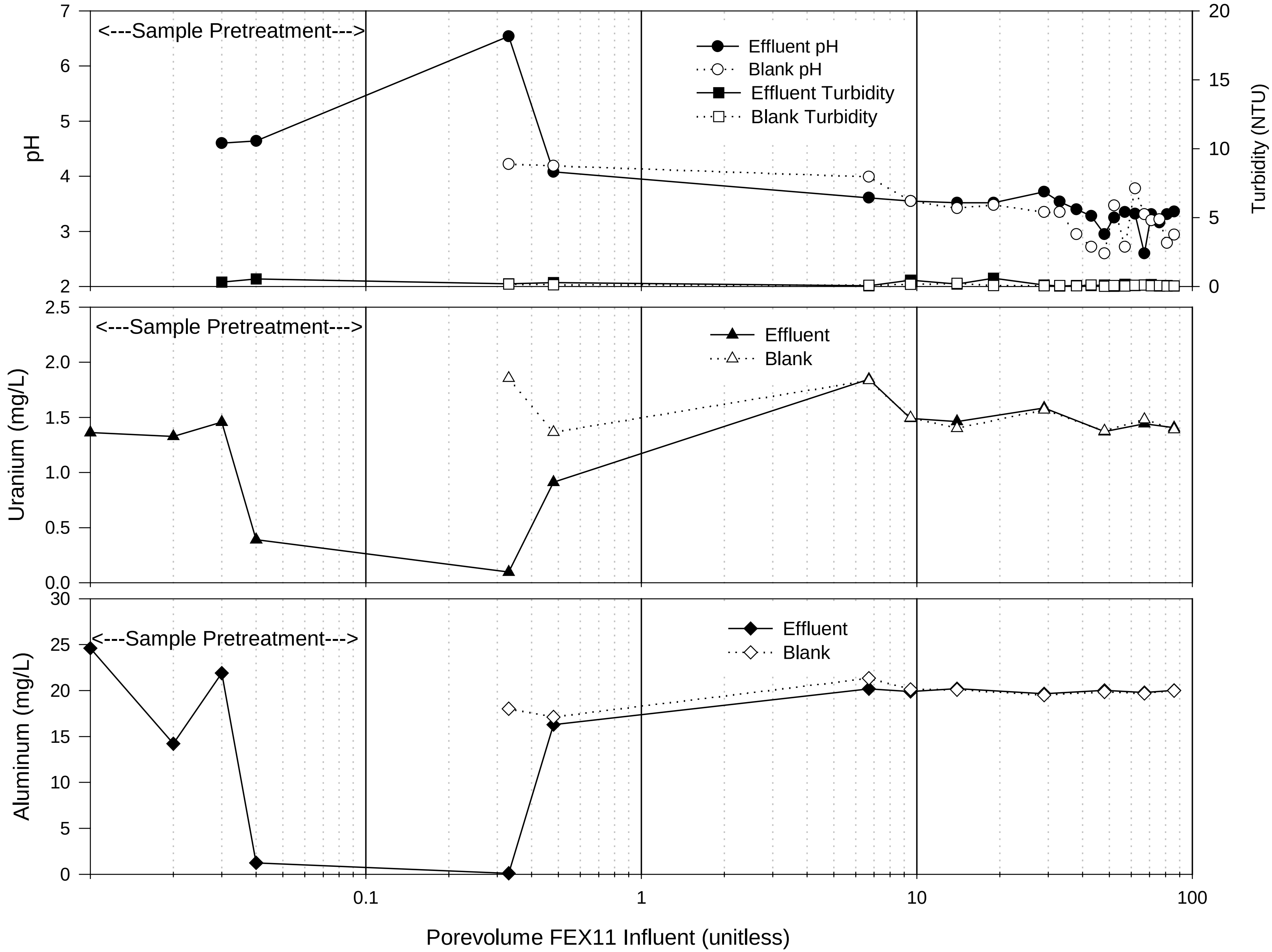


Figure 11 – Pore Volume Versus Effluent Quality NaOH; pH -10.0; Carbonate Excluded

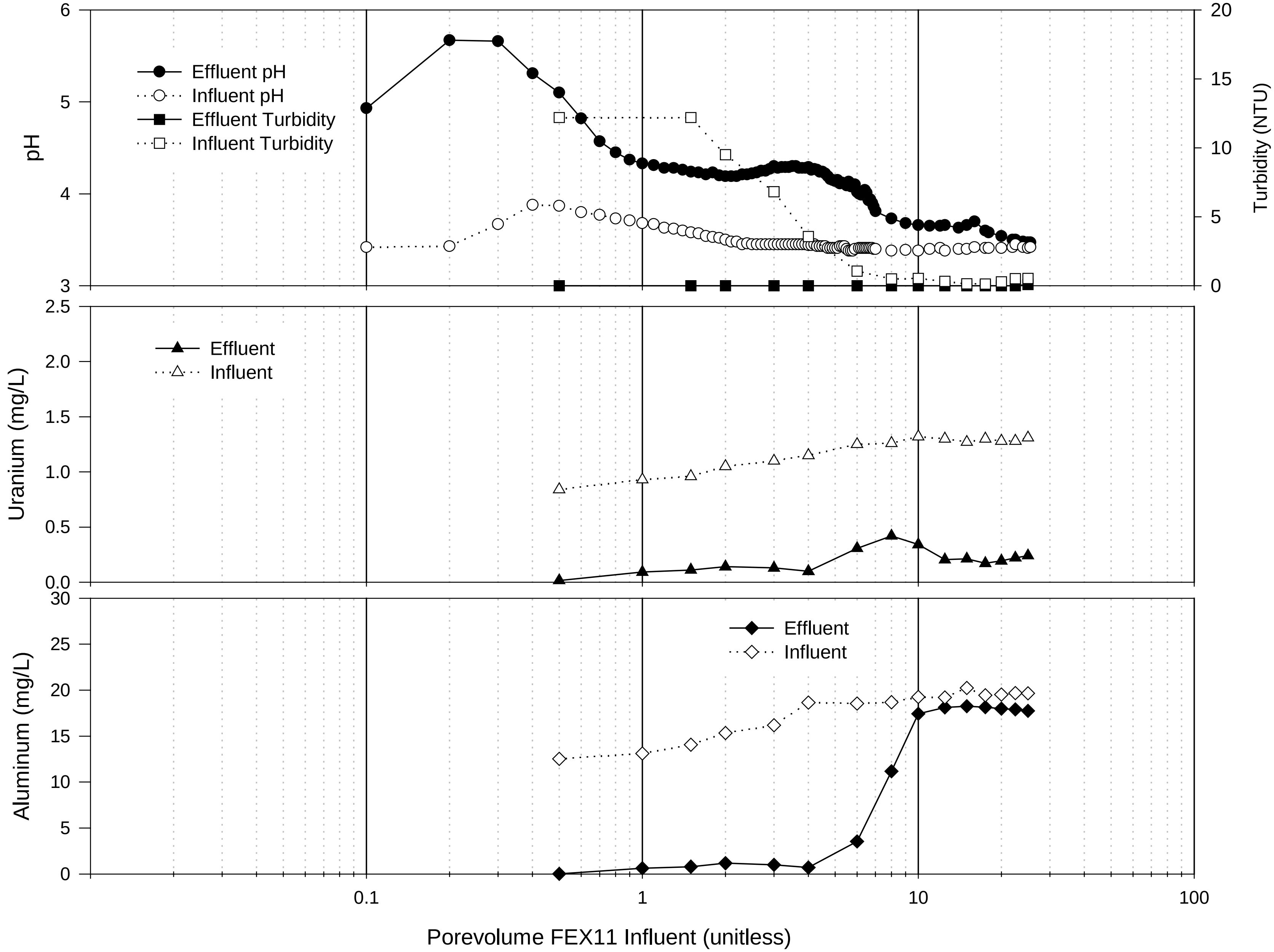


Figure 12 – Pore Volume Versus Effluent Quality Na_3PO_4 ; pH – 8.5; Carbonate Saturated

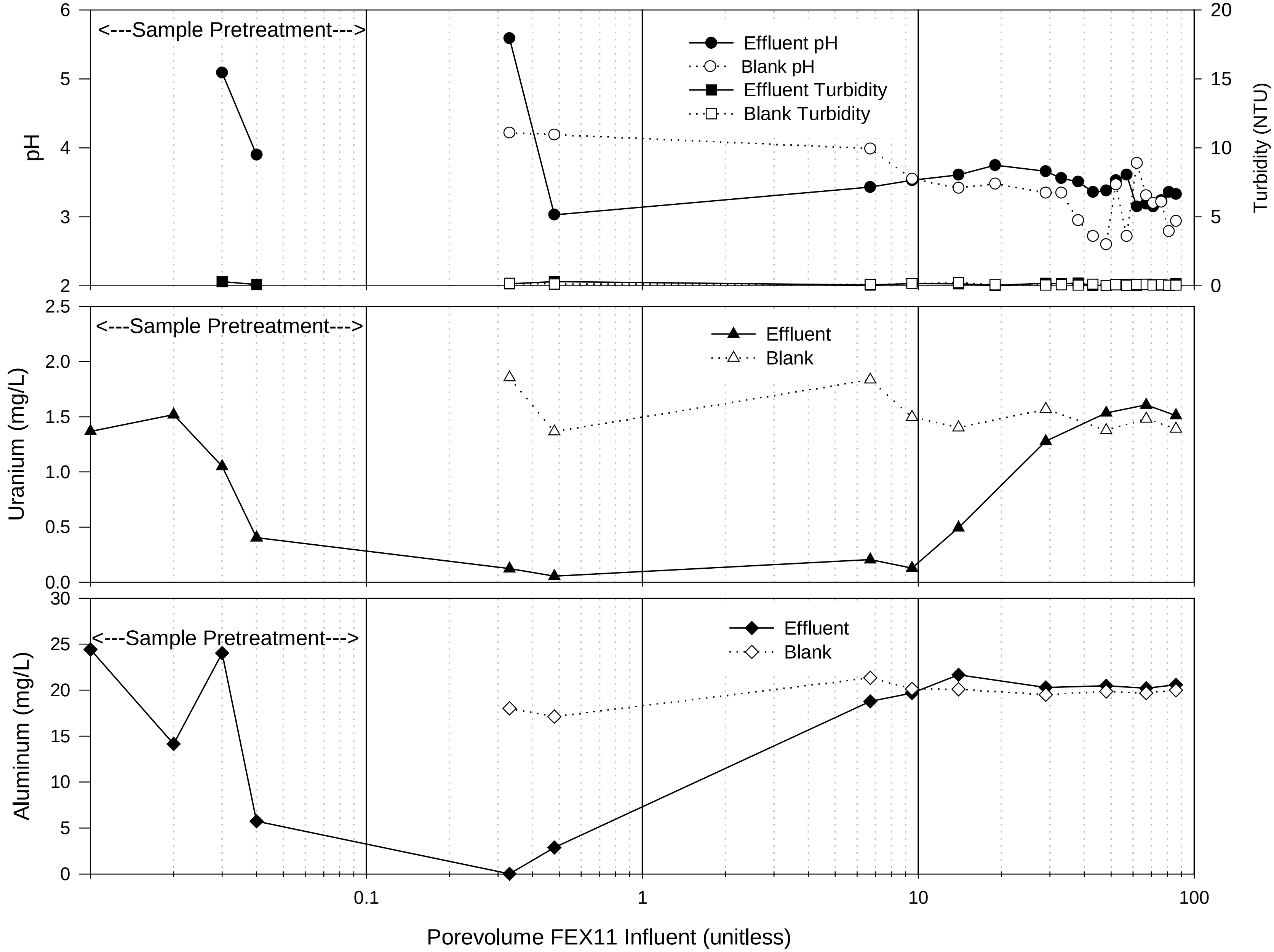
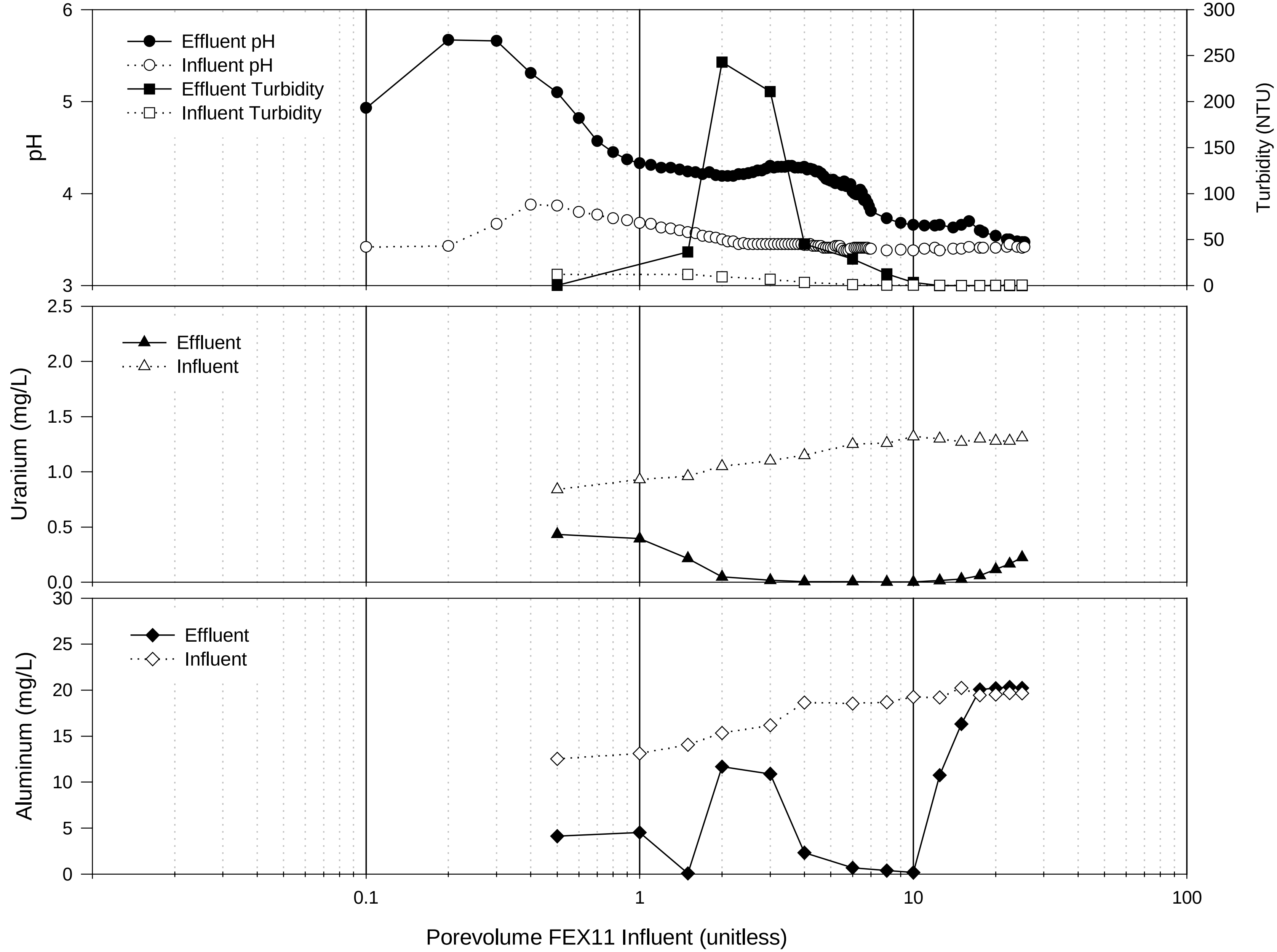


Figure 13 – Pore Volume Versus Effluent Quality Na_3PO_4; pH – 10.0; Carbonate Saturated



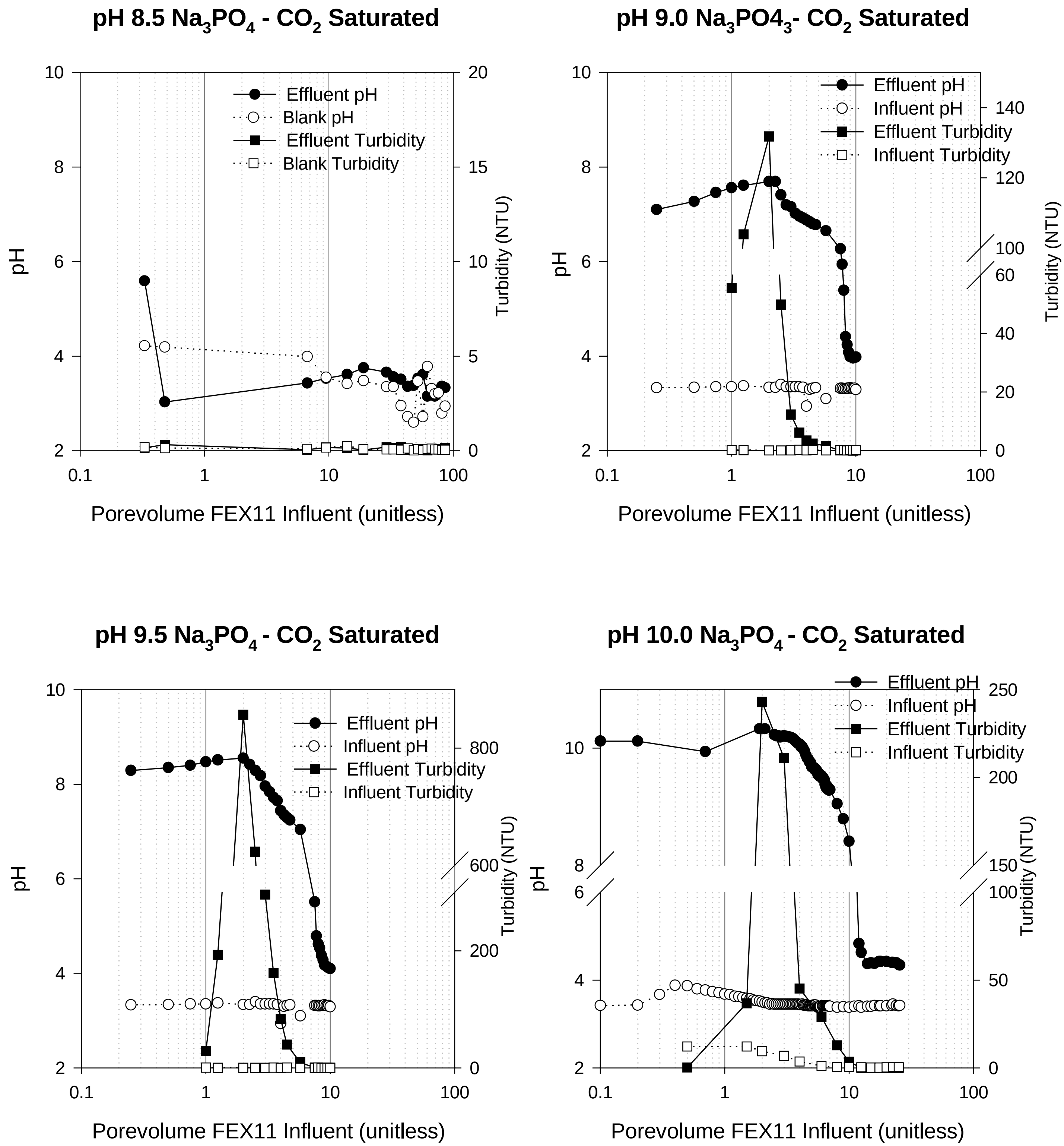


Figure 14 – Pore Volume Versus Effluent Quality Na_3PO_4; pH- All ;Carbonate Saturated

Figure 15 – Pore Volume Versus Effluent Quality CaO (Lime) Sandwich

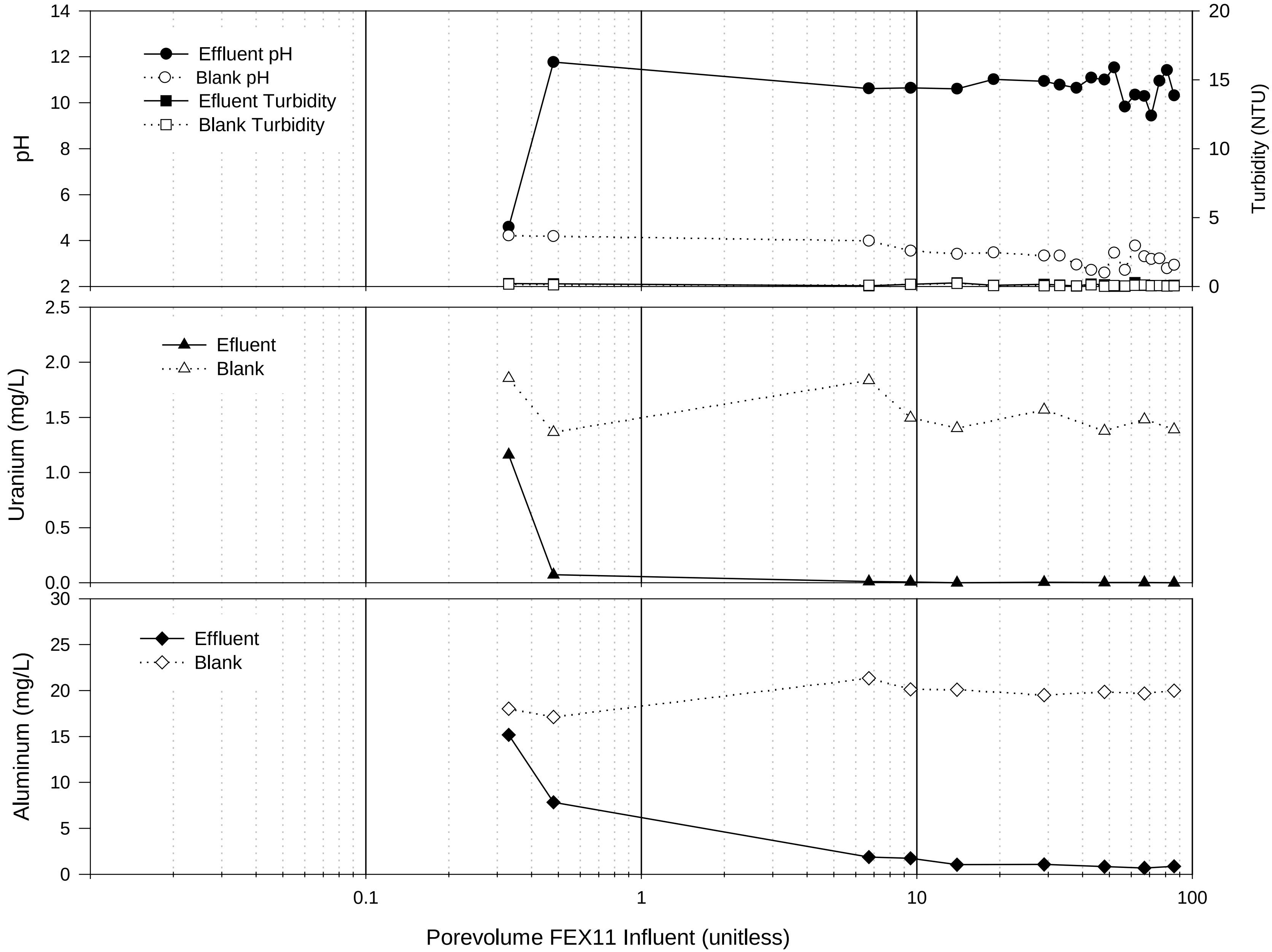


Figure 16 – Pore Volume Versus Effluent Quality Fe(0) Sandwich

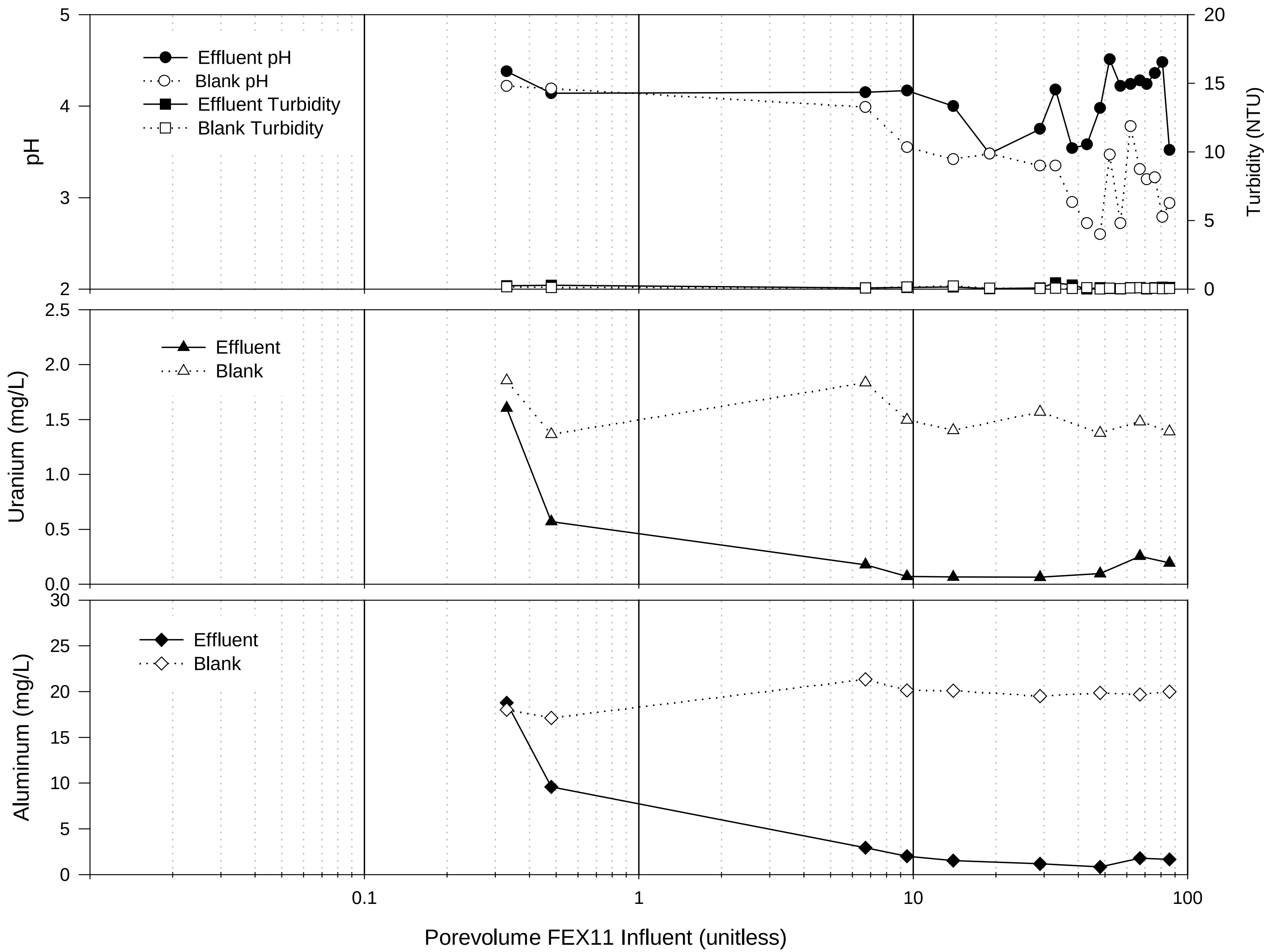


Figure 17 – Pore Volume Versus Effluent Quality Fe(0) Mixed w/ Soil

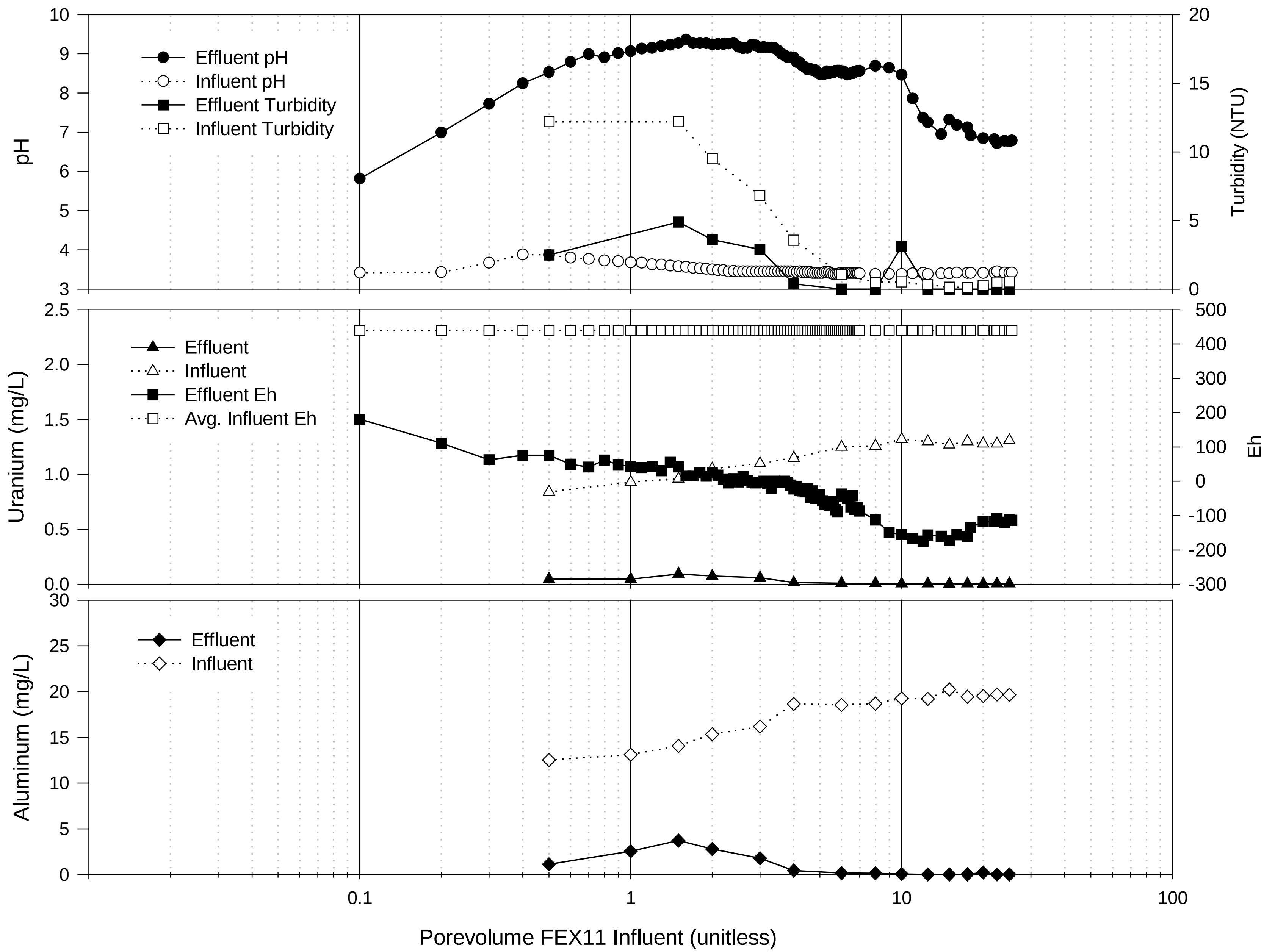


Figure 18 – Pore Volume Versus Effluent Quality Fe(0) and Apatite Mixed w/ Soil

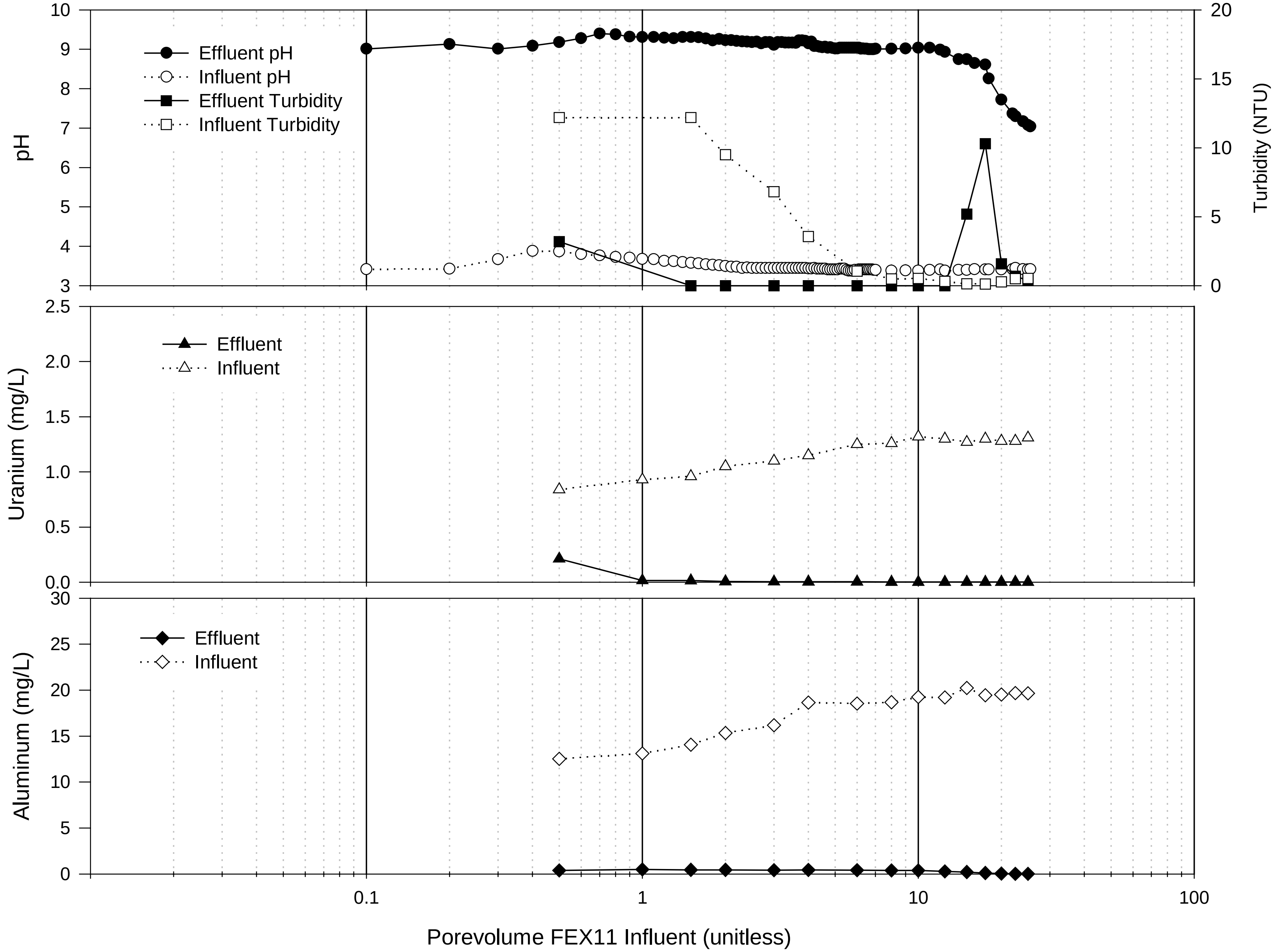
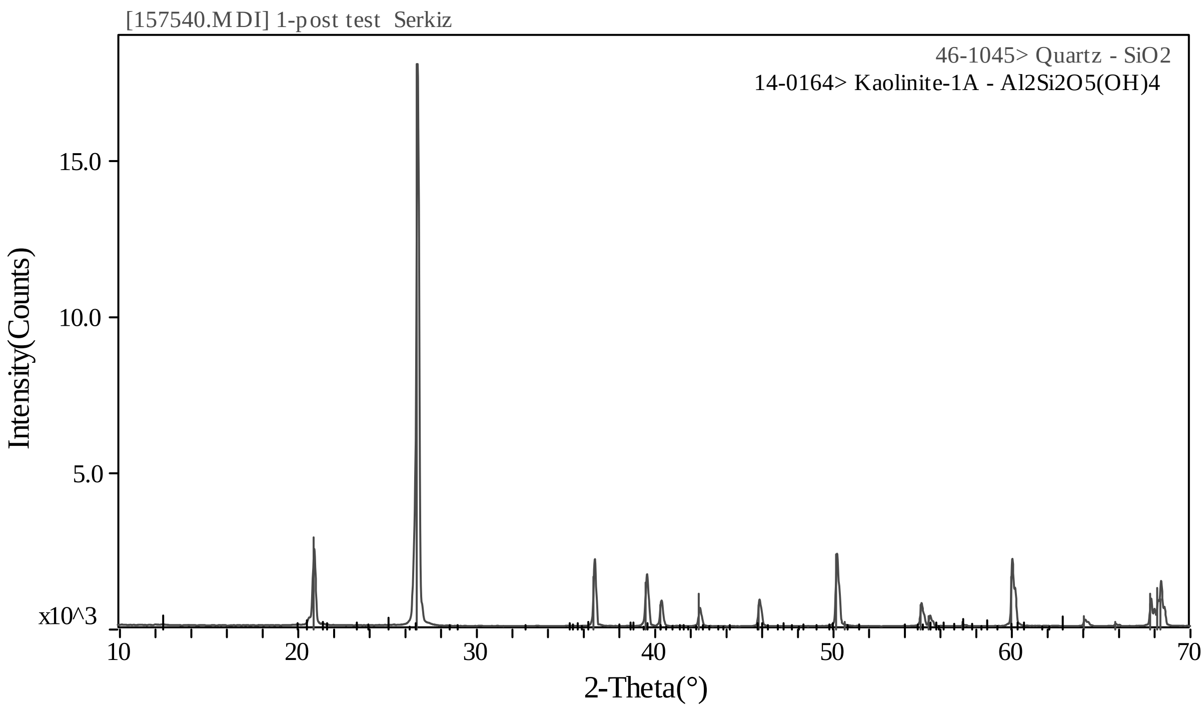


Figure 19 – Photograph of High Turbidity Effluent from NaOH pH=10; Carbonate Saturated Experiment

Figure 20 – XRD Diffraction Pattern for NaOH Treated Soil



Appendix A – Email from Thibault

Jeffrey Thibault

To: Steven Serkiz/WSRC/Srs@Srs
cc: R Gelinas/SUB/Srs@Srs, Stephani Fuller/BSRI/Srs@Srs, Bob Sentelle/BSRI/Srs@Srs, Janelle Janssen/WSRC/Srs@Srs, Gerald Blount/WSRC/Srs@Srs

12/22/00 12:37 PM

Subject:FASB Soil Sample

Steve -

The soil sample from F Area was transported to SRTC (received at the high level cell facility?) on Friday, Dec 22nd. The sample was collected from an augered boring using a 3-inch inner diameter split spoon sampler (24-inches long). The sampled interval was from 85 ft to 103 ft below ground surface. Stratigraphically this interval is within the Dry Branch Formation and is also within the Upper Aquifer Zone. In general terms the sediment consisted of medium brown, fine to coarse quartz sand, moderately to poorly sorted, with varying amounts of silt/clay (generally less than 25%). The boring was terminated at 103 ft (about 5 ft shy of the predicted terminal depth) due to heaving sands within the augers. Sample recovery was excellent (100% in almost every spoon interval). Approximately 6 gallons volume of sample was collected. The samples were segregated into 4 ft intervals and sealed in plastic bags. Each bag is labeled with the boring ID (FBI-1SB) and depth interval.

Call if you have any questions.

Jeffrey.Thibault@SRS.gov
803 952-6543
Page 18576

Base= NaOH	Form = Liquid	pH	8.5	CO_2?	Excluded

	Pretreatment				Porevolume FEX 11 Effluent (unitless)								
Element	FEX11	Base	Base	Base	0.33	0.48	6.67	9.52	14.29	28.57	47.62	66.67	85.71
Ag	0.008	0.022	0.011	**0.006**	**0.006**	**0.006**	**0.006**	**0.006**	**0.006**	**0.006**	0.009	**0.006**	0.008
Al	24.608	14.222	21.890	1.253	0.105	16.294	20.188	19.897	20.216	19.650	20.025	19.784	20.033
B	0.055	2.628	1.209	1.079	0.415	0.457	0.326	0.254	0.551	0.132	0.085	0.060	0.052
Ba	0.677	0.588	0.616	0.163	0.015	0.360	0.380	0.369	1.839	0.358	0.361	0.353	0.364
Ca	0.007	0.004	6.490	1.999	**0.002**	0.004	0.005	0.004	0.003	0.004	0.006	0.005	0.006
Cd	0.104	0.058	0.006	**0.002**	**0.007**	0.044	0.051	0.051	0.054	0.051	0.054	0.052	0.056
Co	0.015	0.009	0.065	0.017	**0.006**	0.008	0.014	0.010	0.011	0.008	0.010	0.008	0.009
Cr	0.119	0.060	0.014	**0.006**	0.005	0.065	0.063	0.061	0.045	0.037	0.039	0.035	0.040
Cu	5.612	9.884	0.084	0.022	0.384	3.366	4.197	4.184	4.517	4.164	1.061	4.177	4.091
Fe	2.372	0.430	0.882	0.361	0.055	0.357	0.214	0.170	0.173	0.131	0.121	0.114	0.110
La	0.061	0.024	0.040	**0.013**	**0.013**	0.036	0.042	0.036	0.029	**0.013**	0.028	0.026	0.029
Li	0.010	0.010	0.011	0.003	**0.002**	0.007	0.007	0.007	0.007	0.006	0.008	0.007	0.008
Mg	2.188	3.492	2.678	0.943	0.360	1.580	1.923	1.915	1.947	1.879	1.904	1.871	1.854
Mn	2.357	1.619	1.671	0.340	0.044	1.128	1.407	1.407	1.436	1.412	1.446	1.385	1.454
Mo	0.012	0.009	0.012	**0.003**	**0.003**	0.010	0.011	0.009	0.010	0.010	0.009	0.009	0.012
Na	66.612	108.098	69.480	15.057	6.363	52.565	60.995	61.176	68.361	60.940	61.788	60.270	61.953
Ni	0.078	0.072	0.071	0.048	0.023	0.168	0.204	0.126	0.079	0.050	0.040	0.032	0.038
P	0.082	0.094	0.062	**0.037**	**0.037**	0.057	0.067	0.065	0.084	0.071	0.089	0.045	0.065
Pb	0.037	**0.030**	0.045	**0.030**	**0.030**	0.034	0.038	**0.030**	0.050	**0.030**	0.041	**0.030**	0.054
Si	35.289	33.709	33.610	4.690	3.065	27.974	33.604	33.739	34.242	33.278	34.284	33.094	34.435
Sn	0.036	0.036	0.033	**0.017**	**0.017**	0.032	0.037	0.029	0.034	0.038	0.028	0.042	0.023
Sr	0.034	0.030	0.029	0.006	**0.001**	0.019	0.023	0.023	0.039	0.022	0.024	0.023	0.023
Ti	0.036	0.023	0.029	0.006	0.002	0.021	0.026	0.025	0.025	0.023	0.027	0.024	0.027
U	1.361	1.327	1.456	0.390	0.096	0.911	1.846	1.491	1.462	1.584	1.371	1.442	1.406
V	0.005	0.006	0.007	**0.003**	0.004	0.005	0.004	0.004	0.004	**0.003**	0.007	**0.003**	0.006
Zn	0.599	0.131	0.195	0.073	0.026	0.064	0.057	0.055	0.829	0.050	0.057	0.047	0.054
Zr	0.049	0.032	0.043	0.009	0.004	0.029	0.034	0.033	0.035	0.031	0.039	0.032	0.039

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base= NaOH	Form = Liquid	pH	8.5	CO_2? Saturated

	Pretreatment				Porevolume FEX 11 Effluent (unitless)								
Element	FEX11	Base	Base	Base	0.33	0.48	6.67	9.52	14.29	28.57	47.62	66.67	85.71
Ag	0.007	0.011	0.007	**0.006**	**0.006**	**0.006**	**0.006**	**0.006**	**0.006**	**0.006**	0.006	**0.006**	0.007
Al	24.878	17.065	21.554	19.608	1.528	10.817	20.660	20.384	20.711	20.009	20.039	19.608	20.040
B	0.043	1.833	0.552	0.020	0.317	0.389	0.084	0.064	0.367	0.040	0.033	0.020	0.021
Ba	0.708	0.609	0.577	0.356	0.114	1.444	0.374	0.360	1.752	0.358	0.360	0.356	0.360
Ca	0.007	0.006	6.037	0.004	**0.002**	0.002	0.004	0.005	0.004	0.004	0.004	0.004	0.005
Cd	0.085	0.066	0.006	**0.050**	**0.008**	0.038	0.052	0.049	0.052	0.051	0.051	0.050	0.056
Co	0.014	0.010	0.063	0.007	**0.006**	0.006	0.010	0.010	0.011	0.011	0.011	0.007	0.013
Cr	0.115	0.068	0.010	**0.032**	0.014	0.056	0.086	0.075	0.047	0.040	0.042	0.032	0.035
Cu	4.965	9.531	0.079	4.033	1.212	3.552	4.496	4.290	4.513	4.198	4.249	4.033	4.185
Fe	1.786	0.434	0.785	0.117	0.177	0.255	0.205	0.155	0.173	0.154	0.126	0.117	0.115
La	0.061	0.031	0.033	**0.015**	**0.013**	0.028	0.044	0.042	0.029	**0.015**	0.028	0.015	0.025
Li	0.010	0.010	0.009	0.006	**0.002**	0.005	0.007	0.006	0.007	0.006	0.007	0.006	0.008
Mg	2.084	3.086	2.243	1.784	0.447	1.432	1.902	1.853	1.913	1.872	1.899	1.784	1.909
Mn	2.006	1.665	1.510	1.403	0.148	1.016	1.411	1.389	1.428	1.413	1.430	1.403	1.428
Mo	0.013	0.009	0.009	**0.010**	**0.003**	0.006	0.010	0.010	0.011	0.009	0.010	0.010	0.012
Na	65.542	91.534	60.658	60.906	21.694	69.166	60.724	60.473	67.487	60.685	61.245	60.906	60.814
Ni	0.094	0.062	0.062	0.027	0.019	0.081	0.064	0.041	0.039	0.029	0.032	0.027	0.038
P	0.082	0.081	0.060	**0.057**	**0.037**	0.067	0.055	0.058	0.064	0.069	0.067	0.057	0.062
Pb	0.030	**0.047**	0.044	**0.030**	**0.030**	0.030	0.030	**0.034**	0.048	**0.030**	0.037	**0.030**	0.045
Si	33.925	34.460	30.021	33.224	4.062	24.572	33.445	33.361	34.356	33.472	34.035	33.224	34.021
Sn	0.031	0.028	0.033	**0.030**	**0.017**	0.035	0.038	0.039	0.043	0.029	0.028	0.030	0.036
Sr	0.030	0.033	0.029	0.022	**0.004**	0.029	0.023	0.022	0.038	0.022	0.023	0.022	0.024
Ti	0.039	0.032	0.029	0.023	0.003	0.014	0.031	0.037	0.024	0.022	0.026	0.023	0.027
U	1.402	1.591	1.337	0.653	0.338	0.521	1.590	1.575	1.607	1.845	1.364	1.487	1.333
V	0.005	0.008	0.005	**0.003**	0.003	0.003	0.003	0.003	0.004	**0.003**	0.004	**0.003**	0.006
Zn	0.343	0.179	0.175	0.043	0.029	0.645	0.068	0.052	0.745	0.046	0.057	0.043	0.051
Zr	0.053	0.038	0.041	0.030	0.006	0.020	0.041	0.046	0.034	0.030	0.037	0.030	0.038

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base= Na_3PO_4	Form = Liquid	pH	8.5	CO_2?	Saturated

	Pretreatment				Porevolume FEX 11 Effluent (unitless)								
Element	FEX11	Base	Base	Base	0.33	0.48	6.67	9.52	14.29	28.57	47.62	66.67	85.71
Ag	0.007	0.009	0.008	**0.006**	**0.006**	**0.006**	**0.006**	**0.006**	**0.060**	**0.006**	0.007	**0.006**	0.008
Al	24.416	14.160	24.028	5.751	0.023	2.892	18.781	19.684	21.674	20.289	20.482	20.210	20.574
B	0.022	2.530	0.591	0.754	0.354	0.447	0.089	0.060	0.190	0.029	0.029	0.019	0.019
Ba	0.664	0.603	0.619	0.218	0.049	1.535	0.404	0.342	0.354	0.347	0.360	0.360	0.373
Ca	0.006	0.006	5.603	1.940	**0.002**	0.002	0.032	0.004	0.020	0.005	0.004	0.003	0.005
Cd	0.088	0.068	0.006	**0.002**	**0.007**	0.035	0.053	0.050	0.070	0.051	0.053	0.050	0.056
Co	0.014	0.012	0.065	0.013	**0.006**	0.006	0.014	0.006	0.060	0.006	0.011	0.010	0.010
Cr	0.109	0.064	0.010	**0.006**	0.007	0.043	0.105	0.084	0.068	0.044	0.037	0.032	0.035
Cu	5.100	10.071	0.089	0.026	0.741	3.199	4.533	4.143	4.750	4.120	4.332	4.134	4.090
Fe	1.823	0.276	0.785	0.274	0.036	0.099	0.233	0.124	0.102	0.072	0.067	0.067	0.063
La	0.055	0.031	0.037	**0.013**	**0.013**	0.013	0.041	0.050	0.130	**0.018**	0.026	0.018	0.025
Li	0.010	0.010	0.009	0.002	**0.002**	0.005	0.007	0.006	0.020	0.006	0.008	0.007	0.008
Mg	2.078	3.360	2.441	1.217	0.468	1.458	2.026	1.872	1.973	1.859	1.905	1.859	1.856
Mn	2.048	1.834	1.614	0.201	0.030	0.977	1.508	1.411	1.493	1.411	1.453	1.377	1.463
Mo	0.014	0.008	0.013	**0.005**	**0.003**	0.003	0.009	0.009	0.030	0.009	0.012	0.009	0.012
Na	64.911	98.551	68.616	42.227	50.506	104.951	61.179	60.560	63.482	60.825	61.781	59.879	62.138
Ni	0.068	0.065	0.057	0.016	0.016	0.050	0.058	0.036	0.084	0.027	0.037	0.024	0.041
P	0.080	0.104	0.053	**0.039**	**0.037**	5.018	0.803	0.378	0.370	0.473	0.616	0.706	0.622
Pb	0.033	**0.039**	0.041	**0.030**	**0.030**	0.030	0.032	**0.030**	0.300	**0.031**	0.048	**0.036**	0.043
Si	33.756	33.570	34.515	6.761	5.548	28.008	33.492	33.437	36.561	33.297	34.307	32.963	34.644
Sn	0.041	0.038	0.049	**0.017**	**0.019**	0.017	0.037	0.037	0.170	0.036	0.030	0.040	0.034
Sr	0.031	0.031	0.027	0.004	**0.001**	0.028	0.025	0.022	0.022	0.022	0.023	0.023	0.023
Ti	0.038	0.024	0.031	0.007	0.001	0.003	0.032	0.045	0.029	0.023	0.026	0.023	0.027
U	1.367	1.519	1.050	0.403	0.123	0.055	0.205	0.127	0.493	1.277	1.534	1.607	1.511
V	0.005	0.007	0.006	**0.003**	0.003	0.003	0.003	0.003	0.030	**0.003**	0.006	**0.003**	0.007
Zn	0.375	0.138	0.183	0.078	0.017	0.749	0.068	0.052	0.053	0.044	0.061	0.044	0.049
Zr	0.051	0.036	0.045	0.010	0.002	0.005	0.042	0.056	0.046	0.029	0.037	0.032	0.038

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base= CaO	Form = Sandwich	pH	NA	CO_2?	NA

	Pretreat	Porevolume FEX 11 Effluent (unitless)								
Element	FEX11	0.33	0.48	6.67	9.52	14.29	28.57	47.62	66.67	85.71
Ag	0.007	0.006	0.060	**0.006**	**0.006**	**0.060**	**0.006**	**0.060**	**0.006**	**0.060**
Al	0.298	15.168	7.838	1.886	1.746	1.049	1.084	0.841	0.696	0.870
B	0.182	0.551	0.219	0.137	0.086	0.190	0.031	0.190	0.036	0.190
Ba	1.803	0.511	0.131	0.052	0.089	0.186	0.212	0.218	0.222	0.224
Ca	0.004	0.006	0.020	0.004	**0.003**	0.020	0.002	0.028	0.004	0.020
Cd	0.010	0.065	0.070	**0.007**	**0.007**	0.070	0.007	0.070	0.009	0.070
Co	0.109	0.009	0.060	0.015	**0.017**	0.060	0.020	0.156	0.079	0.092
Cr	0.034	0.056	0.029	**0.003**	0.002	0.018	0.002	0.021	0.002	0.023
Cu	1115.802	27.054	595.906	991.985	1028.007	980.987	1034.660	997.402	1039.196	1013.469
Fe	0.028	0.558	0.084	0.018	0.018	0.045	0.018	0.062	0.020	0.058
La	0.283	0.037	0.530	**0.257**	**0.250**	0.695	0.252	0.727	0.257	**0.711**
Li	0.201	0.007	0.020	0.002	**0.002**	0.020	0.002	0.020	0.002	0.020
Mg	0.008	2.396	0.085	0.004	0.002	0.010	0.002	0.012	0.013	0.017
Mn	0.006	1.834	0.063	0.005	0.004	0.012	0.004	0.012	0.008	0.012
Mo	0.004	0.008	0.030	**0.009**	**0.007**	0.030	0.007	0.030	0.004	0.030
Na	140.243	71.366	58.835	63.355	63.030	62.081	63.312	62.598	62.609	63.181
Ni	0.028	0.056	0.070	0.014	0.012	0.070	0.007	0.070	0.010	0.076
P	0.128	0.058	0.370	**0.037**	**0.055**	0.448	0.050	0.370	0.052	0.370
Pb	0.043	**0.035**	0.300	**0.045**	**0.048**	0.300	0.037	**0.300**	0.038	**0.315**
Si	1.734	23.460	4.609	1.666	1.598	4.246	1.663	4.777	1.734	4.407
Sn	0.025	0.037	0.170	**0.027**	**0.031**	0.170	0.028	0.170	0.024	0.170
Sr	58.548	0.031	2.061	0.600	**0.443**	0.363	0.290	0.250	0.214	0.213
Ti	0.003	0.021	0.022	0.001	0.002	0.012	0.001	0.022	0.002	0.019
U	0.003	1.160	0.072	0.011	0.007	0.000	0.004	0.001	0.002	0.000
V	0.020	0.003	0.059	**0.016**	0.017	0.054	0.017	0.068	0.018	**0.065**
Zn	0.011	0.287	0.037	0.003	0.003	0.030	0.003	0.030	0.003	0.030
Zr	0.006	0.027	0.050	0.003	0.005	0.032	0.003	0.040	0.005	0.043

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base= Fe(0)	Form = Sandwich	pH	NA	CO_2?	NA

	Pretreat	Porevolume FEX 11 Effluent (unitless)								
Element	FEX11	0.33	0.48	6.67	9.52	14.29	28.57	47.62	66.67	85.71
Ag	0.006	0.006	0.006	**0.006**	**0.006**	**0.006**	**0.006**	**0.006**	**0.006**	**0.006**
Al	2.160	18.776	9.599	2.939	2.022	1.542	1.184	0.825	1.793	1.683
B	0.189	1.360	0.579	0.108	0.069	0.056	0.043	0.065	0.020	0.019
Ba	0.762	0.638	1.702	0.225	0.246	0.289	0.251	0.276	0.326	0.343
Ca	0.018	0.005	0.011	0.016	**0.016**	0.017	0.016	0.013	0.017	0.016
Cd	0.081	0.064	0.028	**0.039**	**0.040**	0.048	0.043	0.046	0.058	0.056
Co	0.012	0.011	0.010	0.006	**0.006**	0.009	0.006	0.007	0.008	0.010
Cr	0.005	0.080	0.028	**0.007**	0.007	0.007	0.004	0.062	0.005	0.046
Cu	7.505	7.889	6.322	4.901	5.159	4.337	4.015	3.907	5.012	4.285
Fe	63.559	0.707	26.911	48.031	50.336	52.450	51.342	43.915	52.218	50.111
La	0.129	0.159	0.025	**0.013**	**0.013**	0.013	0.013	0.013	0.013	**0.013**
Li	0.013	0.013	0.006	0.005	**0.005**	0.008	0.005	0.009	0.006	0.007
Mg	2.495	2.857	2.044	1.650	1.814	1.855	1.758	1.698	1.824	1.885
Mn	5.198	1.688	3.069	2.631	2.658	2.278	1.946	1.720	1.819	1.760
Mo	0.006	0.009	0.006	**0.004**	**0.003**	0.004	0.003	0.004	0.003	0.003
Na	63.597	80.861	71.007	60.554	60.428	62.545	60.683	61.050	60.302	60.916
Ni	0.124	0.087	0.057	0.066	0.060	0.068	0.057	0.066	0.080	0.078
P	0.092	0.060	0.079	**0.072**	**0.070**	0.060	0.079	0.080	0.077	0.078
Pb	0.033	**0.034**	0.050	**0.035**	**0.030**	0.031	0.030	**0.031**	0.037	**0.030**
Si	18.203	33.093	12.323	13.946	14.609	15.985	15.673	13.649	19.813	20.129
Sn	0.029	0.038	0.020	**0.020**	**0.022**	0.023	0.017	0.017	0.031	0.018
Sr	0.092	0.029	0.044	0.022	**0.024**	0.024	0.021	0.021	0.023	0.023
Ti	0.008	0.025	0.013	0.004	0.002	0.005	0.001	0.003	0.006	0.005
U	0.206	1.603	0.570	0.177	0.071	0.066	0.063	0.096	0.254	0.193
V	0.010	0.005	0.005	**0.006**	0.006	0.010	0.006	0.008	0.007	**0.008**
Zn	0.099	0.212	0.747	0.020	0.019	0.020	0.015	0.057	0.020	0.050
Zr	0.013	0.034	0.018	0.006	0.004	0.008	0.004	0.006	0.009	0.009

All Data in mg/L .... Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Glass Wool Blank - Series 1

	Pretreat	Porevolume FEX 11 Effluent (unitless)							
Element	0.33	0.48	6.67	9.52	14.29	28.57	47.62	66.67	85.71
Ag	0.007	0.006	**0.006**	**0.006**	**0.007**	**0.006**	**0.008**	**0.006**	**0.006**
Al	18.019	17.120	21.331	20.141	20.087	19.502	19.850	19.687	19.984
B	0.384	1.200	0.154	0.107	0.075	0.045	0.035	0.042	0.045
Ba	0.376	1.648	0.392	0.372	0.370	0.357	0.359	0.356	0.365
Ca	0.005	0.004	0.003	**0.005**	0.005	0.003	0.005	0.004	0.004
Cd	0.053	0.053	**0.050**	**0.052**	0.055	0.052	0.054	0.052	0.055
Co	0.010	0.007	0.008	**0.010**	0.009	0.006	0.010	0.006	0.011
Cr	0.054	0.055	**0.055**	0.053	0.045	0.031	0.089	0.031	0.038
Cu	5.137	6.181	4.416	4.296	4.315	4.223	4.138	4.313	4.103
Fe	0.030	0.049	0.050	0.047	0.036	0.024	0.029	0.058	0.033
La	0.150	0.026	**0.019**	**0.016**	0.026	0.017	0.029	0.023	**0.025**
Li	0.011	0.008	0.006	**0.006**	0.008	0.006	0.008	0.007	0.007
Mg	2.187	2.709	2.023	1.961	1.964	1.876	1.890	1.896	1.866
Mn	1.412	1.445	1.414	1.408	1.452	1.406	1.435	1.390	1.444
Mo	0.012	0.009	**0.010**	**0.012**	0.010	0.010	0.010	0.010	0.012
Na	67.180	87.336	62.481	61.316	62.705	60.915	61.662	60.444	62.264
Ni	0.054	0.044	0.032	0.030	0.039	0.029	0.035	0.031	0.034
P	0.062	0.071	**0.055**	**0.055**	0.073	0.073	0.056	0.056	0.077
Pb	**0.041**	0.040	**0.030**	**0.030**	0.056	0.030	**0.041**	0.044	**0.031**
Si	32.943	33.669	33.942	33.574	34.447	33.082	34.136	33.131	34.291
Sn	0.033	0.041	**0.034**	**0.038**	0.023	0.036	0.029	0.041	0.033
Sr	0.024	0.037	0.023	**0.022**	0.024	0.022	0.023	0.023	0.023
Ti	0.023	0.024	0.024	0.023	0.026	0.023	0.027	0.024	0.026
U	1.855	1.364	1.835	1.496	1.401	1.568	1.377	1.481	1.389
V	0.005	0.005	**0.003**	0.003	0.005	0.003	0.006	0.003	**0.005**
Zn	0.075	0.694	0.051	0.050	0.052	0.044	0.088	0.044	0.051
Zr	0.032	0.034	0.032	0.031	0.038	0.030	0.038	0.031	0.037

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base=	NaOH	Form = Liquid	pH	10.0	CO_2?	No

	Porevolume FEX 11 Effluent (unitless)								
Element	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.75
Al	0.019	0.641	0.8	1.177	1.001	0.716	3.553	11.168	17.423
B	0.076	0.017	0.013	0.013	0.015	0.014	0.013	0.012	0.014
Ba	0.005	0.064	0.073	0.095	0.083	0.061	0.171	0.496	0.39
Ca	0.082	0.182	0.239	0.427	0.386	0.345	5.765	10.174	4.571
Cd	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**
Co	**0.005**	**0.005**	**0.005**	0.009	0.006	**0.005**	0.067	0.111	0.052
Cr	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**	0.006	0.009	0.007
Cu	**0.001**	0.002	0.003	0.006	0.005	0.003	0.025	0.045	0.038
Fe	0.01	0.068	0.087	0.125	0.106	0.079	0.147	0.203	0.195
La	**0.01**	**0.010**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	0.016	0.021
Li	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	0.002	0.008	0.008	0.006
Mg	0.06	0.051	0.069	0.141	0.126	0.196	2.717	4.324	2.004
Mn	0.005	0.075	0.112	0.214	0.169	0.164	2.023	3.207	1.493
Mo	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**	0.007
Na	8.951	89.020	114.008	145.871	150.761	137.14	103.122	70.966	69.574
Ni	**0.01**	**0.010**	**0.01**	**0.01**	**0.01**	**0.01**	0.035	0.066	0.025
P	**0.02**	0.029	**0.02**	0.029	0.035	0.035	0.05	0.047	0.044
Pb	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**
Si	2.573	10.072	14.684	23.944	28.172	33.647	34.448	33.729	33.838
Sn	**0.02**	**0.020**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	0.021	**0.02**
Sr	**0.001**	**0.001**	**0.001**	0.002	0.002	**0.001**	0.03	0.056	0.025
Ti	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	0.003	0.012	0.021
U	0.016	0.092	0.111	0.141	0.130	0.098	0.307	0.420	0.341
V	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**
Zn	0.013	0.033	0.051	0.088	0.067	0.022	0.081	0.129	0.063
Zr	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	0.004	0.017	0.029

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base=	NaOH	Form = Liquid	pH	10.0	CO_2?	No

	Porevolume FEX 11 Effluent (unitless)					
Element	7.50	8.00	8.5	9.00	9.50	10.0
Al	18.132	18.243	18.14	17.993	17.908	17.758
B	0.015	0.019	0.011	0.013	0.013	0.016
Ba	0.338	0.32	0.336	0.333	0.333	0.33
Ca	4.284	4.283	4.18	4.159	4.18	4.168
Cd	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	0.004
Co	0.05	0.051	0.049	0.049	0.049	0.051
Cr	0.009	0.008	0.007	0.007	0.006	0.007
Cu	0.033	0.034	0.031	0.03	0.03	0.031
Fe	0.143	0.154	0.119	0.107	0.102	0.098
La	0.033	0.045	0.04	0.035	0.029	0.03
Li	0.006	0.006	0.006	0.006	0.006	0.007
Mg	1.905	1.906	1.868	1.854	1.874	1.874
Mn	1.422	1.421	1.392	1.386	1.401	1.4
Mo	0.008	0.007	0.006	0.007	0.007	0.008
Na	68.045	68.167	68.168	68.431	68.632	68.107
Ni	0.029	0.025	0.028	0.025	0.028	0.032
P	0.038	0.279	0.064	0.034	0.056	0.046
Pb	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**
Si	33.91	34.426	33.64	33.663	33.814	33.704
Sn	0.029	0.021	0.021	**0.02**	0.022	0.026
Sr	0.024	0.024	0.023	0.023	0.023	0.023
Ti	0.035	0.043	0.039	0.031	0.028	0.028
U	0.205	0.212	0.172	0.193	0.221	0.241
V	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**
Zn	0.056	0.062	0.049	0.05	0.05	0.051
Zr	0.05	0.061	0.055	0.044	0.041	0.042

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base=	Na_3PO_4	Form = Liquid	pH	10.0	CO_2?	Saturated

	Porevolume FEX 11 Effluent (unitless)								
Element	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.75
Al	4.122	4.518	**0.09**	11.674	10.898	2.322	0.677	0.38	0.172
B	0.067	**0.05**	**0.05**	1.511	1.944	0.732	0.038	0.029	0.03
Ba	**0.01**	**0.01**	**0.01**	4.353	5.918	2.256	0.027	0.022	0.046
Ca	**0.01**	**0.01**	**0.01**	0.141	0.494	0.464	**0.001**	**0.001**	6.308
Cd	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.003**	**0.003**	**0.003**	**0.003**
Co	**0.05**	**0.05**	**0.05**	0.073	0.068	**0.005**	**0.005**	**0.005**	0.039
Cr	**0.04**	**0.04**	**0.04**	0.053	0.069	**0.004**	**0.004**	0.005	0.01
Cu	**0.01**	**0.01**	**0.01**	0.026	0.027	**0.001**	**0.001**	0.002	**0.001**
Fe	**0.02**	**0.02**	**0.02**	0.881	0.946	0.229	0.389	0.215	0.094
La	**0.1**	**0.1**	**0.1**	0.104	0.168	0.012	**0.01**	0.015	0.021
Li	**0.01**	**0.01**	**0.01**	0.013	0.014	**0.001**	**0.001**	**0.001**	0.012
Mg	0.086	**0.01**	**0.01**	0.098	0.127	0.053	0.033	0.038	3.87
Mn	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.001**	**0.001**	**0.001**	1.712
Mo	0.096	0.112	0.05	**0.04**	**0.04**	**0.004**	**0.004**	**0.004**	**0.004**
Na	4490.092	4326	2915	655	244	154	126	134	110
Ni	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.01**	**0.01**	**0.01**	0.028
P	6.362	6.055	2.777	3.435	7.252	3.885	1.426	0.517	0.139
Pb	**0.51**	**0.51**	**0.51**	**0.51**	**0.51**	**0.051**	**0.051**	**0.051**	**0.051**
Si	1.078	0.557	0.703	1.767	1.78	7.33	17.436	34.219	39.8
Sn	2.049	2.001	1.341	0.324	0.424	0.033	0.023	0.033	0.033
Sr	**0.01**	**0.01**	**0.01**	0.05	0.067	0.025	0.005	0.004	0.031
Ti	**0.01**	**0.01**	**0.01**	0.036	0.034	0.003	0.019	0.012	0.006
U	0.433	0.394	0.215	0.048	0.017	0.004	0.004	0.002	0.001
V	0.114	0.108	0.128	0.301	0.354	0.15	0.068	0.033	0.009
Zn	**0.03**	**0.03**	**0.03**	2.442	3.286	1.226	**0.003**	**0.003**	0.004
Zr	**0.02**	**0.02**	**0.02**	0.1	0.105	0.013	0.004	0.005	0.003

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base=	Na_3PO_4	Form = Liquid	pH	10.0	CO_2?	Saturated

	Porevolume FEX 11 Effluent (unitless)					
Element	7.50	8.00	8.5	9.00	9.50	10.0
Al	10.75	16.327	20.085	20.196	20.331	20.239
B	0.061	0.029	0.021	0.017	0.014	0.013
Ba	0.763	0.803	0.39	0.361	0.356	0.351
Ca	8.275	8.079	4.259	4.122	4.112	4.086
Cd	0.006	0.008	0.004	**0.003**	**0.003**	**0.003**
Co	0.109	0.134	0.059	0.056	0.055	0.056
Cr	0.011	0.011	0.009	0.012	0.009	0.013
Cu	0.05	0.05	0.043	0.039	0.037	0.037
Fe	0.096	0.106	0.1	0.087	0.082	0.079
La	0.068	0.073	0.065	0.047	0.047	0.06
Li	0.012	0.011	0.008	0.007	0.007	0.008
Mg	3.823	3.048	2.01	1.962	1.966	1.951
Mn	2.825	3.164	1.53	1.471	1.468	1.454
Mo	0.007	0.009	0.008	0.009	0.01	0.008
Na	81.832	71.848	69.593	69.48	70.208	70.022
Ni	0.067	0.078	0.038	0.037	0.035	0.031
P	0.064	0.091	0.072	0.088	0.078	0.075
Pb	**0.051**	0.061	**0.051**	0.055	**0.051**	**0.051**
Si	39.492	38.026	37.168	36.832	36.979	36.706
Sn	0.044	0.047	0.051	0.05	0.057	0.054
Sr	0.051	0.055	0.025	0.024	0.023	0.023
Ti	0.048	0.048	0.049	0.032	0.028	0.027
U	0.015	0.028	0.060	0.116	0.166	0.224
V	0.004	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**
Zn	0.138	0.158	0.061	0.056	0.053	0.05
Zr	0.074	0.072	0.07	0.045	0.04	0.039

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base=	NaOH	Form = Liquid	pH	10.0	CO_2?	Saturated

	Porevolume FEX 11 Effluent (unitless)								
Element	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.75
Al	0.679	4.338	6.488	51.082	32.576	3.334	1.407	0.541	0.205
B	0.305	0.151	0.145	0.821	0.963	0.684	0.804	0.014	0.014
Ba	**0.01**	**0.01**	0.012	2.335	2.774	2.008	2.37	0.012	0.057
Ca	2.396	0.064	**0.01**	1.412	1.459	0.518	0.574	**0.001**	4.751
Cd	**0.03**	**0.03**	**0.03**	0.012	0.007	**0.003**	**0.003**	**0.003**	**0.003**
Co	**0.05**	0.075	0.051	0.01	**0.005**	**0.005**	**0.005**	**0.005**	0.035
Cr	0.053	0.223	0.221	0.085	0.024	**0.004**	**0.004**	**0.004**	**0.004**
Cu	0.013	0.029	0.024	0.025	0.016	**0.001**	**0.001**	**0.001**	**0.001**
Fe	0.186	0.192	0.159	27.457	22.922	1.266	0.5	0.304	0.111
La	**0.1**	**0.1**	**0.1**	0.051	0.032	**0.01**	**0.01**	**0.01**	**0.01**
Li	**0.01**	**0.01**	**0.01**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	0.01
Mg	1.956	0.55	0.14	0.395	0.277	0.056	0.058	0.016	2.639
Mn	0.608	0.19	0.057	0.22	0.184	0.016	0.005	0.004	1.459
Mo	**0.04**	0.08	0.073	0.036	0.016	**0.004**	**0.004**	**0.004**	**0.004**
Na	4515.754	14118.35	13876.13	4251.148	523.091	153.713	136.527	131.027	114.929
Ni	**0.1**	**0.1**	**0.1**	0.013	**0.01**	**0.01**	**0.01**	**0.01**	0.019
P	2072.063	6443.121	6142.313	1671.661	199.609	8.277	2.499	0.832	0.743
Pb	**0.51**	**0.51**	**0.51**	0.104	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**
Si	32.494	10.221	4.262	15.649	8.576	7.976	21.266	35.928	39.572
Sn	**0.2**	**0.2**	**0.2**	0.074	0.03	**0.02**	**0.02**	**0.02**	**0.02**
Sr	**0.01**	**0.01**	**0.01**	0.051	0.052	0.024	0.027	0.002	0.021
Ti	**0.01**	0.015	0.018	0.163	0.139	0.008	0.003	0.017	0.007
U	0.367	3.709	4.876	1.985	0.592	0.043	0.016	0.007	0.004
V	0.208	1.486	1.366	0.6	0.294	0.049	0.016	0.009	0.003
Zn	**0.03**	**0.03**	**0.03**	1.431	1.578	1.126	1.309	**0.003**	0.01
Zr	**0.02**	0.061	0.079	0.195	0.155	0.015	0.012	**0.002**	**0.002**

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base=	NaOH	Form = Liquid	pH	10.0	CO_2?	Saturated

	Porevolume FEX 11 Effluent (unitless)					
Element	7.50	8.00	8.5	9.00	9.50	10.0
Al	6.991	18.748	19.676	19.829	20.159	20.333
B	0.028	0.014	0.01	0.011	0.009	0.009
Ba	0.82	0.437	0.365	0.349	0.345	0.344
Ca	16.348	4.705	4.275	4.199	4.204	4.182
Cd	0.009	0.004	**0.003**	0.004	0.004	0.004
Co	0.184	0.063	0.057	0.056	0.053	0.053
Cr	0.017	0.007	0.007	0.008	0.008	0.008
Cu	0.053	0.061	0.045	0.041	0.039	0.038
Fe	0.131	0.143	0.1	0.082	0.073	0.068
La	0.045	0.069	0.051	0.034	0.031	0.031
Li	0.019	0.008	0.008	0.007	0.007	0.007
Mg	7.376	2.086	1.932	1.91	1.907	1.907
Mn	5.595	1.644	1.486	1.457	1.451	1.445
Mo	**0.004**	0.009	0.01	0.009	0.01	0.009
Na	68.879	68.427	67.775	67.546	68.006	68.341
Ni	0.106	0.035	0.03	0.029	0.029	0.029
P	0.059	0.117	0.067	0.067	0.083	0.076
Pb	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**
Si	38.528	36.107	35.781	35.542	35.481	35.468
Sn	0.021	**0.02**	**0.02**	0.036	0.025	**0.02**
Sr	0.086	0.027	0.024	0.024	0.024	0.024
Ti	0.032	0.069	0.045	0.033	0.028	0.027
U	0.091	0.207	0.169	0.177	0.219	0.255
V	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**
Zn	0.188	0.074	0.057	0.052	0.052	0.049
Zr	0.048	0.098	0.061	0.043	0.038	0.036

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base= Fe(0)	Form = Soil Mix	pH	NA	CO_2?	NA

	Porevolume FEX 11 Effluent (unitless)								
Element	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.75
Al	1.136	2.559	3.735	2.794	1.799	0.458	0.175	0.162	0.084
B	0.548	0.413	0.295	0.202	0.168	0.086	0.078	0.074	0.068
Ba	0.06	0.012	0.015	0.017	0.014	0.03	0.037	0.035	0.048
Ca	1.509	0.375	0.246	0.253	0.209	3.789	15.907	14.737	10.683
Cd	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**
Co	0.012	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**
Cr	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**	0.011	0.012	0.013
Cu	0.007	0.003	0.002	0.002	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
Fe	0.264	0.154	0.178	0.108	0.081	0.019	0.005	0.026	0.796
La	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	0.016	0.016	0.013
Li	0.002	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	0.002	0.006
Mg	0.738	0.233	0.143	0.134	0.115	2.019	6.678	5.964	4.476
Mn	0.348	0.053	0.027	0.02	0.016	0.082	0.178	1.984	6.38
Mo	0.026	0.037	0.036	0.026	0.02	0.005	**0.004**	**0.004**	**0.004**
Na	64.527	53.716	66.488	96.084	104.413	93.916	67.364	65.485	65.319
Ni	0.013	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	0.028
P	0.628	1.505	2.111	1.315	0.726	0.135	0.065	0.052	0.074
Pb	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**
Si	5.991	2.798	1.935	1.524	1.335	0.964	0.765	0.758	0.8
Sn	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**
Sr	0.006	**0.001**	**0.001**	**0.001**	**0.001**	0.014	0.07	0.083	0.085
Ti	0.002	**0.001**	0.002	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
U	0.047	0.047	0.093	0.074	0.058	0.016	0.010	0.007	0.004
V	**0.002**	**0.002**	0.003	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	0.003
Zn	0.062	0.01	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**
Zr	0.004	**0.002**	0.003	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base= Fe(0)	Form = Soil Mix	pH	NA	CO_2?	NA

	Porevolume FEX 11 Effluent (unitless)					
Element	7.50	8.00	8.5	9.00	9.50	10.0
Al	0.027	0.03	0.036	0.023	0.024	0.027
B	0.062	0.055	0.05	0.045	0.041	0.037
Ba	0.062	0.055	0.127	0.224	0.302	0.338
Ca	6.813	4.475	6.183	5.084	4.868	4.644
Cd	**0.003**	**0.003**	**0.003**	0.005	0.006	0.006
Co	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**
Cr	0.01	**0.004**	0.01	0.01	0.01	0.01
Cu	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
Fe	5.052	2.858	9.033	13.829	15.988	17.015
La	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Li	0.007	0.006	0.007	0.007	0.007	0.007
Mg	2.743	1.935	2.549	2.18	2.127	2.072
Mn	10.259	5.4	8.079	6.411	5.204	4.386
Mo	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**
Na	65.041	67.218	67.156	67.1	67.623	67.543
Ni	0.042	0.024	0.033	0.032	0.026	0.022
P	0.056	0.082	0.056	0.063	0.046	0.061
Pb	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**
Si	0.773	0.688	0.661	0.592	0.54	0.475
Sn	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**
Sr	0.058	0.034	0.045	0.035	0.032	0.029
Ti	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
U	0.005	0.003	0.005	0.003	0.004	0.006
V	**0.002**	**0.002**	0.003	0.003	0.004	0.004
Zn	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**
Zr	**0.002**	0.004	**0.002**	**0.002**	0.003	0.005

All Data in mg/L .... Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base= Fe(0)/Apatite	Form = Soil Mix	pH	NA	CO_2?	NA

	Porevolume FEX 11 Effluent (unitless)								
Element	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.75
Al	0.401	0.498	0.455	0.459	0.432	0.446	0.406	0.398	0.382
B	1.444	0.165	0.144	0.095	0.084	0.078	0.065	0.061	0.06
Ba	0.028	0.023	0.036	0.051	0.07	0.062	0.048	0.029	0.024
Ca	3.714	4.114	5.887	7.912	11.178	17.903	33.11	37.745	33.936
Cd	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**
Co	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**
Cr	**0.004**	**0.004**	**0.004**	0.005	**0.004**	0.007	0.01	0.012	0.012
Cu	0.002	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
Fe	0.045	0.01	0.007	0.004	0.003	**0.002**	0.004	0.003	0.003
La	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	0.028	0.028	0.026
Li	0.002	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
Mg	2.05	0.775	0.774	0.652	0.73	1.181	1.92	3.782	4.737
Mn	0.043	0.013	0.015	0.015	0.023	0.057	0.063	0.061	0.056
Mo	0.028	0.029	0.021	0.017	0.009	0.007	0.007	0.005	**0.004**
Na	90.6	61.288	67.207	72.437	107.906	105.284	79.267	68.127	67.336
Ni	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
P	0.795	0.418	0.454	0.204	0.124	0.103	0.086	0.075	0.076
Pb	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**
Si	7.829	2.024	1.78	1.512	1.33	1.301	1.11	1.062	1.019
Sn	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**
Sr	0.006	0.015	0.035	0.066	0.105	0.176	0.343	0.396	0.368
Ti	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
U	0.212	0.016	0.014	0.006	0.004	0.003	0.003	0.002	0.002
V	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**
Zn	0.026	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**
Zr	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Base= Fe(0)/Apatite	Form = Soil Mix	pH	NA	CO_2?	NA

	Porevolume FEX 11 Effluent (unitless)					
Element	7.50	8.00	8.5	9.00	9.50	10.0
Al	0.297	0.212	0.12	0.048	0.026	0.023
B	0.06	0.06	0.057	0.056	0.05	0.046
Ba	0.026	0.027	0.033	0.036	0.038	0.045
Ca	30.359	22.377	23.938	20.767	18.875	17.408
Cd	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	0.004
Co	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**
Cr	0.013	0.009	0.011	0.011	0.011	0.01
Cu	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
Fe	0.045	0.975	2.736	5.782	8.043	9.658
La	0.025	0.011	0.018	0.017	0.011	0.012
Li	0.005	0.006	0.007	0.007	0.007	0.007
Mg	4.5	3.105	3.283	2.888	2.683	2.528
Mn	1.573	1.967	3.416	3.662	3.315	3.125
Mo	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**	**0.004**
Na	68.131	69.696	68.264	68.604	68.877	68.098
Ni	**0.01**	**0.01**	0.014	0.016	0.016	0.015
P	0.071	0.095	0.069	0.079	0.089	0.067
Pb	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**	**0.051**
Si	1.094	1.137	1.173	1.245	1.288	1.288
Sn	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**
Sr	0.34	0.25	0.257	0.22	0.195	0.176
Ti	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
U	0.002	0.002	0.001	0.002	0.001	0.001
V	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**
Zn	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**
Zr	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**	**0.002**

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Influent Blank - Series 2

	Porevolume FEX 11 Effluent (unitless)								
Element	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.75
Al	12.537	13.099	14.067	15.341	16.176	18.656	18.555	18.688	19.247
B	0.018	0.012	0.012	0.011	0.009	0.01	0.007	0.007	0.008
Ba	0.241	0.254	0.267	0.286	0.299	0.338	0.336	0.341	0.351
Ca	3.721	3.774	3.809	3.865	3.902	4.077	4.063	4.072	4.145
Cd	0.005	0.005	0.006	0.005	0.006	0.006	0.005	0.006	0.005
Co	0.052	0.052	0.055	0.055	0.056	0.058	0.055	0.055	0.057
Cr	0.014	0.014	0.016	0.015	0.016	0.014	0.012	0.015	0.013
Cu	0.027	0.027	0.029	0.03	0.031	0.033	0.032	0.033	0.034
Fe	0.019	0.019	0.02	0.021	0.022	0.024	0.023	0.023	0.024
La	0.023	0.021	0.024	0.026	0.031	0.028	0.029	0.031	0.033
Li	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Mg	1.788	1.793	1.798	1.808	1.826	1.856	1.845	1.849	1.875
Mn	1.217	1.243	1.258	1.282	1.305	1.37	1.357	1.365	1.393
Mo	0.011	0.01	0.012	0.011	0.012	0.013	0.012	0.013	0.014
Na	162.851	156.715	146.812	132.888	122.749	80.739	80.524	74.627	72.557
Ni	0.035	0.036	0.041	0.038	0.039	0.042	0.037	0.035	0.039
P	38.2	36.75	32.989	27.726	23.928	8.189	8.194	6.422	5.639
Pb	0.05	**0.046**	0.052	**0.046**	0.062	**0.046**	0.049	0.051	**0.046**
Si	32.862	32.407	32.331	32.303	32.434	32.808	32.614	32.615	32.925
Sn	0.028	0.027	0.037	0.032	0.032	0.024	0.034	0.026	0.04
Sr	0.02	0.02	0.021	0.021	0.022	0.023	0.023	0.023	0.024
Ti	0.021	0.021	0.023	0.024	0.026	0.028	0.028	0.028	0.029
U	0.843	0.929	0.964	1.054	1.100	1.152	1.254	1.264	1.319
V	0.009	0.008	0.009	0.009	0.01	0.009	0.007	0.008	0.008
Zn	0.042	0.036	0.039	0.039	0.041	0.042	0.042	0.043	0.043
Zr	0.033	0.034	0.036	0.037	0.04	0.043	0.042	0.042	0.043

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES

Influent Blank - Series 2

	Porevolume FEX 11 Effluent (unitless)					
Element	7.50	8.00	8.5	9.00	9.50	10.0
Al	19.214	20.242	19.444	19.53	19.678	19.651
B	0.007	0.008	0.006	0.007	0.005	0.005
Ba	0.35	0.365	0.352	0.354	0.36	0.36
Ca	4.102	4.277	4.098	4.12	4.146	4.142
Cd	0.005	0.007	0.004	0.005	0.006	0.004
Co	0.057	0.061	0.057	0.055	0.058	0.057
Cr	0.014	0.016	0.014	0.013	0.013	0.013
Cu	0.034	0.036	0.033	0.033	0.034	0.034
Fe	0.023	0.027	0.024	0.024	0.025	0.024
La	0.029	0.036	0.029	0.036	0.03	0.029
Li	0.008	0.009	0.008	0.008	0.008	0.007
Mg	1.847	1.933	1.844	1.852	1.935	1.93
Mn	1.377	1.451	1.373	1.38	1.387	1.384
Mo	0.011	0.014	0.012	0.014	0.011	0.012
Na	68.404	71.052	67.687	68.116	68.124	68.178
Ni	0.04	0.042	0.038	0.037	0.037	0.04
P	3.911	3.564	3.082	3.248	3.683	3.72
Pb	**0.046**	0.05	0.049	**0.046**	**0.046**	**0.046**
Si	32.47	34.121	32.601	32.714	32.911	32.836
Sn	0.027	0.035	0.029	0.021	0.034	0.034
Sr	0.024	0.025	0.024	0.024	0.024	0.024
Ti	0.029	0.031	0.029	0.029	0.028	0.028
U	1.304	1.274	1.304	1.277	1.281	1.305
V	0.008	0.01	0.008	0.008	0.008	0.008
Zn	0.043	0.046	0.043	0.045	0.042	0.043
Zr	0.043	0.047	0.043	0.043	0.038	0.038

All Data in mg/L ....Bolded Data are Below Detection Limit
U Data by ICP-MS all Other by ICP-ES