

## AN ABSTRACT OF THE THESIS OF

Bruce L. Ball for the degree of Master of Science in Civil Engineering presented on February 11, 1992.

Title: Soil Column Desorption Studies on a Chromium Contaminated Soil

Abstract approved: *Redacted for Privacy* \_\_\_\_\_  
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Soil column studies were performed on a chromium contaminated soil from the United Chrome Products Superfund Site currently undergoing a pump-and-treat cleanup process. The goal of the research was to provide insight into the feasibility of chemically changing the injection fluid of the pump-and-treat system to enhance hexavalent chromium (Cr(VI)) mobility. The parameters tested were pH, ionic strength, and competitive anion type and concentration.

Ionic strength effects were investigated by adjusting the NaCl concentration of the extracting solution and by observing the influence of varying anion concentrations on desorption (bicarbonate, sulfate, and phosphate). The results indicated that high ionic strength solutions slow the rate of Cr(VI) desorption. This possibly indicates most of the Cr(VI) was in pore water solution and was adsorbing, slowing the removal process. Cr(VI) desorption was fastest for distilled water solution followed by competitive anion/distilled water solutions. The high ionic strength extracting solutions, 0.05 M and 0.10 M NaCl, had the slowest Cr(VI) desorption rates. Effluent pHs dropped as the ionic strength was increased (increasing NaCl concentrations) which was attributed to a Na-H exchange. Increased concentrations of bicarbonate, sulfate, and phosphate resulted in only small pH differences in the effluent of less than 0.5 pH units.

The effect of pH was investigated by varying the pH of the 0.01 M NaCl solution with strong acid and base and by varying the pH of phosphate competitive anion solutions. The effects of changing 0.01 M NaCl solution pH were inconclusive. Differences between Cr(VI) desorption rates for the soil columns with adjusted influent pHs were small. Cr(VI) desorption

curves and column effluent pH values for phosphate solutions of varying influent pH values were nearly identical, indicating that soil buffering and effluent pH are more important factors than influent pH in achieving Cr(VI) desorption.

Nitrate, bicarbonate, sulfate, and phosphate were investigated to determine the effect of various competitive anions on Cr(VI) desorption. The effectiveness of each anion at extracting Cr(VI) from soil appeared to follow the order of adsorption affinity to the soil.

Soil Column Desorption Studies on a Chromium Contaminated Soil

by

Bruce L. Ball

A THESIS

submitted to

Oregon State University

in partial fulfillment of

the requirements for the

degree of

Master of Science

Completed February 11, 1992

Commencement June 1992

APPROVED:

*Redacted for Privacy*

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Date thesis is presented: February 11, 1992

Presented by: Bruce L. Ball

## **ACKNOWLEDGEMENTS**

I would like to acknowledge Dr. Peter O. Nelson, my major professor, who gave me the opportunity to do this research which proved to be one of the most valuable experiences of my education. I would also like to thank my best friends David Mc Walter and Mark Adreon for their patience, understanding, and encouragement during the times when I became too wrapped up with school and this project.

Funding for this project was provided by the EPA Western Region Hazardous Substance Research Center.

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# SOIL COLUMN DESORPTION STUDIES ON A CHROMIUM CONTAMINATED SOIL

## INTRODUCTION

Chromium is a metallic transition metal, which has been used in a variety of applications, most notably as decorative and corrosion resistant plating material for automobile and aircraft parts and other metal products. Hexavalent chromium (Cr(VI)) is an especially hazardous oxidation state of chromium due both to its toxicity to living organism and its high degree of mobility in groundwater. A known human carcinogen and irritant, severe health affects include damage to kidney tissues, development of lung tumors (Doull et al, 1980), and skin ulcers (Davids, 1951). Cr(VI) has been shown to reduce plant growth at concentration as low as 5 ppm (Barlett and Kimble, 1976).

Numerous chromium contaminated sites are presently listed on the National Priorities List (NPL). Several of these are located in EPA region 9 and 10 and include United Chrome Products Inc., Corvallis, OR; Allied Plating Inc., Portland, OR; and Frontier Hard Chrome Inc., Vancouver, WA.

### Site History

The United Chrome Products Superfund (UCPS) site in Corvallis, Oregon, located at Corvallis Airport Industrial Park was a hard chrome plating facility that operated between 1956 and 1985. The chrome plating process resulted in significant contamination of soils beneath the site with chromium, arsenic, barium, and lead. Although high concentrations of all four toxic metals were present in the soils, the groundwater concentrations of arsenic, barium, and lead were very low and only hexavalent chromium represented a migratory threat (CH2M Hill, Aug. 1990).

The primary sources of chromium contamination were attributed to a leaking plating tank and a dry well used for disposal of wastewaters (Ecology and Environment, July, 1985). Most of the contamination occurred in the upper silts with the plume extending 300 ft (CH2M Hill, June 1990) downgradient from the contaminant sources. Groundwater concentrations were measured

as high as 19,000 mg/L Cr(VI) near the plating tank and 2641 mg/L Cr(VI) in the dry well area (CH2M Hill, June 1990). Soil contamination was observed as high as 16,000 mg/kg Cr(VI) in soils adjacent to the plating tank and 10,000 mg/kg in the dry well (CH2M Hill, Aug. 1990).

Site cleanup was initiated in August, 1988 with the implementation of an EPA approved pump-and-treat system at UCPS site for the removal of Cr(VI) from the groundwater and soil. Twenty-three extraction wells and two infiltration basins for recharge were used to remove contaminated groundwater from the upper aquifer for treatment. As of June, 1990, 20,200 pounds of Cr(VI) have been removed (CH2M Hill, Aug. 1990). Some site specific information may be found in Appendix A.

#### Site Hydrogeology

The upper zone consists of about 18 feet of course to fine silt underlain by a 2 to 10 foot thick aquitard. The aquitard is composed of hard, dark grey clay with few voids or fractures. The lower aquifer consist of interbedded silty sandy gravelly layers (CH2M Hill, June 1990).

The groundwater in the upper zone flows generally to the northeast and the water table varies seasonally between the ground surface and 10 ft below ground (CH2M Hill, Aug. 1990). The estimated hydraulic conductivity of the silts ranges from about 0.5 to 2.5 ft per day and the advective velocity ranges from 3 to 30 ft per year (CH2M Hill, Aug. 1990).

#### Study Objectives

The effectiveness of a pump-and-treat system is dependent on hexavalent chromium sorption and desorption kinetics and the influence of competing solute anions. It has been shown that the efficiency of the pump-and-treat system declines as the cleanup enters the "tailing phase". This tailing phase may require long periods of time and resources to reach acceptable cleanup levels of the remaining exchangeable Cr(VI) in the soil system. Processes that may cause this tailing of concentration in extraction wells include 1) differential time it takes the contaminant water to flow from the plume boundary to extraction well; 2) diffusive mass transport within sediment; 3) mass transfer from non-aqueous phase and solid phase reserve of mineral

precipitate; and 4) sorption-desorption processes (Palmer and Fisher, 1990). The amount of tailing that can be expected and hence cleanup time and cost required are relatively unknown.

The motivation behind this research is to gain an understanding of the desorption behavior of Cr(VI) on UCPS site soils in order to provide insight into the effectiveness of chemical enhancement of a pump-and-treat remediation scheme. The primary objective of this study is to understand the effect of varying influent conditions of the extraction solution on Cr(VI) removal from contaminated soils obtained at the United Chrome Products Superfund site.

The specific objectives are to investigate the effects of: 1) competing anion type and concentration, 2) influent pH and, 3) ionic strength, on Cr(VI) desorption from a contaminated soil.

## LITERATURE REVIEW

A variety of studies related to Cr(VI) adsorption have been published. However, only a few articles address Cr(VI) desorption processes.

Zachara et al. (1987) investigated chromate adsorption on amorphous iron oxyhydroxide in dilute iron suspensions and in solutions of varying ion composition. Chromate adsorption was reduced when paired with anions through a combination of competitive and electrostatic effects. He found that addition of anions to the mixture decreased chromate adsorption further. Cations showed no appreciable influences on chromate adsorption. In a later study Zachara (1989) found soils containing higher concentrations of Al and Fe oxides exhibited increased Cr(VI) adsorption. Eary and Rai (1988, 1989) observed that chromate is reduced by ferrous iron under most conditions, but may be rate-limited by the presence of phosphate or by dissolution rates of hematite or biotite that control iron solubility. Davis and Leckie (1980) concluded that chromate and bichromate are sorbing species on amorphous iron oxyhydroxide.

Barlett and Kimble (1976) performed Cr(VI) adsorption and reduction experiments in soils of contrasting pH's, organic matter contents, and chemical and mineralogical properties. They found the presence of soil organic matter caused immediate reduction of Cr(VI) to Cr(III). Cr(VI) adsorbed to a variety of soils tested except for a pH 7.8 soil. No adsorption occurred in the presence of orthophosphate due to competition for adsorption sites. They concluded that Cr(VI) adsorption behavior is similar to that of orthophosphate in soils. Barlett and James (1979) observed Cr(III) oxidized to Cr(VI) in the presence of oxidized manganese.

Grove and Ellis (1980) studied the effect of soil pH on soil chemistry by adding to the soil Cr(VI), Cr(III), and sludge Cr. Cr(III) addition reduced soil pH while sludge raised soil pH. Soil treated with Cr(VI) initially showed a decrease in soil pH followed by an increase in soil pH above the controlled soils. Water-soluble Cr(III) decreased with time with the rate of removal increasing with increasing soil pH. Cr(VI) also decreased with time but less rapidly as soil pH increased.

Griffin et al. (1977) found Cr(VI) adsorption by kaolinite and montmorillonite clay minerals to be pH dependent for landfill leachate. Cr(VI) adsorption increased as pH decreased due to a decrease of positive surface charges on clays and hydrous oxides. At high pH when chromate is the dominant species no sorption was observed. Below pH 2, Cr(VI) adsorption decreased as the fraction of bichromate present decreased, resulting in less Cr(VI) adsorption. Zachara et al. (1988), Bartlett and Kimble (1976), and Bean (1989) all noted a pH dependence for chromate adsorption on kaolinite.

In a study on horizon soils from the northeastern United States, James and Bartlett (1983) defined the fraction of Cr(VI) removed by 10 mM K-phosphate at pH 7.2 as exchangeable, and that fraction retained on the soil was termed nonexchangeable. The nonexchangeable Cr(VI) had either been reduced to Cr(III) or had been precipitated or very tightly adsorbed by the soil. Addition of sulfate and phosphate to their Cr(VI) adsorption solution decreased Cr(VI) removal by the soil with phosphate having a greater effect than sulfate. Zachara et al. (1988) found that sulfate at low concentrations was not competitive with chromate while at high sulfate concentrations chromate adsorption was enhanced.

Stollenwerk and Grove (1985) studied the reaction of Cr(VI) with alluvium to determine the reaction mechanisms. They found that the amount of Cr(VI) adsorbed in a soil column varied with the type and concentration of other anions in solution. They concluded that Cr(VI) adsorbed by nonspecific processes as well as by specific sorption site processes. Desorption experiments with phosphate indicated a strong competitive effect caused by direct competition for specific surface sites. Chloride and nitrate showed a much smaller effect on Cr(VI) adsorption which was attributed to non specific site adsorption resulting from a decrease in electrostatic potential near the surface of the particle.

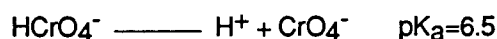
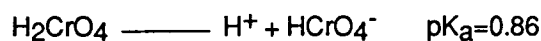
Bean (1989) in his batch reactions observed no difference in Cr(VI) adsorption between distilled water and groundwater suspensions below pH 5, however, above pH 5 Cr(VI) adsorption was higher in soil groundwater suspensions than in soil-distilled water suspensions. Competitive

effects alone were not sufficient to cause net Cr(VI) adsorption to decrease. Griffin et al. (1977) also observed that high ionic strength contributes to high Cr(VI) adsorption by compression of diffused double layer by ionic species or by primary charge reduction of the soil by adsorbed groundwater cations.

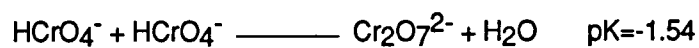
Edzwald et al. (1976) observed in his phosphate adsorption experiments an increase in adsorption in the presence of synthetic seawater concentrations of chloride and sulfate .

### Chromium Chemistry in Soils

Chromium exist in several oxidation states ranging from 0 to +6. The most common oxidation state found in natural systems are +3 (trivalent chromium) and +6 (hexavalent chromium). Three Cr(VI) species predominant at concentrations below 10mM (1 g/L) (see Figure 1):  $\text{H}_2\text{CrO}_4$  (chromic acid),  $\text{HCrO}_4^-$  (bichromate), and  $\text{CrO}_4^{2-}$  (chromate). The following acid dissolution reactions apply:



Total chromium concentration greater than 10 mM (1 g/L) dichromate is the predominant species according to the following reaction:

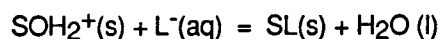
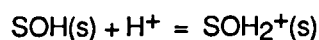


Bichromate and chromate solutions are yellow in color and dichromate is orange at concentrations greater than 1 mg/L.

### Inorganic Oxyanion Chemistry in Soils:

Common oxyanions in soil include  $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{H}_2\text{PO}_4^-$ ,  $\text{HPO}_4^{2-}$ ,  $\text{PO}_4^{3-}$ . There are two generally accepted mechanisms for inorganic oxyanion adsorption by soil minerals (Sposito, 1984):

#### 1) Inner Sphere - two step ligand exchange



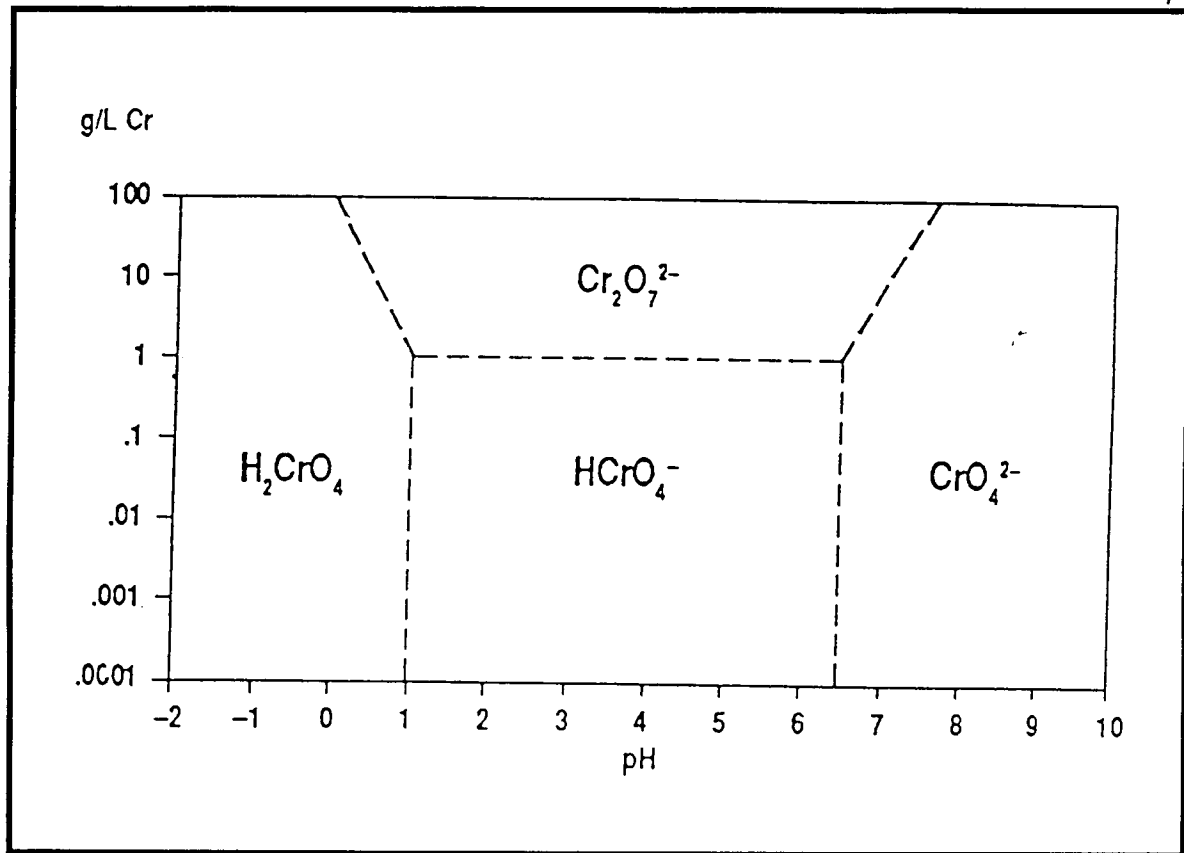
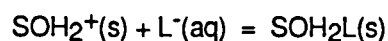


Figure 1. Relative concentration of Cr(VI) species as a function of pH and Cr(VI) concentration.

S = metal cation:  $\text{SOH}(\text{s})$  = surface hydroxyl group;  $\text{L}^-$  = inorganic oxyanion of valence 1. The surface protonation step makes the surface hydroxyl group more exchangeable and explains in part increases in anion adsorption with decreasing pH for soils and soil minerals (Nelson, 1990).

## 2) Outer Sphere



Outer Sphere complexes are weaker than Inner Sphere.

Anion adsorption equilibria on soils and minerals are depicted by langmuir isotherms. The state of protonation of the oxyanion is important to the exchange reaction since adsorption occurs predominantly by ligand exchange with surface  $\text{OH}^-$  or  $\text{OH}_2^+$ . Strong acids ( $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ) adsorb only if surface carries positive charge or when solution is on acid side of point of zero charge



(PZC). Anions of weak acids ( $\text{CrO}_4^{2-}$  and  $\text{CO}_3^{2-}$ ) can adsorb on the alkaline side of PZC since the anion can provide proton in exchange reaction.

## MATERIALS AND METHODS

### Experimental Approach

Soil column studies were performed on a chromium contaminated soil from the United Chrome Products Superfund site (UCPS) in order to satisfy the objectives of this study. The chromium desorption experiments were designed to provide an understanding of the effect of varying pH, conductivity, anion concentration and type of extracting solution on hexavalent chromium removal. Table 1 provides a summary of the experimental conditions and influent solution compositions.

### Experimental Materials

#### *Soil*

Chromium contaminated soils of the Dayton Silty Loam Series were collected from the UCPS site near the initial source of contamination. The soil was taken from a depth of 7-9 ft in shelly tubes during drilling of a deep aquifer monitoring well (31 January 1990) and stored on site at ambient temperatures for eight months prior to being removed and refrigerated at 4°C (CH2M Hill, June and Aug. 1990).

In the lab, the soil was extruded from the shelly tube and the outer 1/8 inch trimmed and discarded. The remaining soil was then broken up, air dried for one week, passed through a "Dynacrush" grinder, sieved through a 2 mm screen to remove rocks and roots, homogenized, and stored in a clean five gallon plastic container at 4°C degrees Celsius.

The prepared soil was chemically and physically characterized to determine the nature of the soil particles, organic and moisture contents, and the concentration of various metals and anions. The results and the methods of testing employed are outlined in Table 2.

#### *Extracting Solution*

To simulate field groundwater ionic strength (CH2M Hill, Aug. 1990), 0.01 M NaCl was chosen as background solution and a basis for comparison. Chloride is considered a

Table 1: Summary of conditions for soil column experiments.

Exp./Col. Number	Electrolyte Solution	Extracting Agent	Influent pH	Column Porosity (%)
1A	Distilled water	-----	5.5	48
1B	0.01 M NaCl	-----	6.6	48
1C	0.05 M NaCl	-----	6.5	49
1E	0.01 M NaCl	0.3 mM HCl	2.7	47
1F	0.01 M NaCl	0.3 mM NaOH	11.5	47
1G	0.10 M NaCl	-----	6.1	48
1H	0.01 M NaCl	-----	6.7	49
1I	Corvallis tapwater	-----	7.1	48
2A	0.01 M NaCl	5 mM Na <sub>2</sub> SO <sub>4</sub>	6.9	49
2B	0.01 M NaCl	0.01 M Na <sub>2</sub> SO <sub>4</sub>	6.0	47
2C	0.01 M NaCl	1 mM Na <sub>2</sub> SO <sub>4</sub>	7.2	48
2D	Distilled water	5 mM Na <sub>2</sub> SO <sub>4</sub>	5.9	50
3A	0.01 M NaCl	0.01 M NaH <sub>2</sub> PO <sub>4</sub>	4.7	48
3B	0.01 M NaCl	5 mM Na <sub>2</sub> HPO <sub>4</sub>	8.3	48
3C	0.01 M NaCl	0.01 M Na <sub>2</sub> HPO <sub>4</sub>	9.2	46
3D	Distilled water	0.02 M Na <sub>2</sub> HPO <sub>4</sub>	9.3	46
3E	0.01 M NaCl	0.01 M Na <sub>3</sub> PO <sub>4</sub>	11.0	47
3F	0.01 M NaCl	0.02 M Na <sub>2</sub> HPO <sub>4</sub>	9.2	47
4A	0.01 M NaCl	0.01 M NaNO <sub>3</sub>	5.6	50
5A	0.01 M NaCl	0.01 M NaHCO <sub>3</sub>	8.3	47
5B	0.01 M NaCl	1 mM NaHCO <sub>3</sub>	8.2	48
5C	0.01 M NaCl	0.02 M NaHCO <sub>3</sub>	8.3	49
5D	Distilled water	0.01 M NaHCO <sub>3</sub>	8.4	49

noncompetitive anion. Griffin (1977) showed no appreciable change in chromate adsorption on clays due to the presence of chloride.

Competitive anion solutes used in the extracting solution included bicarbonate, nitrate, sulfate, and phosphate, all added as sodium salts. Prior to preparing the extracting solutions, double-distilled water was sparged of carbon-dioxide with nitrogen gas.

All chemicals used were ACS reagent grade. Glass and plastic wares were soaked in 10% nitric acid for 12 hours and rinsed well with double distilled water prior to use.

#### Apparatus

The apparatus consisted of four main components: 1) solution reservoir, 2) metering

Table 2. Soil physical and chemical characteristics and methods of determination.

<u>Physical Properties</u>	<u>Values</u>	<u>Method</u>
Clay (%)	42	Hydrometer
Silt (%)	53	Hydrometer
Sand (%)	5	Hydrometer
Moisture Content (%)	2.6	Oven (105C)
Organic Content (%)	3.3	Ignition (505C)
<u>Chemical Properties</u>		
pH	6.9	1:2 Soil/DDW
pH <sub>pzc</sub>	5.9	Titration
Soluble Manganese (mg/L)	17.2	DTPA
Soluble Iron (mg/L)	252.0	DTPA
Hexavalent Chromium (mg/kg)	25.0	Phosphate Extraction
Hexavalent Chromium (mg/kg)	37.1	Alkaline Digestion
Total Chromium (mg/kg)	109.4	Acid Digestion
Calcium (mg/kg)	2665.3	Ammonium Acetate
Magnesium (mg/kg)	862.8	Ammonium Acetate
Potassium (mg/L)	81.0	Ammonium Acetate
Phosphate (mg/L)	7.0	Ion Chromatography
Sulfate (mg/kg)	14.2	Ion Chromatography
Nitrate (mg/kg)	16.8	Ion Chromatography

valve, 3) polyacrylic column, and 4) effluent collector.

Extracting solutions were contained in four liter supply reservoirs opened to the atmosphere through a CO<sub>2</sub> trap containing 0.10 M Ba(OH)<sub>2</sub>. The barium hydroxide reacted with CO<sub>2</sub> to form BaCO<sub>3</sub> precipitate. The Ba(OH)<sub>2</sub> solution was replaced every 6-8 weeks. The reservoir was located seven feet above the 125 cm<sup>3</sup> (25 cm length, 5 cm<sup>2</sup> cross sectional area) polyacrylic column and was connected by 1/8 in polyethylene plastic tubing. A metering valve was used to manually regulate the influent flow rate and a shut-off valve to turn the flow on or off. Plastic tubing was changed before each experiment. Effluent was collected in 50 or 100 mL graduated cylinders sealed with parafilm to prevent evaporation. Parafilm was also used to seal the reservoir cap to reduce CO<sub>2</sub> transfer.

Pore volume is the difference between the dry soil column weight and the wet soil column weight divided by 1 g/cm<sup>3</sup>. Pore volume measures the volume of water contained with the pores of the soil column.

### Experimental Procedures

Polyacrylic columns were hand packed with contaminated soils to a field porosity of approximately 48% (CH2M Hill, Aug. 1990). The soil columns were packed by placing about 1-2 cm of soil into the column and then tamping the soil with a solid column equal to the inside diameter of the soil column. Table 3 list the physical characteristics of each packed column. The packed soil was then wetted by securing the column assembly above a 500 mL bottle containing 0.01 M NaCl and connecting a 1/8 in diameter plastic tube to the effluent port and submerging it in the bottle. A vacuum was exerted at the influent port to evacuate the soil column and draw the 0.01 M NaCl solution into the column. After approximately 15 minutes the vacuum was disconnected and the column was allowed to become saturated through capillary action. The soil columns were wrapped in aluminium foil to prevent light penetration and retard any possible algal growth. The columns remained under a no flow condition for 3-5 days prior to use to allow equilibration with the 0.01 M NaCl solution and the development of interparticle forces. The columns were operated at a ambient temperature of 20°C +- 3°C.

A metering valve located above the shut-off valve was used to maintain an average flow rate at field interstitial velocities of 0.8 cm/hr (2 mL/hr)(CH2M Hill, Aug. 1990).

Effluent was collected every 6-7 hours (0.2-0.25 pore volumes) during the first 2-3 effluent pore volumes and at larger intervals thereafter during the tailing phase. Ambient temperature, effluent volume, pH, and conductivity were measured and recorded at the time of collection. Samples were refrigerated at 4°C in 30 mL polyethylene plastic sample bottles and analyzed for Cr(VI), Cr(III), and anions within 48-72 hours after collection.

### Phosphate Extraction

Upon completion of the soil column study, the remaining exchangeable Cr(VI) on the soil was extracted with 0.10 M KH<sub>2</sub>PO<sub>4</sub>. The exchangeable Cr(VI) was determined by the following procedures:

- (1) Air dry the soil 1 week.

Table 3. Column physical characteristics.

Exp./Col.	Column Vol. (cm <sup>3</sup> )	Sample Weight (g)	Bulk Density (g/cm <sup>3</sup> )	Pore Vol. (cm <sup>3</sup> )
1A	125	166.30	1.33	60.01
1C	125	164.43	1.32	61.77
1E	128	173.63	1.36	60.01
1F	131	182.00	1.39	61.80
1G	125	165.38	1.32	59.74
1H	128	169.47	1.32	62.60
1I	128	170.30	1.33	61.65
2A	125	163.54	1.31	61.07
2B	125	164.78	1.32	59.06
2C	125	163.79	1.31	60.51
2D	125	161.85	1.29	61.95
3A	125	169.78	1.36	60.02
3B	125	169.66	1.36	59.94
3C	125	168.28	1.35	56.97
3D	125	167.47	1.34	57.28
3E	128	172.35	1.35	60.35
3F	125	165.82	1.33	59.28
4A	131	176.79	1.35	65.73
5A	125	167.47	1.34	58.93
5B	125	166.87	1.33	60.10
5C	125	170.25	1.36	60.88
5D	125	162.62	1.30	61.08

(2) Weigh 3-5 grams of soil and place in to a 50 mL centrifuge tube.

(3) Add 35 mL of 0.10 M KH<sub>2</sub>PO<sub>4</sub>.

(4) Shake in rotating shaker for 24-36 hours.

(5) Decant, filter, and analyze supernatant for Cr(VI).

Cr(VI) exchangeable mass balance was calculated by adding total Cr(VI) removed during the extracting experiment to the total Cr(VI) removed by phosphate extraction.

#### Analytical Methods

Cr(VI) and Cr(III) concentrations were determined on a Dionex Series 2000i Ion Chromatograph (IC). The IC is equipped with a visible light absorbance detector and utilizes a post column reaction with a color reagent. The columns used in the IC are a HPIC-CG5 guard column

and a HPIC-CS5 cation separator column. They were operated at a combined flow rate of 1.5 mL/min.

The post column solution consisting of acidified 1,5-diphenyl-carbohydrazide (DPC) was prepared according to the manufacturer's procedures (Dionex, 1987). The eluent solution consisted of pyridine-2,6-dicarboxylic acid (PDCA), disodium hydrogen phosphate, heptahydrate, sodium iodide, ammonium acetate, and lithium hydroxide monohydrate (Dionex, 1987).

Using direct injections of 50  $\mu$ L, the detection limits are approximately 100 ppb for Cr(III) and 1 ppb for Cr(VI) (Dionex, 1987). The concentrations were determined by comparing the unknown samples to a standard curve generated by linear regression of known concentrations. The  $r^2$  value generally ranged between 0.99 and 0.999 for concentrations below 1 mg/L and 0.999 and 0.99995 for concentrations above 1 mg/L.

Anion concentrations ( $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{PO}_4^{3-}$ ) were determined with a Dionex Series 4000i Ion Chromatograph equipped with a conductivity detector utilizing a carbonate/bicarbonate buffer eluent and automatic sampler with 50  $\mu$ L sample loop. The columns used in the IC were a HPIC-AG4A guard column and a HPIC-AS4A anion separator column. They were operated at a 2 mL/min flow rate (Dionex, 1987). The regenerant was prepared by diluting 2.9 mL of concentrated sulfuric acid in 4 liters of 18 M-ohm deionized water.

Anion standards for the concentration range of interest were prepared and used to generate a standard curve through linear regression. Unknown anion concentrations were then determined by comparison to the standard curve. The  $r^2$  value generally ranged between 0.99 and 0.999.

pH values of the samples were measured on an Orion research grade Ag/AgCl glass combination electrode with an Orion model 601A digital analyzer calibrated with appropriate pH buffer solutions.

The conductivity of the samples were measured on the Lab-Line Lectro Mho-meter, model MC-1 Mark IV utilizing a 0.1 cell constant. Measurements were made at 25°C. The ionic strengths were calculated by the following formula (Snocynk and Jenkins, 1980):

$$u = C \times 1.6 \times 10^{-5}$$

Where C = specific conductance (umho/cm) and u = ionic strength (mole/L).



## RESULTS

### General Format

Measured chromium concentration data are presented as relative concentration curves (Cr(VI) desorbed/total exchangeable Cr(VI) on soil) in order to standardize data between soil columns for comparison purposes, as slight variations in total exchangeable Cr(VI) per soil column existed. The relative amount of Cr(VI) removed was presented in graphical format as a function of cumulative column effluent volume (expressed as number of pore volumes). Individual soil column effluent profiles are presented on a double y-axis graph showing anion concentration and pH versus cumulative column effluent volume (expressed as number of pore volumes).

Throughout the text, Cr(VI) is described as desorbing from the soil, however, it is likely that an unknown quantity of Cr(VI) was in pore water solution prior to drying of the soil. It is unclear what fraction of Cr(VI) was physically adsorbed, and care must be taken when interpreting these results. Cr(VI) desorbed is generally defined in this text as all exchangeable Cr(VI) removed with no distinction made between Cr(VI) adsorbed or in solution.

A desorption curve is defined as the cumulative amount of Cr(VI) removed from the soil versus the number of pore volumes of extraction solution passed through the column. The desorption rate was said to be enhanced by the influent solution when desorption occurred more rapidly, displacing the desorption curve to the left relative to a comparative curve, and similarly, the rate of desorption was retarded if a desorption curve was moved to the right. The 0.01 M NaCl (column 1H) was considered the control column and the basis for comparison. The purpose of this solution was to provide a background electrolyte similar to the existing soil solution to facilitate comparing the effect of various influent conditions on Cr(VI) desorption. The desorption curve for the 0.01 M NaCl solution (column 1H) is illustrated in Figure 2. This figure also provides a comparison of duplicate columns. Only slight variations between desorption curves are observed in this figure which can be attributed to small experimental errors. Worksheets for these experiments can be found in Appendix B.

Table 4: Summary of soil column operating characteristics and performance.

Column	1A	1B	1C	1E	1F	1G	1H
Average Temperature (°C)	23	23	23	21	21	21	20
Average Flow Rate (mL/hr)	1.2	2.0	1.6	1.4	1.2	1.7	2.1
Final Effluent pH	7.1	6.3	6.2	6.5	7.3	5.1	6.3
Avg. Conductance (umho/cm)	*	*	4057	1306	1117	6850	1047
Calc. Ionic Strength	**0.001	*	0.065	0.021	0.018	0.110	0.017
Final Cr(VI) Conc. (mg/L)	0.30	0.03	<0.03	<0.03	0.07	0.12	0.19
Cr(VI) Removed (mg/kg)	22.8	23.4	21.7	27.1	28.6	26.9	23.4
Total Extractable Cr(VI) (mg/kg)	23.6	24	22.5	28.2	29.3	27.9	24.8
Effluent Pore Volumes (Total No.)	8.0	19.9	23.6	20.4	17.6	15.8	17.5
Column	1I	2A	2B	2C	2D		
Average Temperature (°C)	21	21	20	21	21		
Average Flow Rate (mL/hr)	1.9	2.0	2.0	2.2	2.0		
Final Effluent pH	7.1	6.7	6.6	6.4	6.3		
Average Conductance (umho/cm)	157	1593	2480	1373	984		
Calculated Ionic Strength	0.003	0.025	0.036	0.022	0.018		
Final Cr(VI) Concentration (mg/L)	0.20	0.33	0.38	0.68	0.30		
Cr(VI) Removed (mg/kg)	26.5	25.2	22.7	23.2	23.6		
Total Extractable Cr(VI) (mg/kg)	27.5	26.6	24.1	25.3	25.0		
Effluent Pore Volumes (Total No.)	12.5	8.1	8.5	10.9	11.1		
Column	3A	3B	3C	3D	3E	3F	
Average Temperature (°C)	20	21	20	20	20	21	
Average Flow Rate (mL/hr)	1.8	1.8	1.5	1.4	1.4	1.9	
Final Effluent pH	5.8	5.9	5.9	5.9	6.1	5.8	
Average Conductance (umho/cm)	1230	1596	1260	340	1213	1396	
Calculated Ionic Strength	0.020	0.026	0.020	0.005	0.019	0.022	
Final Cr(VI) Concentration (mg/L)	0.13	0.11	0.16	0.58	0.31	0.23	
Cr(VI) Removed (mg/kg)	22.5	24.4	23.6	27.3	23.6	21.7	
Total Extractable Cr(VI) (mg/kg)	23.5	25.1	24.4	28.1	24.4	22.8	
Effluent Pore Volumes (Total No.)	7.1	9.6	7.2	6.0	7.8	7.0	
Column	4A	5A	5B	5C	5D		
Average Temperature (°C)	20	21	21	21	21		
Average Flow Rate (mL/hr)	1.9	2.0	2.1	2.0	2.0		
Final Effluent pH	6.5	7.5	6.9	8.0	7.6		
Average Conductance (umho/cm)	1763	1234	1293	1836	729		
Calculated Ionic Strength	0.028	0.020	0.021	0.029	0.012		
Final Cr(VI) Concentration (mg/L)	0.30	0.10	1.02	0.66	0.25		
Cr(VI) Removed (mg/kg)	26.0	24.1	24.2	25.6	27.3		
Total Extractable Cr(VI) (mg/kg)	26.1	25.5	26.3	27.4	28.5		
Effluent Pore Volumes (Total No.)	16.8	9.7	9.8	9.8	12.5		

\* Not measured.

\*\* Estimated based on column experiment 1I.

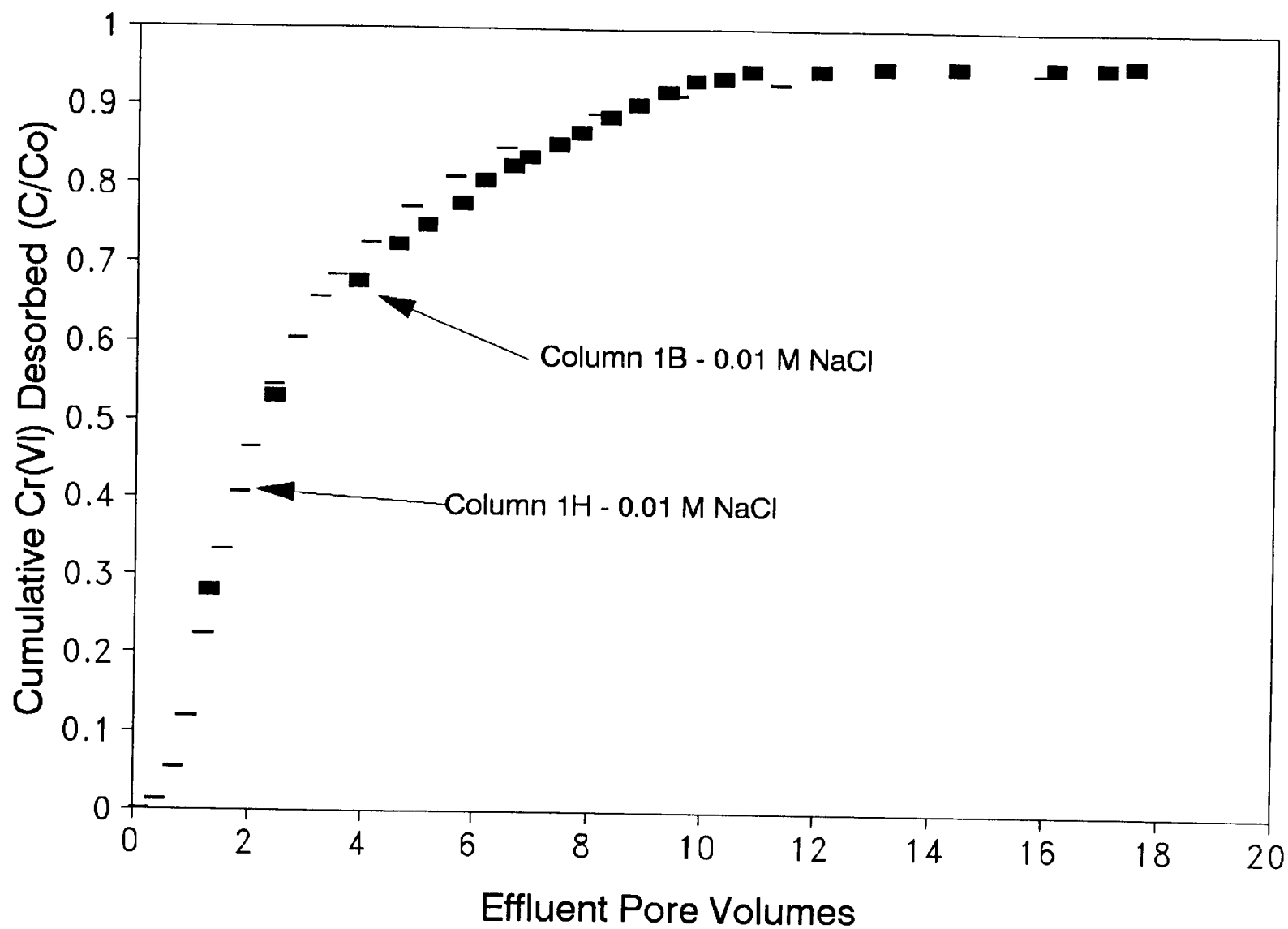


Figure 2. Comparison of duplicate columns.

Individual soil columns are referred to by the name of the influent solution followed by anion type, concentration, and column number in parentheses. Table 4 summarizes the operating characteristics and performance of each column experiment. Refer to Table 1 for experimental conditions.

### Effect of Ionic Strength

#### *NaCl Solution*

Effect of varying the ionic strength of the influent solution on Cr(VI) desorption was determined by changing the NaCl concentration. Distilled water (DW) and Corvallis tapwater (both  $u \leq 0.001$ ) were also used to provide further comparison of the effect of low ionic strength electrolyte solutions.

Chromium VI desorption curves for influent solutions consisting of distilled water (column 1A), Corvallis tap water (column 1I), 0.01 M NaCl, 0.05 M NaCl, and 0.10 M NaCl (columns 1H, 1C, and 1G, respectively) are compared in Figure 3. The distilled water and Corvallis tap water column effluents have similar final pH values, with distilled water affecting a slightly higher desorption rate and lower effluent ionic strength. Of the desorption curves shown, column 1G (0.10 M NaCl) showed the slowest rate of Cr(VI) desorption. To achieve 90% desorption 2.5 pore volumes were required for distilled water, 3 pore volumes for Corvallis tap water, and 8 pore volumes for 0.01 M NaCl, 0.05 M NaCl, and 0.10 M NaCl solutions. Two patterns are apparent in Figure 3: 1) the effluent pH decreased with increasing ionic strength (increasing NaCl concentration; See also Table 4); 2) The rate of Cr(VI) desorption decreased with increasing ionic strength with the largest difference existing between the low ionic strength extraction solutions, distilled water (column 1A) and Corvallis tap water (column 1I), and the high ionic strength extraction solutions, 0.05 M NaCl (column 1C) and 0.10 M NaCl (column 1G). The low ionic strength extraction solutions approached similar desorption rates after one pore volume.

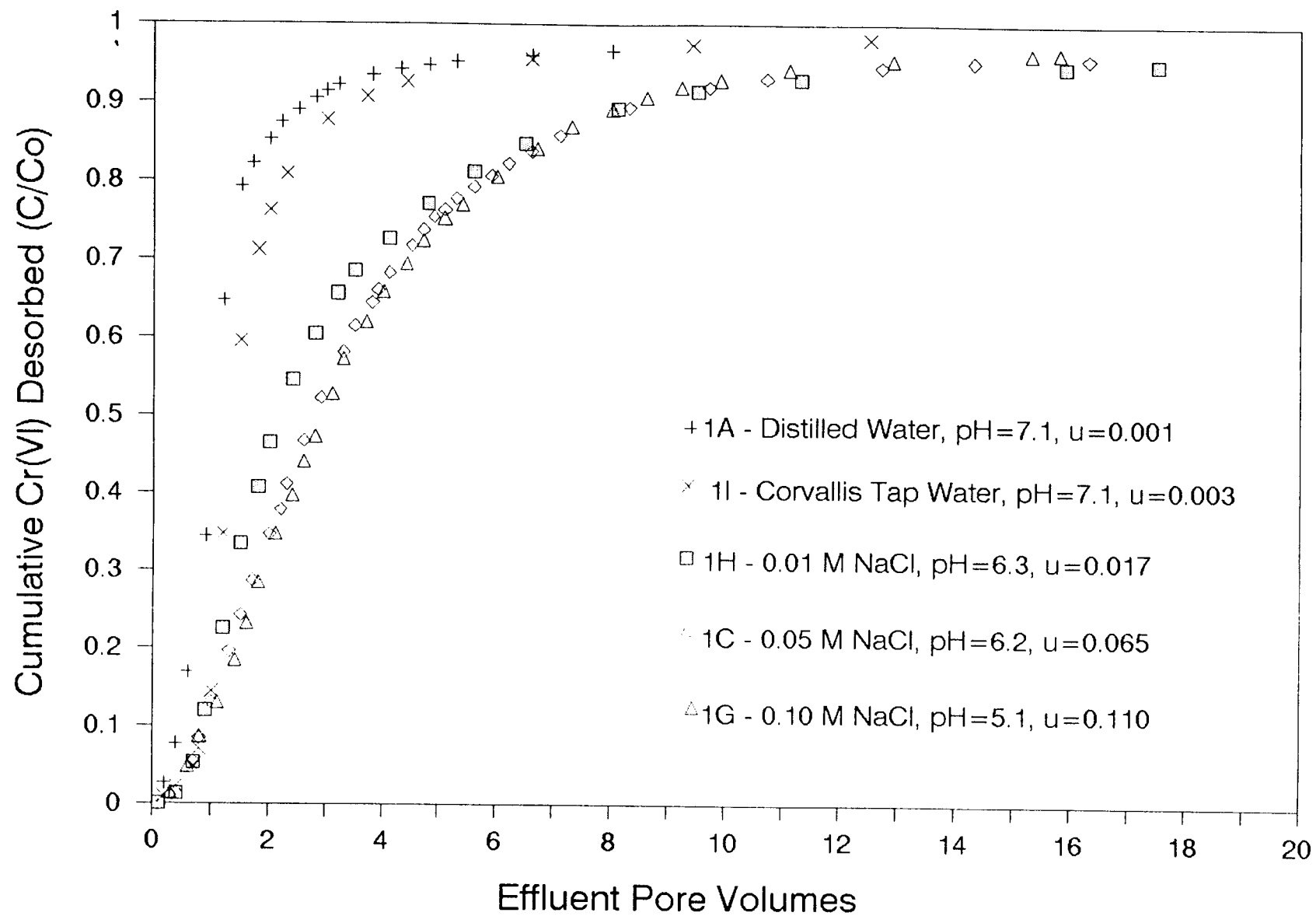


Figure 3. Ionic strength effect on Cr(VI) desorption.

### *Electrolyte Type*

Figures 4, 5, and 6 are, respectively, Cr(VI) desorption curves for phosphate, sulfate, and bicarbonate extraction solutions as a function of electrolyte type (0.01 M NaCl or distilled water). In all cases, Cr(VI) desorbed more rapidly in the anion/DW solutions than in the anion/0.01 M NaCl solutions. Distilled water and phosphate approached similar removal rates (Figure 4) after 2 pore volumes and equaled by phosphate/0.01 M NaCl after 4 pore volumes. In contrast, the convergence of Cr(VI) desorption rates for sulfate (Figure 5) and bicarbonate (Figure 6) in distilled water and sulfate and bicarbonate in 0.01 M NaCl occurred after 5 pore volumes.

The effluent anion profile for Cr(VI) extraction with Corvallis tap water (column 1I) is shown in Figure 7. Exchangeable nitrates, sulfates, and chromate eluted in the order of expected affinity for the soil. Nitrate peaked at 1.0 pore volume followed by sulfate at approximately 1.1 pore volumes and chromate at 1.2 pore volumes. A similar elution order was observed in all effluent profiles. Exchangeable concentrations of sulfate and nitrate in the soil, as determined by soil extraction methods (see Table 2), are 14.2 mg/kg and 16.8 mg/kg, respectively. pH dips approximately 0.8 pH units during the peak desorption phase and then approaches a relatively constant value of 7.1. A similar pH drop during the peak desorption phase was observed in all soil column extraction experiments.

### Effect of pH

Figure 8 illustrates the results of varying pH of the 0.01 M NaCl solution on Cr(VI) desorption. The column (1E) with the lowest influent pH had a final effluent pH higher than that of the 0.01 M NaCl solution (column 1H), 6.5 versus 6.3, respectively. The soil buffered the influent pH in all three columns resulting in a 0.5 pH spread in final pH values. During the first pore volume, Cr(VI) desorption rates for columns 1E and 1F were very slow with little Cr(VI) being removed. This was followed by fast Cr(VI) desorption during pore volumes 1 to 3, after which the Cr(VI) desorption curve became nearly identical.

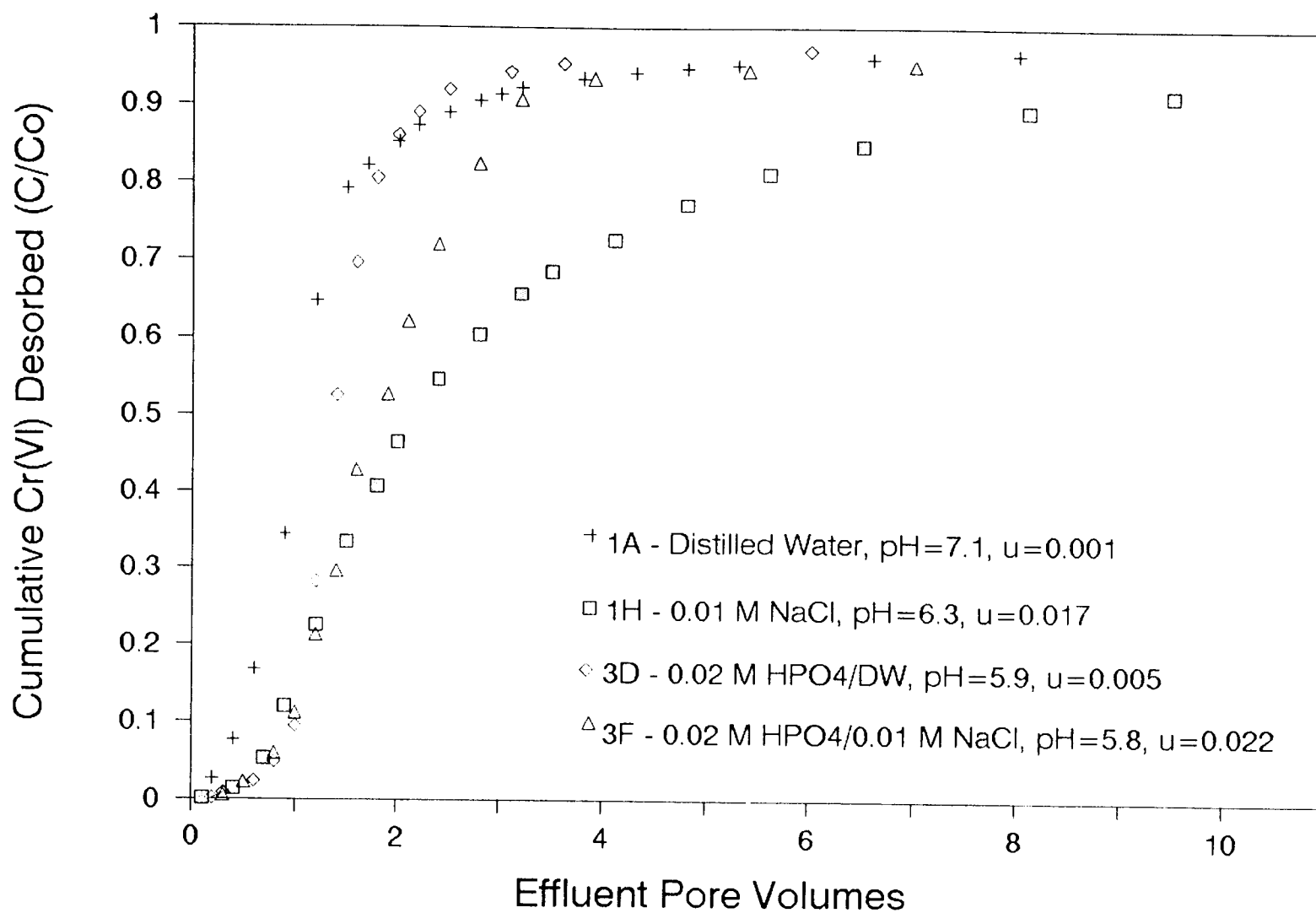


Figure 4. Cr(VI) extraction with phosphate as a function of electrolyte type.

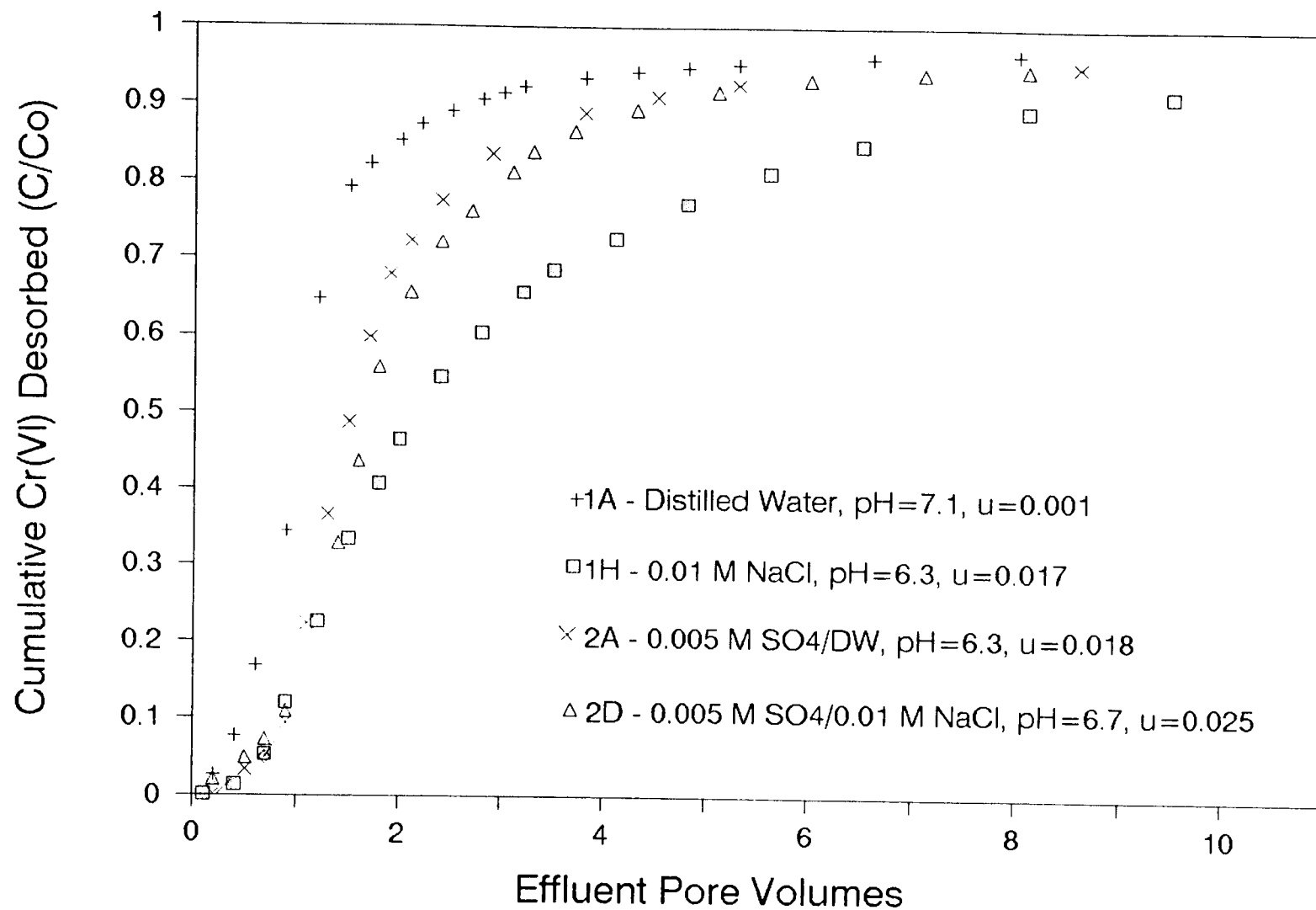


Figure 5. Cr(VI) extraction with sulfate as a function of electrolyte type.



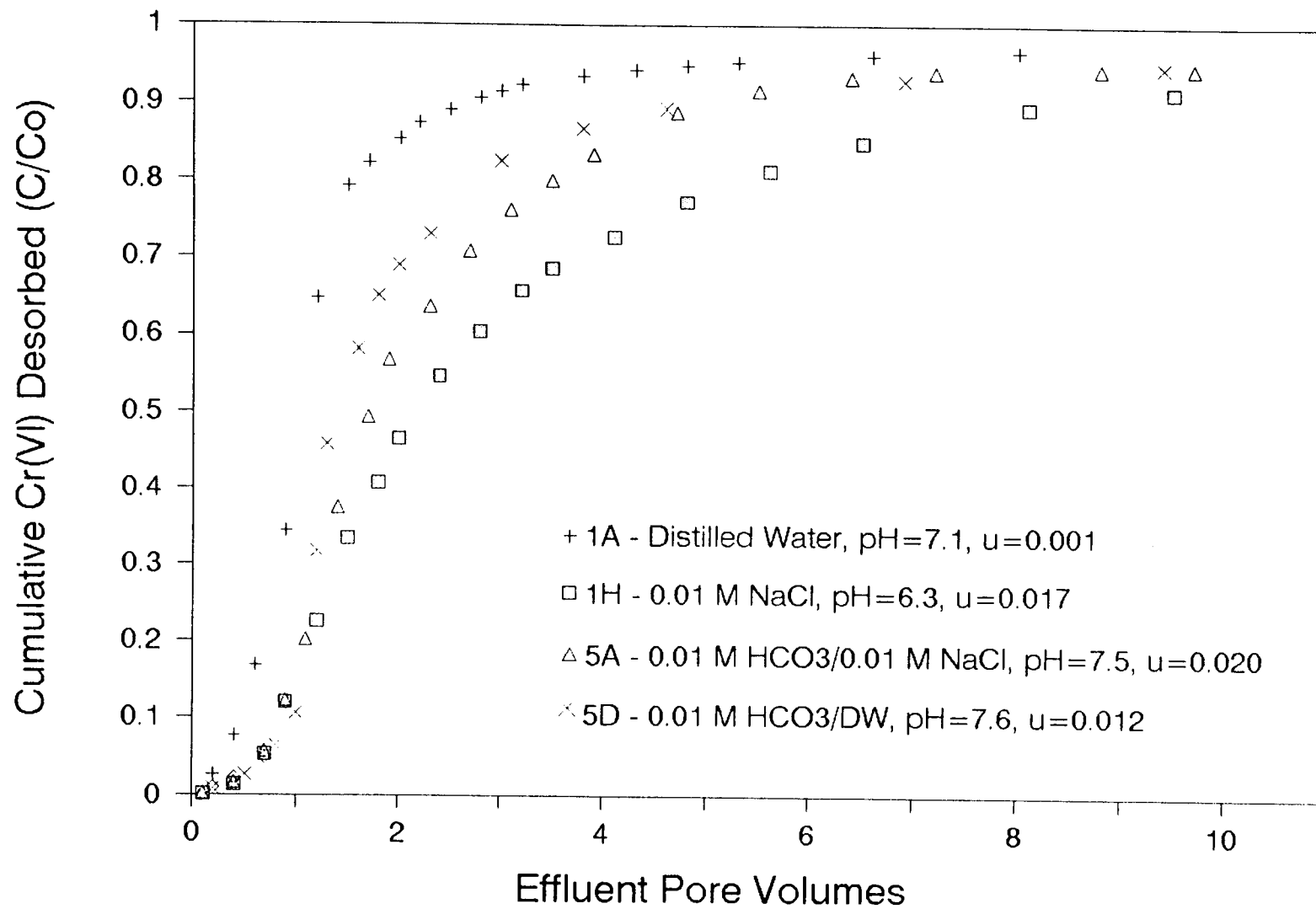


Figure 6. Cr(VI) extraction with bicarbonate as a function of electrolyte type.

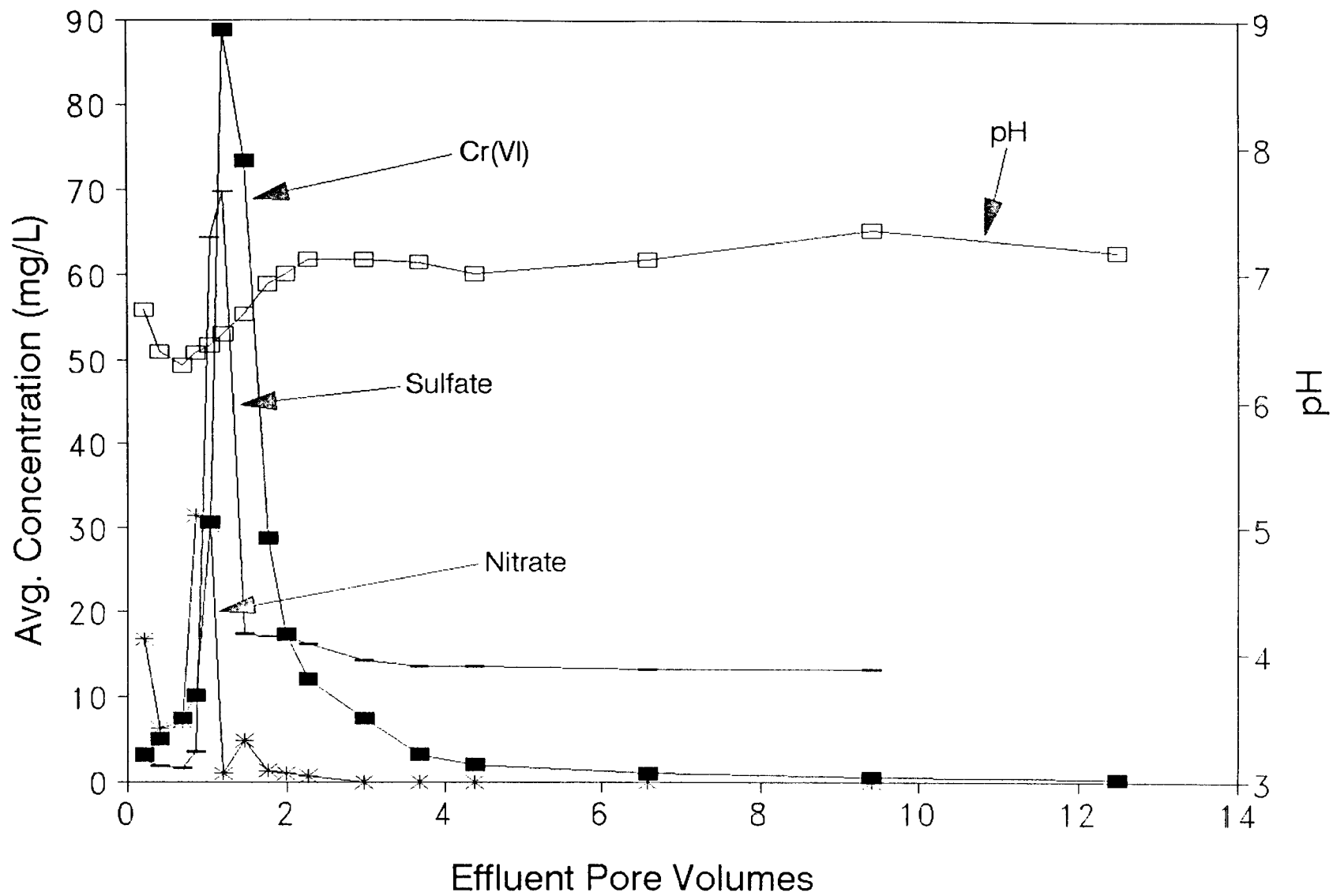


Figure 7. Effluent anion profile for column 11 (Corvallis tap water).

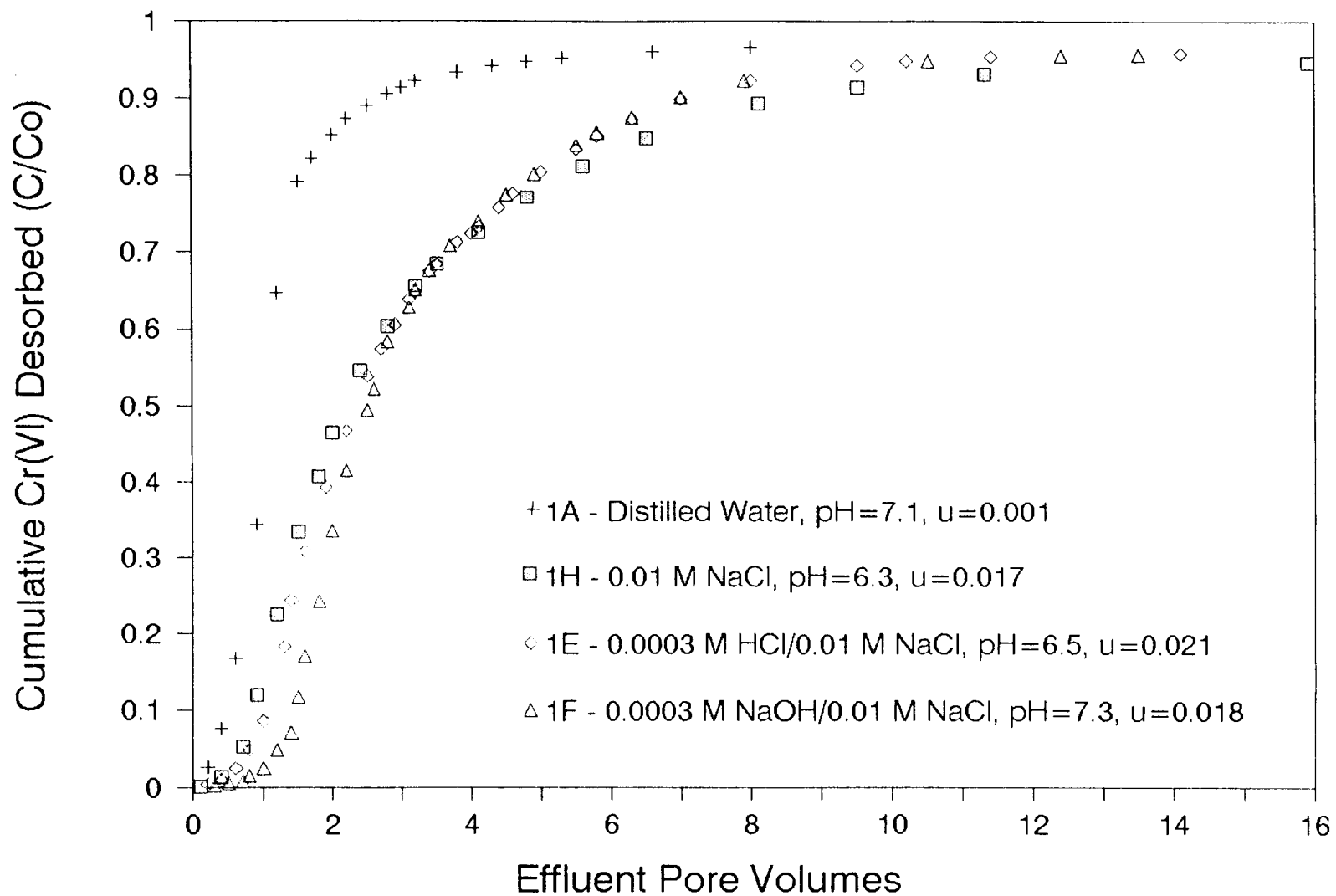


Figure 8. pH effect of Cr(VI) desorption.

Figure 9 summarizes the effect of changing influent phosphate solution pH on Cr(VI) desorption. All three desorption curves were nearly identical despite the influent pH differences (column 3A, pH=4.7; column 3C, pH=9.2; column 3E, pH=11.0). The effluent pH values were buffered by the soil to nearly identical values, thus masking any pH effects.

#### Competitive Anion Experiments

Figure 10 provides a comparison of the competitive effects of 0.01 M of bicarbonate, nitrate, sulfate, and phosphate on Cr(VI) desorption. Nitrate (column 4A) was the least effective of the anions, showing no measurable enhancement of Cr(VI) desorption. Sulfate (column 2B) and bicarbonate (column 5A) solutions caused nearly identical Cr(VI) desorption curves. Phosphate (column 3C) was the most competitive in desorbing Cr(VI). As Figure 10 shows, to achieve 90% desorption required 3.8 pore volumes for the phosphate solution, 5 pore volumes for both sulfate (column 2B) and bicarbonate (column 5A) solutions, and 8.1 pore volumes for nitrate (column 4A) solution. No comparisons were possible based on pH and ionic strength due to the differing characteristics of each anion on the soil system. Although, various anions influence how rapidly Cr(VI) desorption occurs, it appears that over time all solutions approach 99% desorption of exchangeable Cr(VI).

#### *Nitrate Solution*

Figure 11 illustrates the effluent anion profile for column 4A (0.01 M Nitrate). The nitrate adsorption breakthrough occurred after 1 pore volume, indicating the nonsorptive nature of nitrate. Soil exchangeable sulfate elution peaks at approximately the same time as Cr(VI). No phosphate was detected in the effluent indicating little or no exchangeable phosphate in the soil. The effluent pH remained relatively constant at 6.3 with a small dip during the peak desorption phase.

#### *Bicarbonate Solution*

Figure 12 shows Cr(VI) desorption as a function of bicarbonate concentration. Increasing bicarbonate concentration of the influent solution resulted in increased Cr(VI) desorption. This

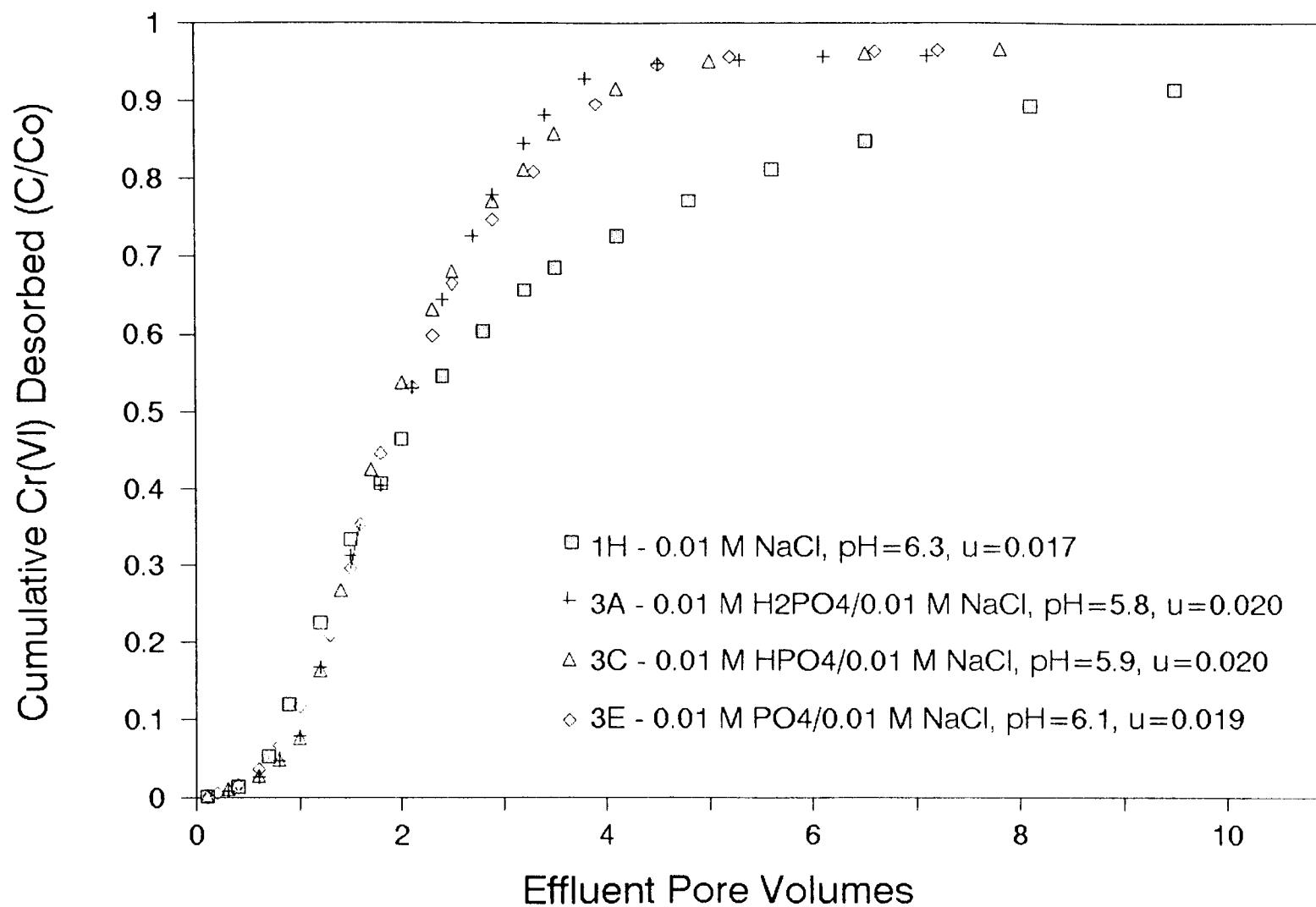


Figure 9. Effect of varying pH of phosphate solution on Cr(VI) desorption.

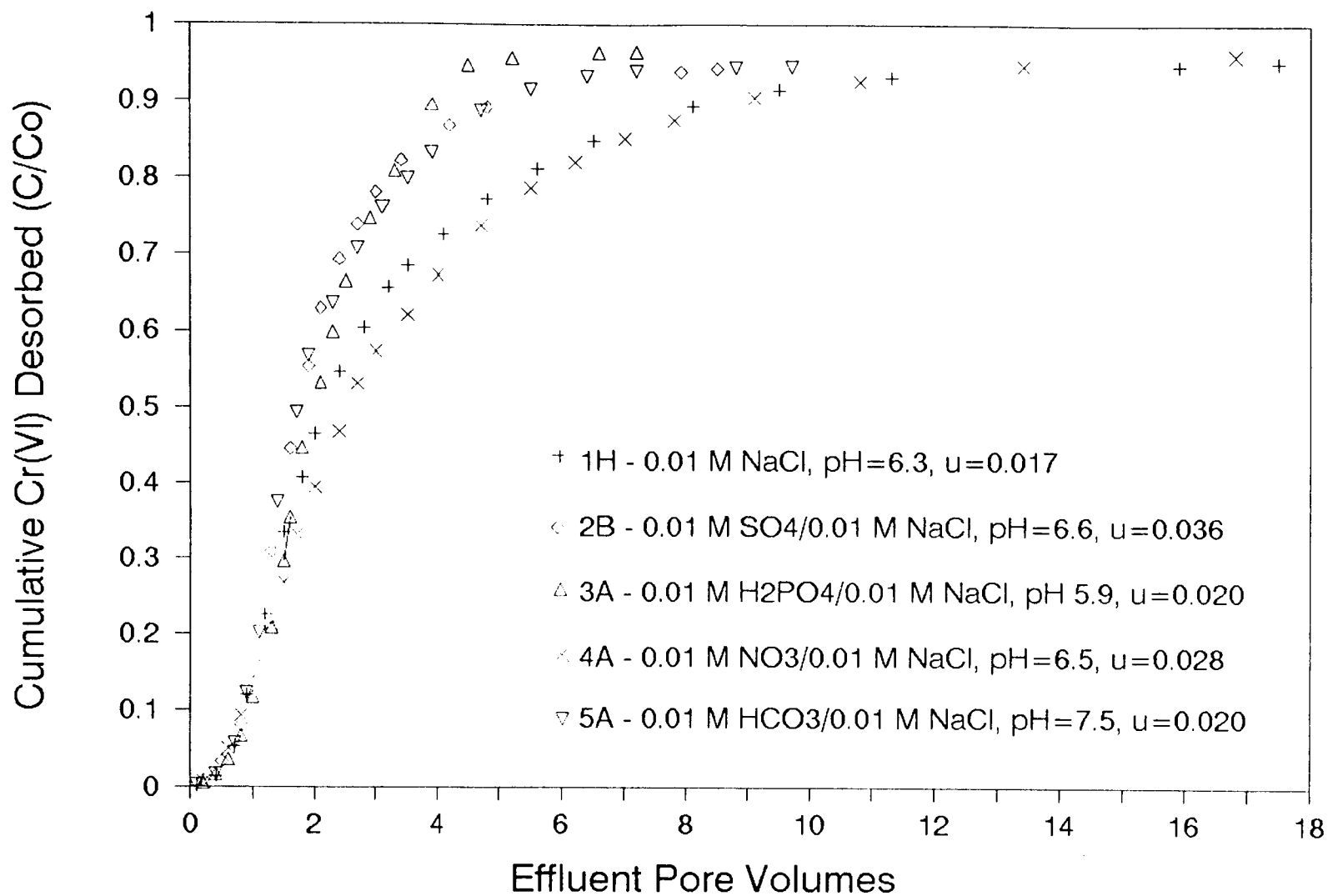


Figure 10. Effect of various competitive anions on Cr(VI) desorption.

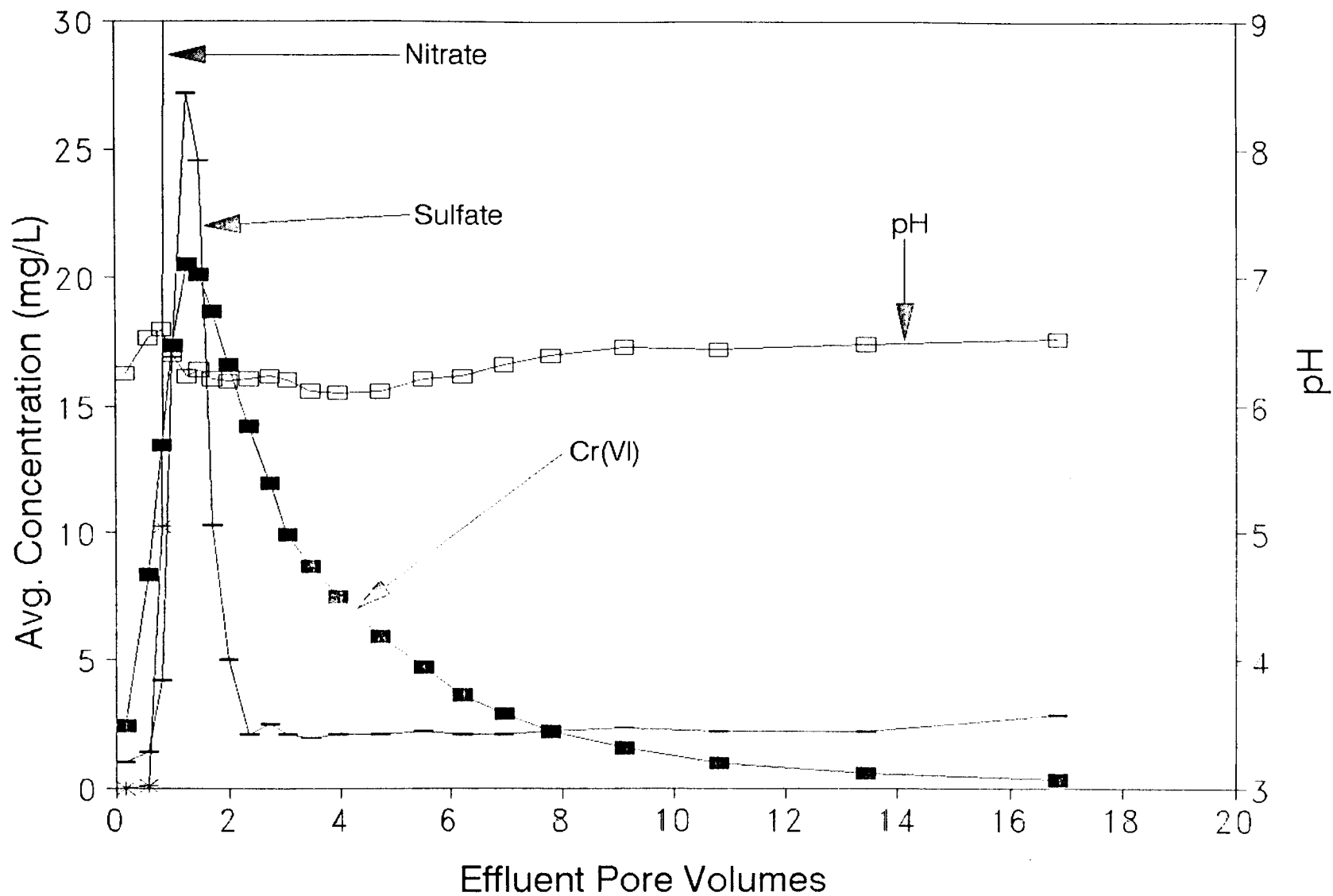


Figure 11. Effluent anion profile for column 4A (0.01 M NO<sub>3</sub>/0.01 M NaCl).

effect was most apparent between columns 5B (0.001 M bicarbonate) and 5A (0.01 M bicarbonate) but minimal between columns 5A and 5C (0.02 M bicarbonate).

The effluent anion profile for column 5D (0.01 M bicarbonate/distilled water) is shown in Figure 13. Cr(VI), sulfate, and nitrate exhibit similar elution profiles as that observed for column 1I (Figure 7). The tailing of sulfate in this column was much less than observed in other columns (1I, 2B, 2C, 3C, and 4A).

pH variation for column 5D was typical of all four bicarbonate columns (5A, 5B, and 5C) and unlike other anion species tested. After the characteristic pH drop during the peak desorption phase (pore volumes 0-2), the pH increased steadily over time, from 6.6 to 7.6, never reaching a constant value. The influent pH values for columns 5A-5D were between 8.2-8.4.

#### *Sulfate Solution*

The variation of Cr(VI) desorption as a function of sulfate concentration is illustrated in Figure 14. Here too, the desorption process was enhanced with increased sulfate concentration. The greatest difference in Cr(VI) desorption occurred between columns 2C (0.001 M sulfate) and 2A (0.005 M sulfate). The Cr(VI) desorption curve for column 2B (0.01 M sulfate) was located to the right of 2A indicating a slightly slower desorption rate. It appears from this figure the higher sulfate concentration solution (column 2B) actually slowed Cr(VI) desorption.

Figures 15 and 16 are effluent anion profiles for columns 2B (0.01 M sulfate) and 2C (0.001 M sulfate), respectively, and illustrates that after 1 pore volume the measured sulfate in the effluent quickly approached the influent concentration (not shown in figure), indicative of a weakly adsorbing anion. The erratic nature of the nitrate desorption curve of column 2B is possibly due to contamination in the nitrate sampling process. It is apparent from the two graphs that the lower concentration sulfate solution took longer to desorb Cr(VI) than the higher sulfate concentration solution.



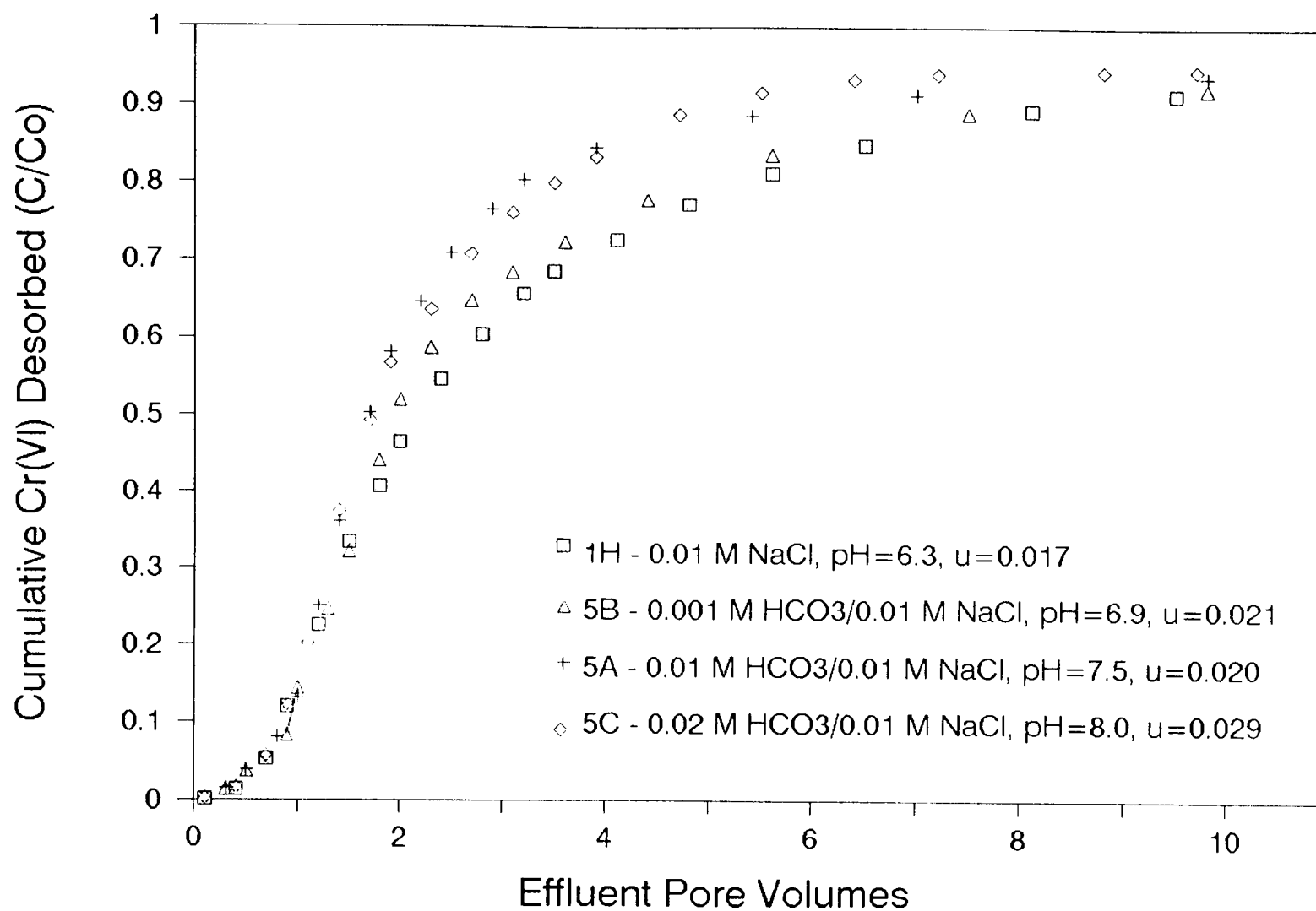


Figure 12. Influence of bicarbonate concentration on Cr(VI) desorption.

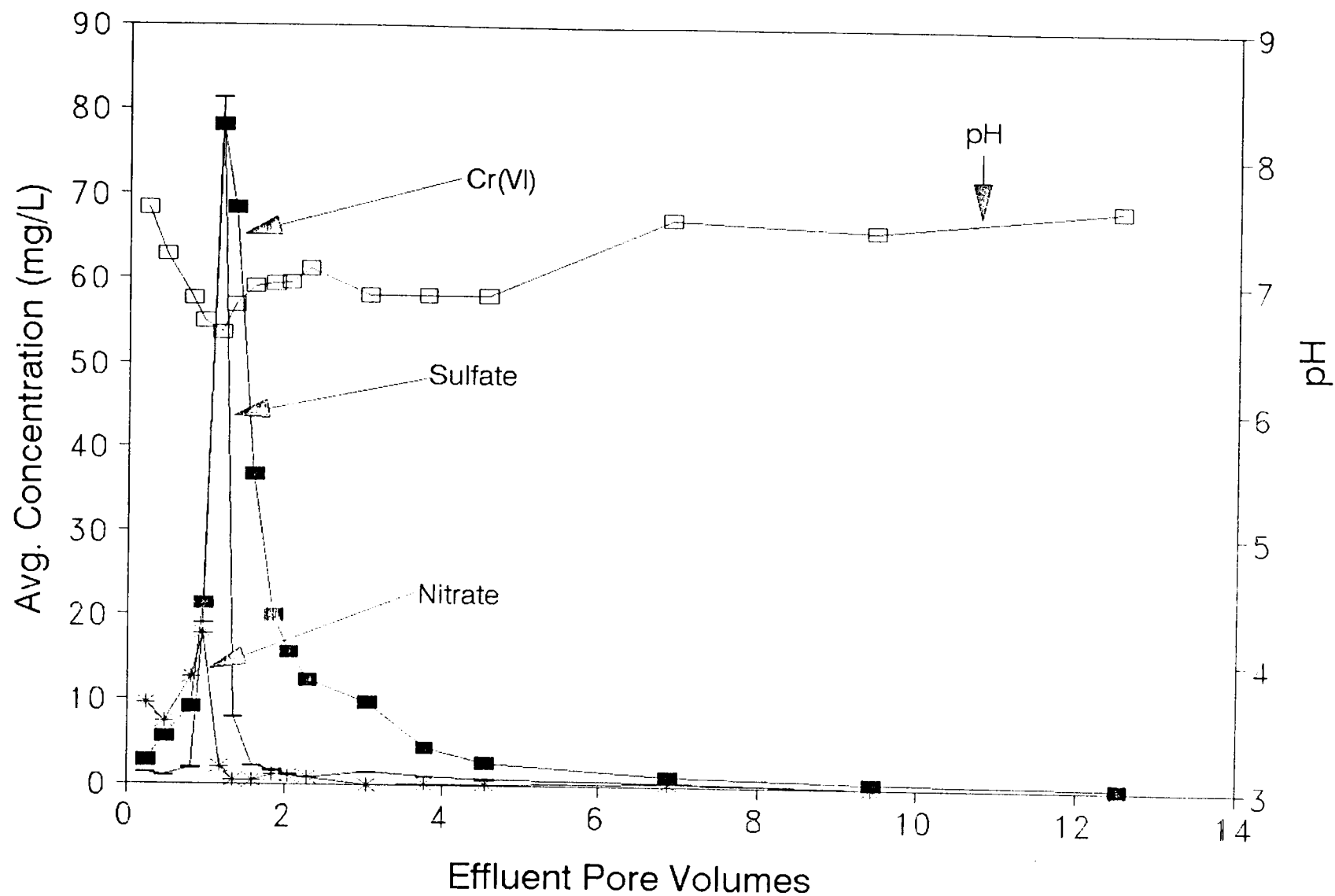


Figure 13. Effluent anion profile for column 5D (0.01 M HCO<sub>3</sub>/DW).

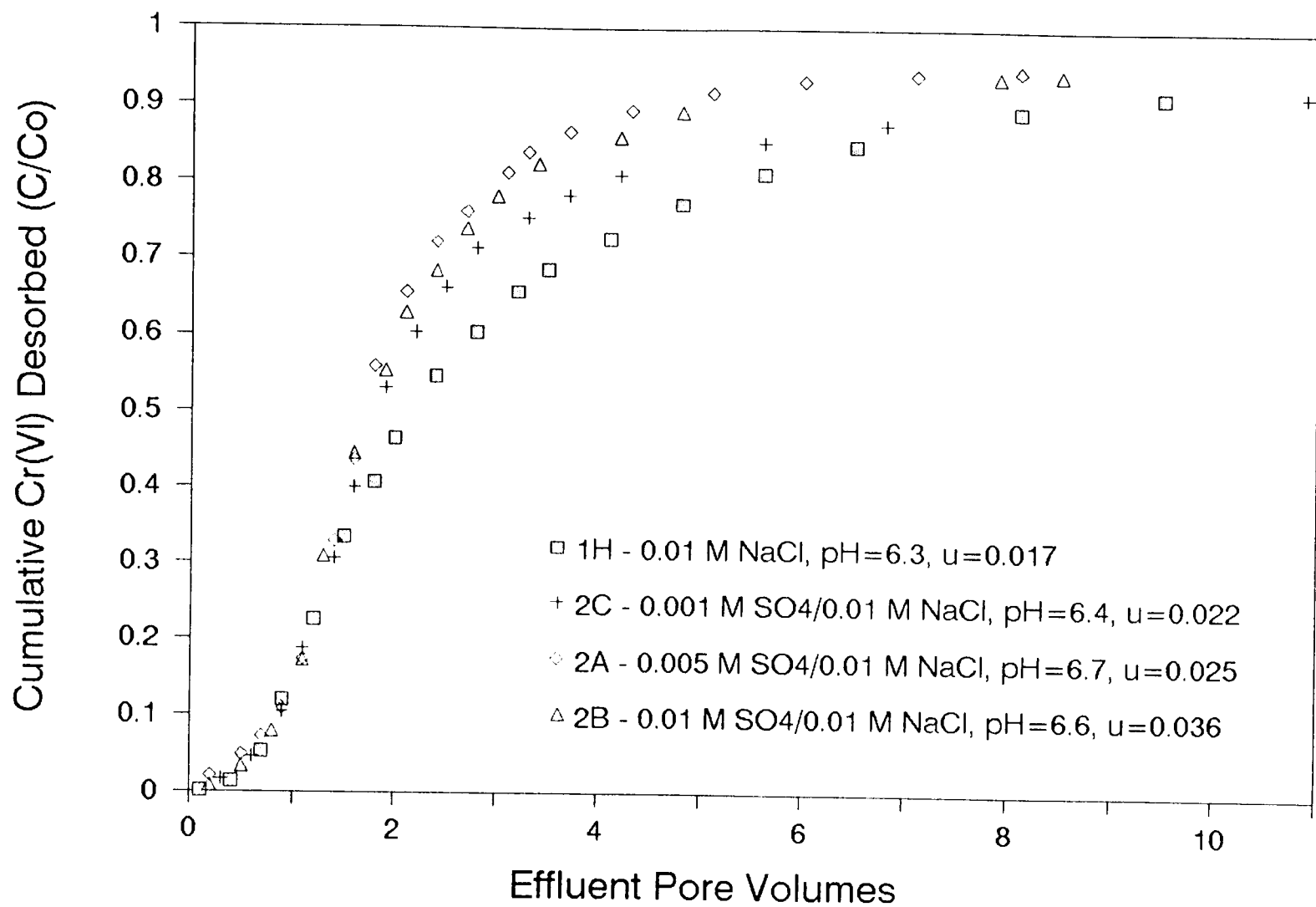


Figure 14. Influence of sulfate concentration on Cr(VI) desorption.

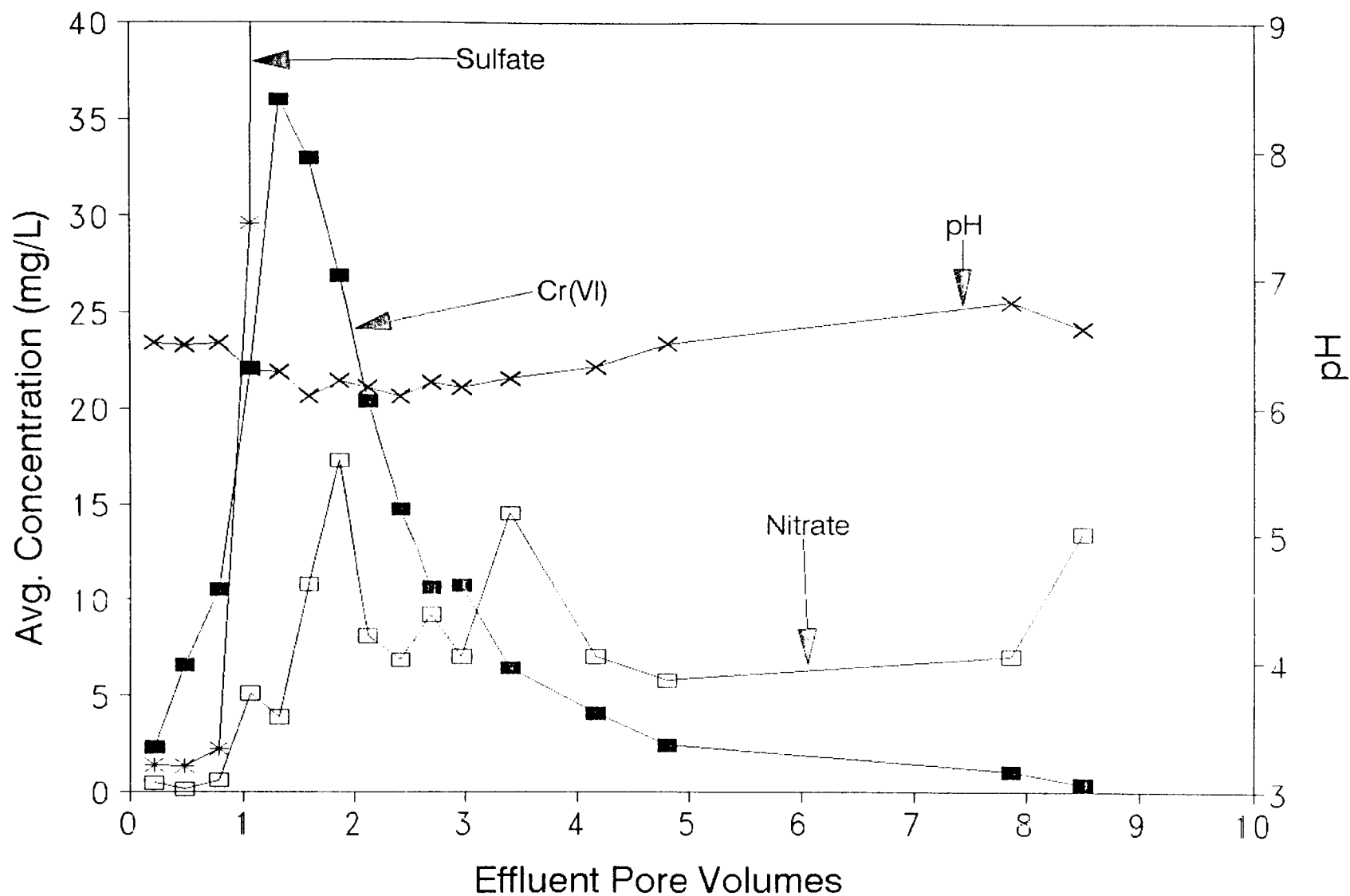


Figure 15. Effluent anion profile for column 2B (0.01 M SO<sub>4</sub>/0.01 M NaCl).

The sulfate columns displayed the characteristic pH drop of about 0.8 pH units during the peak desorption phase. The effluent pH of columns 2A, 2B, and 2C (sulfate/0.01 M NaCl) averaged about 6.3 compared to column 2D (sulfate/distilled water) which averaged 6.6.

#### *Phosphate Solution*

Increasing the concentration of phosphate in the extracting solution enhanced desorption over the concentration range tested (0.005M - 0.02 M K<sub>2</sub>-phosphate) as shown in Figure 17. The effluent profile of column 3C (0.01 M Phosphate), illustrated in Figure 18, shows the influence of phosphate on the desorption process. Except for the first pore volume, no measurable phosphate was observed in the effluent until the fourth pore volume when phosphate adsorption breakthrough occurred. Only periodic spikes of nitrate of concentration less than 1 ppm were observed and are not shown in this figure.

Phosphate influence on soil pH was more predictable than for the other anions tested. The measured effluent pH for all phosphate columns decreased continuously with time, as illustrated in Figure 18 for column 3C. This is opposite to observations for the other protonated anion species tested, bicarbonate. This result was consistent for all phosphate species and was not dependent on the pH of the influent solution. The influent pH ranged from 4.7 for column 3A to 11.0 for column 3E. The final effluent pH of all phosphate columns dropped to 5.8-6.1 (Figure 9 and Table 1).

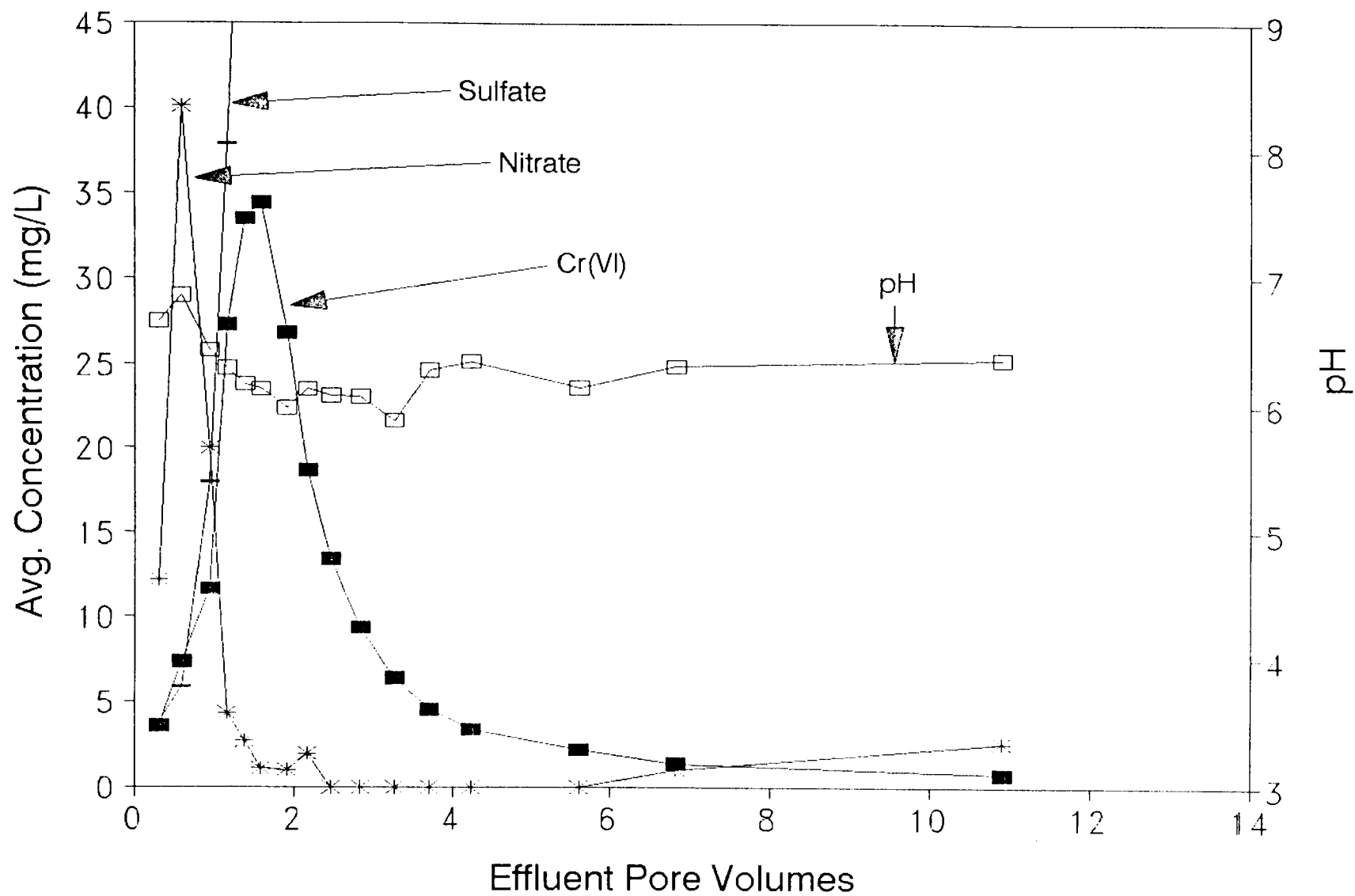


Figure 16. Effluent anion profile for column 2C (0.001 M SO<sub>4</sub>/0.01 M NaCl).

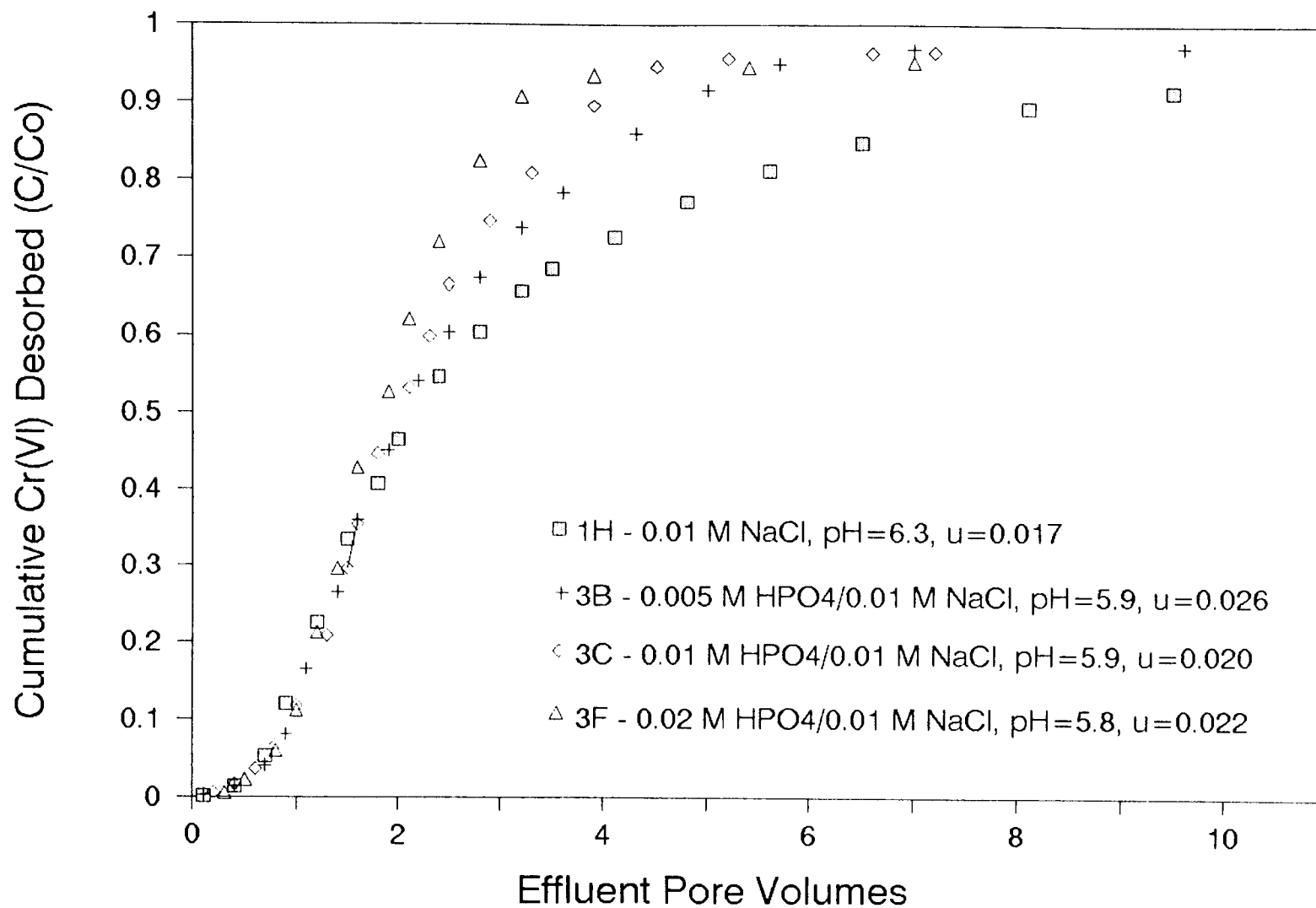


Figure 17. Influence of phosphate concentration on Cr(VI) desorption.

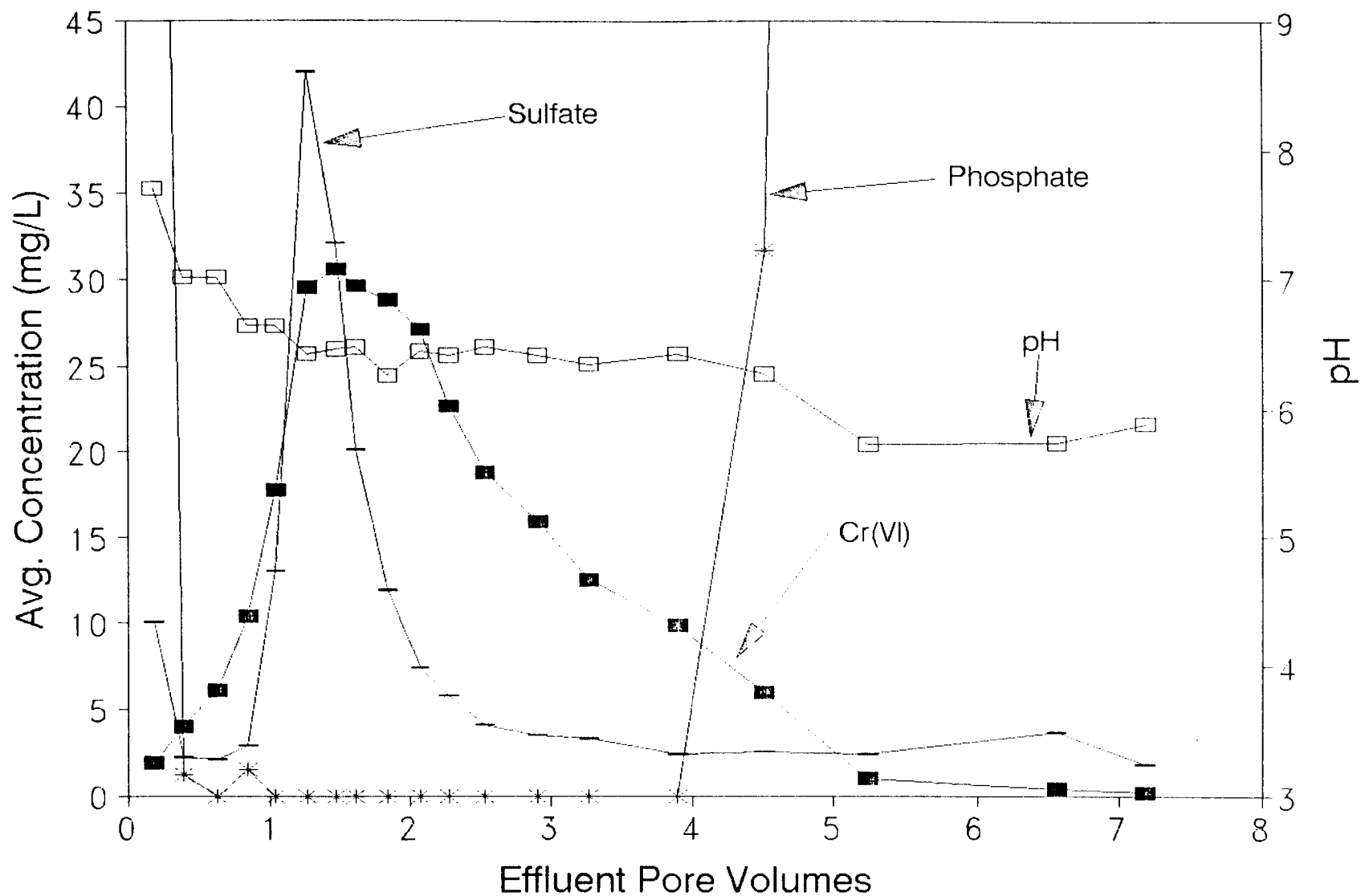


Figure 18. Effluent anion profile for column 3C (0.01 M  $\text{HPO}_4$ /0.01 M  $\text{NaCl}$ ,  $\text{pH}=4.5$ )



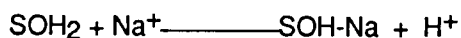
## DISCUSSION

### Ionic Strength Affects

#### *NaCl Solution*

Increasing NaCl concentration of the 0.01 M NaCl solution, thus the ionic strength, leads to slower Cr(VI) desorption and a simultaneous drop in pH (Figure 3). Distilled water (column 1A) and Corvallis tap water (column 1H), both low ionic strength solutions, were subsequently used to confirm this effect. Both columns showed rapid desorption and a steady effluent pH at the soil pH of 7.0. Of the influent solutions tried, distilled water and Corvallis tap water were the only solutions that did not affect the overall soil column pH.

Bartlett and Kimble (1976) observed that adsorption was enhanced at lower pH values. In this study, Cr(VI) desorption was retarded (adsorption enhanced) at pH values below 6.5 (Figure 3) for the NaCl solutions. The pH drops were directly attributed to the competitive effect of sodium anions in the 0.01 M NaCl solution for the hydrogen adsorption site according to the following proposed relationships:



S = metal cation; SOH = surface hydroxyl group; Na<sup>+</sup> = sodium cation

Bean (1989) observed no difference between distilled water and groundwater suspensions on Cr(VI) adsorption in his batch reactions below pH 5. Above pH 5, he observed adsorption was greater in the higher ionic strength solution, groundwater, than in the lower ionic strength distilled water. Griffin et al. (1977) also observed that higher ionic strength solutions contributed to higher adsorption caused by compression of the diffused double layer by ionic species or by primary charge reduction of the soil by adsorbed groundwater cations. Likewise, in this study desorption was greater (adsorption less) in distilled water (lower ionic strength solution) than in the higher ionic strength solutions where Cr(VI) was more tightly adsorbed. Compression

of the diffused double layer enhances Cr(VI) adsorption and similarly, retards the desorption of Cr(VI) in the absence of an anion with a higher affinity for the adsorption site.

In this experiment, it is unclear whether the slower Cr(VI) desorption rates resulted from the pH drop attributed to the Na-H exchange or an electrostatic potential effect caused by high ionic strength influent solution and subsequent compression of the diffused double layer. Despite the differences in ionic strength and desorption rates between columns, total exchangeable Cr(VI) removed was relatively constant between soil columns, a result also observed by Bean in his batch reactions

#### *Nitrate Solution*

Nitrate concentration was not varied. The Cr(VI) desorption curve for nitrate influent solution is located to the right of the 0.01 M NaCl solution in Figure 10 indicating a slower desorption rate. This slower desorption rate is attributed to the high ionic strength of the influent solution ( $u=0.02$ ) and the nonsorbing nature of nitrate. It is hypothesized that an influent solution of 0.02 M NaCl would have the same Cr(VI) desorption characteristics as the 0.01 M nitrate/0.01 M NaCl solution. Hingston et al. (1971) noted that anions specifically adsorbed, such as chromate, at a given pH could not be desorbed by competition with a nonspecifically adsorbed anions, such as nitrate, at the same pH and ionic strength.

#### *Bicarbonate and Sulfate Solution*

Zachara (1989) observed that Cr(VI) adsorption was depressed by the presence of sulfate and carbonate at low concentrations, but was enhanced at high concentrations. A similar phenomena was observed in this study; Cr(VI) desorption was enhanced (adsorption depressed) at low to moderate concentrations, but was retarded at the higher concentrations tested (above 0.01 M) as shown in Figures 12 and 14. The diffused double layer was not sufficiently depressed at low to moderate concentrations to prevent Cr(VI) removal, however, at the higher concentration the diffused double layer became sufficiently depressed to retard Cr(VI) removal by increasing adsorption. This is similar to processes observed by Zachara (1989) and Griffin et al. (1977) in

their adsorption/desorption experiments. Suppression of Cr(VI) desorption at the highest concentration tested of bicarbonate and sulfate might be due to activity effects. Reduction in desorption rates occurred above  $u=0.025$  for both anions. It was not determined if increasing the concentration (or ionic strength) of the influent solution anion above the concentrations tested would cause a further reduction of the Cr(VI) desorption rate or if the maximum desorption rate for both bicarbonate and sulfate are in the vicinity of the Cr(VI) desorption curves for 0.005 M sulfate (column 2A) and 0.01 M bicarbonate (column 5A).

As Figure 5 and 6 illustrate both bicarbonate and sulfate in distilled water solutions were more effective at enhancing Cr(VI) desorption rate when compared to anion/0.01 M NaCl solution. This appears to be more a function of ionic strength than final pH as differences of less than 0.2 pH units existed between the anion/distilled water and anion/0.01 M NaCl solutions. The presence of bicarbonate and sulfate in solution did not drive down pH as was observed with the NaCl solution experiments (columns 1H, 1C, and 1G).

#### *Phosphate Solution*

As Figure 4 shows, the Cr(VI) desorption rate for phosphate/0.01 M NaCl solution (column 3E) was less than the lower ionic strength, phosphate/distilled water (column 3D) solution. To achieve 90% desorption required 2 pore volumes of phosphate/distilled water solution compare to 3.5 pore volumes for phosphate/0.01 M NaCl solution with a difference of 0.2 pH units. This also appears to be the same phenomena observed with the sulfate and bicarbonate extraction experiments. Edzwald et al. (1976) noted a similar behavior with phosphate when he observed that phosphate adsorption on kaolinite and montmorillonite increased in the presence of synthetic seawater concentrations of chloride and sulfate. He noted that if ion exchange played a significant roll in the adsorption process, then high concentrations of chloride and sulfate would have reduced the amount of phosphate adsorbed. He proposed that the electric double layer compression was the primary mechanism since the adsorption capacity for kaolinite was significantly increased.

Results from subsequent experiments performed at Oregon State University (M.A. Azizian, graduate student, personal communication), reveal that the UCPS site soils have low Cr(VI) adsorption capacities. Griffin and others have shown with their experiments that Cr(VI) adsorption was enhanced in high ionic strength solutions due to compression of the diffused double layer (Griffin et al., 1977). The ionic strength effects observed in these experiments seem to indicate that most of the Cr(VI) was in pore water solution and was easily removed when flushed with a low ionic strength extraction solution such as distilled water since the electrostatic effects are not sufficient to cause Cr(VI) to adsorb on to the soil. Conversely, as the ionic strength of the extraction solution increased resulting in a depressed diffuse double layer, the rate of Cr(VI) removal decreased, possibly indicating that some fraction of the Cr(VI) in pore water solution was adsorbing on to the soil slowing the removal process.

#### pH Effects

The pH of 0.01 M NaCl and phosphate solutions were varied to determine the effect on Cr(VI) desorption. pH variations were also observed in the ionic strength extraction experiments as a consequence of the experimental conditions and were discussed under that section. They will not be further discussed in this section since the pH variations are caused by different experimental conditions.

The results from the pH experiments on Cr(VI) contaminated soil columns (columns 1E and 1F; Figure 8) are inconclusive. The soil buffered the effluent pH to near the expected pH of 6.3 for 0.01 M NaCl solution. pH of columns 1E and 1F were slightly higher than the 0.01 M NaCl solution which is probably attributed to the higher ionic strength of the influent solutions. The cause of the slow initial desorption for column 1F during the first pore volume is unclear. It is difficult to ascertain which parameter, pH or ionic strength, was the major factor controlling the desorption process, as only small differences existed between pH, ionic strength, and desorption rates for columns 1H, 1E, and 1F.

The results of the phosphate pH experiments are shown in Figure 9. Varying the pH of phosphate extraction solutions by addition of different phosphate species to the influent solution had virtually no effect on Cr(VI) desorption. The phosphate extraction solution adjusted to pH 4.7 (column 3A; Na<sub>2</sub>-phosphate) was expected to increase the rate of Cr(VI) desorption over the higher pH solutions since phosphate is more strongly adsorbed at that pH (Edzwald, 1976). However, the rate of Cr(VI) desorption was only slightly faster than for the other columns between pore volumes 3 and 4. The final pH range between all phosphate extraction columns (3A, 3B, 3C, 3D, 3E, and 3F) varied less than 0.3 pH units, a remarkably tight pH range considering the varying influent characteristics of each of the phosphate extraction columns.

The soil buffered the effluent pH such that it was nearly always greater than pH<sub>pzc</sub>, this indicates the soil was negatively charged over the pH range for most column experiments. This implies adsorption was lessened due to electrostatic forces.

#### Competitive Anions

Phosphate was the most effective of the competitive anions over the concentration range tested. Chromate is tightly bound compared to such nonspecifically adsorbed anions as nitrate, bicarbonate, and sulfate (Figure 10), but can be desorbed quickly with use of phosphate, a specifically adsorbed anion. Grim (1968) noted nitrate and sulfate cannot be specifically adsorbed because their geometry does not fit that of the silica tetrahedral sheet.

##### *Nitrate Solution*

Nitrate was not competitive and did not enhance desorption of chromate, but acted as an indifferent electrolyte.

##### *Bicarbonate and Sulfate Solution*

Despite sulfates' higher valence, bicarbonate and sulfate had similar effects on Cr(VI) desorption (Figure 10). The effluent anion profiles of columns 2B and 2C (Figures 15 and 16) showed that effluent concentrations of sulfate approached the influent concentration after approximately one pore volume, a behavior similar to nitrate. The measured sulfate and nitrate in

the effluent included both the applied concentration and extractable anion concentration on the soil. Despite the apparent nonsorptive behavior, the presence of both anions enhanced Cr(VI) desorption especially at concentrations of 0.005 - 0.010 M.

The order of the desorption peaks was an indicator of the relative retardation due to the strength of adsorption of the anions. This is typical of competitive adsorption or ion exchange where the more strongly adsorbed ion is retarded more in its transport. Effluent anion profiles generally showed the following order of retardation (from small to large):  $\text{NO}_3 < \text{SO}_4 < \text{CrO}_4 < \text{PO}_4$ .

#### *Phosphate Solution*

Unlike the other anions used, phosphate was strongly adsorbed as shown Figure 18. Between pore volumes 1 and 4 no phosphate was observed in the effluent indicating 100% removal by either adsorption or precipitation. Stollenwerk and Grove (1985) found that phosphate adsorption occurred by decreasing the electrostatic potential and by direct competition for specific adsorption sites. Schroth (1989) observed that phosphate at a concentration of 0.02 M K-phosphate caused Cr(VI) to be desorbed from the soil more rapidly than with distilled water alone. This behavior was also observed for the same phosphate concentration (Figure 4) in column 3D (0.02 M phosphate). However, at lower phosphate concentrations the opposite was true; distilled water desorbed Cr(VI) at a more rapid rate than phosphate (Figure 17).

## CONCLUSIONS

The following general conclusions can be made regarding the experimental results:

1. Increasing ionic strength retards extraction of Cr(VI) from chromium contaminated soil.

Increasing ionic strength has been shown to increase anion adsorption on soils due to double layer effects, this may explain the effect on extraction kinetics. Corvallis tap water and distilled water were the most effective at flushing Cr(VI) from the soil.

2. Varying influent pH had little affect on the rate of Cr(VI) desorption in the soil columns due to the buffering capacity of the soil which maintained the effluent pH in a narrow range between 6.0 and 7.0 for most columns.

3. The effectiveness of competitive anions for extracting Cr(VI) from soil appears to follow the order of adsorption affinity to the soil. Phosphate was the most effective followed by sulfate, bicarbonate, and nitrate. Increasing the concentration of phosphate increased Cr(VI) removal over the concentration range tested. Increasing the concentration of sulfate and bicarbonate only slight enhanced desorption.

Continued flushing of the soils at UCPS site with tap water is the most efficient way of removing Cr(VI) based on these results. Although various influent compositions had an effect on Cr(VI) desorption none were as effective as low ionic strength solutions. High concentrations of phosphate can enhance Cr(VI) removal, however, it is not significant enough to justify the cost or risk of possible adverse environmental affects.

Recommendations for further work:

1. Understanding the effect of ionic strength on Cr(VI) removal. These experiments indicated how important ionic strength was on the desorption process for UCPS site soils, but the causes are not fully understood. Batch reaction experiments would be useful in providing insight to understanding these effects and their influence on the experiment results of these column studies.

2. Determining the fraction of Cr(VI) physically adsorbed verses the amount in pore water solution. Knowledge of this factor might help explain these experimental results. The adsorption capacity of a soil for a particular contaminant is an important parameter in determining the treatment process and ultimate cost of cleaning up a contaminated site.

3. Running similar experiments on undisturbed soils. It is unclear the effect of drying and cleaning the soil had on these experimental results. Undisturbed samples would provide better insight into the feasibility of altering the extraction solution at UCPS site.



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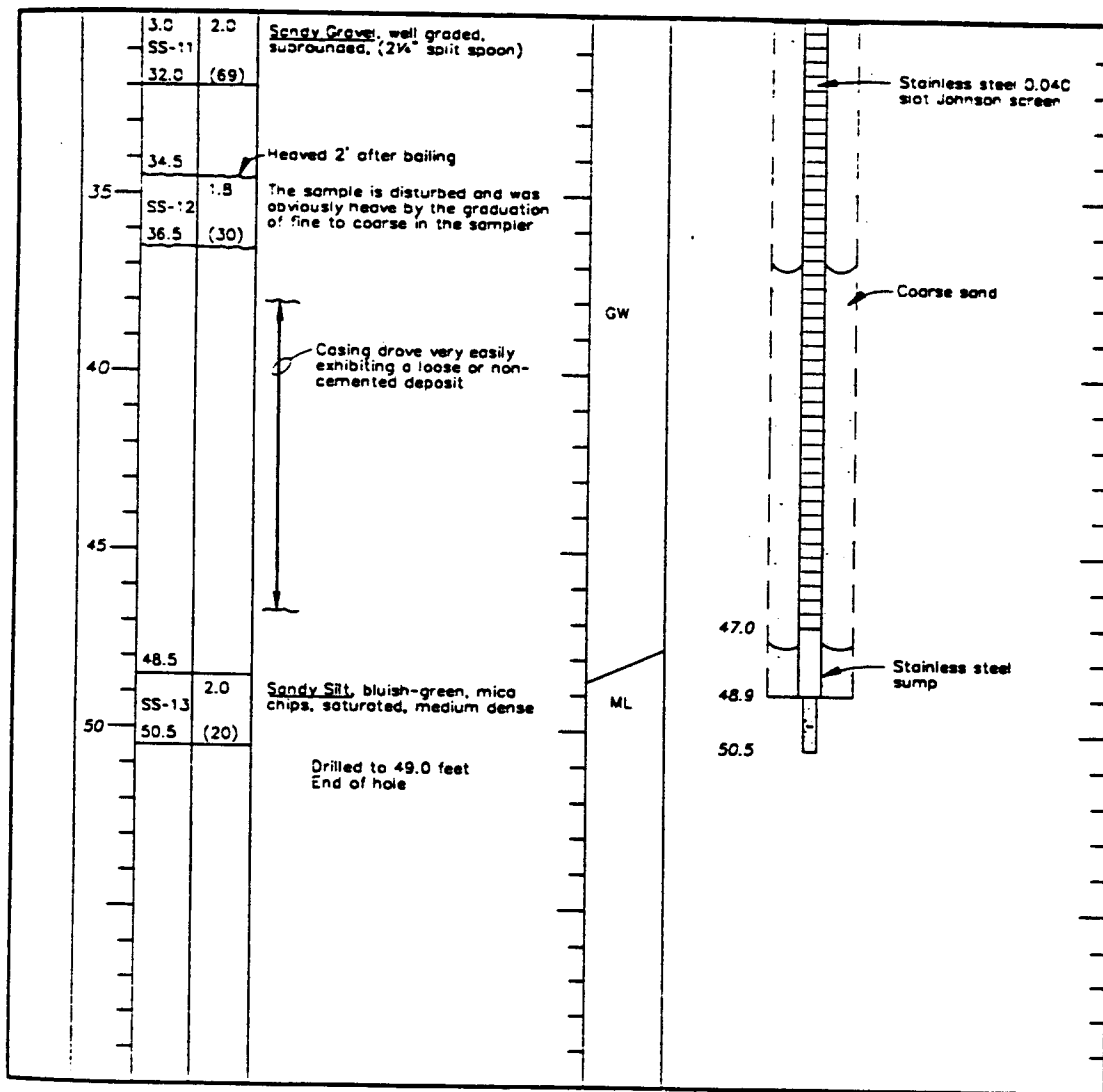
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## **APPENDICES**

**APPENDIX A**  
**SITE INFORMATION**

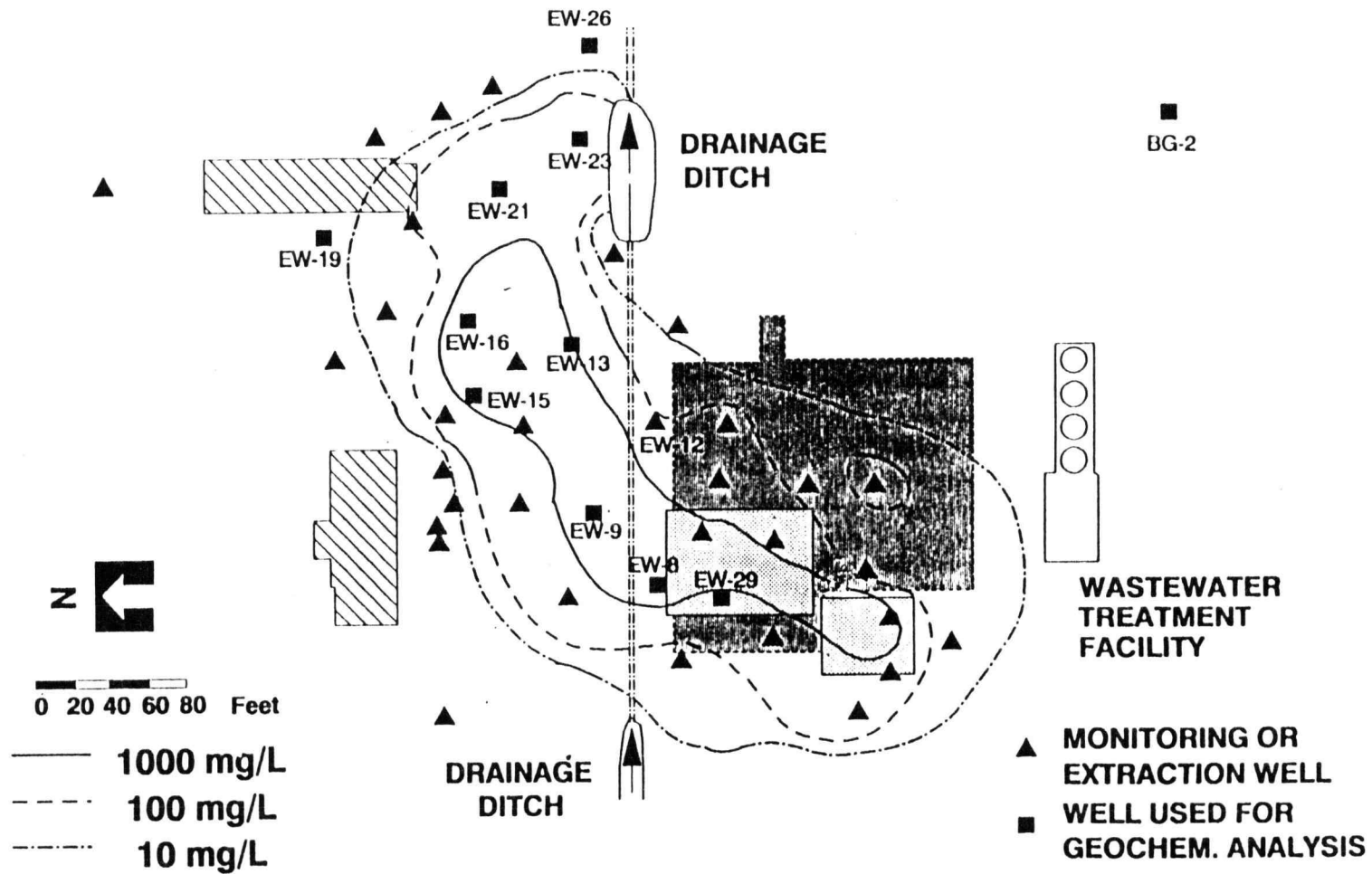


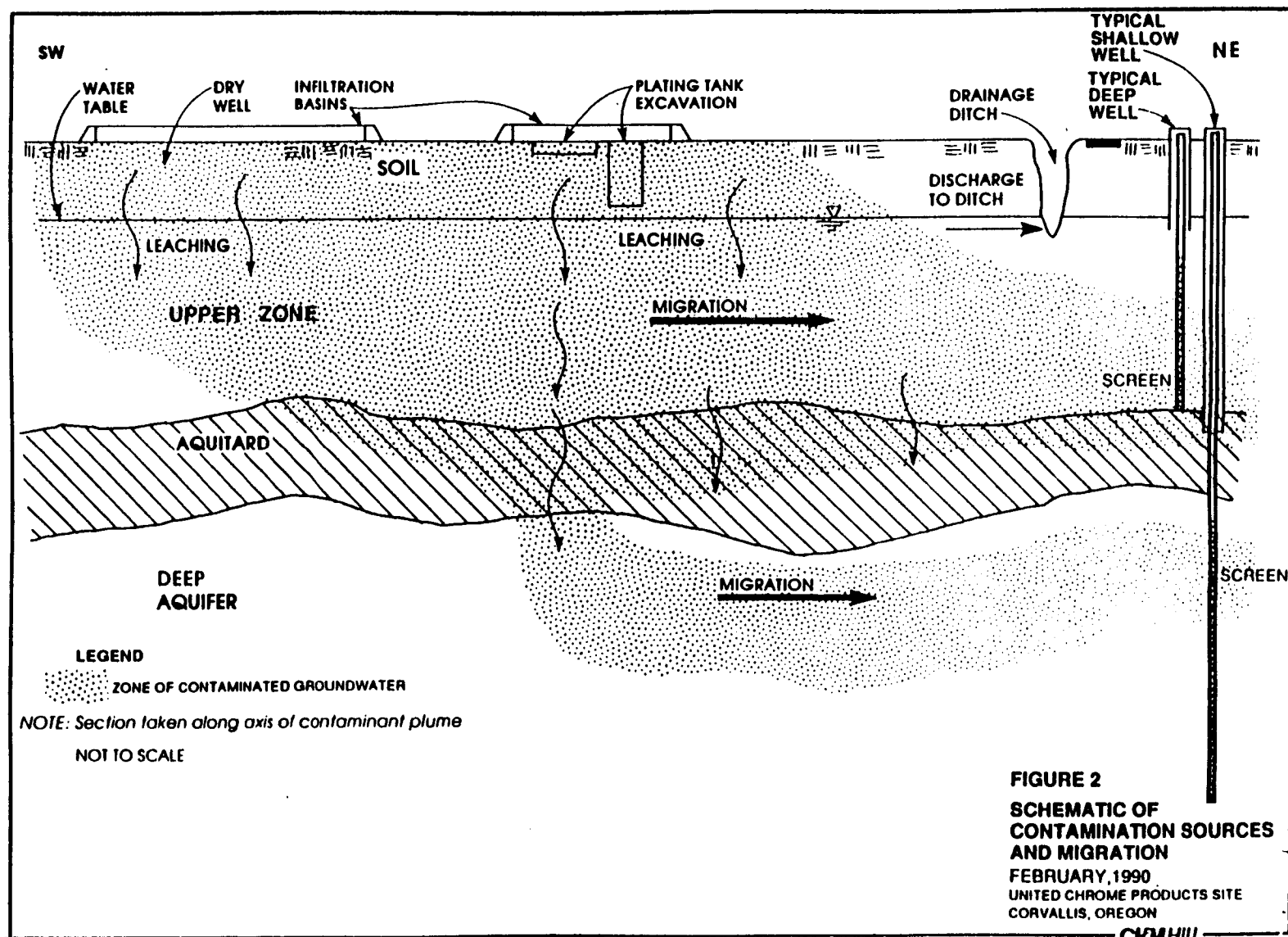
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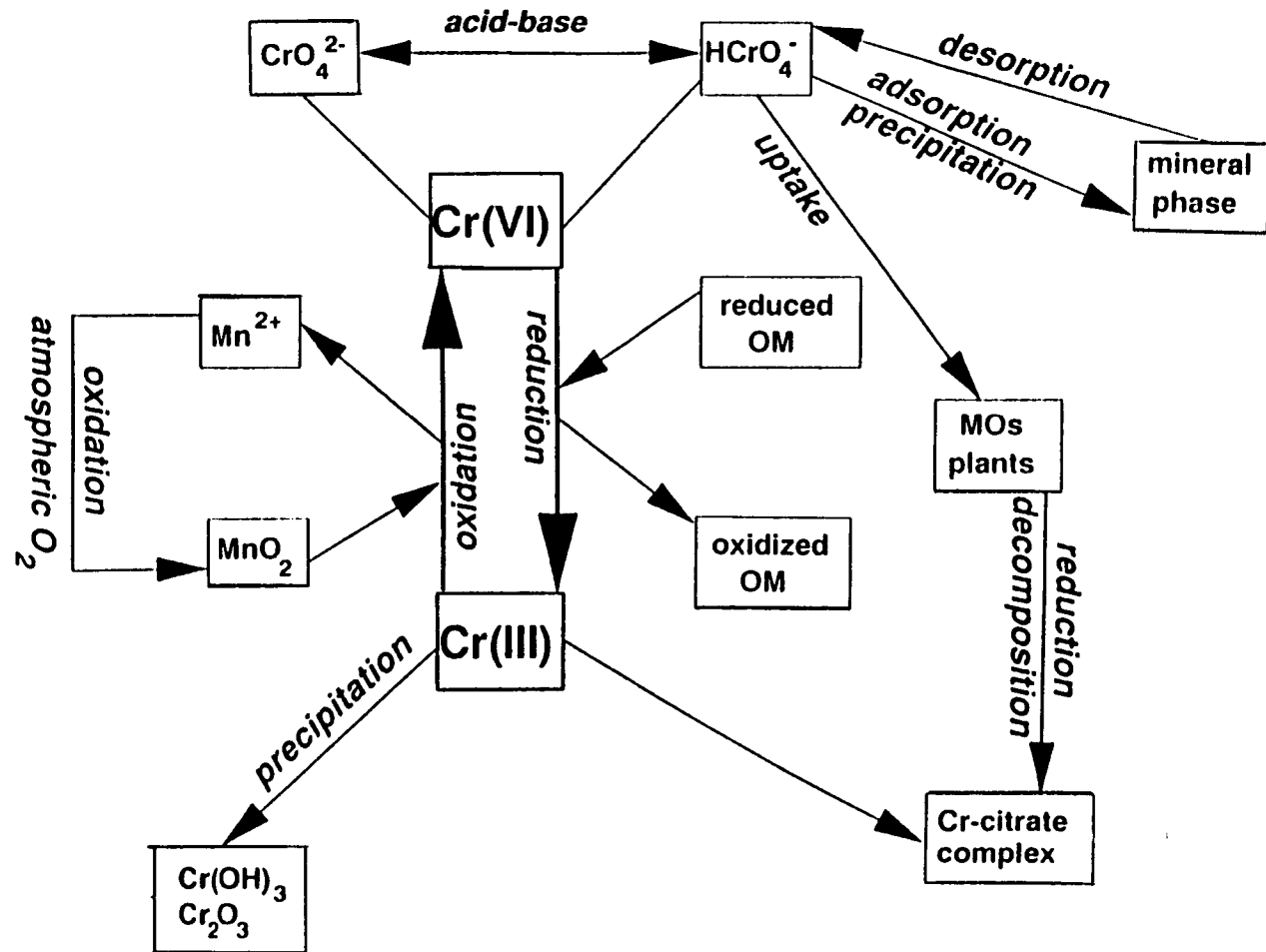


# HEXAVALENT CHROMIUM PLUME IN SILTS AT UCP





## Chromium Cycle in Soils



**APPENDIX B**

**SOIL COLUMN WORKSHEETS**

EXPERIMENT 1 - COLUMN 1A Distilled Water

VARIABLES

Results

Sampl No.	Date	Start Time	Stop Time	Elapsed Cumu.		Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI)	Cumu Cr(VI)	Cr(VI)
				Time (hrs)	Time (hrs)									Removed (mg/kg)	Removed (mg/kg)	Removed (ppm)
1A 1	09/24/90	18:00	08:38	14.63	14.63	23.0	7.00	15.0	15.0	0.2	1.0			0.63	0.63	6.97
1A 2	09/25/90	08:38	20:48	12.17	26.80	24.8	6.40	10.7	25.7	0.4	0.9			1.19	1.82	18.45
1A 3	09/25/90	20:48	08:32	11.73	38.53	23.0	6.30	12.9	38.6	0.6	1.1			2.16	3.98	27.87
1A 4	09/26/90	08:32	20:44	12.20	50.73	24.5	6.40	17.8	56.4	0.9	1.5			4.13	8.11	38.62
1A 5	09/26/90	20:44	09:02	12.30	63.03	22.0	6.40	17.0	73.4	1.2	1.4			7.17	15.28	70.17
1A 6	09/27/90	09:02	20:24	11.37	74.40	24.7	6.70	15.2	88.6	1.5	1.3			3.44	18.73	37.69
1A 7	09/27/90	20:24	08:37	12.22	86.62	23.0	6.70	15.8	104.4	1.7	1.3			0.70	19.43	7.38
1A 8	09/28/90	08:37	21:00	12.38	99.00	24.8	6.90	15.7	120.1	2.0	1.3			0.71	20.14	7.50
1A 9	09/28/90	21:00	09:20	12.33	111.33	24.0	7.00	15.0	135.1	2.2	1.2			0.51	20.65	5.64
1A 10	09/29/90	09:20	20:43	11.38	122.72	25.0	6.90	14.7	149.8	2.5	1.3			0.39	21.04	4.44
1A 11	09/29/90	20:43	09:37	12.90	135.62	23.8	6.90	17.1	166.9	2.8	1.3			0.35	21.39	3.41
1A 12	09/30/90	09:37	20:07	10.50	146.12	24.7	6.90	13.8	180.7	3.0	1.3			0.22	21.61	2.64
1A 13	09/30/90	20:07	08:07	12.00	158.12	22.0	7.00	15.6	196.3	3.2	1.3			0.19	21.80	2.06
1A 14	10/01/90	08:07	08:26	24.32	182.43	21.0	7.10	30.6	226.9	3.8	1.3			0.28	22.08	1.52
1A 15	10/02/90	08:26	08:51	24.42	206.85	21.4	7.20	30.7	257.6	4.3	1.3			0.19	22.27	1.02
1A 16	10/03/90	08:51	09:21	24.50	231.35	22.0	7.20	32.0	289.6	4.8	1.3			0.14	22.41	0.72
1A 17	10/04/90	09:21	08:10	22.82	254.17	21.2	7.10	28.9	318.5	5.3	1.3			0.10	22.51	0.57
1A 18	10/05/90	13:02	10:30	69.47	323.63	20.0	7.20	82.8	401.3	6.6	1.2			0.19	22.70	0.38
1A 19	10/08/90	12:55	11:03	70.13	393.77	20.3	7.00	81.1	482.4	8.0	1.2			0.15	22.84	0.30
1A 20	10/11/90	11:03														
Avg. Values						22.9	6.9				1.2					

EXPERIMENT 1 - COLUMN C 0.05 M NaCl

Parameters												Results				
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
1C 1	10/11/90	13:35	20:52	7.28	7.28	21.9	6.65	15.9	15.9	0.3	2.2			0.21	0.21	2.13
1C 2	10/11/90	20:52	09:45	12.88	20.17	21.5	6.62	25.9	41.8	0.7	2.0			1.02	1.23	6.50
1C 3	10/12/90	09:45	17:05	7.33	27.50	22.0	6.93	9.2	51.0	0.8	1.3			0.64	1.88	11.47
1C 4	10/12/90	17:05	00:05	7.00	34.50	22.5	6.57	13.8	64.8	1.0	2.0			1.05	2.93	12.51
1C 5	10/13/90	00:05	09:50	9.75	44.25	21.7	6.23	17.2	82.0	1.3	1.8			1.47	4.40	14.09
1C 6	10/13/90	09:50	16:47	6.95	51.20	22.2	6.30	12.0	94.0	1.5	1.7			1.03	5.43	14.13
1C 7	10/13/90	16:47	23:52	7.08	58.28	21.9	6.29	12.2	106.2	1.7	1.7			1.01	6.44	13.66
1C 8	10/13/90	23:52	10:01	10.15	68.43	20.8	6.18	17.0	123.2	2.0	1.7			1.34	7.78	12.92
1C 9	10/14/90	10:01	16:10	6.15	74.58	21.8	6.05	9.9	133.1	2.2	1.6			0.72	8.50	12.04
1C 10	10/14/90	16:10	23:12	7.03	81.62	22.0	6.05	10.4	143.5	2.3	1.5			0.73	9.24	11.60
1C 11	10/14/90	23:12	09:30	10.30	91.92	21.3	6.04	17.9	161.4	2.6	1.7			1.27	10.51	11.65
1C 12	10/15/90	09:30	19:35	10.08	102.00	22.8	6.00	18.3	179.7	2.9	1.8			1.24	11.74	11.10
1C 13	10/15/90	19:35	07:30	11.92	113.92	21.5	6.00	22.2	201.9	3.3	1.9			1.32	13.06	9.75
1C 14	10/16/90	07:30	15:00	7.50	121.42	22.0	6.04	14.6	216.5	3.5	1.9			0.75	13.81	8.43
1C 15	10/16/90	15:00	22:34	7.57	128.98	22.0	6.27	15.2	231.7	3.8	2.0			0.70	14.50	7.54
1C 16	10/16/90	22:34	08:18	9.73	138.72	20.5	6.00	8.7	240.4	3.9	0.9			0.35	14.85	6.59
1C 17	10/17/90	08:18	20:02	11.73	150.45	22.0	6.45	13.0	253.4	4.1	1.1			0.50	15.35	6.27
1C 18	10/17/90	20:02	08:35	12.55	163.00	21.0	6.44	23.0	276.4	4.5	1.8			0.79	16.14	5.64
1C 19	10/18/90	08:35	19:33	10.97	173.97	21.9	6.31	14.9	291.3	4.7	1.4			0.45	16.58	4.92
1C 20	10/18/90	19:33	07:30	11.95	185.92	20.0	6.08	14.0	305.3	4.9	1.2			0.38	16.96	4.48
1C 21	10/19/90	07:30	16:00	8.50	194.42	21.2	6.47	8.7	314.0	5.1	1.0			0.21	17.17	3.92
1C 22	10/22/90	11:15	20:55	9.67	204.08	21.5	6.62	14.9	328.9	5.3	1.5			0.32	17.50	3.57

1C 23		10/22/90	20:55	08:55	12.00	216.08	21.0	6.41	16.8	345.7	5.6	1.4			0.33	17.82	3.19
1C 24		10/23/90	08:55	20:15	11.33	227.42	22.0	6.50	18.0	363.7	5.9	1.6	4000	0.064	0.33	18.15	2.99
1C 25		10/23/90	20:15	14:00	17.75	245.17	21.3	6.32	21.6	385.3	6.2	1.2	4100	0.066	0.36	18.51	2.72
1C 26		10/24/90	14:00	08:00	18.00	263.17	21.0	6.32	22.8	408.1	6.6	1.3	4000	0.064	0.35	18.85	2.50
1C 27		10/25/90	08:00	08:15	24.25	287.42	21.4	6.11	32.1	440.2	7.1	1.3			0.46	19.31	2.35
1C 28		10/26/90	08:15	10:45	74.50	361.92	21.3	6.13	73.8	514.0	8.3	1.0	4100	0.066	0.81	20.12	1.81
1C 29		10/29/90	10:45	09:15	46.50	408.42	21.8	6.26	84.8	598.8	9.7	1.8			0.57	20.69	1.10
1C 30		10/31/90	09:15	08:15	47.00	455.42	20.0	6.16	63.5	662.3	10.7	1.4	4100	0.066	0.26	20.95	0.67
1C 31		11/02/90	08:15	13:00	76.75	532.17	21.4	6.43	121.5	783.8	12.7	1.6			0.32	21.27	0.43
1C 32		11/05/90	13:00	08:00	67.00	599.17	20.5	6.20	98.2	882.0	14.3	1.5			0.16	21.42	0.26
1C 33		11/09/90	09:10	10:55	73.75	672.92	21.0	6.27	123.4	1005.4	16.3	1.7	4000	0.064	0.11	21.53	0.15
1C 34		11/12/90	10:55	08:20	69.42	742.33	20.8	6.10	115.6	1121.0	18.1	1.7			0.09	21.63	0.13
1C 35		11/15/90	08:20	11:55	147.58	889.92	22.0	6.42	154.2	1275.2	20.6	1.0			0.07	21.69	0.07
1C 36		11/21/90	11:55	12:35	312.67	1202.58	21.0	6.18	184.9	1460.1	23.6	0.6	4100	0.066	0.00	21.69	0.00
		12/04/90	12:35														
Avg. Values							21.5	6.3				1.5	4057	0.065			

EXPERIMENT 1 - COLUMN E 0.0003 M HCl/0.01 M NaCl

Parameters											Results					
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
1E-1	10/12/90	10:00	17:10	7.17	7.17	22.0	6.97	11.2	11.2	0.2	1.6	1300	0.021	0.09	0.09	1.34
1E-2	10/12/90	17:10	00:14	7.07	14.23	22.5	6.99	11.3	22.5	0.4	1.6			0.18	0.27	2.81
1E-3	10/13/90	00:14	09:50	9.60	23.83	21.7	6.72	15.1	37.6	0.6	1.6			0.45	0.72	5.17
1E-4	10/13/90	09:50	16:47	6.95	30.78	22.2	6.90	10.9	48.5	0.8	1.6			0.66	1.38	10.59
1E-5	10/13/90	16:47	23:42	6.92	37.70	21.9	6.71	11.2	59.7	1.0	1.6			1.07	2.45	16.60
1E-6	10/13/90	23:42	10:01	10.32	48.02	20.8	6.60	16.0	75.7	1.3	1.6			2.70	5.16	29.34
1E-7	10/14/90	10:01	16:10	6.15	54.17	21.8	6.48	10.0	85.7	1.4	1.6			1.72	6.88	29.88
1E-8	10/14/90	16:10	23:12	7.03	61.20	22.0	6.52	11.6	97.3	1.6	1.6			1.83	8.71	27.38
1E-9	10/14/90	23:12	09:30	10.30	71.50	21.3	6.49	15.9	113.2	1.9	1.5			2.36	11.06	25.72
1E-10	10/15/90	09:30	19:35	10.08	81.58	22.8	6.42	15.9	129.1	2.2	1.6			2.11	13.18	23.08
1E-11	10/15/90	19:35	07:30	11.92	93.50	21.5	6.49	18.8	147.9	2.5	1.6	1400	0.022	1.99	15.17	18.41
1E-12	10/16/90	07:30	15:00	7.50	101.00	22.0	6.34	12.2	160.1	2.7	1.6			1.00	16.17	14.25
1E-13	10/16/90	15:00	22:34	7.57	108.57	22.0	6.45	12.2	172.3	2.9	1.6			0.91	17.08	12.88
1E-14	10/16/90	22:34	08:18	9.73	118.30	20.5	6.50	14.9	187.2	3.1	1.5			0.92	18.00	10.74
1E-15	10/17/90	08:18	20:02	11.73	130.03	21.0	6.50	5.4	192.6	3.2	0.5			0.31	18.30	9.84
1E-16	10/17/90	20:02	08:35	12.55	142.58	21.0	6.50	14.0	206.6	3.4	1.1			0.75	19.05	9.29
1E-17	10/18/90	08:35	19:33	10.97	153.55	21.9	6.61	5.2	211.8	3.5	0.5			0.25	19.30	8.33
1E-18	10/18/90	19:33	07:30	11.95	165.50	20.0	6.32	18.4	230.2	3.8	1.5			0.81	20.11	7.66
1E-19	10/19/90	07:30	16:00	8.50	174.00	21.2	6.59	8.1	238.3	4.0	1.0			0.32	20.43	6.80
1E-20	10/22/90	16:00	20:55	4.92	178.92	21.5	6.91	6.1	244.4	4.1	1.2			0.25	20.68	7.16
1E-21	10/22/90	20:55	08:55	12.00	190.92	21.0	6.65	18.7	263.1	4.4	1.6			0.69	21.38	6.45
1E-22	10/23/90	08:55	20:15	11.33	202.25	22.0	6.51	14.3	277.4	4.6	1.3	1270	0.020	0.50	21.88	6.12



1E-23	10/23/90	20:15	14:00	17.75	220.00	21.3	6.40	24.5	301.9	5.0	1.4	1300	0.021	0.78	22.67	5.55
1E-24	10/24/90	14:00	08:00	18.00	238.00	21.0	6.33	29.5	331.4	5.5	1.6	1200	0.019	0.84	23.50	4.92
1E-25	10/25/90	08:00	08:15	24.25	262.25	21.3	6.42	19.4	350.8	5.8	0.8			0.48	23.99	4.33
1E-26	10/29/90	10:45	09:05	22.33	284.58	21.1	6.55	27.6	378.4	6.3	1.2	1400	0.022	0.62	24.60	3.87
1E-27	10/30/90	09:05	09:15	24.17	308.75	21.8	6.43	41.3	419.7	7.0	1.7	1300	0.021	0.73	25.33	3.07
1E-28	10/31/90	09:15	08:15	47.00	355.75	20.0	6.40	59.1	478.8	8.0	1.3	1350	0.022	0.66	25.99	1.94
1E-29	11/05/90	13:00	09:10	68.17	423.92	20.3	6.62	91.8	570.6	9.5	1.3	1350	0.022	0.58	26.57	1.10
1E-30	11/08/90	09:10	08:00	22.83	446.75	20.5	6.43	39.9	610.5	10.2	1.7			0.14	26.71	0.59
1E-31	11/09/90	08:00	00:18	64.30	511.05	21.0	6.61	72.4	682.9	11.4	1.1	1200	0.019	0.16	26.87	0.38
1E-32	11/12/90	00:18	08:20	80.03	591.08	20.8	6.30	165.7	848.6	14.1	2.1	1300	0.021	0.14	27.01	0.15
1E-33	11/15/90	08:20	11:55	147.58	738.67	22.0	6.39	242.5	1091.1	18.2	1.6	1280	0.020	0.08	27.08	0.05
1E-34	11/28/90	17:30	12:35	115.08	853.75	21.0	6.45	135.2	1226.3	20.4	1.2			0.00	27.08	0.00
	12/03/90	10:00														
	Avg. Values					21.4	6.55				1.4	1306	0.021			

EXPERIMENT 1 - COLUMN F 0.0003 NaOH/0.01 M NaCl

Parameters												Results				
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
1F-1	10/12/90	10:00	11:10	1.17	1.17	21.5	7.44	16.8	16.8	0.3	14.4			0.06	0.06	0.65
1F-2	10/12/90	11:10	17:05	5.92	7.08	22.0	7.38	12.3	29.1	0.5	2.1			0.07	0.13	1.03
1F-3	10/12/90	17:05	09:50	16.75	23.83	21.7	7.33	13.6	42.7	0.7	0.8			0.12	0.25	1.63
1F-4	10/13/90	09:50	16:47	6.95	30.78	22.2	7.23	9.1	51.8	0.8	1.3			0.18	0.44	3.68
1F-5	10/13/90	16:47	23:42	6.92	37.70	21.9	7.24	10.0	61.8	1.0	1.4			0.28	0.72	5.09
1F-6	10/13/90	23:42	10:01	10.32	48.02	20.8	7.24	14.1	75.9	1.2	1.4			0.69	1.41	8.91
1F-7	10/14/90	10:01	16:10	6.15	54.17	21.8	7.16	8.1	84.0	1.4	1.3			0.69	2.09	15.47
1F-8	10/14/90	16:10	23:12	7.03	61.20	22.0	7.06	9.1	93.1	1.5	1.3			1.33	3.43	26.67
1F-9	10/14/90	23:12	09:30	10.30	71.50	21.3	6.93	7.9	101.0	1.6	0.8			1.59	5.02	36.68
1F-10	10/16/90	05:30	12:34	7.07	78.57	21.9	7.05	10.6	111.6	1.8	1.5			2.09	7.11	35.96
1F-11	10/16/90	12:34	22:34	10.00	88.57	22.0	7.05	14.0	125.6	2.0	1.4			2.70	9.82	35.13
1F-12	10/16/90	22:34	08:18	9.73	98.30	20.5	7.00	13.2	138.8	2.2	1.4			2.34	12.16	32.31
1F-13	10/17/90	08:18	20:02	11.73	110.03	22.0	7.30	14.8	153.6	2.5	1.3			2.33	14.49	28.61
1F-14	10/17/90	20:02	03:00	6.97	117.00	21.0	7.31	6.1	159.7	2.6	0.9			0.83	15.31	24.72
1F-15	10/18/90	08:35	19:33	10.97	127.97	21.9	7.20	15.2	174.9	2.8	1.4			1.78	17.09	21.31
1F-16	10/18/90	19:33	07:30	11.95	139.92	20.0	6.85	15.8	190.7	3.1	1.3			1.31	18.41	15.13
1F-17	10/19/90	07:30	16:00	8.50	148.42	21.2	6.80	10.0	200.7	3.2	1.2			0.69	19.09	12.49
1F-18	10/22/90	11:15	20:55	9.67	158.08	21.5	7.20	11.4	212.1	3.4	1.2			0.73	19.82	11.58
1F-19	10/23/90	06:55	20:15	13.33	171.42	22.0	6.90	17.9	230.0	3.7	1.3	1100	0.018	0.93	20.75	9.46
1F-20	10/23/90	20:15	14:00	17.75	189.17	21.3	6.73	21.5	251.5	4.1	1.2			0.93	21.68	7.91
1F-21	10/24/90	14:00	08:00	18.00	207.17	21.0	6.67	26.7	278.2	4.5	1.5	1100	0.018	1.02	22.70	6.94

1F-21		10/24/90	14:00	08:00	18.00	207.17	21.0	6.67	26.7	278.2	4.5	1.5	1100	0.018	1.02	22.70	6.94
1F-22		10/25/90	08:00	08:15	24.25	231.42	21.3	6.75	24.0	302.2	4.9	1.0			0.79	23.49	5.99
1F-23		10/29/90	10:45	09:05	22.33	253.75	21.1	6.64	39.5	341.7	5.5	1.8	1100	0.018	1.09	24.58	5.02
1F-24		10/30/90	09:05	09:15	24.17	277.92	21.8	6.66	18.0	359.7	5.8	0.7			0.46	25.04	4.65
1F-25		10/31/90	09:15	08:15	47.00	324.92	20.0	6.65	26.8	386.5	6.3	0.6	1000	0.016	0.60	25.64	4.07
1F-26		11/02/90	08:15	13:00	76.75	401.67	21.4	6.63	46.8	433.3	7.0	0.6			0.76	26.40	2.95
1F-27		11/05/90	13:00	09:10	68.17	469.83	21.5	6.50	56.1	489.4	7.9	0.8			0.62	27.02	2.03
1F-28		11/08/90	09:10	10:55	97.75	567.58	21.0	6.95	158.8	648.2	10.5	1.6	1200	0.019	0.76	27.78	0.87
1F-29		11/12/90	10:55	08:20	69.42	637.00	20.8	6.83	119.3	767.5	12.4	1.7	1200	0.019	0.19	27.97	0.29
1F-30		11/19/90	12:30	11:55	47.42	684.42	22.0	7.61	65.4	832.9	13.5	1.4	1060	0.017	0.05	28.02	0.15
1F-31		11/21/90	11:55	12:35	312.67	997.08	21.0	7.32	255.7	1088.6	17.6	0.8	1080	0.017	0.09	28.12	0.07
		12/04/90															
		Avg. Values					21.4	7.0				1.2	1117	0.018			

EXPERIMENT 1 - COLUMN G 0.10 M NaCl

Parameters											Results					
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
1G 1	11/06/90	14:45	22:45	8.00	8.00	20.4	7.10	16.0	16.0	0.3	2.0			0.40	0.40	4.11
1G 2	11/06/90	22:45	09:10	10.42	18.42	20.3	6.76	20.2	36.2	0.6	1.9			0.93	1.33	7.63
1G 3	11/07/90	09:10	16:07	6.95	25.37	22.0	6.49	14.1	50.3	0.8	2.0			1.07	2.40	12.54
1G 4	11/07/90	16:07	23:32	7.42	32.78	21.0	5.97	14.6	64.9	1.1	2.0			1.24	3.64	14.09
1G 5	11/07/90	23:32	08:00	8.47	41.25	20.5	5.66	16.0	80.9	1.4	1.9			1.50	5.14	15.46
1G 6	11/08/90	08:00	15:05	7.08	48.33	21.8	5.96	13.5	94.4	1.6	1.9			1.29	6.43	15.80
1G 7	11/08/90	15:05	23:20	8.25	56.58	22.7	5.95	15.7	110.1	1.8	1.9	7000	0.112	1.46	7.89	15.39
1G 8	11/08/90	23:20	09:10	9.83	66.42	21.5	5.95	18.0	128.1	2.1	1.8			1.77	9.66	16.27
1G 9	11/09/90	09:10	16:10	7.00	73.42	22.0	5.95	13.2	141.3	2.4	1.9			1.39	11.05	17.37
1G 10	11/12/90	10:50	18:10	7.33	80.75	21.5	6.06	13.4	154.7	2.6	1.8			1.22	12.26	15.02
1G 11	11/12/90	18:10	23:45	5.58	86.33	21.8	5.96	10.1	164.8	2.8	1.8			0.91	13.17	14.92
1G 12	11/12/90	23:45	10:05	10.33	96.67	21.0	5.63	18.3	183.1	3.1	1.8			1.53	14.70	13.82
1G 13	11/13/90	10:05	19:31	9.43	106.10	21.7	5.40	17.0	200.1	3.3	1.8			1.24	15.94	12.03
1G 14	11/13/90	19:31	07:50	12.32	118.42	20.0	5.15	21.5	221.6	3.7	1.7	7000	0.112	1.33	17.27	10.21
1G 15	11/14/90	07:50	19:30	11.67	130.08	21.5	5.20	20.2	241.8	4.0	1.7			1.07	18.34	8.78
1G 16	11/14/90	19:30	07:57	12.45	142.53	20.8	5.05	21.6	263.4	4.4	1.7			1.00	19.34	7.69
1G 17	11/15/90	07:57	19:36	11.65	154.18	22.0	5.15	20.2	283.6	4.7	1.7	6500	0.104	0.82	20.16	6.71
1G 18	11/15/90	19:36	08:00	12.40	166.58	20.0	5.03	21.9	305.5	5.1	1.8			0.79	20.96	5.98
1G 19	11/16/90	08:00	16:48	8.80	175.38	21.2	5.31	14.8	320.3	5.4	1.7			0.47	21.43	5.25
1G 20	11/19/90	12:25	11:02	22.62	198.00	20.0	5.80	37.0	357.3	6.0	1.6			1.04	22.46	4.63
1G 21	11/20/90	11:02	11:55	24.88	222.88	22.0	5.20	41.4	398.7	6.7	1.7	7000	0.112	0.99	23.46	3.97

1G 22		11/26/90	11:10	10:45	23.58	246.47	21.9	6.11	38.2	436.9	7.3	1.6			0.78	24.23	3.36
1G 23		11/27/90	10:45	11:12	24.45	270.92	20.0	5.17	38.5	475.4	8.0	1.6			0.61	24.84	2.63
1G 24		11/28/90	11:12	11:45	24.55	295.47	20.4	5.16	38.7	514.1	8.6	1.6	6800	0.109	0.44	25.29	1.89
1G 25		11/29/90	11:45	13:08	25.38	320.85	20.0	5.17	38.1	552.2	9.2	1.5			0.33	25.62	1.43
1G 26		12/03/90	14:00	15:38	25.63	346.48	21.5	5.36	40.4	592.6	9.9	1.6			0.28	25.90	1.17
1G 27		12/04/90	15:38	15:45	48.12	394.60	20.2	5.04	71.2	663.8	11.1	1.5	6900	0.110	0.35	26.25	0.82
1G 28		12/06/90	15:45	12:30	68.75	463.35	21.0	5.04	105.3	769.1	12.9	1.5	6800	0.109	0.33	26.58	0.52
1G 29		12/09/90	12:30	13:10	96.67	560.02	19.5	5.08	143.4	912.5	15.3	1.5	6800	0.109	0.28	26.86	0.32
1G 30		01/02/91	14:38	12:10	21.53	581.55	20.0	6.57	31.0	943.5	15.8	1.4			0.02	26.88	0.12
		01/03/91	00:00														
Avg. Values							21.0	5.65				1.7	6850	0.110			

EXPERIMENT 1 - COLUMN H 0.01 M NaCl

Parameters										Results						
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
1H 1	01/03/91	12:38	16:30	3.87	3.87	21.7	5.85	8.0	8.0	0.1	2.1			0.01	0.01	0.14
1H 2	01/03/91	16:30	23:35	7.08	10.95	21.0	6.24	15.5	23.5	0.4	2.2			0.31	0.32	3.40
1H 3	01/03/91	23:35	08:37	9.03	19.98	19.6	6.58	19.7	43.2	0.7	2.2	1100	0.018	0.99	1.31	8.55
1H 4	01/04/91	08:37	16:05	7.47	27.45	19.0	6.64	16.0	59.2	0.9	2.1			1.65	2.96	17.47
1H 5	01/04/91	16:05	23:55	7.83	35.28	20.0	6.43	16.1	75.3	1.2	2.1			2.62	5.58	27.62
1H 6	01/04/91	23:55	09:23	9.47	44.75	15.0	6.21	18.8	94.1	1.5	2.0			2.66	8.25	24.00
1H 7	01/05/91	09:23	17:00	7.62	52.37	21.0	6.32	15.8	109.9	1.8	2.1			1.83	10.07	19.61
1H 8	01/05/91	17:00	23:51	6.85	59.22	18.0	6.32	14.2	124.1	2.0	2.1			1.43	11.50	17.04
1H 9	01/05/91	23:51	12:00	12.15	71.37	19.0	6.31	25.1	149.2	2.4	2.1	1050	0.017	2.01	13.51	13.55
1H 10	01/06/91	12:00	23:14	11.23	82.60	20.0	6.32	24.4	173.6	2.8	2.2			1.45	14.96	10.08
1H 11	01/06/91	23:14	12:30	13.27	95.87	21.0	6.37	28.9	202.5	3.2	2.2	1000	0.016	1.30	16.26	7.63
1H 12	01/07/91	12:30	21:04	8.57	104.43	21.0	6.42	19.1	221.6	3.5	2.2			0.70	16.96	6.25
1H 13	01/07/91	21:04	12:38	15.57	120.00	20.2	6.35	34.1	255.7	4.1	2.2	1120	0.018	1.02	17.98	5.05
1H 14	01/08/91	12:38	09:25	20.78	140.78	19.4	6.17	46.0	301.7	4.8	2.2	945	0.015	1.13	19.11	4.17
1H 15	01/09/91	09:25	08:30	23.08	163.87	20.7	6.18	50.4	352.1	5.6	2.2	980	0.016	1.00	20.11	3.35
1H 16	01/10/91	08:30	08:28	23.97	187.83	22.4	6.21	54.8	406.9	6.5	2.3	1000	0.016	0.90	21.00	2.77
1H 17	01/11/91	08:28	10:18	49.83	237.67	21.8	6.16	99.0	505.9	8.1	2.0	980	0.016	1.10	22.11	1.89
1H 18	01/13/91	10:18	09:30	71.20	308.87	19.1	6.33	89.4	595.3	9.5	1.3			0.55	22.66	1.05
1H 19	01/16/91	09:30	09:30	48.00	356.87	19.0	6.39	111.0	706.3	11.3	2.3	1180	0.019	0.39	23.05	0.60
1H 20	01/18/91	09:30	12:10	98.67	455.53	18.5	6.51	287.1	993.4	15.9	2.9	1050	0.017	0.39	23.44	0.23
1H 21	01/22/91	12:10	12:00	47.83	503.37	20.3	6.33	100.3	1093.7	17.5	2.1	1110	0.018	0.11	23.55	0.19
	01/24/91															
	Avg. Values					19.9	6.32				2.1	1047	0.017			

EXPERIMENT 1 - COLUMN I CORVALLIS TAP WATER

Parameters												Results				
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
11- 1	03/27/91	10:45	17:12	6.45	6.45	21.5	6.73	12.7	12.7	0.2	2.0			0.24	0.24	3.18
11- 2	03/27/91	17:12	23:12	6.00	12.45	21.5	6.40	12.0	24.7	0.4	2.0			0.35	0.59	5.00
11- 3	03/27/91	23:12	07:47	8.58	21.03	20.1	6.29	16.4	41.1	0.7	1.9			0.73	1.31	7.53
11- 4	03/28/91	07:47	12:35	4.80	25.83	20.9	6.39	9.8	50.9	0.8	2.0			0.58	1.90	10.11
11- 5	03/28/91	12:35	18:08	5.55	31.38	21.7	6.45	11.0	61.9	1.0	2.0			1.98	3.88	30.71
11- 6	03/28/91	18:08	23:30	5.37	36.75	21.0	6.54	10.5	72.4	1.2	2.0			5.47	9.35	88.79
11- 7	03/28/91	23:30	07:55	8.42	45.17	19.5	6.70	15.6	88.0	1.5	1.9			6.71	16.07	73.30
11- 8	04/01/91	09:25	17:20	7.92	53.08	25.0	6.93	18.5	106.5	1.8	2.3			3.14	19.20	28.86
11- 9	04/01/91	17:20	23:35	6.25	59.33	24.0	7.01	13.5	120.0	2.0	2.2			1.38	20.58	17.36
11- 10	04/01/91	23:35	09:00	9.42	68.75	21.0	7.12	17.6	137.6	2.3	1.9			1.25	21.83	12.10
11- 11	04/02/91	09:00	08:57	23.95	92.70	20.7	7.12	42.2	179.8	3.0	1.8	185	0.003	1.85	23.68	7.47
11- 12	04/03/91	08:57	09:00	24.05	116.75	20.9	7.10	43.1	222.9	3.7	1.8	160	0.003	0.82	24.50	3.23
11- 13	04/04/91	09:00	09:05	24.08	140.83	21.0	7.01	43.1	266.0	4.4	1.8	145	0.002	0.51	25.01	2.02
11- 14	04/05/91	09:05	12:46	75.68	216.52	19.8	7.12	132.8	398.8	6.6	1.8	140	0.002	0.79	25.80	1.01
11- 15	04/08/91	12:46	10:50	94.07	310.58	19.7	7.36	170.8	569.6	9.4	1.8	155	0.002	0.47	26.27	0.47
11- 16	04/12/91	10:50	11:30	96.67	407.25	20.6	7.18	187.0	756.6	12.5	1.9			0.22	26.49	0.20
11- 17	04/16/91	11:30														
Avg. Values						21.2	6.84				1.9	157	0.003			

EXPERIMENT 2 - COLUMN A 0.005 M SO<sub>4</sub>/0.01 M NaCl

Parameters												Results				
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
2A 1	12/05/90	15:50	23:05	7.25	7.25	20.2	5.24	15.8	15.8	0.2	2.2			0.54	0.54	5.59
2A 2	12/05/90	23:05	07:12	8.12	15.37	19.2	6.97	17.7	33.5	0.5	2.2			0.76	1.30	7.04
2A 3	12/06/90	07:12	12:30	5.30	20.67	20.0	6.81	11.6	45.1	0.7	2.2			0.62	1.92	8.73
2A 4	12/06/90	12:30	17:52	5.37	26.03	20.7	6.42	11.8	56.9	0.9	2.2			1.00	2.92	13.90
2A 5	12/06/90	17:52	23:45	5.88	31.92	20.9	6.19	12.2	69.1	1.1	2.1			1.68	4.61	22.57
2A 6	12/06/90	23:45	08:30	8.75	40.67	20.3	6.24	17.9	87.0	1.4	2.0			4.12	8.73	37.64
2A 7	12/07/90	08:30	14:30	6.00	46.67	21.0	6.20	12.4	99.4	1.6	2.1			2.89	11.62	38.11
2A 8	12/07/90	14:30	22:50	8.33	55.00	21.3	6.17	17.1	116.5	1.8	2.1			3.24	14.86	31.01
2A 9	12/07/90	22:50	08:22	9.53	64.53	20.2	6.21	19.3	135.8	2.1	2.0			2.60	17.46	22.02
2A 10	12/08/90	08:22	17:15	8.88	73.42	22.1	6.22	18.6	154.4	2.4	2.1			1.73	19.18	15.19
2A 11	12/08/90	17:15	23:45	6.50	79.92	22.8	6.20	14.4	168.8	2.7	2.2			1.06	20.25	12.09
2A 12	12/08/90	23:45	12:23	12.63	92.55	21.0	6.29	26.8	195.6	3.1	2.1	1650	0.026	1.35	21.59	8.21
2A 13	12/09/90	12:23	20:30	8.12	100.67	21.9	6.19	17.2	212.8	3.3	2.1			0.70	22.30	6.70
2A 14	12/09/90	20:30	09:30	13.00	113.67	21.5	6.23	25.4	238.2	3.7	2.0	1625	0.026	0.73	23.02	4.67
2A 15	12/10/90	09:30	09:15	23.75	137.42	20.0	6.03	37.3	275.5	4.3	1.6			0.76	23.78	3.32
2A 16	12/11/90	09:15	10:15	25.00	162.42	20.0	6.22	48.6	324.1	5.1	1.9	1580	0.025	0.62	24.41	2.10
2A 17	12/12/90	10:15	13:10	26.92	189.33	19.5	6.00	55.2	379.3	6.0	2.1	1600	0.026	0.41	24.81	1.20
2A 18	01/02/91	14:38	15:00	48.37	237.70	19.0	6.92	70.5	449.8	7.1	1.5	1550	0.025	0.24	25.05	0.55
2A 19	01/04/91	15:00	12:00	45.00	282.70	19.0	6.70	64.0	513.8	8.1	1.4	1550	0.025	0.13	25.17	0.33
	01/06/91															
	Avg. Values					20.6	6.29				2.0	1593	0.025			



EXPERIMENT 2 - COLUMN B 0.01 M SO<sub>4</sub>/0.01 M NaCl

Parameters

Results

Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
2B 1	01/28/91	09:50	16:05	6.25	6.25	20.0	6.51	12.7	12.7	0.2	2.0			0.18	0.18	2.29
2B 2	01/28/91	16:05	23:30	7.42	13.67	20.0	6.49	15.7	28.4	0.5	2.1			0.62	0.80	6.53
2B 3	01/28/91	23:30	08:15	8.75	22.42	17.8	6.51	17.9	46.3	0.8	2.0			1.14	1.94	10.52
2B 4	01/29/91	08:15	16:48	8.55	30.97	19.0	6.30	16.5	62.8	1.1	1.9			2.21	4.15	22.09
2B 5	01/29/91	16:48	23:48	7.00	37.97	19.0	6.28	15.0	77.8	1.3	2.1			3.27	7.43	35.98
2B 6	01/29/91	23:48	08:18	8.50	46.47	16.9	6.09	16.4	94.2	1.6	1.9			3.28	10.71	32.94
2B 7	01/30/91	08:18	16:00	7.70	54.17	18.5	6.21	16.0	110.2	1.9	2.1			2.61	13.31	26.85
2B 8	01/30/91	16:00	23:11	7.18	61.35	19.7	6.16	15.0	125.2	2.1	2.1			1.85	15.16	20.33
2B 9	01/30/91	23:11	07:40	8.48	69.83	19.0	6.09	17.1	142.3	2.4	2.0			1.52	16.69	14.68
2B 10	01/31/91	07:40	16:08	8.47	78.30	21.0	6.20	17.3	159.6	2.7	2.0	2100	0.032	1.12	17.80	10.63
2B 11	01/31/91	16:08	23:16	7.13	85.43	22.0	6.16	15.7	175.3	3.0	2.2			1.02	18.82	10.70
2B 12	01/31/91	23:16	11:30	12.23	97.67	21.0	6.23	25.4	200.7	3.4	2.1	2400	0.036	0.99	19.81	6.39
2B 13	02/01/91	11:30	11:15	23.75	121.42	20.0	6.32	45.1	245.8	4.2	1.9	2300	0.035	1.11	20.92	4.07
2B 14	02/02/91	11:15	10:30	23.25	144.67	21.0	6.50	37.9	283.7	4.8	1.6	2500	0.038	0.55	21.47	2.40
2B 15	02/03/91	10:30	12:15	97.75	242.42	21.0	6.82	180.3	464.0	7.9	1.8	2600	0.039	1.13	22.61	1.04
2B 16	02/07/91	12:15	10:50	22.58	265.00	20.0	6.62	37.5	501.5	8.5	1.7	2600	0.039	0.09	22.69	0.38
	02/08/91															
	Avg. Values					19.7	6.34				2.0	2417	0.036			

EXPERIMENT 2 - COLUMN C 0.001 M SO<sub>4</sub>/0.01 M NaCl

Parameters												Results					
Sampl No.		Date	Start Time	Stop Time	Elapsed Cumu.		Temp. (C)	pH	Sampl Cumu.		Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI)	Cumu Cr(VI)	Cr(VI)
					Time (hrs)	Time (hrs)			Vol. (mL)	Vol. (mL)					Removed (mg/kg)	Removed (mg/kg)	Removed (ppm)
2C 1		02/27/91	08:05	16:00	7.92	7.92	22.5	6.67	18.9	18.9	0.3	2.4			0.41	0.41	3.56
2C 2		02/27/91	16:00	22:30	6.50	14.42	22.5	6.86	16.4	35.3	0.6	2.5			0.74	1.15	7.37
2C 3		02/27/91	22:30	07:10	8.67	23.08	21.0	6.44	20.9	56.2	0.9	2.4			1.49	2.64	11.68
2C 4		02/28/91	07:10	12:30	5.33	28.42	21.0	6.30	12.7	68.9	1.1	2.4			2.12	4.76	27.30
2C 5		02/28/91	12:30	18:28	5.97	34.38	22.3	6.17	14.6	83.5	1.4	2.4			2.99	7.74	33.49
2C 6		02/28/91	18:28	23:12	4.73	39.12	22.0	6.13	11.3	94.8	1.6	2.4			2.38	10.12	34.46
2C 7		02/28/91	23:12	08:05	8.88	48.00	21.0	5.99	20.2	115.0	1.9	2.3	1380	0.022	3.31	13.43	26.81
2C 8		03/01/91	08:05	15:10	7.08	55.08	22.5	6.13	16.2	131.2	2.2	2.3			1.84	15.27	18.65
2C 9		03/01/91	15:10	23:03	7.88	62.97	22.0	6.08	18.1	149.3	2.5	2.3			1.48	16.76	13.43
2C 10		03/01/91	23:03	09:00	9.95	72.92	21.0	6.07	22.5	171.8	2.8	2.3	1400	0.022	1.29	18.04	9.39
2C 11		03/02/91	09:00	20:37	11.62	84.53	21.5	5.89	26.0	197.8	3.3	2.2	1380	0.022	1.02	19.06	6.41
2C 12		03/02/91	20:37	09:03	12.43	96.97	20.2	6.28	26.5	224.3	3.7	2.1	1380	0.022	0.74	19.80	4.56
2C 13		03/03/91	09:03	08:10	23.12	120.08	20.8	6.35	31.6	255.9	4.2	1.4	1350	0.022	0.66	20.46	3.40
2C 14		03/04/91	08:10	09:50	49.67	169.75	19.0	6.14	83.0	338.9	5.6	1.7	1420	0.023	1.11	21.57	2.20
2C 15		03/06/91	09:50	14:16	52.43	222.18	20.0	6.31	73.8	412.7	6.8	1.4	1300	0.021	0.63	22.20	1.39
2C 16		03/08/91	14:16	10:45	116.48	338.67	19.8	6.36	246.7	659.4	10.9	2.1			1.03	23.23	0.68
		03/13/91	10:45														

EXPERIMENT 2 - COLUMN D 0.005 M SO<sub>4</sub>/DW

Parameters											Results						
Sampl No.		Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumulative Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumulative Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI)	Cumulative Cr(VI)	Cr(VI)
															Removed (mg/kg)	Removed (mg/kg)	Removed (ppm)
2D 1		03/27/91	10:55	17:12	6.28	6.28	21.5	6.51	15.9	15.9	0.3	2.5			0.24	0.24	2.45
2D 2		03/27/91	17:12	23:12	6.00	12.28	21.5	6.79	15.8	31.7	0.5	2.6			0.59	0.83	6.01
2D 3		03/27/91	23:12	07:47	8.58	20.87	20.1	6.69	22.0	53.7	0.9	2.6	1775	0.028	1.46	2.28	10.72
2D 4		03/28/91	07:47	12:35	4.80	25.67	20.9	6.63	11.2	64.9	1.1	2.3			3.17	5.45	45.77
2D 5		03/28/91	12:35	18:08	5.55	31.22	21.7	6.52	12.0	76.9	1.3	2.2			3.51	8.96	47.28
2D 6		03/28/91	18:08	23:30	5.37	36.58	21.0	6.47	10.9	87.8	1.5	2.0			2.98	11.94	44.23
2D 7		03/28/91	23:30	07:55	8.42	45.00	19.5	6.57	13.0	100.8	1.7	1.5			2.70	14.63	33.58
2D 8		04/01/91	09:25	17:20	7.92	52.92	25.0	6.88	15.4	116.2	1.9	1.9			2.02	16.65	21.21
2D 9		04/01/91	17:20	23:35	6.25	59.17	24.0	6.56	10.7	126.9	2.1	1.7			1.07	17.72	16.19
2D 10		04/01/91	23:35	09:00	9.42	68.58	21.0	6.54	18.0	144.9	2.4	1.9			1.28	19.00	11.47
2D 11		04/02/91	09:00	08:57	23.95	92.53	20.7	6.75	32.5	177.4	2.9	1.4	1020	0.016	1.46	20.46	7.27
2D 12		04/03/91	08:57	09:00	24.05	116.58	20.9	6.42	53.8	231.2	3.8	2.2	980	0.016	1.30	21.76	3.92
2D 13		04/04/91	09:00	09:05	24.08	140.67	21.0	6.49	40.1	271.3	4.5	1.7	970	0.016	0.53	22.29	2.16
2D 14		04/05/91	09:05	12:45	27.67	168.33	19.8	6.65	48.5	319.8	5.3	1.8	970	0.016	0.39	22.68	1.29
2D 15		04/08/91	12:45	10:50	94.08	262.42	19.7	5.99	197.1	516.9	8.6	2.1	980	0.016	0.62	23.30	0.51
2D 16		04/12/91	10:50	11:30	96.67	359.08	20.6	6.27	147.8	664.7	11.1	1.5			0.27	23.58	0.30
		04/16/91	11:30														

EXPERIMENT 3 - COLUMN A 0.01 M H<sub>2</sub>PO<sub>4</sub>/0.01 M NaCl

Parameters											Results					
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
3A 1	12/05/90	15:50	23:05	7.25	7.25	20.4	7.01	16.1	16.1	0.3	2.2			0.19	0.19	2.03
3A 2	12/05/90	23:05	07:12	8.12	15.37	19.2	6.88	16.5	32.6	0.6	2.0			0.43	0.62	4.44
3A 3	12/06/90	07:12	12:30	5.30	20.67	20.0	6.83	11.1	43.7	0.8	2.1			0.48	1.10	7.27
3A 4	12/06/90	12:30	17:52	5.37	26.03	20.7	6.63	11.2	54.9	1.0	2.1			0.77	1.87	11.62
3A 5	12/06/90	17:52	23:45	5.88	31.92	20.9	6.06	12.7	67.6	1.2	2.2			2.07	3.94	27.68
3A 6	12/06/90	23:45	08:30	8.75	40.67	20.3	6.23	18.4	86.0	1.5	2.1			3.41	7.34	31.42
3A 7	12/07/90	08:30	14:30	6.00	46.67	21.0	6.27	12.5	98.5	1.8	2.1			2.13	9.47	28.95
3A 8	12/07/90	14:30	22:50	8.33	55.00	21.3	6.20	17.3	115.8	2.1	2.1			2.97	12.44	29.13
3A 9	12/07/90	22:50	08:22	9.53	64.53	20.2	6.26	18.5	134.3	2.4	1.9			2.69	15.13	24.69
3A 10	12/08/90	08:22	17:30	9.13	73.67	22.1	6.24	16.0	150.3	2.7	1.8			1.91	17.04	20.28
3A 11	12/08/90	17:30	23:45	6.25	79.92	22.8	6.24	11.8	162.1	2.9	1.9			1.24	18.28	17.85
3A 12	12/08/90	23:45	12:23	12.63	92.55	21.0	6.30	17.9	180.0	3.2	1.4			1.57	19.85	14.89
3A 13	12/09/90	12:23	20:30	8.12	100.67	21.9	6.29	11.1	191.1	3.4	1.4			0.86	20.71	13.11
3A 14	12/09/90	20:30	09:30	13.00	113.67	21.5	6.09	20.9	212.0	3.8	1.6	1100	0.018	1.16	21.87	9.41
3A 15	12/10/90	09:30	09:15	23.75	137.42	20.0	5.56	42.0	254.0	4.5	1.8			0.38	22.25	1.53
3A 16	12/11/90	09:15	10:15	25.00	162.42	20.0	5.63	42.3	296.3	5.3	1.7	1300	0.021	0.11	22.36	0.45
3A 17	12/12/90	10:15	13:10	26.92	189.33	19.5	5.69	43.8	340.1	6.1	1.6	1380	0.022	0.08	22.44	0.31
3A 18	01/03/91	10:00	10:00	48.00	237.33	15.0	5.83	58.9	399.0	7.1	1.2	1140	0.018	0.05	22.49	0.13
	01/05/91	10:00														
	Avg. Values					20.4	6.24				1.8	1230	0.020			

EXPERIMENT 3 - COLUMN B 0.005 HPO<sub>4</sub>/0.01 M NaCl

Parameters											Results					
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumm Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
3B 1	01/10/91	12:15	16:15	4.00	4.00	22.1	7.03	8.0	8.0	0.1	2.0			0.07	0.07	1.51
3B 2	01/10/91	16:15	23:40	7.42	11.42	23.0	7.03	14.2	22.2	0.4	1.9			0.28	0.36	3.40
3B 3	01/10/91	23:40	08:28	8.80	20.22	22.4	6.78	17.0	39.2	0.7	1.9			0.65	1.01	6.50
3B 4	01/11/91	08:28	16:00	7.53	27.75	21.9	6.62	13.9	53.1	0.9	1.8			1.05	2.05	12.79
3B 5	01/11/91	16:00	00:00	8.00	35.75	21.8	6.37	14.8	67.9	1.1	1.9			2.10	4.15	24.07
3B 6	01/11/91	00:00	08:09	8.15	43.90	21.8	6.27	15.0	82.9	1.4	1.8			2.49	6.65	28.20
3B 7	01/12/91	08:09	16:12	8.05	51.95	24.0	6.29	15.5	98.4	1.6	1.9			2.38	9.02	26.01
3B 8	01/12/91	16:12	00:25	8.22	60.17	22.5	6.23	15.5	113.9	1.9	1.9			2.29	11.32	25.09
3B 9	01/13/91	00:25	10:18	9.88	70.05	21.8	6.19	18.1	132.0	2.2	1.8			2.26	13.58	21.22
3B 10	01/13/91	10:18	20:35	10.28	80.33	22.1	6.39	15.7	147.7	2.5	1.5			1.57	15.15	16.94
3B 11	01/13/91	20:35	08:20	11.75	92.08	21.9	6.37	22.0	169.7	2.8	1.9	1450	0.023	1.79	16.94	13.83
3B 12	01/14/91	08:20	21:03	12.72	104.80	22.0	6.34	23.5	193.2	3.2	1.8			1.60	18.54	11.53
3B 13	01/14/91	21:03	08:55	11.87	116.67	20.5	6.19	21.2	214.4	3.6	1.8	1400	0.022	1.16	19.70	9.29
3B 14	01/15/91	08:55	09:30	24.58	141.25	19.1	6.27	43.5	257.9	4.3	1.8			1.89	21.59	7.38
3B 15	01/16/91	09:30	08:30	23.00	164.25	19.0	6.09	40.2	298.1	5.0	1.7	1700	0.027	1.41	23.00	5.93
3B 16	01/17/91	08:30	09:30	25.00	189.25	19.0	6.21	43.1	341.2	5.7	1.7	1700	0.027	0.87	23.86	3.42
3B 17	01/22/91	12:10	12:30	48.33	237.58	20.5	6.15	79.9	421.1	7.0	1.7	1675	0.027	0.45	24.32	0.96
3B 18	01/24/91	12:30	09:30	93.00	330.58	18.0	5.91	155.4	576.5	9.6	1.7	1650	0.026	0.10	24.41	0.11
	01/28/91															
	Avg. Values					21.3	6.37				1.8	1596	0.026			

EXPERIMENT 3 - COLUMN C 0.01 M HPO<sub>4</sub>/0.01 M NaCl

Parameters															Results		
Sampl No.		Date	Start Time	Stop Time	Elapsed	Cumu.	Temp. (C)	pH	Sampl	Cumu.	Pore Vol.	Flow	Spec.	Cr(VI) Removed (mg/kg)	Cumu	Cr(VI)	
					Time (hrs)	Time (hrs)			Vol. (mL)	Vol. (mL)		Rate (mL/hr)	Conduct. (umho/cm)		Removed (mg/kg)	Removed (mg/kg)	Removed (ppm)
3C 1		01/28/91	10:00	16:05	6.08	6.08	20.0	7.70	10.4	10.4	0.2	1.7			0.12	0.12	1.92
3C 2		01/28/91	16:05	23:30	7.42	13.50	20.0	7.02	11.6	22.0	0.4	1.6			0.28	0.40	4.07
3C 3		01/28/91	23:30	08:15	8.75	22.25	17.8	7.02	13.5	35.5	0.6	1.5			0.49	0.89	6.09
3C 4		01/29/91	08:15	16:28	8.22	30.47	19.0	6.65	12.3	47.8	0.8	1.5			0.76	1.65	10.36
3C 5		01/29/91	16:28	23:48	7.33	37.80	19.0	6.65	11.6	59.4	1.0	1.6			1.23	2.87	17.80
3C 6		01/29/91	23:48	08:18	8.50	46.30	17.9	6.43	12.6	72.0	1.3	1.5			2.21	5.09	29.57
3C 7		01/30/91	08:18	16:00	7.70	54.00	18.5	6.47	11.8	83.8	1.5	1.5			2.14	7.23	30.59
3C 8		01/30/91	16:00	23:11	7.18	61.18	19.7	6.48	8.0	91.8	1.6	1.1			1.41	8.64	29.65
3C 9		01/30/91	23:11	07:40	8.48	69.67	19.0	6.26	13.1	104.9	1.8	1.5			2.24	10.88	28.81
3C 10		01/31/91	07:40	16:08	8.47	78.13	21.0	6.45	13.1	118.0	2.1	1.5			2.11	13.00	27.14
3C 11		01/31/91	16:08	23:16	7.13	85.27	22.0	6.42	11.9	129.9	2.3	1.7			1.60	14.60	22.68
3C 12		01/31/91	23:16	08:18	9.03	94.30	21.4	6.48	14.6	144.5	2.5	1.6			1.63	16.23	18.84
3C 13		02/01/91	08:18	22:08	13.83	108.13	21.6	6.42	21.4	165.9	2.9	1.5	1200	0.019	2.03	18.26	15.95
3C 14		02/01/91	22:08	11:15	13.12	121.25	20.0	6.35	20.0	185.9	3.3	1.5	1140	0.018	1.49	19.75	12.54
3C 15		02/02/91	11:15	10:30	23.25	144.50	21.0	6.43	36.0	221.9	3.9	1.5	1180	0.019	2.11	21.87	9.88
3C 16		02/03/91	10:30	09:36	23.10	167.60	20.8	6.27	35.1	257.0	4.5	1.5	1120	0.018	1.24	23.10	5.92
3C 17		02/04/91	09:36	12:39	27.05	194.65	20.8	5.73	41.1	298.1	5.2	1.5	1420	0.023	0.25	23.35	1.02
3C 18		02/05/91	12:39	11:40	47.02	241.67	21.2	5.74	75.3	373.4	6.6	1.6	1500	0.024	0.17	23.53	0.38
3C 19		02/07/91	11:40	10:50	23.17	264.83	20.0	5.89	35.5	408.9	7.2	1.5	1500	0.024	0.03	23.56	0.16
		02/08/91	10:50														
		Avg. Values					20.0	6.50				1.5	1260	0.020			

EXPERIMENT 3 - COLUMN D 0.02 MHPO4/Distilled Water

Parameters												Results				
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
3D 1	01/28/91	10:00	16:05	6.08	6.08	20.0	7.12	8.8	8.8	0.2	1.4			0.01	0.01	0.23
3D 2	01/28/91	16:05	23:30	7.42	13.50	20.0	6.35	11.1	19.9	0.3	1.5			0.21	0.22	3.21
3D 3	01/28/91	23:30	08:15	8.75	22.25	17.8	6.61	12.7	32.6	0.6	1.5			0.45	0.67	5.93
3D 4	01/29/91	08:15	16:28	8.22	30.47	19.0	6.40	11.9	44.5	0.8	1.4			0.68	1.36	9.62
3D 5	01/29/91	16:28	23:48	7.33	37.80	19.0	6.69	10.9	55.4	1.0	1.5			1.31	2.67	20.11
3D 6	01/29/91	23:48	08:18	8.50	46.30	17.9	6.64	11.8	67.2	1.2	1.4			5.26	7.93	74.63
3D 7	01/30/91	08:18	16:00	7.70	54.00	18.5	6.64	10.9	78.1	1.4	1.4			6.83	14.75	104.88
3D 8	01/30/91	16:00	23:11	7.18	61.18	19.7		10.8	88.9	1.6	1.5			4.84	19.59	75.00
3D 9	01/30/91	23:11	07:40	8.48	69.67	19.0	6.99	12.6	101.5	1.8	1.5			3.05	22.64	40.58
3D 10	01/31/91	07:40	16:08	8.47	78.13	21.0	7.25	12.6	114.1	2.0	1.5			1.56	24.20	20.74
3D 11	01/31/91	16:08	23:16	7.13	85.27	22.0	7.33	11.0	125.1	2.2	1.5			0.83	25.04	12.68
3D 12	01/31/91	23:16	11:30	12.23	97.50	21.0	7.30	17.9	143.0	2.5	1.5	140	0.002	0.80	25.84	7.52
3D 13	02/01/91	11:30	11:15	23.75	121.25	20.0	7.17	32.0	175.0	3.1	1.3	80	0.001	0.67	26.51	3.53
3D 14	02/02/91	11:15	10:30	23.25	144.50	21.0	6.16	31.2	206.2	3.6	1.3	400	0.006	0.29	26.80	1.53
3D 15	02/03/91	10:30	13:00	98.50	243.00	21.0	5.88	135.1	341.3	6.0	1.4	740	0.012	0.47	27.26	0.58
	02/07/91	13:00														
	Avg. Values					19.8	6.75				1.4	340	0.005			

EXPERIMENT 3 - COLUMN E 0.01 M PO<sub>4</sub>/0.01 M NaCl

Parameters												Results				
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
3E 1	01/29/91	11:25	16:28	5.05	5.05	19.0	6.73	8.2	8.2	0.1	1.6			0.06	0.06	1.16
3E 2	01/29/91	16:28	23:48	7.33	12.38	19.0	7.20	12.5	20.7	0.3	1.7			0.23	0.28	3.13
3E 3	01/29/91	23:48	08:18	8.50	20.88	17.9	7.33	13.8	34.5	0.6	1.6			0.39	0.67	4.90
3E 4	01/30/91	08:18	16:00	7.70	28.58	18.5	7.57	12.5	47.0	0.8	1.6			0.51	1.19	7.07
3E 5	01/30/91	16:00	23:11	7.18	35.77	19.7	7.56	12.1	59.1	1.0	1.7			0.68	1.87	9.68
3E 6	01/30/91	23:11	07:40	8.48	44.25	19.0	7.48	13.9	73.0	1.2	1.6			2.12	3.99	26.34
3E 7	01/31/91	07:40	16:08	8.47	52.72	21.0	7.51	12.3	85.3	1.4	1.5			2.54	6.53	35.54
3E 8	01/31/91	22:00	08:18	10.30	63.02	21.4	7.00	17.8	103.1	1.7	1.7	940	0.015	3.86	10.38	37.33
3E 9	02/01/91	08:18	22:08	13.83	76.85	21.5	6.86	16.2	119.3	2.0	1.2			2.74	13.12	29.13
3E 10	02/01/91	22:08	11:15	13.12	89.97	20.0	6.71	18.1	137.4	2.3	1.4	1180	0.019	2.28	15.40	21.67
3E 11	02/02/91	11:15	10:30	23.25	113.22	21.0	7.39	12.0	149.4	2.5	0.5			1.22	16.61	17.46
3E 12	02/03/91	10:30	09:36	23.10	136.32	20.8	6.84	27.4	176.8	2.9	1.2	1180	0.019	2.21	18.82	13.88
3E 13	02/04/91	09:36	18:00	32.40	168.72	20.8	6.74	15.4	192.2	3.2	0.5			0.99	19.81	11.08
3E 14	02/05/91	18:00	09:30	15.50	184.22	22.0	7.00	20.1	212.3	3.5	1.3	1300	0.021	1.12	20.93	9.64
3E 15	02/06/91	09:30	11:15	25.75	209.97	21.2	7.00	32.4	244.7	4.1	1.3	1250	0.020	1.39	22.32	7.40
3E 16	02/10/91	16:00	12:34	44.57	254.53	20.0	6.50	56.1	300.8	5.0	1.3	1300	0.021	0.89	23.21	2.73
3E 17	02/12/91	12:34	10:41	46.12	300.65	22.9	5.83	89.1	389.9	6.5	1.9	1250	0.020	0.23	23.44	0.44
3E 18	02/14/91	10:41	12:50	50.15	350.80	21.2	6.14	80.0	469.9	7.8	1.6	1300	0.021	0.14	23.58	0.31
	02/16/91															
						20.4	6.97				1.4	1213	0.019			



EXPERIMENT 3 - COLUMN F HPO<sub>4</sub>/0.01 M NaCl

Parameters											Results					
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
3F 1	02/27/91	08:15	16:00	7.75	7.75	22.5	6.72	16.0	16.0	0.3	2.1			0.11	0.11	1.16
3F 2	02/27/91	16:00	22:30	6.50	14.25	22.5	6.55	14.0	30.0	0.5	2.2			0.38	0.49	4.49
3F 3	02/27/91	22:30	07:10	8.67	22.92	21.0	6.29	17.6	47.6	0.8	2.0	1440	0.023	0.88	1.37	8.32
3F 4	02/28/91	07:10	12:30	5.33	28.25	21.0	6.18	10.7	58.3	1.0	2.0			1.17	2.54	18.10
3F 5	02/28/91	12:30	18:28	5.97	34.22	22.3	6.24	12.3	70.6	1.2	2.1			2.29	4.84	30.93
3F 6	02/28/91	18:28	23:12	4.73	38.95	22.0	6.17	10.0	80.6	1.4	2.1			1.90	6.74	31.59
3F 7	02/28/91	23:12	08:05	8.88	47.83	21.0	6.05	17.1	97.7	1.6	1.9	1040	0.017	3.02	9.76	29.32
3F 8	03/01/91	08:05	15:10	7.08	54.92	22.5	6.22	14.0	111.7	1.9	2.0			2.22	11.98	26.30
3F 9	03/01/91	15:10	23:03	7.88	62.80	22.0	6.15	14.4	126.1	2.1	1.8			2.14	14.12	24.60
3F 10	03/01/91	23:03	09:00	9.95	72.75	21.0	6.23	18.0	144.1	2.4	1.8	1200	0.019	2.30	16.42	21.19
3F 11	03/02/91	09:00	20:37	11.62	84.37	21.5	6.20	21.8	165.9	2.8	1.9	1260	0.020	2.36	18.78	17.98
3F 12	03/02/91	20:37	09:03	12.43	96.80	20.2	6.27	23.2	189.1	3.2	1.9	1250	0.020	1.88	20.67	13.45
3F 13	03/03/91	09:03	08:10	23.12	119.92	20.8	5.77	42.4	231.5	3.9	1.8	1600	0.026	0.63	21.29	2.45
3F 14	03/04/91	08:10	09:50	49.67	169.58	19.0	5.63	86.4	317.9	5.4	1.7	1725	0.028	0.25	21.54	0.48
3F 15	03/06/91	09:50	14:06	52.27	221.85	20.0	5.78	94.8	412.7	7.0	1.8	1650	0.026	0.13	21.67	0.23
	03/08/91	14:06														
Avg. Values						21.3	6.16				1.9	1396	0.022			

EXPERIMENT 4 - COLUMN A 0.01 M NO3/0.01 M NaCl

Parameters													Results				
Sampl No.		Date	Start Time	Stop Time	Elapse Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
4A 1		01/03/91	12:38	23:35	10.95	10.95	21.0	6.25	12.2	12.2	0.2	1.1			0.17	0.17	2.44
4A 2		01/03/91	23:35	08:37	9.03	19.98	19.6	6.53	25.2	37.4	0.6	2.8	950	0.015	1.19	1.36	8.38
4A 3		01/04/91	08:37	16:05	7.47	27.45	19.0	6.60	15.2	52.6	0.8	2.0			1.16	2.52	13.44
4A 4		01/04/91	16:05	23:55	7.83	35.28	20.0	6.40	13.7	66.3	1.0	1.7			1.34	3.86	17.34
4A 5		01/04/91	23:55	09:23	9.47	44.75	15.0	6.23	16.3	82.6	1.3	1.7			1.89	5.75	20.51
4A 6		01/05/91	09:23	17:00	7.62	52.37	21.0	6.28	13.2	95.8	1.5	1.7			1.50	7.25	20.10
4A 7		01/05/91	17:00	23:51	6.85	59.22	18.0	6.21	16.1	111.9	1.7	2.4			1.70	8.95	18.66
4A 8		01/05/91	23:51	09:15	9.40	68.62	18.0	6.19	18.1	130.0	2.0	1.9	1750	0.028	1.70	10.65	16.61
4A 9		01/06/91	09:15	23:14	13.98	82.60	20.0	6.21	24.9	154.9	2.4	1.8			2.00	12.65	14.20
4A 10		01/06/91	23:14	12:30	13.27	95.87	21.0	6.23	25.0	179.9	2.7	1.9	1750	0.028	1.69	14.35	11.96
4A 11		01/07/91	12:30	21:04	8.57	104.43	21.0	6.20	20.4	200.3	3.0	2.4			1.14	15.49	9.90
4A 12		01/07/91	21:04	12:38	15.57	120.00	20.2	6.11	26.8	227.1	3.5	1.7	2050	0.033	1.31	16.80	8.67
4A 13		01/08/91	12:38	09:25	20.78	140.78	19.4	6.10	33.1	260.2	4.0	1.6	1700	0.027	1.40	18.20	7.48
4A 14		01/09/91	09:25	08:30	23.08	163.87	20.7	6.11	51.8	312.0	4.7	2.2	1750	0.028	1.72	19.93	5.89
4A 15		01/10/91	08:30	08:28	23.97	187.83	22.4	6.21	49.8	361.8	5.5	2.1	1700	0.027	1.32	21.25	4.70
4A 16		01/11/91	08:28	08:09	23.68	211.52	21.8	6.23	46.4	408.2	6.2	2.0			0.95	22.20	3.62
4A 17		01/12/91	08:09	10:18	26.15	237.67	21.8	6.32	50.1	458.3	7.0	1.9	1750	0.028	0.82	23.02	2.89
4A 18		01/13/91	10:18	08:20	22.03	259.70	21.9	6.39	53.2	511.5	7.8	2.4	1800	0.029	0.66	23.68	2.18
4A 19		01/14/91	08:20	09:30	49.17	308.87	19.1	6.46	87.3	598.8	9.1	1.8			0.77	24.44	1.56
4A 20		01/16/91	09:30	09:30	48.00	356.87	19.0	6.44	110.5	709.3	10.8	2.3	2150	0.034	0.60	25.04	0.96
4A 21		01/18/91	09:30	12:10	98.67	455.53	18.5	6.48	173.0	882.3	13.4	1.8	1900	0.030	0.55	25.59	0.56
4A 22		01/22/91	12:10	09:30	141.33	596.87	18.0	6.52	223.5	1105.8	16.8	1.6	1900	0.030	0.38	25.97	0.30
4A 23		01/28/91															
		Avg. Values					19.8	6.30				1.9	1763	0.028			

EXPERIMENT 5 - COLUMN A 0.01 M HCO<sub>3</sub>/0.01 M NaCl

Parameters											Results					
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
5A 1	01/05/91	13:15	17:00	3.75	3.75	21.0	7.01	7.0	7.0	0.1	1.9			0.04	0.04	0.94
5A 2	01/05/91	17:00	23:51	6.85	10.60	18.0	6.58	13.8	20.8	0.4	2.0	950	0.015	0.39	0.43	4.79
5A 3	01/05/91	23:51	09:04	9.22	19.82	18.0	6.45	18.0	38.8	0.7	2.0			1.03	1.47	9.60
5A 4	01/06/91	09:04	16:45	7.68	27.50	20.0	6.55	15.0	53.8	0.9	2.0			1.66	3.13	18.58
5A 5	01/06/91	16:45	23:14	6.48	33.98	20.0	6.49	13.0	66.8	1.1	2.0			2.01	5.14	25.93
5A 6	01/06/91	23:14	08:20	9.10	43.08	20.3	6.66	18.0	84.8	1.4	2.0			4.41	9.55	41.06
5A 7	01/07/91	08:20	15:35	7.25	50.33	21.5	6.63	14.8	99.6	1.7	2.0			3.02	12.58	34.22
5A 8	01/07/91	15:35	21:04	5.48	55.82	21.0	6.65	11.2	110.8	1.9	2.0			1.90	14.48	28.40
5A 9	01/07/91	21:04	08:16	11.20	67.02	20.0	6.52	22.1	132.9	2.3	2.0	1280	0.020	1.76	16.24	13.36
5A 10	01/08/91	08:16	20:30	12.23	79.25	21.2	6.53	24.4	157.3	2.7	2.0			1.82	18.06	12.49
5A 11	01/08/91	20:30	09:25	12.92	92.17	19.4	6.67	25.1	182.4	3.1	1.9	1080	0.017	1.34	19.40	8.92
5A 12	01/09/91	09:25	21:09	11.73	103.90	20.9	6.60	23.0	205.4	3.5	2.0			1.00	20.40	7.28
5A 13	01/09/91	21:09	08:30	11.35	115.25	20.7	6.80	22.5	227.9	3.9	2.0	1150	0.018	0.85	21.25	6.32
5A 14	01/10/91	08:30	08:28	23.97	139.22	22.4	7.09	48.9	276.8	4.7	2.0	1200	0.019	1.39	22.64	4.76
5A 15	01/11/91	08:28	08:09	23.68	162.90	21.8	7.12	47.1	323.9	5.5	2.0			0.72	23.36	2.56
5A 16	01/12/91	08:09	10:18	26.15	189.05	21.8	7.20	53.4	377.3	6.4	2.0	1400	0.022	0.43	23.79	1.35
5A 17	01/13/91	10:18	08:20	22.03	211.08	21.9	7.30	45.1	422.4	7.2	2.0	1410	0.023	0.17	23.96	0.63
5A 18	01/14/91	08:20	09:30	49.17	260.25	19.1	7.35	97.8	520.2	8.8	2.0	1400	0.022	0.14	24.09	0.24
5A 19	01/16/91	09:30	11:11	25.68	285.93	19.8	7.49	52.0	572.2	9.7	2.0			0.03	24.12	0.10
	01/17/91															
	Avg. Values					20.5	6.83				2.0	1234	0.020			

EXPERIMENT 5 - COLUMN B 0.001 M HCO<sub>3</sub>/0.01 M NaCl

Parameters											Results					
Sampl No.	Date	Start Time	Stop Time	Elapsed Time (hrs)	Cumu. Time (hrs)	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Pore Vol.	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI) Removed (mg/kg)	Cumu Cr(VI) Removed (mg/kg)	Cr(VI) Removed (ppm)
5B 1	02/27/91	08:00	16:00	8.00	8.00	22.5	7.25	17.3	17.3	0.3	2.2	1340	0.021	0.34	0.34	3.30
5B 2	02/27/91	16:00	22:30	6.50	14.50	22.5	6.76	15.0	32.3	0.5	2.3			0.63	0.97	6.97
5B 3	02/27/91	22:30	07:10	8.67	23.17	21.0	6.42	19.0	51.3	0.9	2.2	1500	0.024	1.24	2.21	10.90
5B 4	02/28/91	07:10	12:30	5.33	28.50	21.0	6.23	11.6	62.9	1.0	2.2			1.57	3.78	22.53
5B 5	02/28/91	12:30	18:28	5.97	34.47	22.3	6.18	13.6	76.5	1.3	2.3			2.70	6.47	33.09
5B 6	02/28/91	18:28	23:12	4.73	39.20	22.0	6.23	10.8	87.3	1.5	2.3			1.97	8.44	30.46
5B 7	02/28/91	23:12	08:05	8.88	48.08	21.0	6.17	19.4	106.7	1.8	2.2	1280	0.020	3.11	11.55	26.73
5B 8	03/01/91	08:05	15:10	7.08	55.17	22.5	6.32	15.8	122.5	2.0	2.2			2.08	13.63	21.92
5B 9	03/01/91	15:10	23:03	7.88	63.05	22.0	6.36	17.7	140.2	2.3	2.2			1.78	15.41	16.80
5B 10	03/01/91	23:03	09:00	9.95	73.00	21.0	6.28	21.8	162.0	2.7	2.2	1280	0.020	1.58	16.99	12.08
5B 11	03/02/91	09:00	20:37	11.62	84.62	21.5	6.31	25.0	187.0	3.1	2.2	1240	0.020	0.97	17.95	6.45
5B 12	03/02/91	20:37	09:03	12.43	97.05	20.2	6.51	26.7	213.7	3.6	2.1	1240	0.020	1.04	18.99	6.50
5B 13	03/03/91	09:03	09:03	24.00	121.05	20.8	6.43	48.5	262.2	4.4	2.0	1260	0.020	1.42	20.41	4.88
5B 14	03/04/91	09:03	09:50	48.78	169.83	19.0	6.63	76.0	338.2	5.6	1.6	1200	0.019	1.52	21.93	3.35
5B 15	03/06/91	09:50	14:23	52.55	222.38	20.0	6.52	112.3	450.5	7.5	2.1			1.41	23.34	2.09
5B 16	03/08/91	14:23	10:45	92.37	314.75	19.8	6.93	140.0	590.5	9.8	1.5			0.86	24.20	1.03
	03/12/91	10:45														
Avg. Values						21.2	6.47				2.1	1293	0.021			

EXPERIMENT 5 - COLUMN C 0.02 m HCO<sub>3</sub>/0.01 M NaCl

Parameters													Results				
Sampl No.		Date	Start Time	Stop Time	Elapsed		Temp. (C)	pH	Sampl	Cumu.	Pore Vol.	Flow Rate (mL/hr)	Spec.	Ionic Strength	Cr(VI)	Cumu Cr(VI)	Cr(VI)
					Time (hrs)	Time (hrs)			Vol. (mL)	Vol. (mL)			Conduct. (umho/cm)		Removed (mg/kg)	Removed (mg/kg)	Removed (ppm)
5C 1		02/27/91	07:50	16:00	8.17	8.17	22.5	7.23	18.1	18.1	0.3	2.2	1600	0.026	0.41	0.41	3.88
5C 2		02/27/91	16:00	22:30	6.50	14.67	22.5	6.97	14.8	32.9	0.5	2.3			0.66	1.07	7.56
5C 3		02/27/91	22:30	07:10	8.67	23.33	21.0	6.69	18.0	50.9	0.8	2.1	1600	0.026	1.14	2.21	10.78
5C 4		02/28/91	07:10	12:30	5.33	28.67	21.0	6.46	11.0	61.9	1.0	2.1			1.38	3.59	21.37
5C 5		02/28/91	12:30	18:28	5.97	34.63	22.3	6.52	12.6	74.5	1.2	2.1			3.28	6.87	44.30
5C 6		02/28/91	18:28	23:12	4.73	39.37	22.0	6.79	9.9	84.4	1.4	2.1			3.00	9.87	51.65
5C 7		02/28/91	23:12	08:05	8.88	48.25	21.0	6.63	17.5	101.9	1.7	2.0			3.88	13.75	37.71
5C 8		03/01/91	08:05	15:10	7.08	55.33	22.5	6.77	14.3	116.2	1.9	2.0			2.17	15.92	25.85
5C 9		03/01/91	15:10	23:03	7.88	63.22	22.0	6.70	15.2	131.4	2.2	1.9			1.74	17.66	19.44
5C 10		03/01/91	23:03	09:00	9.95	73.17	21.0	6.57	19.8	151.2	2.5	2.0	1600	0.026	1.74	19.39	14.92
5C 11		03/02/91	09:00	20:37	11.62	84.78	21.5	6.90	22.6	173.8	2.9	1.9	1600	0.026	1.54	20.93	11.57
5C 12		03/02/91	20:37	09:03	12.43	97.22	20.2	7.13	23.6	197.4	3.2	1.9	1950	0.031	1.05	21.97	7.56
5C 13		03/03/91	09:03	08:10	23.12	120.33	20.8	7.39	43.0	240.4	3.9	1.9	2200	0.035	1.13	23.11	4.49
5C 14		03/04/91	08:10	09:50	49.67	170.00	19.0	7.72	88.9	329.3	5.4	1.8	2300	0.037	1.14	24.25	2.18
5C 15		03/06/91	09:50	14:28	52.63	222.63	20.0	8.06	98.1	427.4	7.0	1.9			0.73	24.98	1.27
5C 16		03/08/91	14:28	10:45	92.28	314.92	19.8	8.01	167.4	594.8	9.8	1.8			0.65	25.62	0.66
		03/12/91	10:45														
		Avg. Values						21.2	7.03			2.0	1836	0.029			

EXPERIMENT 5 - COLUMN D 0.01 M HCO<sub>3</sub>

Parameters													Results				
Sampl No.		Date	Start Time	Stop Time	Elapsed	Cumu.	Temp. (C)	pH	Sampl Vol. (mL)	Cumu. Vol. (mL)	Flow Rate (mL/hr)	Spec. Conduct. (umho/cm)	Ionic Strength	Cr(VI)	Cumu	Cr(VI)	
					Time (hrs)	Time (hrs)								Removed (mg/kg)	Removed (mg/kg)	Removed (ppm)	
5D 1		03/27/91	11:00	17:12	6.20	6.20	21.5	7.55	14.4	14.4	0.2	2.3		0.24	0.24	2.76	
5D 2		03/27/91	17:12	23:12	6.00	12.20	21.5	7.19	14.4	28.8	0.5	2.4		0.49	0.73	5.50	
5D 3		03/27/91	23:12	07:47	8.58	20.78	20.1	6.84	19.7	48.5	0.8	2.3	1675	0.027	1.09	1.83	9.03
5D 4		03/28/91	07:47	12:35	4.80	25.58	20.9	6.67	9.0	57.5	1.0	1.9		1.19	3.01	21.45	
5D 5		03/28/91	12:35	18:08	5.55	31.13	21.7	6.58	12.5	70.0	1.2	2.3		6.00	9.01	78.01	
5D 6		03/28/91	18:08	23:30	5.37	36.50	21.0	6.79	9.6	79.6	1.3	1.8		4.03	13.04	68.34	
5D 7		03/28/91	23:30	07:55	8.42	44.92	19.5	6.94	15.5	95.1	1.6	1.8		3.50	16.55	36.73	
5D 8		04/01/91	09:25	17:20	7.92	52.83	25.0	6.96	16.0	111.1	1.8	2.0		1.97	18.52	20.05	
5D 9		04/01/91	17:20	23:35	6.25	59.08	24.0	6.97	11.7	122.8	2.0	1.9		1.12	19.64	15.61	
5D 10		04/01/91	23:35	09:00	9.42	68.50	21.0	7.08	15.2	138.0	2.3	1.6		1.15	20.80	12.35	
5D 11		04/02/91	09:00	08:57	23.95	92.45	20.7	6.87	45.2	183.2	3.0	1.9	480	0.008	2.69	23.49	9.68
5D 12		04/03/91	08:57	09:00	24.05	116.50	20.9	6.87	44.9	228.1	3.8	1.9	420	0.007	1.19	24.68	4.30
5D 13		04/04/91	09:00	09:05	24.08	140.58	21.0	6.87	47.1	275.2	4.6	2.0	450	0.007	0.75	25.42	2.58
5D 14		04/05/91	09:05	12:45	75.67	216.25	19.8	7.49	140.1	415.3	6.9	1.9	610	0.010	1.02	26.44	1.18
5D 15		04/08/91	12:45	10:50	94.08	310.33	19.7	7.41	155.0	570.3	9.4	1.6	740	0.012	0.52	26.96	0.55
5D 16		04/12/91	10:50	11:30	96.67	407.00	20.6	7.58	186.5	756.8	12.5	1.9		0.29	27.25	0.25	
		04/16/91	11:30														
		Avg. Values					21.2	7.04			2.0	729	0.012				