

**Bench-Scale Treatability Report of the EnviroMetal Process  
at the BSB Site in Kent, Washington**

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## 1.0 INTRODUCTION AND BACKGROUND

This bench-scale test report was prepared for EMCON, as part of the initial evaluation of the use of the EnviroMetal Process for treatment of dissolved volatile organic compounds (VOCs) present in groundwater at the BSB Diversified Site, Kent, Washington (the "site"). This report presents the procedures, results and data interpretation of a column test conducted at the Institute for Groundwater Research, University of Waterloo (UW), Waterloo, Ontario, Canada, under contract to EnviroMetal Technologies Inc. (ETI).

### 1.1 Background Information on the EnviroMetal Process

As a consequence of the significant limitations of pump-and-treat systems, *in-situ* permeable reactive barriers (PRBs) have been identified as an innovative alternative groundwater remediation technology (Gillham, 1996; O'Hannesin and Gillham, 1998). The concept involves the construction of a permeable wall or barrier, containing appropriate reactive materials, across the path of a contaminant plume. As the contaminated groundwater passes through the wall, the contaminants are removed through chemical or physical processes. Various configurations of *in-situ* treatment systems have been evaluated, based on site-specific conditions. Advantages of *in-situ* reactive barriers include:

- conservation of groundwater resources
- long-term passive treatment
- absence of waste materials requiring treatment or disposal
- absence of invasive surface structures and equipment
- low operations and maintenance costs

Several types of materials have been suggested for use in *in-situ* treatment zones. The most advanced stage of application has been achieved with systems using zero-valent iron to degrade chlorinated organic compounds. Under highly reducing conditions and in the presence of metallic surfaces, certain dissolved chlorinated organic compounds in groundwater degrade to non-toxic products such as ethene, ethane and chloride (Gillham and O'Hannesin, 1994). The process is abiotic reductive dehalogenation, with the metal serving to lower the solution redox potential (Eh) and as the electron source in the reaction. Using iron as the reactive metal, reaction half-lives (the time required to degrade one half of the original contaminant mass) are commonly several orders of magnitude lower than those measured under natural conditions. The technology is particularly attractive for the

remediation of contaminated groundwater because of the high rates of degradation, the iron is relatively inexpensive, the process requires no external energy supply and because most compounds are degraded with production of few, if any, hazardous (chlorinated) organic by-products.

Since 1994, thirty-seven PRBs containing granular iron have been installed to remediate volatile organic compounds (VOCs) throughout the United States, Europe and Australia. There are currently 22 *in-situ* full scale systems removing VOCs from groundwater, in addition to 15 pilot-scale systems which have been installed to provide “proof of concept” data and more recently to demonstrate innovative construction methods.

## **1.2 Approach to Technology Implementation at the BSB Site in Kent, Washington**

The EnviroMetal process has been proposed as an *in-situ* treatment alternative to degrade VOCs in groundwater at the BSB Site. When viewed in the context of previous successful applications, the BSB Site appears quite amenable to treatment using this technology:

- (1) the primary VOCs present, trichloroethene and *cis* 1,2-dichloroethene, have been successfully treated at other sites.
- (2) the inorganic chemistry of the plume appears to pose no significant impediment to technology application.

Several design parameters need to be addressed and quantified in order to apply the EnviroMetal process in the field, and to determine its cost-competitiveness with other treatment technologies. The bench-scale test was initiated to provide design parameters (VOC degradation rates) for use in the design of the treatment system. Specifically, the following factors need to be investigated to facilitate field implementation of a treatment system at the site:

- i) The degradation rates of chlorinated VOCs present in site groundwater. Degradation rates determined using site groundwater allow refinement of the degradation rates and resulting residence time. This residence time within the iron treatment zone will provide the time for the VOCs to achieve the regulated cleanup criteria.

- ii) The production and subsequent degradation rates of chlorinated compounds produced from the VOCs originally present in the site groundwater (e.g., dichloroethene isomers and vinyl chloride from trichloroethene). These can also affect the dimensions of the treatment system.
- iii) The volume of iron material required. This volume is based on the concentrations of VOCs present in groundwater entering the treatment zone and potential breakdown products, removal/degradation rates and groundwater flow velocity.
- iv) The effects of the process on the inorganic chemistry of the groundwater, in particular, the potential for mineral precipitation. Mineral precipitates could affect the long-term operations and maintenance (O&M) requirements of the treatment system.

### **1.3 Bench-Scale Test Report Organization**

The remainder of this report is organized as follows:

- Section 2.0 presents the detailed objectives and methods for the bench-scale test.
- Section 3.0 presents the organic and inorganic bench-scale test results.
- Section 4.0 discusses the calculated residence time required to meet the target levels.
- Section 5.0 summarizes the results.

## 2.0 BENCH-SCALE TEST OBJECTIVES AND METHODS

### 2.1 Bench-Scale Test Objectives

The primary objective of the bench-scale test was to provide the data necessary to determine the required residence time to degrade the VOCs present (and their chlorinated breakdown products) in groundwater at the BSB Site in Kent, Washington to below their regulatory criteria. Samples collected during the laboratory column test were used to evaluate the following specific objectives:

- determine degradation rates of VOCs in site groundwater using granular iron;
- characterization of chlorinated breakdown products, and evaluation of the rates of degradation of these products;
- magnitude of Eh and pH changes; and
- changes in inorganic geochemistry as a result of the pH and Eh changes, including possible mineral precipitation.

### 2.2 Bench-Scale Test Methods

The granular iron used in the test was obtained from Connelly-GPM, Inc. of Chicago, Illinois (a commercial granular iron source). The grain size of the iron ranged from 2.0 to 0.25 mm (–8 to +50 mesh, US Standard Sieve Mesh No.). The specific surface area was 1.1 m<sup>2</sup>/g determined by the BET method (Brunauer et al., 1938) on a Micromeretic Gemini 2375 surface analyzer. A hydraulic conductivity value of 5.0 x 10<sup>-2</sup> cm/sec (143 ft/day) was obtained using a falling head permeameter test.

The column was constructed of Plexiglas™ with a length of 1.64 ft (50 cm) and an internal diameter of 1.5 in (3.8 cm). Seven sampling ports were positioned along the length at distances of 0.08, 0.16, 0.33, 0.5, 0.66, 1.0 and 1.3 ft from the inlet end. The column also allowed for the collection of samples from the influent and effluent solutions (Figure 1). Each sampling port consisted of a nylon Swagelok fitting (1/16 in) tapped into the side of the column, with a syringe needle (16G) secured by the fitting. Glass wool was placed in the

needle to exclude the iron particles. The sampling ports allowed samples to be collected along the central axis of the column. Each sample port was fitted with a Luer-Lok™ fitting, such that a glass syringe could be attached to the port to collect a sample. When not in operation the ports were sealed by Luer-Lok™ plugs.

The column was packed with 100% granular iron. To assure a homogeneous mixture, aliquots of iron material were packed vertically in lift sections within the column. Values of bulk density, porosity, and pore volume were determined by weight (Table 1). The column experiment was performed at room temperature.

An Ismatec™ IPN pump was used to feed the site water from a collapsible Teflon® bag to the influent end of the column. The pump tubing consisted of Viton®, and all the other tubing was Teflon® (1/8-inch OD x 1/16-inch ID). A flow velocity of 1.8 ft/day (55 cm/day) was selected in consultation with EMCON to allow the tests to be completed within a reasonable time length.

### **2.2.1 Groundwater Shipment and Storage**

Groundwater was collected from the pump and treat system (HYR-1) by EMCON and shipped to UW in 8 (4L) amber sample bottles with no headspace. The site water was stored at 4°C until required, at which time it was siphoned from the sample bottles into a collapsible Teflon® bag. As noted in Appendix A by reservoir number (RN), all the site water could not be held in the collapsible bag and thus the reservoir had to be filled twice [a-b] over the course of the test. Water was analyzed immediately upon arrival at UW for select VOCs, using the methods described in Section 2.3. The VOCs that were detected included trichloroethene (TCE), cis 1,2-dichloroethene (cDCE), and vinyl chloride (VC) with concentrations of about 3200, 5000 and 700 µg/L, respectively. Trace amounts of 1,1-dichloroethene (11DCE) and trans 1,2-dichloroethene (tDCE) were also detected.

Over the duration of the test, a beige organic floc or precipitate formed within the reservoir, hence the VC concentration declined from an initial value of 500 to <100 µg/L from 18 to 26 pore volumes as shown in Appendix A. It was believed that the VC possibly degraded or sorbed onto the organic floc or precipitate. Due to this decrease in VC concentration, VC was added to the influent reservoir at a similar concentration to the initial reservoir.



## 2.2.2 Sampling and Analysis

The column was sampled periodically over time until steady state concentration profiles were achieved. In the bench-scale tests, steady state is defined as the time when VOC concentration versus distance profiles do not change significantly between sampling events (Appendix A). After removing the stagnant water from the sampling needle, 2.0 to 3.0 mL samples were collected from the sampling ports using glass on glass syringes, transferred to glass sample bottles, and analyzed immediately (no holding time). Samples for organic analyses, redox potential (Eh) and pH measurements were collected from each port as well as from the influent solution and the effluent overflow bottles (Appendix A). Samples for inorganic analyses were obtained from the influent solution and the effluent overflow bottles as steady state conditions were approached (Appendix B).

## 2.3 Analytical Methods

### 2.3.1 Organic Analyses

The less volatile halogenated organics such as TCE, was extracted from the water sample within the glass sample bottle using pentane with an internal standard of 1,2-dibromoethane, at a water to pentane ratio of 2.0 to 2.0 mL. The sample bottles were placed on a rotary shaker for 10 minutes to allow equilibration between the water and the pentane phases, then the pentane phase was transferred to an autosampler bottle. Using a Hewlett Packard 7673 autosampler, a 1.0  $\mu\text{L}$  aliquot of pentane with internal standard was automatically injected directly into a Hewlett Packard 5890 Series II gas chromatograph. The chromatograph was equipped with a Ni<sup>63</sup> electron capture detector (ECD) and DB-624 megabore capillary column (30 m x 0.538 mm ID, film thickness 3  $\mu\text{m}$ ). The gas chromatograph had an initial temperature of 50 °C, with a temperature time program of 15 °C/minute reaching a final temperature of 150 °C. The detector temperature was 300 °C. The carrier gas was helium and makeup gas was 5% methane and 95% argon, with a flow rate of 30 mL/min.

For the more volatile compounds such as the DCE isomers and VC, 3.0 mL samples were collected in glass on glass syringes and placed in 10 mL Teflon<sup>®</sup> faced septa crimp cap vials, creating a headspace with a ratio of 7.0 mL headspace to 3.0 mL aqueous sample. The samples were placed on a rotary shaker for 15 minutes to allow equilibration between the water and gas phase. Using a Hewlett Packard 7694 headspace auto sampler, a 1 mL stainless steel sample loop injected the samples directly onto a Hewlett Packard 5890 Series II gas

chromatograph. The chromatograph was equipped with a HNU photoionization detector (PID) with a bulb ionization potential of 10.2 eV. The gas chromatograph was fitted with a fused silica capillary NSW-PLOT column (15 m x 0.53 mm ID). The samples were placed in the analyzer oven for 2 minutes at 75°C, and subsequently injected onto the gas chromatograph. The temperature program was 160°C for 5.5 minutes, then increased at 20°C/min to 200°C and held for 5.5 minutes. The injector and detector temperatures were 100°C and 120°C, respectively. The carrier gas was helium with a flow rate of 5.5 mL/min. Data was collected with a Pentium 166 computer using HP-Chemstation Version 5.04.

Method detection limits (MDL) were determined for each compound as the minimum concentration of a substance that can be identified, measured and reported with 99% confidence that the analyte concentration is greater than zero. The MDLs were determined from analysis of samples from a solution matrix containing the analytes of interest. Although MDLs are reported, these values are not subtracted from any reported VOC concentrations (Appendix A). The reason for this is that it indicates that the organic concentrations are approaching or advancing within the column, and is helpful when determining degradation rates. Detection limits for all compounds, as given in Table 2, were determined using the EPA procedure for MDL (US EPA, 1982).

### 2.3.2 Inorganic Analyses

Eh was determined using a combination Ag/AgCl reference electrode with a platinum button and a Markson™ Model 90 meter. The electrode was standardized with ZoBell™. Millivolt (mV) readings were converted to Eh, using the electrode reading and the standard potential of the Ag/AgCl electrode at a given temperature. The pH measurements were made using a combination pH/reference electrode and a Markson™ Model 90 meter, standardized with the pH buffer 7 and the appropriate buffer of either 4 or 10. A 2.0 mL sample was collected with a glass on glass syringe and analyzed immediately for Eh and then pH.

Over the course of the test, two water samples were collected from the influent and two from the effluent of the column, and sent to Philip Services, Mississauga, Ontario for cation and anion analyses (Appendix B). Cation analyses, included Fe (total), Na, Mg, Ca, K, Mn and a suite of other cations. These analyses were performed using inductively coupled plasma (ICP). The unfiltered, 60 mL samples were acidified to a pH of 2 with nitric acid and stored at 4 °C until analyzed. Anion analyses, including Cl, NO<sub>3</sub> and SO<sub>4</sub>, were performed using ion chromatography on 60 mL unfiltered samples. Alkalinity (as mg CaCO<sub>3</sub>/L) in water was

determined by colorimetry. Detection limits (DL) for the inorganic parameters are included in Table 2.

### 3.0 BENCH-SCALE TEST RESULTS

#### 3.1 Degradation of Volatile Organic Compounds

Samples for measurement of VOC concentrations along the length of the column were taken approximately every 7 to 10 pore volumes (Appendix A). Although respiking of the influent reservoir caused some variation in the VC influent concentrations during the test, this did not affect interpretation of test results as influent concentrations are monitored at each sampling event. The results obtained when steady state conditions were reached are plotted as VOC concentration ( $\mu\text{g/L}$ ) versus distance along the column (ft). The profiles of most interest are the steady state concentration profiles, collected at the end of the measurement period (46 pore volumes).

Steady state concentration profiles are shown in Figures 2-4. At a flow velocity of 1.8 ft/day (55 cm/day), a total of 46 pore volumes of water had passed through the column. In this case, one pore volume corresponds to a residence time of about 22 hr. Steady declines in concentration were observed for both TCE and cDCE (Figure 2). A steady decline in TCE concentration was observed from an initial value of 2,333  $\mu\text{g/L}$  to non-detectable values at the 0.66 ft distance. The cDCE concentration profile showed an initial increase in concentration from a value of 3,607  $\mu\text{g/L}$  to a peak value of 3,864  $\mu\text{g/L}$  at the 0.08 ft distance (Figure 2). This initial increase in cDCE was attributed to the dechlorination of TCE. From this peak value, a gradual decline in concentration was observed along the column, with non-detectable values at distances of 1.0 , 1.3 and 1.6 ft. Figure 3 shows a gradual decline in VC concentration, from an initial value of 743  $\mu\text{g/L}$  to non-detectable values at the 1 ft distance and for the remainder of the column. Trace amounts of tDCE and 11DCE were observed along the column profile at distances up to 0.16 and 0.33 ft respectively, followed by non-detectable values.

Using the flow velocity, the distance along the column was converted to time and the degradation rate constants were calculated for each VOC in the influent solution groundwater, using the first-order kinetic model:

$$C = C_0 e^{-kt} \quad (1)$$

where: C = VOC concentration in solution at time,  
C<sub>o</sub> = VOC concentration of the influent solution,  
k = first-order rate constant, and  
t = time.

For the VOCs, C<sub>o</sub> is the concentration of the compound in the influent solution at steady state (Table 3). By rearranging and taking the natural log (ln), equation (1) becomes:

$$\ln(C/C_o) = -kt \quad (2)$$

The time at which the initial concentration declines by one-half, (C/C<sub>o</sub> = 0.5), is the half-life (t<sub>1/2</sub>), which, by rearranging equation (2), is given by:

$$t_{1/2} = 0.693/k \quad (3)$$

The decay constants k [1/time], were computed from the slope of the first-order model, obtained by fitting equation 2 to the experimental data. Half-lives, along with corresponding correlation coefficients (r<sup>2</sup>) values are provided in Table 3. The r<sup>2</sup> values indicate how well the first-order model represents the experimental data.

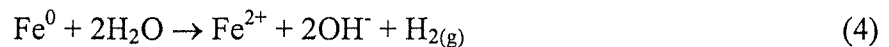
The first-order decay model provided good fits to the TCE, cDCE and VC data, with r<sup>2</sup> values greater than 0.88 (Appendix A). The laboratory half-lives calculated for TCE and VC were 0.9 and 1.5 hr, respectively. Due to the initial increase in cDCE concentrations, the half-life was calculated by setting the initial concentration (C<sub>o</sub>) equal to the peak concentration. This resulted in a half-life calculation of 1.2 hr. These half-lives were quite consistent over several column profiles at steady state (Appendix A).

### 3.2 Inorganic Results

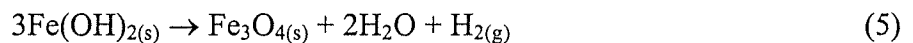
Figure 4 shows the Eh and pH profiles observed at steady state. The Eh profile showed reducing conditions, decreasing from an initial value of +260 to about -283 mV within the granular iron, while pH increased from values of 7.4 to 9.4 (Appendix A).

Two influent and effluent samples were collected from the column as steady state approached (Appendix B). Changes in inorganic chemical constituents observed in the influent and effluent groundwater are summarized in Table 4. Comparison of column influent and effluent results show that concentrations of sodium, potassium, manganese, sulphate, ammonia, nitrate and chloride remained relatively unchanged. Decreases in calcium, magnesium, silica, dissolved organic carbon and alkalinity were observed in the column effluent.

Total iron concentrations decreased from an influent value of 1.2 mg/L to an effluent value of 0.02 mg/L as the groundwater passed through the iron material. Typically, total iron concentrations increase slightly in the iron zone. Independent corrosion rate measurements of metallic iron (Reardon, 1995) indicate that several mmol/L  $\text{Fe}^{2+}$  would be introduced to groundwater as a result of iron corrosion.



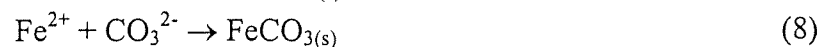
Since the total iron concentration decreased within the column, it appears that very few iron precipitates were forming in the column. Iron minerals which form could include iron carbonate (siderite,  $\text{FeCO}_3$ ) and/or iron hydroxide ( $\text{Fe}(\text{OH})_2$ ). Some iron hydroxides may be converted over time to iron oxide (magnetite,  $\text{Fe}_3\text{O}_4$ ) (Odziemkowski et al., 1998):



Calcium concentrations decreased from 17 mg/L in the influent to 4 mg/L in the effluent. A corresponding decrease in alkalinity from 179 to 93 mg/L was observed as the water passed through the iron. Declines in calcium, magnesium and alkalinity concentrations occur in response to increasing pH values due to the corrosion of iron (Equation 4). Typically, as pH increases to values of about 9.5 in the iron treatment zone, bicarbonate ( $\text{HCO}_3^-$ ) in solution converts to carbonate ( $\text{CO}_3^{2-}$ ) to buffer the pH increase:



The carbonate then combines with cations ( $\text{Ca}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Mg}^{2+}$ , etc.) in solution to form mineral precipitates:





where:  $f$  = mole fraction  
 $k$  = first-order rate constant

In order to determine the VOC concentrations at a given time the following first-order equations are used:

$$dPCE / dt = -k_{PCE}PCE \quad (10)$$

$$dTCE / dt = f_{PCE1}k_{PCE}PCE - k_{TCE}TCE \quad (11)$$

$$dcDCE / dt = f_{PCE2}k_{PCE}PCE + f_{TCE1}k_{TCE}TCE - k_{cDCE}cDCE \quad (12)$$

$$dVC / dt = f_{PCE3}k_{PCE}PCE + f_{TCE2}k_{TCE}TCE + f_{cDCE}k_{cDCE}cDCE - k_{VC}VC \quad (13)$$

These equations can be used directly in Scientist<sup>®</sup> which can perform the integration, or their integrated form may also be used. As an example, integration of equation 10 yields the more familiar form of the first-order equation for parent compounds:

$$PCE = PCE_0 e^{-k_{PCE}t} \quad (14)$$

where:  $t$  = time  
 $PCE$  = PCE concentration at time  $t$   
 $PCE_0$  = PCE concentration at  $t = 0$

Figure 6 gives the molar quantities of a parent compound converted to a degradation product by the model.

Laboratory half-lives established at room temperature (23°C) must be adjusted to the field groundwater temperature (10°C). Previous laboratory and field experience has shown that bench-scale half-lives should be increased to account for field effects including temperature. If it is assumed that the operating (groundwater) temperature will not fall substantially below 10 °C, it is reasonable to increase the effective half-lives by a factor of two.

Figures 7 and 8 show the simulation results using half-lives adjusted for lower groundwater temperature. Based on results of the geoprobe investigation along the proposed line of installation conducted by EMCON, VOC concentrations typical of those anticipated to reach the treatment wall were used in the model. Results of the geoprobe sampling suggest that VOC concentrations vary along the line of installation. Therefore, high and low concentration

scenarios were simulated (Table 5). The highest VOC concentrations were observed to exist in geoprobe boring 13 (GP-13), while the lowest concentrations were observed in GP-12.

Assuming the VOCs require treatment to MCLs (maximum contaminant levels), the residence time required in a field-scale treatment system would be about 1.4 days (34 hr) using the field anticipated high concentration scenario and 0.8 days (20 hr) using the low concentration scenario. Therefore, along the proposed line of installation, the residence time required can range between 1.4 and 0.8 days. During the design phase, further simulations can be undertaken to incorporate variations in concentration distribution both vertically and along the line of installation.

#### **4.2 Possible Effect of Precipitation on Field-Scale Performance**

The rise in pH as a result of corrosion of the iron typically causes the precipitation of carbonate minerals such as calcium carbonate and iron carbonate (siderite), and at pH values in the range of 9 to 10, iron will precipitate as iron hydroxide. Concern has been expressed regarding the potential for these precipitates to reduce the activity of the iron and/or to reduce the permeability through pore clogging. Experience to date indicates calcium carbonate to represent by far the largest volume of precipitates, and also indicates that precipitates have only minor effect on the activity of the iron.

Recent core analyses from pilot-scale systems in New York and Colorado revealed porosity losses in the upgradient few inches of iron in the range of 10% of the initial porosity, with losses declining sharply over the first foot to below 2% (Vogan et al., 1998). These porosity losses were calculated based on carbonate analyses of iron material retrieved by coring the treatment zone. The porosity loss measured in the core samples was consistent with that predicted on the basis of changes in the inorganic water chemistry. Assuming an initial porosity of 0.5, the porosity after 18 months (Colorado) to 2 years (New York) in the first few inches of the iron zones had declined to about 0.45. Concurrent field data (VOC and groundwater velocity measurements) indicated that system hydraulics and iron reactivity had not been adversely affected by the precipitates. A commercial system in Sunnyvale, CA (Szerdy et. al., 1996) has also been performing consistently for over 4.5 years. Groundwater at this site exhibits TDS in the range of 1,000 to 3,500 mg/L. No significant precipitates were observed in cores from an in situ reactive wall at the University of Waterloo Borden test site two and four years after it was installed (O'Hannesin and Gillham, 1998). This wall



performed consistently over a 5 year period, with the expectation that it would continue to perform for at least another five years with no maintenance.

### 4.3 Potential for Biofouling of Reactive Material

There was no evidence of biofouling (sliming, etc.) observed during the treatability studies. Field tests to date from other sites have been encouraging. Cores of the reactive wall at the Borden test site (O'Hannesin and Gillham, 1998), collected two years after the wall was installed, showed no significant population of iron oxidizing microbes, and only low numbers of sulphate reducers (Matheson and Tratnyek, 1994). Phospholipid-fatty acid analysis of groundwater from an above-ground test reactor at an industrial facility in California and an *in-situ* site in New York showed no enhanced microbial population in the reactive material relative to background groundwater samples

Core samples from the two sites described above were also analyzed for microbial population. The results indicated no evidence of increased microbial growth or fouling in the iron zone.

## 5.0 SUMMARY

Bench-scale testing using groundwater from the BSB Site, Kent, Washington showed that:

- i) the EnviroMetal Process will degrade the chlorinated VOCs present to below MCLs;
- ii) rates of VOC degradation were consistent with those measured in previous studies;
- iii) a residence time ranging from about 0.8 to 1.4 days should be adequate to reduce the influent VOC concentrations in the groundwater to below MCLs;
- iv) minimal mineral precipitates (mainly carbonates) will likely occur in a field-scale *in-situ* treatment system. These should not significantly affect system performance for many years.

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**Table 1: Column and Iron Properties**

---

**Iron:**

Source	Connelly-GPM., Chicago, IL
Grain Size	2.0 to 0.25 mm (-8 to +50 mesh)
Surface Area	1.1 m <sup>2</sup> /g
Hydraulic Conductivity	5.0 x 10 <sup>-2</sup> cm/sec (143 ft/day)

---

**Column:**

Flow Velocity	55 cm/day (1.8 ft/day)
Residence Time	22 hr
Pore Volume	338 mL
Porosity	0.59
Bulk Density	2.80 g/cm <sup>3</sup> (175 lb/ft <sup>3</sup> )
Iron to Volume of Solution Ratio	4.7 g : 1 mL
Surface Area to Volume of Solution Ratio	5.2 m <sup>2</sup> : 1 mL

---

**Table 2: Method Detection Limits (MDL) and Detection Limits (DL)**

---

<b>Organic Compounds:</b>	<b>MDL (µg/L)</b>
Tetrachloroethene	0.7
Trichloroethene	0.9
cis 1,2-Dichloroethene	1.4
trans 1,2-Dichloroethene	1.8
1,1-Dichloroethene	2.0
Vinyl Chloride	2.6
<b>Inorganic Compounds</b>	<b>DL (mg/L)</b>
Calcium	0.05
Iron, Total	0.01
Magnesium	0.05
Manganese	0.005
Potassium	1.0
Silica, Reactive	0.05
Sodium	0.10
Ammonia	0.02
Nitrate	0.2
Chloride	0.5
Sulphate	0.5
Alkalinity (as CaCO <sub>3</sub> )	3.0
Total Dissolved Solids (Calculated)	4.0
Dissolved Organic Carbon (DOC)	0.2

---

**Table 3: Bench-Scale Test Half-Lives at Steady State for the BSB Site, Kent, Washington**

Compound	Influent Concentration ( $\mu\text{g/L}$ )	Laboratory Half-Life (hr)	$r^2$
Trichloroethene (TCE)	2,333	0.9	0.893
cis 1,2-Dichloroethene (cDCE)	3,607 3,864 <sup>a</sup>	1.2	0.894
Vinyl Chloride (VC)	743	1.5	0.875

$r^2$  = Correlation Coefficient

<sup>a</sup> Half-life determined from peak concentration

**Table 4: Column Influent and Effluent Inorganic Concentrations at Steady State, BSB Site, Kent, Washington**

	Concentration (mg/L)	
	Influent	Effluent
<b>Cations:</b>		
Calcium	17	4.0
	16	5.0
Iron, Total	1.2	0.02
	0.34	0.02
Magnesium	13	2.2
	12	5.7
Manganese	0.313	<0.005
	<0.005	0.045
Potassium	7.0	7.0
	7.0	5.0
Silica, Reactive	25	0.47
	23	0.46
Sodium	73	71
	73	75
Ammonia	1.9	1.9
	1.7	0.03
<b>Anions:</b>		
Chloride	40	41
	35	47
Sulphate	21	19
	19	2.9
Alkalinity (as mg CaCO <sub>3</sub> /L)	179	93
	180	122
Nitrate	<0.2	0.2
	<0.2	0.2
Dissolved Organic Carbon	7.4	3.1
	7.8	2.8
Total Dissolved Solids	278	199
	271	213

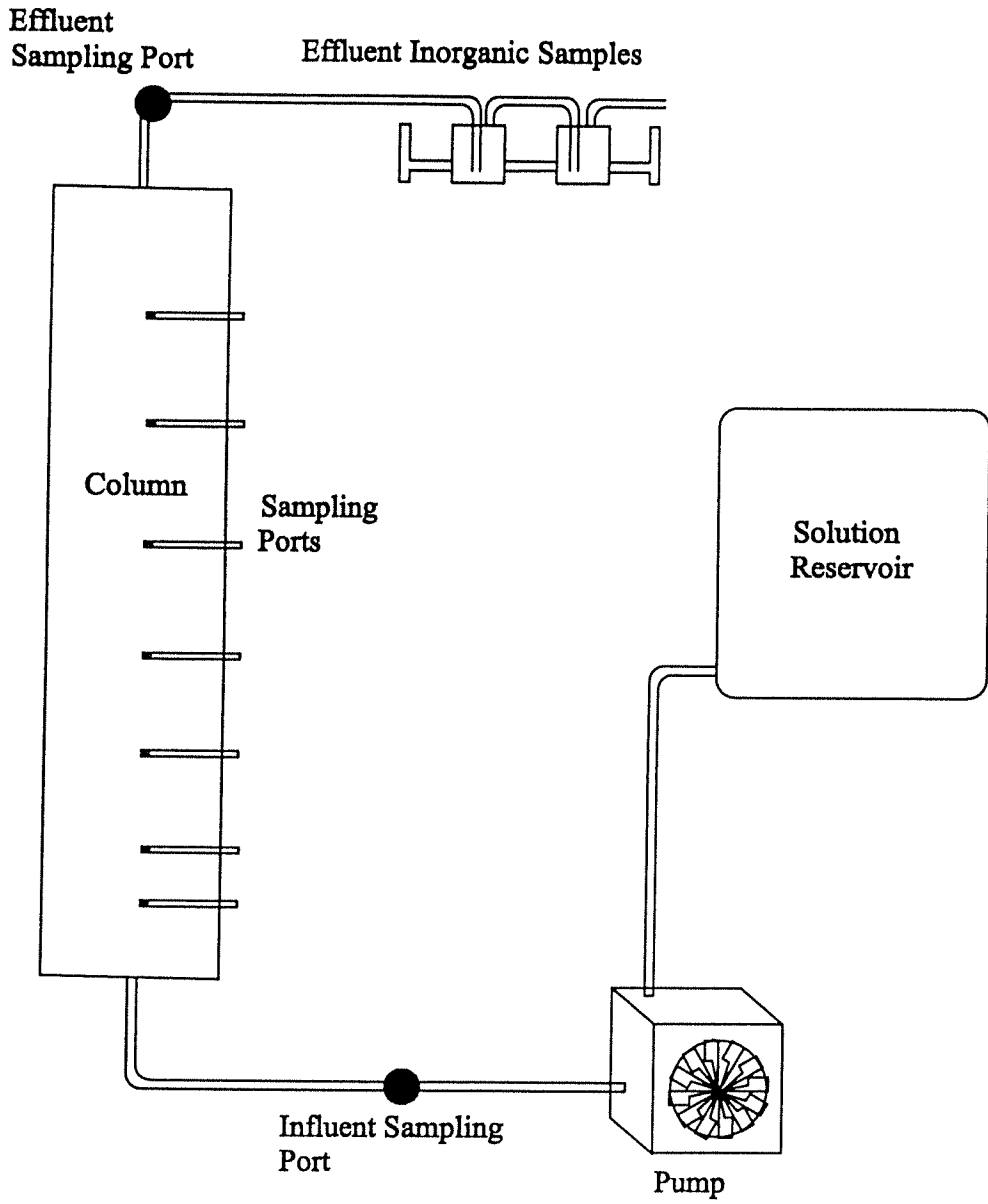
ND = not detected

**Table 5: Design Parameters, BSB Site, Kent, Washington**


VOC	Anticipated Field Conc <sub>n</sub> (µg/L)		MCLs (µg/L)	Laboratory Half Life (hr)	Field Anticipated Half Life (hr)	Residence Time (hr)	
	High Conc <sub>n</sub> Scenario	Low Conc <sub>n</sub> Scenario				High Conc <sub>n</sub> Well	Low Conc <sub>n</sub> Well
TCE	460	0.5	5	0.9	1.8	34	20
cDCE	13000	420	70	1.2	2.4		
VC	3600	180	2	1.5	3.0		
11DCA	84	2.0	800	--	--	Not included in simulation.	

MCLs = Maximum Contaminant Levels





**Schematic of the Apparatus Used in the Bench Scale Test**

 envirometal technologies inc.	<b>Figure 1</b>	1999
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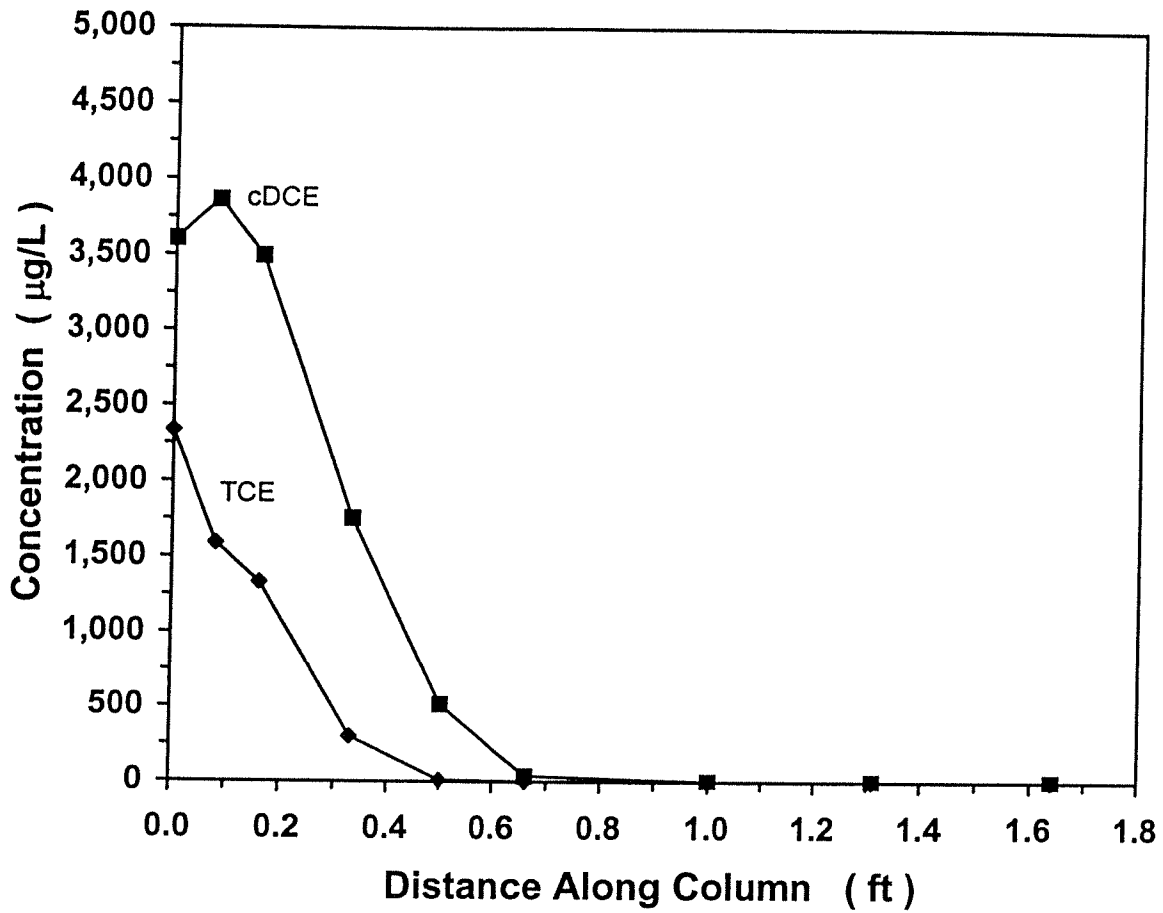


Figure 2: Steady state TCE and cDCE concentration profiles versus distance along the bench-scale column.

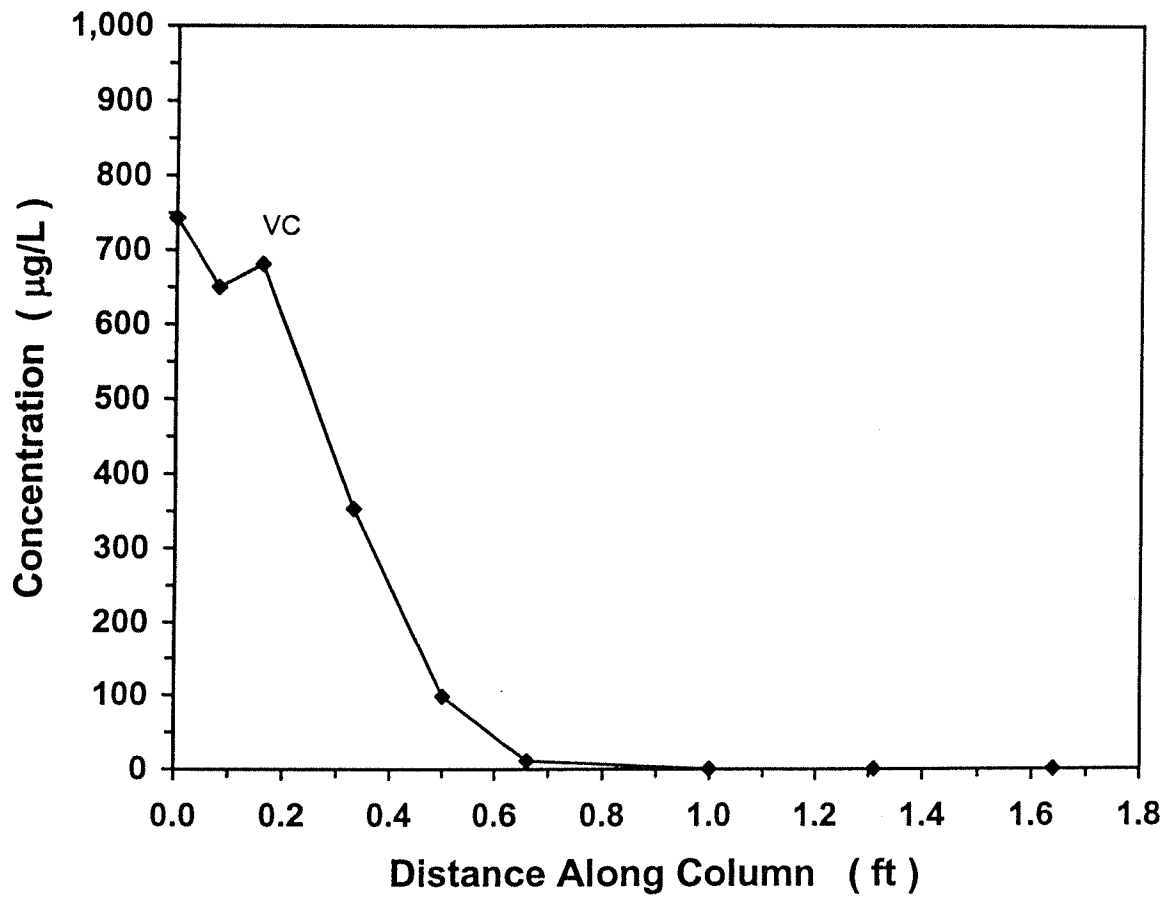


Figure 3: Steady state VC concentration profile versus distance along the bench-scale column.

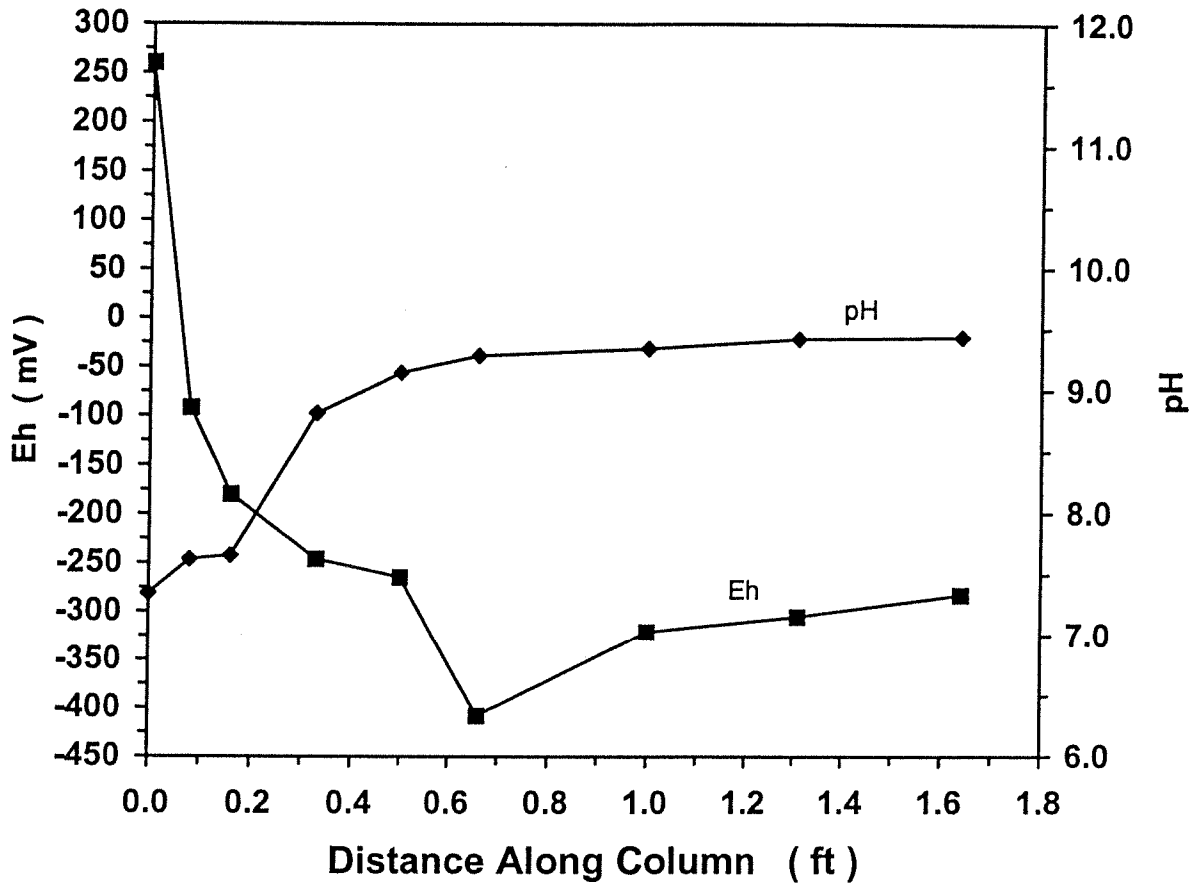


Figure 4: Steady state Eh/pH profiles versus distance along the bench-scale column.

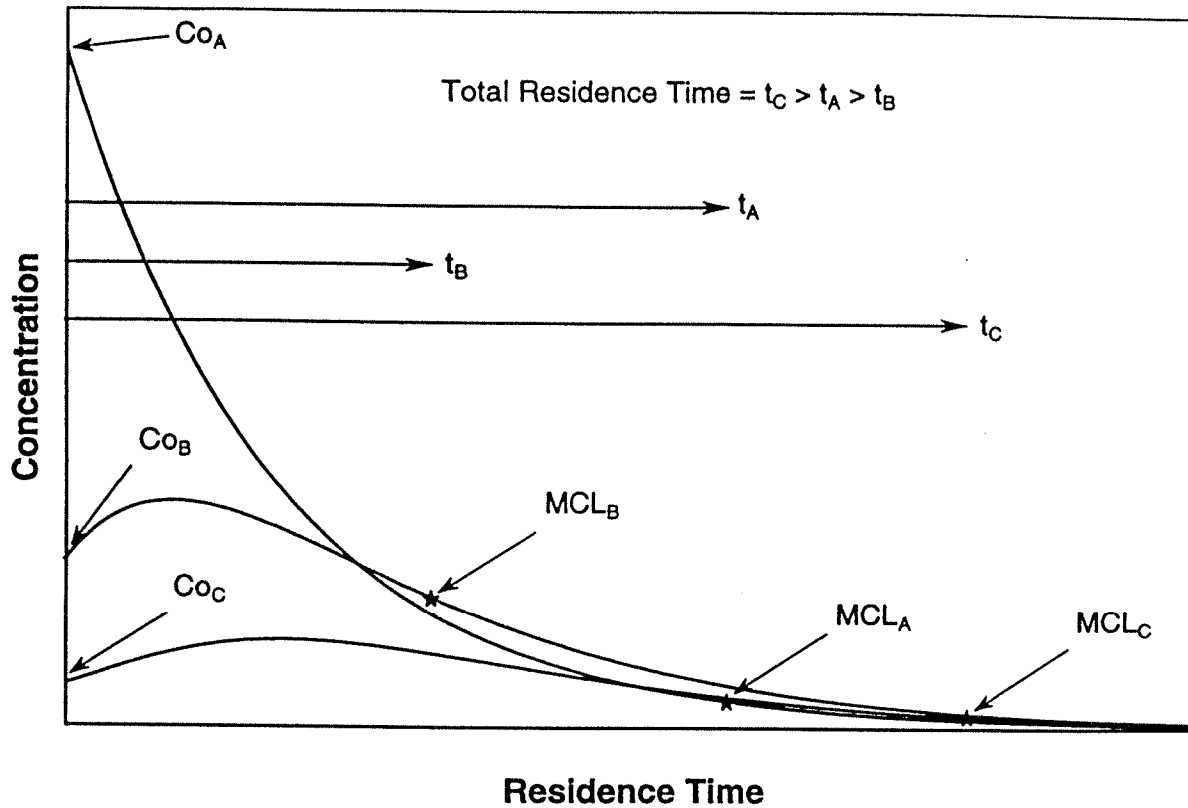


Figure 5: Illustration of residence time calculations using a first-order kinetic model assuming concurrent and sequential degradation.

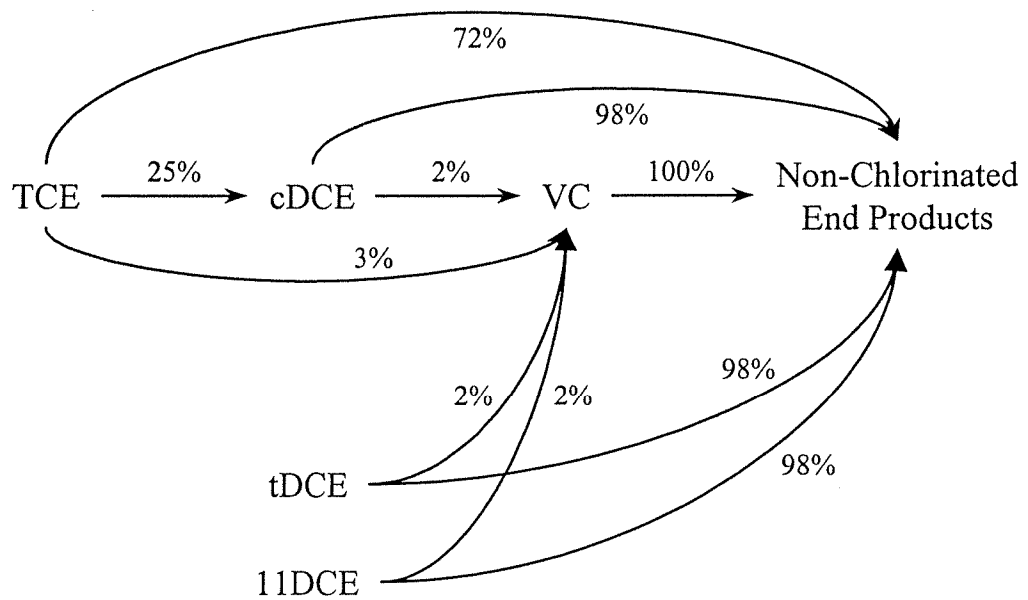


Figure 6: Assumed Molar Conversions, BSB Site, Kent, Washington

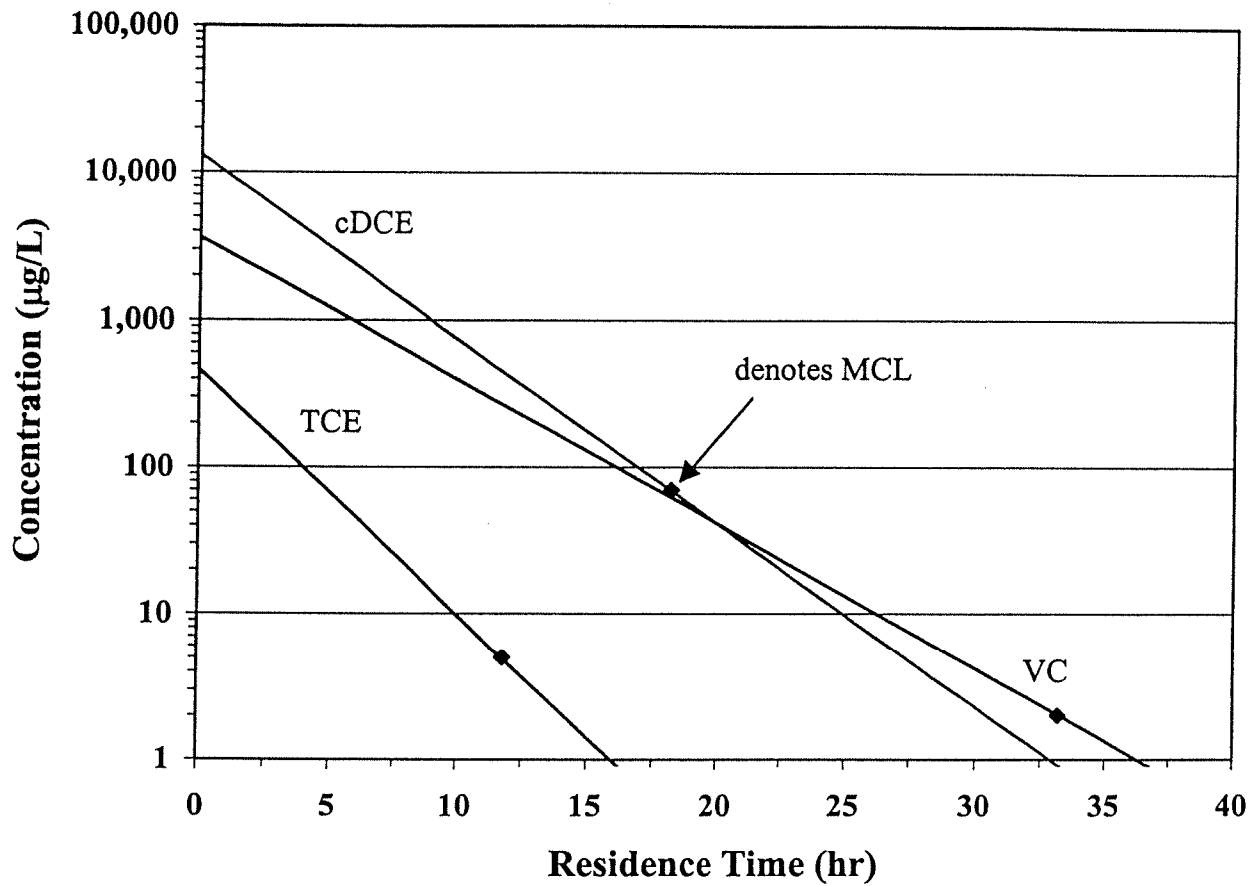


Figure 7: First-order kinetic model results for TCE, cDCE, and VC using anticipated field half-lives and high concentration scenario.

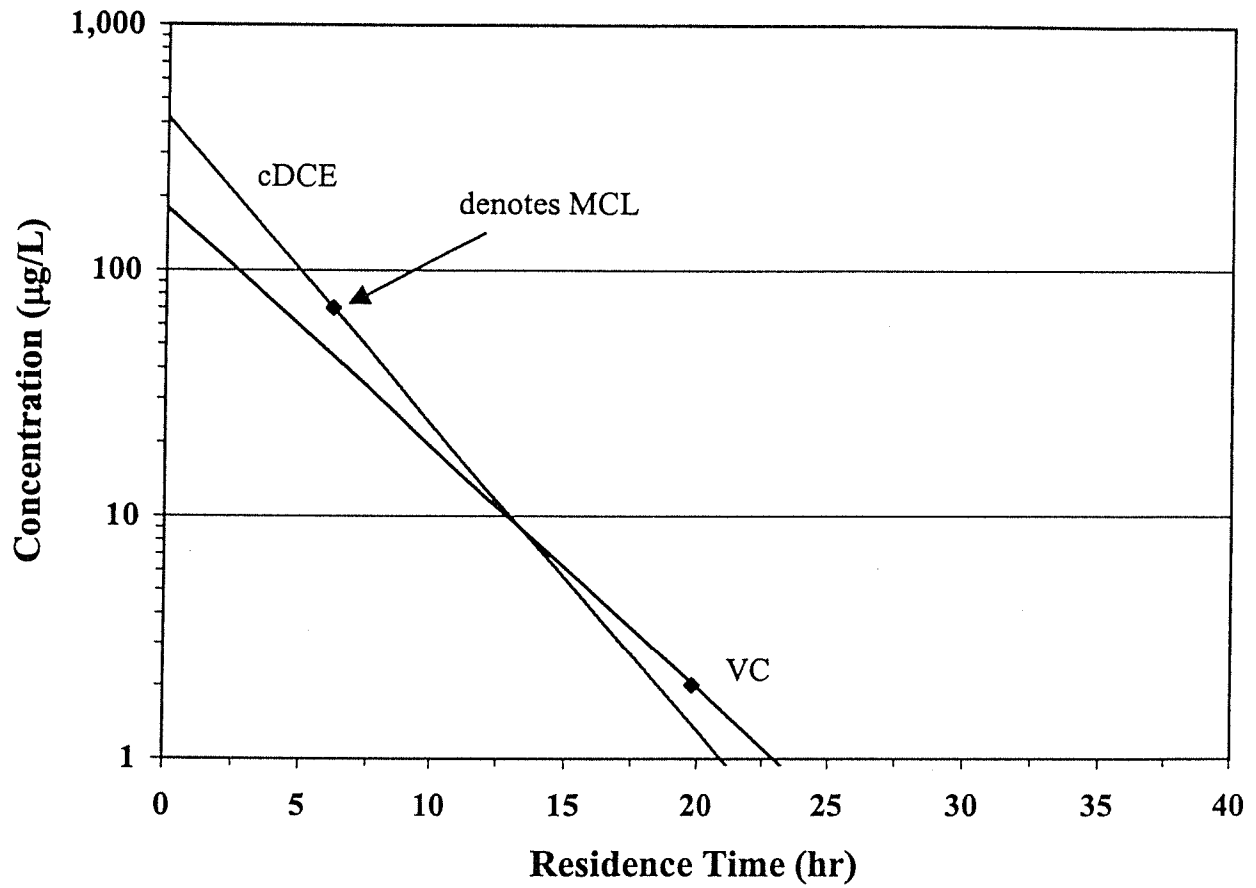


Figure 8: First-order kinetic model results for TCE, cDCE, and VC using anticipated field half-lives and low concentration scenario



## **Appendix A**

### **Laboratory Organic Analyses for Bench-Scale Testing Involving the EnviroMetal Process**

Treatability Test  
EMCON

Column Identification: 292  
 Column Composition: 100 % Connelly Iron (UW#173)  
 Pore Volume (PV): 338 mL  
 Porosity: 0.59  
 Column Length: 1.6 ft (50 cm)  
 Column Diameter: 1.5 in (3.8 cm)  
 Flow Velocity: 1.8 ft/day (54.6 cm/day)

Column Distance (ft)	0.0	0.08	0.16	0.33	0.50	0.66	1.0	1.3	1.6
Residence Time (hr)	0.0	1.1	2.1	4.4	6.7	8.8	13.4	17.6	22.0

	PV	RN	Influent		Organic Concentration ( µg/L )						Effluent	HL	r2
TCE													
	7.4	a	4840	1612	621	7.8	nd	nd	nd	nd	nd		
	15.7	a	4146	1810	721	16	nd	nd	nd	nd	nd		
	24.1	a	3096	2406	1281	97	nd	nd	nd	nd	nd		
	30.8	a	2525	1370	640	29	nd	nd	nd	nd	nd	0.7	0.955
	38.1	b	2879	2619	1744	261	4.4	nd	nd	nd	nd	0.7	0.892
	46.1	b	2333	1591	1331	300	9.1	nd	nd	nd	nd	0.9	0.893
cDCE													
	9.8	a	6237	4364	3750	1178	673	41	nd	nd	nd		
	18.1	a	5648	3518	2306	482	29	nd	nd	nd	nd		
	26.4	a	5091	4500	3630	1250	277	20	nd	nd	nd		
	31.8	b	6120	5442	3250	1430	325	nd	nd	nd	nd	1.5	0.964
	39.2	b	4644	4545	4118	1144	298	36	nd	nd	nd	1.2	0.936
	46.1	b	3607	<b>3864</b>	3495	1758	515	36	nd	nd	nd	1.2	0.894
tDCE													
	9.8	a	24	10	nd	3.4	2.3	2.3	nd	nd	nd		
	18.1	a	16	13	5.3	nd	nd	nd	nd	nd	nd		
	26.4	a	16	12	11	nd	nd	nd	nd	nd	nd		
	31.8	b	24	22	14	nd	nd	nd	nd	nd	nd		
	39.2	b	13	12	6.7	nd	nd	nd	nd	nd	nd		
	46.1	b	6.1	5.0	4.7	nd	nd	nd	nd	nd	nd		
11DCE													
	9.8	a	19	11	nd	nd	nd	nd	nd	nd	nd		
	18.1	a	13	16	7.7	nd	nd	nd	nd	nd	nd		
	26.4	a	13	11	10	3.8	nd	nd	nd	nd	nd		
	31.8	b	15	14	11	nd	nd	nd	nd	nd	nd		
	39.2	b	15	13	7.3	4.6	nd	nd	nd	nd	nd		
	46.1	b	12	9.5	8.6	3.5	nd	nd	nd	nd	nd		

nd = not detected

na = not applicable

RN = reservoir number

HL = half life

r2 = coefficient of variation

**BOLD** = peak concentration

Treatability Test	Column Identification:	292
EMCON	Column Composition:	100 % Connelly Iron (UW#173)
	Pore Volume (PV):	338 mL
	Porosity:	0.59
	Column Length:	1.6 ft (50 cm)
	Column Diameter:	1.5 in (3.8 cm)
	Flow Velocity:	1.8 ft/day (54.6 cm/day)

Column Distance (ft)	0.0	0.08	0.16	0.33	0.50	0.66	1.0	1.3	1.6
Residence Time (hr)	0.0	1.1	2.1	4.4	6.7	8.8	13.4	17.6	22.0

PV	RN	Influent	Organic Concentration ( µg/L )								Effluent	HL	r2
VC													
9.8	a	527	205	19	52	11	nd	nd	nd	nd			
18.1	a	78	81	69	20	8.5	nd	nd	nd	nd			
26.4	a	13	17	34	40	19	nd	nd	nd	nd			
31.8	<b>b*</b>	699	544	350	121	32	nd	nd	nd	nd	1.5	0.983	
46.1	<b>b*</b>	743	650	681	353	98	11	nd	nd	nd	1.5	0.875	

pH Along Column

pH											
3.8	a	6.7	7.5	9.1	8.7	9.6	9.9	10.4	10.8	10.8	
10.9	a	7.2	7.2	8.1	9.0	9.3	9.4	9.6	10.0	10.2	
16.9	a	7.3	7.5	8.2	9.0	9.2	9.2	9.4	9.5	9.7	
25.3	a	7.5	8.0	8.4	9.0	9.2	9.2	9.2	9.4	9.4	
33.7	b	7.1	7.1	7.4	8.7	8.9	9.1	9.1	9.1	9.5	
40.3	b	7.4	7.6	7.7	8.8	9.2	9.3	9.4	9.4	9.4	

Redox Potential Along Column ( mV )

Eh											
3.8	a	419	-351	-343	-262	-222	-221	-164	-101	-45	
10.9	a	402	-350	-333	-364	-348	-427	-471	-423	-486	
16.9	a	309	-183	-152	-206	-213	-133	-176	-295	-357	
25.3	a	399	-139	-220	-257	-316	-279	-269	-239	-275	
33.7	b	282	-374	-316	-223	-116	-126	-237	-224	-221	
40.3	b	260	-92	-180	-246	-265	-408	-321	-305	-283	

nd = not detected  
na = not applicable  
RN = reservoir number  
HL = half life  
r2 = coefficient of variation  
**BOLD** = peak concentration  
\* increased reservoir concentration

## **Appendix B**

### **Laboratory Inorganic Analyses for Bench-Scale Testing Involving the EnviroMetal Process**

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Page: 1  
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Attn: Wayne Noble  
 Project:

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PO #:

Job: 9953747

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Water Samples

Sample Id	Ag ICAP mg/L	Al ICAP mg/L	As ICAP mg/L	B ICAP mg/L	Ba ICAP mg/L	Be ICAP mg/L	Bi ICAP mg/L	Ca ICAP mg/L
DW-223 - influent	<0.005	<0.05	<0.1	0.23	<0.005	<0.0005	<0.1	17.0
DW-224 291, eff, pv 28.4, rna	<0.005	<0.05	<0.1	0.20	0.007	<0.0005	<0.1	5.29
DW-225 292, eff, pv 30.8, rna	<0.005	0.07	<0.1	0.35	0.010	<0.0005	<0.1	4.02
DW-226 - influent	<0.005	<0.05	<0.1	0.25	<0.005	<0.0005	<0.1	16.4
DW-227 291, eff, pv 32.4, rna	<0.005	<0.05	<0.1	0.17	<0.005	<0.0005	<0.1	6.41
Blank	<0.005	<0.05	<0.1	<0.01	<0.005	<0.0005	<0.1	<0.05
QC Standard (Found)	0.932	1.02	1.0	0.99	0.977	0.967	1.0	45.5
QC Standard (expected)	1.00	1.00	1.0	1.00	1.00	1.00	1.0	50.0
Repeat DW-223	<0.005	<0.05	<0.1	0.20	<0.005	<0.0005	<0.1	16.3

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PAGE 03

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Water Samples

Sample Id	Cd ICAP mg/L	Co ICAP mg/L	Cr ICAP mg/L	Cu ICAP mg/L	Fa ICAP mg/L	K ICAP mg/L	Mg ICAP mg/L	Mn ICAP mg/L
UW-223 influent	<0.005	<0.005	<0.005	0.005	1.17	7	13.1	0.313
UW-224 col 291, eff, p.v. 28.4, rna	<0.005	<0.005	<0.005	0.004	0.16	7	4.11	0.034
UW-225 col 292, eff, p.v. 30.8, rna	<0.005	<0.005	0.006	0.009	0.02	7	2.19	<0.005
UW-226 influent	<0.005	<0.005	<0.005	0.005	0.34	7	12.3	<0.005
UW-227 col 291, eff, p.v. 30.7, rna	<0.005	<0.005	<0.005	0.003	0.34	6	6.34	<0.005
Blank	<0.005	<0.005	<0.005	0.004	0.01	<1	<0.05	<0.005
QC Standard (found)	0.944	0.995	0.960	1.03	0.98	47	9.75	0.973
QC Standard (expected)	1.00	1.00	1.00	1.00	1.00	50	10.0	1.00
Repeat UW-223	<0.005	<0.005	<0.005	0.004	1.07	6	12.4	0.295

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PAGE 04

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Water Samples

Sample Id	Mo ICAP mg/L	Na ICAP mg/L	Ni ICAP mg/L	P ICAP mg/L	Pb ICAP mg/L	S ICAP mg/L	Sb ICAP mg/L	Se ICAP mg/L
UW-223 influent	<0.02	72.5	<0.02	0.5	<0.05	7.3	<0.1	<0.1
UW-224 col 29, eff, p.v. 28.4, rna	0.06	72.4	<0.02	0.2	<0.05	4.9	<0.1	<0.1
UW-225 col 29.2, eff, p.v. 30.8, rna	<0.02	71.0	<0.02	0.1	<0.05	6.0	<0.1	<0.1
UW-226 influent	0.02	73.2	<0.02	0.2	<0.05	6.1	<0.1	<0.1
UW-227 col 29, eff, p.v. 30.4, rna	0.04	72.3	<0.02	0.1	<0.05	4.4	<0.1	<0.1
Blank	<0.02	<0.1	<0.02	<0.1	<0.05	0.0	<0.1	<0.1
QC Standard (found)	0.97	50.0	1.00	1.0	0.97	1.0	1.0	1.0
QC Standard (expected)	1.00	50.0	1.00	1.0	1.00	1.0	1.0	1.0
Repeat UW-223	<0.02	67.2	<0.02	0.5	<0.05	6.6	<0.1	<0.1

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Water Samples

Sample Id	Si ICAP mg/L	Sn ICAP mg/L	Sr ICAP mg/L	Ti ICAP mg/L	V ICAP mg/L	Zn ICAP mg/L	P- SM 4500P mg/L	Cl- SM 4110B mg/L
UW-223 influent	25.0	<0.05	0.071	<0.005	<0.005	0.011	0.4	40.2
UW-224 col 291, eff, p.v. 28.4, ma	2.93	<0.05	0.024	<0.005	<0.005	<0.005	0.2	50.2
UW-225 col 292, eff, p.v. 30.8, ma	0.47	<0.05	0.025	<0.005	0.005	<0.005	0.3	40.5
UW-226 influent	23.1	<0.05	0.077	<0.005	<0.005	<0.005	0.2	35.3
UW-227 col 291, eff, p.v. 30.4, ma	3.26	<0.05	0.028	<0.005	<0.005	<0.005	0.2	42.3
Blank	<0.05	<0.05	<0.001	<0.005	<0.005	<0.005	<0.1	<0.5
QC Standard (found)	0.47	<0.05	0.977	0.978	0.983	0.989	4.4	58.3
QC Standard (expected)	0.50	<0.05	1.00	1.00	1.00	1.00	4.4	60.0
Repeat UW-223	23.3	<0.05	0.067	<0.005	<0.005	0.007	0.2	39.6







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Water Samples

Sample Id	Alk 4.2 SM 2320B mg CaCO3/L	NH3-N SM 4500H mg/L	DOC SM 5310C mg/L	Th. TDS Calc. mg/L	pHs Calc. pH Units	CAD Calc. %	Hard(Calc) SM 2340B mg CaCO3/L
UW-223 influent	179	1.90	7.4	278	7.97	-2.20	96.6
UW-224 col 291, eff, p.v. 284, ma	102	1.77	2.9	213	8.72	-4.07	30.2
UW-225 col 292, eff, p.v. 30.8, ma	93	1.94	3.1	199	8.87	-5.28	19.0
UW-226 influent	180	1.66	7.8	271	7.98	-3.14	91.7
UW-227 col 291, eff, p.v. 304, ma	120	1.72	2.6	218	8.57	-5.28	42.1
Blank	3	<0.02	<0.2	4	12.14	42.9	0.3
QC Standard (found)	52	1.52	10.1	302	8.09	-22.4	153.8
QC Standard (expected)	50	1.50	10.0	310	8.07	-24.5	166.0
Repeat UW-223	179	1.90	7.2	270	7.98	0.81	92.3

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Water Samples

Sample Id	CO3=	HCO3-	L.I.	A.I.	R.S.I.	Colour	Turb.	Sp. Cond.
	Calc. mg/L	Calc. mg/L	Calc. None	Calc. None	Calc. None	SM 2120B TCU	SM 2130B NTU	SM 2510B umhos/cm
UW-223 influent	1	215.2	-0.1	12.11	8.1	626	151.	495
UW-224 col 291, eff, p.v. 28.4, ma	15	58.8	0.9	13.09	7.8	8	1.0	397
UW-225 col 292, eff, p.v. 30.8, ma	14	56.1	0.7	12.85	8.1	6	0.6	389
UW-226 influent	1	217.2	-0.8	11.44	8.7	424	74.0	499
UW-227 col 291, eff, p.v. 30.4, ma	15	81.3	1.0	13.30	7.5	8	0.8	408
Blank	nan	nan	nan	nan	nan	<1	0.2	2
QC Standard (found)	74	0.0	-1.1	10.91	9.2	52	1.8	739
QC Standard (expected)	75	0.0	-1.1	10.92	9.1	50	1.8	718
Repeat UW-223	1	215.6	-0.1	12.09	8.1	634	151.	493

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Signed:

Ralph Siebert, B.Sc.  
Project Manager

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Water Samples

Sample Id	Ag ICAP mg/L	Al ICAP mg/L	As ICAP mg/L	B ICAP mg/L	Ba ICAP mg/L	Be ICAP mg/L	Bi ICAP mg/L	Ca ICAP mg/L
UW-228 col 292, eff, pv47, ma	<0.003	<0.03	<0.1	0.27	0.013	<0.0005	<0.1	4.99
Blank	<0.003	<0.03	<0.1	<0.01	<0.005	<0.0005	<0.1	<0.05
QC Standard (found)	0.035	10.3	1.1	0.21	0.963	1.00	1.1	51.3
QC Standard (expected)	0.030	10.0	1.0	0.20	1.00	1.00	1.0	51.0
Repeat UW-228	<0.003	<0.03	<0.1	0.27	0.017	<0.0005	<0.1	5.64

Sample Id	Cd ICAP mg/L	Co ICAP mg/L	Cr ICAP mg/L	Cu ICAP mg/L	Fe ICAP mg/L	K ICAP mg/L	Mg ICAP mg/L	Mn ICAP mg/L
UW-228 col 292, eff, pv47, ma	<0.005	<0.005	<0.005	<0.003	0.02	5	5.72	0.045
Blank	<0.005	<0.005	<0.005	<0.003	<0.01	<1	<0.05	<0.005
QC Standard (found)	0.956	0.959	0.954	0.966	1.04	10	11.0	0.960
QC Standard (expected)	1.00	1.00	1.00	1.00	1.00	10	11.0	1.00
Repeat UW-228	<0.005	<0.005	<0.005	<0.003	0.02	5	5.85	0.055





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Water Samples

Sample Id	Mo ICAP mg/L	Na ICAP mg/L	Ni ICAP mg/L	P ICAP mg/L	Pb ICAP mg/L	S ICAP mg/L	Sb ICAP mg/L	Se ICAP mg/L
UN-228 col 292, eff, pv. 47, rna	0.11	74.5	<0.02	<0.1	<0.05	1.7	<0.1	<0.1
Blank	<0.02	<0.1	<0.02	<0.1	<0.05	<0.1	<0.1	<0.1
QC Standard (found)	1.09	50.6	0.97	2.0	0.94	10.3	1.0	1.1
QC Standard (expected)	1.10	50.0	1.00	2.0	1.00	10.0	1.0	1.0
Repeat UW-228	0.08	73.5	<0.02	<0.1	<0.05	1.6	<0.1	<0.1

Sample Id	Si ICAP mg/L	Sr ICAP mg/L	Sr ICAP mg/L	Ti ICAP mg/L	V ICAP mg/L	Zn ICAP mg/L	F- SM 4500F mg/L	Cl- SM 4110B mg/L
UN-228 col 292, eff, pv. 47, rna	0.46	<0.05	0.015	<0.005	<0.005	0.035	0.2	46.5
Blank	<0.05	<0.05	<0.001	<0.005	<0.005	<0.005	<0.1	<0.5
QC Standard (found)	2.12	0.99	0.954	0.950	0.968	0.975	4.6	58.7
QC Standard (expected)	2.00	1.00	1.00	1.00	1.00	1.00	4.5	60.0
Repeat UW-228	0.45	<0.05	0.017	<0.005	<0.005	0.039	0.3	48.8



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Water Samples

Sample Id	NO2-N	PO4-3	Br-	NO3-N	SO4=	pH	Alk 8.3
	SM 4110B	SM 4110B	SM 4110B	SM 4110B	SM 4110B	SM 4500B	SM 2320B
	mg/L	mg/L	mg/L	mg/L	mg/L	pH Units	mg CaCO3/L
UW-228 Col 292, eff, p.v. 47, ma	<0.2	<1	<0.5	0.2	2.9	8.48	<1
Blank	<0.2	<1	<0.5	<0.2	<0.5	---	---
QC Standard (found)	9.5	18	9.5	29.4	57.4	7.01	<1
QC Standard (expected)	10.0	19	10.0	30.0	60.0	7.00	---
Repeat UW-228	<0.2	<1	<0.5	<0.2	2.9	8.54	<1

Sample Id	Alk 4.2	ME3-N	EOC	Th. TDS	pHs	CAB	Hard( Calc)
	SM 2320B	SM 4500H	SM 5310C	Calc.	Calc.	Calc.	SM 2340B
	mg CaCO3/L	mg/L	mg/L	mg/L	pH Units	%	mg CaCO3/L
UW-228 Col 292, eff, p.v. 47, ma	122	0.03	2.8	213	8.66	-3.45	36.0
Blank	<1	<0.02	<0.2	3	12.61	7.89	0.3
QC Standard (found)	253	0.32	5.6	391	7.36	14.1	173.6
QC Standard (expected)	250	0.30	5.0	392	7.36	14.7	172.6
Repeat UW-228	121	0.03	2.9	215	8.62	-3.07	38.1

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Water Samples

Sample Id	CO3=	HCO3-	L.I.	A.I.	R.S.I.	Turb.	Colour	Sp. Cond.
	Calc. mg/L	Calc. mg/L	Calc. None	Calc. None	Calc. None	SM 2130B NTU	SM 2120B TCU	SM 2510B µmhos/cm
UW-228 col 292, eff, pv. 47, rna	1	146.5	-0.2	12.12	8.8	1.2	<1	391
Blank	nan	nan	nan	nan	nan	<0.1	<1	<1
QC Standard (found)	1	306.0	-0.3	11.65	7.7	1.8	26	727
QC Standard (expected)	nan	nan	-0.4	11.64	7.7	1.8	25	718
Repeat UW-228	0	145.3	-0.1	12.20	8.7	1.2	<1	394







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.....  
Ralph Siebert, B.Sc.  
Project Manager

