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**Bench-Scale Treatability Report in Support of a Granular
Iron Permeable Reactive Barrier Installation
at the Ash Landfill, Seneca Army Depot Activity, Romulus,
New York**

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1.0 INTRODUCTION AND BACKGROUND

This bench-scale treatability report was prepared for Parsons Engineering Science, Inc. (Parsons ES) to support the design of granular iron permeable reactive barriers (PRBs) for treatment of dissolved chlorinated volatile organic compounds (VOCs) present in groundwater at the Ash Landfill, Seneca Army Depot Activity, Romulus, NY (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

In-situ PRBs involve 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 implemented, based on site-specific conditions. Advantages of *in-situ* PRBs 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 used in PRBs, with most involving granular 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, over 60 PRBs containing granular iron have been installed to remediate VOCs throughout the United States, Europe and Australia. There are currently 40 *in-situ* full-scale systems removing VOCs from groundwater, 7 of which have been installed at DOD facilities, in addition to over 20 pilot-scale systems, which have been installed to provide “proof of concept” data and more recently to demonstrate innovative construction methods.

1.2 Rationale for Column Testing

Based on information received from Parsons ES, three granular iron PRB locations have been proposed at the site: a Source wall located downgradient of the VOC source area, a Middle wall located in the center of the VOC plume, and a Compliance wall intercepting the toe of the plume. The groundwater table level in the vicinity of the proposed PRBs varies, with the highest levels at about 1 to 2 ft below ground surface. The groundwater system includes a till aquifer and a weathered bedrock aquifer. The till aquifer is comprised of silt, clay, sand and gravel horizons, with a total vertical thickness of about 10 to 13 ft. The bedrock aquifer consists of a weathered zone of calcareous shales and mudstones that is underlain by the competent bedrock.

The primary VOCs present, trichloroethene (TCE) and *cis* 1,2-dichloroethene (cDCE), have been successfully treated at other sites. Monitoring results from a pilot-scale iron PRB located at the toe of the VOC plume at this site (about 800 ft downgradient of the wells sampled for the bench-scale test) showed complete degradation of TCE. However, cDCE concentrations at some locations in the pilot PRB indicated that this compound was not treated to target levels, either due to insufficient residence time within the iron and/or slower than anticipated degradation rates of this compound.

The bench-scale test was initiated to provide design parameters (VOC degradation rates) for the full-scale PRBs proposed at the site. As mentioned above, data from the pilot-scale provided mixed results. In particular, the uncertainty in velocity through the pilot, combined with the spatial variability of VOC monitoring data, prevented calculation of reliable “field scale” degradation rates which could be used for the design of future PRBs at the site. Moreover, at one of the three proposed wall locations the VOC concentrations are an order of

magnitude higher than observed in the pilot. Specifically, the following factors were investigated to facilitate field implementation of a treatment system at the site:

- i) The degradation rates of chlorinated VOCs present in site groundwater using two major iron sources currently available. This will support the selection of the iron source for future field-scale applications.
- ii) The production and subsequent degradation rates of chlorinated compounds produced from the VOCs originally present in the site groundwater (e.g., dichloroethene (DCE) isomers and vinyl chloride (VC) from TCE). These can also affect the dimensions of the treatment system.
- iii) The effects of dissolved organic carbon (DOC) present in groundwater at the site on VOC degradation rates. Certain types of DOC can have an adverse effect on VOC degradation rates, a phenomenon only realized recently.
- 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.
- v) 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.

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 results from the bench-scale test.
- Section 4.0 discusses the calculated residence time required to meet the target levels and provides a preliminary conceptual design for the treatment systems.
- 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 at the site and their chlorinated breakdown products 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 two different commercial sources of granular iron;
- characterization of chlorinated breakdown products, and evaluation of the rates of degradation of these products;
- effects of DOC on degradation rates;
- changes in inorganic geochemistry as a result of the pH and Eh changes, including possible mineral precipitation.

2.2 Bench-Scale Test Methods

The bench-scale testing included two columns using groundwater collected by Parsons ES from a location in the vicinity of the proposed Source iron wall. The columns contained 100% granular iron obtained either from Connelly GPM of Chicago, IL (-8 to +50 US Standard Mesh size) or Peerless Metal Powders and Abrasives, Inc. of Detroit, MI (-8 to +50 US Standard Mesh size). The specific surface area of the granular iron was 1.8 and 1.5 m²/g for Connelly and Peerless iron, respectively, as determined by the BET method (Brunauer et al., 1938) on a Micromeretic Gemini 2375 surface analyzer. Hydraulic conductivity values of about 6×10⁻² cm/sec (170 ft/day) were obtained for both iron sources using a falling head permeameter test.

The columns were constructed of Plexiglas™ with a length of 1.6 ft (50 cm) and an internal diameter of 1.5 in (3.8 cm) (Figure 1). 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 columns also allowed for the collection of samples from the influent and effluent solutions. 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 columns were packed with 100% granular iron. To assure a homogeneous mixture, aliquots of iron 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 experiments were performed at room temperature (25 °C).

An Ismatec™ IPN pump was used to feed the site water from a collapsible Teflon® bag to the influent end of the columns. 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 about 1.6 ft/day (49 cm/day) was selected in consultation with Parsons ES to allow the tests to be completed within a reasonable time length.

On request from Parsons ES, an additional batch test using both iron sources was conducted at the end of the column test. The purpose of this test was to show whether complete VOC removal could be achieved within granular iron zone, given sufficient time. Batches of 100% Connelly iron and 100% Peerless iron were prepared in reactive glass vials (40 mL) containing about 60 g of iron and about 29 mL of water obtained at the conclusion of the column test from the effluents of the two columns. The vials were placed on a rotating disc allowing for complete mixing without agitation. At specified sampling times (1, 6, 23, 49, 120 and 195 hrs), samples were extracted for cDCE and VC analysis. These vials were sacrificed for each sampling event. The test was conducted at room temperature (25 °C).

2.2.1 Groundwater Shipment and Storage

Groundwater was collected from monitoring wells PT-12A and PT-18A at the site by Parsons ES and shipped to UW in four 20-L plastic polyethylene bags. Each bag was fingerprinted for VOCs. There appeared to be a distinct trend with 2 samples having higher concentration of VOCs and 2 samples with lower VOC concentrations. Thus, a bag of high and low concentrations was mixed for the column influent reservoir. The volatile organic compounds

(VOCs) that were detected in the mixed site water included trichloroethene (TCE) and cis 1,2-dichloroethene (cDCE) with concentrations of about 2,000 and 5,000 $\mu\text{g/L}$, respectively. Smaller amounts of trans 1,2-dichloroethene (tDCE) and vinyl chloride (VC) at about 60 and 160 $\mu\text{g/L}$, respectively, and trace amounts of 1,1-dichloroethene (11DCE) were also detected in the site water.

After mixing, the site water was stored at 4° C until required, at which time it siphoned from the storage 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 three times (a-c) over the course of the test.

2.2.2 Sampling and Analysis

The columns were sampled every 1 to 9 pore volumes until steady state concentration profiles were achieved. In the bench-scale column test, steady state is defined as the time when VOC concentrations versus distance profiles do not change significantly between sampling events. Sampling in the batch tests was conducted according to the procedure described in Section 2.2.

After removing the stagnant water from the sampling needle, 2.0 to 4.0 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. Samples for inorganic analyses were obtained from the influent solution and the effluent overflow bottles as steady state conditions were approached.

2.3 Analytical Methods

2.3.1 Organic Analyses

The less volatile halogenated organic 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 μL 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^{63} electron capture detector (ECD) and DB-624 megabore capillary column (30 m x 0.538 mm ID, film thickness 3 μm). The gas chromatograph had an initial temperature of 50 $^{\circ}\text{C}$, with a temperature time program of 15 $^{\circ}\text{C}/\text{minute}$ reaching a final temperature of 150 $^{\circ}\text{C}$. The detector temperature was 300 $^{\circ}\text{C}$. 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, 4.0 mL samples were collected in glass on glass syringes and placed in 10 mL Teflon[®] faced septa crimp cap vials, creating a headspace with a ratio of 6.0 mL headspace to 4.0 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 $^{\circ}\text{C}$, and subsequently injected onto the gas chromatograph. The temperature program was 160 $^{\circ}\text{C}$ for 5.5 minutes, then increased at 20 $^{\circ}\text{C}/\text{min}$ to 200 $^{\circ}\text{C}$ and held for 5.5 minutes. The injector and detector temperatures were 100 $^{\circ}\text{C}$ and 120 $^{\circ}\text{C}$, 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 and C). 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, and sent to Philip Services, Mississauga, Ontario for cation and anion analyses. 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, NO₃ and SO₄, were performed using ion chromatography on 60 mL unfiltered samples. Alkalinity (as mg CaCO₃/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 in the Column Test

Samples for measurement of VOC concentrations along the length of the column were taken approximately every 1 to 9 pore volumes (Appendix A). The results obtained when steady state conditions were reached are plotted as VOC concentration ($\mu\text{g/L}$) versus residence time along the column (hr). The profiles of most interest are the steady state concentration profiles, collected at the end of the measurement period. Influent concentrations for most VOCs were relatively consistent throughout the test (Table 3 and Appendix A). Although some fluctuations in the influent concentrations occurred, this did not affect interpretation of the observed results, as the influent concentration for each profile was used to determine the degradation rates for that particular profile.

The final steady-state concentration profiles are shown in Figures 2 to 5. At a flow velocity of about 1.6 ft/day (49 cm/day) and 1.4 ft/day (43 cm/day), one pore volume corresponds to a residence time of about 25 and 28 hrs in the Connelly iron column and Peerless iron column, respectively. A total of 47 and 41 pore volumes of water were passed through the two columns, respectively.

In the Connelly column, the TCE concentrations were reduced from an influent value of 2,066 $\mu\text{g/L}$ to non-detectable values within a residence time of 9.9 hrs along the column (Figure 2). The cDCE concentration declined from an influent value of 6,170 $\mu\text{g/L}$ to 676 $\mu\text{g/L}$ in the column effluent (a residence time of 24.6 hrs) (Figure 2). The concentrations of tDCE, detected at 36 $\mu\text{g/L}$ in the influent, decreased to non-detectable values within a residence time of 7.5 hrs along the column (Figure 3). Concentrations of VC decreased from an initial concentration of 106 $\mu\text{g/L}$ to 41 $\mu\text{g/L}$ at a residence time of 24.6 hrs (column effluent) (Figure 3).

In the Peerless column, the TCE concentrations decreased from an influent value of 2,066 $\mu\text{g/L}$ to non-detectable values within a residence time of 11.2 hrs along the column (Figure 4). The cDCE concentration declined from an influent value of 6,170 $\mu\text{g/L}$ to 573 $\mu\text{g/L}$ in the column effluent (a residence time of 27.9 hrs) (Figure 4). Concentrations of tDCE declined within the column from an influent value of 36 $\mu\text{g/L}$ to non-detectable concentration within a residence time of 8.5 hrs (Figure 5). Concentrations of VC decreased from 106 $\mu\text{g/L}$ in the column influent to 31 $\mu\text{g/L}$ within a residence time of 27.9 hrs (column effluent) (Figure 5).

Periodically, trace concentrations of 11DCE were observed in the two columns over the test period (Appendix A).

3.1.1 Degradation of Volatile Organic Compounds in the Batch Test

Figure 6 and 7 show the cDCE and VC results of the batch test plotted as concentration in $\mu\text{g/L}$ versus time in hours. Note that cDCE and VC were the only contaminants detected in the effluent of the Connelly and Peerless column used as the source water for the batches (Appendix C). Figure 6 shows concentrations of cDCE declined from 791 and 353 $\mu\text{g/L}$ in the Connelly and Peerless vials to 14 and 8 $\mu\text{g/L}$ in the two tests, respectively, over the duration of the test (195 hr). The VC concentrations declined from initial values of 39 and 14 $\mu\text{g/L}$ in the Connelly and Peerless vials, respectively, to non-detectable values in both irons at the end of the test (Figure 7).

Because of the static nature of the batch test, VOC degradation rates were not calculated from the observed batch test data. However, the batch test results illustrate that the decreasing cDCE and VC concentration trends observed in the column test would continue over time and therefore that remediation targets for these compounds can be achieved, given a sufficient residence time within the iron zone.

3.2 Determination of VOC Degradation Parameters

The VOC degradation trends observed in groundwater in contact with granular iron are typically described using first-order kinetics:

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

or

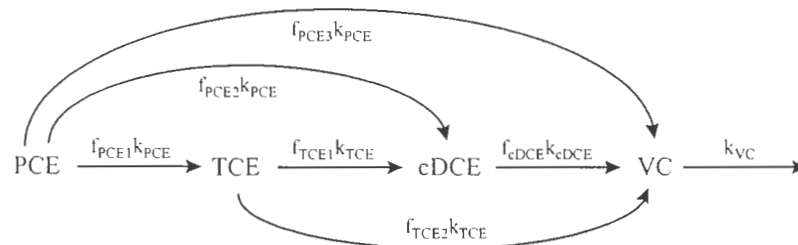
$$\ln\left(\frac{C}{C_0}\right) = -kt \quad (2)$$

where: C = VOC concentration in solution at time t ,

C_o = VOC concentration of the influent solution,
 k = first-order rate constant, and
 t = time.

The time at which the initial concentration declines by one-half, ($C/C_o = 0.5$), is the half-life. ETI has developed a first-order kinetic model to simulate the degradation of VOCs with granular iron. In the model, potential breakdown products are concurrently produced and degraded as described by first-order kinetic equations. The model is an expression of the chemistry that is observed in the solution phase. For example, for the chlorinated ethenes (PCE, TCE, cDCE and VC) the production of chlorinated acetylene via a β -elimination pathway is considered to be the dominant degradation pathway (Eykholt, 1998; Arnold and Roberts, 1999). However, since chlorinated acetylenes are unstable, short-lived, intermediates that are rapidly reduced to ethene (Roberts et al., 1996; Sivavec et al., 1997), they are not typically detected in the solution phase and are therefore not explicitly contained in the degradation model.

The equations contained in the model were developed by ETI to describe the first-order kinetic degradation process occurring in a granular iron groundwater treatment zone. For PCE, TCE, cDCE and VC the model takes the form:



where: f = mole fraction (or percent molar conversions)
 k = first-order rate constant

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

$$dPCE / dt = -k_{PCE}PCE \quad (3)$$

$$dTCE / dt = f_{PCE1}k_{PCE}PCE - k_{TCE}TCE \quad (4)$$

$$dcDCE / dt = f_{PCE2}k_{PCE}PCE + f_{TCE1}k_{TCE}TCE - k_{cDCE}cDCE \quad (5)$$

$$dVC / dt = f_{PCE3}k_{PCE}PCE + f_{TCE2}k_{TCE}TCE + f_{cDCE}k_{cDCE}cDCE - k_{VC}VC \quad (6)$$

These equations were adapted for the computer program Scientist[®] for Windows[®] Version 2.0 (1995). The Scientist[®] program can be used to fit the first-order equations to experimental data using the least squares best-fit method. Least squares fitting is performed using a modified Powell algorithm to find a local minimum of the sum of squared deviations between observed data and model calculations. The degradation rate and molar conversion are determined for each compound sequentially starting with the most chlorinated compound.

The results from the model include half-lives and molar conversions for all VOCs selected and statistical fit data including coefficient of determination (r^2) values. The r^2 values indicate how well the degradation model represents the experimental data. The half-lives determined for either the last six (TCE) or the last three (DCE-isomer and VC) profiles (steady state) were averaged and are shown in Table 3, along with their standard deviations. Also shown are ranges of corresponding r^2 values.

The degradation model provided good fits to the TCE, cDCE, and tDCE profiles, with r^2 values greater than 0.90 and average half-life values of 1.2 and 0.93 hrs for TCE, 4.1 and 7.7 hrs for cDCE, and 0.8 and 1.1 hrs for tDCE in the Connelly column and the Peerless column, respectively (Table 3 and Appendix A). For VC the r^2 for the model fits were poorer (but greater than 0.72) with average half-lives of 9.5 and 9.8 hrs observed in the Connelly column and the Peerless column, respectively.

Figure 8 summarizes the average molar conversions and their standard deviations determined using the degradation model. Although the TCE half-life values observed in the columns are similar to those observed in previous tests using groundwater containing similar TCE concentrations, the cDCE and VC half-lives are somewhat higher than those typically observed. These higher half-life values for cDCE and VC may be influenced by the DOC concentrations, found in this site water, as discussed in section 3.3.1, or by the total VOCs (about 10 mg/L) present in solution, causing competition for reactive sites. The half-life data are used to develop residence time estimates for a field-scale PRB in Section 4.1.

The TCE and cDCE degradation rates determined above are generally in agreement with the degradation trends observed in the pilot-scale PRB at the Ash Landfill installed using Peerless iron. Field results from the pilot PRB showed complete degradation of TCE, but cDCE concentrations were only slightly lower than the upgradient values. While these results indicate that cDCE degradation rates in the pilot-scale PRB are lower than expected, we

expect that unanticipated groundwater flow patterns in the pilot-scale PRB also contribute to observed cDCE concentration trends.

The relative behavior of the two iron sources is similar to that observed in other tests, that is similar degradation rates we observed for TCE, but higher cDCE and VC rates were obtained in the Connelly iron than in the Peerless iron.

3.3 Geochemical Results

3.3.1 DOC Effects on VOC Degradation

As indicated in the previous section, the half-lives observed in the columns for cDCE and VC, are somewhat higher than those observed in waters with similar VOCs. Recent research suggests that VOC degradation rates may be affected by certain chemicals found in site groundwater. Some of this research suggests that accumulation of certain types of organic matter, such as humic acids, on the surface of iron particles can inhibit electron transfer between the underlying metal and the contaminant, resulting in surface passivation and decreasing rates of contaminant reduction (Tratnyek and Scherer, 1998). Another process postulated to inhibit the rates of VOC degradation is hydrophobic partitioning, whereby hydrophobic contaminants (e.g. chlorinated hydrocarbons) are preferentially partitioned to micelle or membrane-like hydrophobic interiors formed by surfactant aggregates (Tratnyek and Scherer, 1998). As a result of this process, certain contaminants are made more soluble and less prone to contact the iron surface, resulting in slower degradation rates. There is no clear indication from the column data which of the two mechanisms occurred during the column test.

ETI has observed that some types of DOC could adversely affect the VOC degradation rates when in contact with iron. This phenomenon is typically observed at the bench-scale when there is a decline in DOC in the effluent relative to the DOC in the influent. For the Ash Landfill site, a DOC concentration of about 22 mg/L was measured in the influent of the two columns. As the water passed through the columns, the DOC concentrations remained essentially unchanged in both columns (Table 4). Therefore, the DOC does not appear to affect the half-lives achieved in the current bench-scale test at steady state.

ETI has also observed the DOC can influence VOC degradation by causing non-reducing conditions to exist over time at the influent end of the column. This phenomenon was not

observed in these tests (Figure 9) and is not expected to affect field-scale performance of the PRBs.

3.3.2 Inorganic Results

Similar to other subsurface environments, the composition of groundwater flowing through a granular iron PRB will undergo acid-base reactions, mineral precipitation/dissolution, oxidation/reduction reactions and mixing. These changes may lead to significant changes in aqueous inorganic chemistry, and the potential precipitation of a variety of mineral phases.

Two influent and effluent samples were collected from the columns 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 shows similar trends in both columns, which are comparable to previous results. Concentration of potassium, sodium, and bromide remained relatively unchanged in the columns. Concentration of calcium, magnesium, silica, strontium, chloride sulphate and alkalinity decreased in the columns, while concentration of boron, iron and manganese increased in both columns.

When iron is exposed to water, several reactions occur as a result of iron corrosion:



This iron corrosion drives the geochemical changes that occur as groundwater flows through the PRB. Figure 9 shows the Eh and pH profiles observed at steady state in both columns. The Eh profiles showed reducing conditions in both columns, decreasing from initial values of +359 and +351 mV to minimum values below -303 and -277 mV within in the Connelly column and Peerless column, respectively (Figure 9; Appendix A). Values of pH increased from 7.4 in both columns to maximum values of 8.8 and 8.5 along the distance in the Connelly column and Peerless column, respectively (Figure 9; Appendix A). These pH and Eh trends are generally consistent with previous treatability studies.

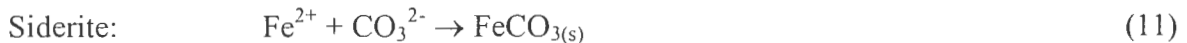
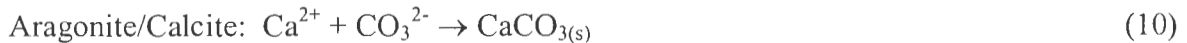
After depletion of dissolved oxygen, the water corrosion of iron dominates to produce hydrogen and hydroxide:



As pH increases due to water corrosion, bicarbonate (HCO_3^-) in solution converts to carbonate (CO_3^{2-}) to buffer some of the pH increase:



The carbonate ion may then combine with cations (Ca^{2+} , Fe^{2+} , and Mg^{2+}) in solution to form a variety of mineral precipitates, predominantly the following:



Calcium concentration decreased from 251 mg/L in the influent to 142 and 144 mg/L in the effluent of the Connelly column and Peerless column, respectively. Corresponding decreases in alkalinity from about 245 mg/L in the influent to 8 mg/L were observed as the water passed through the two columns. Declines in calcium and alkalinity concentrations indicate formation of calcium carbonate minerals (see above). In analyses of iron obtained from previous laboratory studies and field sites, siderite as well as both calcite and aragonite, which are forms of calcium carbonate, have been identified.

Concentration of magnesium declined from 40 mg/L in the influent of both columns to 34 and 37 mg/L, as groundwater flowed through the Connelly column and Peerless column, respectively. Magnesium is known to substitute for calcium and iron in the structure of calcium and iron carbonates. A decline in concentration of silica from 4.5 mg/L to about 0.1 mg/L within both columns is likely due to formation of $\text{SiO}_{2(a)}$ and/or adsorption onto $\text{Fe}(\text{OH})_2$.

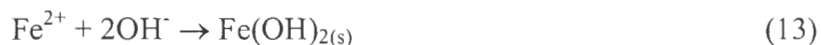
At high Eh, the stable form of sulphur is sulphate (SO_4^{2-}), while at very low Eh sulphide (H_2S or HS^-) is the stable form with HS^- being predominant at pH greater than 7. Given the low solubility of iron sulphide (FeS), the hydrogen sulphide produced precipitates out of solution.



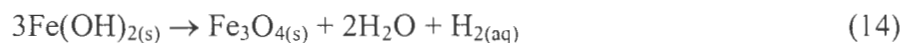
Over time, iron sulphides transform into pyrite (FeS_2) and/or marcasite, a polymorph of pyrite. Declines in sulphate concentrations have been observed at a number of field sites as groundwater passes through iron treatment zones. Sass et al. (2001) found evidence for the formation of marcasite in cores from two PRB field sites. Concentration of sulphate in both

columns declined by about 30 mg/L as groundwater passed through the columns. Sulphate and other anions may also be incorporated in the iron hydroxide precipitates known as green rusts.

Once carbonate and/or sulphate concentrations have been depleted, the primary precipitate will be $\text{Fe}(\text{OH})_2$.



Iron hydroxides are converted over time to the more stable iron oxide magnetite (Fe_3O_4) (Drever, 1997; Reardon, 1995; and Odziemkowski et al., 1998):



Although several mg/L of Fe^{2+} are produced as a result of Equation 9, iron concentrations remained relatively low in both columns, increasing from non-detectable values in the influent to less than 0.03 mg/L in the effluent. Since the total iron concentration did not increase significantly within the column, it appears that iron precipitates (i.e. iron carbonates and iron hydroxides) were forming.

A slight increase in manganese and boron concentrations occurred due to leaching from the granular iron material. This leaching is not expected to persist in the long-term in the field. A decrease in strontium concentrations was likely due to sorption onto iron hydroxides. Inorganic species not involved in precipitation/dissolution reactions (i.e. potassium, sodium and bromide) remained relatively unchanged as the site water passed through the column.

These inorganic changes are similar to those observed in other column PRB studies. The implication of these data to field scale PRB application is discussed in Section 4.4.

4.0 FIELD-SCALE TREATMENT SYSTEM DESIGN CONSIDERATIONS

4.1 Required Residence Time

The Scientist[®] program described in Section 3.3 may also be used to simulate the change in VOC concentrations over time using the first-order kinetic equations. In simulation mode, the model calculates the VOC concentrations over time, from which the time required for the VOCs to degrade to their regulatory criteria can be determined. The residence time calculation is shown conceptually in Figure 10.

Degradation rates and molar conversions determined in Section 3.2 along with the anticipated field concentrations provided by Parsons ES were input into the model to determine possible residence time requirements in a field-scale system.

Previous laboratory and field experience has shown that bench-scale half-lives established at room temperature (25°C) must be adjusted to the field groundwater temperature. Based on the reported minimum groundwater temperature at the site of 5 °C, it is reasonable to increase the laboratory half-lives by a factor of 2.5.

Figures 11 to 13 show the simulation results using the field-anticipated half-lives and anticipated field VOC concentrations (supplied by Parsons ES) with the residence times required to achieve the New York State Department of Environmental Conservation Class GA Standards for each VOC compound. The standards at the site are 5 µg/L for TCE and cDCE, and 2 µg/L for VC. The obtained residence times are also summarized in Table 5. The residence times required to degrade all VOC compounds to below the standards in each of the proposed locations of the PRBs at the site using Connelly iron source are 168 hrs (7 days) in the source wall, 72 hrs (3 days) in the middle wall and 51 hrs (2.2 days) in the compliance wall. For Peerless iron source, the residence time requirements are 179 hrs (7.5 days) in the source wall, 76 hrs (3.2 days) in the middle wall and 95 hrs (4 days) in the compliance wall.

4.2 Conceptual System Design

The required amount of iron and the wall thickness, calculated based on a reported groundwater flow velocities and New York State Standards for each iron source and three PRB locations are presented in Table 6. The PRB flow-through thickness range from 1.3 to 3.5 ft for Connelly iron and from 1.4 to 6.4 ft for Peerless iron.

The amount of iron required for each PRB can be calculated using the following formula:

$$\text{Amount of Iron} = \text{length of treatment zone} \times \text{saturated depth} \times \text{flow-through thickness} \times \text{iron bulk density (0.075 ton/ft}^3\text{)}$$

The required iron amounts for each PRB and iron source are shown in Table 6.

A continuous permeable treatment walls to maximum depths of about 15 ft could be constructed by a number of methods including trench box/shored excavation and continuous trenching. An estimated cost of installing each of the three iron walls at the site, based on previous construction costs at sites with similar geotechnical conditions to the Ash Landfill, is summarized in Table 7. The site license fee for use of the technology at DOD facilities is currently 13% of capital cost (construction of treatment system and delivered iron costs). Costs for activities such as soil disposal, site preparation, permitting, site construction management, etc., which are not included in the above estimate, should also be taken into account.

4.3 Iron Consumption

As discussed in Section 3.3, there are many processes such as water corrosion, VOC degradation, DO reduction, sulphate reduction and methane production that may consume the iron. If water corrosion were to remain constant over time at a typical rate of 0.1 to 1.0 mmol/kg Fe/day, the iron is predicted to last between 49 and 490 years. Although Reardon (1995) noted declining hydrogen production over time at room temperature, Sorel et al. (2000; 2001) found that after 5 years, the groundwater pH at the first commercial PRB in Sunnyvale, CA continues to increase from a value of 7.5 in the upgradient aquifer to a value of about 11 in the PRB, and that dissolved hydrogen concentrations approach solubility. Clearly, water corrosion is still occurring at significant rates at this site after 6 years.

In summary, although there is some uncertainty in the conditions that may exist decades in the future, it seems reasonable to expect the iron in the PRB to last for many decades.

4.4 Geochemical Effects on Field-Scale Performance

4.4.1 Possible Effects of Dissolved Organic Carbon

Concern has been expressed regarding the potential for dissolved organic carbon to adversely affect the activity of the iron in the proposed PRBs. Based on laboratory data from this bench-scale study that showed dissolved organic carbon concentrations virtually unchanged between influent and effluent concentrations, reduction in the reactivity of iron is not expected to occur at the Ash Landfill site.

4.4.1 Possible Effects of Inorganic Precipitation

Concern has been expressed regarding the potential for inorganic precipitates to reduce the activity of the iron and/or to reduce the permeability through pore clogging. The laboratory data, coupled with the field experience at other sites and at the Ash Landfill, indicates that precipitate build-up should not be an issue for many years.

Core analyses from a pilot-scale system in New York revealed porosity losses in the upgradient few inches of iron in the range of 6% of the initial porosity, with losses declining sharply over the first foot to below 2% (Vogan et al., 1998 and 1999). 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 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. Laboratory permeameter tests performed on intact core samples from a New York pilot of nearly the same age gave hydraulic conductivity values ranging from 6×10^{-2} to 10^{-1} cm/s. These compare favorably with hydraulic conductivity values of 5×10^{-2} to 10^{-1} cm/s for “fresh” iron.

A commercial system in Sunnyvale, CA (Sorel et al., 2001) has also been performing consistently for over 6 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.

Results of carbonate analyses conducted by ETI on the iron/sand material collected from the pilot-scale PRB at the Ash Landfill 2 years after system installation showed that approximately 1.3% of the original porosity had been lost at the midpoint of the PRB to calcium carbonate precipitates during this operating period (ETI Memorandum to Parsons ES of 22 January 2001). This is consistent with other site data.

In order to assess PRB longevity at this site, selected inorganic parameters in the site groundwater which can affect iron permeability and reactivity are compared in Table 8 to data collected from pilot PRBs in New York and Denver, CO and a full-scale system in Sunnyvale, CA. The important inorganic species influencing precipitate formation are calcium, magnesium, iron, alkalinity and sulphate. Based on the data in Table 8, concentrations of calcium, magnesium, alkalinity and sulphate at the site are similar to those observed at Denver, CO and Sunnyvale, CA. In comparing these sites it is important to look at the mass flux of inorganics as well as the concentration. Given that the groundwater flow velocity is similar the other two sites, the amount of carbonate and sulphide precipitates formed should also be similar. The rate of formation of iron oxides and hydroxides is largely independent of groundwater flow velocity and inorganic chemistry and therefore should also be similar at all these sites. Therefore, it is expected that the Ash Landfill site would be equally favorable for long-term low-maintenance PRB operation as the Denver and Sunnyvale systems, where iron PRBs have performed well without any maintenance for over 6 years. We note that the iron in the original PRB installation at the UW Borden test has retained its reactivity for 10 years.

In summary, extrapolations from coring observations, laboratory testing and modeling of PRB behavior indicate that the system at the Ash Landfill should operate efficiently for well over 10 years.

4.5 Potential for Biofouling of Reactive Material

There was no evidence of biofouling (sliming, etc.) observed during the bench-scale test. 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.

Of the sixty PRBs in place, there are only two sites we know of where increased microbial activity and possible biofouling has been observed. One is in a stagnant zone in a treatment gate of the Denver Federal Center, where little or no flow has occurred for several years. Gu et al. (2001) found biomass 1 to 3 orders of magnitude higher in an iron PRB treating radionuclides and 120 mg/L of nitrate, compared to background soil and groundwater. They identified abundant sulphate reducers and denitrifiers in the PRB. However, no evidence of biofouling has been observed at this site after about 2 years of operation.

In summary, there is no reason to expect that microbial fouling would adversely affect PRB performance at the Ash Landfill.

4.6 Operations and Maintenance

Other than groundwater monitoring, the major factor affecting O&M costs is the possible need for periodic rejuvenation of iron sections affected by precipitates.

The objective of rejuvenation of the granular iron would be to restore the permeability loss due to precipitates and possibly to remove the precipitate from the iron to restore any lost reactivity of the iron. Possible rejuvenation methods may include:

- i) Using ultrasound to break-up the precipitate;
- ii) Using pressure pulse technology to break-up the precipitate;
- iii) Jetting the PRB with water under high pressure; and
- iv) Using solid-stem augers to agitate the PRB.

To date these possible rejuvenation methods have not been needed and only ultrasound has been tested in a few limited field-scale tests to determine its effectiveness. At this point we can only state that these methods may prove to be successful in rejuvenating a PRB. Although inorganic results from the treatability study and data collected from long-term bench-scale tests and field sites indicate that mineral precipitates may not be a problem for

perhaps decades at the site, to be conservative, ETI recommends that costing models consider implementation of these possible methods on a 10-year interval. Costs for mechanical agitation methods such as jetting or augering are estimated to be in the range of \$4 to \$10 per square foot.

5.0 SUMMARY

Bench-scale testing using groundwater from the Ash Landfill showed that:

- i) the EnviroMetal Process can degrade the chlorinated VOCs present to below the site remediation goals;
- ii) molar conversions and VOC degradation rates in the site water are similar to those observed in previous tests with relatively high total VOC concentrations and high dissolved organic carbon levels;
- iv) using the first-order degradation model adjusted for lower groundwater temperatures to simulate degradation of VOCs in the field, the residence times to degrade the anticipated VOC concentrations to below the New York State Class GA Standards range from 2.2 to 7 days for the Connelly iron source and from 3.2 to 7.5 days for the Peerless iron source;
- v) based on the reported groundwater velocity ranging from 0.43 ft/day (the source and middle wall) to 1.6 ft/day (the compliance wall), iron zone flow-through thickness requirements to achieve the New York State Class GA Standards are:
 - 3 and 3.2 ft for Connelly and Peerless iron, respectively in the source wall;
 - 1.3 and 1.4 ft for Connelly and Peerless iron, respectively, in the middle wall; and
 - 3.5 and 6.4 ft for Connelly and Peerless iron, respectively, in the compliance wall.
- vi) redox potential (Eh) and pH trends were consistent with bench-scale tests for other sites with relatively high total VOC concentrations;
- vii) although a variety of 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

Materials:		
Iron Source	Connelly-GPM, Chicago, IL	Peerless Metal Powders and Abrasives, Inc. Detroit, MI
Iron Grain Size	2.0 to 0.25 mm (-8 to +50 mesh)	2.0 to 0.25 mm (-8 to +50 mesh)
Iron Surface Area	1.8 m ² /g	1.5 m ² /g
Hydraulic conductivity	6×10 ⁻² (170 ft/day)	
Column:		
	100% Connelly Iron	100% Peerless Iron
Flow Velocity (ft/day)	1.6	1.4
Flow Velocity (cm/day)	49	43
Residence Time (hrs)	24.6	27.9
Pore Volume (mL)	352	358
Porosity	0.62	0.63
Bulk Density (g/cm ³)	2.68	2.25
Bulk Density (lb/ft ³)	167	141
Iron to Volume of Solution Ratio (g:mL)	4.3	3.6
Surface Area to Volume of Solution Ratio (m ² :mL)	7.8	5.4

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

Organic Compounds:	MDL (µg/L)
Trichloroethene	2.1
cis-1,2-Dichloroethene	1.3
trans-1,2-Dichloroethene	2.4
1,1-Dichloroethene	2.9
Vinyl Chloride	1.3
Inorganic Compounds	DL (mg/L)
Boron	0.01
Barium	0.005
Calcium	0.05
Iron, Total	0.01
Magnesium	0.05
Manganese	0.005
Potassium	1
Silica, Reactive	0.05
Sodium	0.1
Zinc	0.005
Ammonia (N)	0.03
Strontium	0.001
Nitrate (N)	0.2
Chloride	2
Sulphate	2
Bromide	0.5
Alkalinity (mg CaCO ₃ /L)	1
Dissolved Organic Carbon (DOC)	0.2
Total Dissolved Solids (Calculated)	6

Table 3: Room Temperature Bench-Scale Test Half-Lives at Steady State

Volatile Organic Compound	Influent Concentration^a (µg/L)	Half-Life^b (hr)	r^{2c}
Connelly iron column			
Trichloroethene	2282 ± 275	1.2 ± 0.1	0.984 - 0.999
cis-1,2-Dichloroethene	5364 ± 247	4.1 ± 1.0	0.904 - 0.991
trans-1,2-Dichloroethene	36 ± 1	0.8 ± 0.4	0.999
Vinyl Chloride	101 ± 8	9.5 ± 1.7	0.721 - 0.998
Peerless iron column			
Trichloroethene	2275 ± 238	0.93 ± 0.13	0.983 - 0.999
cis-1,2-Dichloroethene	5255 ± 230	7.7 ± 0.8	0.900 - 0.994
trans-1,2-Dichloroethene	36 ± 2	1.1 ± 0.5	0.999
Vinyl Chloride	101 ± 8	9.8 ± 5.7	0.909 - 0.989

r² = Coefficient of Determination

- a Average ± standard deviation measured in the influent of the last three VOC profiles in the bench-scale column test.
- b Average ± standard deviation for the least squares best fit curves determined from the last three VOC profiles in the bench-scale column test.
- c Range in r² for the least squares best fit curves determined from the last three VOC profiles in the bench-scale column test.

Table 4: Column Influent and Effluent Inorganic Concentrations at Steady State

	Influent	Effluent	
		Connelly	Peerless
		Concentration (mg/L)	
Cations:			
Barium	0.026	0.028	0.014
	0.024	0.022	0.011
Boron	0.39	0.45	0.51
	0.37	0.44	0.51
Calcium	221	140	141
	251	142	144
Iron	0.03	0.08	0.07
	nd	0.03	0.01
Magnesium	40	35	37
	40	34	37
Manganese	0.028	0.258	0.660
	0.005	0.227	0.571
Potassium	3	3	3
	3	3	4
Silica, Reactive	4.6	0.21	0.18
	4.5	0.10	0.11
Sodium	74	73	74
	78	74	74
Strontium	1.3	0.63	0.62
	1.3	0.60	0.62
Zinc	0.08	0.03	0.01
	0.08	nd	nd
Ammonia (as N)	nd	0.05	0.04
	0.03	0.03	0.03
Anions:			
Chloride	212	194	202
	213	192	194
Sulphate	426	389	387
	417	383	386
Bromide	1.7	1.9	2.2
	1.8	1.5	2.2
Alkalinity (as mg CaCO ₃ /L)	197	13	8
	245	8	7
Nitrate (as N)	nd	nd	nd
	nd	nd	nd
DOC	18	21	22
	22	21	22
TDS	1095	842	849
	1149	833	844

nd - not detected

Table 5: Residence Times the Proposed Iron PRBs at the Ash Landfill.

VOC	Anticipated Field Conc. (µg/L)	MCLs (µg/L)	Connelly iron		Peerless iron	
			Field Anticipated Half Life ^c (hr)	Residence Time (hrs) (days)	Field Anticipated Half Life ^c (hr)	Residence Time (hrs) (days)
<i>Source Wall ^a</i>						
TCE	1,000	5	3.0	92	2.4	171
cDCE	2,300	5	10.3	(3.8)	19.3	(7.1)
VC	27	2	23.8		24.5	
<i>Middle Wall ^b</i>						
TCE	530	5	3.0	72	2.4	76
cDCE	32	5	10.3	(3)	19.3	(3.2)
VC	16	2	23.8		24.5	
<i>Compliance Wall ^b</i>						
TCE	52	5	3.0	51	2.4	95
cDCE	150	5	10.3	(2.2)	19.3	(4.0)
VC	4	2	23.8		24.5	

Concentrations supplied by Parsons ES on 21 December 2001

Concentrations supplied by Parsons ES on 20 September 2001

Average half-lives obtained from the bench-scale test and adjusted by a factor of 2.5 for field temperature effect.



Table 6: Iron Requirements for the Proposed Iron PRBs at the Ash Landfill.

PRB location	PRB Parameter ^a	100% Connelly iron			100% Peerless iron		
		Residence time (days)	Required iron thickness ^b (ft)	Total amount of iron ^c (tons)	Residence time (days)	Required iron thickness ^b (ft)	Total amount of iron ^c (tons)
<i>Source wall</i>							
Length (ft)	700						
Saturated depth (ft)	11	3.8 ^d	1.6	924	7.1 ^d	3.1	1,790
GW velocity (ft/d)	0.43						
<i>Middle wall</i>							
Length (ft)	700						
Saturated depth (ft)	9	3	1.3	546	3.2	1.4	588
GW velocity (ft/d)	0.43						
<i>Compliance wall</i>							
Length (ft)	645						
Saturated depth (ft)	8	2.2	2.6 – 3.5	880 – 1,185	4	4.8 – 6.4	1,625 – 2,167
GW velocity (ft/d)	1.2 – 1.6						

Provided by Parsons ES

Residence time × groundwater velocity

Iron wall length × saturated depth × wall thickness × iron bulk density (0.075 ton/ft³)

Revised 21 December 2001

Table 7: Iron and Installation Cost (US\$) for the Proposed PRBs at the Ash Landfill.

Parameter	Connelly iron	Peerless iron
Source wall		
Amount of iron ^a (tons)	924	1,790
Iron cost @\$400 per ton	\$370,000	\$716,000
Construction Cost ^b @\$15/ft ²	\$140,000	
Subtotal	\$510,000	\$856,000
License fee (13%)	\$66,000	\$111,000
Total cost	\$576,000	\$967,000
Middle wall		
Amount of iron ^a (tons)	546	588
Iron cost @\$400 per ton	\$218,000	\$235,000
Construction Cost ^b @\$15/ft ²	\$120,000	
Subtotal	\$338,000	\$355,000
License fee (13%)	\$44,000	\$46,000
Total cost	\$382,000	\$401,000
Compliance wall		
Amount of iron ^{a, c} (tons)	880	1,625
Iron cost ^b @\$400 per ton	\$352,000	\$650,000
Construction Cost ^c @\$15/ft ²	\$102,000	
Subtotal	\$454,000	\$752,000
License fee (13%)	\$59,000	\$980,000
Total cost	\$513,000	\$850,000

^a From Table 6

^b Total depth of each PRB was assumed to be 2 ft more than the saturated depth, cost of construction plus mobilization/demobilization cost of \$25,000 was assumed

^c Iron amount determined based on a groundwater velocity value in the compliance wall of 1.2 ft/d

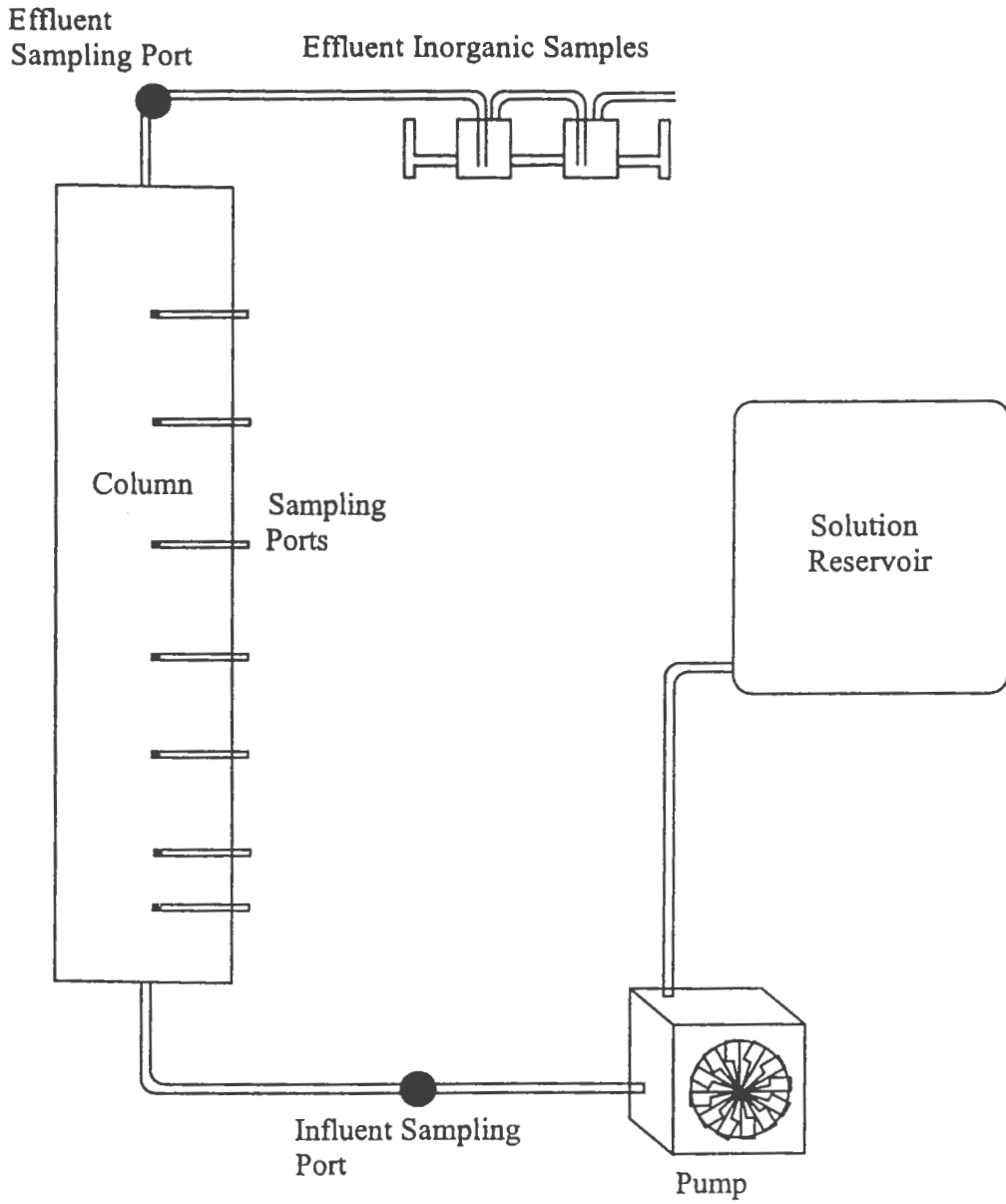
^d Revised 21 December 2001

Table 8: Comparison of Site Groundwater Inorganic Parameters to Other Installed Permeable Reactive Barrier Sites

Influent Groundwater Parameter	Ash Landfill, NY	Upstate, NY	Denver, CO	Sunnyvale, CA
Operational Data				
Date Installed	Proposed	May 1995	December 1995	February 1995
Years of Monitoring		2 ^a	3 ^a	6 ^b
Groundwater Flow Velocity (ft/day)	0.4 - 1.2	0.7 - 2.3	0.2 - 0.5	0.5 - 1.0
Iron Content (Percent)		100	100	100
Total VOCs (mg/L)	< 9.0	0.1 - 1.0	0.2 - 1.5	0.1 - 2.0
Inorganic Chemistry ^c				
Calcium (mg/L)	289	85 - 95	250 - 375	50 - 100
Magnesium (mg/L)	45	10 - 15	50	50 - 100
Total Iron (mg/L)	0.02	0.05 - 0.2	<0.1	0.05
Alkalinity (mg CaCO ₃ /L)	520	200 - 260	450 - 700	200 - 400
Sulphate (mg/L)	570	5 - 20	1,000 - 1,250	400
Nitrate/Nitrite (mg N/L)	0.03	0.2 - 0.5	0.1 - 2.5	NA
Total Dissolved Solids (mg/L)	1,200	375 - 475	2,000 - 2,500	1,500 - 3,000
Dissolved Organic Carbon (mg/L)	6.9	NA	NA	NA
Dissolved Oxygen (mg/L)	3.4	NA	0.1 - 1.0	1.5 - 2.5
pH	6.8	6.5 - 7.5	6 - 8	7.5 - 8.0
Eh (mV)	+108 ^d	+300 to -50	+200 to -100 ^d	+50 to +150

NA = Not Analyzed

- a Pilot-scale PRB still operational, but has not been monitored for the last few years.
- b Full-scale PRB still in operation and being monitored quarterly.
- c Inorganic data for Ash Landfill are based on monitoring data in well PT-18A from January 2000
- d Measurements of Oxidation-Reduction Potential (ORP), not converted to Eh.



Schematic of the Apparatus Used in the Bench Scale Test

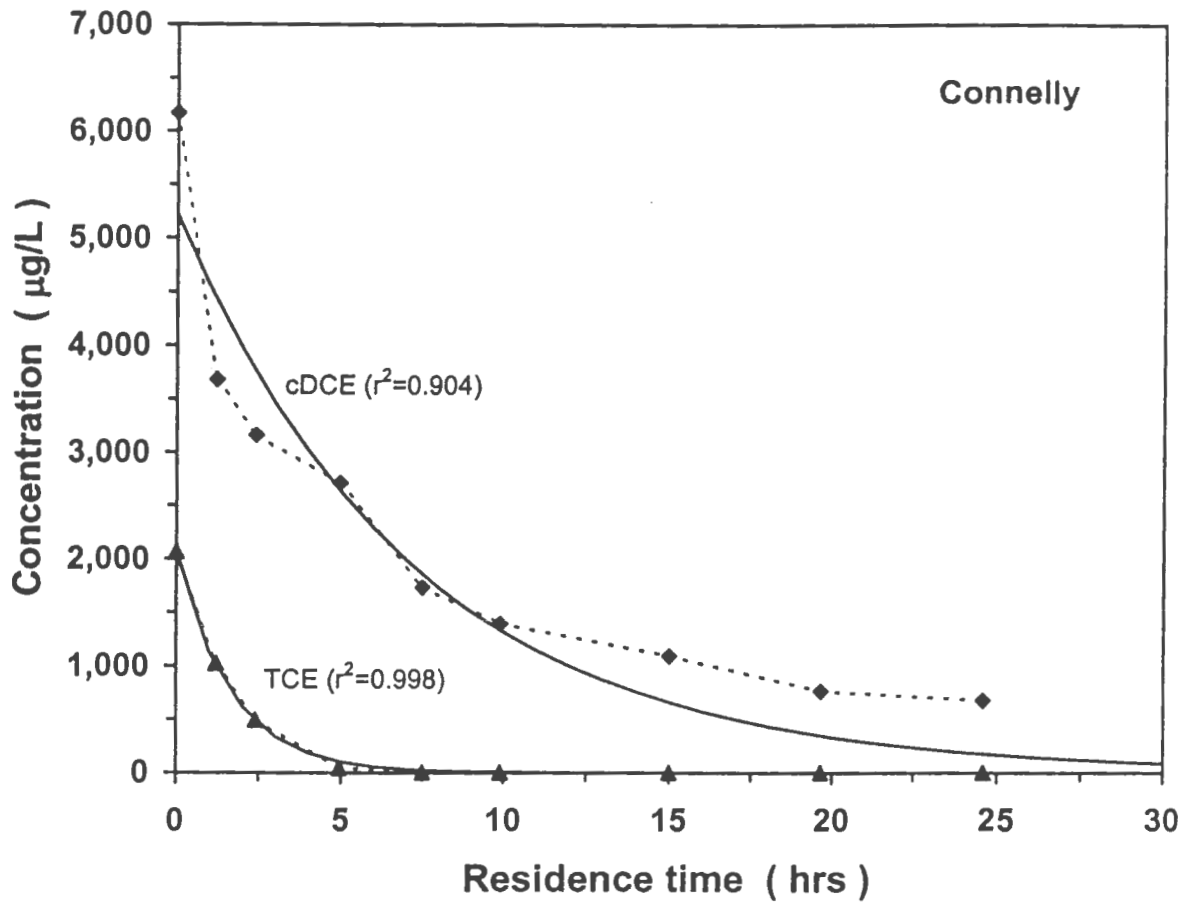


Figure 2: Trichloroethene (TCE) and cis-1,2-dichloroethene (cDCE) concentration profiles versus residence time (dotted lines) along the Connolly column. The solid lines represent the least squares best fits of the first-order kinetic model to the data.

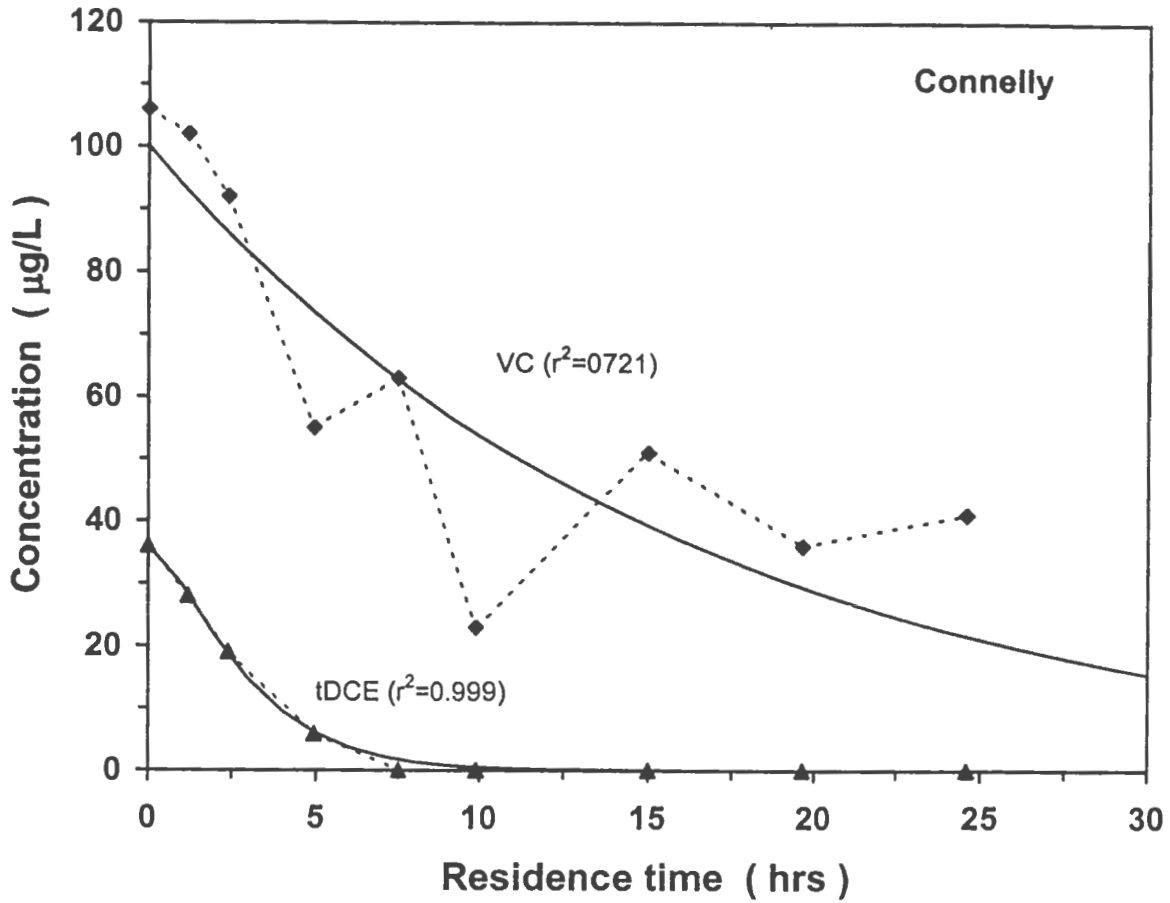


Figure 3: Trans 1,2 dichloroethene (tDCE) and vinyl chloride (VC) concentration profiles versus residence time (dotted lines) along the Connelly column. The solid lines represent the least squares best fits of the first-order kinetic model to the data.

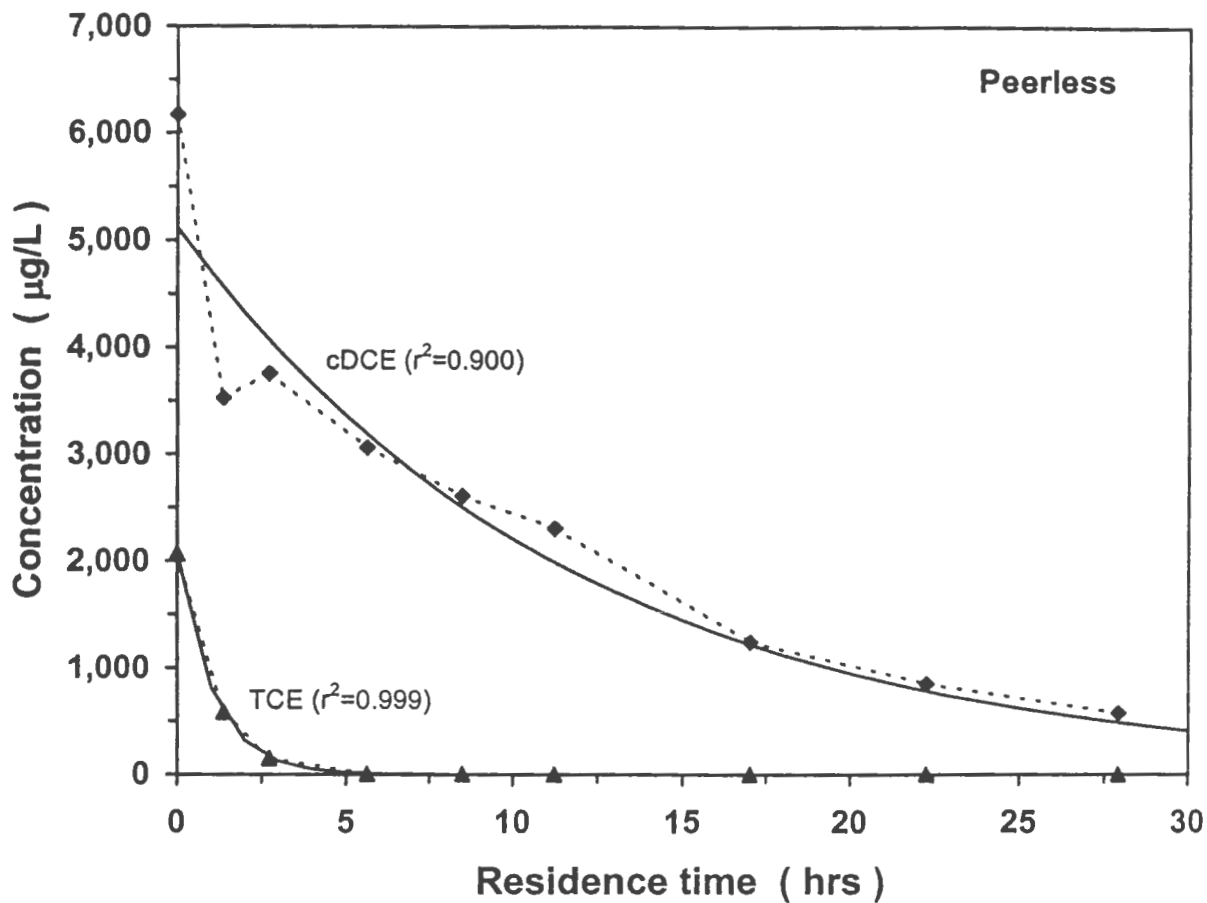


Figure 4: Trichloroethene (TCE) and cis-1,2-dichloroethene (cDCE) concentration profiles versus residence time (dotted lines) along the Peerless column. The solid lines represent the least squares best fits of the first-order kinetic model to the data.

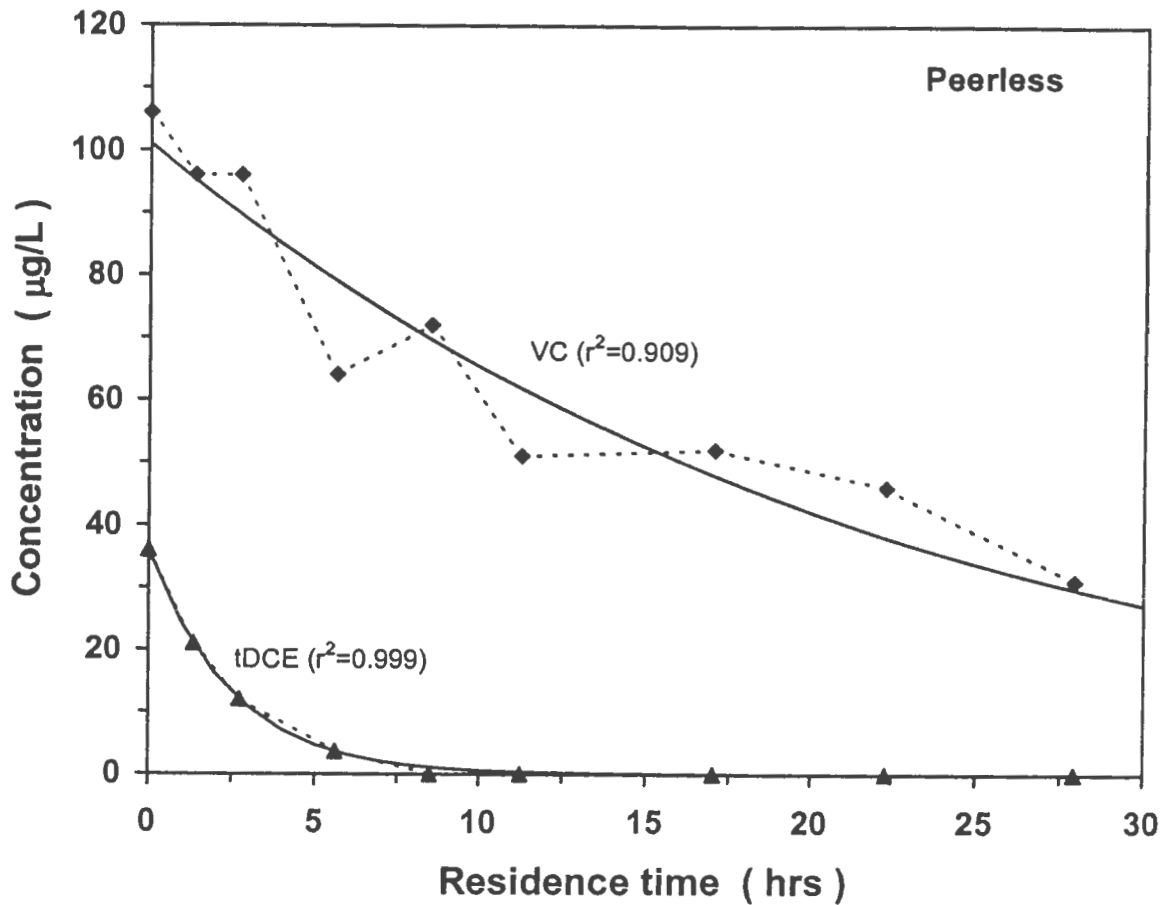


Figure 5: Trans 1,2 dichloroethene (tDCE) and vinyl chloride (VC) concentration profiles versus residence time (dotted lines) along the Peerless column. The solid lines represent the least squares best fits of the first-order kinetic model to the data.

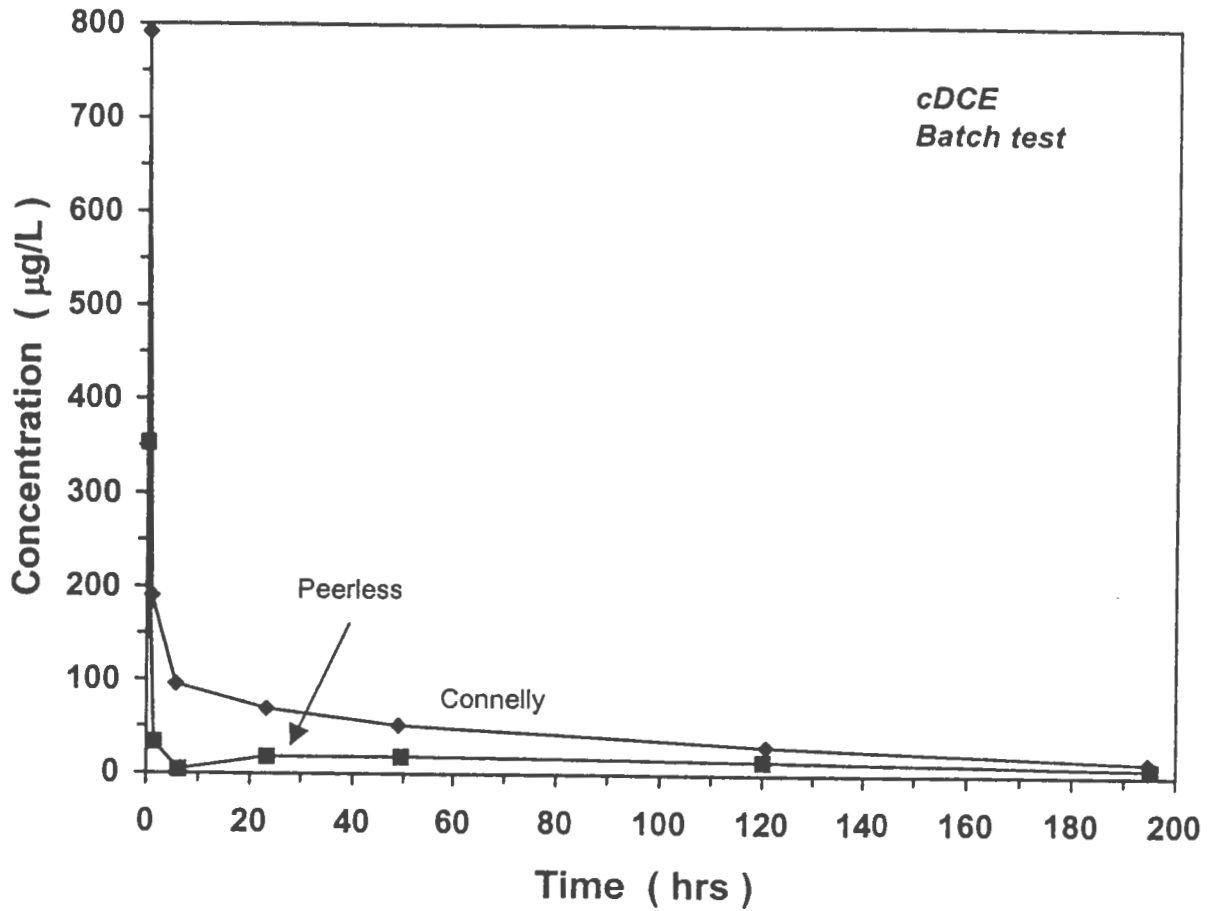


Figure 6: cDCE concentration versus time in the batch test.

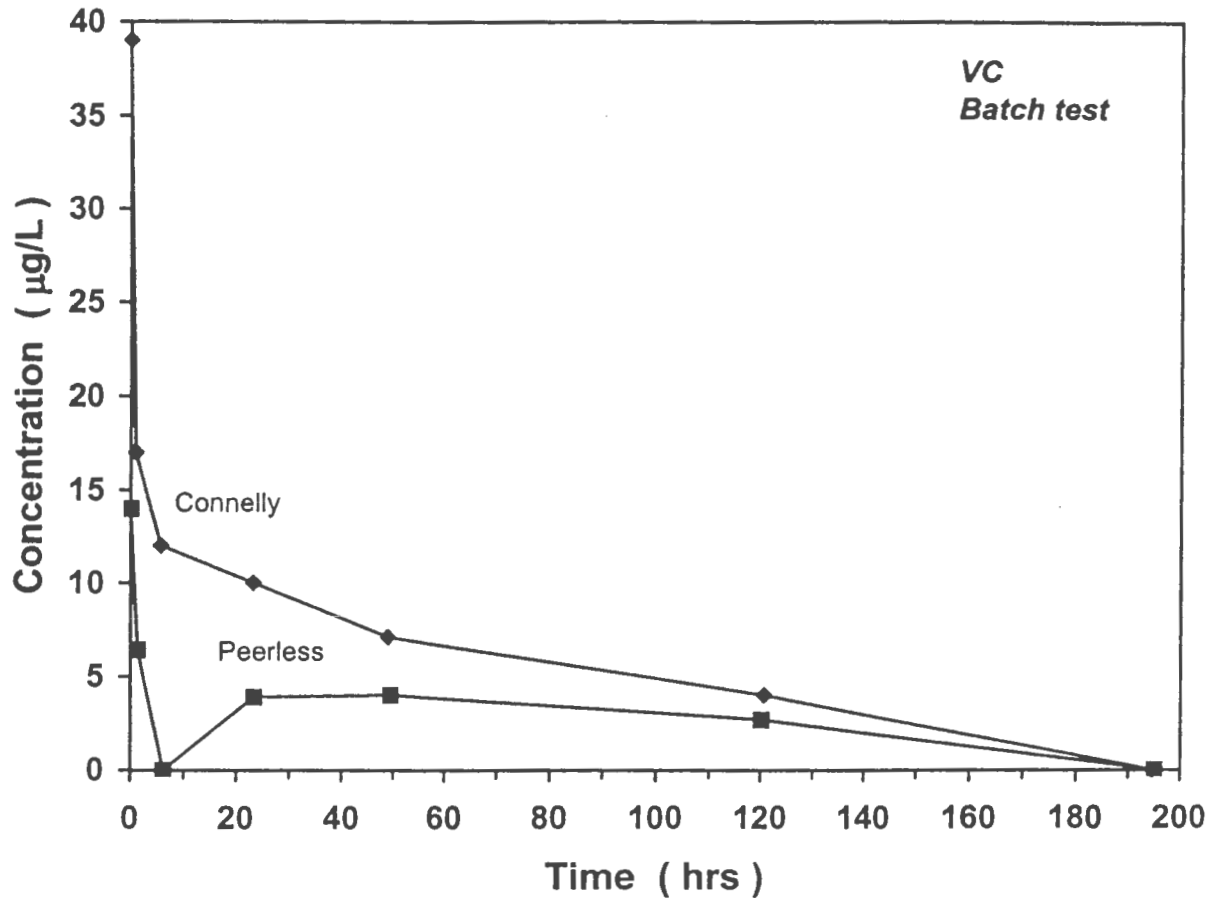
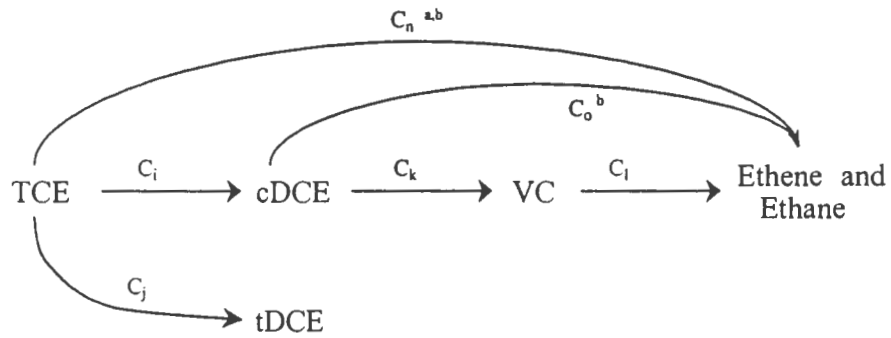


Figure 7: VC concentration versus time in the batch test.



- ^a Degradation pathway through chloroacetylene
^b Degradation pathway through acetylene

Conversion factor	Column	
	Connelly	Peerless
C_i (TCE \Rightarrow cDCE)	11%	0%
C_j (TCE \Rightarrow tDCE)	3%	1%
C_k (cDCE \Rightarrow VC)	0%	2%
C_l (VC \Rightarrow Eth.)	100%	100%
C_n (TCE \Rightarrow Eth.)	86%	99%
C_o (cDCE \Rightarrow Eth.)	100%	98%

Figure 8: Molar conversions obtained from the bench-scale column data.

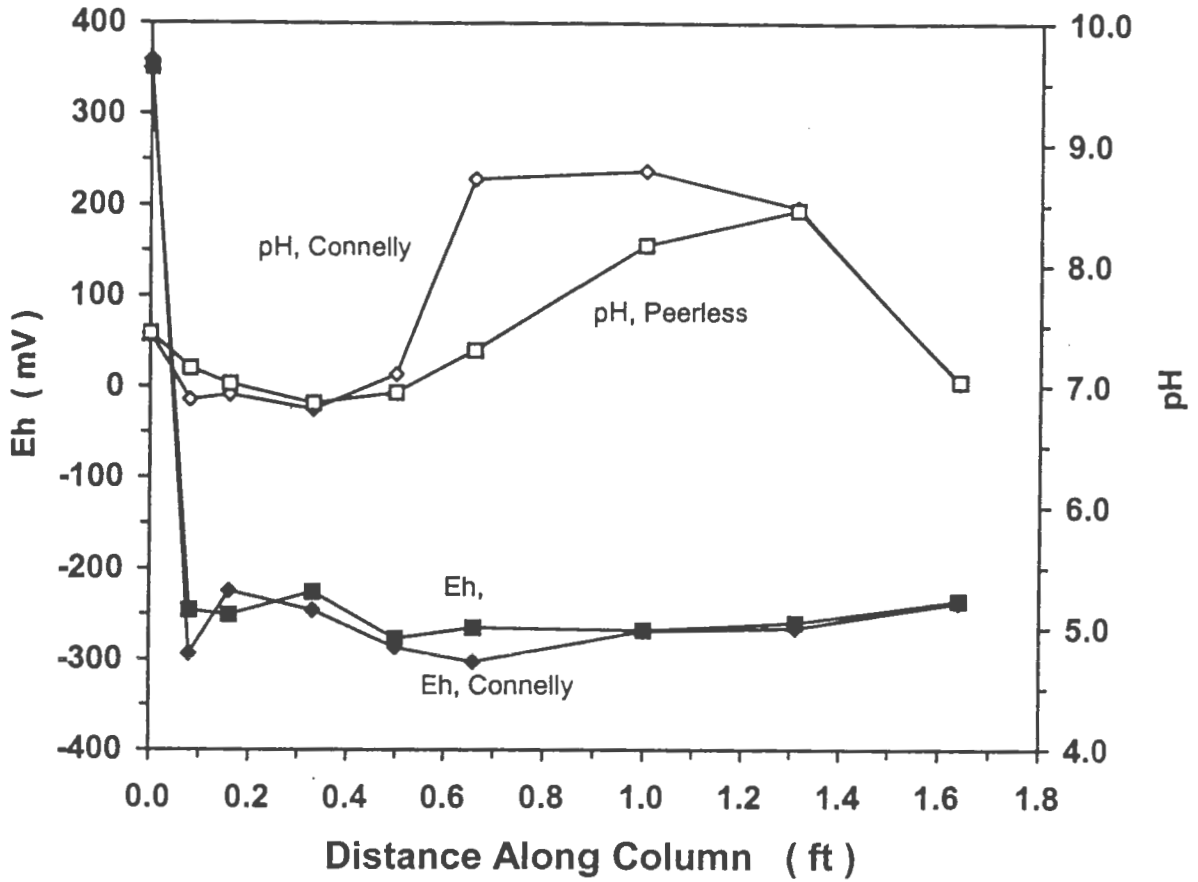


Figure 9: Redox potential (Eh) and pH profiles versus residence time along the columns.

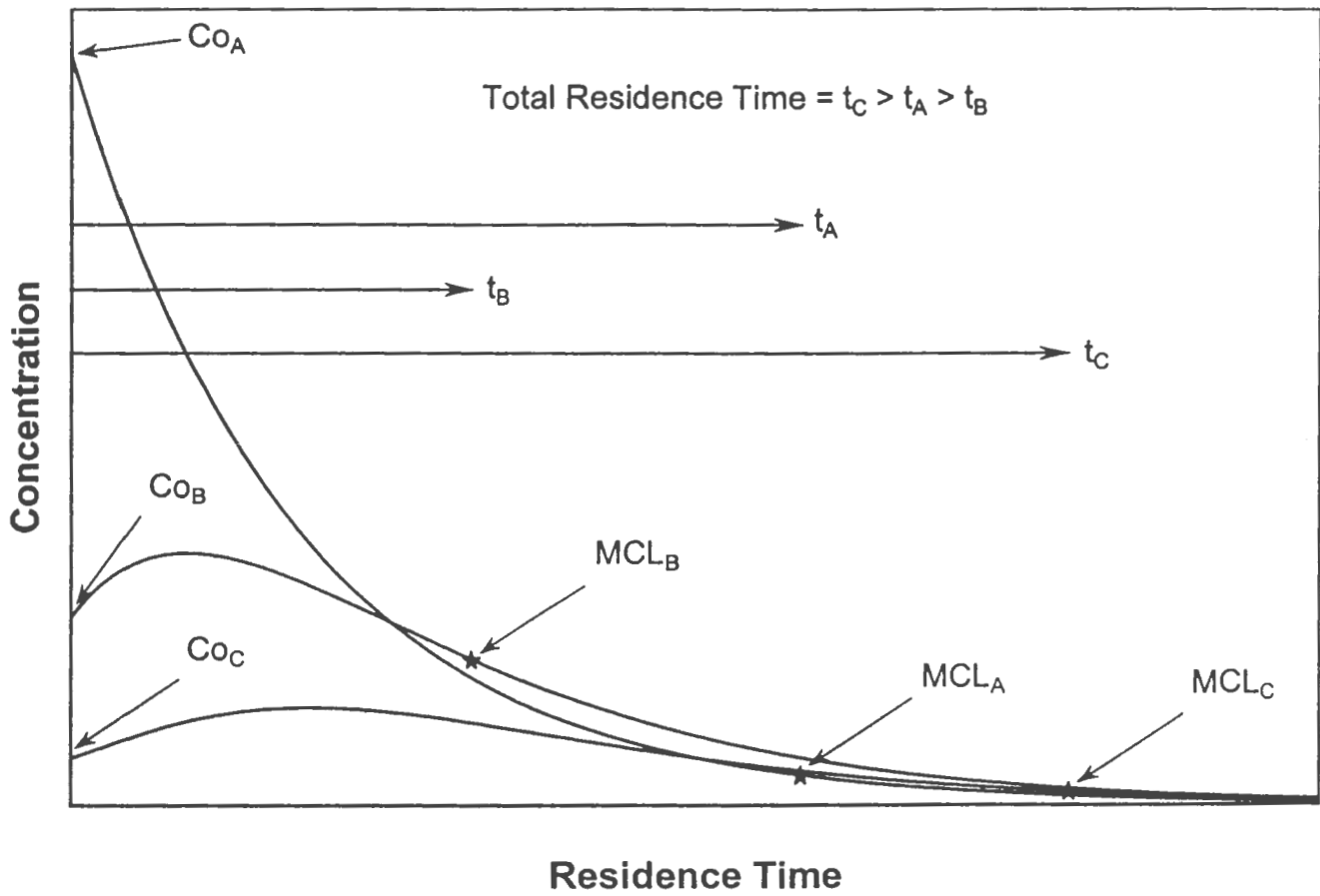


Figure 10: Illustration of residence time calculations using the degradation model.

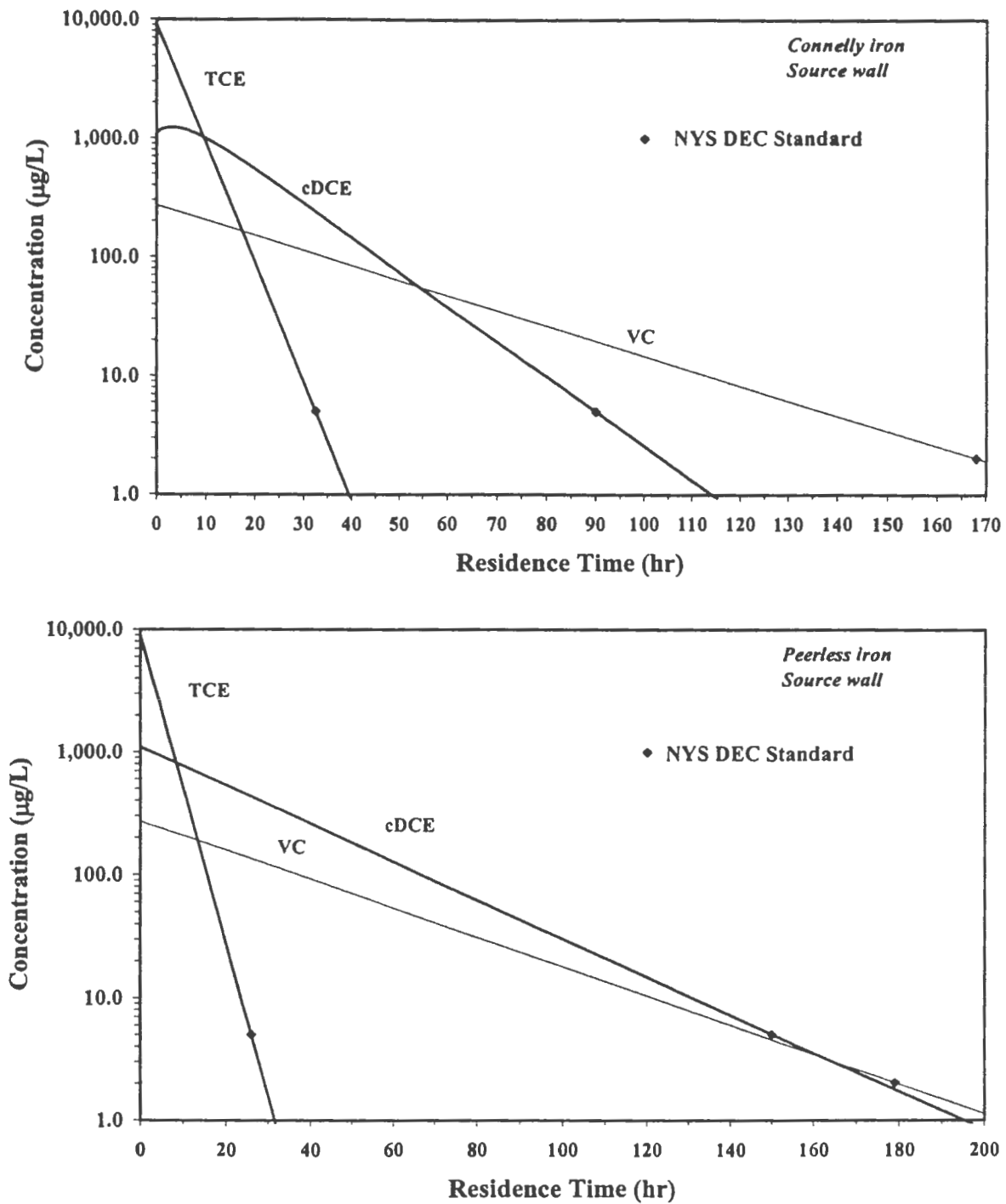


Figure 11: First-order kinetic model results for TCE, cDCE and VC for Connelly and Peerless iron using anticipated field concentrations and field-anticipated half-life values in the source wall.

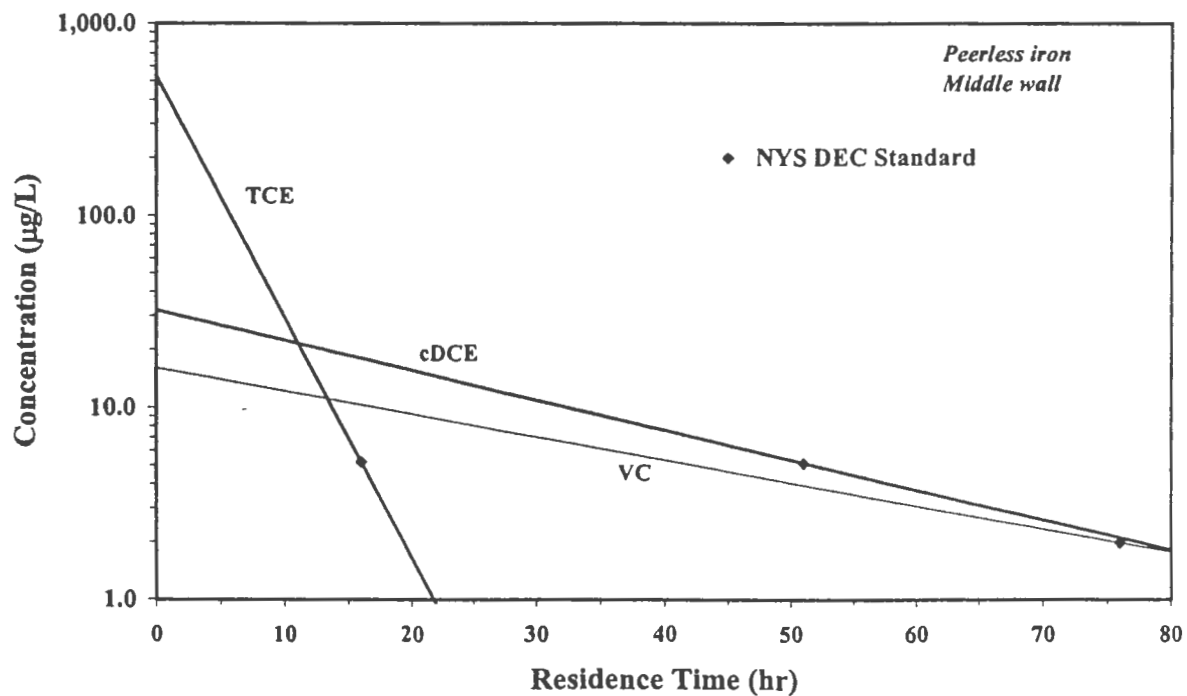
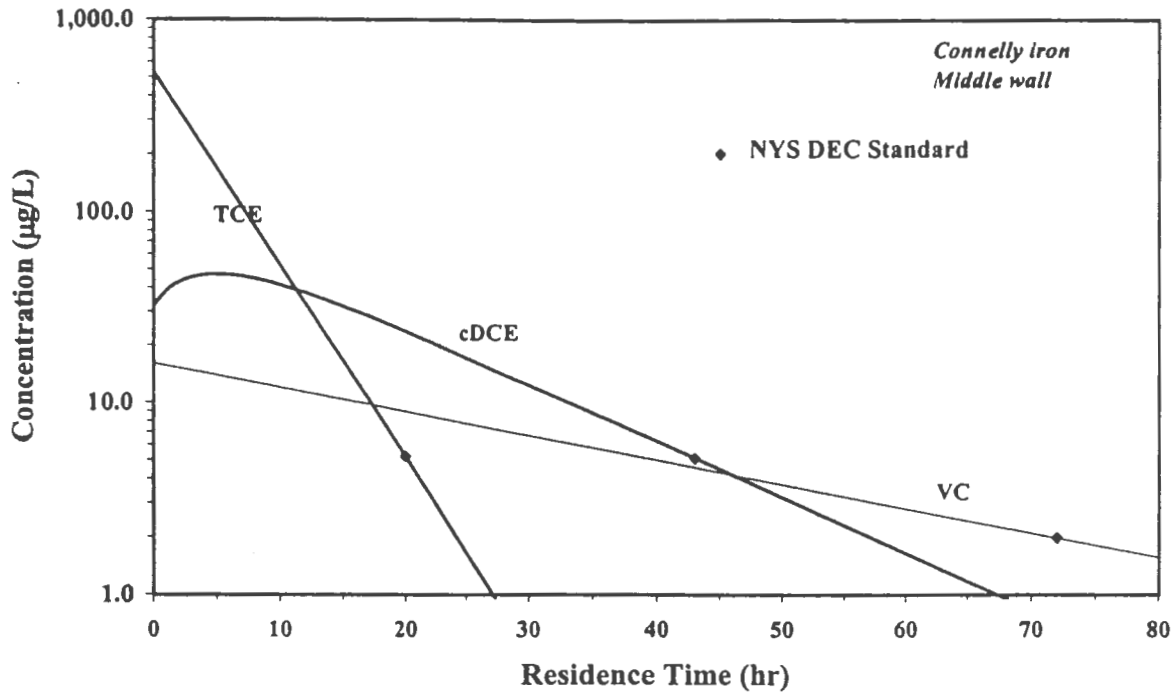


Figure 12: First-order kinetic model results for TCE, cDCE and VC for Connelly and Peerless iron using anticipated field concentrations and field-anticipated half-life values in the middle wall.

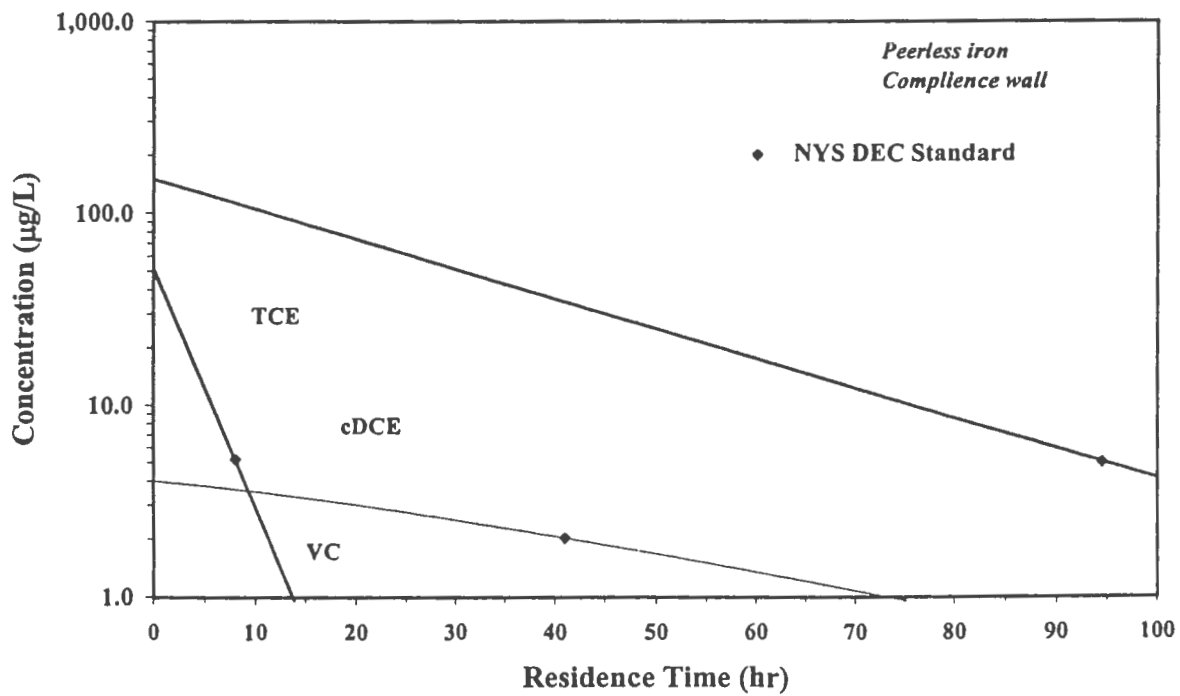
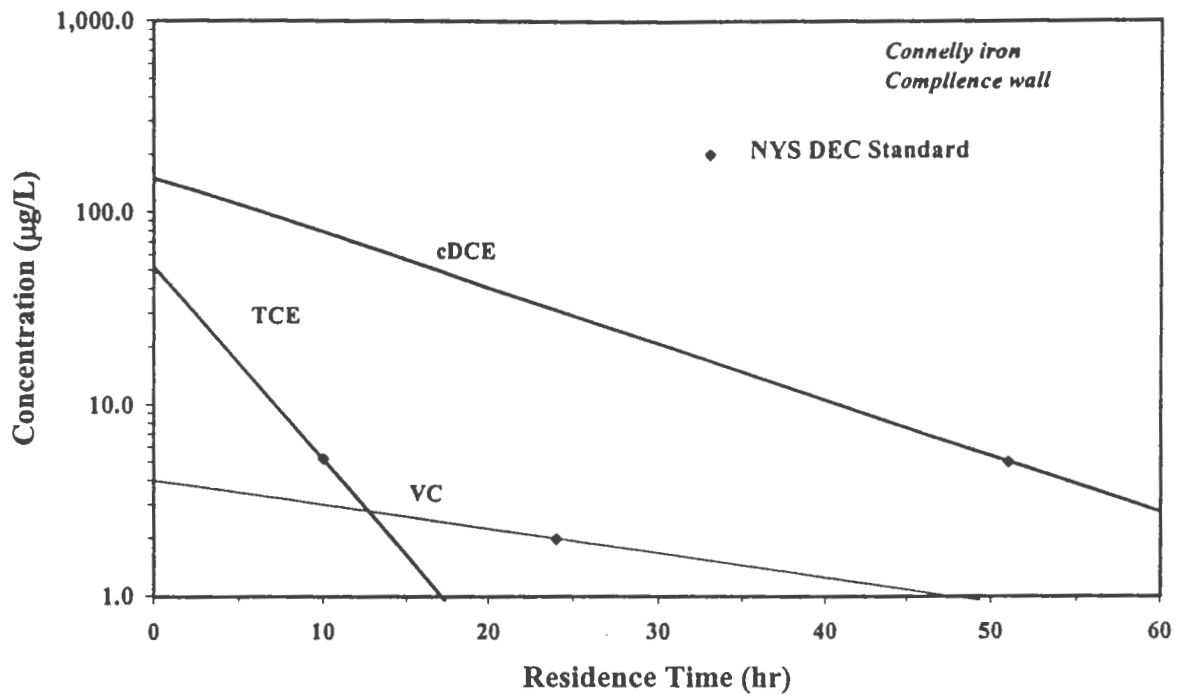


Figure 13: First-order kinetic model results for TCE, cDCE and VC for Connelly and Peerless iron using anticipated field concentrations and field-anticipated half-life values in the compliance wall.

Appendix A

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

Treatability Test
 Ash Landfill

Column Identification: 452
 Column Composition: 100% Connelly
 Pore Volume (PV): 352
 Porosity: 0.62
 Column Length: 1.6 ft (50 cm)
 Column Diameter: 1.5 in (3.8 cm)
 Flow Velocity: 1.6 ft/day (49 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	1.2	2.4	5.0	7.5	9.9	15.0	19.7	24.6

	PV	RN	Influent	Organic Concentration (µg/L)							Effluent	HL	r2
TCE													
	6.3	a	2253	242	27	2.2	nd	nd	nd	nd	nd		
	7.2	a	2072	294	45	6.2	nd	nd	nd	nd	nd		
	10.4	a	1404	64	26	nd	nd	nd	nd	nd	nd		
	10.4	a	1403	120	30	nd	nd	nd	nd	nd	nd		
	19.2	a	1332	214	37	15	4.6	2.3	nd	nd	nd		
	20.0	a	1278	197	31	11	6.3	4.9	nd	nd	nd		
	27.3	a	2023	732	179	7.4	nd	nd	nd	nd	nd		
	28.3	a	2203	843	216	10	nd	nd	nd	nd	nd		
	34.5	a	2760	1562	593	21	nd	nd	nd	nd	nd	1.2	0.986
	35.4	a	2693	1518	576	24	nd	nd	nd	nd	nd	1.2	0.987
	39.1	b	2209	1323	537	40	nd	nd	nd	nd	nd	1.3	0.984
	40.1	b	2241	1291	533	39	2.9	1.8	nd	nd	nd	1.2	0.992
	44.8	b	2062	1010	539	69	nd	nd	nd	nd	nd	1.2	0.999
	46.6	c	2066	1025	491	41	3.6	nd	nd	nd	nd	1.1	0.998
cDCE													
	6.3	a	5784	4416	3196	2746	3240	2631	1358	375	61		
	10.4	a	4061	1618	1548	872	816	473	136	74	24		
	19.2	a	5288	1500	928	596	327	440	489	473	187		
	28.3	a	6236	4476	1940	1242	590	371	128	86	71		
	35.4	a	5533	5020	3300	2150	1314	751	290	129	79	3.1	0.991
	40.1	b	5335	4499	3084	2416	1536	1038	651	482	282	4.3	0.985
	46.6	c	6170	3681	3158	2708	1732	1394	1092	761	676	5.0	0.904
tDCE													
	6.3	a	60	11	4.7	1.7	2.1	nd	nd	nd	nd		
	10.4	a	38	2.9	4.3	nd	nd	nd	nd	nd	nd		
	19.2	a	35	7.1	2.5	1.5	nd	nd	nd	nd	nd		
	28.3	a	45	17	7.7	3.0	nd	nd	nd	nd	nd		
	35.4	a	36	23	12	3.1	nd	nd	nd	nd	nd	0.42	0.999
	40.1	b	37	25	15	4.4	nd	nd	nd	nd	nd	1.8	0.994
	46.6	c	36	28	19	5.8	nd	nd	nd	nd	nd	1.1	0.999

nd = not detected
 RN = reservoir number
 HL = half life (hours)
 r2 = coefficient of variation

Treatability Test
 Ash Landfill

Column Identification: 452
 Column Composition: 100% Connelly
 Pore Volume (PV): 352
 Porosity: 0.62
 Column Length: 1.6 ft (50 cm)
 Column Diameter: 1.5 in (3.8 cm)
 Flow Velocity: 1.6 ft/day (49 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	1.2	2.4	5.0	7.5	9.9	15.0	19.7	24.6

	PV	RN	Influent	Organic Concentration (µg/L)							Effluent	HL	r2
11DCE													
	6.3	a	2.0	4.3	3.6	2.0	1.7	nd	nd	nd	nd		
	10.4	a	2.8	nd	2.9	nd	nd	nd	nd	nd	nd		
	19.2	a	2.7	2.4	1.5	1.7	nd	nd	nd	nd	nd		
	28.3	a	2.8	5.6	4.3	3.1	nd	nd	nd	nd	nd		
	35.4	a	2.4	4.3	4.4	2.2	nd	nd	nd	nd	nd	ND	
	40.1	b	1.7	2.9	3.7	2.0	nd	nd	nd	nd	nd	ND	
	46.6	c	nd	2.3	2.7	1.6	1.9	nd	nd	2.7	nd	ND	
VC													
	6.3	a	159	115	95	95	92	82	68	55	15		
	10.4	a	99	22	49	40	37	32	18	10	5.2		
	19.2	a	91	40	28	19	9.2	15	16	12	8.4		
	28.3	a	80	62	44	37	27	19	11	9.2	7.2		
	35.4	a	98	91	78	63	52	43	27	17	9.9	7.7 0.998	
	40.1	b	111	95	83	68	55	46	38	31	25	9.7 0.967	
	46.6	c	106	102	92	55	63	23	51	36	41	11.1 0.721	
pH Along Column													
pH													
	4.5	a	7.4	7.2	7.5	7.9	8.6	8.6	8.2	8.2	7.0		
	11.1	a	7.3	7.1	7.5	8.6	8.7	8.8	8.8	8.5	7.9		
	21.9	a	7.3	7.0	7.2	7.4	8.0	7.6	8.8	8.7	8.1		
	26.6	a	7.3	7.0	7.2	7.6	8.3	8.8	9.1	9.3	8.7		
	33.6	a	7.7	7.3	7.4	7.6	7.6	8.6	9.1	9.2	7.9		
	41.9	b	7.4	6.9	6.9	6.8	7.1	8.7	8.8	8.5	7.0		
Redox Potential Along Column (mV)													
Eh													
	4.5	a	331	-313	-296	-357	-303	-348	-373	-398	-308		
	11.1	a	293	-310	-367	-375	-332	-379	-350	-361	-323		
	21.9	a	332	-234	-189	-297	-274	-273	-336	-258	-300		
	26.6	a	271	-292	-288	-282	-301	-269	-304	-282	-225		
	33.6	a	281	-358	-317	-246	-326	-432	-484	-549	-356		
	41.9	b	359	-294	-225	-246	-287	-303	-269	-266	-238		

nd = not detected
 ND = not determined
 RN = reservoir number
 HL = half life (hours)
 r2 = coefficient of variation

Treatability Test
 Ash Landfill

Column Identification: 453
 Column Composition: 100% Peerless
 Pore Volume (PV): 358
 Porosity: 0.63
 Column Length: 1.6 ft (50 cm)
 Column Diameter: 1.5 in (3.8 cm)
 Flow Velocity: 1.4 ft/day (43 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	1.4	2.7	5.6	8.5	11.2	17.0	22.3	27.9

	PV	RN	Influent	Organic Concentration (µg/L)							Effluent	HL	r2
TCE													
	5.5	a	2213	228	5.8	nd	nd	nd	nd	nd	nd		
	6.2	a	2162	277	10	nd	nd	nd	nd	nd	nd		
	9.0	a	1403	229	6.3	nd	nd	nd	nd	nd	nd		
	9.0	a	1411	242	5.6	nd	nd	nd	nd	nd	nd		
	16.7	a	1182	215	37	11	nd	nd	nd	nd	nd		
	17.4	a	1215	203	28	8.2	4.3	nd	nd	nd	nd		
	23.8	a	2023	756	98	5.0	nd	nd	nd	nd	nd		
	24.6	a	2203	965	156	3.0	nd	nd	nd	nd	nd		
	30.4	a	2717	1003	227	6.6	5.3	nd	nd	nd	nd	0.88	0.997
	31.3	a	2638	994	238	3.2	nd	nd	nd	nd	nd	0.90	0.997
	34.6	b	2270	994	222	6.2	nd	nd	nd	nd	nd	1.0	0.991
	35.5	b	2266	1093	217	5.3	nd	nd	nd	nd	nd	1.1	0.983
	39.6	b	2060	791	186	nd	nd	nd	nd	nd	nd	0.91	0.998
	41.3	c	2066	584	150	4.0	2.1	nd	nd	nd	nd	0.70	0.999
cDCE													
	5.5	a	5784	8267	5912	4726	4326	3183	15	nd	nd		
	9.0	a	4104	3003	5832	1874	912	173	147	62	21		
	16.7	a	3562	2264	3128	2333	2272	2034	1246	1314	716		
	24.6	a	6236	5126	3682	2696	1860	1544	888	435	172		
	31.3	a	5533	4891	4071	3060	2152	1980	1060	419	245	6.8	0.994
	35.5	b	5178	4826	3537	3188	2612	2036	1186	670	383	8.0	0.984
	41.3	c	6170	3525	3756	3060	2604	2304	1244	848	573	8.2	0.900
tDCE													
	5.5	a	59	16	5.4	nd	nd	nd	nd	nd	nd		
	9.0	a	37	11	2.7	nd	nd	nd	nd	nd	nd		
	16.7	a	31	8.5	4.1	2.7	nd	1.1	nd	nd	nd		
	24.6	a	45	23	8.4	1.7	nd	nd	nd	nd	nd		
	31.3	a	35	21	10	1.9	nd	nd	nd	nd	nd	0.14	0.998
	35.5	b	38	25	13	2.7	nd	nd	nd	nd	nd	0.80	0.999
	41.3	c	36	21	12	3.6	nd	nd	nd	nd	nd	1.6	0.999

nd = not detected
 RN = reservoir number
 HL = half life (hours)
 r2 = coefficient of variation

Treatability Test
 Ash Landfill
 Column Identification: 453
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 Flow Velocity: 1.4 ft/day (43 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	1.4	2.7	5.6	8.5	11.2	17.0	22.3	27.9

	PV	RN	Influent	Organic Concentration (µg/L)							Effluent	HL	r2
11DCE													
	5.5	a	2.2	3.5	2.2	nd	nd	nd	nd	nd	nd		
	9.0	a	2.8	2.4	nd	nd	nd	nd	nd	nd	nd		
	16.7	a	2.7	2.3	1.6	nd	nd	nd	nd	nd	nd		
	24.6	a	2.8	5.5	3.2	nd	nd	nd	nd	nd	nd		
	31.3	a	2.1	3.1	2.8	nd	nd	nd	nd	nd	nd	ND	
	35.5	b	1.7	2.7	2.2	nd	nd	nd	nd	nd	nd	ND	
	41.3	c	nd	3.9	3.3	1.7	4.2	2.0	2.6	nd	3.1	ND	
VC													
	5.5	a	157	138	141	115	123	119	88	16	1.7		
	9.0	a	99	77	45	32	55	16	12	8.1	2.2		
	16.7	a	83	56	55	48	48	44	30	26	37		
	24.6	a	80	77	68	59	55	27	35	24	13		
	31.3	a	95	94	86	84	67	66	40	15	15	11.5 0.674	
	35.5	b	112	102	92	86	80	61	49	29	27	13.6 0.981	
	41.3	c	106	96	96	64	72	51	52	46	31	15.8 0.909	
pH Along Column													
pH													
	3.9	a	7.3	7.2	7.4	8.4	8.7	8.5	8.8	8.3	7.0		
	9.7	a	7.3	7.1	7.2	8.0	8.8	8.7	8.8	8.6	8.2		
	19.0	a	7.4	7.0	7.1	7.3	8.2	7.3	8.2	8.3	7.9		
	23.1	a	7.3	7.0	7.1	7.2	8.0	8.4	9.1	8.7	8.3		
	28.8	a	7.4	7.0	7.1	7.3	8.3	8.0	8.5	8.1	7.4		
	37.1	b	7.4	7.2	7.0	6.9	7.0	7.3	8.2	8.5	7.0		
Redox Potential Along Column (mV)													
Eh													
	3.9	a	320	-322	-346	-314	-291	-335	-424	-392	-324		
	9.7	a	293	-286	-313	-390	-409	-318	-341	-346	-297		
	19.0	a	324	-269	-289	-220	-250	-265	-276	-235	-198		
	23.1	a	276	-300	-282	-302	-290	-293	-253	-283	-216		
	28.8	a	329	-216	-264	-281	-276	-296	-311	-207	-181		
	37.1	b	351	-246	-251	-226	-277	-265	-268	-260	-236		

nd = not detected
 ND = not determined
 RN = reservoir number
 HL = half life (hours)
 r2 = coefficient of variation

Appendix B

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



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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	C ICAP mg
2 influent	<0.005	<0.03	<0.2	0.39	0.026	<0.0005	<0.2	22
3 Effluent Connolly 33 PV	<0.005	0.03	<0.2	0.45	0.028	<0.0005	<0.2	14
4 Effluent Keenless 28 PV	<0.005	<0.03	<0.2	0.51	0.014	<0.0005	<0.2	14
5 influent	<0.005	<0.03	<0.2	0.37	0.024	<0.0005	<0.2	25
5 Effluent Connolly 35 PV	<0.005	<0.03	<0.2	0.44	0.022	<0.0005	<0.2	14
7 Effluent Keenless 31 PV	<0.005	<0.03	<0.2	0.51	0.011	<0.0005	<0.2	14
8+Spike (found)	---	---	1.0	---	---	0.964	---	---
8+Spike (expected)	---	---	1.0	---	---	1.00	---	---
Standard (found)	<0.005	<0.03	<0.2	<0.01	<0.005	<0.0005	<0.2	<
Standard (expected)	0.029	9.63	1.1	0.10	0.955	0.974	1.1	53
Standard (expected)	0.030	10.0	1.0	0.20	1.00	1.00	1.0	51
Standard (expected)	<0.005	<0.03	<0.2	0.37	0.023	<0.0005	<0.2	232

UW-462



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Water Samples

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
2 Influent	<0.005	<0.005	<0.005	<0.005	0.03	3	39.9	0
3 Effluent CON 33PV	<0.005	<0.005	<0.005	<0.005	0.08	3	34.7	0
4 Effluent PL 29PV	<0.005	<0.005	<0.005	<0.005	0.07	3	36.5	0
5 Influent	<0.005	<0.005	<0.005	<0.005	<0.01	3	39.6	0
6 Effluent CON 35PV	<0.005	<0.005	<0.005	<0.005	0.03	3	33.9	0
7 Effluent PL 31PV	<0.005	<0.005	<0.005	<0.005	0.01	4	36.7	0
8 e+Spike (found)	0.973	0.948	0.939	0.924	0.95	---	---	---
9 e+Spike (expected)	1.00	1.00	1.00	1.00	1.03	---	---	1
10 Standard (found)	<0.005	<0.005	<0.005	<0.005	<0.01	<1	<0.05	<0
11 Standard (expected)	1.03	0.995	0.976	0.928	0.96	9	10.8	0
12 Standard (expected)	1.00	1.00	1.00	1.00	1.00	10	11.0	1
13 e UW-462	<0.005	<0.005	<0.005	0.006	0.02	4	39.9	0



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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	IC
2 Influent	<0.02	73.7	<0.02	<0.1	<0.05	137.	<0.2	mg
3 Effluent 33PV CON	<0.02	72.6	<0.02	0.1	<0.05	132.	<0.2	
4 Effluent 29PV PL	<0.02	74.1	<0.02	0.2	<0.05	136.	<0.2	
5 Influent	<0.02	77.6	<0.02	0.1	<0.05	144.	<0.2	
6 Effluent 35PV CON	<0.02	73.5	<0.02	<0.1	<0.05	133.	<0.2	
7 Effluent 31PV PL	<0.02	73.7	<0.02	<0.1	<0.05	137.	<0.2	
8+Spike (found)	0.92	---	0.94	---	0.96	---	1.0	
9+Spike (expected)	1.00	---	1.00	---	1.00	---	1.0	
10 Standard (found)	<0.02	<0.1	<0.02	<0.1	<0.05	<0.1	<0.2	
11 Standard (expected)	1.09	46.4	1.00	2.1	1.03	10.3	1.0	
12 Standard (expected)	1.10	50.0	1.00	2.0	1.00	10.0	1.0	
13 UW-462	<0.02	71.4	<0.02	<0.1	<0.05	141.	<0.2	



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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	F- SM 4500F mg/L	Cl- SM 4500 mg
2 Influent	4.62	<0.05	1.30	<0.005	<0.005	0.008	<0.1	21
3 Effluent CON 33PV	0.21	<0.05	0.634	<0.005	<0.005	0.030	<0.1	19
4 Effluent PL 28PV	0.18	<0.05	0.624	<0.005	<0.005	0.010	<0.1	20
5 Influent	4.50	<0.05	1.29	<0.005	<0.005	0.008	<0.1	21
5 Effluent CON 35PV	0.10	<0.05	0.597	<0.005	<0.005	<0.005	<0.1	19
7 Effluent PL 31PV	0.11	<0.05	0.622	<0.005	<0.005	<0.005	<0.1	19
++Spike (found)	---	---	---	0.896	0.941	0.978	---	---
++Spike (expected)	---	---	---	1.00	1.00	1.00	---	---
Standard (found)	<0.05	<0.05	<0.001	<0.005	<0.005	<0.005	<0.1	<0.1
Standard (expected)	2.06	1.07	0.898	0.908	0.952	0.983	5.6	35
Standard (expected)	2.00	1.00	1.00	1.00	1.00	1.00	6.0	35
UW-462	4.66	<0.05	1.16	<0.005	<0.005	0.008	<0.1	<0.1



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Sample Id	NO2-N SM 4110B	PO4-3 SM 4110B	Br- SM 4110B	NO3-N SM 4110B	SO4= SM 4110B	pH SM 4500B	Alk 8.3 SM 2320B
	mg/L	mg/L	mg/L	mg/L	mg/L	Units	mg CaCO3/L
2 Influent	<0.2	<1	1.7	<0.2	426.	7.74	<1
3 Effluent CON 33PV	<0.2	<1	1.9	<0.2	389.	6.76	<1
4 Effluent PL 28PV	<0.2	<1	2.2	<0.2	387.	6.69	<1
5 Influent	<0.2	<1	1.8	<0.2	417.	7.68	<1
6 Effluent CON 35PV	<0.2	<1	1.5	<0.2	383.	6.82	<1
7 Effluent PL 31PV	<0.2	<1	2.2	<0.2	386.	6.71	<1
e+Spike (found)	---	---	---	---	---	---	---
e+Spike (expected)	---	---	---	---	---	---	---
standard (found)	<0.2	<1	<0.5	<0.2	<2.0	---	<1
standard (expected)	10.0	9	9.8	17.0	439.	7.03	114
t UW-462	10.0	9	10.0	17.0	450.	7.00	125
	<0.2	<1	1.9	<0.2	---	7.76	---



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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	CAB Calc. %	Hard(Calc) SM 2340B mg CaCO3/L
2 Influent	197	<0.03	18.2	1095	6.88	3.12	718.3
3 Effluent 33PV CON	13	0.05	20.8	842	8.24	2.65	493.6
4 Effluent 24PV PL	8	0.04	22.1	849	8.43	1.97	504.1
5 Influent	245	0.03	21.6	1149	6.73	0.77	792.1
6 Effluent 35PV CON	8	0.03	21.0	833	8.43	1.40	494.8
7 Effluent 31PV PL	7	0.03	22.1	844	8.48	0.29	513.3
ee+Spike (found)	---	0.58	---	nan	nan	nan	nan
ee+Spike (expected)	---	---	---	nan	nan	nan	nan
andard (found)	1	<0.03	<0.2	6	12.50	52.4	0.3
andard (expected)	50	1.48	9.7	939	8.08	54.2	178.5
t UW-462	50	1.50	10.0	952	8.10	54.3	172.6
	---	0.10	21.1	nan	nan	nan	744.1



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Sample Id	CO3= Calc. mg/L	HCO3- Calc. mg/L	L.I. Calc.		A.I. Calc.		R.S.I. Calc.		Turb. NTU	Sp. Cond. SM 2510B umhos/cm
			None	None	None	None	None	None		
2 Influent	1	238	0.9	12.89	6.0	1.2	1364			
3 Effluent CON 31PV	1	13	-1.5	10.57	9.7	0.6	1149			
4 Effluent PL 29PV	1	8	-1.7	10.32	10.2	0.4	1157			
5 Influent	1	296	0.9	12.97	5.8	1.0	1487			
5 Effluent CON 35PV	1	8	-1.6	10.43	10.0	0.6	1136			
7 Effluent PL 31PV	1	6	-1.8	10.28	10.3	0.4	1143			
8+Spike (found)	nan	nan	nan	nan	nan	---	---			
8+Spike (expected)	nan	nan	nan	nan	nan	---	---			
Standard (found)	68	0	-1.0	10.98	9.1	<0.2	731			
Standard (expected)	75	0	-1.1	10.94	9.2	1.8	718			
Standard UW-462	nan	nan	nan	nan	nan	---	1361			



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Work recorded herein has been done in accordance with normal professional standards using accepted testing methodologies and QA/QC procedures. Philip Analytical is limited in liability to the actual work of the pertinent analyses done unless otherwise agreed upon by actual arrangement. Your samples will be retained by PASC for a period of 30 days following reporting or as per specific contractual agreements.

Approved by:

Signature:

Ralph Siebert, B.Sc.
Section Supervisor, Metals

Appendix C

Laboratory Organic Analyses for Batch Testing Involving the EnviroMetal Process

Batch 181

Start date : 05-Sept-2001

Column 452 - Connelly Iron

Column 453 - Peerless Iron

Column 452 Connelly Iron

	VC (ug/L)	cDCE (ug/L)	Time (hr)
Start	43	830	0
Middle	41	765	0
End	39	791	0
6096	39	791	0
6097	17	190	1.0
6098	12	95	5.7
6099	10	69	23.2
6100	7.1	51	49.0
6101	4.0	30	120.7
6102	0	14	194.7

Column 453 Peerless Iron

	VC (ug/L)	cDCE (ug/L)	Time (hr)
Start	28	449	0
Middle	27	584	0
End	25	562	0
6084	14	353	0
6085	6.4	33	1.4
6086	nd	4.2	6.2
6087	3.9	18	23.3
6088	4.0	18	49.5
6089	2.7	14	120.1
6090	0	7.7	195.1

Iron Weights

	Wt of Iron (g)	Wt of Sol'n (g)
6097	59.6084	28.8323
6098	59.5546	28.9472
6099	59.5371	28.6703
6100	59.6776	29.6428
6101	59.5984	29.0824
6102	59.5994	29.0824

	Wt of Iron (g)	Wt of Sol'n (g)
6085	59.4626	28.3876
6086	59.5740	28.2684
6087	59.5425	28.2284
6088	59.6036	28.8484
6089	59.5341	28.1280
6090	59.6188	29.5842