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BENCH SCALE TEST REPORT TREATABILITY STUDY OF PERMEABLE REACTIVE BARRIERS FOR REMEDIATION OF ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE GROUNDWATER

Prepared for

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LIST OF ACRONYMS AND SYMBOLS

11DCE	1,1-dichloroethene
111TCA	1,1,1-trichloroethane
C	concentration in solution at time t
C_o	initial concentration in solution
cDCE	cis-1,2-dichloroethene
CT	tetrachloromethane (carbon tetrachloride)
DCM	dichloromethane (methylene chloride)
DOE	Department of Energy
ECD	electron capture Detector
Eh	redox potential
EPA	Environmental Protection Agency
ETI	EnviroMetal Technologies Inc
ft	feet
hr	hour
ID	inside diameter
in	inch
k	first-order rate constant
L	litre
MCL	maximum contaminant level
MDL	method detection limit
mg	milligram
µg	microgram
mL	millilitre
n	porosity
ND	not determined
O&M	operations and maintenance
OD	outside diameter
ORNL	Oak Ridge National Laboratories
PCE	tetrachloroethene (perchloroethene)
PID	photoionization detector
PV	pore volume
Q	flow rate
QA/QC	quality assurance/quality control
r^2	correlation coefficient
RFETS	Rocky Flats Environmental Site

RMRS	Rocky Mountain Remediation Services
SI	saturation index
SNL	Sandia National Laboratories
SOW	Scope of Work
t	time
$t_{1/2}$	half-life
TCE	trichloroethene
tDCE	trans-1,2-dichloroethene
TCM	trichloromethane (chloroform)
U S	United States
UW	University of Waterloo
VC	chloroethene (vinyl chloride)
VOC	volatile organic compounds
vol	reactor volume

1.0 BACKGROUND AND GENERAL OBJECTIVE

This bench scale test report, prepared for Rocky Mountain Remediation Services (RMRS), presents the procedures, results and data interpretation of column tests conducted as part of the evaluation of permeable barrier materials to treat dissolved organic compounds and trace metals present in groundwater at the Rocky Flats Environmental Technology Site (RFETS) The protocol for the tests was presented in EnviroMetal Technologies Inc 's (ETI's) bench scale test plan (March 1997), and prepared in accordance with the Scope of Work supplied by RMRS

1.1 Site Description and Background Information

A demonstration of the applicability of reactive barrier technologies will be conducted at the RFETS as part of a Department of Energy (DOE) EM-50 Subsurface Contaminants Focus Group sponsored program to identify cost-effective technologies for treating contaminated groundwater at DOE sites Laboratory bench scale testing is required to identify, test and develop suitable reactive materials for the demonstration of the applicability of reactive barrier technologies to treat volatile organic compounds (VOCs) in three contaminated groundwater plumes at RFETS The site identified for initial testing is surface water seep SW059 which is at the distant end of the Mound Plume Water from SW059 is currently collected and transported to Building 891 at RFETS where it is treated ETI has commercialized a patented method for metal-enhanced abiotic degradation of chlorinated organic compounds which could be used for treating VOCs not only in the SW059 plume, but also those present in the East Trench plume and in 903Pad/Ryan's Pit plume The system for the SW059 seep may also need to remove trace metals and radionuclides and may be designed to incorporate a removable "cassette" type of material container to facilitate periodic operations and maintenance (O&M) requirements

1.2 Treatment Technology Description

As a consequence of the significant limitations of pump-and-treat systems, *in-situ* permeable reaction barriers have been identified as an innovative alternative groundwater remediation technology (Gillham, 1996) The concept is remarkably simple, involving 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

these *in-situ* treatment systems have been evaluated, based on site-specific conditions Particular advantages that one would hope to achieve from *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
- reduced capital cost
- low operations and maintenance costs

Several different types of materials have been suggested for use in *in-situ* treatment zones The most advanced stage of application has been achieved with zero valent metal based systems to remove both chlorinated organic compounds and trace metals

Under highly reducing conditions and in the presence of metallic surfaces, certain dissolved chlorinated organic compounds in groundwater will degrade to non-toxic compounds such as ethene, ethane, and chloride (Gillham and O'Hannesin, 1994, Gillham, 1996) The process appears to be 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 appears to have great promise for the remediation of contaminated groundwater because of these high rates of degradation, 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

Concurrent research has been conducted to evaluate the use of iron based systems to remove trace metal contaminants from groundwater Metals which have been shown to be removed include chromium and nickel (Blowes et al, 1995, Puls et al, 1995), strontium (Marozas, 1996) and technicium (Clausen et al, 1995)

Field applications of iron based permeable treatment walls have been undertaken to remediate VOC and trace metal plumes There are currently 12 *in-situ* systems removing VOCs (mainly trichloroethene) from groundwater, and one system treating a combined VOC and trace metals plume Field trials have also been conducted at United States (U S) DOE facilities and mine tailings sites in Canada to demonstrate trace metals removal using this technology

Recent laboratory research has shown that the presence of another metal with iron may greatly enhance the VOC degradation rates relative to those obtained with iron alone These materials may therefore decrease the amount of reactive material required in a given situation Various bimetallic materials have been investigated, including palladium/iron, copper/iron, and nickel/iron The University of Waterloo (UW) has shown considerable success with nickel/iron material in preliminary laboratory experiments (Gillham et al , 1997) The nickel/iron material will be referred to herein as enhanced iron

In certain instances, periodic replacement of the reactive materials may be necessary to rejuvenate the reactive surface and/or remove the accumulated trace metals from the material In these cases, a low density, more easily handled reactive material relative to granular metallic iron is desirable to facilitate these periodic O&M activities The low density metallic foam materials produced by Cercona Inc have the potential to concurrently remove both VOCs and trace metals from solution

The following factors need to be investigated to facilitate field implementation of permeable treatment systems at any site

i) The dimensions and composition of treatment systems needed These are determined from the degradation rate of VOCs and removal rates of trace metals present in site groundwater and the groundwater velocity which would occur in an *in-situ* or *ex-situ* treatment section at the site

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 treatment section dimensions

iii) The amount of VOC degradation and trace metal removal possible versus required cleanup standards

iv) The effects of the process on the inorganic chemistry of the groundwater, in particular, the potential for mineral precipitation Mineral precipitation rates and trace metal removal affect long-term O&M requirements of the treatment system.

These factors are evaluated in the normal course of developing designs for field applications involving "conventional" granular iron Because of the shorter period of experience, their

evaluation is particularly important when considering use of the recently developed enhanced iron and iron foams

A meeting was held in December 1996 at RFETS to discuss the planned testing program Based on this meeting, it was decided to evaluate three types of reactive material, metallic iron, bimetallic material (nickel and iron), and iron foam pellets developed by Cercona Inc , of Dayton, Ohio It was originally planned to test an iron-zeolite foam pellet, however this material is in a very early stage of development A foam composed of iron plus an iron alloy (an "HSI" foam) was tested instead Tests by Oak Ridge National Laboratories (ORNL) and the University of Arizona have indicated this material to have the potential to remove both trace metals and VOCs Rationale supporting this modification were presented in the column test Work Plan (ETI, 1997)

1.3 General Objectives and Approach

The general objective of the bench scale testing was to examine VOC degradation rates with different iron materials suitable for use in reactive barrier technologies at RFETS Sandia National Laboratories (SNL) examined suitability of iron, iron foam, and Humisorb™ media for the removal of trace metal and radionuclides in parallel tests

The degradation rate constants calculated from the laboratory data, and the measured changes in inorganic geochemical parameters, were used to develop capital cost estimates and to assess potential O&M requirements for field-scale systems for the SW059 plume As mentioned previously, these data may also be used at a later date to develop field-scale designs for the East Trench and 903 Pad/Ryan's Pit plumes

1.4 Bench Scale Testing Report Organization

The remainder of this report is organized as follows

- Section 2 0 presents the detailed objectives and the scope of work for the bench scale tests

- Section 3 0 presents the bench scale test results

- In Section 4 0, the results are applied in the context of a reactive treatment system design for the SW059 plume at RFETS, including recommendations of the metallic material to be used The residence time required for VOC degradation to performance standards is calculated therein, along with the corresponding reactive material volume and cost

- Section 5 0 summarizes significant findings of this study and related recommendations

2.0 OBJECTIVES, SCOPE OF WORK, AND METHODS

2.1 Bench Scale Test Objectives

The general objective of the bench scale test was to determine VOC degradation rates in order to arrive at a suitable material for use in reactive barrier technologies at RFETS Samples collected during laboratory column tests were used to evaluate the following list of specific objectives for each type of reactive material tested

- VOC degradation rates,
- the level of VOC treatment possible relative to the performance standards for the RFETS (Segment 5 Action Levels),
- magnitude of Eh and pH changes,
- changes in inorganic geochemistry as a result of the pH and Eh changes, including possible mineral precipitation, and
- characterization of chlorinated breakdown products of VOCs, and evaluation of the rates of degradation of these products

2.2 Bench Scale Test Methods

Groundwater from the RFETS was passed through three laboratory columns at a constant flow rate Uncontaminated groundwater (sample identification code G-W-WL-TE-1), from RFETS was spiked in the laboratory with analytical grade VOCs The flow velocity for the test (2 8 ft/day) was selected in consultation with RMRS staff This flow rate was expected to approximate the flow velocities through a field scale treatment system, and allowed the tests to be completed within the project's scheduling requirements The iron materials used in the test were

1) -8 to +40 mesh iron obtained from Connelly-GPM, Inc of Chicago, Illinois (a commercial granular iron source),

2) enhanced iron, consisting of Connelly iron (same as in 1 above) plated with about 0 25% nickel, and
3) a low density granular bimetallic iron foam (HSI foam) from Cercona Inc of Dayton, Ohio

The bench scale testing was completed at the Institute for Groundwater Research, UW, under contract to ETI This section describes the equipment and materials used by UW to conduct the tests Analytical and quality assurance/quality control (QA/QC) procedures are summarized here and are presented in more detail in Appendix A

2.2.1 Bench Scale Equipment and Materials

The 1 64 ft long, 1 5 inch inside diameter (ID) Plexiglas™ columns used in this study were equipped with several sampling ports along the length of each column at distances of 0 08, 0 16, 0 33, 0 50, 0 66, 1 00 and 1 31 ft from the inlet end Sampling ports were also located in the influent and effluent lines (Figure 1) Each sampling port consisted of a nylon Swagelok fitting (1/16 in) tapped into the column side, with a sterilized syringe needle placed inside To prevent column packing materials from entering the needle, glass wool was placed in the barrel The sampling ports allowed samples to be collected along the central axis of each column Each syringe needle was fitted with a Luer-Lok™ fitting, to which a syringe was attached to collect a sample The sampling ports were sealed by a Luer-Lok™ plug, which was twisted snugly into the syringe needle between sampling events

To fill the columns with the reactive materials, aliquots of iron material were packed vertically in lift sections within the columns Each column was packed to assure a homogeneous mixture Values of bulk density, porosity, and pore volume were determined by weight (Table A1, Appendix A) All column experiments were performed at room temperature

Using an Ismatec IPN pump, solution (groundwater from RFETS spiked with the VOCs of interest) was fed at a constant flow rate from a collapsible Teflon® bag to the influent end of each column The Teflon® bag was filled by gravity, leaving no headspace All the site water could not be held in the collapsible bag and consequently the bag was refilled periodically during the test The pump tubing consisted of Viton®, and all the other tubing was Teflon® (1/8-inch OD x 1/16-inch ID)

2.2.2 Sampling and Analysis

The columns were sampled periodically over time until a steady-state profile was achieved at the test flow velocity In these column studies, steady-state is defined as the time when VOC versus distance profiles do not change significantly between sample events After removing a volume equivalent to the volume of the sampling port needle from the port, 2 0 to 3 0 mL samples were collected for analyses for VOCs from each port Groundwater samples were also collected from the influent and from the effluent overflow bottle

Tetrachloromethane (CT), trichloromethane (TCM), dichloromethane (DCM), tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cDCE), trans-1,2-dichloroethene (tDCE), 1,1-dichloroethene (11DCE), vinyl chloride (VC) and 1,1,1-trichloroethane (111TCA) concentrations were monitored at the inlet, outlet, and sampling ports of each column (i e "a profile" of the column) to determine when steady state had been reached These profiles, together with profiles of Eh and pH, were collected every 5 to 7 pore volumes Flow rates were measured using a graduated cylinder and stopwatch

Two influent and two effluent (outlet) samples from each column were analyzed for major cations (Ca^{2+}, Mg^{2+}, Fe^{2+}, Mn^{2+}, Ni^{2+}, Na^{+}, K^{+}), major anions (SO_4^{2-}, Cl^{-}, NO_2^{-}, NO_3^{-}) and alkalinity

2.2.3 Analytical Protocols

The analytical protocols used by UW for organic and inorganic analyses are described in detail in Appendix A In summary, the following methods were used

- VOCs were analyzed using solvent-extraction methods and a gas chromatograph equipped with an election capture detector (ECD), and by headspace analysis using a gas chromatograph with a photoionization detector (PID),
- pH and Eh were measured using appropriate electrodes,
- dissolved cations were analyzed using inductively coupled plasma methods,
- anions were analyzed by ion chromatography or colorimetry, and

- alkalinity was measured using a titration method

Method detection limits (MDLs) calculated by UW for the above methods are given in Appendix A

2.3 Deviations from Test Plan

There were no significant deviations from the procedures described in the test plan (March 1997) Between 50 and 60 pore volumes of groundwater passed through each column, which were sampled every 5 to 10 pore volumes Due to periodic refilling of the Teflon reservoir, there was some variability of influent VOC concentrations (Table 1) relative to the desired influent levels, but this did not affect the interpretation of the results

3.0 BENCH SCALE TEST RESULTS

3.1 Data Quality

Rigorous QA/QC procedures were followed during the laboratory tests Results of daily spiked blank samples and method blanks analyzed with the column samples for VOC analyses are contained in the laboratory report (Appendix A) For the most part, the percent recovery calculated for the spiked blanks (measured concentration divided by actual concentration x 100%) were close to 100%, and method blank concentrations were below the MDLs for the compounds tested

The results of VOC analyses of both of the influent reservoirs (Appendix A), indicate that there was some variability in influent (reservoir) VOC concentrations over time, predominantly due to the periodic refilling of the reservoirs with additional groundwater, but possibly due also to sorption and diffusion losses in the Teflon® reservoir

Initial (reservoir) concentrations were monitored during each sample profile event to account for this temporal variability and to characterize the VOC concentration being treated at each time Therefore, the variability should not appreciably affect the interpretation of VOC treatment rates

Inorganic results from the influent reservoirs (Table 3) showed that sample storage had little effect on major cation and anion concentrations

3.2 Similarity of Groundwater Used in the Bench Scale Test to Groundwater at the Site

Uncontaminated groundwater from the RFETS was received by UW Based on historical concentrations, analytical grade VOCs were added to the groundwater to create the influent concentrations listed in Table 1 These concentrations, close to historical maximums at the three potential treatment locations, allow for a realistic assessment of the ability of the technology to treat field scale VOC levels in each of these plumes The inorganic chemistry of the influent groundwater is included in Table 3

3.3 Observed Degradation of Volatile Organic Compounds

Several measurements of VOC concentrations along the length of each column were taken approximately every 5 to 10 pore volumes (Appendix A) to allow calculations of VOC degradation rates Figures 2 to 7 show the VOC concentration versus residence time profiles obtained at steady state for each column As described in the bench scale test plan, degradation rates were calculated for each compound using a first order kinetic model

For each test column, VOC concentration was plotted as a function of distance along the column The flow rate was used to calculate the residence time at each sampling position (relative to the influent) for each profile Degradation rate constants were calculated for each VOC in the influent solution groundwater, using the first-order kinetic model

$$C = C_o e^{-kt} \tag{1}$$

where C = VOC concentration in solution at time t,
C_o = initial VOC concentration of the influent solution,
k = first order rate constant, and
t = time

For most VOCs, C_o is the concentration of the compound in the influent solution at steady state (Table 1) Exceptions occur where breakdown products such as cDCE and TCM, result in a peak concentration in the interior of the column as more chlorinated compounds degrade In these cases, the peak concentration was used as C_o

By rearranging and taking the natural log (ln), equation (1) becomes

$$\ln(C/C_o) = -kt \tag{2}$$

The time at which the initial concentration declines by one-half, (C/C_o = 0 5), is the half-life ($t_{1/2}$), which, by rearranging equation (2), is given by

$$t_{1/2} = 0\ 693/k \tag{3}$$

The decay constants k [l/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^2) values are provided in Table 2 The r^2 values indicate how well the first-order model represents the experimental data

Organic results from the bench scale test can be summarized as follows

1) 100% Connelly Iron

A total of 61 pore volumes were passed through the column at a flow velocity of 2 9 ft/day This flow velocity resulted in a residence time of 13 4 hr Figures 2 and 3 show the rapid decline in CT, PCE, TCE, 11DCE, VC and 111TCA to non-detectable concentrations during the 13 4 hr residence time in the column Concentrations of TCM increased in the first few inches of the column and then declined rapidly to non-detectable concentrations within 2 7 hr of residence time Similarly, cDCE concentrations increase in response to PCE and TCE degradation, then decline as groundwater moves farther along the column DCM concentrations fluctuated within the column, and similar to other studies with granular iron, did not show any signs of appreciable degradation

The first-order kinetic model generally provided good fits (r^2>0 81) for all the compounds Table 2 presents the half-lives calculated from the final steady state profile Of particular relevance to the SW059 seep design are the half-lives for PCE (0 96 hr), TCE (0 65 hr), 11DCE (0 89 hr), cDCE (1 5 hr) and VC (1 2 hr) The rates of chlorinated ethene degradation exert a large influence on the design These are typical of values obtained in previous studies with 100% Connelly iron

2) 100% Enhanced Iron

A total of 59 pore volumes were passed through the column at a flow velocity of 2 9 ft/day This flow velocity resulted in a residence time of 13.9 hr Figures 4 and 5 show very rapid declines in CT, TCM, cDCE, 11DCE, VC and 111TCA to non-detectable concentrations Detection limits were reached within the time (0 7 hr) taken for the water to travel the distance to the first sampling port Concentrations of PCE and TCE also degraded rapidly to below detectable concentrations within 8 3 hr DCM concentrations declined slightly over the 13 9 hr residence time from 112 to 94 µg/L

The first-order kinetic model generally provided good fits (r^2>0 98) for PCE and TCE (Table 2) The half-lives obtained for the final steady state profile were 0 45 and 0 13 hr for PCE and TCE respectively A DCM half-life of 39 hr was determined, however the r^2 value (0 57) indicated a poor fit to the first order model CT, TCM, cDCE, 11DCE, VC and 111TCA half-

lives were less than 0 08, 0 11, 0 23, 0 11, 0 10 and 0 15 hr Because the concentrations for these compounds were below the MDLs by the first sampling port, it can be said with certainty that the half-lives were below these values, though the actual values are unknown In order to determine the half-lives, a higher flow velocity would have to be used

3) 100% HSI Foam

A total of 56 pore volumes were passed through the column at a flow velocity of 2 7 ft/day This flow velocity resulted in a residence time of 14 5 hr Figures 6 and 7 show rapid declines in CT and 111TCA to non-detectable concentrations within the time (1 5 hr) taken for the water to travel the distance to the second sampling port Concentrations of PCE, TCE, 11DCE and VC also degraded along the length of the column, but at significantly lower rates The residence time was not sufficient to degrade these compounds to below detection limits As a result of CT dechlorination, initial TCM concentrations increased to 362 µg/L in 1 5 hr of residence time, and then declined to 80 µg/L in the effluent Similarly, cDCE concentrations increased in the column due to PCE and TCE degradation, however, the residence time in the column was not sufficient to observe a decline in cDCE concentration which would be expected once PCE and TCE were removed DCM concentrations did not indicate appreciable degradation

The first-order kinetic model generally provided good fits (r^2>0 80) for all the compounds (Table 2) Half-lives observed in the HSI foam column are, for most compounds, at least 4 times longer than those observed with Connelly iron

3.4 Inorganic Results

Changes in inorganic chemical constituents observed in the groundwater as it passed through the reactive iron are summarized in Table 3 Two influent and effluent samples were collected from each column as they approached steady state Comparison of column influent and effluent results show that concentrations of potassium, sodium, and sulphate remained relatively unchanged Nitrate and nitrite concentrations were below detection limits in the influent as well as the effluent Chloride concentrations increased slightly due to dechlorination of the VOCs

Influent magnesium concentrations did not change in the enhanced or HSI foam, but declined by 6 mg/L in the Connelly iron column Manganese concentrations did not change significantly

in the Connelly and HSI columns but increased from 0 49 to 2 mg/L in the enhanced iron Nickel concentrations increased only in the enhanced iron column, from below detection to 1 6 mg/L In other lab and field tests with the enhanced iron, the amount of nickel dissolved in the effluent has been observed to decrease over the first tens to hundreds of pore volumes to non-detectable values

Total iron concentrations remained relatively low (<1 1 mg/L) in the Connelly and HSI foam columns Iron concentrations for the enhanced iron increased to about 70 mg/L due to the lower pH and/or increased corrosion rates in this column compared to the other two Calcium and alkalinity concentrations decreased in the effluent of all three columns relative to the influent values The largest declines were observed for Connelly iron and the least in the HSI foam. The decline in calcium and alkalinity concentrations in the Connelly and HSI foam columns are in response to increasing pH caused by the corrosion of iron

$$Fe^{o} + 2H_2O \rightarrow Fe^{2+} + 2OH^{-} + H_{2(g)} \quad (4)$$

In the Connelly iron and HSI foam, pH values in the column were as high as 9 3 and 8 0 respectively (Figure 8) As the pH of the solution increases, bicarbonate (HCO_3^-) ions are converted to carbonate ions (CO_3^{2-}) to buffer the increase in pH The CO_3^{2-} ion formed then combines with the cations present in solution (Ca^{2+}, Fe^{2+}) to form carbonate mineral precipitates Although pH values did not increase in the enhanced iron column, the dissolved iron concentrations are such that siderite ($FeCO_3$) is expected to have formed

The changes in calcium, iron and alkalinity concentration between column influent and effluent samples, which reflect mineral precipitation in the columns, are summarized in Table 4 As shown in Table 4, iron concentrations increased as groundwater moved through these columns However, independent corrosion rate measurements of metallic iron (Reardon, 1995) indicate that several mmol/L Fe^{2+} would be introduced to groundwater in these columns due to iron corrosion It therefore appears that iron precipitates were occurring in the column Based on effluent Fe^{2+} concentrations, more iron precipitates likely occurred in the Connelly iron and HSI foam then in the enhanced iron Iron minerals which form include siderite and iron hydroxide ($Fe(OH)_2$) In each column the observed higher carbonate alkalinity loss relative to the amount of calcium loss indicates that siderite did indeed form in addition to calcium carbonate Iron hydroxides, which form in the column, are converted over time to magnetite (Fe_3O_4)

$$3Fe(OH)_2 \rightarrow Fe_3O_4 + 2H_2O + H_{2(g)} \quad (5)$$

Results of the influent and effluent inorganic chemical analyses were also input to a geochemical speciation model MINTEQA2 (U S EPA, 1991) In MINTEQA2, aqueous concentrations are used to calculate the saturation indices (SIs) of various mineral species (Table 4) The SIs can be used to gauge the potential for these minerals to precipitate A negative SI indicates undersaturation with respect to the particular mineral phase, while a positive SI indicates oversaturation To obtain the maximum SI for calcium ($CaCO_3$), aragonite ($CaCO_3$) and siderite, the maximum pH in a given column at the time of inorganic sampling was input along with the effluent inorganic chemistry Although some caution must be used in interpreting these results, which assume equilibrium conditions, the results showed expected trends That is, the influent water entering the columns was undersaturated with respect to calcium carbonate minerals and siderite The SIs for siderite indicates that it became oversaturated in all three columns because of pH increases and the production of Fe^{2+} from the corrosion of iron by water Calcium carbonate also became oversaturated in the Connelly iron and HSI foam columns due to increasing pH The SI for calcium carbonate in the enhanced iron column remained relatively constant as pH remained about the same and alkalinity declined as siderite formed

4.0 USE OF BENCH SCALE TEST RESULTS IN FIELD SCALE TREATMENT SYSTEM DESIGN, SW059 PLUME

This section presents recommended design parameters for use in the field scale treatment system currently being planned for the SW059 plume at RFETS These design parameters are based on the results of the bench scale tests, and the results of hydrogeologic investigations completed at the site

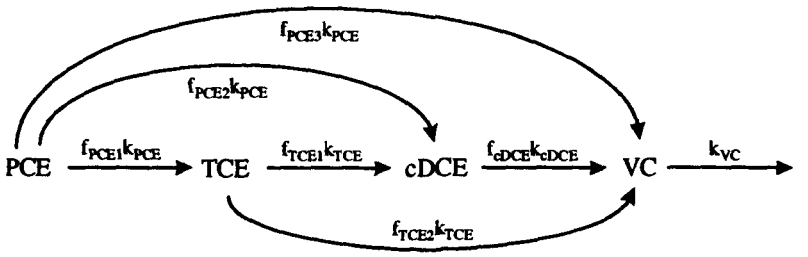
4.1 Required Residence Time

As noted previously, the bench scale tests were conducted using background RFETS groundwater spiked with VOCs to approximate historical maximum concentrations observed at the three plume areas were the technology is being considered In order to assess the residence time required in the field scale system for the SW059 plume, groundwater VOC concentration data from the recent investigations and historical data for this area was reviewed The average, maximum and two times maximum concentrations measured in this area are summarized in Table 5, and were used as influent concentrations in the design Five different simulations were performed using the different iron materials and influent concentration data

	Connelly	Enhanced	HSI
Average Concentrations	✓		
Maximum Concentrations	✓		
Two Times Maximum Concentrations	✓	✓	✓

To calculate the residence time required in a field scale treatment system, the design influent concentrations (Table 5) and half-lives measured in the laboratory were used in a mathematical model representing sequential VOC degradation The degradation model calculates the VOC concentrations over time, from which the time required for the VOCs to degrade to the Segment 5 Action Levels can be determined The residence time calculation is shown conceptually in Figure 9 In the model, potential breakdown products are concurrently produced and degraded as described by first-order kinetic equations The equations are similar to those found in many chemical kinetic texts and were adapted by ETI to describe the EnviroMetal Process The software Scientist® for Windows® Ver 2 0 was used to perform the calculations

The model is an expression of the chemistry that is observed in the solution phase For PCE, TCE, cDCE and VC, the model takes the form



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

$$dPCE / dt = -k_{PCE}PCE \quad (6)$$

$$dTCE / dt = f_{PCE1}k_{PCE}PCE - k_{TCE}TCE \quad (7)$$

$$dcDCE / dt = f_{PCE2}k_{PCE}PCE + f_{TCE1}k_{TCE}TCE - k_{cDCE}cDCE \quad (8)$$

$$dVC / dt = f_{PCE3}k_{PCE}PCE + f_{TCE2}k_{TCE}TCE + f_{cDCE}k_{cDCE}cDCE - k_{VC}VC \quad (9)$$

These equations can be used directly in Scientist® which can perform the integration, or their integrated form may also be used As an example, integration of equation 6 yields the more familiar form of the first-order equation for parent compounds

$$PCE = PCE_0 e^{-kPCEt} \quad (10)$$

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

Similar equations were developed to represent the concentrations of chlorinated methanes, ethanes and ethenes at a given time t

Table 5 gives the molar quantities of a parent compound considered to be converted to a degradation product The values used for Connelly iron are typical for values observed previously using commercial iron sources Since very little data exists for the HSI foam, similar conversion amounts are assumed Given the similarity of cDCE and VC half-lives in other source materials, the half-life for cDCE in the HSI foam was assumed to be similar to that of VC (Recall that no cDCE half-life was determined in this test) Although little or no

chlorinated breakdown products have been observed in these or other previous laboratory tests of enhanced iron, the conversion factors for the commercial iron source were used for conservatism.

Figures 10 to 14 show the simulation results Using the two times maximum concentrations, about 10, 4 and 164 hr of residence time would be needed using Connelly, enhanced and HSI foam, respectively (Table 6) Assuming maximum and average influent concentrations the required residence time using Connelly iron would be reduced to 8 and 5 hr respectively As shown by the simulations, assuming average concentrations, which are about an order of magnitude less than the two times maximum concentrations, would only reduce the iron required and thus the iron cost by half

Residence times obtained using bench scale half-lives need to be adjusted to account for anticipated slower degradation rates in the field due to groundwater temperature being lower than ambient laboratory temperature Previous laboratory and field experience has shown that residence times determined from laboratory data should be increased by about a factor of 2 to account for field effects including temperatures If it is assumed that a factor of 2 will apply at the RFETS, then the residence time required in a field scale treatment system, to provide degradation of two times maximum VOC concentrations to less than the Segment 5 Action Levels, is about 20, 8 and 328 hr using Connelly iron, enhanced iron and HSI foam respectively (Table 7)

4.2 Volume and Cost of Reactive Materials

It is our understanding that an impermeable barrier will be constructed to deliver the groundwater requiring treatment in the spring area to a flow-through treatment structure, which may consist of an *in-situ* reactor bed or vessel. It is our understanding that flow through the system may approach as much as 2 gpm. The residence times calculated above can be used to calculate the volume of iron needed using the formula

$$vol = \frac{tQ}{n} \tag{12}$$

where vol = reactor volume (ft^3)
t = residence time (d)
Q = flow rate (385 ft^3/d or 2 gpm)
n = porosity (assumed at 0 45 for Connelly and enhanced iron, 0 55 for HSI foam)

Knowing the volume, the mass and cost of Connelly iron can be calculated using a bulk density of about 0 08 tons/ft^3 and a unit cost of $425/ton (or $34/$ft^3$) The enhanced iron should have about the same density, but will likely cost at least $1,500/ton to produce in commercial quantities, based on our efforts in manufacturing about 2 tons for our test program in New Jersey This gives a cost of about $120/$ft^3$ The HSI foam, based on recent discussions with Cercona Inc , may cost in the neighbourhood of $60 to $70/$ft^3$ Estimated iron volumes and costs are shown in Table 7

4.3 Reactive Material Selection

As outlined in Section 1, the objective of this study was to identify a suitable reactive material for use in an *in-situ* treatment system at the RFETS At the outset of the study, there was some question as to the presence of significant trace metal contamination in the SW059 plume It is our understanding that recent investigations have revealed no significant trace metals, and thus the treatment material will be selected primarily on its cost-effectiveness in removing VOCs from the influent groundwater From Table 7, it is clear that the commercial granular iron is the most cost-effective material Based on this analysis, and the absence of long-term performance data for the HSI material and enhanced iron, Connelly iron is recommended as the preferred material for use in the field scale treatment system.

4.4 Possible Effect of Precipitation on Field-Scale Performance

As described in Section 3 4, changes in inorganic chemical concentrations indicated that calcium carbonate, iron carbonate, and iron hydroxide precipitates occurred in the Connelly iron material during the laboratory column tests The column results can be used to estimate the amount of porosity loss that could occur in the reactive material over time The following discussion examines the Connelly iron column data, which reflected the most precipitation of the three materials tested Based on the cost analysis, Connelly iron may well be used in the field trial

As noted previously, the precipitates in the granular iron occur in response to increasing pH due to corrosion of iron

$$Fe^{o} + 2H_2O \rightarrow Fe^{2+} + 2OH^{-} + H_{2(g)} \quad (4)$$

Bicarbonate ions in solution convert to carbonate ions to buffer this pH increase

$$HCO_3^{-} \rightarrow CO_3^{2-} + H^{+} \quad (13)$$

The carbonate ion then combines with cations in solution to form mineral precipitates

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_{3(s)} \quad (14)$$

$$Fe^{2+} + CO_3^{2-} \rightarrow FeCO_{3(s)} \quad (15)$$

More iron is introduced into solution due to corrosion than can be precipitated as siderite As the pH increases, precipitation of iron hydroxide occurs

$$Fe^{2+} + 2OH \rightarrow Fe(OH)_{2(s)} \quad (16)$$

The iron hydroxide is in turn converted over time to magnetite at the iron surface (Odziemkowski et al, in submittal)

$$3Fe(OH)_2 \rightarrow Fe_3O_4 + 2H_2O + H_{2(g)} \quad (5)$$

The following calculation assumes that the amount of calcium carbonate precipitation, which would occur in the granular iron material in the field, can be approximated by the maximum measured difference in influent and effluent concentrations of dissolved calcium in the column studies The amount of siderite formed is then similarly estimated using the amount of carbonate alkalinity loss, which can not be accounted for by the precipitation of calcium carbonate alone The amount of iron hydroxide formed once the carbonate buffering capacity is exhausted is calculated based on the concentration of ferrous dissolved iron produced from metal corrosion The amount of ferrous iron produced is estimated from the experiments of Reardon (1995)

The rate of porosity loss per pore volume of flow in the field is calculated below using these assumptions, and equated to an annual loss by assuming that the flow rate through the system will be about 1 2 pore volume/day, equivalent to 438 pore volumes of groundwater per year That is, a residence time in the reactor of 20 hr will cause VOCs in each pore volume to be

degraded to their MCLs The results of calculations using the enhanced iron column are presented after these detailed calculations Note that the porosity value used is based on bulk density measurements of granular iron in the field at other sites

4.4.1 Estimated Porosity Losses in Granular Iron

- At an assumed field porosity of 0 45, 1 cm^3 of granular iron contains 0 45 mL of water The measured difference in influent/effluent calcium concentrations in the laboratory was about 37 mg/L or 0 9 mmol/L Therefore, 0 9 mmol/L/pore volume x 0.00045 L x 438 pore volumes/year = 0 177 mmol/yr of calcium carbonate may precipitate in 1 cm^3 of the granular iron

- This calcium carbonate precipitation rate needs to be equated to the volume of precipitate formed The molar volume of calcite (36 8 cm^3/mol), a polymorph of calcium carbonate, is used in the following calculation rather than aragonite which has a smaller molar volume The yearly volume of precipitate generated in 1 cm^3 of wall material would be 0 177 mmol/yr x 0 001 mol/mmol x 36 8 cm^3/mol = 0 007 cm^3/year

- The yearly precipitation of iron carbonate (siderite) can be similarly calculated The measured difference in influent/effluent alkalinity (128 mg/L or 2 56 mmol/L) was about 1 7 mmol/L greater than the decline in calcium. Thus 1 7 mmol/L of iron carbonate was assumed to have formed Siderite has a molar volume of 30 4 cm^3 The yearly volume of siderite in 1 cm^3 would therefore be 1 7 mmol/L/pore volume x 0 00045 L x 438 pore volumes/yr x 0 001 mol/mmol x 30 4 cm^3/mol = 0 010 cm^3/year

From these calculations the amount of carbonate precipitates (calcium + iron) formed in 1 cm^3 of granular iron will be 0 017 cm^3/year This would be equivalent to 0 017/0 45 x 100 = 3 8% of the original porosity

The reduction in the volume of granular iron can be estimated, using a corrosion rate of 0 5 mmol (Fe^{2+})/kg Fe/day, measured in previous laboratory studies (Reardon, 1995) Assuming this corrosion rate and a measured bulk density of iron of about 3 g/cm^3, the corrosion rate of iron can be calculated as

$$\text{iron corrosion rate} = 0\ 5 \text{ mmol of } Fe^{2+}\text{/kg Fe/day} \times 0\ 003 \text{ kg/cm}^3$$
$$= 0\ 0015 \text{ mmol/day/cm}^3$$

This rate is independent of the residence time of the water in the reactor and will cause a reduction in the volume of granular iron Using the above corrosion rate and a molar volume of iron metal of 7 06 cm^3/mol, the volume reduction in 1 cm^3 of iron material would be 0 0015 mmol/day x 365 days/yr x 7 06 cm^3/mol x 0 001 mol/mmol = 0 004 cm^3/year This small loss in volume indicates the iron metal itself should last for tens of years

In addition to iron carbonate, iron hydroxide could also precipitate The maximum amount of iron hydroxide precipitate formed in 1 cm^3 of the medium is equal to the amount formed from the corrosion of iron, that is 0 0015 mmol/day x 365 days/year = 0 548 mmoles per year Assuming an iron hydroxide molar volume of 26 4 cm^3, the yearly volume of precipitate in 1 cm^3 of iron would be 0 548 mmol/yr x 0 001 mol/mmol x 26 4 cm^3/mol = 0 014 cm^3 Taking into account the porosity "gain" due to corrosion of the iron metal, iron hydroxide precipitation might cause a reduction in pore space of (0 014 - 0 004)/ 0 45 x 100 = 2 2%

Recent laboratory studies (Odziemkowski et al, in submittal) have shown that iron hydroxide precipitate will convert to magnetite over time Magnetite precipitate occupies a smaller volume than the iron hydroxide precipitate Three moles of iron hydroxide will convert to 1 mole of magnetite with a molar volume of 44 7 cm^3 The volume of magnetite precipitate is 0 548 mmol/yr – 3 x 0 001 mol/mmol x 44 7 cm^3/mol = 0 008 cm^3/yr This would amount to a reduction in pore space of (0 008 - 0 004)/0 45 x 100 = 0 9%

In summary, porosity losses in the reactive material could theoretically amount to about 1 to 6% of the original porosity per year, at least in the first year, based on laboratory measurements of carbonate and hydroxide precipitate formation This latter value assumes concurrent precipitation of carbonate minerals and iron oxides and hydroxides

4.4.2 Significance of Porosity Loss Estimates on Possible Operations and Maintenance Requirements

The rates of porosity loss given above may well decrease over time due to varying (decreasing) iron corrosion rates, and could also vary depending on temporal changes in the influent groundwater geochemistry That is, we anticipate the rate of precipitate build-up (and porosity loss) will decrease in a non-linear fashion at a given point over time, and that a "precipitate front" will move through the material The reliability of laboratory data to gauge the potential effect of precipitates on performance of a field scale treatment system is dependent on the location of precipitation sites *in-situ*, as well as the extent and kinetics of precipitation under

field conditions From previous studies and field applications, it appears that most of the carbonate precipitation would occur in the iron material at the influent end of a reactor This can be expected as the greatest rate of pH increase occurs in the initial portion of the iron If the carbonate precipitates were to form quickly (only in the initial portion of the iron), then the porosity loss in this area would be higher

Operations and maintenance requirements to ameliorate the effects of these precipitates could be fairly straight forward, depending on the field design In the New Jersey iron reactor, the upgradient portion of the reactive zone was scarified every few weeks to restore the porosity, and after 18 months the upper foot of the 5 5 foot reactive section was replaced with new iron Other design options which could be considered include

i creation of a sacrificial iron/gravel mixture where most precipitates would occur upstream of the main reactive section,

ii use of coarse grained iron in upstream portions, allowing precipitates to occur in a coarser section without having as much effect on overall system performance,

iii reducing the hardness of the groundwater by conventional treatment methods prior to introducing it into the iron section

4.5 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, 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 There has also been no evidence of microbial fouling within the iron at an above-ground reactor site in New Jersey, which has been operating since November 1994

4.6 Conceptual *In-Situ* System Design

The following conceptual design assumes that an impermeable barrier and collection system will be installed parallel to the creek, near the bottom of the slope, to intercept and collect groundwater moving towards the current seep discharge zone Several design options for both the collection and treatment systems may need to be considered in light of the site topography and other conditions One possible design for the treatment system would be a flow-through gravity fed system that utilizes the head on the hill-slope to move water through the treatment material A conceptual design for this system is shown in Figure 15 Water from the collection system enters and ponds at the top of the reactor, and moves downwards through the granular iron The outlet elevation is controlled at the top of the iron, so this material remains saturated at all times

Advantages of this design include

i by building sufficient volume at the top of the reactor, variations in influent flow rate can be accommodated,

ii the reactor affords easy access,

iii should a downstream polishing unit be necessary, it could easily be accommodated

Two reaction vessels about 8 ft high and 10 ft in diameter (Figure 15) could hold the 710 ft^3 of Connelly iron estimated in Section 4 2 Each vessel might cost about $15,000 to $20,000, based on previous quotations for other projects Together with the iron costs, the total cost of the treatment system would be on the order of $65,000

5.0 SUMMARY

Column tests using groundwater from the RFETS facility indicate that degradation of the chlorinated VOCs present in groundwater at concentrations greater than Segment 5 Action Levels to concentrations meeting these criteria should be achieved by *in-situ* treatment systems containing zero valent iron VOC degradation rates observed during these tests indicate the following

1) that iron produced by Connelly-GPM represents the most cost-effective material of the three tested,

2) that a residence time of 20 hours (0 83 d) should be adequate to degrade VOCs found in the SW059 plume to below Segment 5 Action Levels, and

3) Consideration should be given a gravity flow system in the field scale treatment system design

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Table 1: Column Influent Concentrations and Segment 5 Action Levels, Rocky Flats Bench Scale Test

Compound	Concentration (µg/L)			Plume in Which VOC is Present
	Influent Target (ETI Workplan)	Influent at Steady State	Segment 5 Action Levels	
Carbon Tetrachloride (CT)	850	1,004	5	all
Trichloromethane (TCM)	55	110	8	all
HSI Foam	50	111	5	all
Tetrachloroethene (PCE)	4,000	5,496	5	all
Trichloroethene (TCE)	4,000	5,250	5	all
Cis-1,2-dichloroethene (cDCE)	50	64	70	SW059, east trench
1,1-Dichloroethene (11DCE)	350	318	7	all
Vinyl Chloride (VC)	50	102	2	possible breakdown product
1,1,1-Trichloroethane (111TCA)	25	37	200	SW059, east trench

all - SW059, east trench and 903 Pad/Ryan's Pit plumes

Table 2: Laboratory Column Half-Lives, Rocky Flats Bench Scale Test

Compound	Connelly Iron		Enhanced Iron		HSI Foam	
	$t_{1/2}$ (hr)	r^2	$t_{1/2}$ (hr)	r^2	$t_{1/2}$ (hr)	r^2
Carbon Tetrachloride (CT)	0 09[a]	1 00	0 08[c]	1 00	0 09[a]	1 00
Trichloromethane (TCM)	0 14[a,b]	1 00	0 11[c]	1 00	6 60[b]	0 98
Dichloromethane (DCM)	ND		39 1	0 57	ND	
HSI Foam	0 96	0 97	0 45	1 00	6 97	0 95
Trichloroethene (TCE)	0 65	0 99	0 13	0 98	2 79	0 99
Cis-1,2-dichloroethene (cDCE)	1 45[b]	0 81	0 23[c]	1 00	ND	
1,1-Dichloroethene (11DCE)	0 89	0 96	0 11[c]	1 00	6 12	0 99
Vinyl Chloride (VC)	1 19	0 96	0 10[c]	1 00	22 8	0 80
1,1,1-Trichloroethane (111TCA)	0 28[a]	1 00	0 15[c]	1 00	0 52[a]	1 00

ND - Not Determined

[a] determined from a two point line
[b] determined from peak concentration
[c] determined using MDL as concentration at second point

Table 3: Inorganic Geochemical Changes, Rocky Flats Bench Scale Test

	Inorganic Concentrations (mg/L)			
	Influent	Connelly Effluent	Enhanced Effluent	HSI Effluent
Cations				
Calcium (Ca)	61	25	55	59
	62	26	55	57
Magnesium (Mg)	15	8 5	14	15
	15	8 8	14	14
Sodium (Na)	54	55	58	56
	54	55	57	55
Total Iron (Fe)	0 05	0 37	78	1 09
	0 02	0 17	65	0.59
Manganese (Mn)	0 49	0 24	2 1	0 26
	0.50	0 21	2 8	0 21
Potassium (K)	5 3	5 9	5 9	5 7
	5 3	5 8	5 7	5 5
Nickel (Ni)	<0 01	<0 01	1 6	<0 01
	<0 01	<0 01	1 4	<0 01
Anions				
Sulphate (SO_4)	52	61	52	54
	55	59	56	54
Chloride (Cl)	84	97	97	95
	91	94	95	95
Nitrate (as N)	<0 05	<0 05	<0 05	<0 05
	<0 05	<0 05	<0 05	<0 05
Nitrite (as N)	<0 01	<0 01	<0 01	<0 01
	<0 01	<0 01	<0 01	<0 01
Alkalinity ($CaCO_3$)	164	33	97	146
	167	39	97	143

Table 4: Changes in Column Inorganic Chemistry Reflecting Mineral Precipitates, Rocky Flats Bench Scale Test

		Connelly Column		Enhanced Column		HSI Column	
Change in Concentration[a]:		**mg/L**	**mmol/L**	**mg/L**	**mmol/L**	**mg/L**	**mmol/L**
Calcium		-36 -37	-0 90 -0 92	-6 -7	-0 15 -0 18	-2 -5	-0 06 -0 13
Total Iron		<1 <1	<0 01 <0 01	78 65	1 40 1 17	1 1	0 02 0.01
Alkalinity[b]		-131 -128	-2 62 -2 56	-67 -70	-1 34 -1 40	-18 -24	-0 36 -0 48
Saturation Indices[c]:	**Influent**	**Connelly Effluent**		**Enhanced Effluent**		**HSI Effluent**	
Aragonite ($CaCO_3$)	-0 65 -0 53	0 24 0 40		-0 64 -0 54		0 27 0 06	
Calcite ($CaCO_3$)	-0 51 -0 39	0 38 0 54		-0.51 -0 40		0 42 0 20	
Siderite ($FeCO_3$)	-1 65 -1 95	0 41 0 22		1 58 1 61		0 62 0 15	

[a] changes between influent and effluent concentrations in each column

[b] alkalinity as mg/L $CaCO_3$ and meq/L (or mmol/L CO_3^-)

[c] saturation indices determined using effluent inorganic chemistry and highest pH observed in column

Table 5: Design Influent VOC Concentrations, SW059 Plume

VOC	Concentration (µg/L)			
	Average	Maximum	Two Times Maximum	Segment 5 Action Levels
PCE	61	261	522	5
TCE	181	845	1689	5
HSI Foam	155	808	1616	70
11DCE	94	17	188	7
VC	12	55	110	2
CT	4	34	68	5
TCM	16	177	354	8
DCM	4	18	36	5
111TCA	--	--	--	200

Taken from data table supplied by RMRS

Assumed Molar Conversions

PCE to cDCE	30%
TCE to cDCE	25%
PCE to VC	4%
TCE to VC	3%
cDCE to VC	2%
11DCE to VC	2%
CT to TCM	70%
TCM to DCM	50%

Table 6: Residence Time Required, SW059 Plume

	SW059 Plume Concentration (µg/L)		
	Average	Maximum	Two Times Maximum
Connelly Iron	5	8	10
Enhanced Iron	ND	ND	4
HSI Foam	ND	ND	164

ND – Not Determined

Table 7: Estimated Iron Volume and Cost

Material	Residence Time Required[a]		Volume Required (ft^3)	Cost (to nearest thousand) ($)
	(hr)	(d)		
Granular Iron	20	0 83	710	24,000
Enhanced Iron	8	0 33	282	34,000
HSI Foam	328	13 7	9,590	575,000

[a] a factor of 2 has been applied to account for slower field degradation rates

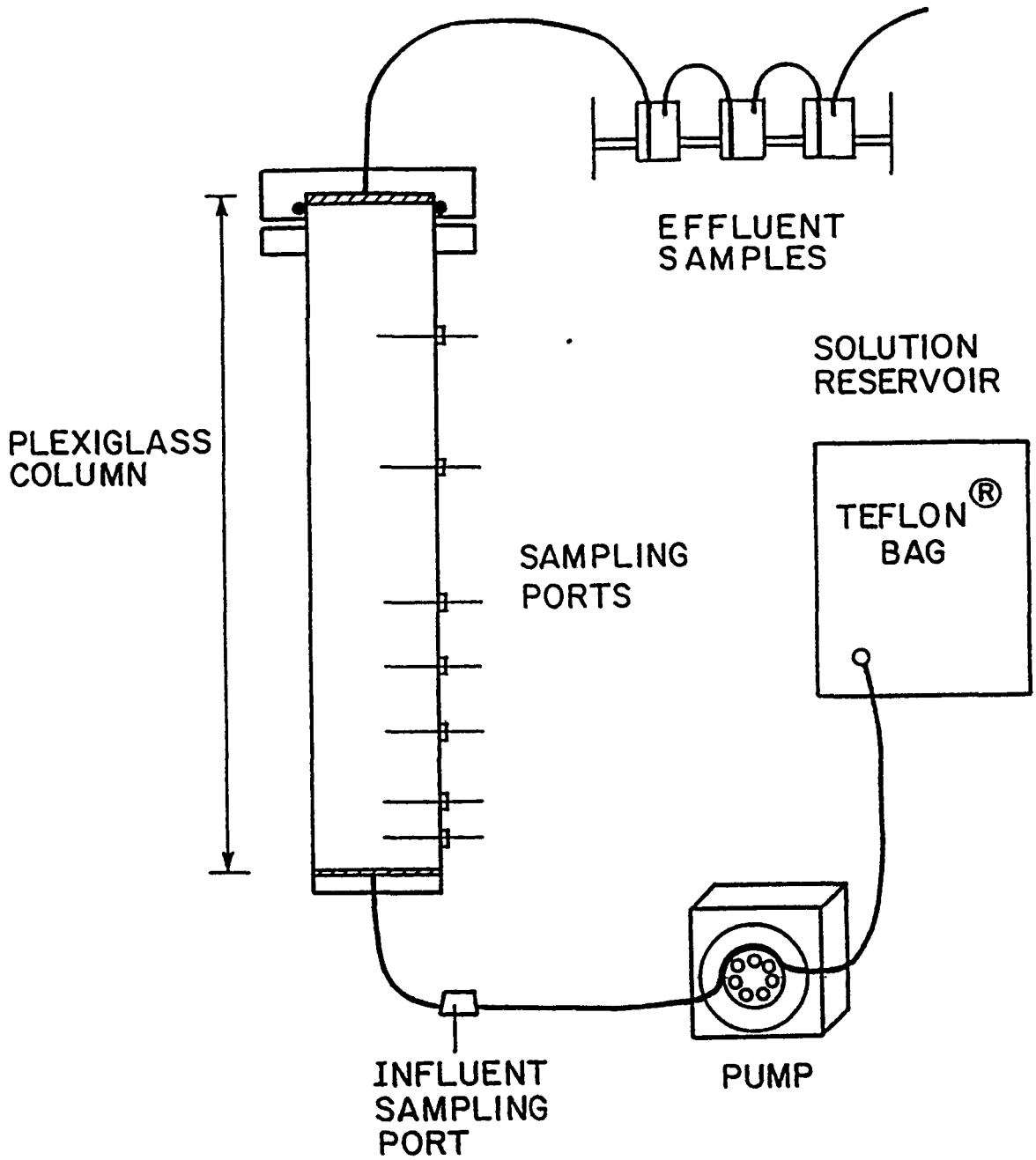
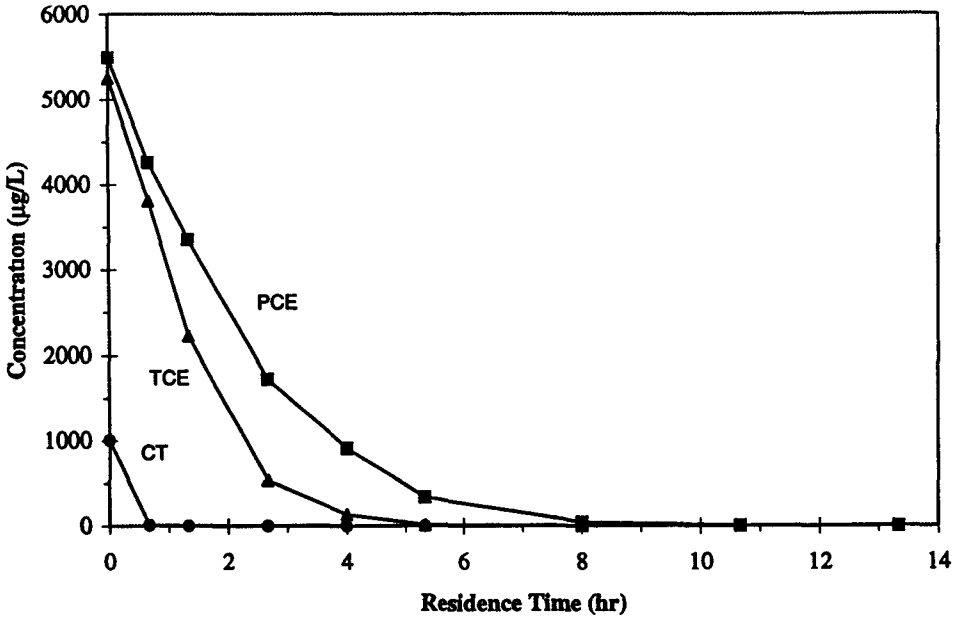


Figure 1: Schematic of column equipment used in bench scale testing

A)



B)

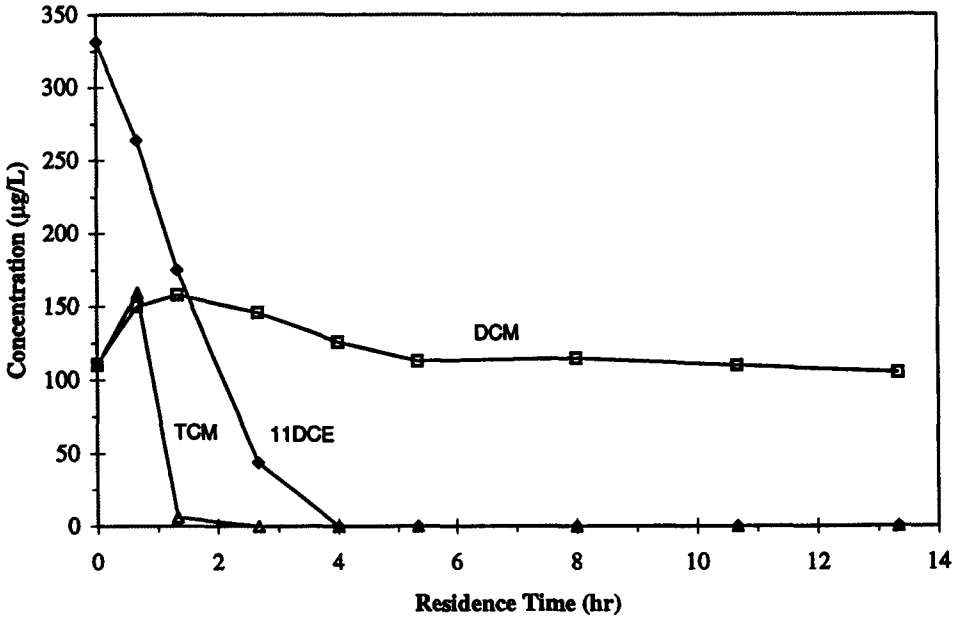


Figure 2. Organic concentration profiles versus residence time in the Connelly iron column A) PCE, TCE and CT B) 11DCE, DCM and TCM

A)

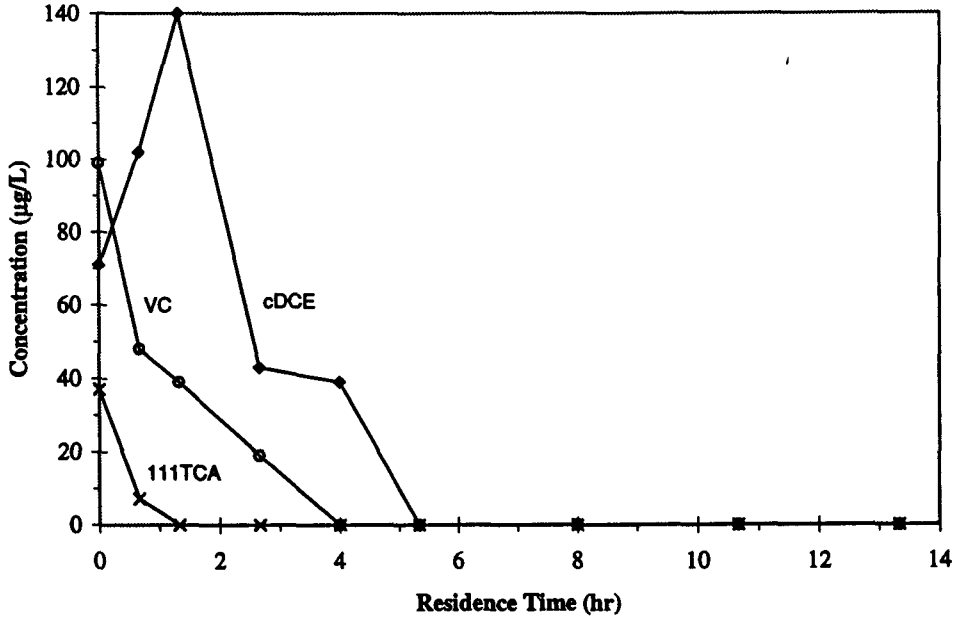
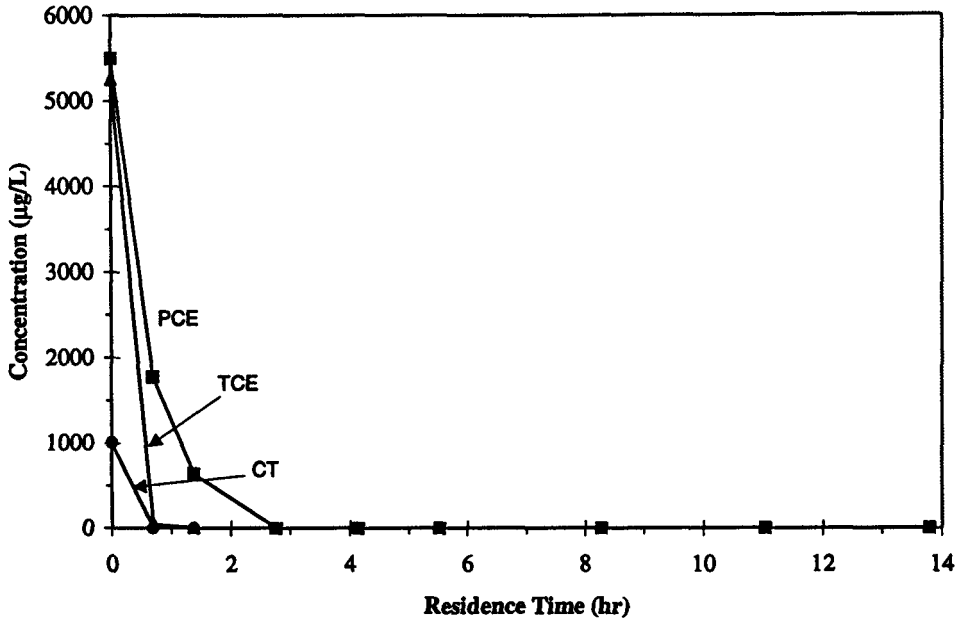


Figure 3 Organic concentration profiles versus residence time in the Connelly iron column. A) cDCE, VC and 111TCA

A)



B)

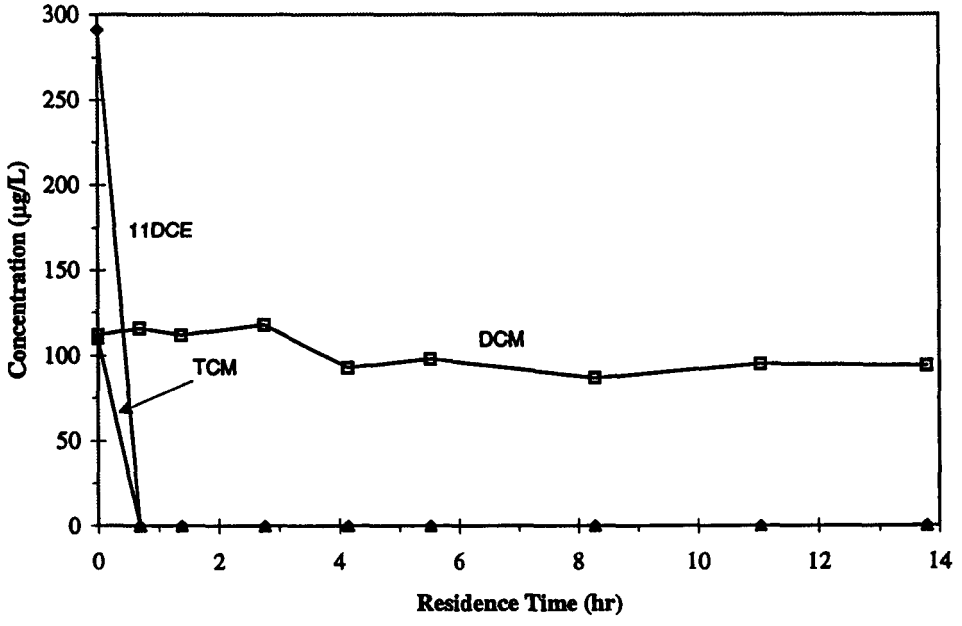


Figure 4: Organic concentration profiles versus residence time in the enhanced iron column A) PCE, TCE and CT B) 11DCE, DCM and TCM

A)

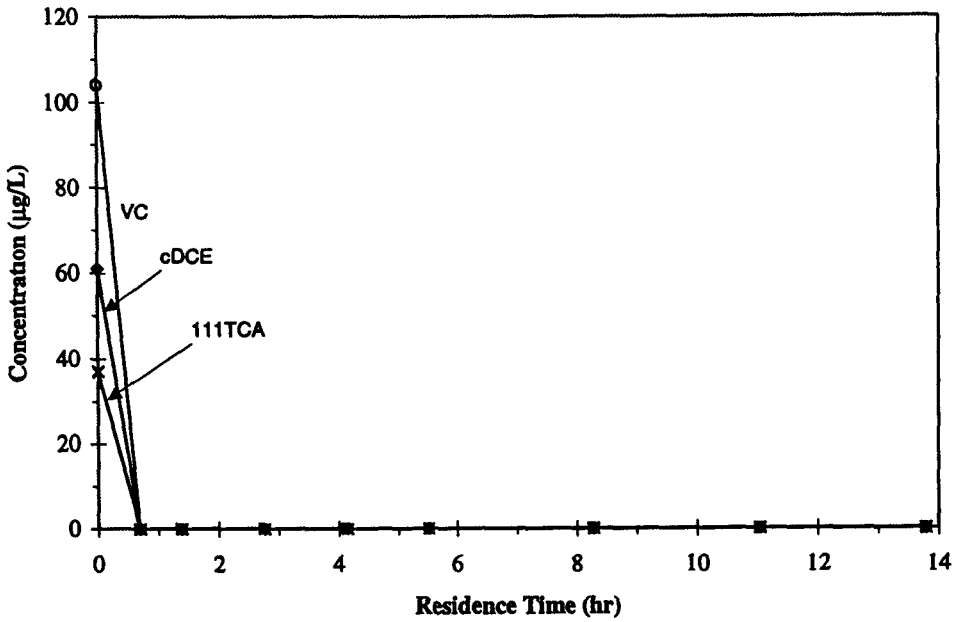
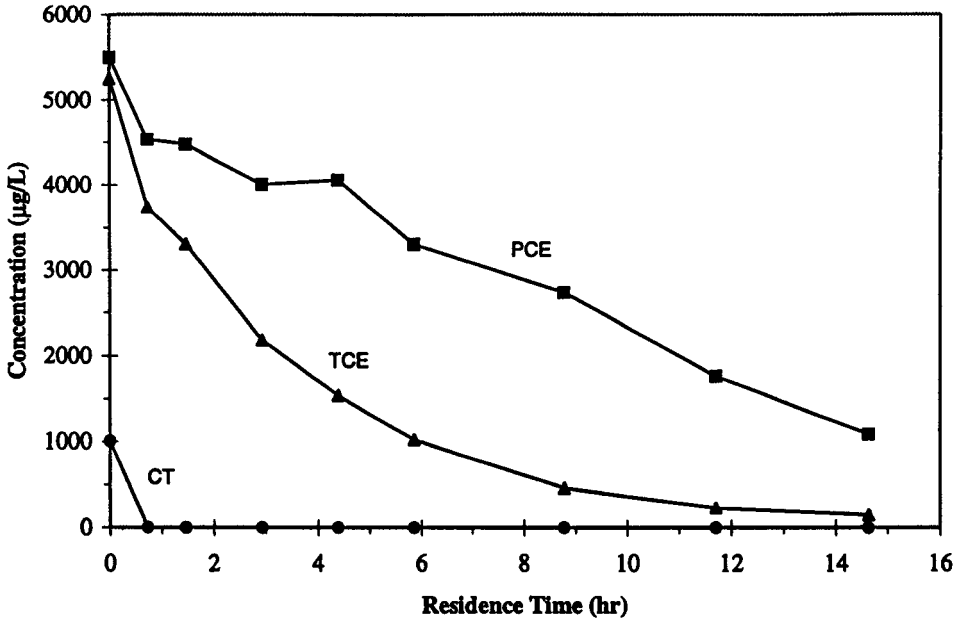


Figure 5. Organic concentration profiles versus residence time in the enhanced iron column A) cDCE, VC and 111TCA

A)



B)

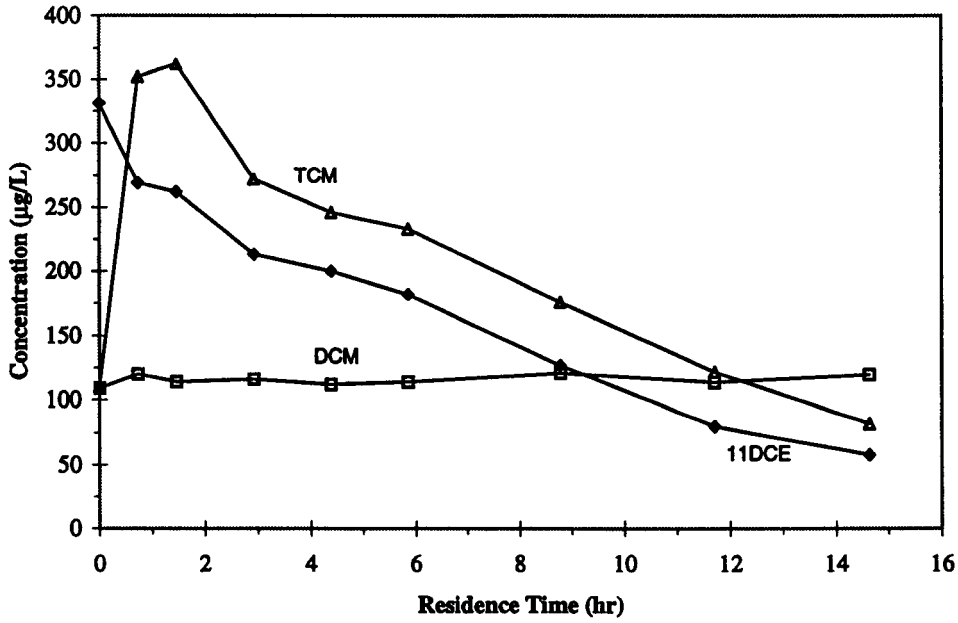


Figure 6 Organic concentration profiles versus residence time in the HSI foam column A) PCE, TCE and CT B) 11DCE, DCM and TCM

A)

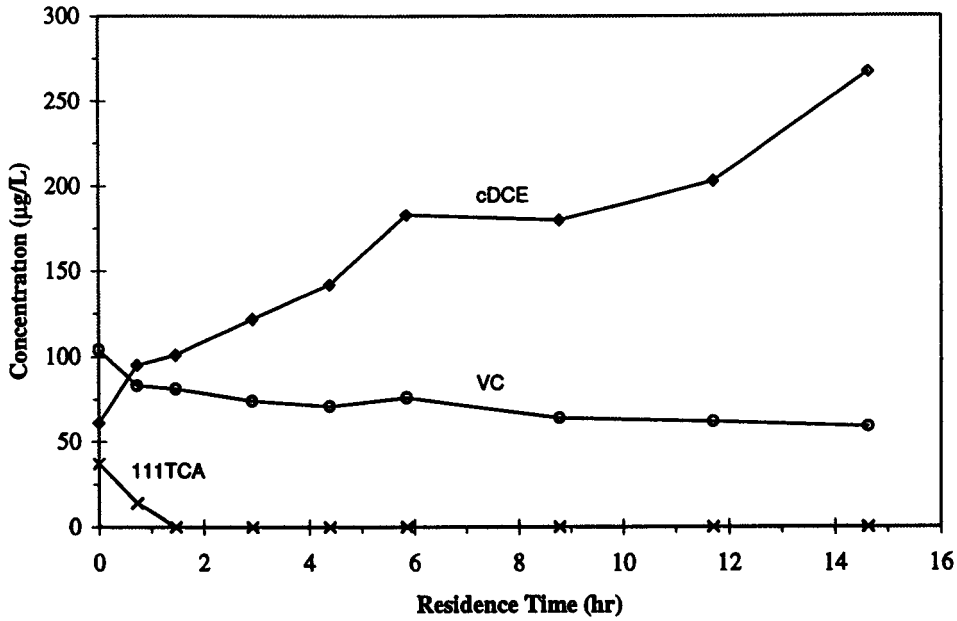
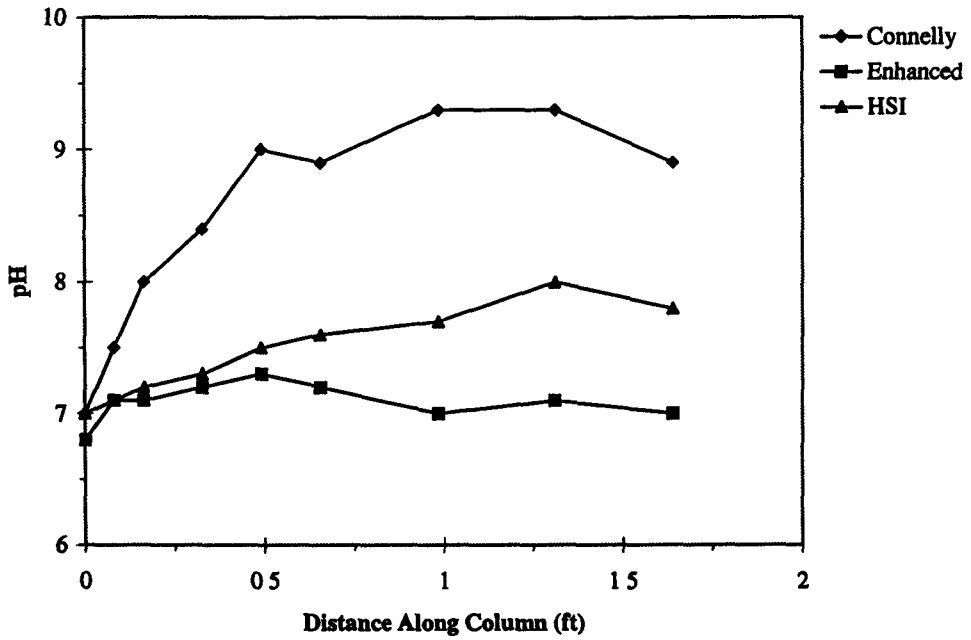


Figure 7· Organic concentration profiles versus residence time in the HSI foam column. A) cDCE, VC and 111TCA

A)



B)

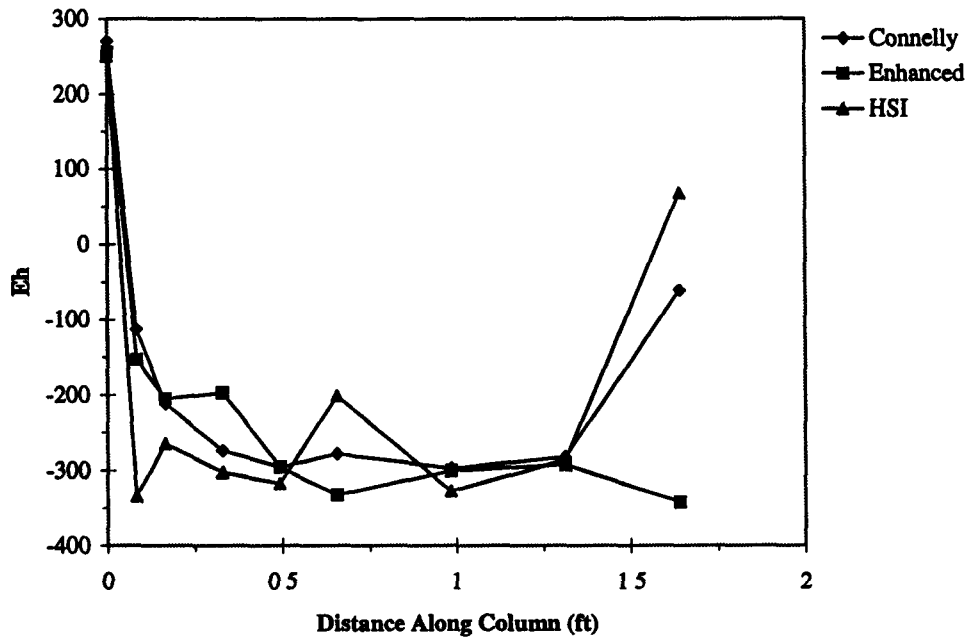
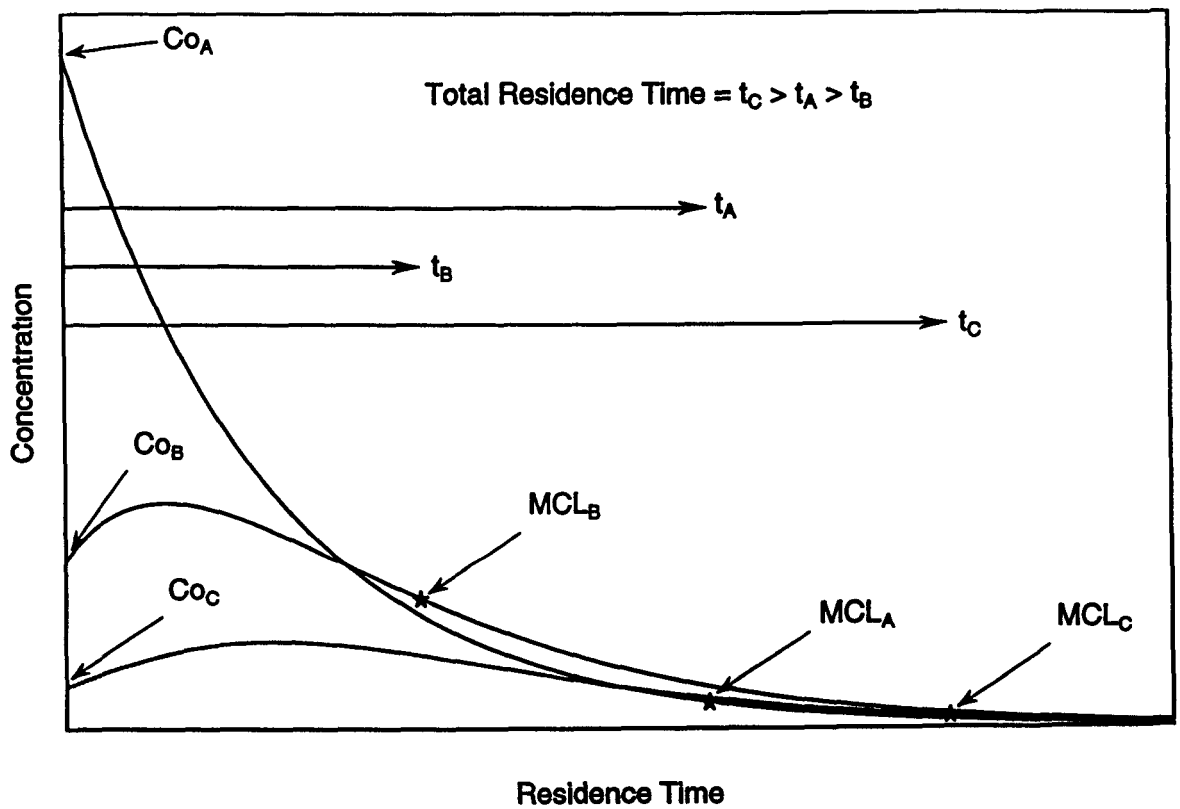


Figure 8 Steady state pH and Eh profiles

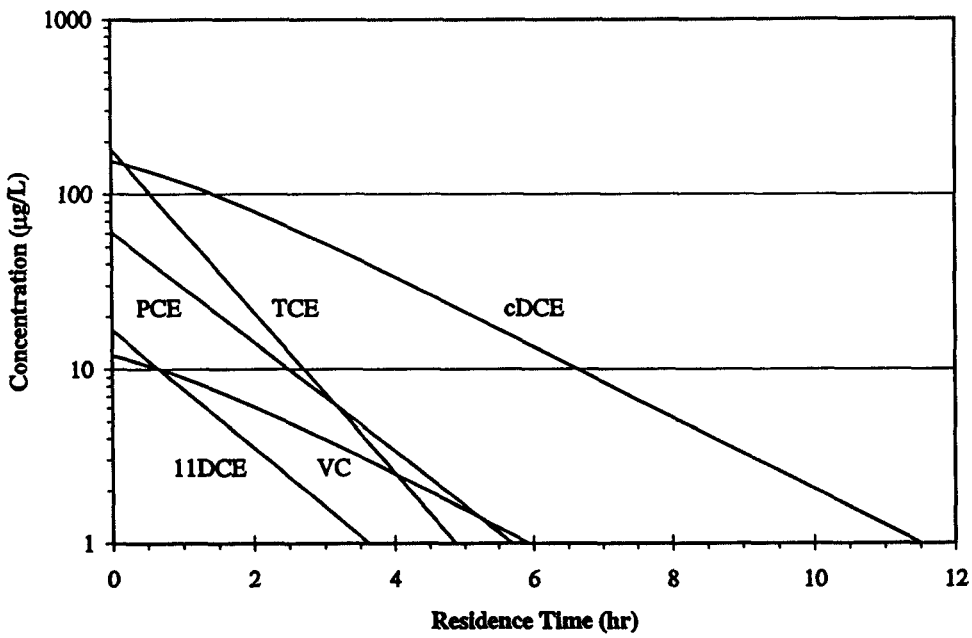
Reaction : A → B → C



Co - Initial Concentration
MCL - Maximum Contaminant Level
T - Residence Time

Figure 9 Illustration of residence time calculations using a first-order kinetic model assuming concurrent and sequential degradation

A)



B)

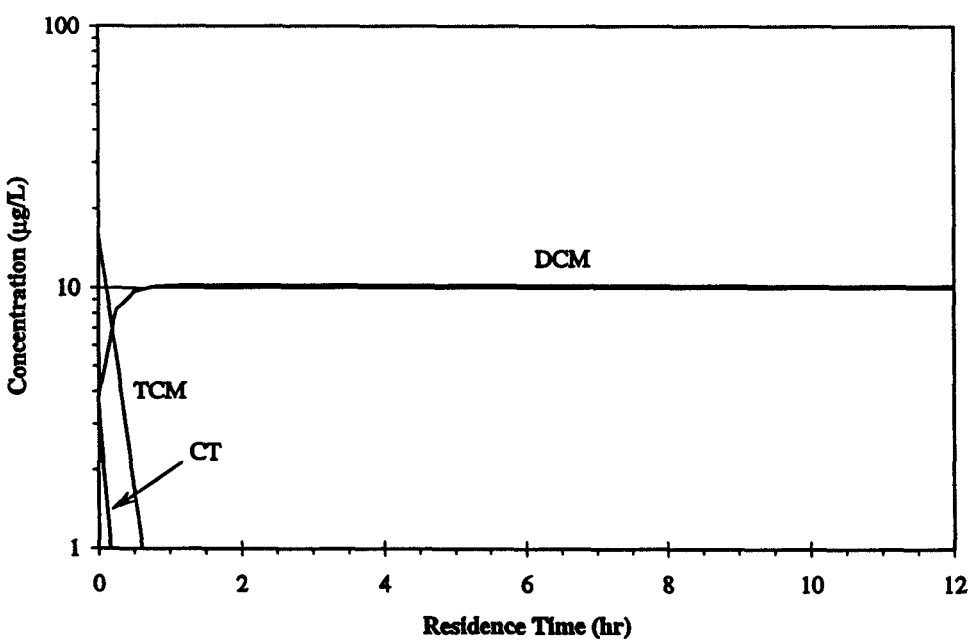
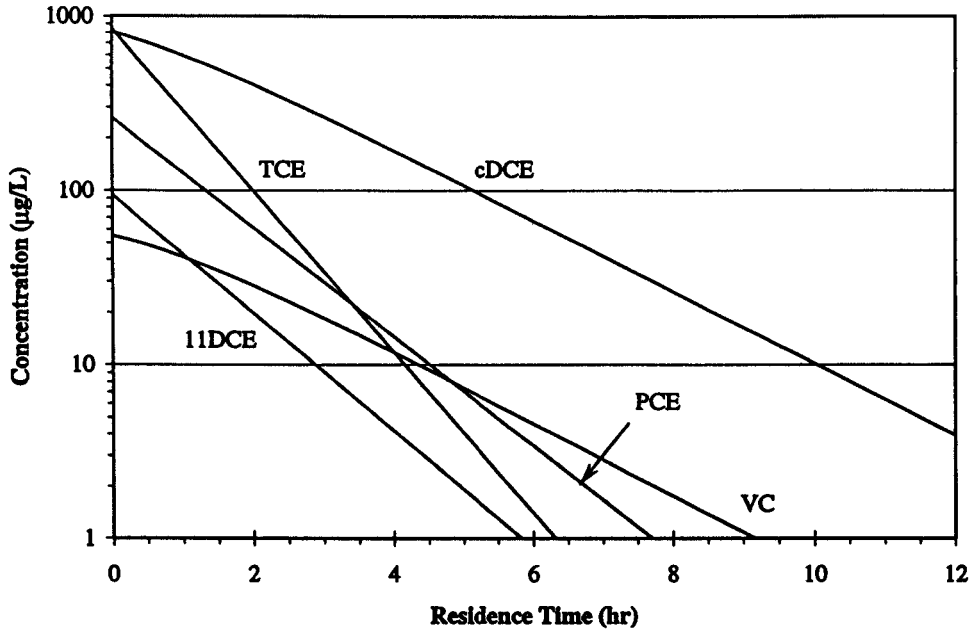


Figure 10 Estimated residence time requirement using Connelly iron and average SW059 groundwater VOC concentrations A) PCE, TCE, cDCE, 11DCE and VC B) CT, TCM and DCM

A)



B)

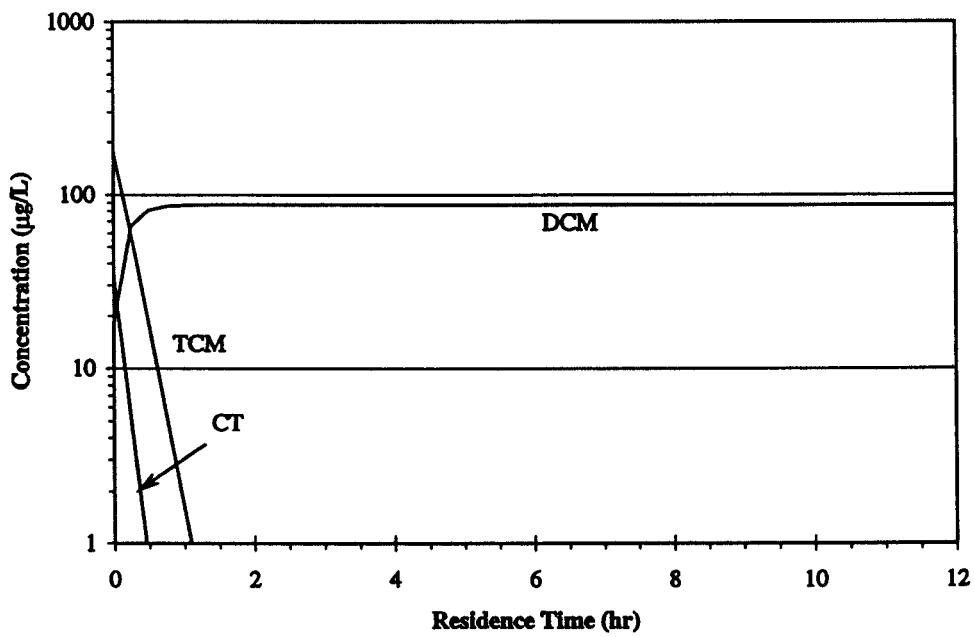
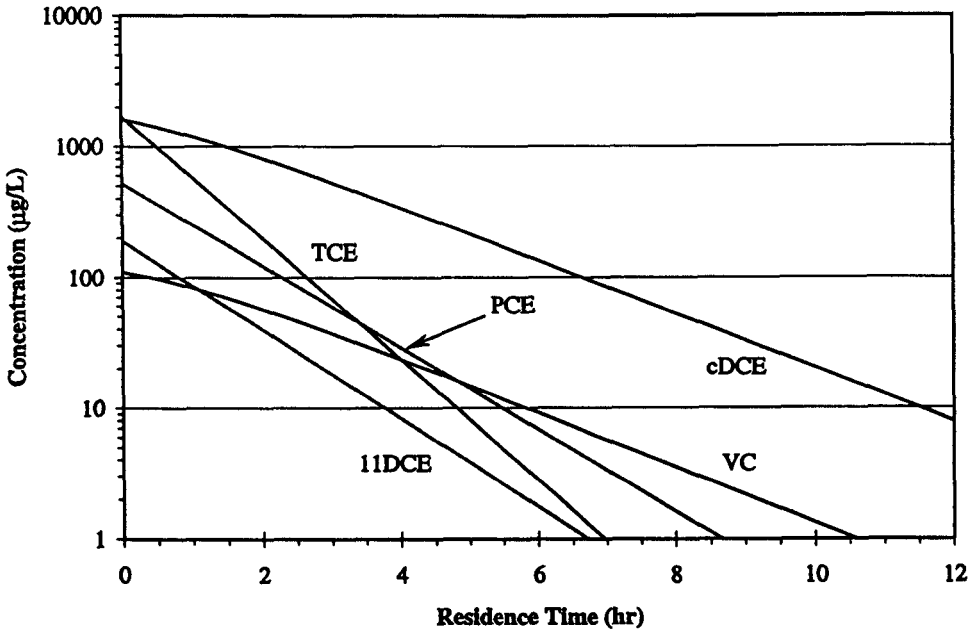


Figure 11· Estimated residence time requirement using Connelly iron and maximum SW059 groundwater VOC concentrations. A) PCE, TCE, cDCE, 11DCE and VC B) CT, TCM and DCM

A)



B)

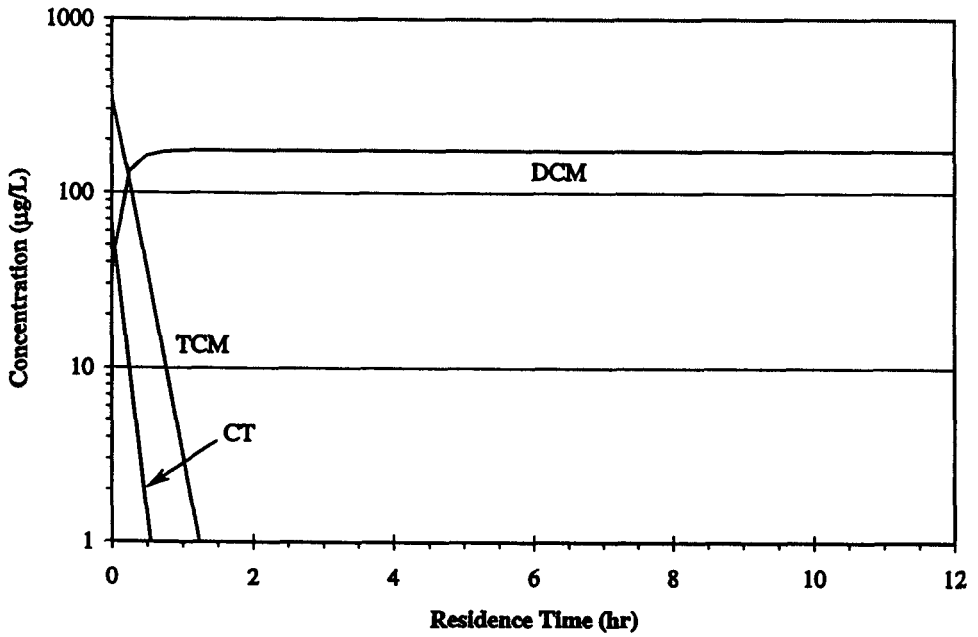
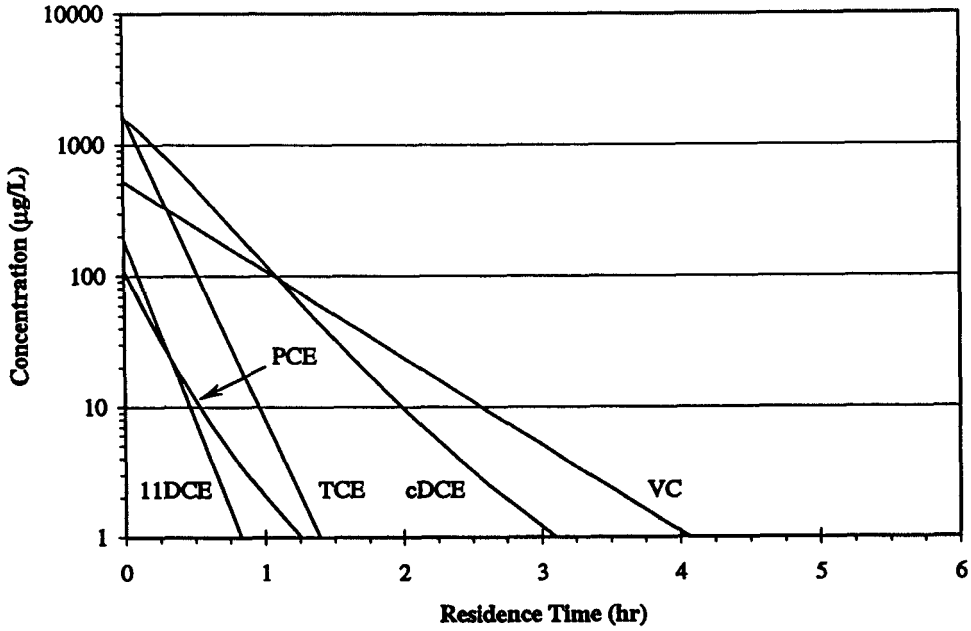


Figure 12: Estimated residence time requirement using Connelly iron and two times maximum SW059 groundwater VOC concentrations A) PCE, TCE, cDCE, 11DCE and VC B) CT, TCM and DCM

A)



B)

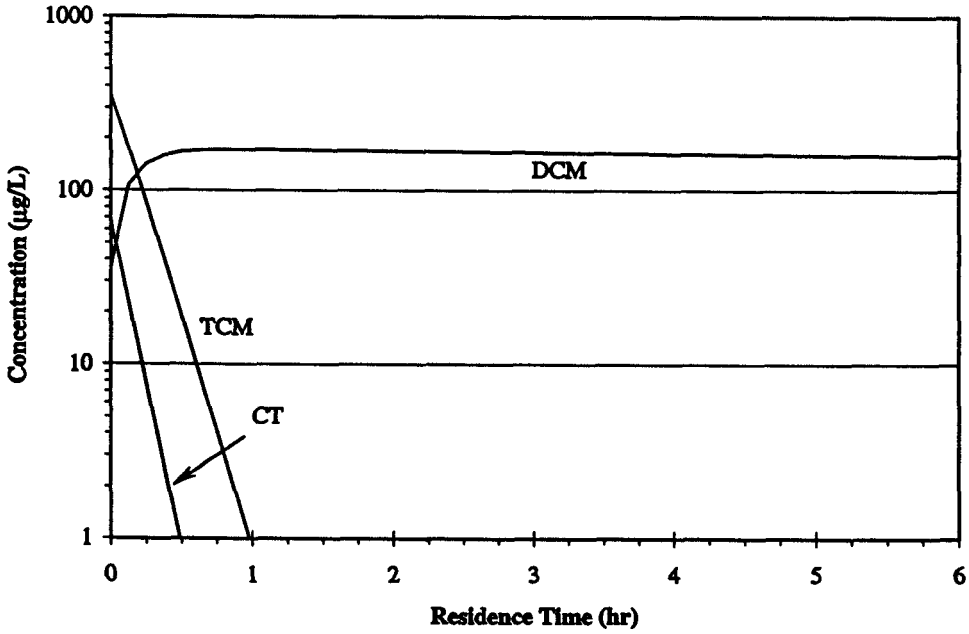
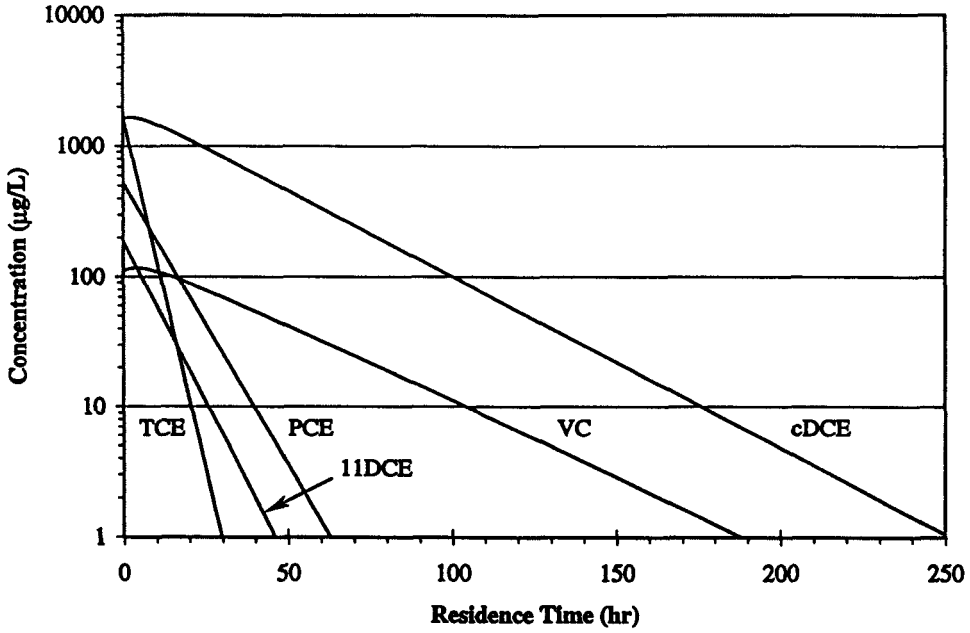


Figure 13· Estimated residence time requirement using enhanced iron and two times maximum SW059 groundwater VOC concentrations A) PCE, TCE, cDCE, 11DCE and VC B) CT, TCM and DCM

A)



B)

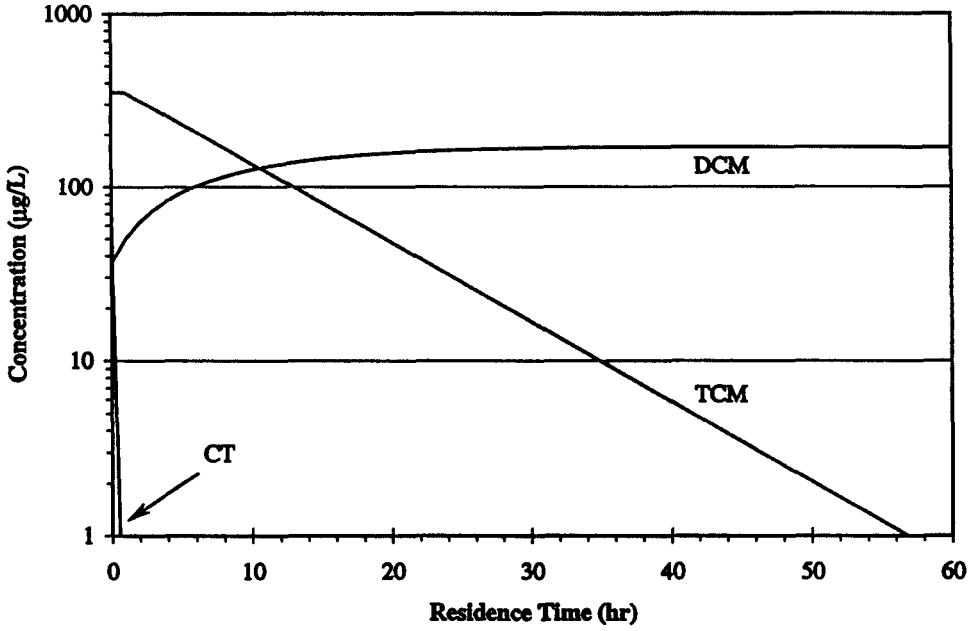
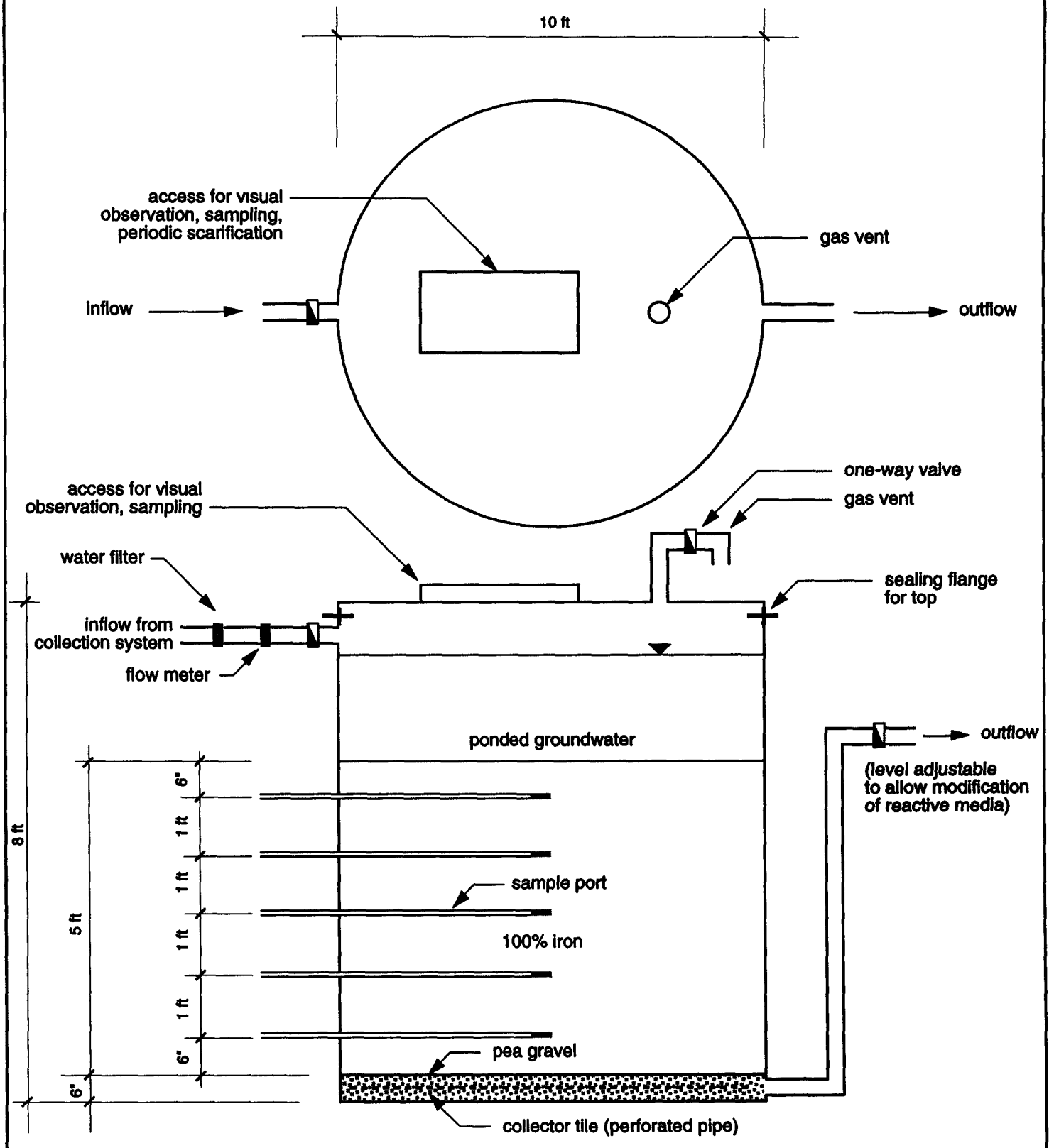


Figure 14 Estimated residence time requirement using HSI foam and two times maximum SW059 groundwater VOC concentrations A) PCE, TCE, cDCE, 11DCE and VC B) CT, TCM and DCM



Possible *In-Situ* Reactor Design
Rocky Flats Facility

enviromental technologies inc	Figure 15	June 1997 Rev 00

Appendix A

Laboratory Analyses
for
Bench Scale Studies involving the EnviroMetal Process

Institute for Groundwater Research
University of Waterloo
Waterloo, Ontario, Canada N2L 3G1

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Table A1: Column properties

	100% Granular Iron	100% Enhanced Iron	100% Cercona HSI Foam
Flow Velocity (FV) (ft/day) (cm/day)	2 9 90	2.9 87	2 7 82
Residence Time (hours)	13 4	13 9	14 5
Pore Volume (mL)	303	310	329
Porosity	0 53	0 54	0 58
Bulk Density (g/cm^3)	2.9	2 9	2 4
Iron to Volume of Solution Ratio (g mL)	5 5 1	5 4 · 1	4 1 1

Column test conducted March 7 to April 10, 1997

Appendix A-2

Organic Results

Organic Analytical Procedures

The less volatile halogenated organics such as tetrachloroethene (PCE), trichloroethene (TCE), 1,1,1-trichloroethane (111TCA), carbon tetrachloride (CT), chloroform (TCM) and dichloromethane (DCM) are extracted from the aqueous phase using pentane micro-extraction technique. The extraction from the aqueous phase uses a methodology derived from a pentane liquid-liquid extraction (US EPA, 1979; Glaze et al , 1981). This method is especially suited for bench scale studies, since it can accommodate small sample sizes

After removing a flush volume from the sampling port needle, a 2.0 mL aqueous phase sample is taken directly from the column using a 2.0 mL glass syringe. The organic analyses is performed immediately, and has no holding time associated with it. This sample is then transferred directly from the glass syringe to a Teflon®-faced septa screw cap vial containing 2.0 mL pentane with an internal standard of 1,2-dibromoethane, at a aqueous sample to pentane ratio of 2.0 to 2.0 mL. A ratio of 3.0 mL aqueous sample to 1.0 mL of internal standard was used for DCM analyses The sample is placed on a rotary shaker for 10 minutes to allow equilibration between the water and pentane phases The pentane phase is removed and transferred to an autosampler vial for injection into the gas chromatograph

Using a Hewlett Packard 7673 auto sampler, a 1.0 μL aliquot of pentane with internal standard was automatically injected directly onto 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 has an initial temperature of 50°C, with a temperature time program of 5°C/minute reaching a final temperature of 105°C. The detector temperature is 300°C. The carrier gas is helium and the makeup gas is 5% methane and 95% argon, at a flow rate of 30 mL/min.

For the more volatile compounds such as cis 1,2-dichloroethene (cDCE), trans 1,2-dichloroethene (tDCE), 1,1-dichloroethene (11DCE) and vinyl chloride (VC) a headspace analysis is conducted. A 2.5 mL aqueous phase sample is taken directly from the column using a 3.0 mL glass syringe. This sample is then transferred directly to a Teflon®-faced septa screw cap vial, creating a headspace with a ratio of 2.5 mL headspace to 2.5 mL aqueous sample. The samples are placed on a rotary shaker for 15 minutes to allow equilibration between the water phase and gas phase. For analysis, a 500 μL gas sample is injected directly onto a Hewlett Packard 5890 Series II gas chromatograph. The chromatograph is equipped with a HNU photoionization detector (PID) with a bulb ionization potential of 10.2 eV. The gas chromatograph is fitted with a fused silica capillary NSW-PLOT column (15 m x 0.53 mm ID). An isothermal oven temperature of 160°C and a detector temperature of 120°C are used. The carrier gas is helium with a flow rate of 4 1 mL/min.

Quality Control and Quality Assurance Program

Quality control procedures were used to evaluate the information on the analytical data and to determine if corrective action to the procedures was necessary. To evaluate these procedures, precision, accuracy, detection limits and other quantifiable and qualitative indicators were monitored These measures were used to monitor the program and to ensure that all data generated were suitable for their intended use. Our quality control and assurance procedures closely follow those given in U S EPA, 1986

Analytical quality control involved method blanks which were carried through the entire analytical procedures, as well as spiked blanks which were spiked with VOCs from laboratory grade reagents in order to monitor the execution of the analytical method, with percent recoveries recorded (%R) The two blanks and 10 to 15 spiked blanks were analysed every time sampling was undertaken. The results from the daily QA/QC procedures are shown in Appendix B

Method detection limits were determined from recent and ongoing laboratory studies 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 method detection limits were determined from analysis of samples from a solution matrix containing the analytes of interest. Detection limits for all compounds studied, as given in Table 2, were determined using the EPA procedure for Method Detection Limit (MDL) (US EPA, 1982).

References

Glaze, W.H., Rawley, R., Burleson, J.L , Mapel, D. and Scott, D R., 1981. Further optimization of the pentane liquid-liquid extraction method of the analysis of trace organic compounds in waster. In: Advances in the identification and analysis of organic pollutants in water. Volume 1, Keith, L.H. ed., Ann Arbor Science Publishers, Ann Arbor, MI.

United States Environmental Protection Agency, 1979. Analysis of trihalomethanes in drinking water by liquid-liquid extraction. Federal Register, Vol. 44, No. 231: 68683.

United States Environmental Protection Agency, 1982. Methods for organic chemical analyses of municipal and industrial wastewater. EPA-600/4-82-057. J.E. Longbottom and J.J. Lichtenberg (eds), Cinncinnati, Ohio, Appendix A.

United States Environmental Protection Agency, 1986. Test methods for evaluating solid waste, Volume 1B: Laboratory manual physical/chemical methods, SW846

Table A2: Method Detection Limits (MDL)

Organic Compounds	MDL (μg/L)
Tetrachloroethene (PCE)	1 4
Trichloroethene (TCE)	1 3
1,1,1-Trichloroethane (111TCA)	1 5
Carbon Tetrachloride (CT)	2 0
Chloroform (TCM)	1 3
Dichloromethane (DCM)	3 1
cis-1,2-Dichloroethene (cDCE)	7 8
trans-1,2-Dichloroethene (tDCE)	1 9
1,1-Dichloroethene (11DCE)	3 2
Vinyl Chloride (VC)	0 7

REACTIVE COLUMN 183

Column Composition	Granular Iron (Connelly UofW #113A)
Pore Volume (PV)	303 mL
Porosity	0 53
Flow Velocity (FV)	90 cm/day (2 9 ft/day)
Residence Time	13 4 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent	Organic Concentration (ug/L)							Effluent	HL	r2
TCE													
	7 2	a	4092	3800	2932	2387	1723	1132	288	3 2	1 0		
	12 9	a	4294	3032	2279	1667	985	601	172	26	nd		
	22 1	a	3924	2536	1765	939	438	172	22	3 7	1 9		
	25 8	b	4401	3372	2028	716	290	80	8 7	1 3	1 1		
	33 0	b	4670	2962	2062	785	356	104	5 7	nd	nd		
	36 4	b	4416	2600	1677	624	244	56	4 3	nd	nd		
	43 4	b	4086	2409	1459	447	139	24	4 8	1 3	2 5	1 1	0 92
	49 0	b	3698	2201	1221	273	73	13	2 2	nd	nd	0 71	0 99
	55 1	c	5250	3810	2226	535	132	12	1 8	nd	nd	0 65	0 99
PCE													
	7 2	a	4262	3598	2585	1323	168	1 9	nd	nd	nd		
	12 9	a	4056	3116	2432	1870	981	362	1 1	nd	nd		
	22 1	a	3324	2694	1718	1139	624	97	nd	nd	nd		
	25 8	b	4090	3684	2661	1491	1022	570	109	1 4	nd		
	33 0	b	4010	3558	3072	1851	1267	726	128	4 2	nd		
	36 4	b	4018	3170	2752	1835	1221	670	139	4 6	nd		
	43 4	b	3820	2876	2234	1540	991	547	113	4 9	nd	1 2	0 93
	49 0	b	3470	2888	2147	1300	841	434	75	3 8	nd	1 2	0 95
	55 1	c	5496	4264	3357	1724	914	342	41	1 9	nd	0 96	0 97
111 TCA													
	7 2	a	62	nd	nd	nd	nd	nd	nd	nd	nd		
	12 9	a	31	nd	nd	nd	nd	nd	nd	nd	nd		
	22 1	a	28	nd	nd	nd	nd	nd	nd	nd	nd		
	25 8	b	30	nd	nd	nd	nd	nd	nd	nd	nd		
	33 0	b	31	nd	nd	nd	nd	nd	nd	nd	nd		
	36 4	b	29	nd	nd	nd	nd	nd	nd	nd	nd		
	43 4	b	29	nd	nd	nd	nd	nd	nd	nd	nd		
	49 0	b	29	nd	nd	nd	nd	nd	nd	nd	nd		
	55 1	c	37	7 2	nd	nd	nd	nd	nd	nd	nd	0 28	1 0

nd = not detected
RN = reservoir number

REACTIVE COLUMN 183

Column Composition	Granular Iron (Connelly UofW #113A)
Pore Volume (PV)	303 mL
Porosity	0 53
Flow Velocity (FV)	90 cm/day (2 9 ft/day)
Residence Time	13 4 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent	Organic Concentration (ug/L)							Effluent	HL	r2
CT													
	7 2	a	835	nd	nd	nd	nd	nd	nd	nd	nd		
	12 9	a	938	nd	nd	nd	nd	nd	nd	nd	nd		
	22 1	a	886	nd	nd	nd	nd	nd	nd	nd	nd		
	25 8	b	951	nd	nd	nd	nd	nd	nd	nd	nd		
	33 0	b	957	nd	nd	nd	nd	nd	nd	nd	nd		
	36 4	b	892	nd	nd	nd	nd	nd	nd	nd	nd		
	43 4	b	860	nd	nd	nd	nd	nd	nd	nd	nd		
	49 0	b	886	nd	nd	nd	nd	nd	nd	nd	nd		
	55 1	c	1004	7 6	nd	nd	nd	nd	nd	nd	nd	0 09	1 0
TCM													
	7 2	a	82	74	5 7	nd	nd	nd	nd	nd	nd		
	12 9	a	86	26	nd	nd	nd	nd	nd	nd	nd		
	22 1	a	78	13	nd	nd	nd	nd	nd	nd	nd		
	25 8	b	80	30	nd	nd	nd	nd	nd	nd	nd		
	33 0	b	88	8 4	nd	nd	nd	nd	nd	nd	nd		
	36 4	b	87	10	nd	nd	nd	nd	nd	nd	nd		
	43 4	b	96	15	nd	nd	nd	nd	nd	nd	nd	0 25	1 0
	49 0	b	92	35	nd	nd	nd	nd	nd	nd	nd	0 48	1 0
	55 1	c	110	159	6 2	nd	nd	nd	nd	nd	nd	0 14	1 0
cDCE													
	10 9	a	72	62	96	70	95	95	78	65	23		
	24 0	a	68	61	61	59	32	15	8 0	nd	nd		
	31 2	b	64	81	43	36	40	26	nd	nd	nd		
	36 3	b	56	71	43	28	23	nd	nd	nd	nd		
	47 0	b	60	57	44	24	5 9	nd	nd	65	7 7		
	48 7	b	59	77	49	17	22	28	21	26	18		
	56 9	c	86	93	130	35	39	nd	nd	nd	nd	1 5	0 68
	60 5	c	71	102	140	43	39	nd	nd	nd	nd	1 5	0 81

nd = not detected
RN = reservoir number

REACTIVE COLUMN 183

Column Composition	Granular Iron (Connelly UofW #113A)
Pore Volume (PV)	303 mL
Porosity	0 53
Flow Velocity (FV)	90 cm/day (2 9 ft/day)
Residence Time	13 4 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent	Organic Concentration (ug/L)							Effluent	HL	r2
tDCE													
	10 9	a	nd	nd	nd	nd	nd	nd	nd	nd	nd		
	24 0	a	1 1	nd	nd	nd	nd	nd	nd	nd	nd		
	31 2	b	2 3	nd	nd	nd	nd	nd	nd	nd	nd		
	36 3	b	4 8	nd	nd	nd	nd	nd	nd	nd	nd		
	47 0	b	3 8	nd	nd	nd	nd	nd	nd	nd	nd		
	48 7	b	7 9	1 5	nd	nd	nd	nd	nd	nd	nd		
	56 9	c	nd	nd	nd	nd	nd	nd	nd	nd	nd		
	60 5	c	nd	nd	nd	nd	nd	nd	nd	nd	nd		
11DCE													
	10 9	a	405	334	354	126	121	102	74	73	18		
	24 0	a	353	202	100	59	33	9 7	4 9	5 8	4 1		
	31 2	b	351	251	55	44	37	13	4 9	4 2	3 6		
	36 3	b	247	224	91	29	16	8 7	8 7	2 5	5 2		
	47 0	b	187	93	49	21	6 2	8 0	6 4	6 0	6 6		
	48 7	b	173	243	72	2 0	nd	nd	nd	nd	nd	0 38	0 87
	56 9	c	340	262	171	17	nd	nd	nd	nd	nd	0 60	0 92
	60 5	c	331	264	175	44	nd	nd	nd	nd	nd	0 89	0 96
VC													
	10 9	a	72	32	30	22	10	17	11	13	nd		
	24 0	a	63	19	12	9 0	3 1	nd	nd	nd	nd		
	31.2	b	85	57	15	8 0	8 4	nd	nd	nd	nd		
	36 3	b	91	66	3 0	3 0	nd	nd	nd	nd	nd		
	47 0	b	62	36	17	nd	nd	nd	nd	nd	nd		
	48 7	b	66	32	nd	nd	nd	nd	nd	nd	nd	0 64	1 0
	56 9	c	91	36	8 8	nd	nd	nd	nd	nd	nd	0 40	0 99
	60 5	c	99	48	39	19	nd	nd	nd	nd	nd	1 2	0 96

nd = not detected
RN = reservoir number

REACTIVE COLUMN 183

Column Composition	Granular Iron (Connelly UofW #113A)
Pore Volume (PV)	303 mL
Porosity	0 53
Flow Velocity (FV)	90 cm/day (2 9 ft/day)
Residence Time	13 4 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent			Organic Concentration (ug/L)					Effluent	HL	r2
DCM													
	20 2	a	83	130	113	101	99	97	91	87	88		
	24 1	a	85	116	112	100	93	89	89	83	82		
	31 4	b	93	132	128	107	112	107	106	100	90		
	34 7	b	103	145	132	121	118	109	104	99	105		
	45 3	b	89	120	131	123	124	109	105	92	95		
	59 0	c	111	150	158	146	126	113	115	110	105		
			pH Along Column										
pH													
	9 2	a	7 3	8 7	8 9	8 8	8 7	8 1	6 2	6 2	6 4		
	18 4	a	7 3	8 3	7 9	7 7	8 4	8 9	8 2	6 9	6 9		
	26 0	b	7 1	8 0	8 4	8 7	8 7	8 5	8 2	7 1	6 8		
	33 2	b	7 2	7 5	7 6	8 0	8 5	8 9	9 0	8 2	6 7		
	43 7	b	6 9	7 4	7 7	7 9	8 5	8 3	8 9	8 8	8 1		
	47.2	b	6 9	7 4	7 9	8 5	8 4	8 5	8 8	9 0	7 3		
	50 0	b	7 0	7 3	7 9	7 9	8 3	7 5	7 8	8 8	7 6		
	55 3	c	7 0	7 4	8 0	8 7	9 0	9 0	9 1	9 0	8 2		
	60 7	c	7 0	7 5	8 0	8 4	9 0	8 9	9 3	9 3	8 9		
			Redox Potential Along Column (mV)										
Eh													
	9 2	a	244	-171	-208	-110	-93	-55	75	70	302		
	18 4	a	348	-136	-349	-356	-302	-287	-230	-8	329		
	26 0	b	344	-233	-272	-272	-251	-274	-256	-169	214		
	33 2	b	243	-393	-328	-364	-428	-396	-493	-361	240		
	43 7	b	273	-293	-309	-370	-309	-326	-343	-361	186		
	47 2	b	275	-215	-304	-343	-369	-349	-364	-337	-120		
	50 0	b	350	-228	-264	-292	-316	-312	-362	-326	118		
	55 3	c	240	-331	-65	-258	-299	-295	-280	-289	-130		
	60 7	c	270	-113	-212	-274	-295	-278	-297	-282	-61		

nd = not detected
RN = reservoir number

eof//

REACTIVE COLUMN 184

Column Composition	Enhanced Iron, Ni-Fe (Connelly Iron Plated, UofW #113E)
Pore Volume (PV)	310 mL
Porosity	0 54
Flow Velocity (FV)	87 cm/day (2 9 ft/day)
Residence Time	13 9 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent	Organic Concentration (ug/L)							Effluent	HL	r2
TCE													
	6 6	a	4092	78	18	5 5	1 9	nd	nd	nd	nd		
	12 1	a	4294	48	7 9	3 7	2.0	nd	nd	nd	1 4		
	21 1	a	3860	18	4 4	1 9	1 0	nd	nd	nd	nd		
	24 6	b	4706	60	6 5	1 8	nd	nd	nd	nd	nd		
	31 5	b	4350	183	8 0	1 5	nd	nd	nd	nd	nd		
	34 9	b	4334	33	6 5	1 2	nd	nd	nd	nd	nd		
	41 6	b	4086	24	3 4	1 3	1 0	nd	nd	nd	nd	0 41	0 67
	46 7	b	3698	32	2 7	0 8	1 0	1 0	nd	nd	nd	0 58	0 59
	53 1	c	5250	47	3 3	nd	nd	nd	nd	nd	nd	0 13	0 98
PCE													
	6 6	a	4262	2237	1879	883	310	31 0	nd	nd	nd		
	12 1	a	4056	1818	1350	864	422	119	1 7	nd	nd		
	21 1	a	3206	1312	1013	432	194	54	nd	nd	nd		
	24 6	b	4406	2298	1350	396	82	14	nd	nd	nd		
	31 5	b	4642	2546	1512	295	49	4 7	nd	nd	nd		
	34 9	b	4018	1825	1297	165	9 4	nd	nd	nd	nd		
	41 6	b	3820	1326	673	22	2 1	nd	nd	nd	nd	0 37	0 99
	46 7	b	3470	1256	485	1 4	nd	1 2	nd	nd	nd	0 41	0 84
	53 1	c	5496	1776	642	nd	nd	nd	nd	nd	nd	0 45	1 00
111 TCA													
	6 6	a	62	nd	nd	nd	nd	nd	nd	nd	nd		
	12 1	a	31	nd	nd	nd	nd	nd	nd	nd	nd		
	21 1	a	28	nd	nd	nd	nd	nd	nd	nd	nd		
	24 6	b	30	nd	nd	nd	nd	nd	nd	nd	nd		
	31 5	b	31	nd	nd	nd	nd	nd	nd	nd	nd		
	34 9	b	29	nd	nd	nd	nd	nd	nd	nd	nd		
	41 6	b	29	nd	nd	nd	nd	nd	nd	nd	nd	0.16	1 00
	46 7	b	27	nd	nd	nd	nd	nd	nd	nd	nd	0 17	1 00
	53 1	c	37	nd	nd	nd	nd	nd	nd	nd	nd	0 15	1 00

nd = not detected
RN = reservoir number

REACTIVE COLUMN 184

Column Composition	Enhanced Iron, Ni-Fe (Connelly Iron Plated, UofW #113E)
Pore Volume (PV)	310 mL
Porosity	0 54
Flow Velocity (FV)	87 cm/day (2 9 ft/day)
Residence Time	13 9 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent	Organic Concentration (ug/L)							Effluent	HL	r2
CT													
	6 6	a	836	nd	nd	nd	nd	nd	nd	nd	nd		
	12 1	a	938	nd	nd	nd	nd	nd	nd	nd	nd		
	21 1	a	886	nd	nd	nd	nd	nd	nd	nd	nd		
	24 6	b	951	nd	nd	nd	nd	nd	nd	nd	nd		
	31 5	b	957	nd	nd	nd	nd	nd	nd	nd	nd		
	34 9	b	884	nd	nd	nd	nd	nd	nd	nd	nd		
	41 6	b	860	nd	nd	nd	nd	nd	nd	nd	nd	0 08	1 00
	46 7	b	811	nd	nd	nd	nd	nd	nd	nd	nd	0 08	1 00
	53 1	c	1004	nd	nd	nd	nd	nd	nd	nd	nd	0 08	1 00
TCM													
	6 6	a	75	nd	nd	nd	nd	nd	nd	nd	nd		
	12 1	a	86	nd	nd	nd	nd	nd	nd	nd	nd		
	21 1	a	79	nd	nd	nd	nd	nd	nd	nd	nd		
	24 6	b	80	nd	nd	nd	nd	nd	nd	nd	nd		
	31 5	b	88	2 9	nd	nd	nd	nd	nd	nd	nd		
	34 9	b	89	1 8	nd	nd	nd	nd	nd	nd	nd		
	41 6	b	96	nd	nd	nd	nd	nd	nd	nd	nd		
	46 7	b	95	1.2	nd	nd	nd	nd	nd	nd	nd	0 11	1 00
	53 1	c	110	nd	nd	nd	nd	nd	nd	nd	nd	0 11	1 00
cDCE													
	10 2	a	72	nd	nd	nd	nd	nd	nd	nd	nd		
	22 9	a	70	nd	nd	nd	nd	nd	nd	nd	nd		
	29 7	b	74	5 6	nd	nd	nd	nd	nd	nd	nd		
	34 8	b	56	nd	nd	nd	nd	nd	nd	nd	nd		
	44 8	b	52	19	nd	1 9	nd	nd	nd	6 7	nd		
	46 5	b	59	nd	nd	nd	nd	nd	nd	nd	nd	0.24	1 00
	54 9	c	61	nd	nd	nd	nd	nd	nd	nd	nd	0 23	1 00
	58 5	c	61	nd	nd	nd	nd	nd	nd	nd	nd	0 23	1 00

nd = not detected
RN = reservoir number

REACTIVE COLUMN 184

Column Composition	Enhanced Iron, Ni-Fe (Connelly Iron Plated, UofW #113E)
Pore Volume (PV)	310 mL
Porosity	0 54
Flow Velocity (FV)	87 cm/day (2 9 ft/day)
Residence Time	13 9 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent	Organic Concentration (ug/L)							Effluent	HL	r2
tDCE													
	10 2	a	3 0	nd	nd	nd	nd	nd	nd	nd	nd		
	22 9	a	1 1	nd	nd	nd	nd	nd	nd	nd	nd		
	29 7	b	2 3	nd	nd	nd	nd	nd	nd	nd	nd		
	34 8	b	4 8	nd	nd	nd	nd	nd	nd	nd	nd		
	44 8	b	3 8	nd	nd	nd	nd	nd	nd	nd	nd		
	46 5	b	7 9	nd	nd	nd	nd	nd	nd	nd	nd		
	54 9	c	nd	nd	nd	nd	nd	nd	nd	nd	nd		
	58 5	c	nd	nd	nd	nd	nd	nd	nd	nd	nd		
11DCE													
	10 2	a	411	11	12	14	11	14	17	13	13		
	22 9	a	358	6 8	9 2	6 0	7 0	6 5	7 2	7 1	7 1		
	29 7	b	351	17	13	5 6	13	6 7	6 3	9 7	4 3		
	34 8	b	247	12	9 4	12	8 1	9 9	7 4	8 9	8 5		
	44 8	b	186	11	9 7	9 9	8 6	5 4	5 6	6 2	6 1		
	46 5	b	291	nd	nd	nd	nd	nd	nd	nd	nd	0 11	1 00
	54 9	c	273	nd	nd	nd	nd	nd	nd	nd	nd	0 11	1 00
	58 5	c	291	nd	nd	nd	nd	nd	nd	nd	nd	0 11	1 00
VC													
	10 2	a	72	nd	nd	nd	nd	nd	nd	nd	nd		
	22.9	a	64	nd	nd	nd	nd	nd	nd	nd	nd		
	29 7	b	69	nd	nd	nd	nd	nd	nd	nd	nd		
	34 8	b	91	nd	nd	nd	nd	nd	nd	nd	nd		
	44 8	b	59	nd	nd	nd	nd	nd	nd	nd	nd		
	46 5	b	66	nd	nd	nd	nd	nd	nd	nd	nd	0 11	1 00
	54 9	c	91	nd	nd	nd	nd	nd	nd	nd	nd	0 10	1 00
	58 5	c	104	nd	nd	nd	nd	nd	nd	nd	nd	0 10	1 00

nd = not detected
RN = reservoir number

REACTIVE COLUMN 184

Column Composition	Enhanced Iron, Ni-Fe (Connelly Iron Plated, UofW #113E)
Pore Volume (PV)	310 mL
Porosity	0 54
Flow Velocity (FV)	87 cm/day (2 9 ft/day)
Residence Time	13 9 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent			Organic Concentration (ug/L)					Effluent	HL	r2
DCM													
	19 3	a	88	84	84	78	82	81	79	71	74		
	22 9	a	85	83	81	80	72	73	68	74	69		
	30 0	b	92	87	93	91	89	94	92	87	87		
	33 2	b	105	102	98	104	97	97	99	93	75	39 9	0 69
	43 2	b	77	102	104	97	102	102	97	71	86		
	56 9	c	112	116	112	118	93	98	87	95	94	39 1	0 57
			pH Along Column										
pH													
	8 6	a	7 3	7 0	7 1	7 1	7 1	7 1	7 1	6 9	7 2		
	17 5	a	7 3	7 2	7 2	7 1	7 2	7 1	7 1	7 0	7 1		
	24 9	b	7 0	7 0	7 1	7 0	7 0	7 0	7 1	7 0	6 6		
	31 7	b	7.2	7 0	7 0	7.2	7 0	7 1	7 1	7 1	8 4		
	41 8	b	7 0	7 0	7 1	7 1	7 1	7 1	7 2	7 0	7 1		
	45 0	b	7 0	7 0	7 2	7 3	7 2	7 1	7 0	7 1	6 8		
	48 2	b	7 1	7 0	7 0	7 1	7 1	7 0	7 1	7 0	7 0		
	53 4	c	7 0	6 8	7 0	7 1	7 1	7 1	7 0	6 8	6 9		
	58 7	c	6 8	7 1	7 1	7.2	7 3	7 2	7 0	7 1	7 0		
			Redox Potential Along Column (mV)										
Eh													
	8 6	a	265	-40	-48	-74	-120	-154	-96	-15	15		
	17 5	a	346	-345	-158	-78	-312	-217	-86	8	67		
	24 9	b	367	-203	-212	-241	-219	-246	-312	-199	154		
	31 7	b	317	-242	-270	-392	-356	-381	-402	-381	206		
	41 8	b	275	-153	-281	-295	-292	-294	-350	-283	-251		
	45 0	b	209	-131	-325	-369	-378	-343	-295	-346	-160		
	48 2	b	316	-212	-194	-244	-208	-232	-282	-250	-248		
	53 4	c	271	-308	-239	-197	-93	-265	-355	-297	-345		
	58 7	c	256	-153	-205	-197	-295	-332	-300	-292	-342		

nd = not detected
RN = reservoir number

eof//

REACTIVE COLUMN 185

Column Composition	Cercona HSI Foam (UofW # 127)
Pore Volume (PV)	329 mL
Porosity	0 58
Flow Velocity (FV)	82 cm/day (2 7 ft/day)
Residence Time	14 5 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent			Organic Concentration (ug/L)					Effluent	HL	r2
TCE													
	6 9	a	4092	3258	2856	2614	1651	860	38	nd	1 8		
	12 1	a	4294	3234	2968	2297	1655	1248	313	19	26		
	20 4	a	3768	3148	2946	2168	1547	1092	574	172	14		
	23 6	b	3604	3454	3044	2158	1486	975	472	194	25		
	29 7	b	4312	3584	3288	2539	1836	1304	668	371	118		
	32 9	b	4334	3094	2714	2091	1527	1037	566	312	143		
	39 4	b	4086	2988	2768	1938	1345	941	459	245	155	3 1	1 00
	44 6	b	3698	2734	2212	1520	1051	758	340	196	144	3 1	0 98
	50 9	c	5250	3740	3308	2183	1540	1024	460	228	145	2 8	0 99
PCE													
	6 9	a	4262	3364	2876	2145	432	98	nd	1 5	4 9		
	12 1	a	4056	3300	3306	2892	1953	1042	6 0	12	27		
	20 4	a	3206	3016	3024	2934	2592	2098	723	10	nd		
	23 6	b	3190	3910	3858	3332	2778	2143	1012	70	1 3		
	29 7	b	3878	3884	3854	3748	3642	3259	2076	885	76		
	32 9	b	3868	3376	3416	3396	2988	2956	2257	1195	251		
	39 4	b	3820	3404	3604	3140	3150	2852	2117	1437	709	6 8	0 90
	44 6	b	3470	3276	3158	3016	2788	2646	2061	1533	940	8 5	0 94
	50 9	c	5496	4536	4478	4004	4058	3306	2740	1766	1088	7 0	0 95
111 TCA													
	6 9	a	68	56	36	nd	nd	nd	nd	nd	nd		
	12 1	a	31	20	nd	nd	nd	nd	nd	nd	nd		
	20 4	a	31	27	25	nd	nd	nd	nd	nd	nd		
	23 6	b	30	17	nd	nd	nd	nd	nd	nd	nd		
	29 7	b	31	18	18	nd	nd	nd	nd	nd	nd		
	32 9	b	27	14	15	nd	nd	nd	nd	nd	nd		
	39 4	b	29	15	nd	nd	nd	nd	nd	nd	nd	0 77	1 00
	44 6	b	28	12	nd	nd	nd	nd	nd	nd	nd	0 60	1 00
	50 9	c	37	14	nd	nd	nd	nd	nd	nd	nd	0 52	1 00

nd = not detected
RN = reservoir number

REACTIVE COLUMN
185

Column Composition	Cercona HSI Foam (UofW # 127)
Pore Volume (PV)	329 mL
Porosity	0 58
Flow Velocity (FV)	82 cm/day (2 7 ft/day)
Residence Time	14 5 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent	Organic Concentration (ug/L)							Effluent	HL	r2
CT													
	6 9	a	836	nd	nd	nd	nd	nd	nd	nd	nd		
	12.1	a	938	nd	nd	nd	nd	nd	nd	nd	nd		
	20 4	a	952	36	nd	nd	nd	nd	nd	nd	nd		
	23 6	b	964	nd	nd	nd	nd	nd	nd	nd	nd		
	29 7	b	957	11	nd	nd	nd	nd	nd	nd	nd		
	32 9	b	859	5 3	nd	nd	nd	nd	nd	nd	nd		
	39 4	b	860	10	nd	nd	nd	nd	nd	nd	nd	0 11	1 00
	44 6	b	838	4 0	nd	nd	nd	nd	nd	nd	nd	0 09	1 00
	50 9	c	1004	3 1	nd	nd	nd	nd	nd	nd	nd	0 09	1 00
TCM													
	6 9	a	74	436	436	399	322	252	117	38	9 2		
	12 1	a	86	486	463	423	347	306	195	100	34		
	20 4	a	85	450	451	386	350	311	214	138	69		
	23 6	b	80	408	396	363	340	303	212	140	75		
	29 7	b	88	425	408	404	357	329	248	179	117		
	32 9	b	81	388	364	349	311	274	220	147	103		
	39 4	b	96	390	369	324	286	264	207	150	118	8 1	1 00
	44 6	b	95	322	302	277	254	221	153	108	77	6 7	0 99
	50 9	c	110	352	362	272	246	233	176	122	82	6 6	0 98
cDCE													
	10 3	a	63	86	119	212	281	572	570	563	157		
	22 1	a	67	85	109	152	170	181	247	301	273		
	28 0	b	74	91	116	130	207	206	315	320	333		
	32 8	b	56	80	84	145	223	200	235	306	310		
	42 8	b	52	79	84	122	156	174	212	273	289		
	44 4	b	59	79	124	164	212	240	332	365	432		
	52 6	c	62	104	109	147	191	219	201	155	162	17 4	0 81
	56 1	c	61	95	101	122	142	183	180	203	267		

nd = not detected
RN = reservoir number

REACTIVE COLUMN 185

Column Composition	Cercona HSI Foam (UofW # 127)
Pore Volume (PV)	329 mL
Porosity	0 58
Flow Velocity (FV)	82 cm/day (2 7 ft/day)
Residence Time	14 5 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent	Organic Concentration (ug/L)							Effluent	HL	r2
tDCE													
	10 3	a	1 3	nd	nd	nd	nd	nd	nd	nd	nd		
	22 1	a	1 1	nd	nd	nd	nd	nd	nd	nd	nd		
	28 0	b	2 3	nd	nd	nd	nd	nd	nd	nd	nd		
	32 8	b	3 8	nd	nd	nd	nd	nd	nd	nd	nd		
	42 8	b	3 8	nd	nd	nd	nd	nd	nd	nd	nd		
	44 4	b	7 9	0 6	1 2	nd	nd	nd	nd	nd	nd		
	52 6	c	nd	nd	nd	nd	nd	nd	nd	nd	nd		
	56 1	c	nd	nd	nd	nd	nd	nd	nd	nd	nd		
11DCE													
	10 3	a	364	342	370	381	169	386	346	168	76		
	22 1	a	353	281	264	267	236	172	162	150	90		
	28 0	b	351	324	296	229	272	198	213	184	163		
	32 8	b	247	209	178	203	217	157	115	108	83		
	42 8	b	186	128	122	93	95	63	59	43	40		
	44 4	b	316	229	239	152	134	89	68	33	23	4 0	0 99
	52.6	c	338	256	262	238	216	207	118	75	26	4 6	0 91
	56 1	c	331	269	262	213	200	182	127	80	58	6 1	0 99
VC													
	10 3	a	72	35	51	64	147	78	55	98	60		
	22.1	a	63	52	62	56	55	26	50	49	25		
	28 0	b	80	74	72	60	74	60	68	64	62		
	32 8	b	91	71	59	71	89	68	60	67	57		
	42 8	b	59	43	44	42	43	40	40	40	36		
	44 4	b	70	43	44	46	45	47	45	39	31	22 6	0 55
	52 6	c	84	66	63	63	70	63	55	48	48	22.3	0 79
	56 1	c	104	83	81	74	71	76	64	62	59	22 8	0 80

nd = not detected
RN = reservoir number

REACTIVE COLUMN
185

Column Composition	Cercona HSI Foam (UofW # 127)
Pore Volume (PV)	329 mL
Porosity	0 58
Flow Velocity (FV)	82 cm/day (2 7 ft/day)
Residence Time	14 5 hr

			Distance Along Column (ft)										
			0 00	0 08	0 16	0 33	0 50	0 66	1 00	1 31	1 64		
	PV	RN	Influent			Organic Concentration (ug/L)					Effluent	HL	r2
DCM													
	18 7	a	88	96	96	101	107	113	99	103	107		
	22 2	a	85	95	97	96	100	102	94	98	98		
	28 2	b	92	96	118	123	125	118	119	114	122		
	31 3	b	102	117	122	113	116	126	123	124	127		
	41 1	b	84	98	106	104	106	89	109	104	116		
	54 6	c	109	120	114	116	112	114	121	114	120		
			pH Along Column										
pH													
	8 7	a	7 3	7 3	7 3	7 4	7 4	7 5	7 9	8 2	8 0		
	17 0	a	7 3	7 4	7 4	7 5	7 5	7 6	8 0	8 0	7 9		
	23 8	b	7 1	7 1	7 1	7 1	7 2	7 1	7 2	7 6	7 5		
	29 9	b	7 1	7 1	7 1	7 2	7 2	7 3	7 5	7 7	7 4		
	39 6	b	7 0	7 0	7 1	7 1	7 3	7 4	7 5	7 9	7 6		
	43 0	b	6 9	7 0	7 1	7.2	7 3	7 4	7 6	7 7	7 7		
	46 1	b	7 0	7 1	7 1	7 2	7 4	7 4	7 6	7 7	7 5		
	51 1	c	7 0	7 1	7 2	7 5	7 8	7 8	8 0	7 7	7 4		
	56 3	c	7 0	7 1	7 2	7 3	7 5	7 6	7 7	8 0	7 8		
			Redox Potential Along Column (mV)										
Eh													
	8 7	a	220	-159	-214	-244	-246	-188	-170	-202	-110		
	17 0	a	344	-383	-376	-328	-343	-387	-396	-389	-318		
	23 8	b	289	-279	-298	-242	-263	-290	-301	-335	-165		
	29 9	b	265	-363	-382	-381	-391	-360	-347	-359	-310		
	39 6	b	290	-297	-263	-335	-305	-365	-299	-296	-287		
	43 0	b	220	-296	-257	-275	-295	-264	-335	-212	-83		
	46 1	b	343	-213	-205	-240	-257	-271	-264	-279	-254		
	51 1	c	265	-366	-297	-375	-365	-328	-327	-297	-210		
	56 3	c	250	-334	-265	-302	-317	-201	-327	-286	68		

nd = not detected
RN = reservoir number

eof//

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Carbon Tetrachloride (CT)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
11 Mar	Spiked Blanks		2729	2738	99 7
		FV1	2242	2306	97 2
		100% Connelly Fe (7 2 pv)	1084	1095	99 0
		100% NiFe (6 6 pv)	578	593	97 5
		100% Cercona Fe (6 9 pv)	114	111	102 7
			54	52	103 8
			11 0	10 5	104 8
			2624	2738	95 8
			2161	2306	93 7
			1049	1095	95 8
			560	593	94 4
			109	111	98 2
			57	52	109 6
			11 0	10 5	104 8
	Blanks			0	
				0	
14 Mar	Spiked Blanks		2758	2758	100 0
		FV1	2334	2300	101 5
		100% Connelly Fe (12.9pv)	1052	1092	96 3
		100% NiFe (12 1 pv)	552	554	99 6
		100% Cercona Fe (12 1 pv)	114	111	102 7
			54	53	101 9
			12 0	11 0	109 1
			3027	2758	109 8
			2554	2300	111 0
			1075	1092	98 4
			583	554	105.2
			120	111	108 1
			11 0	11 0	100 0
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Carbon Tetrachloride (CT)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
19 Mar	Spiked Blanks		2259	2249	100 4
		FV1	1137	1088	104 5
		100% Connelly Fe (22 1pv)	618	534	115 7
		100% NiFe (21 1 pv)	118	115	102 6
		100% Cercona Fe (20 4 pv)	57	52	109 6
			13 0	10 0	130 0
			2317	2249	103 0
			1098	1088	100 9
			596	534	111 6
			108	115	93 9
			12 0	10 0	120 0
	Blanks			0	
				0	
21 Mar	Spiked Blanks		3062	2824	108 4
		FV1	2393	2311	103 5
		100% Connelly Fe (25 8pv)	1132	1139	99 4
		100% NiFe (24 6 pv)	604	576	104 9
		100% Cercona Fe (23 6 pv)	123	116	106 0
			59	52	113 5
			11 0	11 0	100 0
			2369	2311	102.5
			1116	1139	98 0
			590	576	102 4
			105	116	90 5
			56	52	107 7
			11 0	11 0	100 0
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Carbon Tetrachloride (CT)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
25 Mar	Spiked Blanks		2295	2204	104 1
		FV1	1110	1168	95 0
		100% Connelly Fe (33 pv)	605	585	103 4
		100% NiFe (31 5 pv)	116	112	103 6
		100% Cercona Fe (29 7 pv)	55	52	105 8
			11 0	10 5	104 8
			2360	2204	107 1
			1090	1168	93 3
			634	585	108 4
			128	112	114 3
			44	52	84 6
			11 0	10 5	104 8
	Blank			0	
				0	
27 Mar	Spiked Blanks		2409	2305	104 5
		FV1	1140	1159	98 4
		100% Connelly Fe (36 4 pv)	547	559	97 9
		100% NiFe (34 9 pv)	110	111	99 1
		100% Cercona Fe (32 9 pv)	51	52	98 1
			11 0	10 5	104 8
			2514	2305	109 1
			1206	1159	104 1
			587	559	105 0
			121	111	109 0
			40	52	76 9
			10 0	10 5	95 2
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Carbon Tetrachloride (CT)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
31 Mar	Spiked Blanks		2441	2163	112 9
		FV1	1168	1120	104 3
		100% Connelly Fe (43 4 pv)	611	576	106 1
		100% NiFe (41 6 pv)	112	109	102 8
		100% Cercona Fe (39 4 pv)	65	53	122 6
			11 5	10 5	109 5
			2275	2163	105.2
			1150	1120	102 7
			583	576	101 2
			113	109	103 7
			57	53	107 5
			11 7	10 5	111 4
	Blank			0	
				0	
3 Apr	Spiked Blanks		2872	2840	101 1
		FV1	2251	2199	102 4
		100% Connelly Fe (49 pv)	1181	1107	106 7
		100% NiFe (46 7 pv)	591	569	103 9
		100% Cercona Fe (44 6 pv)	119	117	101 7
			51	53	96 2
			11 0	10 5	104 8
			2791	2840	98 3
			2327	2199	105 8
			1165	1107	105.2
			595	569	104 6
			120	117	102 6
			54	53	101 9
			12 0	10 5	114 3
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Carbon Tetrachloride (CT)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
7 Apr	Spiked Blanks		2361	2238	105 5
		FV1	1132	1146	98 8
		100% Connelly Fe (55 1 pv)	629	574	109 6
		100% NiFe (53 1 pv)	110	111	99 1
		100% Cercona Fe (50 9 pv)	58	52	111 5
			11 2	10 5	106 7
			2106	2238	94 1
			1075	1146	93 8
			606	574	105 6
			111	111	100 0
			52	52	100 0
			11 3	10 5	107 6
	Blank			0	
				0	

Eof/

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Chloroform (TCM)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
11 Mar	Spiked Blanks		2457	2483	99 0
		FV1	2022	2091	96 7
		100% Connelly Fe (7 2 pv)	981	993	98 8
		100% NiFe (6 6 pv)	538	537	100.2
		100% Cercona Fe (6 9 pv)	105	101	104 0
			46	48	95 8
			9 3	9 5	97 9
			2408	2483	97 0
			1987	2091	95 0
			947	993	95 4
			511	537	95 2
			99	101	98 0
			50	48	104 2
			9 2	9 5	96 8
	Blanks			3 6	
				3 6	
14 Mar	Spiked Blanks		2500	2501	100 0
		FV1	2078	2086	99 6
		100% Connelly Fe (12 9pv)	976	990	98 6
		100% NiFe (12 1 pv)	491	502	97 8
		100% Cercona Fe (12 1 pv)	111	101	109 9
			47	48	97 9
			10 0	9 5	105 3
			2589	2501	103 5
			2194	2086	105 2
			976	990	98 6
			510	502	101 6
			111	101	109 9
			9 2	9 5	96 8
	Blank			3 8	
				4 0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Chloroform (TCM)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
19 Mar	Spiked Blanks		2687	2604	103 2
		FV1	1911	2040	93 7
		100% Connelly Fe (22 1pv)	986	987	99 9
		100% NiFe (21 1 pv)	513	484	106 0
		100% Cercona Fe (20 4 pv)	104	104	100 0
			48	48	100 0
			9 9	9 4	105 3
			2026	2040	99 3
			997	987	101 0
			520	484	107 4
			103	104	99 0
			10 0	9 4	106 4
	Blanks			3 6	
				3 8	
21 Mar	Spiked Blanks		2694	2560	105 2
		FV1	2032	2096	96 9
		100% Connelly Fe (25 8pv)	1011	1032	98 0
		100% NiFe (24 6 pv)	506	522	96 9
		100% Cercona Fe (23 6 pv)	108	105	102 9
			48	48	100 0
			9 3	9 6	96 9
			2571	2560	100 4
			2043	2096	97 5
			1006	1032	97 5
			513	522	98 3
			97	105	92 4
			47	48	97 9
			9 4	9 6	97 9
	Blank			4 0	
				3 6	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Chloroform (TCM)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
25 Mar	Spiked Blanks		2778	2643	105 1
		FV1	2054	1999	102 8
		100% Connelly Fe (33 pv)	1030	1059	97 3
		100% NiFe (31 5 pv)	550	531	103 6
		100% Cercona Fe (29 7 pv)	114	102	111 8
			50	47	106 4
			10 4	9 5	109 5
			2826	2643	106 9
			2029	1999	101 5
			978	1059	92 4
			552	531	104 0
			113	102	110 8
			40	47	85 1
			9 5	9 5	100 0
	Blank			3 7	
				4 1	
27 Mar	Spiked Blanks		2192	2090	104 9
		FV1	1081	1051	102 9
		100% Connelly Fe (36 4 pv)	512	507	101 0
		100% NiFe (34 9 pv)	110	101	108 9
		100% Cercona Fe (32 9 pv)	51	48	106 3
			12 0	9 5	126 3
			2169	2090	103 8
			1091	1051	103 8
			518	507	102 2
			112	101	110 9
			42	48	87 5
			11 0	9 5	115 8
	Blank			3 6	
				4 6	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Chloroform (TCM)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
31 Mar	Spiked Blanks		2692	2582	104 3
		FV1	2120	1961	108 1
		100% Connelly Fe (43 4 pv)	1099	1016	108 2
		100% NiFe (41 6 pv)	541	523	103 4
		100% Cercona Fe (39 4 pv)	112	99	113 1
			58	48	
			11 5	9 5	121 1
			2772	2582	107 4
			1981	1961	101 0
			1032	1016	101 6
			511	523	97 7
			103	99	104 0
			50	48	104 2
			10 9	9 5	114 7
	Blank			3 8	
				3 8	
3 Apr	Spiked Blanks		2542	2576	98 7
		FV1	1996	1994	100 1
		100% Connelly Fe (49 pv)	1068	1004	106 4
		100% NiFe (46 7 pv)	538	516	104 3
		100% Cercona Fe (44 6 pv)	108	106	101 9
			45	48	93 8
			12.0	9 6	125 0
			2529	2576	98 2
			2051	1994	102 9
			1077	1004	107 3
			527	516	102 1
			111	106	104 7
			45	48	93 8
			9 6	9 6	100 0
	Blank			4 6	
				4 1	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Chloroform (TCM)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
7 Apr	Spiked Blanks		2688	2576	104 3
		FV1	2053	2030	101 1
		100% Connelly Fe (55 1 pv)	1060	1039	102 0
		100% NiFe (53 1 pv)	560	520	107 7
		100% Cercona Fe (50 9 pv)	108	100	108 0
			57	47	121 3
			11 3	9 5	118 9
			2649	2576	102 8
			1906	2030	93 9
			999	1039	96 2
			537	520	103 3
			104	100	104 0
			50	47	106 4
			10 1	9 5	106 3
	Blank			4 4	
				3 6	

Eof/

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound cis-1,2 Dichloroethene (cDCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
13 Mar	Spiked Blanks		1037	1118	92.8
		FV1	801	772	103 8
		100% Connelly Fe (10 9 pv)	667	554	120 4
		100% NiFe (10 2 pv)	276	283	97 5
		100% Cercona Fe (10 3 pv)	129	107	120 6
			52	54	96 7
			24	26	91 4
			13	17	79 8
			8.6	10 1	85 1
			1186	1118	106 1
			884	772	114 5
			632	554	114 1
			259	283	91 5
			109	107	101 9
			49	54	90 9
			23	26	87 9
			19	17	110 1
			8 0	10 1	79 2
	Blanks			0	
				0	
20 Mar	Spiked Blanks		1167	1093	106 8
		FV1	838	813	103.1
		100% Connelly Fe (24 0pv)	574	534	107 5
		100% NiFe (22.9 pv)	242	280	86 4
		100% Cercona Fe (22.1 pv)	125	107	116 8
			60	54	111 1
			19	27	70 0
			15	17	90 6
			7 8	9 4	83 0
			1075	1093	98 4
			777	813	95 6
			573	534	107 3
			280	280	100 0
			118	107	110 3
			62	54	114 8
			17	27	61 5
			12.8	17	75 3
			9 0	9 4	95.7
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound cis-1 2-Dichloroethene (cDCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
24 Mar	Spiked Blanks		1236	1216	101 6
		FV1	722	728	99 2
		100% Connelly Fe (31 2pv)	578	535	108 0
		100% NiFe (29 7 pv)	303	288	105 2
		100% Cercona Fe (28 0 pv)	101	106	95 5
			56	54	104 1
			25	27	93 6
			11 9	17	70 8
			6 6	10 1	65 3
			1270	1216	104 4
			729	728	100 1
			524	535	97 9
			108	106	102 1
			58	54	108 0
			11 2	17	66 7
			6 5	10 1	64 4
	Blanks			0	
				0	
27 Mar	Spiked Blanks		1172	1179	99 4
		FV1	721	695	103 8
		100% Connelly Fe (36 3pv)	507	535	94 7
		100% NiFe (34 8 pv)	293	287	102.1
		100% Cercona Fe (32.8 pv)	90	106	85 1
			69	54	128.2
			27	27	100 4
			17	17	103 6
			10 3	10 2	101 0
			1133	1179	96 1
			503	535	93.9
			307	287	107 1
			95	106	89 7
			47	54	87 5
			27	27	100 4
			13	17	78 0
			10 4	10 2	102.0
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound cis-1,2-Dichloroethene (cDCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
2 Apr	Spiked Blanks		1321	1143	115 5
		FV1	758	737	103.0
		100% Connelly Fe (47 pv)	573	552	103 9
		100% NiFe (44 8 pv)	301	280	107 5
		100% Cercona Fe (42.8 pv)	121	106	113 8
			45	53	85 0
			21	26	77 7
			17	17	103 0
			9 0	10 1	89 1
			1018	1143	89 0
			564	552	102 3
			298	280	106 6
			102	106	96 2
			47	53	88 4
			21	26	78 4
			18	17	107 1
			7 9	10 1	78 2
	Blank			0	
				0	
3 Apr	Spiked Blanks		1227	1204	102.0
		FV1	709	710	99 8
		100% Connelly Fe (48 7 pv)	474	551	86 0
		100% NiFe (46.5 pv)	267	285	93 8
		100% Cercona Fe (44 4 pv)	218	112	194 8
			54	54	100 7
			27	26	103 1
			12	17	71 4
			10	10 1	99 0
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound cis-1,2-Dichloroethene (cDCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
8 Apr	Spiked Blanks		642	540	118 9
		FV1	420	427	98 4
		100% Connelly Fe (56 9 pv)	225	211	106 8
		100% NiFe (54 9 pv)	169	162	104 1
		100% Cercona Fe (52.6 pv)	115	112	102.7
			40	51	79 2
			26	25	103 6
			12.0	10 1	118 8
			147	162	90 6
			126	112	112.5
			58	51	114 9
			22	25	87 6
			10 0	10 1	99 0
	Blank			0	
				0	
10 Apr	Spiked Blanks		1209	1216	99 4
		FV1	610	566	107 8
		100% Connelly Fe (60 5 pv)	364	417	87 2
		100% NiFe (58 5 pv)	203	224	90 5
		100% Cercona Fe (56 1 pv)	120	110	108 6
			69	74	93 4
			41	51	80 7
			10	10 1	99 0
			1209	1216	99 4
			626	566	110 6
			357	417	85 5
			224	224	99 9
			10	10 1	99 0
	Blank			0	
				0	

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Analytical Accuracy

%R = (Qd / Qa) x 100

Compound trans-1,2-Dichloroethene (tDCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
13 Mar	Spiked Blanks		1041	1039	100 2
		FV1	714	718	99 4
		100% Connelly Fe (10 9 pv)	609	515	118 3
		100% NiFe (10.2 pv)	244	263	92 8
		100% Cercona Fe (10 3 pv)	103	99	104 0
			54	50	108 0
			23	24	95 8
			17	16	107 1
			7 9	9 4	84 0
			1079	1039	103 8
			801	718	111 6
			580	515	112 7
			227	263	86 4
			45	50	89 8
			22	24	91 6
			19	16	119 9
			8 4	9 4	89 4
	Blanks			0	
				0	
20 Mar	Spiked Blanks		980	1017	96 4
		FV1	713	756	94 3
		100% Connelly Fe (24 0pv)	533	496	107 5
		100% NiFe (22.9 pv)	234	260	90 0
		100% Cercona Fe (22 1 pv)	106	100	106 3
			51	50	101 8
			23	25	90 4
			17	16	107 1
			7 2	8 8	81 8
			1034	1017	101 7
			690	756	91 3
			535	496	107 9
			271	260	104 2
			95	100	95 4
			50	50	99 2
			14 1	16	90 4
			9 1	8 8	103 4
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound trans-1,2-Dichloroethene (tDCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
24 Mar	Spiked Blanks		1200	1130	106 2
		FV1	643	676	95 1
		100% Connelly Fe (31 2pv)	518	497	104 2
		100% NiFe (29 7 pv)	290	268	108 2
		100% Cercona Fe (28 0 pv)	91	98	92 9
			53	50	106 6
			18	25	72 4
			13 5	16	84 4
			6 3	9 4	67 0
			1165	1130	103 1
			641	676	94 8
			486	497	97 8
			97	98	98 7
			56	50	112 4
			12 0	16	76 9
			6 3	9 4	67 0
	Blanks			0	
				0	
27 Mar	Spiked Blanks		1092	1196	91 3
		FV1	675	646	104 5
		100% Connelly Fe (36 3pv)	465	498	93 4
		100% NiFe (34 8 pv)	259	267	97 0
		100% Cercona Fe (32.8 pv)	104	98	106 1
			51	50	101 8
			25	25	99 6
			15	16	93 1
			9 0	9 5	94 7
			1005	1096	91 7
			471	498	94 6
			290	267	108 6
			97	98	99 2
			50	50	99 6
			24	25	94 8
			16	16	101 9
			9 2	9 5	96 8
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound trans-1,2-Dichloroethene (tDCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
2 Apr	Spiked Blanks		1209	1063	113 7
		FV1	684	685	99 9
		100% Connelly Fe (47 pv)	564	513	109 9
		100% NiFe (44 8 pv)	281	260	108 1
		100% Cercona Fe (42.8 pv)	96	99	97 9
			48	50	97 0
			27	25	109 0
			16	16	105 1
			8 7	9 4	92 6
			900	1063	84 6
			562	513	109 5
			280	260	107 7
			92	99	92 9
			50	50	100 2
			27	25	109 0
			17	16	109 0
	Blank			0	
				0	
3 Apr	Spiked Blanks		1376	1107	124 3
		FV1	662	653	101 4
		100% Connelly Fe (48 7 pv)	503	507	99.2
		100% NiFe (46 5 pv)	246	262	93 9
		100% Cercona Fe (44 4 pv)	107	103	103 9
			45	49	91 8
			22	24	91 7
			18	15	119 2
			14	9 3	150 5
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound trans-1,2-Dichloroethene (tDCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
8 Apr	Spiked Blanks		507	497	102.1
		FV1	362	393	92 1
		100% Connelly Fe (56 9 pv)	208	194	107 3
		100% NiFe (54 9 pv)	176	149	117 9
		100% Cercona Fe (52 6 pv)	81	103	78 6
			34	47	73 1
			24	23	103 9
			13 0	9 3	139 8
			526	497	105 9
			444	393	112 9
			244	194	125 9
			113	149	75 7
			19	23	82 3
			13 0	9 3	139 8
	Blank			0	
				0	
10 Apr	Spiked Blanks		1102	1119	98 5
		FV1	566	521	108 7
		100% Connelly Fe (60 5 pv)	380	384	99 0
		100% NiFe (58 5 pv)	182	206	88 2
		100% Cercona Fe (56 1 pv)	104	102	102 5
			58	68	85 3
			40	47	85 7
			15	9 3	161 3
			1081	1119	96 6
			524	521	100 6
			401	384	104 4
			199	206	96 5
			62	68	91 2
			12	9 3	129 0
	Blank			0	
				0	

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Analytical Accuracy

%R = (Qd / Qa) x 100

Compound 1 1-Dichloroethene (11DCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
13 Mar	Spiked Blanks		669	701	95 4
		FV1	481	484	99 4
		100% Connelly Fe (10 9 pv)	413	347	119 0
		100% NiFe (10.2 pv)	163	177	92.1
		100% Cercona Fe (10.3 pv)	86	88	97 7
			28	34	82.4
			16	16	102.5
			12	11	112.3
			4 6	6 3	73 0
			691	701	98 6
			537	484	111 0
			394	347	113 5
			148	177	83 6
			86	88	97 7
			31	34	91 2
			16	16	97 5
			13	11	125 5
			5 4	6 3	85 7
	Blanks			0	
				0	
20 Mar	Spiked Blanks		736	686	107 3
		FV1	468	510	91 8
		100% Connelly Fe (24 0pv)	382	335	114 1
		100% NiFe (22.9 pv)	155	176	88 1
		100% Cercona Fe (22.1 pv)	68	67	101 3
			36	34	104 4
			18	17	104 7
			11	11	104 8
			4 0	5 9	67 8
			672	686	98.0
			488	510	95 8
			382	335	113 9
			173	176	98 5
			55	67	82.1
			33	34	97 1
			12	17	67 6
			9 0	11	85 7
			5 0	5 9	84 7
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound 1,1-Dichloroethene (11DCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
24 Mar	Spiked Blanks		866	763	113 5
		FV1	429	457	93 8
		100% Connelly Fe (31 2pv)	338	335	100 9
		100% NiFe (29 7 pv)	198	181	109 5
		100% Cercona Fe (28 0 pv)	55	62	88 2
			35	34	104 4
			11	17	66 1
			9 0	11	85 7
			3 8	6 3	60 3
			774	763	101 4
			425	457	93 0
			348	335	103 9
			59	66	88 8
			38	34	113 3
			5 6	11	53 3
			3 7	6 3	58 7
	Blanks			0	
				0	
27 Mar	Spiked Blanks		733	740	99 1
		FV1	454	436	104 1
		100% Connelly Fe (36 3pv)	312	336	93 0
		100% NiFe (34 8 pv)	168	180	93 5
		100% Cercona Fe (32.8 pv)	70	66	105 6
			36	34	107 7
			17	17	100 0
			11	11	104 8
			5 2	6 4	81 3
			632	740	85 4
			316	336	94 2
			210	180	116 6
			64	66	97 0
			36	34	105 7
			14	17	85 7
			10	11	99 0
			4 7	6 4	73 4
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound 1,1-Dichloroethene (11DCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
2 Apr	Spiked Blanks		763	717	106 3
		FV1	431	462	93 2
		100% Connelly Fe (47 pv)	395	346	114 2
		100% NiFe (44 8 pv)	191	175	109 0
		100% Cercona Fe (42.8 pv)	57	67	85 6
			34	36	96 3
			17	17	105 5
			9	11	84 8
			5 9	6 4	92 2
			368	346	106 2
			192	175	109 7
			60	67	90 4
			32	36	88 7
			14	17	82.4
			10	11	96 2
			3 4	6 4	53 1
	Blank			0	
				0	
3 Apr	Spiked Blanks		720	755	95 4
		FV1	476	446	106 8
		100% Connelly Fe (48 7 pv)	371	346	107 3
		100% NiFe (46 5 pv)	183	179	102.4
		100% Cercona Fe (44 4 pv)	72	70	102.6
			37	34	110 1
			12	16	73 2
			6	11	57 1
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound 1,1-Dichloroethene (11DCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
8 Apr	Spiked Blanks		340	339	100 3
		FV1	255	268	95.1
		100% Connelly Fe (56 9 pv)	152	132	115 2
		100% NiFe (54 9 pv)	111	102	108 8
		100% Cercona Fe (52.6 pv)	58	70	82.5
			24	32	75 7
			14	16	88 6
			8 0	6 4	125 0
			371	339	109 4
			299	268	111 6
			183	132	138 6
			85	102	83 3
			51	70	72.5
			22	32	69 4
			11	16	69 6
			7 0	6 4	109 4
	Blank			0	
				0	
10 Apr	Spiked Blanks		753	763	98.7
		FV1	371	355	104 5
		100% Connelly Fe (60 5 pv)	276	262	105 3
		100% NiFe (58 5 pv)	123	141	87 2
		100% Cercona Fe (56 1 pv)	66	69	95.7
			43	46	93 5
			37	32	115 6
			12	6 3	190 5
			734	763	96 2
			352	355	99 2
			276	262	105 3
			154	141	109 2
			52	69	75 4
			47	46	102.2
			14	32	43 8
			11	6 3	174 6
	Blank			0	
				0	

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Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Dichloromethane (DCM)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
18 Mar	Spiked Blanks		655	663	98 8
		FV1	125	128	97 7
		100% Connelly Fe (20 2 pv)	63	59	106 8
		100% NiFe (19 3 pv)	29	29	100 0
		100% Cercona Fe (18 7 pv)	11	12	91 7
			628	663	94 7
			121	128	94 5
			55	59	93 2
			28	29	96 6
			12	12	100 0
	Blanks			0	
				0	
20 Mar	Spiked Blanks		259	264	98 1
		FV1	100	132	75 8
		100% Connelly Fe (24 1pv)	58	59	98 3
		100% NiFe (22 9 pv)	23	29	79 3
		100% Cercona Fe (22 2 pv)	10 0	11 8	84 7
			245	264	92 8
			108	132	81 8
			49	59	83 1
			21	29	72 4
			12 0	11 8	101 7
	Blank			0	
				0	
24 Mar	Spiked Blanks		282	271	104 1
		FV1	127	132	96.2
		100% Connelly Fe (31 4pv)	57	59	96 6
		100% NiFe (30 0 pv)	15	29	51 7
		100% Cercona Fe (28 2 pv)	10 0	11 8	84 7
			279	271	103 0
			127	132	96 2
			46	59	78 0
			10 9	11 8	92 4
	Blanks			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Dichloromethane (DCM)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
26 Mar	Spiked Blanks		286	256	111 7
		FV1	147	135	108 9
		100% Connelly Fe (34 7pv)	37	59	62.9
		100% NiFe (33 2 pv)	19	29	65 5
		100% Cercona Fe (31 3 pv)	12 0	11 8	101 7
			270	256	105 5
			136	135	100 7
			56	59	95 2
			29	29	100 0
			13 0	11 8	110 2
	Blank			0	
				0	
1 Apr	Spiked Blanks		262	259	101.2
		FV1	126	118	106 8
		100% Connelly Fe (45 3 pv)	51	59	86 4
		100% NiFe (43 2 pv)	24	30	80 0
		100% Cercona Fe (41 1 pv)	9 1	11 8	77 1
			258	259	99 6
			127	118	107 6
			12 0	11 8	101 7
	Blank			0	
				0	
9 Apr	Spiked Blanks		289	263	109 9
		FV1	127	129	98 4
		100% Connelly Fe (59 pv)	64	59	108 5
		100% NiFe (56 9 pv)	21	29	72 4
		100% Cercona Fe (54 6 pv)	12.2	11 8	103 4
			262	263	99 6
			128	129	99.2
			57	59	96 6
			11 0	11 8	93 2
	Blank			0	
				0	

Eof/

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Tetrachloroethene (PCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
11 Mar	Spiked Blanks		2657	2658	100 0
		FV1	2189	2239	97 8
		100% Connelly Fe (7 2 pv)	1064	1063	100 1
		100% NiFe (6 6 pv)	582	575	101 2
		100% Cercona Fe (6 9 pv)	114	108	105 6
			51	51	100 0
			11 0	10 7	102 8
			2568	2658	96 6
			2119	2239	94 6
			1033	1063	97.2
			551	575	95 8
			107	108	99 1
			54	51	105 9
			11 0	10 7	102 8
	Blanks			0	
				0	
14 Mar	Spiked Blanks		2677	2677	100 0
		FV1	2233	2233	100 0
		100% Connelly Fe (12 9pv)	1036	1060	97 7
		100% NiFe (12.1 pv)	535	538	99 4
		100% Cercona Fe (12.1 pv)	116	108	107 4
			51	51	100 0
			11 0	10 0	110 0
			2778	2677	103 8
			2401	2233	107 5
			1058	1060	99 8
			563	538	104 6
			121	108	112 0
			10 0	10 0	100 0
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Tetrachloroethene (PCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
19 Mar	Spiked Blanks		2947	2787	105 7
		FV1	2123	2183	97 3
		100% Connelly Fe (22 1pv)	1095	1057	103 6
		100% NiFe (21 1 pv)	582	518	112 4
		100% Cercona Fe (20 4 pv)	115	111	103 6
			54	51	105 9
			13 0	10 0	130 0
			2175	2183	99 6
			1064	1057	100 7
			564	518	108 9
			107	111	96 4
	Blanks			0	
				0	
21 Mar	Spiked Blanks		2975	2741	108 5
		FV1	2214	2243	98 7
		100% Connelly Fe (25 8pv)	1091	1106	98 6
		100% NiFe (24 6 pv)	565	559	101 1
		100% Cercona Fe (23 6 pv)	119	112	106 3
			55	51	107 8
			13 0	10 0	130 0
			2850	2741	104 0
			2214	2243	98 7
			1090	1106	98 6
			563	559	100 7
			104	112	92 9
			52	51	102 0
			11 0	10 0	110 0
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Tetrachloroethene (PCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
25 Mar	Spiked Blanks		2937	2829	103 8
		FV1	2209	2140	103 2
		100% Connelly Fe (33 pv)	1109	1140	97 3
		100% NiFe (31 5 pv)	594	568	104 6
		100% Cercona Fe (29 7 pv)	119	109	109.2
			54	51	105 9
			10 1	10.2	99 0
			3187	2829	112 7
			2234	2140	104 4
			1069	1140	93 8
			613	568	107 9
			127	109	116 5
			45	51	88 2
			9 4	10 2	92 2
	Blank			0	
				0	
27 Mar	Spiked Blanks		3246	2853	113 8
		FV1	2335	2238	104 3
		100% Connelly Fe (36 4 pv)	1163	1125	103 4
		100% NiFe (34 9 pv)	551	542	101 7
		100% Cercona Fe (32.9 pv)	116	108	107 4
			51	51	100 0
			10 1	10.2	99 0
			3032	2853	106 3
			2373	2238	106 0
			1092	1125	97 1
			572	542	105 5
			120	108	111 1
			41	51	80 4
			8 3	10 2	81 4
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Tetrachloroethene (PCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
31 Mar	Spiked Blanks		3094	2764	111 9
		FV1	2326	2100	110 8
		100% Connelly Fe (43 4 pv)	1174	1087	108 0
		100% NiFe (41 6 pv)	606	560	108 2
		100% Cercona Fe (39 4 pv)	116	106	109 4
			65	51	127 5
			11 0	10 0	110 0
			3038	2764	109 9
			2195	2100	104 5
			1152	1087	106 0
			571	560	102 0
			114	106	107 5
			56	51	109 8
			11 8	10 0	118 0
	Blank			0	
				0	
3 Apr	Spiked Blanks		2823	2757	102 4
		FV1	2150	2135	100 7
		100% Connelly Fe (49 pv)	1164	1075	108 3
		100% NiFe (46 7 pv)	579	552	104 9
		100% Cercona Fe (44 6 pv)	119	114	104 4
			50	51	98 0
			12.0	10 0	120 0
			2759	2757	100 1
			2245	2135	105 2
			1172	1075	109 0
			582	552	105 4
			121	114	106 1
			52	51	102 0
			12 0	10 0	120 0
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Tetrachloroethene (PCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
7 Apr	Spiked Blanks		2899	2758	105 1
		FV1	2244	2173	103 3
		100% Connelly Fe (55 1 pv)	1131	1113	101 6
		100% NiFe (53 1 pv)	618	557	111 0
		100% Cercona Fe (50 9 pv)	112	107	104 7
			59	50	118 0
			10 2	10 2	100 0
			2955	2758	107 1
			2042	2173	94 0
			1070	1113	96 1
			591	557	106 1
			111	107	103 7
			49	50	98 0
			10 4	10 2	102 0
	Blank			0	
				0	

Eof/

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound 1,1,1-Trichloroethane (111TCA)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
11 Mar	Spiked Blanks		2868	2793	102.7
		FV1	2339	2352	99 4
		100% Connelly Fe (7 2 pv)	1140	1117	102 1
		100% NiFe (6 6 pv)	565	605	93 4
		100% Cercona Fe (6 9 pv)	129	114	113 2
			81	54	150 0
			13 0	10 4	125 0
			2724	2793	97 5
			2267	2352	96 4
			1098	1117	98 3
			542	605	89 6
			122	114	107 0
			80	54	148 1
			10 6	10 4	101 9
	Blanks			0	
				0	
14 Mar	Spiked Blanks		2813	2813	100 0
		FV1	2378	2346	101 4
		100% Connelly Fe (12 9pv)	1039	1114	93 3
		100% NiFe (12 1 pv)	563	565	99 6
		100% Cercona Fe (12 1 pv)	114	113	100 9
			54	54	100 0
			11 0	11 0	100 0
			3073	2813	109 2
			2611	2346	111 3
			1053	1114	94 5
			593	565	105 0
			113	113	100 0
			10 0	11 0	90 9
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound 1,1,1-Trichloroethane (111TCA)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
19 Mar	Spiked Blanks		2300	2294	100 3
		FV1	1148	1088	105 5
		100% Connelly Fe (22 1pv)	641	534	120 0
		100% NiFe (21 1 pv)	121	115	105 2
		100% Cercona Fe (20 4 pv)	46	53	86 8
			11 0	10 0	110 0
			3195	2929	109 1
			2394	2294	104 4
			1126	1088	103 5
			616	534	115 4
			112	115	97 4
			56	53	105 7
			10 0	10 0	100 0
	Blanks			0	
				0	
21 Mar	Spiked Blanks		2318	2358	98 3
		FV1	1157	1162	99 6
		100% Connelly Fe (25 8pv)	617	587	105 1
		100% NiFe (24 6 pv)	121	118	102 5
		100% Cercona Fe (23 6 pv)	55	54	101 9
			11 0	11 0	100 0
			2468	2358	104 7
			1151	1162	99 1
			600	587	102.2
			104	118	88 1
			54	54	100 0
			11 0	11 0	100 0
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound 1,1,1-Trichloroethane (111TCA)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
25 Mar	Spiked Blanks		2338	2249	104 0
		FV1	1189	1192	99 7
		100% Connelly Fe (33 pv)	628	597	105 2
		100% NiFe (31 5 pv)	126	122	103 3
		100% Cercona Fe (29 7 pv)	54	53	101 9
			11 0	11 0	100 0
			2382	2249	105 9
			1178	1192	98 8
			650	597	108 9
			139	122	113 9
			6 6	11 0	60 0
	Blank			0	
				0	
27 Mar	Spiked Blanks		2471	2352	105 1
		FV1	1151	1182	97 4
		100% Connelly Fe (36 4 pv)	587	570	103 0
		100% NiFe (34 9 pv)	114	113	100 9
		100% Cercona Fe (32 9 pv)	51	54	94 4
			11 0	10 7	102.8
			2536	2352	107 8
			1194	1182	101 0
			617	570	108.2
			129	113	114.2
			8 0	10 7	74 8
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound 1,1,1-Trichloroethane (111TCA)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
31 Mar	Spiked Blanks		2589	2206	117 4
		FV1	1211	1142	106 0
		100% Connelly Fe (43 4 pv)	629	588	107 0
		100% NiFe (41 6 pv)	117	111	105 4
		100% Cercona Fe (39 4 pv)	57	54	105 6
			10 9	10 7	101 9
			2358	2206	106 9
			1167	1142	102 2
			601	588	102 2
			112	111	100 9
			48	54	88 9
			10 7	10 7	100 0
	Blank			0	
				0	
3 Apr	Spiked Blanks		2943	2898	101 6
		FV1	2316	2244	103.2
		100% Connelly Fe (49 pv)	1154	1130	102 1
		100% NiFe (46 7 pv)	614	581	105 7
		100% Cercona Fe (44 6 pv)	118	120	98 3
			41	54	75 9
			6 6	10 8	61 1
			2863	2898	98 8
			2379	2244	106 0
			1135	1130	100 4
			615	581	105 9
			119	120	99 2
			54	54	100 0
			11 0	10 8	101 9
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound 1,1,1-Trichloroethane (111TCA)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
7 Apr	Spiked Blanks		2401	2284	105 1
		FV1	1179	1169	100 9
		100% Connelly Fe (55 1 pv)	653	585	111 6
		100% NiFe (53 1 pv)	114	113	100 9
		100% Ceroona Fe (50 9 pv)	52	53	98 1
			11 7	10 7	109 3
			2161	2284	94 6
			1122	1169	96 0
			595	585	101 7
			117	113	103 5
			10 8	10 7	100 9
	Blank			0	
				0	

Eof/

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Trichloroethene (TCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
11 Mar	Spiked Blanks		2454	2458	99 8
		FV1	2014	2070	97 3
		100% Connelly Fe (7.2 pv)	982	983	99 9
		100% NiFe (6 6 pv)	538	532	101 1
		100% Cercona Fe (6 9 pv)	106	100	106 0
			47	47	100 0
			9 7	9 4	103 2
			2368	2458	96 3
			1954	2070	94 4
			945	983	96 1
			507	532	95 3
			99	100	99 0
			49	47	104 3
			9 4	9 4	100 0
	Blanks			0	
				0	
14 Mar	Spiked Blanks		2476	2476	100 0
		FV1	2110	2065	102.2
		100% Connelly Fe (12 9pv)	961	980	98 1
		100% NiFe (12 1 pv)	490	497	98 6
		100% Cercona Fe (12.1 pv)	109	100	109 0
			46	47	97 9
			11 0	9 4	117 0
			2579	2476	104 2
			2224	2065	107 7
			971	980	99 1
			508	497	102 2
			111	100	111 0
			10 0	9 4	106 4
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Trichloroethene (TCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
19 Mar	Spiked Blanks		2742	2577	106 4
		FV1	1974	2019	97 8
		100% Connelly Fe (22 1pv)	1024	977	104 8
		100% NiFe (21 1 pv)	569	479	118 8
		100% Cercona Fe (20 4 pv)	135	103	131 1
			53	47	112 8
			2064	2019	102 2
			1007	977	103 1
			558	479	116 5
			128	103	124 3
	Blanks			0	
				0	
21 Mar	Spiked Blanks		2735	2534	107 9
		FV1	2057	2075	99 1
		100% Connelly Fe (25 8pv)	1000	1022	97 8
		100% NiFe (24 6 pv)	512	517	99 0
		100% Cercona Fe (23 6 pv)	100	104	96 2
			49	47	104 3
			12.0	9 5	126 3
			2603	2534	102.7
			2065	2075	99 5
			993	1022	97 2
			511	517	98 8
			96	104	92 3
			46	47	97 9
			10 0	9 5	105 3
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Trichloroethene (TCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
25 Mar	Spiked Blanks		2732	2616	104 4
		FV1	2066	1979	104 4
		100% Connelly Fe (33 pv)	1017	1049	96 9
		100% NiFe (31 5 pv)	544	525	103 6
		100% Cercona Fe (29 7 pv)	111	101	109 9
			48	47	102 1
			9 8	9 4	104 3
			2904	2616	111 0
			2070	1979	104 6
			978	1049	93 2
			556	525	105 9
			115	101	113 9
			40	47	85 1
			8 8	9 4	93 6
	Blank			0	
				0	
27 Mar	Spiked Blanks		2987	2638	113 2
		FV1	2197	2069	106 2
		100% Connelly Fe (36 4 pv)	1066	1040	102 5
		100% NiFe (34 9 pv)	504	502	100 4
		100% Cercona Fe (32 9 pv)	106	100	106 0
			46	47	97 9
			9 5	9 5	100 0
			2787	2638	105 6
			2202	2069	106 4
			1092	1040	105 0
			518	502	103 2
			110	100	110 0
			37	47	78 7
			8 2	9 5	86 3
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Trichloroethene (TCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
31 Mar	Spiked Blanks		2792	2556	109 2
		FV1	2146	1942	110 5
		100% Connelly Fe (43 4 pv)	1081	1005	107 6
		100% NiFe (41 6 pv)	545	517	105 4
		100% Cercona Fe (39 4 pv)	109	98	111 2
			58	47	123 4
			10 8	9 4	114 9
			2773	2556	108 5
			2002	1942	103 1
			1038	1005	103 3
			513	517	99 2
			104	98	106 1
			48	47	102 1
			10 7	9 4	113 8
	Blank			0	
				0	
3 Apr	Spiked Blanks		2529	2550	99 2
		FV1	2008	1974	101 7
		100% Connelly Fe (49 pv)	1066	994	107 2
		100% NiFe (46 7 pv)	534	510	104 7
		100% Cercona Fe (44 6 pv)	110	105	104 8
			44	47	93 6
			9 8	9 5	103 2
			2500	2550	98 0
			2099	1974	106 3
			1078	994	108 5
			532	510	104 3
			113	105	107 6
			46	47	97 9
			11 0	9 5	115 8
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Trichloroethene (TCE)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
7 Apr	Spiked Blanks		2697	2550	105 8
		FV1	2112	2009	105 1
		100% Connelly Fe (55 1 pv)	1060	1029	103 0
		100% NiFe (53 1 pv)	569	515	110 5
		100% Cercona Fe (50 9 pv)	105	99	106 1
			55	47	117 0
			9 9	9 4	105 3
			2723	2550	106 8
			1907	2009	94 9
			990	1029	96 2
			537	515	104 3
			102	99	103 0
			44	47	93 6
			9 5	9 4	101 1
	Blank			0	
				0	

Eof/

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Vinyl Chloride (VC)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
13 Mar	Spiked Blanks		1156	1089	106 2
		FV1	785	752	104 4
		100% Connelly Fe (10 9 pv)	638	539	118.4
		100% NiFe (10 2 pv)	260	275	94 5
		100% Cercona Fe (10 3 pv)	124	104	119 2
			45	52	86 5
			25	26	96 2
			15	16	90 6
			8 6	9 8	87 8
			1180	1089	108 4
			791	752	105 2
			596	539	110 6
			228	275	82.9
			91	104	87 2
			40	52	77 3
			22	26	85 8
			17	16	103.1
			10 1	9 8	103 1
	Blanks			0	
				0	
20 Mar	Spiked Blanks		1081	1172	92.2
		FV1	757	792	95 6
		100% Connelly Fe (24 0pv)	593	520	114 0
		100% NiFe (22.9 pv)	277	280	98 9
		100% Cercona Fe (22.1 pv)	104	104	100 0
			66	52	126 9
			21	26	78 7
			12	16	71 8
			8 3	9 8	84 7
			1180	1172	100 7
			751	792	94 8
			600	520	115 4
			274	280	97 9
			85	104	81 7
			49	52	94 2
			19	26	72.2
			13	16	78 5
			10 3	9 8	105 1
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Vinyl Chloride (VC)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
24 Mar	Spiked Blanks		1389	1185	117 2
		FV1	722	710	101 7
		100% Connelly Fe (31 2pv)	543	521	104 2
		100% NiFe (29 7 pv)	276	281	98 2
		100% Cercona Fe (28 0 pv)	99	103	96 1
			53	53	100 0
			39	26	150 0
			18	16	111 7
			10 7	9 8	109 2
			1217	1185	102.7
			732	710	103 1
			509	521	97 7
			303	281	107 8
			116	103	112.6
			58	53	109 4
			9 0	9 8	91 8
	Blanks			0	
				0	
27 Mar	Spiked Blanks		1143	1149	99 5
		FV1	602	677	88.9
		100% Connelly Fe (36 3pv)	425	522	81 4
		100% NiFe (34 8 pv)	216	279	77 4
		100% Cercona Fe (32.8 pv)	100	103	97 1
			50	52	96 2
			26	26	100 0
			16	16	96 9
			3 4	9 9	34 3
			972	1149	84 6
			590	677	87 1
			428	522	82 0
			262	279	93 9
			102	103	99 0
			51	52	98 1
			14	16	87 5
			3 7	9 9	37 4
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Vinyl Chloride (VC)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
2 Apr	Spiked Blanks		1300	1114	116 7
		FV1	711	718	99 0
		100% Connelly Fe (47 pv)	584	537	108.8
		100% NiFe (44 8 pv)	269	272	98 9
		100% Cercona Fe (42.6 pv)	114	103	110 7
			48	52	92.3
			34	26	129 3
			18	16	109 8
			12.1	9 9	122.2
			923	1114	82.9
			601	537	111 9
			267	272	98 2
			96	103	93 2
			59	52	113 5
			29	26	110 3
			14	16	85 4
			14 6	9 9	147 5
	Blank			0	
				0	
3 Apr	Spiked Blanks		1174	1172	100 2
		FV1	704	692	101 7
		100% Connelly Fe (48 7 pv)	516	537	96 1
		100% NiFe (46 5 pv)	282	277	101 8
		100% Cercona Fe (44 4 pv)	100 0	109 0	91 7
			56	52	107 7
			26	26	100 0
			16	16	100 0
			10 0	9 9	101 0
	Blank			0	
				0	

Analytical Accuracy

%R = (Qd / Qa) x 100

Compound Vinyl Chloride (VC)

%R = percent recovery
Qd = quantity determined by analysis
Qa = true value

Date 1997	Type	Column ID	Qd (ug/L)	Qa (ug/L)	%R
8 Apr	Spiked Blanks		501	526	95 2
		FV1	395	416	95 0
		100% Connelly Fe (56 9 pv)	278	205	135 6
		100% NiFe (54 9 pv)	165	154	107 1
		100% Cercona Fe (52.6 pv)	101	109	92.7
			52	49	106 1
			25	25	102.0
			14 0	9 9	141 4
			589	526	112 0
			430	416	103 4
			253	205	123 4
			108	154	70 1
			55	109	50 5
			22	25	89 8
			9 0	9 9	90 9
	Blank			0	
				0	
10 Apr	Spiked Blanks		1194	1185	100 8
		FV1	535	551	97 1
		100% Connelly Fe (60 5 pv)	406	407	99 8
		100% NiFe (58 5 pv)	210	218	96.3
		100% Cercona Fe (56 1 pv)	102	108	94 4
			62	72	86 1
			43	50	86 0
			7 0	9 9	70 7
			1006	1185	84 9
			441	551	80 0
			417	407	102.5
			205	218	94 0
			104	108	96 3
			69	72	95 8
			52	50	104 0
			6 0	9 9	60 6
	Blank			0	
				0	

EOF/

Appendix A-3

Inorganic Results

Inorganic Analyses

Redox potential (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 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 analysed immediately for Eh and then pH

Aqueous water samples are collected from the influent and effluent of each column and sent to MDS Environmental Services Ltd , 6850 Goreway Drive, Mississauga, Ontario for cation and anion analyses Cation analyses include Fe (total), Na, Mg, Mn, Ca, K and a suite of other cations These analyses are 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 analysed Anion analyses, including Cl, SO_4 and others are performed on 120 mL unfiltered samples using ion chromatography Alkalinity is determined by automated colorimetry

Table A2: Detection Limits (DL)

Inorganic Compounds	DL (mg/L)
Iron, total (Fe)	0 02
Nickel (Ni)	0 01
Sodium (Na)	0 10
Magnesium (Mg)	0 10
Calcium (Ca)	0 10
Potassium (K)	0 50
Manganese (Mn)	0 005
Silica (Si)	0 50
Zinc (Zn)	0 005
Chloride (Cl)	1 0
Sulphate (SO_4)	2 0
Alkalinity (as $CaCO_3$)	1 0

Table A3: Inorganic concentrations of the columns for both influent effluent samples at steady state conditions. (nd= not detected)

Inorganic	Influent Concn	Ganular Iron	Enhanced Iron	Cercona HSI Foam
	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Iron, total (Fe)	0 05 0 02	0 37 0 17	78 65	1 1 0 59
Nickel (Ni)	nd nd	nd nd	1 6 1 4	nd nd
Calcium (Ca)	61 62	25 25	55 55	59 57
Magnesium (Mg)	14 5 14 8	8 5 8 8	14 14	15 14
Sodium (Na)	53 5 54 2	55 55	58 57	56 55
Phosphorus (P)	nd nd	0 2 0 1	45 43	nd nd
Potassium (K)	5 3 5 3	5 9 5 8	5 9 5 7	5 7 5 5
Manganese (Mn)	0 49 0 50	0 24 0 10	2 1 2 8	0 26 0 21
Silica (Si)	13 9 14 1	1 8 2 6	1 4 1 4	8 8 8 8
Zinc (Zn)	nd nd	0 08 0 02	0 13 0 03	0 06 0 04
Chloride (Cl)	84 91	97 94	97 95	95 95
Sulphate (SO_4)	52 55	61 59	52 56	54 54
Alkalinity (as $CaCO_3$)	164 167	33 39	97 97	146 143
TDS (Calculated)				

MDS
Environmental Services Limited

Client	University Of Waterloo Earth Sciences Department - BFG Waterloo, ONT, CANADA N2L 3G1	Date Submitted Date Reported MDS Ref# MDS Quote#	April 3/97 April 10/97 972823 96-564-EG
Attn	Stephanie F O'Hannesin		

Certificate of Analysis

Analysis Performed

Alkalinity
Ammonia
Anions(Cl,NO2,NO3,o-PO4 & SO4)
RCAP 50 Package, 24 Element ICPAES Scan
Reactive Silica
Lead, by ICP-MS
RCAP Calculations
Manual Conventionals(pH,Turbidity,Conductivity,Color)
Dissolved Organic Carbon, as Carbon(Autoanalyzer)

Methodology

1) Determination of alkalinity in water by automated colourimetry
U S EPA Method No 310 2
2) Analysis of ammonia in water by colourimetry in a continuous liquid flow
ASTM Method No D1426-79 C
Refer - Method No 1100106 Issue 122289
3) Analysis of anions in water by ion chromatography and/or by colorimetry
U S EPA Method No 300 0 or
U S EPA Method No 350 1, 354 1, 353 1, 365 1 and 375 4

Client	University Of Waterloo Earth Sciences Department - BFG Waterloo, ONT, CANADA N2L 3G1	Date Submitted Date Reported MDS Ref# MDS Quote#	April 3/97 April 10/97 972823 96-564-EG

Attn. Stephanie F O'Hannesin

Certificate of Analysis

Methodology (Cont'd)

4) Analysis of trace metals in water by inductively coupled plasma atomic emission spectrometry
U S EPA Method No 200 7
5) Analysis of silicon in water by ICPAES and conversion to silica
Standard Methods(17th ed) No 4500-Si G
6) Analysis of lead in water by Inductively Coupled Plasma Mass Spectrophotometry or by graphite furnace atomic absorption spectrometry
U S EPA Method No 200 8(Modification)
U S EPA Method No 239 2
7) Determination of theoretical RCAP parameters by calculation.
EPL Internal Reference Method
8) Analysis of water for pH(by electrode), conductivity(by measuring resistance in micro siemens/cm), turbidity(by nephelometry) and color(by UV Visible Spectrometry)
U S EPA Method No 150 1, 120 1, 180 1 and 110 3

MDS
Environmental Services Limited

Client	University Of Waterloo Earth Sciences Department - BFG Waterloo, ONT, CANADA N2L 3G1	Date Submitted Date Reported MDS Ref# MDS Quote#	April 3/97 April 10/97 972823 96-564-EG
Attn	Stephanie F O'Hannesin		

Certificate of Analysis

Methodology (Cont'd)

9) Sample is filtered, followed by the colourimetric determination of dissolved organic carbon in a continuous liquid flow
MOE Method No ROM - 102AC2
Refer - Method No 1102106 Issue 122989

Instrumentation

1, 2) Cobas Fara Centrifugal Analyzer
3) Dionex Ion Chromatograph, 4500i/4000i or Cobas Fara II Analyzer
4, 5) Thermo Jarrell Ash ICAP 61E Plasma Spectrophotometer
6) PE Sciex ELAN 6000 ICP-MS Spectrometer
7) Calculation from existing results, no instrumentation required
8) Orion pH meter/Radiometer Conductometer/Turbidity meter/UV-Visible
9) Technicon Autoanalyzer

Sample Description. Water

QA/QC Refer to CERTIFICATE OF QUALITY CONTROL report

Results Refer to REPORT of ANALYSIS attached

Certified By
Eva Cottenden
Service Manager

for Certified By
M Hartwell, M Sc
Director, Laboratory Operations

MDS Environmental Services Limited

Certificate of Quality Control

University of Waterloo

Client University Of Waterloo
Contact Stephanie F O'Hannesin

Date Reported April 10/97
MDS Ref # 972823
MDS Quote# 96-564-EG

Analysis of Water

Parameter	SAMPLE ID (spike)	LOQ	Units	Process Blank Result	Process Blank Upper Limit	Process Blank Accept	Process % Recovery Result	Process % Recovery Lower Limit	Process % Recovery Upper Limit	Process % Recovery Accept	Matrix Spike Result	Matrix Spike Target	Matrix Spike Lower Limit	Matrix Spike Upper Limit	Matrix Spike Accept	Overall QC Acceptable
Alkalinity(as CaCO3)	na	1	mg/L	nd(b)	2	yes	99	87	113	yes	na	na	na	na	na	yes
Ammonia(as N)	na	0 05	mg/L	nd(b)	0 10	yes	97	81	118	yes	na	na	na	na	na	yes
Chloride	na	1	mg/L	nd(b)	2	yes	96	90	113	yes	na	na	na	na	na	yes
Nitrate(as N)	UW-57	0 05	mg/L	nd(b)	0 1	yes	105	88	114	yes	0 31	0 30	0 18	0 42	yes	yes
Nitrite(as N)	na	0 01	mg/L	nd(b)	0 03	yes	91	80	116	yes	na	na	na	na	na	yes
Orthophosphate(as P)	UW-57	0 01	mg/L	nd(b)	0 03	yes	97	90	110	yes	0 91	1 0	0 6	1 4	yes	yes
Sulphate	na	2	mg/L	nd(b)	3	yes	99	90	113	yes	na	na	na	na	na	yes
Aluminum	UW 57	0 025	mg/L	nd(b)	0 10	yes	108	85	115	yes	1 04	1 0	0 6	1 4	yes	yes
Barium	na	0 005	mg/L	nd(b)	0 01	yes	103	85	115	yes	na	na	na	na	na	yes
Beryllium	UW-57	0 005	mg/L	nd(b)	0 01	yes	103	85	115	yes	1 03	1 0	0 6	1 4	yes	yes
Bismuth	UW-57	0 05	mg/L	nd(b)	0 1	yes	103	85	115	yes	0 93	1 0	0 3	1 7	yes	yes
Boron	UW 57	0 01	mg/L	nd(b)	0 02	yes	102	85	115	yes	1 02	1 0	0 6	1 4	yes	yes
Cadmium	UW-57	0 003	mg/L	nd(b)	0 006	yes	101	85	115	yes	1 00	1 0	0 6	1 4	yes	yes
Calcium	UW 57	0 1	mg/L	nd(b)	0 2	yes	100	85	115	yes	*	*	*	*	*	yes
Chromium	UW 57	0 005	mg/L	nd(b)	0 01	yes	104	85	115	yes	1 01	1 0	0 6	1 4	yes	yes
Cobalt	UW-57	0 005	mg/L	nd(b)	0 01	yes	104	85	115	yes	0 994	1 0	0 6	1 4	yes	yes
Copper	UW 57	0 003	mg/L	nd(b)	0 006	yes	104	85	115	yes	1 02	1 0	0 6	1 4	yes	yes
Iron	UW-57	0 02	mg/L	nd(b)	0 05	yes	102	85	115	yes	0 98	1 0	0 4	1 6	yes	yes
Magnesium	UW-57	0 1	mg/L	nd(b)	0 2	yes	100	85	115	yes	0 8	1 0	0 2	1 6	yes	yes
Manganese	UW-57	0 005	mg/L	nd(b)	0 01	yes	102	85	115	yes	0 982	1 0	0 6	1 4	yes	yes

LOQ = Limit of Quantitation = lowest level of the parameter that can be quantified with confidence
* = Unavailable due to dilution required for analysis
na = Not Applicable
ns = Insufficient Sample Submitted
nd = Parameter not detected
TR = trace level less than LOQ
(b) = Analyte results on REPORT of ANALYSIS have been background corrected for the process blank.

MDS Environmental Services Limited

Certificate of Quality Control

University of Waterloo

Client University Of Waterloo
Contact Stephanie F O'Hannesin

Date Reported April 10/97
MDS Ref # 972823
MDS Quote# 96-564-EG

Analysis of Water

Parameter	SAMPLE ID (spike)	LOQ	Units	Process Blank Result	Process Blank Upper Limit	Process Blank Accept	Process % Recovery Result	Process % Recovery Lower Limit	Process % Recovery Upper Limit	Process % Recovery Accept	Matrix Spike Result	Matrix Spike Target	Matrix Spike Lower Limit	Matrix Spike Upper Limit	Matrix Spike Accept	Overall QC Acceptable
Molybdenum	UW-57	0 01	mg/L	nd(b)	0 03	yes	105	85	115	yes	1 01	1 0	0 6	1 4	yes	yes
Nickel	UW-57	0 01	mg/L	nd(b)	0 02	yes	103	85	115	yes	0 99	1 0	0 6	1 4	yes	yes
Phosphorus	UW 57	0 1	mg/L	nd(b)	0 2	yes	103	85	115	yes	1 1	1 0	0 4	1 6	yes	yes
Potassium	UW 57	0 5	mg/L	nd(b)	1 0	yes	113	85	115	yes	4 9	5 0	1 0	8 0	yes	yes
Silver	na	0 003	mg/L	nd(b)	0 006	yes	98	85	115	yes	na	na	na	na	na	yes
Sodium	UW-57	0 1	mg/L	nd(b)	0 2	yes	88	85	115	yes	*	*	*	*	*	yes
Strontium	UW 57	0 005	mg/L	nd(b)	0 01	yes	108	85	115	yes	1 04	1 0	0 6	1 4	yes	yes
Tin	UW 57	0 05	mg/L	nd(b)	0 15	yes	100	85	115	yes	0 94	1 0	0 4	1 6	yes	yes
Titanium	UW 57	0 05	mg/L	nd(b)	0 1	yes	110	85	115	yes	1 08	1 0	0 6	1 4	yes	yes
Vanadium	UW 57	0 01	mg/L	nd(b)	0 02	yes	102	85	115	yes	1 02	1 0	0 6	1 4	yes	yes
Zinc	UW-57	0 005	mg/L	nd(b)	0 02	yes	104	85	115	yes	1 03	1 0	0 6	1 4	yes	yes
Reactive Silica(SiO2)	na	0 5	mg/L	nd(b)	1 0	yes	99	80	120	yes	na	na	na	na	na	yes
Lead	na	0 002	mg/L	na(b)	na	na	99	85	115	yes	na	na	na	na	na	yes
Colour	UW 57	5	TCU	nd(b)	10	yes	102	85	115	yes	ns	ns	ns	ns	ns	yes
Conductivity @25°C	na	1	us/cm	na(b)	na	na	99	91	109	yes	na	na	na	na	na	yes
pH	na	0 1	Units	na(b)	na	na	99	98	102	yes	na	na	na	na	na	yes
Turbidity	UW 57	0 1	NTU	nd(b)	0 5	yes	99	81	129	yes	ns	ns	ns	ns	ns	yes
Dissolved Organic Carbon(DOC)	na	0 5	mg/L	nd	1 0	yes	94	80	116	yes	na	na	na	na	na	yes

LOQ = Limit of Quantitation = lowest level of the parameter that can be quantified with confidence
* = Unavailable due to dilution required for analysis
na = Not Applicable
ns = Insufficient Sample Submitted
nd = parameter not detected
TR = trace level less than LOQ

MDS Environmental Services Limited

Report of Analysis

Client University Of Waterloo
Contact Stephanie F O'Hannesin

Report Date April 10/97
MDS Ref # 972823
MDS Quote # 96-564-EG

Analysis of Water

Parameter	LOQ	Units	UW-57 (Co (Initial Conc) RNB Influent)	UW-57 Replicate	UW-58 (Co RNB Influent)	UW-59 (Eff 183 RNB 43.4 pv)	UW-60 (Eff 184 RNB 41.6 pv)
Alkalinity(as CaCO3)	1	mg/L	164	160	167	33	97
Ammonia(as N)	0 05	mg/L	nd	nd	nd	nd	nd
Chloride	1	mg/L	84	na	91	97	97
Nitrate(as N)	0 05	mg/L	nd	nd	nd	nd	nd
Nitrite(as N)	0 01	mg/L	nd	nd	nd	nd	nd
Orthophosphate(as P)	0 01	mg/L	nd	nd	0 01	0 07	nd
Sulphate	2	mg/L	52	na	55	61	52
Aluminum	0 025	mg/L	nd	nd	nd	nd	nd
Barium	0 005	mg/L	0 124	0 124	0 124	0 015	0 067
Beryllium	0 005	mg/L	nd	nd	nd	nd	nd
Bismuth	0 05	mg/L	nd	nd	nd	nd	nd
Boron	0 01	mg/L	0 05	0 04	0 05	0 16	0 87
Cadmium	0 003	mg/L	nd	nd	nd	nd	nd
Calcium	0 1	mg/L	61 2	61 5	62 3	25 3	55 0
Chromium	0 005	mg/L	nd	nd	nd	nd	nd
Cobalt	0 005	mg/L	nd	nd	nd	nd	0 010
Copper	0 003	mg/L	nd	nd	nd	0 018	nd
Iron	0 02	mg/L	0 05	0 06	0 02	0 37	78 0
Magnesium	0 1	mg/L	14 5	14 6	14 8	8 5	14 1
Manganese	0 005	mg/L	0 489	0 488	0 495	0 236	2 96
Molybdenum	0 01	mg/L	nd	nd	nd	0 06	0 03
Nickel	0 01	mg/L	nd	nd	nd	nd	1 63
Phosphorus	0 1	mg/L	nd	nd	nd	0 2	44 5
Potassium	0 5	mg/L	5 3	5 7	5 3	5 9	5 9
Reactive Silica(SiO2)	0 5	mg/L	13 9	14 0	14 1	1 8	1 4
Silver	0 003	mg/L	nd	nd	nd	nd	nd
Sodium	0 1	mg/L	53 5	53 7	54 2	55 2	57 6

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Analysis of Water

Parameter	LOQ	Units	UW-57 (Influent Co RNB)	UW-57 Replicate (Influent Co RNB)	UW-58	UW-59 (Eff 183 RNB 43.4 pv)	UW-60 (Eff 184 RNB 41.6 pv)
Strontium	0 005	mg/L	0 417	0 418	0 421	0 194	0 381
Tin	0 05	mg/L	nd	nd	nd	nd	nd
Titanium	0 05	mg/L	nd	nd	nd	nd	nd
Vanadium	0 01	mg/L	nd	nd	nd	nd	nd
Zinc	0 005	mg/L	nd	nd	nd	0 085	0 132
Lead	0 002	mg/L	0 002	-	0 005	0 004	0 008
Anion Sum	na	meq/L	6 72	-	7 05	4 67	5 76
Bicarbonate(as CaCO3, calculated)	1	mg/L	163	-	167	33	97
Carbonate(as CaCO3, calculated)	1	mg/L	nd	-	nd	nd	nd
Cation Sum	na	meq/L	6 72	-	6 82	4 51	6 57
Colour	5	TCU	ns	ns	6	11	82
Conductivity - @25°C	1	us/cm	655	658	656	498	660
Hardness(as CaCO3)	0 1	mg/L	213	-	217	98 1	196
Ion Balance	0 01	%	0 05	-	1 63	1 77	6 52
Langelier Index at 20°C	na	na	0 202	-	-0 234	-1 50	-1 17
Langelier Index at 4°C	na	na	-0 198	-	-0 634	-1 90	-1 57
pH	0 1	Units	7 7	7 7	7 2	7 1	6 6
Saturation pH at 20°C	na	units	7 48	-	7 46	8 55	7 75
Saturation pH at 4°C	na	units	7 88	-	7 86	8 95	8 15
Total Dissolved Solids(Calculated)	1	mg/L	383	-	397	275	341
Turbidity	0 1	NTU	0 4	ns	0 3	0 2	34 0
Dissolved Organic Carbon(DOC)	0 5	mg/L	20 3	-	19 1	20 3	18 4

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Analysis of Water

Parameter	LOQ	Units	UW-61 (EFF 185 RUB 394 PV)	UW-62 (EFF 183 RUB 470 PV)	UW-63 (EFF 184 RUB 448 PV)	UW-64 (EFF 185 RUB 428 PV)	UW-64 Replicate
Alkalinity(as CaCO3)	1	mg/L	146	39	97	143	-
Ammonia(as N)	0 05	mg/L	nd	nd	nd	nd	-
Chloride	1	mg/L	95	94	95	95	-
Nitrate(as N)	0 05	mg/L	nd	nd	nd	nd	-
Nitrite(as N)	0 01	mg/L	nd	nd	nd	nd	-
Orthophosphate(as P)	0 01	mg/L	nd	0 06	nd	0 14	-
Sulphate	2	mg/L	54	59	56	54	-
Aluminum	0 025	mg/L	nd	nd	nd	nd	
Barium	0 005	mg/L	0 093	0 016	0 068	0 086	-
Beryllium	0 005	mg/L	nd	nd	nd	nd	-
Bismuth	0 05	mg/L	nd	nd	nd	nd	-
Boron	0 01	mg/L	0 05	0 15	0 83	0 05	-
Cadmium	0 003	mg/L	nd	nd	nd	nd	-
Calcium	0 1	mg/L	58 8	25 4	55 2	57 1	-
Chromium	0 005	mg/L	nd	nd	nd	nd	-
Cobalt	0 005	mg/L	nd	nd	0 008	nd	-
Copper	0 003	mg/L	nd	0 006	nd	nd	-
Iron	0 02	mg/L	1 09	0 17	65 2	0 59	-
Magnesium	0 1	mg/L	14 6	8 8	14 0	14 2	-
Manganese	0 005	mg/L	0 259	0 102	2 81	0 207	-
Molybdenum	0 01	mg/L	0 03	0 07	0 03	0 03	-
Nickel	0 01	mg/L	nd	nd	1 40	nd	
Phosphorus	0 1	mg/L	nd	0 1	43 3	nd	-
Potassium	0 5	mg/L	5 7	5 8	5 7	5 5	-
Reactive Silica(SiO2)	0 5	mg/L	8 8	2 6	1 4	8 8	-
Silver	0 003	mg/L	nd	nd	nd	nd	-
Sodium	0 1	mg/L	55 8	55 1	57 2	55 0	-

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Analysis of Water

Parameter	LOQ	Units	UW-61 Eff 185 RNB 39.4 pv	UW-62 Eff 183 RNB 47.0 pv	UW-63 Eff 184 RNB 44.8 pv	UW-64 Eff 185 RNB 42.8 pv	UW-64 Replicate
Strontium	0 005	mg/L	0 422	0 192	0 381	0 411	-
Tin	0 05	mg/L	nd	nd	nd	nd	-
Titanium	0 05	mg/L	nd	nd	nd	nd	-
Vanadium	0 01	mg/L	nd	nd	nd	nd	-
Zinc	0 005	mg/L	0 059	0 023	0 032	0 039	-
Lead	0 002	mg/L	0 018	0 008	0 010	0 012	-
Anion Sum	na	meq/L	6 74	4 65	5 79	6 68	-
Bicarbonate(as CaCO3, calculated)	1	mg/L	145	39	97	142	-
Carbonate(as CaCO3, calculated)	1	mg/L	nd	nd	nd	nd	-
Cation Sum	na	meq/L	6 70	4 54	6 54	6 55	-
Colour	5	TCU	19	9	8	15	-
Conductivity - @25°C	1	us/cm	661	501	633	651	-
Hardness(as CaCO3)	0 1	mg/L	207	99 5	196	201	-
Ion Balance	0 01	%	0 25	1 21	6 11	0 98	-
Langelier Index at 20°C	na	na	0 064	-1 03	-1 11	0 232	-
Langelier Index at 4°C	na	na	-0 337	-1 43	-1 51	-0 168	-
pH	0 1	Units	7 6	7 4	6 6	7 8	-
Saturation pH at 20°C	na	units	7 55	8 47	7 75	7 57	-
Saturation pH at 4°C	na	units	7 95	8 87	8 15	7 97	-
Total Dissolved Solids(Calculated)	1	mg/L	381	274	343	376	-
Turbidity	0 1	NTU	3 3	0 3	19 8	2 4	-
Dissolved Organic Carbon(DOC)	0 5	mg/L	18 4	18 5	18 5	16 9	-

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