ADVENTUS
REMEDIATION TECHNOLOGIES

HRC-X™, EOS®, AND EHC™ TREATABILITY STUDY FOR THE TREATMENT OF TRICHLOROETHENE IN GROUNDWATER FROM THE SILTRONIC CORPORATION SITE IN PORTLAND, OREGON (THE SITE)

FINAL REPORT

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EXECUTIVE SUMMARY

A bench-scale treatability study was completed at the Adventus laboratory in Mississauga, Ontario for the treatment of groundwater impacted with trichloroethene (TCE) from the Siltronic Corporation Site in Portland, Oregon (the Site). The primary constituent of interest (COI) was TCE; however, benzene and naphthalene were also present in the Site groundwater. The overall objective was to treat TCE and its daughter products in the presence of benzene and naphthalene which are contaminants associated with manufactured gas plants (MGP). The specific objectives of the test were as follows:

(i) determine the ability of HRC-X™, EOS® and EHC™ to treat TCE and its daughter products;
(ii) identify which of the three products is most effective;
(iii) assess whether bioaugmentation with KB-1 will improve degradation of TCE and its daughter products, and
(iv) determine the optimal application rate of the selected product for full-scale treatment.

A set of eight flow-through column systems was set up, which included two control columns (sterile and non-sterile), two HRC-X columns, two EOS columns, and two EHC columns. EHC, EOS and HRC-X were added to the respective columns at application rates of 1%, 1.37% and 0.27% by wt of soil in the columns, respectively. One column from each of the three pairs of columns that were amended with a substrate was inoculated with KB-1. In addition, vitamin B_{12} supplement was added only to the two EOS columns. The effectiveness of these treatment systems was assessed by conducting four batch-tests. Two tests were conducted at a contact time of 14-days and one each at a contact time of 21 and 28-days over a period of 77 days. After each contact time, groundwater was drained from the columns and analyzed for the COI, the daughter products and other geochemical parameters to explain the performance.

Removal of TCE was observed in all columns that received amendments at a high percentage (+99%). TCE removal was also high in the non-sterile control (85%) indicating that if the site conditions were same as the test conditions in the column, TCE would naturally degrade.

Removal of cis-dichloroethene (cis-DCE) increased only in the third and fourth test indicating that there was a lag-time associated with cis-DCE degradation. cis-DCE degradation was significantly enhanced in the EHC and EOS columns under the presence of KB-1. There was only a marginal increase in cis-DCE degradation in the HRC-X w/KB-1 column.

Vinyl chloride (VC) was produced in all the columns. The data indicates that KB-1 did enhance VC degradation in the EHC column. KB-1 also enhanced VC degradation in the EOS column, but the enhancement was marginal and observed only in the third test (28 day contact time). In the case of HRC-X, VC concentration in the column with KB-1 was always higher than the column without KB-1 which indicated that VC mineralization was limited.

Ethene was measured during the second and fourth tests. During the second test (21 days contact time) ethene was only detected in the EOS w/KB-1 column. In the fourth test (14 days contact time), the highest ethene was detected in EHC w/KB-1 column (5.35 umoles/L) followed by EOS w/KB-1 column (4.99 umoles/L), EHC column (2.24 umoles/L), and HRC-X w/KB-1 (0.132

umoles/L). This indicates that EHC was able to promote complete mineralization without the use of KB-1. This is most likely due to the synergistic effects of three mechanisms (chemical, biological and thermodynamic) responsible for the degradation of chlorinated solvents in the presence of EHC. It also shows that complete mineralization (breakdown of TCE to carbon dioxide, water and chloride) was enhanced in columns that were amended with KB-1.

Total cVOCs results from all the tests combined show that 23% of the feed cVOCs were degraded in the EHC column compared to 59% in the EHC w/KB-1 column. For EOS, 19% of the feed cVOCs were degraded compared to 79% when EOS was accompanied by KB-1. For HRC-X, the total cVOCs removal was -12% compared to 28% when KB-1 was added to HRC-X. This shows that KB-1 did increase the degradation of daughter products which make up the total cVOCs. The data also shows that both EHC and EOS performed better than HRC-X when it came to degradation of total cVOCs.

Total Organic Carbon (TOC) measurements indicate the amount of electron donor released by the substrate and the consumption of the electron donor during the reductive dechlorination process. TOC data shows that there was a two order of magnitude reduction in TOC levels in EHC and HRC-X columns through the four tests, while there was only a 4-time reduction in the TOC values of EOS columns. Some TOC was lost when columns were drained after each test. For example, the losses were high in the case of EHC and HRC-X columns after the first test as groundwater with TOC in the range of 1,700 to 2,000 mg/L was removed from the test columns for sampling. As a comparison, TOC in groundwater of the EOS columns ranged from only 550 to 560 mg/L. It is clear that EOS with its high affinity to bind to soil performed better and had the lowest loss of TOC. The low level of TOC did have a negative impact on the performance of HRC-X columns during the fourth test. At the end of the fourth test, an analysis of the TOC in soil showed that EHC, EOS and HRC-X column had 850 mg/Kg, 5200 mg/Kg, and 590 mg/Kg of TOC, respectively. The background soil had a TOC of 600 mg/Kg, indicating that TOC source was depleted in the HRC-X columns, somewhat depleted in the EHC columns, and stayed high in the EOS columns.

Chloride was produced and detected in all the columns that received amendments. Chloride mass balance showed a lot of variability due to the build up and degradation of daughter products. With a few exceptions, more chloride was produced than calculated from stoichiometric equations. This is most likely from the degradation of methylene chloride, a co-contaminant that was unknowingly introduced in the test via leaching from the new Plexiglas columns. In any case a positive chloride mass balance is desirable then a negative one.

For the best case scenario, the ORP of the columns ranged between –188 mV and -15 mV. The EHC and EHC w/KB-1 columns had ORP values of –188 mV and -75 mV, respectively. The ORP values in the HRC-X and HRC–X w/KB-1 columns were -78 mV and -88 mV, respectively. The EOS and EOS w/KB-1 columns had ORP values of –76 mV and –65 mV. The EHC column exhibited the lowest ORP of all the columns. Ideally, much lower ORP values (-300 to -600 mV) should be achieved in the field with EHC. The higher ORP observed in the column test is because of frequent draining and filling of the columns. However, the recorded ORP values indicate that biological degradation and iron reduction were the primary removal mechanisms for EHC. Thermodynamic decomposition occurs only at ORP values lower than -400 mV.

The half life of TCE during the second 14-day exposure period was calculated to be 1.2 days for both the EHC and EHC w/KB-1 treatments. The calculated half lives of TCE for the EOS and

EOS w/KB-1 treatments were 1.9 and 1.2 days, respectively. The calculated half lives for TCE in the presence of HRC-X and HRC-X w/KB-1 treatments were 1.6 and 1.4 day, respectively. The true half life of TCE and its daughter products in the EOS columns are most likely longer if the effect of contaminant partioning into the EOS is neglected. As expected, the calculated half lives of TCE in the control systems were longer than those calculated for columns which received amendments. The TCE half lives for the control and sterile control were 4 and 38 days, respectively.

Benzene and naphthalene appeared to degrade in all the columns in the fourth test except the two EOS columns and the sterile control. Data for benzene clearly showed that it partitioned heavily to the EOS substrate. The EOS column continued to show higher benzene concentration in groundwater than the feed as benzene partitioned into groundwater from the soil during the second, third and fourth tests. It is possible that the partioning of the cVOCs to EOS may have limited the bioavailability and subsequent degradation of the cVOCs in a similar way. The percentage of physical removal of cVOCs by this mechanism could not be accounted for in the results for EOS columns.

In conclusion, EHC and EOS columns exhibited the best overall performance while HRC-X did not. Without KB-1, the percentage of total cVOCs degraded (combined from all four tests) was best in the EHC column. With KB-1, percentage of total cVOCs degraded (combined from all four tests) was best in the EOS column. EHC columns performed equally or better than the EOS columns considering that the application rate of EHC was 1.4 times lower than EOS. The calculated half-life of TCE was the least for EHC columns followed closely by EOS w/KB-1. However, the difference between all three is only marginal. The only column without KB-1 which showed ethene was that of EHC indicating that EHC by itself is capable of complete mineralization. Ethene was detected in all columns with KB-1, indicating that KB-1 did accelerate the complete mineralization process.

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1. INTRODUCTION

1.1. Project Background

Adventus was contracted by Maul Foster & Alongi Inc. (MFA) to conduct a bench-scale treatability study to assess the ability of HRC-X™, EOS® and EHC™ to remove trichloroethene (TCE) and its daughter products from groundwater present at the Siltronic Site in Portland, Oregon (the Site). Benzene and naphthalene were also present in the Site groundwater. This report was prepared for MFA and presents the results and data interpretation of the bench-scale treatability study completed between November 2005 and February 2006.

1.2. Technology Background

1.2.1 HRC-X

HRC-X is composed of glycerol polylactate and is specifically designed to release lactic acid when hydrated. This product contains more lactic acid and is much more viscous than standard HRC. The purpose of HRC-X is to time release lactic acid when hydrated which is then metabolized by subsurface microbes that indirectly produce hydrogen. Hydrogen is a key ingredient in an anaerobic contaminant degrading process known as reductive dechlorination. This process is the mechanism by which chlorinated compounds are biodegraded. Functionality HRC-X is typically applied using direct-injection techniques. This pressure injection process allows HRC-X to be placed into the zone of contamination and forced out into the aquifer. Once in the subsurface, HRC-X will reside within the soil matrix fueling reductive dechlorination for up to 36 months through the extra-slow release of lactic acid. (Source: www.regenesis.com/products/hrc-x)

1.2.2 EOS

The EOS amendment when injected into the aquifer is designed to stimulate the anaerobic biodegradation of a wide variety of chlorinated solvents (e.g., PCE, TCE, TCA, cis-DCE and 1,2-DCA), energetic materials (perchlorate, RDX, TNT, etc.), and some heavy metals and some radionuclides, into non-toxic end products. The EOS amendment is easy to handle, has a low viscosity similar to milk, does not clog aquifers, and lasts well in excess of three years. In a two-step reductive dechlorination reaction carried out by microorganisms residing in or added to the aquifer, the oil is slowly degraded with the consumption of oxygen and the production of hydrogen. The hydrogen is then available to support anaerobic conditions and reductive dechlorination. Anaerobic degradation of other compounds occurs by microbes using EOS for both carbon and energy. (Source: www.eosremediation.com)

1.2.3 EHC

Adventus has adapted its patented combination of controlled-release solid carbon and zero-valent iron (ZVI) particles to yield a material for stimulating reductive dechlorination of persistent organic solvents in groundwater and source zones. Variations of these materials have been used for the treatment of more than 800,000 tons of soils and sediments contaminated with recalcitrant; hazardous organic COIs as part of the company's DARAMEND® bioremediation technology. For groundwater applications, the materials are known as EHC™ and can be injected into the saturated

zones in a variety of ways yielding *in situ* chemical reduction and accelerated anaerobic biodegradation of targeted organics.

Following placement of EHC into the saturated zone, a number of physical, chemical and microbiological processes combine to create strong reducing conditions that stimulate dechlorination of organic solvents and other recalcitrant organics (*e.g.*, perchlorate). The organic component of EHC (fibrous organic material) is nutrient rich, hydrophilic, and has high surface area; thus, it is an ideal support for growth of bacteria in the groundwater environment. As they grow on EHC particle surfaces, indigenous heterotrophic bacteria consume dissolved oxygen and thereby reduce the redox potential in groundwater.

In addition, as the bacteria grow on the organic particles they ferment carbon and release a variety of volatile fatty acids (acetic, propionic, butyric), which diffuse into the groundwater plume and serve as electron donors for other bacteria including dehalogenators and halorespiring species. The ability of the substrate to release electron donor is determined by measuring the TOC in groundwater. Finally, the small ZVI particles (*i.e.*, <50 μm diameter) provide substantial reactive surface area that stimulates direct chemical dechlorination and an additional drop in the redox potential (Eh; measured in mV) of the groundwater. Typically, ORP in the range of -500 to -600 mV can be reached, and under these extreme environments thermodynamic decomposition of COIs is possible. These physical, chemical and biological processes combine to create an environment that stimulates chemical and microbiological dechlorination of solvents, defined herein as *in situ* chemical reduction, or ISCR.

The solid-phase EHC can be placed in the subsurface using a variety of techniques, each suited for the type of geology encountered, the depth of treatment zone and treatment goal among others. The granular EHC can be placed using the conventional trench approach and is applicable for treatment of shallow plumes. The powder form of EHC can be injected as a slurry (20 to 40% by wt. solids) using direct push technology in medium to fine sands and even silty sands. EHC slurry can also be injected using hydraulic and pneumatic fracturing in tighter formations. EHC-A (the aqueous form) can be injected via direct push technology as well as through standard monitoring and injection wells. Other liquid ISCR reagents are also available. The choice of injection methodology depends primarily on the formation and then on the type of EHC being recommended *(i.e.* granular, powder or liquid).

2. PROJECT OBJECTIVES AND METHODS

2.1 Project Objectives

The aim of this bench-scale feasibility study was to determine the ability of HRC-X™, EOS® and EHC™ to treat TCE and its daughter products in the presence of benzene and naphthalene in groundwater collected from the Site. Specific objectives included:

- determine the ability of HRC-X™, EOS® and EHC™ to treat the TCE and its daughter products;
- to identify which of the three products is most effective;
- to assess whether bioaugmentation with KB-1 will improve degradation of TCE and its daughter products; and
- to determine the optimal application rate of the selected product for full-scale treatment.

2.2 Initial Groundwater and Soil Characterization

On October 7, 2005 Adventus received two plastic pails of groundwater (WS12-125) and 8 Geoprobe sleeves with soil from the Site. All samples were placed into cold room storage upon receipt.

On October 11, 2005 a sample of the groundwater was submitted for volatile organic compounds (VOCs), total organic carbon (TOC), chloride (Cl), alkalinity (Alk), pH, nitrate (NO_3-N), sulfate (SO_4), total iron, dissolved iron and poly aromatic hydrocarbons (PAH) analyses. A composite soil sample was submitted for VOC, TOC, Cl, Alk, pH, NO_3-N, SO_4, total iron, and PAH. All samples were shipped via overnight courier to Severn Trent Laboratories (STL) – Chicago for analysis.

The initial groundwater and soil VOCs results are presented in **Table 1**. TCE was not detected in the groundwater sample that Adventus received (WS12-125) and only 0.107 umoles/kg of TCE was detected in the Site soil. A trace amount of benzene was detected in the Site groundwater while benzene was not detected in the soil. Naphthalene was not detected in the Site groundwater but was detected in the soil at a concentration of 0.148 umoles/kg. The concentrations of TCE, benzene and naphthalene were lower than expected and thus MFA requested that the groundwater for the study be spiked with 10 ppm (76.1 umoles/L) TCE, 1 ppm (12.8 umoles/L) benzene, and 2.5 ppm(19.5 umoles/L) naphthalene.

The TOC concentration in soil was 600 mg/kg, and that in groundwater was 6.2 mg/L. The Site soil and groundwater were relatively neutral and had pH values of 6.4 and 6.83, respectively. The groundwater had a sulfate concentration of 13 mg/L and nitrate was not detected (<0.1 mg/L). The chloride concentrations in the Site soil and groundwater samples were 8.6 mg/kg and 17 mg/L, respectively. The soil had a high concentration of iron (21,000 mg/kg) while the Site groundwater had total iron and dissolved iron concentrations of 1.2 mg/L and 0.17 mg/L, respectively.

The remaining initial characterization data is presented in **Appendix A**.

2.3 Column Test Set Up

On November 4th, 2005 eight columns were set up with the Site soil. Each column was loaded with 50 g of gravel followed by 1,350 g of Site soil. The Site soil for the sterile control column was autoclaved (121°C for 20 minutes) and amended with 10 mL of 5% mercuric chloride ($HgCl_2$) and 10 mL of 5% sodium azide (NaN_3) prior to loading the column. The columns were filled with a sodium sulfite solution (50 ppm) and were allowed to incubate for 65 hours. On November 7th a collapsible Tedlar bag filled with nitrogen was attached to the top of each column and the sodium sulfite solution was drained by gravity. On November 8th several of the columns still had sodium sulfite solution in them and thus each column was purged with nitrogen for 5 minutes. The Site groundwater was spiked with trichloroethylene (10 ppm), benzene (1 ppm), and naphthalene (2.5 ppm) and was pumped into the columns at a flow rate of 1 mL/min. During the filling of the columns, deflated collapsible Tedlar bags were connected to the effluent lines of the columns.

On November 9th the columns were saturated with the spiked Site groundwater and the treatment materials were injected into the columns (**Table 2**).

EHC™ was injected into columns 1 and 2 (**Appendix C - Photograph A**). The EHC slurry was prepared by mixing 11 g of EHC with 25.7 g of distilled water. The injection rod (1/4" OD x 1/8" ID Teflon tubing) was filled with spiked Site groundwater and inserted through the top fitting of the column. The injection rod was inserted approximately 4 inches into the soil. The EHC slurry was then injected into the column. Following the EHC injection, 20 mL of spiked Site groundwater was injected through the injection rod to ensure that the full amount of EHC was delivered into the column. The same procedure was repeated for the second EHC column. EHC application rate was 1% by wt. of soil in the column. It should be noted that approximately half or 0.5% is the slow release organic carbon fraction and the other half (0.5%) is ZVI.

EOS® was injected into columns 3 and 4. An EOS solution was prepared by mixing 15 g of EOS Concentrate 598 B42 (Lot No. 147) with 100 mL of distilled water (Sheri Knox - Solutions, IES, November 4, 2005). A new piece of Teflon tubing was used as the injection rod and was inserted into the column as described above for the EHC column. The EOS solution was injected into the column and was followed by the injection of 20 mL of spiked Site groundwater. The same procedure was repeated for the second EOS column. EOS application rate was 1.37% by wt. of soil in the column.

Hydrogen release compound – extended release formula (HRC-X™) was injected into columns 5 and 6 (**Appendix C - Photograph B**). Due to the high viscosity of HRC-X, the HRC-X was warmed to 45°C in a water bath. Using a 10 mL syringe, 2.3 mL of HRC-X (HRC-X density = 1.3 g/cm^3, therefore 2.3 mL = 3 g) was measured into the syringe (Anna Willett - Regenesis, November 2, 2005). The weight of the syringe was also recorded before and after filling to ensure that 3 g of HRC-X was added to the column. The warm (45°C) HRC-X was still relatively viscous and thus the product was diluted with 10 mL warm distilled water prior to injection. A new piece of Teflon tubing was used as the injection rod and was inserted into the column as described above for the EHC column. Following the injection of the HRC-X solution, 20 mL of spiked Site groundwater was injected though the injection rod. The same procedure was repeated for the second HRC-X column. The application rate of HRC-X was 0.27 % by wt. of soil in the column.

During the injection of the three materials, the bottom of the column was unclamped to allow the water displaced by the amendment to drain out of the column. After the materials were injected, the top and bottom of the columns were clamped and the columns were left stagnant overnight.

On November 9th, the spiked Site groundwater was sampled for volatile organic compounds (VOCs) and submitted via overnight courier to Severn Trent Laboratories – Chicago.

On November 10th the feed pump was turned on and approximately 60 mL of the spiked Site groundwater was pumped through the columns (**Appendix C - Photograph C**).

On November 11th columns 2, 4, and 6 were inoculated with 10 mL of the KB-1™ culture (SiREM, Guelph, ON). After the selected columns were inoculated the feed pump was turned on and the flow rate was set to approximately 45 mL/day.

On November 13th the EOS columns were amended with EOS® Vitamin B_{12} Supplement. The required volume (30 μL) of EOS Vitamin B_{12} Supplement (Sheri Knox - Solutions, IES, November 4, 2005) was diluted in 5 mL of spiked Site groundwater and injected into the bottom of the column.

Following the B_{12} injection, 5 mL of spiked Site groundwater was injected into the bottom of each EOS column.

On November 14, 2005 the columns were set up to operate in a continuous closed loop (**Appendix C - Photograph D**). Water from the top of the columns was continuously pumped via a peristaltic pump to the bottom of the column. After 2 weeks (November 28th – Sampling #1) of closed loop operation the columns were set up for sampling. A Tedlar bag filled with nitrogen was connected to the top of the column and tubing on the effluent side of the peristaltic pump was connected to a glass syringe. As the syringe was filled with water it was transferred into the required sampling containers. The water in each column was sampled for VOCs, total organic carbon (TOC), chloride, and alkalinity at Severn Trent Laboratories - Chicago.

Following the sampling event, the influent side of the peristaltic pump was connected to a Tedlar bag filled with Site groundwater spiked with TCE, benzene, and naphthalene and the feed was pumped into the columns. Once the columns were saturated with feed, the nitrogen filled Tedlar bags were disconnected from the columns and the effluent from the column was collected in a jar. After the column was flushed with approximately 300 mL of feed the columns were set up to operate in a continuous closed loop.

On December 19th (Sampling #2) the columns were sampled using the method outlined above for the following analyses: VOC, methane, ethene, volatile fatty acids, TOC, alkalinity, and chloride. There was not sufficient water in the columns to collect all the scheduled samples thus only the following analyses were submitted: VOC (STL-Chicago), methane and ethene (STL-Burlington), and VFA (STL-Tallahassee). Following the sampling, approximately 300 mL of spiked Site groundwater was flushed through the columns and the columns were operated in a closed loop.

On January 16th (Sampling #3) the columns were sampled for the same analysis as outlined above for Sampling #1. Column #3 (EOS) was having some problems with flow and thus only the TOC samples were collected from the bottom of the column. The VOC, chloride, and alkalinity samples were collected from the freestanding water on top of the soil. Following the sampling, approximately 300 mL of spiked Site groundwater was flushed through the columns and the columns were operated in a closed loop.

On January 30th (Sampling #4) the columns were sampled for the same analysis as outlined above for Sampling #2. Following the sampling the columns were filled with spiked Site groundwater and a 1L jar was inserted between the effluent line of the column and the influent line of the peristaltic pump (**Figure A**). Once the jar was filled with groundwater from the column, the system was set up to operate in a closed loop.

On February 13th (Sampling #5) the columns were sampled for PAHs (**Figure B**). After the water samples were collected, the soil in columns 1, 3, and 5 was sampled for TOC. The TOC soil samples were collected in a glove bag filled with nitrogen. The glove bag was not large enough to reload the soil into the columns within the glove bag and thus the soil was placed back into the columns in a fume hood. Each column was purged with nitrogen for 10 minutes to displace the air that may have entered the pore spaces in the soil. The columns were re-filled with spiked Site groundwater.

3. COLUMN RESULTS

3.1 First Test (14-day contact time)

The concentrations of TCE, benzene, and naphthalene in the feed spiked for the first exposure period (14 days contact time) were 83.72 umoles/L, 128.02 umoles/L and 19.5 umoles/L, respectively (**Table 3**). The TCE concentration was slightly above the targeted value of 76.1 umoles/L while the benzene concentration was an order of magnitude greater than the targeted value. This batch of Site groundwater was mistakenly spiked with 10X the required benzene.

Reductions in the TCE concentrations were observed in all the columns during the first 14-day contact period. TCE was reduced by 98% in both EHC columns (with and without KB-1), by 99% in both EOS columns, and by 98% and 99% in the HRC-X columns, with and without KB-1, respectively. The control and sterile control columns also supported 69% and 50% removal of TCE.

Cis-DCE, a byproduct of TCE degradation was produced in all columns, which suggested that reductive dechlorination was occurring in the columns. Ideally, one mole of cis-DCE is produced for every mole of TCE. Consequently, 83.72 umoles/L of cis-DCE would be produced from 83.72 umoles/L of TCE. The EHC and EHC w/KB-1 columns produced approximately 78% and 74%, respectively of the theoretical cis-DCE amounts. The HRC-X and HRC–X w/KB-1 columns produced approximately 172% and 74%, respectively of the theoretical cis-DCE amounts. The high percentage of cis-DCE created in the HRC-X column is most likely an error. The EOS and EOS w/KB-1 columns produced approximately 11% and 16%, respectively of the theoretical cis-DCE amounts, indicating that EOS columns were able to either degrade more cis-DCE when compared to EHC and HRC-X columns (with or without KB-1) or cis-DCE partitioned into the EOS. Since the columns were under a lag phase, it is unlikely that significant amount of cis-DCE was degraded in the EOS columns. A look at the chloride data shows that chloride produced in the EOS columns ranged from 25 to 39 mg/L, in the EHC columns chloride ranged from 77 to 100 mg/L, and in the HRC-X column it ranged from 25 to 34 mg/L. This shows that a higher percentage of reductive dechlorination occurred in the EHC columns as compared to the EOS and HRC-X columns during the first 14-day contact test. This shows that the low concentration of cis-DCE in the EOS columns was due to partitioning of cis-DCE to EOS. Data with and without KB-1 from all columns indicate that during this contact period, KB-1 did not have much of an effect in enhancing the degradation of cis-DCE.

Low concentrations of VC were detected in the EHC, EHC w/KB-1, and EOS W/KB-1 systems which suggested that these systems supported further dechlorination of cis-DCE.

Methylene chloride was also detected in all the columns after the first 14-day contact test (the data is presented in section 3.5).

A chloride mass balance was obtained by comparing the measured increase in chloride concentration ($[Cl^-]_{effluent} - [Cl^-]_{feed}$) with the theoretical concentration of chloride produced (calculated from VOC concentrations) (**Appendix D**). The EHC systems showed a large increase in the chloride concentration for the first 14-day contact test; however this increase was not entirely from the dechlorination of VOCs. The EOS system showed a chloride mass balance of 98%. The high cis-DCE concentration in the HRC-X system resulted in a negative mass balance. The measured

chloride concentration in sterile control was greater than the theoretical since chloride was present in the soil from the addition of mercuric chloride during the column set up.

The alkalinity concentration increased in response to the addition of the three substrates (EHC, EOS, and HRC-X). The greatest increase in alkalinity was observed in the EHC treatments where the alkalinity concentrations were 700 and 850 mg/L in the columns amended with EHC and EHC W/KB-1. It should be noted that a high alkalinity is preferred by the microorganisms as it buffers the low pH created by reductive dechlorination. The TOC concentration also increased after the addition of EHC, EOS, and HRC-X. The TOC concentration increased from 6.2 mg/L in the feed to: 1,700 mg/L and 1,800 mg/L in the EHC and EHC W/KB-1 columns; 550 mg/L and 560 mg/L in the EOS and EOS W/KB-1 columns; and 2,000 mg/L and 1,900 mg/L in the HRC-X and HRC-X W/KB-1 columns. Both EHC and HRC-X were able to establish high TOC levels very early in the process when compared to EOS.

Some removal of benzene was observed in all the columns including the controls. This is primarily due to partitioning of benzene to the soil. A relatively large decrease was seen in both the EOS columns, which suggests that large quantities of benzene partitioned in to the soil amended with EOS.

Naphthalene concentrations in groundwater were significantly lower as a percentage when compared to benzene. This is because naphthalene has a higher partitioning coefficient than benzene. Once again, the relatively low levels of naphthalene in EOS columns indicate higher partioning of naphthalene to EOS when compared to other columns.

The ORP of the columns ranged from –35 mV to +180 mV. The EHC and EHC w/KB-1 columns had ORP values of 0 mV and +12 mV, respectively. The ORP values in the HRC-X and HRC –X w/KB-1 columns were +19 mV and +28 mV, respectively. The EOS and EOS w/KB-1 columns had ORP values of –30 mV and –36 mV. ORP values of the control and sterile control were 7.2 mV and 179.8 mV, respectively.

The average pH value of the controls was 5.9 and the average pH values of the EHC, EOS, and HRC-X amended columns were 5.5, 5.8, and 5.2, respectively.

Methane, ethane, and ethene were not sampled for the first 14-day contact test.

3.2 Second Test (21 day contact time)

The concentrations of TCE, benzene, and naphthalene in the feed spiked for the second exposure period (21-days contact time) were 76.1 umoles/L, 20.48 umoles/L and 15.6 umoles/L, respectively (**Table 4**). The benzene concentration was slightly above the targeted value of 12.8 umoles/L, while the naphthalene concentration was slightly below the targeted value of 19.5 umoles/L.

For the 21-day contact time test, all columns continued to show reductions in TCE. The EOS W/KB-1 system supported complete removal (detection limit 0.076 umoles/L) of TCE while the EHC and HRC-X systems supported 99% removal of TCE. The control and sterile control systems supported 87% and 28% removal, respectively. The high removal of TCE observed in the non-sterile control was similar to the observations made during the first 14-day contact time test, and indicates that TCE will degrade naturally without enhancements.

A decrease in TCE was accompanied by an increase in cis-DCE. The theoretical concentration of cis-DCE that would be produced if 76.1 umoles/L TCE were converted to cis-DCE is 76.1 umoles/L. The EHC and EHC w/KB-1 columns produced approximately 88% and 78%, respectively of the theoretical cis-DCE amounts. The HRC-X and HRC–X w/KB-1 columns produced approximately 84% and 85%, respectively of the theoretical cis-DCE amounts. The EOS and EOS w/KB-1 columns produced approximately 58% and 37%, respectively of the theoretical cis-DCE amounts. Once again, the low cis-DCE levels in the EOS columns would suggest that either the EOS columns were able to degrade more cis-DCE when compared to EHC and HRC-X columns or it was the partitioning effect. A look at the VC data (discussed below) indicates that more cis-DCE was degraded in the EOS columns. Cis-DCE data with and without KB-1 from the EHC and EOS columns indicate that during this contact period, KB-1 marginally enhanced the degradation of cis-DCE.

VC was detected in the six systems amended with substrates but was not detected in the controls. VC was detected in the EOS w/KB-1 column at a concentration of 20.8 umole/L, which was one to two orders of magnitude higher than what was detected in the EHC and HRC-X columns. Ethane was not detected in any of the columns. Ethene was only detected in the EOS w/KB-1 column at a concentration of 1.46 umoles/L, but methane was detected in all columns sampled.

Propionic acid, acetic acid, and butyric acid were detected in the EHC and EOS systems. The EOS system without KB-1 also showed the presence of pyruvic acid. Although lactic acid was not detected in the HRC-X systems, its fermentation products, acetic acid and propionic acid, were detected. The total VFA's were in the same order of magnitude range for all columns (280 to 912 mg/L) except in the HRC-X w/KB-1 column, where they were detected at a concentration of one order of magnitude less (65.3 mg/L).

Benzene data shows that the concentrations in the test columns (except the non-sterile control) were higher than the feed. This is because the large amount of benzene that originally partitioned to the soil from the first test was partitioning back into the aqueous phase.

Naphthalene concentrations were again significantly lower as a percentage when compared to benzene. This is because naphthalene has a higher partitioning coefficient than benzene. Once again, the relatively low levels of naphthalene in EOS columns indicate higher partioning with EOS when compared to other columns. Data from the non-sterile control column indicates that naphthalene and benzene were being degraded.

The ORP of the columns ranged from –83 mV to +243 mV. The EHC and EHC w/KB-1 columns had ORP values of -83 mV and -70 mV, respectively. The ORP values in the HRC-X and HRC–X w/KB-1 columns were -45 mV and -54 mV, respectively. The EOS and EOS w/KB-1 columns had ORP values of –36 mV and –60 mV. ORP was in the desired negative mV range for all columns that received amendments.

The average pH value of the controls was 6.4 and the average pH values of the EHC, EOS, and HRC-X amended columns were 6.3, 6.1, and 6.3, respectively.

3.3 Third Test (28 day contact time)

The concentrations of TCE, benzene, and naphthalene in the feed spiked for the third exposure period (28-days contact time) were 71.54 umoles/L, 14.08 umoles/L and 16.38 umoles/L, respectively (**Table 5**). The TCE and naphthalene concentrations were slightly below their targeted values of 76.1 umoles/L and 19.5 umoles/L, respectively. The benzene concentration was slightly above the targeted value of 12.8 umoles/L.

Complete removal of TCE (Detection limits = 0.038 and 0.076 umoles/L) was observed in most of the amended columns during the 28-day contact time of the third exposure period. A trace amount of TCE (0.989 umoles/L) was detected in the EOS without KB-1 column. The control and sterile control columns supported 95% and 35% removal of TCE, respectively.

The theoretical concentration of cis-DCE that would be produced if 71.54 umoles/L TCE were converted to cis-DCE is 71.54 umoles/L. The EHC and EHC w/KB-1 columns produced approximately 75% and 0.1%, respectively of the theoretical cis-DCE amounts. The EOS and EOS W/KB-1 columns produced approximately 123% and 0.3%, respectively of the theoretical cis-DCE amounts. The HRC-X and HRC-X w/KB-1 columns produced approximately 62% and 39%, respectively of the theoretical cis-DCE amounts. During this contact period, all columns with KB-1 showed a significantly higher removal rate of cis-DCE. Furthermore, in the presence of KB-1, EOS and EHC columns degraded a higher percentage of cis-DCE when compared to HRC-X.

The total VOC concentration decreased from 71.54 umoles/L in the feed to 0.097 umoles/L in response to the EHC W/KB-1 (99.9% removal), to 0.47 umoles/L in response to EOS w/KB-1 treatment (99.6% removal), and to 31.75 umoles/L in response to HRC-X /w KB-1 treatment (55.6% removal).

VC was detected in all test columns except EHC+KB-1 and the sterile control.

With the exception of the EOS system, chloride was produced in all the treatment columns during the 28-day exposure period. The chloride mass balance revealed that the measured chloride concentration was greater than the calculated theoretical chloride concentration. The DCM present in the groundwater from the column may have contributed to the measured chloride concentration however it was not included in the chloride mass balance since the initial DCM concentration was not known.

On day 63 (after the 28-day contact test) alkalinity in the columns amended with EHC, EOS and HRC-X were only slightly greater than those observed in the controls. The TOC concentrations in the amended columns were greater than that of the control. Highest TOC was detected in the EOS columns (260 and 410 mg/L), followed by EHC (15 and 56 mg/L), and then HRC-X (8.9 and 9.9 mg/L).

Benzene data shows that the concentration remained higher than the feed in the EOS column from continued partioning from the soil. Benzene in the EHC w/KB-1 was marginally higher (20.48umoles/L) than the feed (16.08 umoles/L). Benzene in the sterile column was same as the feed. In the remaining columns, the benzene concentrations were significantly lower than that in the feed suggesting that some degradation might be occurring. The lowest benzene concentration was observed in the non-sterile control at 0.614 umoles/L (96% removal).

Naphthalene concentrations were again significantly lower as a percentage when compared to benzene. Data from the non-sterile control column indicates that naphthalene and benzene were being degraded.

Methane, ethane, and ethene were not sampled for the 28-day contact test. ORP and pH were not monitored during the third test.

3.4 Fourth Test (14 days contact time - repeat)

The concentrations of TCE, benzene, and naphthalene in the feed spiked for the fourth exposure period (14-days) were 83.72 umoles/L, 14.01 umoles/L and 17.16 umoles/L, respectively (**Table 6**). The TCE and benzene concentrations were slightly above their targeted values of 76.1 umoles/L and 12.8 umoles/L, respectively. The naphthalene concentration was slightly below the targeted value of 19.5 umoles/L.

During the first 14-day contact test, the microorganisms were in the lag phase and the release profiles of the amendments had not completely developed. Consequently, the 14-day contact test was repeated. At the end of the second 14-day contact test, all columns continued to show reductions in TCE. The EHC system supported complete removal (detection limit 0.019 umoles/L) of TCE while the remaining EHC, EOS, and HRC-X systems supported greater than 99% removal. The control and sterile control systems supported 91% and 23% removal, respectively.

The theoretical concentration of cis-DCE that would be produced if 83.72 umoles/L TCE were converted to cis-DCE is 83.72 umoles/L. The EHC and EHC w/KB-1 columns produced approximately 3.7 % and 0.4%, respectively of the theoretical cis-DCE amounts. The EOS and EOS W/KB-1 columns produced approximately 116% and 1.2%, respectively of the theoretical cis-DCE amounts. The higher percentage of cis-DCE in the EOS column could be due to partitioning from the soil to the aqueous phase. However, in the presence of KB-1, rapid degradation of cis-DCE was observed. The HRC-X and HRC-X w/KB-1 columns produced approximately 97.5% and 57%, respectively of the theoretical cis-DCE amounts. During this contact period, all columns with KB-1 showed a significantly higher removal rate of cis-DCE. In addition, in the presence of KB-1, EOS and EHC columns degraded a higher percentage of cis-DCE when compared to HRC. It was also observed that EHC alone was able to degrade a higher percentage of cis-DCE when compared to EOS and HRC-X without the use of KB-1.

VC was detected in all the columns except the sterile control. The highest VC was detected in the EHC column without KB-1 and supports the conclusion above for the degradation of cis-DCE. However, in the presence of KB-1, there was only a minimal build up of VC in the EHC column.

The total VOC concentration decreased from 83.72 umoles/L in the feed to 0.76 umoles/L in response to the EHC w/KB-1 treatment (99.1% removal), to 3.30 umoles/L in response to EOS w/KB-1 treatment (96.1% removal), and to 60.99 umoles/L in response to HRC-X w/KB-1 treatment (27.2% removal). The high total VOCs removal in EHC w/KB-1 column is due to the combined effect of ZVI and the slow-release organic carbon coupled with KB-1. The high total VOCs removal in EOS w/KB-1 column is due to the combined effect of high organic carbon coupled with KB-1. The low removal of total VOCs in the HRC-X w/KB-1 column is due to low TOC in the column during this final exposure period. Ethene was detected in the EHC, EHC

w/KB-1, EOS w/KB-1, and HRC-X w/KB-1 systems, which confirmed that VC, an intermediate breakdown product, was further dechlorinated to ethene.

Chloride was produced in each column during the second 14-day exposure period. Once again, the chloride mass balance revealed that the measured chloride concentration was greater than the calculated theoretical chloride concentration.

During the final exposure period, volatile fatty acids were not detected in the EHC, EHC w/KB-1, and HRC systems. A trace amount of acetic acid was detected in the HRC w/KB-1 system and propionic acid, acetic acid, and butyric acid were detected EOS systems. The TOC levels ranged from 17 to 18 mg/L in the EHC columns, from 91 to 160 mg/L in the EOS columns, and from 7.4 to 7.7 mg/L in the HRC-X columns.

Benzene and naphthalene appeared to degrade in all the columns except the two EOS columns and the sterile control. The EOS columns showed higher benzene concentrations than the feed as benzene continued to partition into the groundwater from the soil.

The ORP of the columns ranged between –188 mV and -15 mV. The EHC and EHC w/KB-1 columns had ORP values of –188 mV and -75 mV, respectively. The ORP values in the HRC-X and HRC–X w/KB-1 columns were -78 mV and -88 mV, respectively. The EOS and EOS w/KB-1 columns had ORP values of –76 mV and –65 mV. The EHC column exhibited the lowest ORP of all the columns.

The average pH value of the controls was 7.3 and the average pH values of the EHC, EOS, and HRC-X amended columns were 7.2, 6.9, and 7.3, respectively.

3.5 Calculated Half Lives of TCE, DCE and VC

Calculated half lives for TCE, DCE and VC are presented in **Table 7**. As seen in **Table 7**, the half life of TCE decreased with an increase in contact time and as the microorganisms established over the test period. The lowest half lives for TCE were seen in the second 14-day contact test. The half life of TCE during the second 14-day exposure period was calculated to be 1.2 days for both the EHC and EHC w/KB-1 treatments. The calculated half lives of TCE for the EOS and EOS w/KB-1 treatments were 1.9 and 1.2 days, respectively. The calculated half lives for TCE in the presence of HRC-X and HRC-X w/KB-1 treatments were 1.6 and 1.4 day, respectively. The true half life of TCE and its daughter products in the EOS columns are most likely longer if the effect of contaminant partioning into the EOS is neglected. As expected, the calculated half lives of TCE in the control systems were longer than those calculated for columns which received amendments. The TCE half lives for the control and sterile control were 4 and 38 days, respectively.

The half lives of DCE and VC were calculated by assuming that one mole of TCE degraded results in one mole of DCE, and one mole of DCE degraded results in one mole of VC. For TCE we knew the starting concentration and the final concentration so the half-life calculation is accurate. For DCE and VC an assumption was made that all the DCE generated from TCE and all the VC generated from DCE were produced at time zero. This is not the case in reality so the half life calculations for DCE and VC are not true half-lives. For DCE, the lowest half life was calculated to be 2.9, 1.8, 4.4, 2.2, 30.4 and 15.4 days for EHC, EHC w/KB-1, EOS, EOS w/KB-1, HRC-X, and HRC-X w/KB-1,

respectively. For VC, the lowest half life was calculated to be 3.3, 2.8, 1.8, 1.8, 3.0 and 2.4 days for EHC, EHC w/KB-1, EOS, EOS w/KB-1, HRC-X, and HRC-X w/KB-1, respectively.

3.6 Methylene Chloride Concentrations

Methylene chloride (DCM) was detected in all the column systems during the first test (14 day contact time). However; DCM was not detected in the feed and MFA confirmed that it was not present at the Site. Further testing revealed that the source of DCM was the material used to construct the columns. A summary of the DCM concentrations in the columns during the 77-day study is provided in **Table 8**. DCM concentrations decreased with each subsequent sampling event and were not detected in most of the amended systems on day 77. DCM was detected in the sterile control during all four sampling events.

SUMMARY AND CONCLUSIONS

The purpose of this bench-scale feasibility study was to assess the ability of HRC-X™, EOS® and EHC™ to remove TCE and its daughter products from groundwater in the presence of benzene and naphthalene which are also present at the Siltronic Site in Portland, Oregon. The following summary is provided based on the results presented herein:

- The initial characterization of the Site groundwater revealed that the groundwater sample shipped to Adventus had lower than expected concentrations of the COIs (TCE, benzene, and naphthalene), thus the Site groundwater was spiked with these COI to better represent the Site conditions.

- The initial characterization of the Site soil revealed that the soil had low VOC concentrations and a high TOC concentration.

- All three treatments showed significant and sustained reductions in the TCE concentrations throughout the study (**Figures C-H, Table 9**). However, the non-sterile control system also showed some reductions (**Figures I & J, Table 9**). This indicates that natural degradation of TCE can occur provided the right conditions prevail at the site. TCE removal averaged between 99 to 100% for the six columns that received amendments. TCE removal averaged 85% and 34%, in the non-sterile and sterile control columns, respectively. Please note that the tests were conducted in a static environment whereas, groundwater and soil at the site under natural settings exists in a dynamic environment. Consequently, the high TCE degradation observed in the non-sterile control will not be observed at the site under the natural conditions. The abiotic removal of TCE in the sterile control was presumably due to reactions such as adsorption or volatilization despite the undertaking of special efforts to avoid such losses.

- Significant enhancement in the removal of cis-DCE in columns with KB-1 was not seen during the first 14-day and the 21-day contact tests. This is most likely due to the lag-time associated with establishing the right conditions in the columns. Cis-DCE removal was very high in the 28-day and the second 14-day contact tests, but only in EOS and EHC columns that had KB-1. The HRC-X column with KB-1 showed only a marginal increase in the removal of cis-DCE. The low removal rate of cis-DCE in the HRC-X w/KB-1 column is most likely due to a low TOC level in the column.

- VC was detected in the two EHC columns and the EOS w/KB-1 column after the first 14-day contact time. This indicates that EHC, EHC w/KB-1 and EOS w/KB-1 were quickly able to establish the right conditions for degradation of daughter products. VC was detected in all columns after the 21-day contact test at higher concentrations. This indicated that cis-DCE was being degraded. VC. VC in the EHC column increased steadily from 0.912 umoles/L and reached a high of 44.8 umoles/L during the fourth test. In the EHC w/KB-1 column, VC increased to a high of 2.08 umoles/L in the second test after which it decreased rapidly to 0.336 umoles/L. This shows that KB-1 did enhance VC degradation in the EHC column. KB-1 also enhanced VC degradation in the EOS column, but the enhancement was marginal and observed only in the third test. For HRC-X, VC concentration in the column with KB-1 was always higher than the column without KB-1 which indicated that VC mineralization was limited.

- Ethene was monitored during the second (21 day contact time) and the fourth (14 day contact time) tests. Ethene was only detected in the EOS w/KB-1 column during the second exposure period (21 days). In the fourth exposure period (second 14-day contact test), the highest ethene was detected in EHC w/KB-1 column (5.35 umoles/L) followed by EOS w/KB-1 column (4.99 umoles/L), EHC column (2.24 umoles/L), and HRC-X +KB-1 (0.132 umoles/L). This indicates that EHC was able to promote complete mineralization without the use of KB-1. It also shows that the rate of mineralization was accelerated in columns that were amended with KB-1.

- Total VOCs data **(Appendix E)** from all the tests combined show that 23% of the feed VOCs were degraded in the EHC column compared to 59% in the EHC w/KB-1 column. For EOS, 19% of the feed VOCs were degraded compared to 79% when EOS was accompanied by KB-1. For HRC-X, the total VOCs removal was -12% compared to 28% when KB-1 was added to HRC-X. This shows that KB-1 did increase the degradation of daughter products, which make up the total VOCs. The data also shows that both EHC and EOS performed better than HRC-X when it came to degradation of total VOCs.

- The EHC, EOS, HRC-X treatments inoculated with KB-1 reduced the total chlorinated VOC concentrations from 83.72 μmoles/L in the feed to 0.76 μmoles/L, 3.30 μmoles/L, and 60.99 μmoles/L, respectively in the second 14-day contact test. This corresponded to 99%, 96%, and 27% removal in the EHC, EOS, and HRC-X systems inoculated with KB-1, respectively. The total chlorinated VOC concentrations in the control systems were reduced from 83.72 μmoles/L in the feed to 72.97 μmoles/L (13%) and 64.94 umoles/L (22%), in the control and sterile control, respectively.

- TOC, a critical parameter for these tests was measured during Tests 1, 3 and 4. During Test 2, TOC was substituted with the VFA test. TOC in the EHC columns averaged 1,750 mg/L in the first test and fell to 35.5 and 17.5 mg/L in the third and fourth Tests. TOC in the EOS columns averaged 555 mg/L in the first test and fell to 335 and 125.5 mg/L in the third and fourth Tests. TOC in the HRC-X columns averaged 1,950 mg/L in the first test and fell to 9.4 and 7.6 mg/L in the third and fourth Tests. This data is not a true representation of the release and utilization of TOC in these columns, as variable loss of TOC would have occurred when the columns were drained after each test. It is clear that EOS with its high affinity to bind to soil performed better and had the lowest loss of TOC. It should also be noted that EOS was injected at an application rate 1.4 times higher than EHC and 5 times higher than HRC-X when compared from a TOC

source. At the end of the fourth test, an analysis of the TOC in soil showed that EHC, EOS and HRC-X column had 850 mg/Kg, 5200 mg/Kg, and 590 mg/Kg of TOC, respectively. The background soil had a TOC of 600 mg/Kg, indicating that TOC source was depleted in the HRC-X columns, somewhat depleted in the EHC columns, and stayed high in the EOS columns.

- The TCE half life during the second 14-day exposure period was calculated to be 1.2 days for both the EHC and EHC + KB-1 treatments. The EOS and EOS w/KB-1 treatments had TCE half lives of 1.9 and 1.2 days, respectively. The TCE half lives for the HRC-X and HRC-X w/ KB-1 treatments were 1.6 and 1.4 day, respectively. As expected, the control systems had greater TCE half lives than the treatments. The TCE half lives for the control and sterile control were 4 and 38 days, respectively.

- The lowest ORP reading was recorded at -188.4 mV in the EHC column during the second 14-day contact test. Ideally, much lower ORP values (-300 to -600 mV) should be achieved in the field with EHC. The higher ORP observed in the column test is because of frequent draining and filling of the columns. However, the recorded ORP values indicate that biological degradation and iron reduction were the primary removal mechanisms for EHC. Thermodynamic decomposition occurs only at ORP values lower than -400 mV.

- Initially, pH in the test columns ranged from 5.21 to 5.84 and in the control columns it ranged from 5.87 to 5.93. There was an increase in pH in all the columns during the test. At the end of the last test, pH in the test columns ranged from 6.58 to 7.34 and in the control columns it ranged from 7.23 to 7.43. The data indicates that pH remained in the desired range to promote reductive dechlorination.

- Chloride was produced and detected in all the columns that received amendments. Chloride mass balance showed a lot of variability due to the build up and degradation of daughter products. With a few exceptions, more chloride was produced than calculated from stoichiometric equations. A positive chloride mass balance is preferred as a negative mass balance would indicate physical losses of the COIs.

- Benzene and naphthalene appeared to degrade in all the columns in the fourth test except the two EOS columns and the sterile control. The EOS column continued to show higher benzene concentration than the feed as benzene partitioned into the groundwater from the soil.

- The partioning effect of contaminants and their bioavailability for degradation could not be factored into the results for EOS columns. Data for benzene clearly shows that it partitioned heavily to the EOS substrate.

- In conclusion, EHC and EOS columns exhibited the best overall performance while HRC-X did not. Without KB-1, the percentage of total cVOCs degraded (combined from all four tests) was best in the EHC column. With KB-1, percentage of total cVOCs degraded (combined from all four tests) was best in the EOS column. EHC columns performed equally or better than the EOS columns considering that the application rate of EHC was 1.4 times lower than EOS. The calculated half-life of TCE was the least for EHC columns followed closely by HRC-X and EOS. However, the difference between all three is only marginal. The only column without KB-1 which

showed ethene was that of EHC indicating complete mineralization. Ethene was detected in all columns with KB-1, indicating that KB-1 did aid in complete mineralization.

RECOMMENDATIONS

Adventus recommends that pilot tests be conducted for EHC and EOS to evaluate performance under site specific-conditions.

EHC™ is a trademark of Adventus Intellectual Property Inc.
EOS® is a registered trademark of EOS Remediation, Inc.
HRC-X™ is a trademark of Regenesis
KB-1™ is a trademark of SiREM

TABLES

FINAL REPORT: HRC-X™, EOS®, AND EHC™ TREATABILITY STUDY FOR THE TREATMENT OF TRICHLOROETHENE IN GROUNDWATER FROM THE SILTRONIC CORPORATION SITE IN PORTLAND, OREGON (THE SITE)

Table 1: Initial VOC results in the Site soil and groundwater samples

Parameter	Soil	Units	WS12-125	Units	Target (H_2O)	Units
Vinyl Chloride	ND (0.10)	µmoles/kg	0.114	µmoles/L	---	---
Carbon disulfide	ND (0.083)	µmoles/kg	0.041	µmoles/L	---	---
Acetone	0.516	µmoles/kg	ND (0.086)	µmoles/L	---	---
Cis-1,2-Dichloroethene	0.949	µmoles/kg	0.029	µmoles/L	---	---
Benzene	ND (0.081)	µmoles/kg	0.054	µmoles/L	12.80	µmoles/L
Trichloroethene	0.107	µmoles/kg	ND (0.008)	µmoles/L	76.11	µmoles/L
Toluene	ND (0.068)	µmoles/kg	0.013	µmoles/L	---	---
M&p-Xylenes	ND (0.061)	µmoles/kg	0.005	µmoles/L	---	---
Naphthalene	0.148	µmoles/kg	ND (0.008)	µmoles/L	19.51	µmoles/L
Total VOCs	**1.72**	**µmoles/kg**	**0.256**	**µmoles/L**	**108.42**	**µmoles/L**

ND = non detect (detection limit)

Table 2: Summary of the Column Testing

Column #	Description	Mass (g) of product	Application Rate[1] (%)
1	EHC	11	1
2	EHC	11	1
3	EOS	15	1.37
4	EOS	15	1.37
5	HRC-X	3	0.27
6	HRC-X	3	0.27
7	Control	0	NA
8	Sterile Control	0	NA

[1]application rate based on dry weight of soil

Table 3: Influence of EHC, EOS, HRC-X, and KB-1 on organic and inorganic parameters, after the first exposure period (14 days contact time)

Parameter	Feed	EHC	EHC W/KB-1	EOS	EOS W/KB-1	HRC-X	HRC-X W/KB-1	Control	Sterile Control
Alkalinity (mg/L)	330[1]	700	850	470	500	650	490	150	140
Chloride (mg/L)	17[1]	77	100	25	39	25	34	15	45
TOC (mg/L)	6.2[1]	1,700	1,800	550	560	2,000	1,900	9	26
ORP (mV)	NM	0	+11.7	-30.1	-34.6	+19	+28.2	+7.2	+179.8
pH (pH units)	NM	5.57	5.35	5.79	5.84	5.26	5.21	5.93	5.87
VOC (umoles/L)									
VC	ND (0.800)	0.912	0.608	ND (0.320)	0.368	ND (1.60)	ND (0.320)	ND (0.320)	ND (0.320)
1,1-DCE	ND (0.516)	0.413	0.371	ND (0.206)	ND (0.103)	ND (1.03)	ND (0.206)	ND (0.206)	ND (0.206)
trans-1,2-DCE	ND (0.516)	0.340	0.299	ND (0.206)	0.547	ND (1.03)	1.86	ND (0.206)	ND (0.206)
cis-1,2-DCE	ND (0.516)	64.99	61.89	8.97	13.41	144.41	64.99	4.13	0.248
TCE	83.72	1.98	1.90	0.989	0.206	2.06	0.411	25.88	41.86
Total cVOC	**83.72**	**68.64**	**65.07**	**9.96**	**14.53**	**146.47**	**67.26**	**30.01**	**42.11**
Benzene	128.02	103.70	97.29	8.96	15.36	204.83	98.57	67.85	110.10
Naphthalene	19.50	0.858	0.858	0.273	0.780	3.67	2.34	0.780	5.93

[1] Values from baseline sampling
ND = non detect (detection limit)
NM = not monitored

Table 4: Influence of EHC, EOS, HRC-X, and KB-1 on organic and inorganic parameters, after the second exposure period (21 days contact time)

Parameter	Feed	EHC	EHC W/KB-1	EOS	EOS W/KB-1	HRC-X	HRC-X W/KB-1	Control	Sterile Control
ORP (mV)	NM	-82.7	-69.6	-35.5	-60.2	-45.4	-54.3	+186.1	+243.4
pH (pH units)	NM	6.47	6.08	6.05	6.13	6.22	6.36	6.75	6.08
Soluble Gases (umoles/L)									
Methane	NS	20.57	13.09	2.99	25.56	0.324	1.309	0.598	NS
Ethane	NS	ND (0.266)	ND (0.133)	ND (0.133)	ND (0.266)	ND (0.133)	ND (0.133)	ND (0.133)	NS
Ethene	NS	ND (0.214)	ND (0.107)	ND (0.107)	1.46	ND (0.107)	ND (0.107)	ND (0.107)	NS
Volatile Fatty Acids (mg/L)									
Propionic acid	NS	3.6	16	200	210	69	2.3	NS	NS
Pyruvic acid	NS	ND (2)	ND (2)	2.6	ND (2)	ND (2)	ND (2)	NS	NS
Butyric acid	NS	2.3	19	33	82	ND (0.5)	ND (0.5)	NS	NS
Lactic acid	NS	ND (10)	ND (10)	ND (10)	ND (10)	ND (10)	ND (10)	NS	NS
Acetic acid	NS	280	590	480	620	190	63	NS	NS
VOC (umoles/L)									
VC	ND (0.800)	1.04	2.08	1.18	20.80	0.096	1.58	ND (0.160)	ND (0.160)
1,1-DCE	ND (0.516)	0.155	0.113	0.072J	ND (0.103)	0.113	0.083 J	0.062 J	ND (0.103)
trans-1,2-DCE	ND (0.516)	0.206	0.206	0.165	0.165	0.309	0.309	0.299	ND (0.103)
cis-1,2-DCE	ND (0.516)	67.05	59.83	44.36	27.85	63.95	64.99	45.39	0.144
TCE	76.11	0.571	0.502	1.90	ND (0.076)	0.266	0.221	9.89	54.80
Total cVOC	**76.11**	**69.02**	**62.73**	**47.68**	**48.82**	**64.73**	**67.18**	**55.64**	**54.94**
Benzene	20.48	35.85	43.53	52.49	38.41	40.97	38.41	1.25	26.88
Naphthalene	15.60	7.72	3.04	0.328	0.390	6.01	6.55	0.398	7.41

NM = not monitored, J = estimated value below RL, NS = not sampled, ND = non detect (detection limit)

Table 5: Influence of EHC, EOS, HRC-X, and KB-1 on organic and inorganic parameters, after the third exposure period (28 days contact time)

Parameter	Feed	EHC	EHC W/KB-1	EOS	EOS W/KB-1	HRC-X	HRC-X W/KB-1	Control	Sterile Control
Alkalinity (mg/L)	330[1]	260	220	300	330	250	260	200	220
Chloride (mg/L)	17[1]	28	37	8.4	46	31	32	27	22
TOC (mg/L)	6.2[1]	15	56	410	260	9.9	8.9	5.6	25
VOC (umoles/L)									
VC	ND (0.800)	4.16	ND (0.080)	2.08	0.224	0.288	3.52	0.160	ND (0.080)
1,1-DCE	ND (0.516)	0.081 J	ND (0.052)	0.175	ND (0.052)	0.091	ND (0.103)	0.124	ND (0.052)
trans-1,2-DCE	ND (0.516)	0.268	0.030 J	0.495	0.026 J	0.309	0.382	0.743	ND (0.052)
cis-1,2-DCE	ND (0.516)	53.64	0.067	88.71	0.217	44.36	27.85	63.95	0.155
TCE	71.54	ND (0.076)	ND (0.038)	0.989	ND (0.038)	0.022 J	ND (0.076)	3.73	46.43
Total cVOC	**71.54**	**58.15**	**0.097**	**92.45**	**0.47**	**45.07**	**31.75**	**68.71**	**46.59**
Benzene	14.08	4.22	20.48	43.53	42.25	33.71	0.666	0.614	15.36
Naphthalene	16.38	ND (0.078)	ND (0.039)	1.17	0.320	ND (0.039)	ND (0.078)	ND (0.039)	9.36

[1]Values from baseline sampling
J = estimated value below RL
NS = not sampled
ND = non detect (detection limit)
ORP and pH were not monitored during this sampling event

Table 6: Influence of EHC, EOS, HRC-X, and KB-1 on organic and inorganic parameters, after the fourth exposure period (14 days contact time)

Parameter	Feed	EHC	EHC W/KB-1	EOS	EOS W/KB-1	HRC-X	HRC-X W/KB-1	Control	Sterile Control
Alkalinity (mg/L)	330[1]	260	270	230	230	270	280	260	320
Chloride (mg/L)	17[1]	31	32	27	35	26	26	23	20
TOC (mg/L)	6.2[1]	17	18	91	160	7.4	7.7	6.2	25
ORP (mV)	NM	-188.4	-75.3	-75.9	-64.8	-77.8	-88.4	-48.7	-14.6
pH (pH units)	NM	7.05	7.30	6.58	7.33	7.28	7.34	7.43	7.23
Soluble Gases (umoles/L)									
Methane	NS	61.09 E	47.99	74.80	143.37	0.686	2.87	0.623	NS
Ethane	NS	ND (0.133)	ND (0.665)	ND (0.665)	ND (1.330)	ND (0.133)	ND (0.133)	ND (0.133)	NS
Ethene	NS	2.24	5.35	ND (0.535)	4.99	ND (0.107)	0.132	ND (0.107)	NS
Volatile Fatty Acids (mg/L)									
Propionic acid	NS	ND (0.5)	ND (0.5)	12	9.5	ND (0.5)	ND (0.5)	NS	NS
Pyruvic acid	NS	ND (2)	ND (2)	ND (2)	ND (2)	ND (2)	ND (2)	NS	NS
Butyric acid	NS	ND (0.5)	ND (0.5)	6.6	8.6	ND (0.5)	ND (0.5)	NS	NS
Lactic acid	NS	ND (10)	ND (10)	ND (10)	ND (10)	ND (10)	ND (10)	NS	NS
Acetic acid	NS	ND (0.5)	ND (0.5)	48	130	ND (0.5)	ND (0.5)	NS	NS
VOC (umoles/L)									
VC	ND (0.800)	44.80	0.336	2.24	2.24	8.32	10.08	0.112	ND (0.160)
1,1-DCE	ND (0.516)	ND (0.026)	ND (0.026)	0.186	ND (0.026)	0.175	0.052	0.144	ND (0.103)
trans-1,2-DCE	ND (0.516)	ND (0.026)	0.072	0.083	0.041	0.072	0.237	0.196	ND (0.103)
cis-1,2-DCE	ND (0.516)	3.09	0.330	103.15	1.00	86.65	50.54	64.99	0.248
TCE	83.72	ND (0.019)	0.023	0.540	0.023	0.198	0.084	7.53	64.69
Total cVOC	**83.72**	**47.89**	**0.76**	**106.20**	**3.30**	**95.42**	**60.99**	**72.97**	**64.94**
Benzene	14.08	1.28	2.69	28.16	28.16	1.08	1.66	1.01	14.08
Naphthalene	17.16	ND (0.019)	ND (0.019)	1.01	0.109	ND (0.019)	ND (0.019)	ND (0.019)	13.26

[1]Values from baseline sampling NM = not monitored
ND = non detect (detection limit) NS = not sampled
E = concentration exceeded the upper limit of the calibration range of the instrument

Table 7: Calculated TCE, DCE and VC Half Life

Exposure Period	Treatment	Half Life (days)		
		TCE	Cis-DCE	VC
1 (14 days)	EHC	2.6	42.3	3.3
	EHC W/KB-1	2.6	34.8	2.8
	EOS	2.2	4.4	1.8
	EOS W/KB-1	1.6	5.3	1.8
	HRC-X	2.6	NC	NC
	HRC-X W/KB-1	1.8	39.2	2.4
	Control	8.3	3.7	1.9
	Sterile Control	14.0	1.9	2.0
2 (21 days)	EHC	3.0	121.6	6.9
	EHC W/KB-1	2.9	62.4	7.2
	EOS	3.9	28.3	4.5
	EOS W/KB-1	2.1	14.5	17.3
	HRC-X	2.6	85.6	3.0
	HRC-X W/KB-1	2.5	93.6	7.5
	Control	7.1	38.5	3.0
	Sterile Control	44.4	2.9	3.0
3 (28 days)	EHC	2.8	50.6	13.3
	EHC W/KB-1	2.6	2.1	2.9
	EOS	4.5	NC	NC
	EOS W/KB-1	2.6	2.5	3.4
	HRC-X	2.4	30.4	4.3
	HRC-X W/KB-1	2.8	15.4	7.7
	Control	6.6	247.5	6.1
	Sterile Control	45.0	2.9	3.4
4 (14 days)	EHC	1.2	2.9	16.5
	EHC W/KB-1	1.2	1.8	1.8
	EOS	1.9	NC	NC
	EOS W/KB-1	1.2	2.2	2.7
	HRC-X	1.6	NC	NC
	HRC-X W/KB-1	1.4	19.3	8.2
	Control	4.0	60.8	2.1
	Sterile Control	37.7	2.2	1.6

Table 8: DCM[1] concentrations in the test columns

Exposure Period	Concentration (umoles/L)								
	Feed	EHC	EHC W/KB-1	EOS	EOS W/KB-1	HRC-X	HRC-X W/KB-1	Control	Sterile Control
1 (14 days)	ND (0.589)	75.35	55.34	58.87	22.37	188.38	37.68	91.84	54.16
2 (21 days)	ND (0.589)	32.97	28.26	36.50	ND (0.117)	38.85	23.55	28.26	29.44
3 (28 days)	ND (0.589)	ND (0.117)	ND (0.059)	7.89	ND (0.059)	ND (0.059)	ND (0.117)	0.483	29.44
4 (14 days)	ND (0.589)	0.059	ND (0.029)	0.094	ND (0.029)	ND (0.029)	0.035	0.683	11.66

`[1]additional testing reveled that a material used to construct the columns was a source of DCM
H = alternate peak selection upon analytical review
ND = non detect (detection limit)

Table 9: Summary of chlorinated VOCs and ethene

Exposure Period	Parameter	Concentration (umoles/L)								
		Feed	EHC	EHC W/KB-1	EOS	EOS W/KB-1	HRC-X	HRC-X W/KB-1	Control	Sterile Control
1 (14 days)	TCE	83.72	1.98	1.90	0.989	0.206	2.06	0.411	25.88	41.86
	DCE	ND (0.516)	65.74	62.56	8.97	13.96	144.41	66.85	4.13	0.248
	VC	ND (0.800)	0.912	0.608	ND (0.320)	0.368	ND (1.60)	ND (0.320)	ND (0.320)	ND (0.320)
	Ethene	NS	NS	NS	NS	NS	NS	NS	NS	NS
2 (21 days)	TCE	76.11	0.571	0.502	1.90	ND (0.076)	0.266	0.221	9.89	54.80
	DCE	ND (0.516)	67.41	60.15	44.60	28.02	64.37	65.38	45.75	0.144
	VC	ND (0.800)	1.04	2.08	1.18	20.80	0.096	1.58	ND (0.160)	ND (0.160)
	Ethene	NS	ND (0.214)	ND (0.107)	ND (0.107)	1.46	ND (0.107)	ND (0.107)	ND (0.107)	NS
3 (28 days)	TCE	71.54	ND (0.076)	ND (0.038)	0.989	ND (0.038)	0.022 J	ND (0.076)	3.73	46.43
	DCE	ND (0.516)	53.99	0.097	89.38	0.243	44.76	28.23	64.82	0.155
	VC	ND (0.800)	4.16	ND (0.080)	2.08	0.224	0.288	3.52	0.160	ND (0.080)
	Ethene	NS	NS	NS	NS	NS	NS	NS	NS	NS
4 (14 days)	TCE	83.72	ND (0.019)	0.023	0.540	0.023	0.198	0.084	7.53	64.69
	DCE	ND (0.516)	3.09	0.402	103.42	1.04	86.90	50.83	65.33	0.248
	VC	ND (0.800)	44.80	0.336	2.24	2.24	8.32	10.08	0.112	ND (0.160)
	Ethene	NS	2.24	5.35	ND (0.535)	4.99	ND (0.107)	0.132	ND (0.107)	NS

ND = non detect (detection limit)
NS = not sampled

FIGURES

FINAL REPORT: HRC-X™, EOS®, AND EHC™ TREATABILITY STUDY FOR THE TREATMENT OF TRICHLOROETHENE IN GROUNDWATER FROM THE SILTRONIC CORPORATION SITE IN PORTLAND, OREGON (THE SITE)

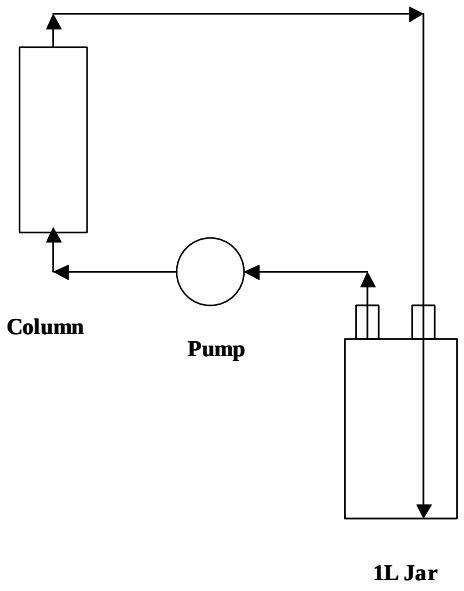


Figure A: Schematic of column set up (Sampling #5)

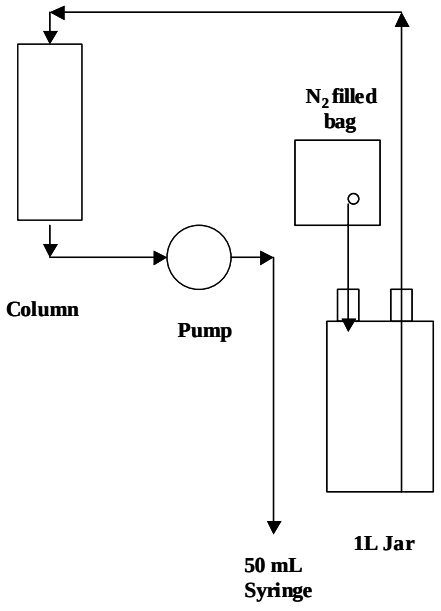


Figure B: Schematic of column sampling #5)

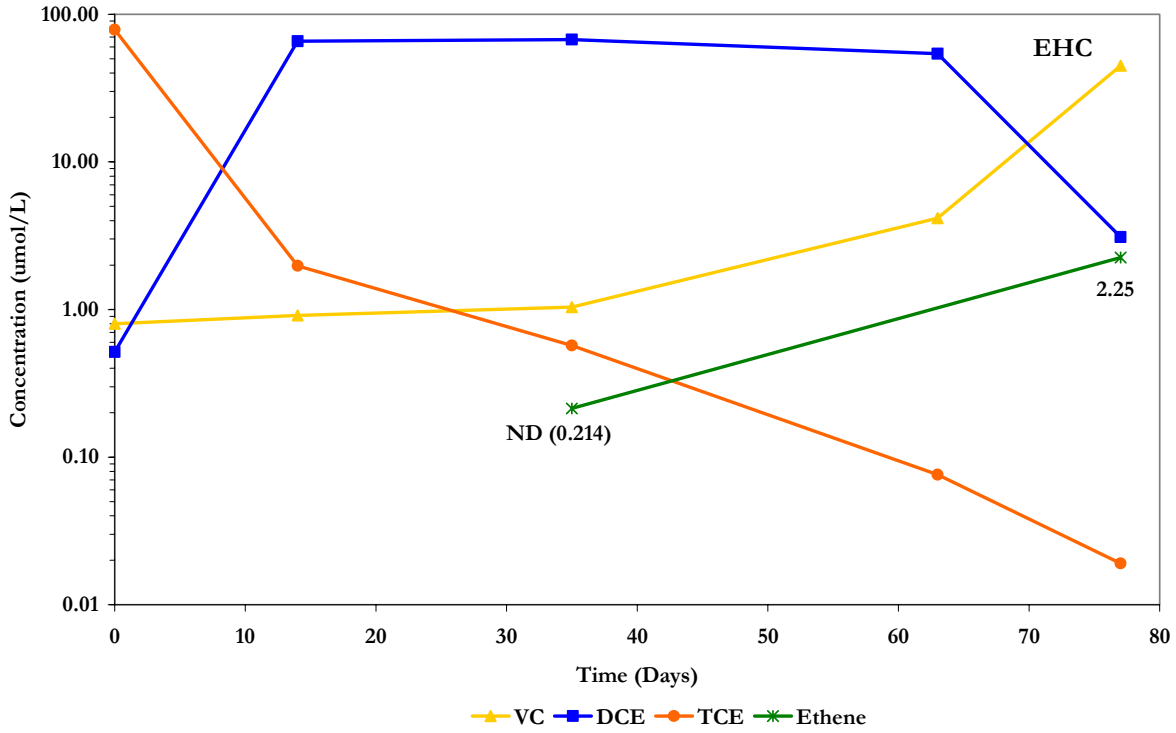


Figure C: Influence of EHC on TCE, DCE, VC, and ethene

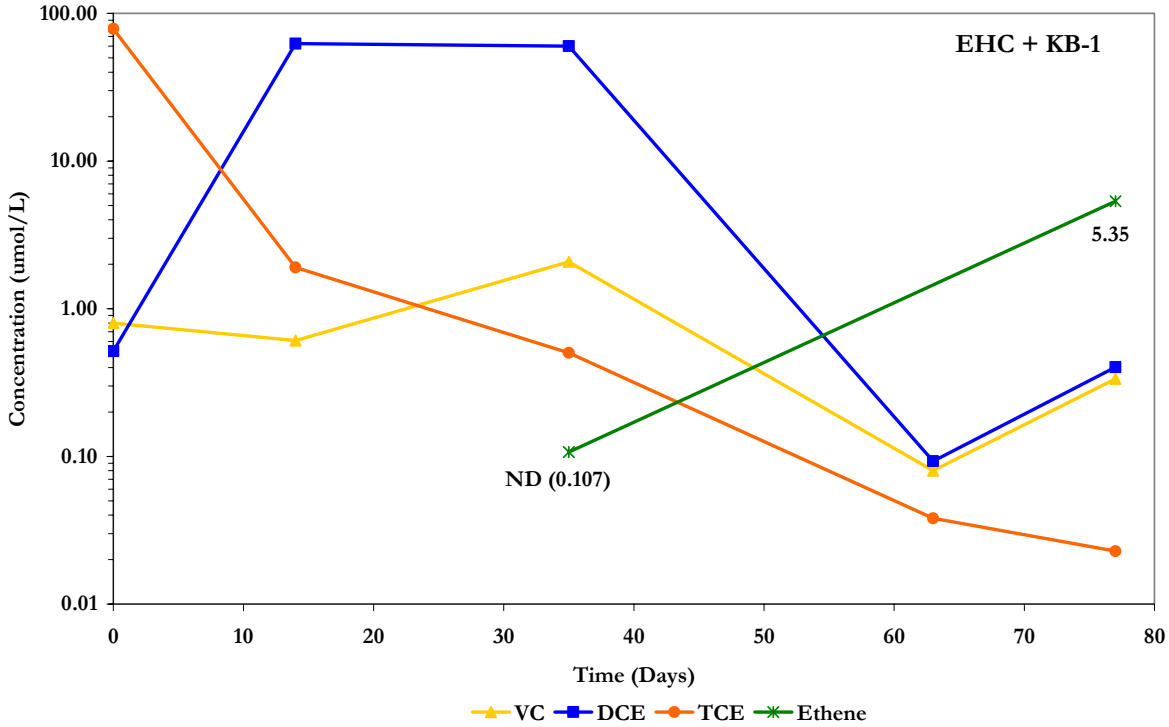


Figure D: Influence of EHC W/KB-1 on TCE, DCE, VC, and ethene

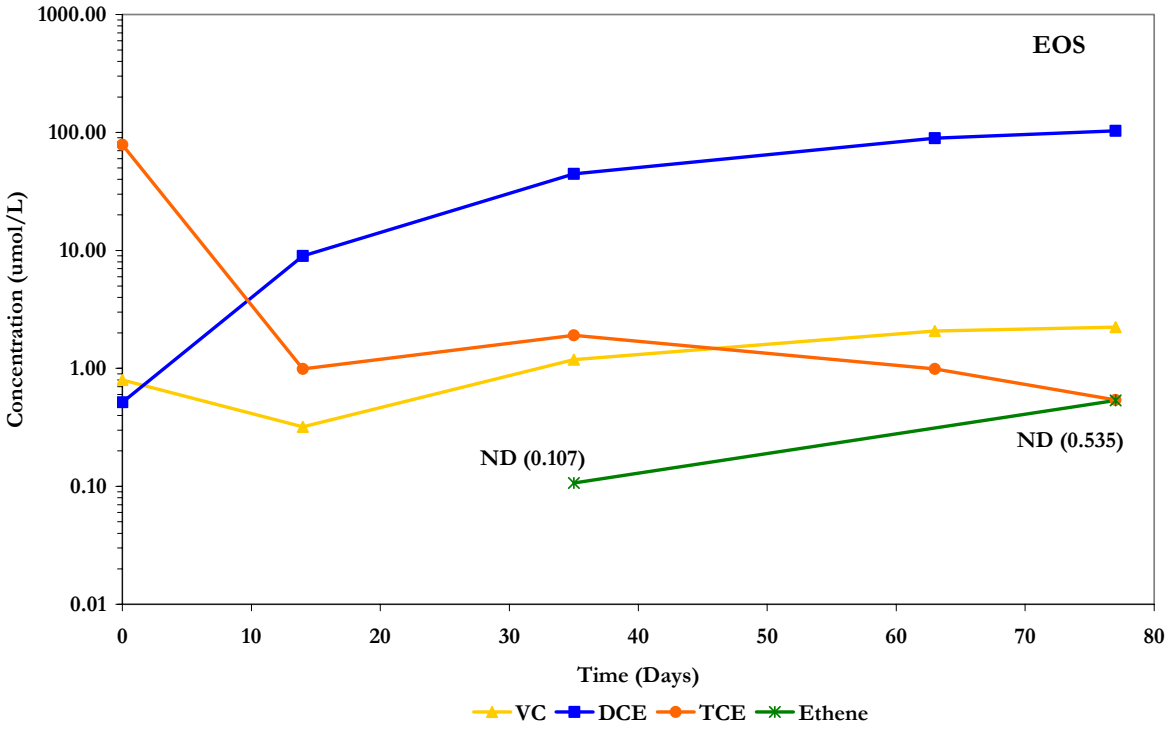


Figure E: Influence of EOS on TCE, DCE, VC, and ethene

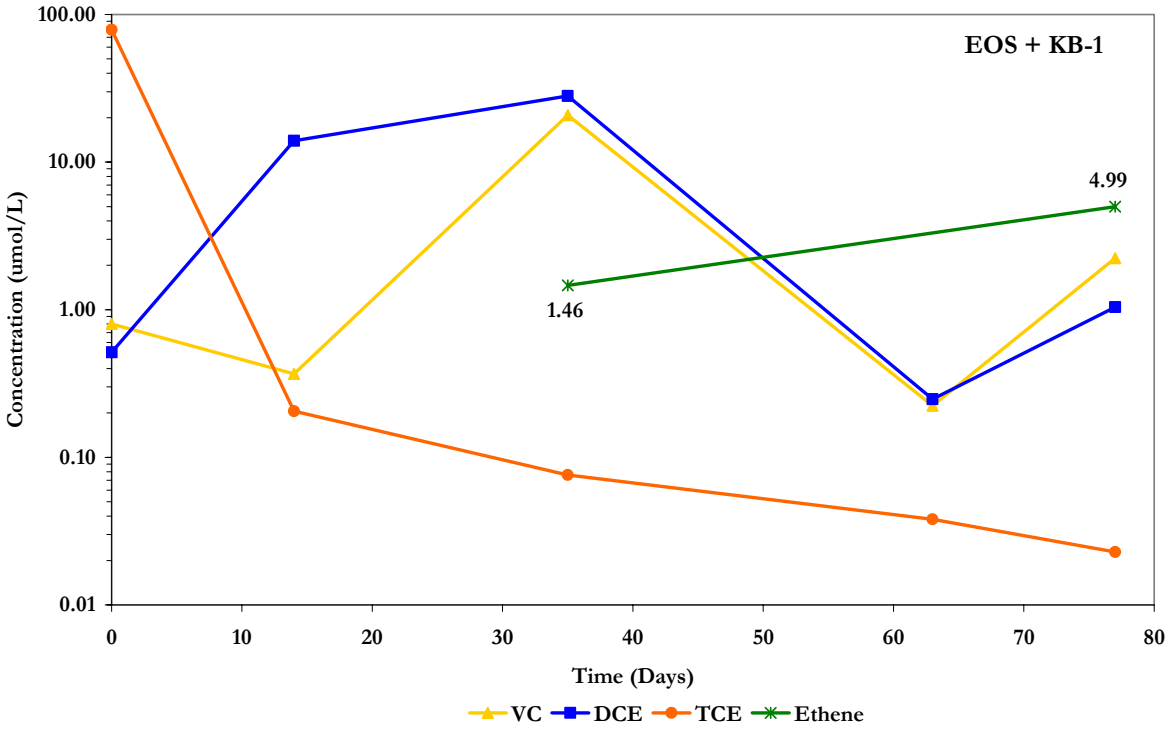


Figure F: Influence of EOS W/KB-1 on TCE, DCE, VC, and ethane

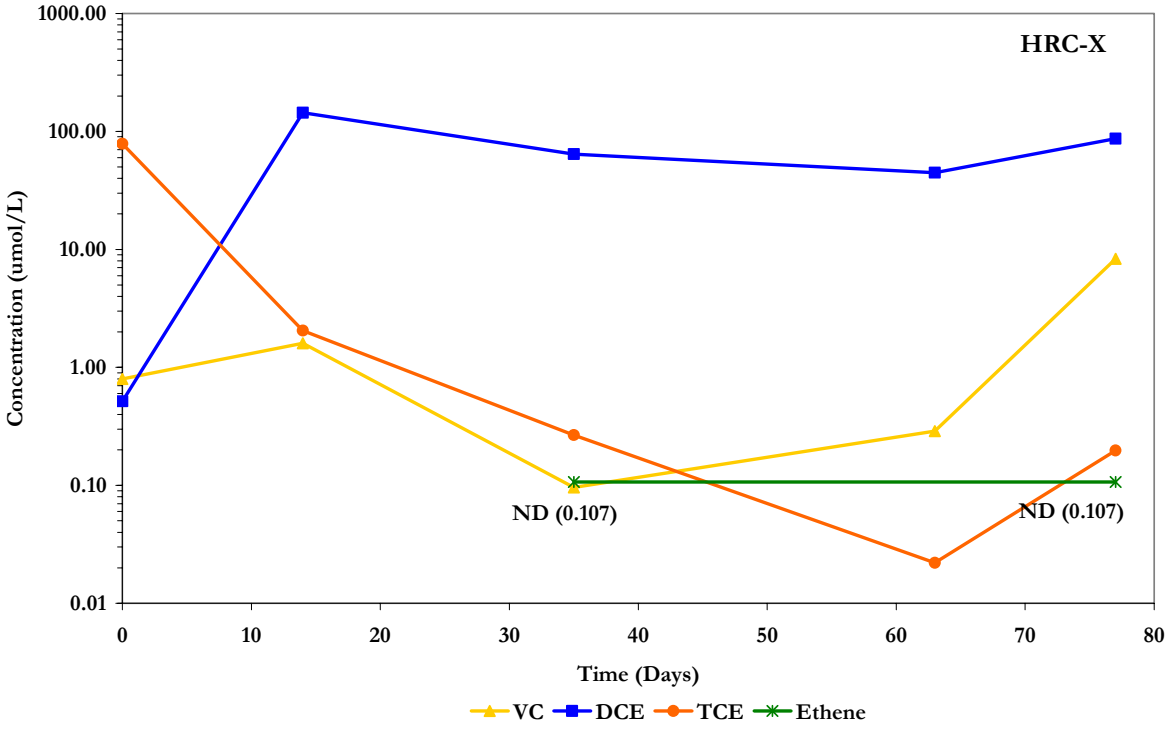


Figure G: Influence of HRC-X on TCE, DCE, VC, and ethene

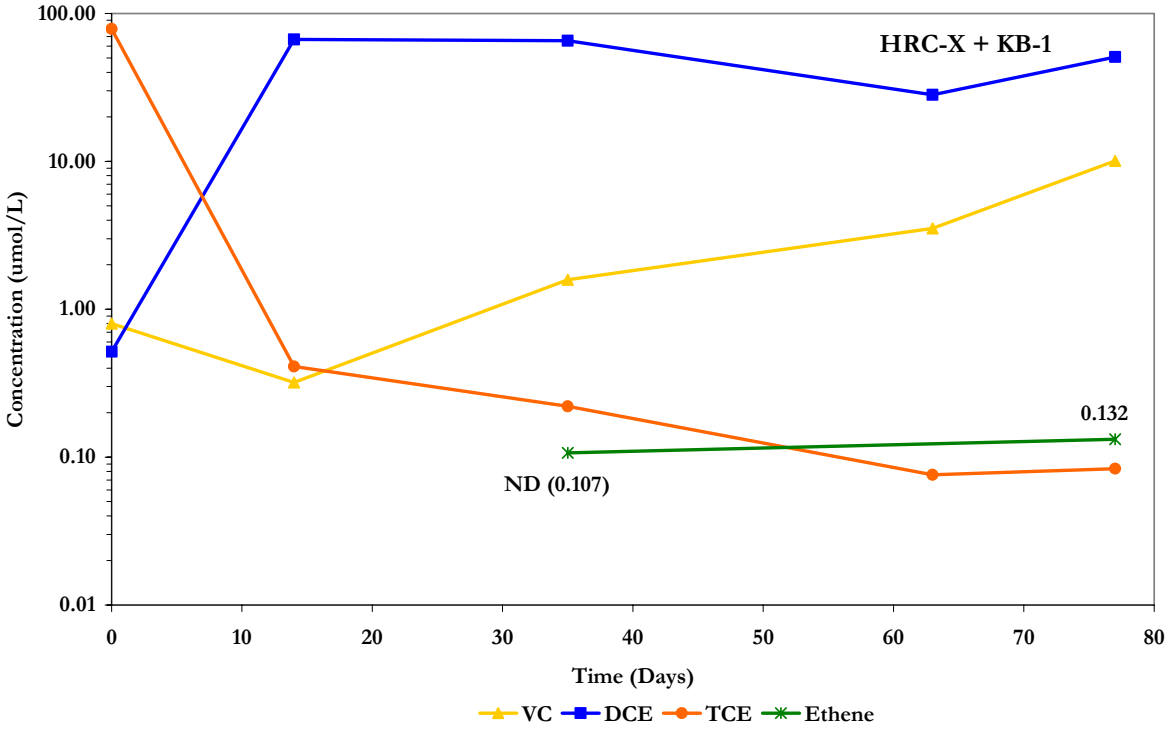


Figure H: Influence of HRC-X W/KB-1 on TCE, DCE, VC, and ethene

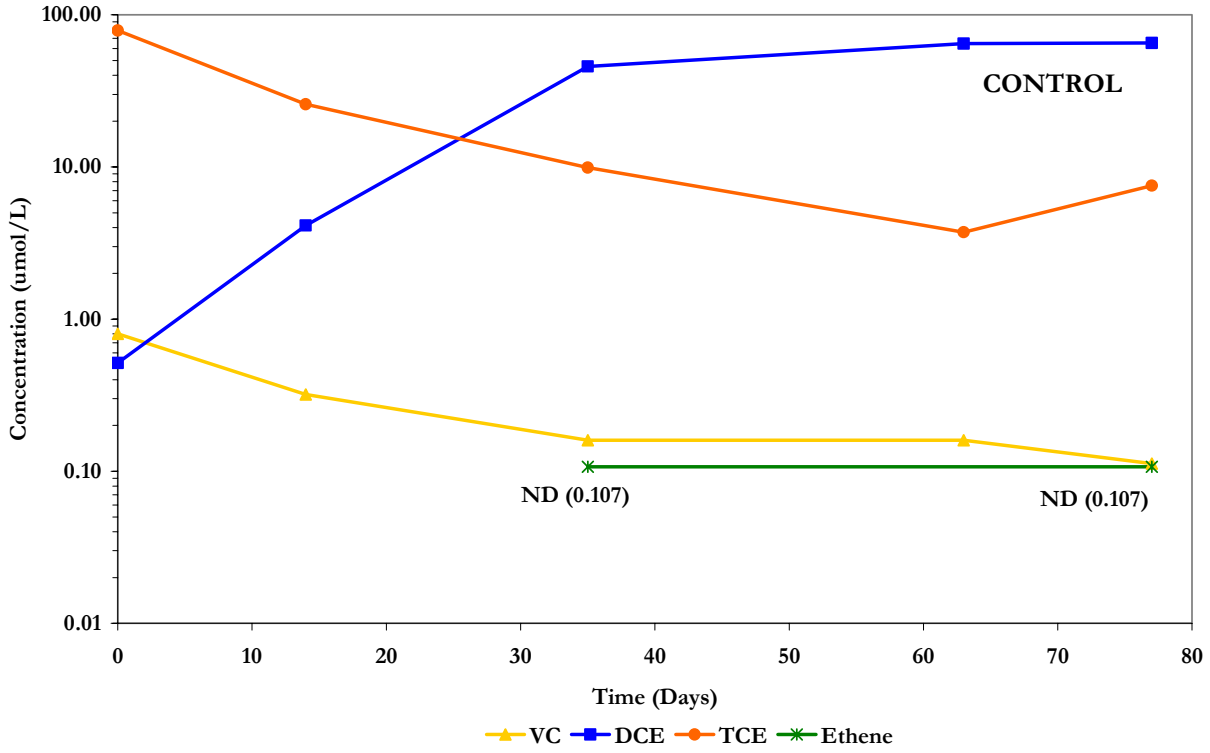


Figure I: TCE, DCE, VC, and ethene concentration in the control

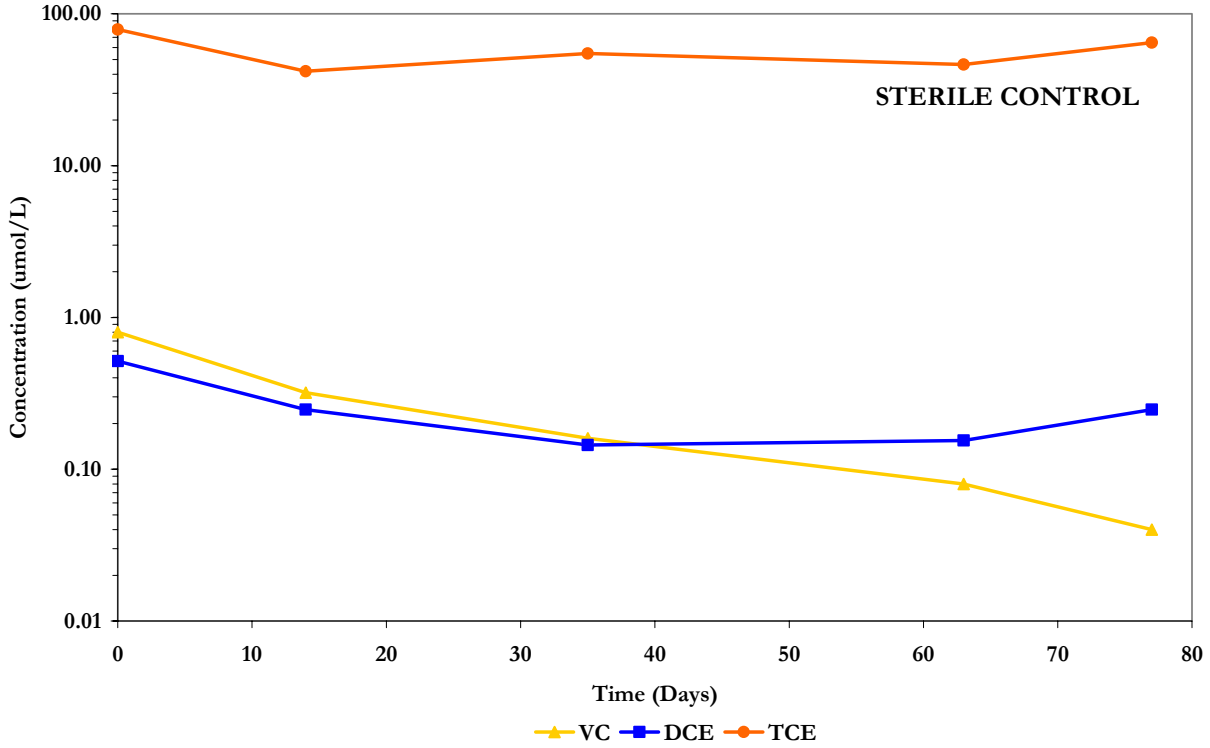


Figure J: TCE, DCE, and VC concentrations in the sterile control

APPENDICIES

FINAL REPORT: HRC-X™, EOS®, AND EHC™ TREATABILITY STUDY FOR THE TREATMENT OF TRICHLOROETHENE IN GROUNDWATER FROM THE SILTRONIC CORPORATION SITE IN PORTLAND, OREGON (THE SITE)

Appendix A: Initial Groundwater and Soil Characterization

Analyte	Groundwater (WS12-125)	Units	Composite Soil	Units
Alkalinity, total as CaCO3	330		ND (280)	
Chloride	17		8.6	
Nitrate	ND (0.1)	mg/L	1.3	---
Sulfate	13	mg/L	22	---
TOC	6.2	mg/L	600	mg/kg
pH	6.83	pH units	6.4	pH units
Total Iron	1.2		21,000	
Dissolved Iron	0.17		---	---
% solids	---	---	79.8	%
Volatile Organic Compounds				
Dichlorodifluoromethane	ND (1)	µg/L	ND (6.3)	µg/kg
Chloromethane	ND (1)	µg/L	ND (6.3)	µg/kg
Vinyl Chloride	7.1	µg/L	ND (6.3)	µg/kg
Bromomethane	ND (1)	µg/L	6.3	µg/kg
Chloroethane	ND (1)	µg/L	ND (6.3)	µg/kg
Trichlorofluoromethane	ND (1)	µg/L	ND (6.3)	µg/kg
1,1-Dichloroethene	ND (1)	µg/L	ND (6.3)	µg/kg
Carbon disulfide	3.1	µg/L	ND (6.3)	µg/kg
Acetone	ND (5)	µg/L	30	µg/kg
Methylene chloride	ND (1)	µg/L	ND (6.3)	µg/kg
trans-1,2-Dichloroethene	ND (1)	µg/L	ND (6.3)	µg/kg
Methyl-tert-butyl-ether (MTBE)	ND (1)	µg/L	ND (6.3)	µg/kg
1,1-Dichloroethane	ND (1)	µg/L	ND (6.3)	µg/kg
2,2-Dichloropropane	ND (1)	µg/L	ND (6.3)	µg/kg
Cis-1,2-Dichloroethene	2.9	µg/L	92	µg/kg
2-Butanone (MEK)	ND (5)	µg/L	ND (6.3)	µg/kg
Bromochloromethane	ND (1)	µg/L	ND (6.3)	µg/kg
Chloroform	ND (1)	µg/L	ND (6.3)	µg/kg
1,1,1-Trichloroethane	ND (1)	µg/L	ND (6.3)	µg/kg
1,1-Dichloropropene	ND (1)	µg/L	ND (6.3)	µg/kg
Carbon tetrachloride	ND (1)	µg/L	ND (6.3)	µg/kg
Benzene	4.2	µg/L	ND (6.3)	µg/kg
1,2-Dichloroethane	ND (1)	µg/L	ND (6.3)	µg/kg
Trichloroethene	ND (1)	µg/L	14	µg/kg
1,2-Dichloropropane	ND (1)	µg/L	ND (6.3)	µg/kg
Dibromomethane	ND (1)	µg/L	ND (6.3)	µg/kg
Bromodichloromethane	ND (1)	µg/L	ND (6.3)	µg/kg
Cis-1,3-Dichloropropene	ND (1)	µg/L	ND (6.3)	µg/kg

4-Methyl-2-pentanone (MIBK)	ND (5)	µg/L	ND (6.3)	µg/kg
Toluene	1.2	µg/L	ND (6.3)	µg/kg
Trans-1,3-Dichloropropene	ND (1)	µg/L	ND (6.3)	µg/kg
1,1,2-Trichloroethane	ND (1)	µg/L	ND (6.3)	µg/kg
Tetrachloroethene	ND (1)	µg/L	ND (6.3)	µg/kg
1,3-Dichloropropane	ND (1)	µg/L	ND (6.3)	µg/kg
2-Hexanone	ND (5)	µg/L	ND (6.3)	µg/kg
Dibromochloromethane	ND (1)	µg/L	ND (6.3)	µg/kg
1,2-Dibromoethane (EDB)	ND (1)	µg/L	ND (6.3)	µg/kg
Chlorobenzene	ND (1)	µg/L	ND (6.3)	µg/kg
1,1,1,2-Tetrachloroethane	ND (1)	µg/L	ND (6.3)	µg/kg
Ethylbenzene	1.1	µg/L	ND (6.3)	µg/kg
m&p-Xylenes	ND (1)	µg/L	ND (13)	µg/kg
o-Xylene	ND (1)	µg/L	ND (6.3)	µg/kg
Styrene	ND (1)	µg/L	ND (6.3)	µg/kg
Bromoform	ND (1)	µg/L	ND (6.3)	µg/kg
Isopropylbenzene	ND (1)	µg/L	ND (6.3)	µg/kg
Bromobenzene	ND (1)	µg/L	ND (6.3)	µg/kg
1,1,2,2-Tetrachloroethane	ND (1)	µg/L	ND (6.3)	µg/kg
1,2,3-Trichloropropane	ND (1)	µg/L	ND (6.3)	µg/kg
n-propylbenzene	ND (1)	µg/L	ND (6.3)	µg/kg
2-Chlorotoluene	ND (1)	µg/L	ND (6.3)	µg/kg
1,3,5-Trimethylbenzene	ND (1)	µg/L	ND (6.3)	µg/kg
4-Chlorotoluene	ND (1)	µg/L	ND (6.3)	µg/kg
tert-Butylbenzene	ND (1)	µg/L	ND (6.3)	µg/kg
1,2,4-Trimethylbenzene	ND (1)	µg/L	ND (6.3)	µg/kg
sec-Butylbenzene	ND (1)	µg/L	ND (6.3)	µg/kg
1,3-Dichlorobenzene	ND (1)	µg/L	ND (6.3)	µg/kg
p-Isopropyltoluene	ND (1)	µg/L	ND (6.3)	µg/kg
1,4-Dichlorobenzene	ND (1)	µg/L	ND (6.3)	µg/kg
n-Butylbenzene	ND (1)	µg/L	ND (6.3)	µg/kg
1,2-Dichlorobenzene	ND (1)	µg/L	ND (6.3)	µg/kg
1,2-Dibromo-3-chloropropane	ND (1)	µg/L	ND (6.3)	µg/kg
1,3,5-Trichlorobenzene	ND (1)	µg/L	---	µg/kg
1,2,4-Trichlorobenzene	ND (1)	µg/L	ND (6.3)	µg/kg
Hexachlorobutadiene	ND (1)	µg/L	ND (6.3)	µg/kg
Naphthalene	ND (1)	µg/L	19	µg/kg
1,2,3-Trichlorobenzene	ND (1)	µg/L	ND (6.3)	µg/kg

PAH	Groundwater (WS12-125)	Units	Composite Soil	Units
Naphthalene	ND (2)	µg/L	31 J	µg/kg
Acenaphthylene	ND (2)	µg/L	ND (41)	µg/kg
Acenaphthene	ND (2)	µg/L	ND (41)	µg/kg
Fluorene	ND (2)	µg/L	ND (41)	µg/kg
Phenanthrene	2	µg/L	ND (41)	µg/kg
Anthracene	ND (2)	µg/L	ND (41)	µg/kg
Fluoranthene	ND (2)	µg/L	ND (41)	µg/kg
Pyrene	ND (2)	µg/L	ND (41)	µg/kg
Benzo(a)anthracene	ND (0.4)	µg/L	ND (41)	µg/kg
Chrysene	ND (1)	µg/L	ND (41)	µg/kg
Benzo(b)fluoranthene	0.4	µg/L	ND (41)	µg/kg
Benzo(k)fluoranthene	ND (0.4)	µg/L	ND (41)	µg/kg
Benzo(a)pyrene	ND (0.4)	µg/L	ND (41)	µg/kg
Indeno(1,2,3-cd)pyrene	ND (0.4)	µg/L	ND (41)	µg/kg
Dibenzo(a,h)anthracene	ND (0.6)	µg/L	ND (41)	µg/kg
Benzo(g,h,i)perylene	ND (2)	µg/L	ND (41)	µg/kg

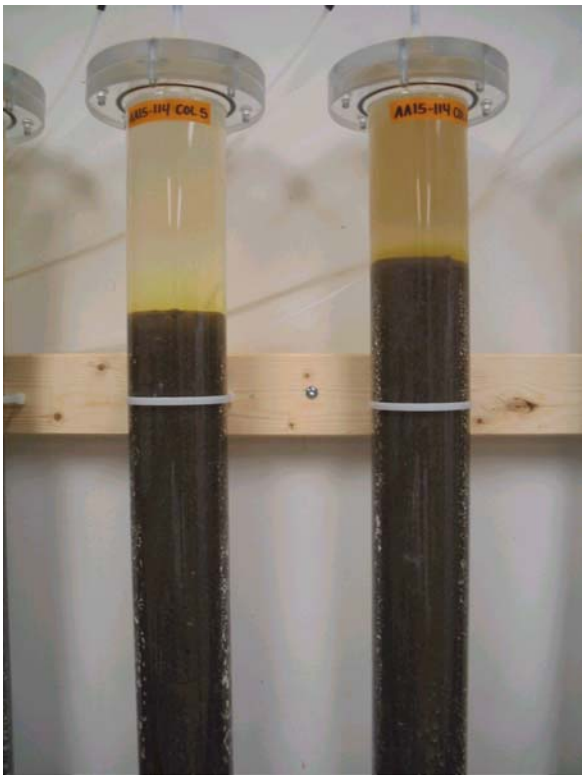
J = result is an estimated value below the reporting limit

Appendix B – List of Analytical Methods Used in the Study

Analysis	Method
VOC	8260B
PAHs	8270C
Alkalinity	310.1
Chloride	9056
TOC	415.1
Nitrate	9056
Sulfate	9056
Total Fe	6010B
Methane, Ethene, Ethane	RSK-175
VFA	SW846 VFA
pH	9040B (water) 9045C (soil)

Appendix C – Photographs of Column Set Up

Photograph A – Columns 1-4 (L to R). EHC Column #2 with the injection rod inserted through the top fitting. Also note column #3 has been injected with EOS. Some of the EOS injected into the soil has migrated to the water above the soil and appears as a white emulsion.



Photograph B – Columns 5 and 6 (L to R) one day after HRC-X was injected. Note the yellowish color above the soil.

Appendix C (cont.) – Photographs of Column Set Up

Photograph C – Laboratory Column set up – Columns 1 to 8 (L to R). Feed pumped via the peristaltic pump into the bottom of the columns.

Photograph D – Laboratory Column set up – Columns 1 to 8 (L to R). Columns set up on a closed loop.

Appendix D – Chloride Mass Balance Calculations (Sampling #1)

	VC	DCE	TCE	PCE	Total	Cl Mass Balance	Corrected Cl Mass Balance
Feed (ug/L)	0	0	11,000	0	11,000		
EHC	57	6,373	260	0	6,690		
Theor. Cl (mg/L)	0.0	-4.7	8.7	0.0	**4.0**		
Measured CL (mg/L)					**60**	**1495.5%**	**798%**
EHC + KB-1	38	6,065	250	0	6,353		
Theor. Cl (mg/L)	0.0	-4.4	8.7	0.0	**4.3**		
Measured CL (mg/L)					**83**	**1949.9%**	**1292%**
EOS	0	870	130	0	1,000		
Theor. Cl (mg/L)	0.0	-0.6	8.8	0.0	**8.2**		
Measured CL (mg/L)					**8**	**97.8%**	**-244%**
EOS + KB-1	23	1,353	27	0	1,403		
Theor. Cl (mg/L)	0.0	-1.0	8.9	0.0	**7.9**		
Measured CL (mg/L)					**22**	**278.6%**	**-76%**
HRC-X	0	14,000	270	0	14,270		
Theor. Cl (mg/L)	0.0	-10.3	8.7	0.0	**-1.5**		
Measured CL (mg/L)					**8**	**-516.2%**	**1290%**
HRC-X + KB-1	0	6,480	54	0	6,534		
Theor. Cl (mg/L)	0.0	-4.7	8.9	0.0	**4.1**		
Measured CL (mg/L)					**17**	**411.3%**	**-266%**
CONTROL	0	400	3,400	0	3,800		
Theor. Cl (mg/L)	0.0	-0.3	6.2	0.0	**5.9**		
Measured CL (mg/L)					**-2**	**-34.1%**	**-511%**
STERILE CONTROL	0	24	5,500	0	5,524		
Theor. Cl (mg/L)	0.0	0.0	4.5	0.0	**4.4**		
Measured CL (mg/L)					**28**	**630.1%**	**0%**

The corrected chloride mass balance was calculated by subtracting the measured chloride concentration in the sterile control from the measured chloride concentration in each column.

Appendix D (cont.) – Chloride Mass Balance Calculations (Sampling #3)

	VC	DCE	TCE	PCE	Total	Cl Mass Balance	Corrected Cl Mass Balance
Feed (ug/L)	0	0	9,400	0	9,400		
EHC	260	5,234	0	0	5,494		
Theor. Cl (mg/L)	-0.1	-3.8	7.6	0.0	**3.6**		
Measured CL (mg/L)					**11**	**301.9%**	**165%**
EHC + KB-1	0	9	0	0	9		
Theor. Cl (mg/L)	0.0	0.0	7.6	0.0	**7.6**		
Measured CL (mg/L)					**20**	**262.5%**	**197%**
EOS	130	8,665	130	0	8,925		
Theor. Cl (mg/L)	-0.1	-6.3	7.5	0.0	**1.1**		
Measured CL (mg/L)					**-8.6**	**-782.2%**	**-1237%**
EOS + KB-1	14	24	0	0	38		
Theor. Cl (mg/L)	0.0	0.0	7.6	0.0	**7.6**		
Measured CL (mg/L)					**29**	**381.6%**	**316%**
HRC-X	18	4,339	2.9	0	4,360		
Theor. Cl (mg/L)	0.0	-3.2	7.6	0.0	**4.4**		
Measured CL (mg/L)					**14**	**315.7%**	**203%**
HRC-X + KB-1	220	2,737	0	0	2,957		
Theor. Cl (mg/L)	-0.1	-2.0	7.6	0.0	**5.5**		
Measured CL (mg/L)					**15**	**272.9%**	**182%**
CONTROL	10	6,284	490	0	6,784		
Theor. Cl (mg/L)	0.0	-4.6	7.2	0.0	**2.6**		
Measured CL (mg/L)					**10**	**381.8%**	**191%**
STERILE CONTROL	0	15	6,100	0	6,115		
Theor. Cl (mg/L)	0.0	0.0	2.7	0.0	**2.7**		
Measured CL (mg/L)					**5**	**187.6%**	**0%**

The corrected chloride mass balance was calculated by subtracting the measured chloride concentration in the sterile control from the measured chloride concentration in each column.

Appendix D (cont.) – Chloride Mass Balance Calculations (Sampling #4)

	VC	DCE	TCE	PCE	Total	Cl Mass Balance	Corrected Cl Mass Balance
Feed (ug/L)	0	0	11,000	0	11,000		
EHC	2,800	300	0	0	3,100		
Theor. Cl (mg/L)	-1.6	-0.2	8.9	0.0	**7.1**		
Measured CL (mg/L)					**14**	**196.8%**	**155%**
EHC + KB-1	21	39	3	0	63		
Theor. Cl (mg/L)	0.0	0.0	8.9	0.0	**8.9**		
Measured CL (mg/L)					**15**	**168.9%**	**135%**
EOS	140	10,026	71	0	10,237		
Theor. Cl (mg/L)	-0.1	-7.3	8.9	0.0	**1.4**		
Measured CL (mg/L)					**10**	**693.1%**	**485%**
EOS + KB-1	140	101	3	0	244		
Theor. Cl (mg/L)	-0.1	-0.1	8.9	0.0	**8.8**		
Measured CL (mg/L)					**18**	**205.3%**	**171%**
HRC-X	520	8424	26	0	8,970		
Theor. Cl (mg/L)	-0.3	-6.2	8.9	0.0	**2.4**		
Measured CL (mg/L)					**9**	**369.4%**	**246%**
HRC-X + KB-1	630	4928	11	0	5,569		
Theor. Cl (mg/L)	-0.4	-3.6	8.9	0.0	**4.9**		
Measured CL (mg/L)					**9**	**181.9%**	**121%**
CONTROL	7	6333	990	0	7,330		
Theor. Cl (mg/L)	0.0	-4.6	8.1	0.0	**3.5**		
Measured CL (mg/L)					**6**	**172.5%**	**86%**
STERILE CONTROL	0	24	8500	0	8,524		
Theor. Cl (mg/L)	0.0	0.0	2.0	0.0	**2.0**		
Measured CL (mg/L)					**3**	**149.2%**	**0%**

The corrected chloride mass balance was calculated by subtracting the measured chloride concentration in the sterile control from the measured chloride concentration in each column.

Appendix E – Total TCE and cVOC Summaries

TOTAL TCE SUMMARY

	Concentration (umoles/L)								
Exposure Period	**Feed**	**EHC**	**EHC + KB1**	**EOS**	**EOS + KB1**	**HRC**	**HRC + KB1**	**Control**	**Sterile Con.**
1 (14 days)	83.72	1.98	1.90	0.99	0.21	2.05	0.41	25.88	41.86
2 (21 days)	76.11	0.57	0.50	1.90	ND	0.27	0.22	9.89	54.80
3 (28 days)	71.54	ND	ND	0.99	ND	0.02	ND	3.73	46.43
4 (14 days)	83.72	ND	0.02	0.54	0.02	0.20	0.08	7.53	64.69
Total TCE	**315.10**	**2.55**	**2.43**	**4.42**	**0.23**	**2.54**	**0.72**	**47.04**	**207.78**
Average TCE	78.77	1.27	0.81	1.11	0.11	0.64	0.24	11.76	51.95
Total Degraded	0	312.55	312.67	310.67	314.87	312.55	314.38	268.06	107.32
Average TCE Degraded	0	77.50	77.96	77.67	78.66	78.14	78.54	67.01	26.83
% TCE Degraded	0	**99%**	**99%**	**99%**	**100%**	**99%**	**100%**	**85%**	**34%**

TOTAL cVOC SUMMARY

	Concentration (umoles/L)								
Exposure Period	**Feed**	**EHC**	**EHC + KB1**	**EOS**	**EOS + KB1**	**HRC**	**HRC + KB1**	**Control**	**Sterile Con.**
1 (14 days)	83.72	68.63	65.07	9.96	14.53	146.47	67.25	30.00	42.11
2 (21 days)	76.11	69.02	62.73	47.68	48.82	64.74	67.18	55.64	54.94
3 (28 days)	71.54	58.15	0.09	92.45	0.47	45.07	31.75	68.71	46.58
4 (14 days)	83.72	47.90	0.76	106.20	3.30	95.41	61.00	72.97	64.94
Total cVOC	**315.10**	**243.70**	**128.66**	**256.30**	**67.12**	**351.69**	**227.19**	**227.33**	**208.57**
Average cVOC	78.77	60.92	32.16	64.07	16.78	87.92	56.80	56.83	52.14
Total Degraded	0	71.40	186.44	58.80	247.97	-36.60	87.91	87.77	106.52
Average cVOC Degraded	0	17.85	46.61	14.70	61.99	-9.15	21.98	21.94	26.63
% cVOC Degraded	0	**23%**	**59%**	**19%**	**79%**	**-12%**	**28%**	**28%**	**34%**

Appendix F – Sample TCE Half Life Calculation

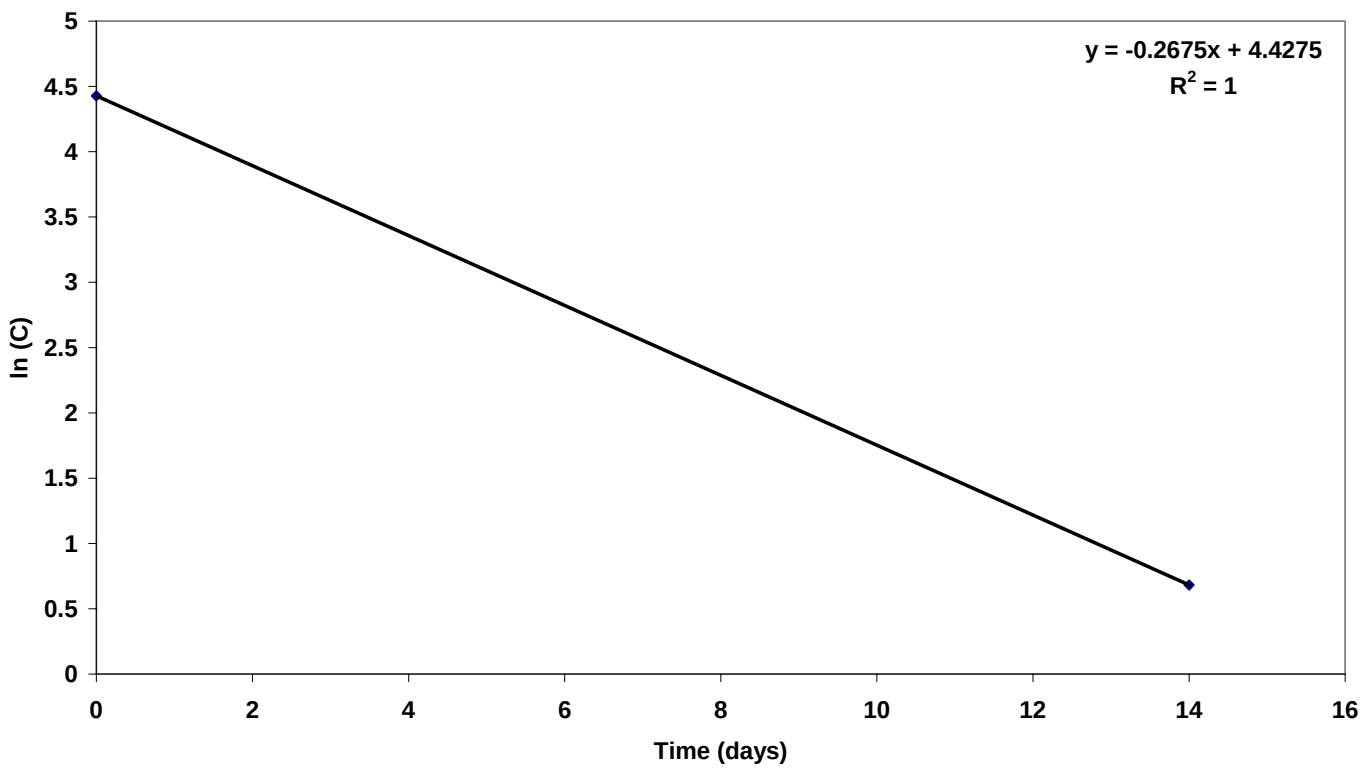
Half life equation used:

$$\ln(C/C_0)=-kt_{1/2} \qquad \text{(Equation 1)}$$

C_0 = TCE concentration in feed at t=0
C = TCE concentration at end of exposure period
At the half life of the compound $C/C_0 = 0.5$
k = -slope

Therefore Equation 1 becomes:

$$t_{1/2} = \ln(0.5)/-k$$
$$t_{1/2} = 0.693/k$$



Sample plot of log [TCE] vs. time