AN ABSTRACT OF THE THESIS OF
Delancy R. Albers for the degree of Honors Baccalaureate of Science in Chemical Engineering presented on May 31, 2013.

Title: Anaerobic Dechlorination of PCE to Ethene, Modeling, and Characterization of the Factors Affecting the Transformation Rates

Abstract approved: ___________________ & _____________________
Lewis Semprini Mohammad Azizian

Tetrachlorethene (PCE) and trichloroethene (TCE) were common solvents used in the 1970’s that are now frequently observed groundwater contaminants. One method of remediating these contaminants is in-situ bioremediation that uses a dechlorinating microbial population. The microbial population performs the sequential reductive dechlorination of PCE and TCE to cis-1,2-dichloroethene (c-DCE), vinyl chloride (VC) and finally to the non-toxic compound ethene. For the in-situ bioremediation process to be feasible, kinetic parameters for different environmental conditions must be fully characterized. A model based on Monod kinetics with competitive inhibition between the chlorinated ethenes was applied to the experimental data to calculate kinetic parameters. PCE and TCE transformation data from cultures grown in chemostat reactors in the presence of excess and limited electron donors were modeled, as well as high and low initial PCE concentrations. Results show that the maximum rate of VC transformation with cells grown under limited electron donor conditions affected the maximum rates the most. Therefore, the ability to achieve a feasible and sustainable anaerobic bioremediation strategy for PCE and TCE transformation to ethene in the contaminated groundwater is to obtain a better understanding of the electron donors and acceptors in the environment.

Key Words: In-situ bioremediation, chlorinated aliphatic hydrocarbons, dechlorination, kinetic parameters

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Anaerobic Dechlorination of PCE to Ethene, Modeling, and Characterization of the Factors Affecting the Transformation Rates

by

Delancy R. Albers

A PROJECT
submitted to
Oregon State University
University Honors College

in partial fulfillment of
the requirements for the degree of
Honors Baccalaureate of Science in Chemical Engineering

Presented May 31, 2013
Commencement June, 2013
Honors Baccalaureate of Science in Chemical Engineering project of Delancy R. Albers presented on May 31, 2013.

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______________________________________________
Delancy R. Albers, Author
Acknowledgements

I would like to thank Lew Semprini and Mohammad Azizian for guiding me through my thesis and research. I could not have done all my research without their help and support. I appreciate Dusty Berggern for trusting me to monitor her experiments while she was gone and helping me to understand the microorganisms and experiments. I would like to thank my family and friends for their support and encouraging me to continue my research. Finally, thanks to the Sub-Surface Biosphere Initiative and the Pete and Rosalie Johnson Foundation for giving me the opportunity to start my research.
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Anaerobic Dechlorination of PCE to Ethene, Modeling, and Characterization of the Factors Affecting the Transformation Rates

Introduction

Groundwater is often contaminated by chlorocarbons that can be treated by in-situ bioremediation. Chlorinated aliphatic hydrocarbons (CAHs) such as tetrachloroethene (PCE) and trichloroethene (TCE) were used as degreasing and cleaning agents before the 1980’s. Now, they are one of the most common groundwater contaminants due to poor disposal methods (Lofller & Edwards, 2006). The EPA has listed several adverse health effects from both chlorinated substances and their dechlorinated products (US EPA, 2013).

The characteristics of these substances are such that made them desirable as solvents (ex. non-flammable), but it is difficult to remediate these contaminates from groundwater. In-situ bioremediation has the ability to dechlorinated PCE and TCE contaminants in the sub-surface. The ideal bioremediation process would be increasing the population of dechlorinating microbial communities in the groundwater to reduce the CAHs to non-toxic compounds such as ethene. Several microbial cultures have been introduced in PCE or TCE contaminated sites, e.g. Dehalococcoides like microbes (Duhamel, 2006), that have the potential to transform PCE and TCE to ethene. These microorganisms need to be characterized in terms of their kinetics to aid the engineering design of remediation systems.
Three different cultures were used in this thesis that have been enriched from contaminated sites. The Evanite culture (EV) was enriched from a contaminated site in Corvallis, Oregon (Yu, Dolan, & Semprini, 2005). The Point Mugu (PM) culture was enriched from contaminated ground water from the Point Mugu Naval Weapon Station in California (Yu, Dolan, & Semprini, 2005). The VS culture was enriched from the Victoria site in Texas (Cupples, Spormann, & McCarty, 2004). All the cultures have the potential of transforming PCE and TCE to ethene.

The cultures described above and used in this thesis were harvested from chemostats, which are operating under different electron donor and acceptor conditions. Formate and lactate were the electron donors and PCE and TCE were electron acceptors. The dechlorination products were cis-dichloroethene (c-DCE), vinyl chloride (VC) and ethene. The schematics of the PCE and TCE dechlorination to ethene are shown in Figure 1; the process involves removing a chlorine atom each step and replacing it with a hydrogen molecule until the final product, non-toxic ethene, is achieved. When the microorganisms use the chlorinated ethene as an electron acceptor for energy, the process is known as halo respiration (Loffler & Edwards, 2006).

Figure 1. The dechlorination of PCE to TCE, cis-DCE, VC and ethene.
One drawback of the in-situ bioremediation is the possibility of the accumulation of potentially carcinogenic compounds such as cis-DCE and VC (US EPA, 2013). Usually, PCE transforms to TCE and cis-DCE at higher rates, while the transformation of cis-DCE to VC to ethene are slow (Cupples, Spormann, & McCarty, 2004). The factors that contribute to the slow transformation rates must be studied for the remediation approach to be feasible. The dechlorination kinetics of the microorganisms with respect to their growth in the presence of excess or limited electron donors could provide insight into a key factor affecting the remediation process.

The objectives of this thesis were; (a) conduct PCE and TCE transformation rate studies with three different dehalogenating cultures grown in chemostats, (b) determine the kinetic parameters by fitting a kinetic model to the results of the batch tests, and (c) compare the findings with the previous work done on characterizing the kinetic ability of the cultures. The PCE and TCE transformation rate studies were conducted using batch reactor bottles with cultures harvested from each chemostat. The CAHs concentrations were determined analytically using a GC and the data were fit using a Monod kinetics model with Excel solver.
Methodology

Chemostat Operations.

Three different anaerobic mixed microbial cultures, which are capable of dechlorinating CAHs to ethene, were continuously grown under different chemostat conditions in the environmental engineering laboratory at Oregon State University (Azizian, Personal Communication). The schematic of the chemostat process is shown in Figure 2 (Berggren, 2013). Each culture was grown in either a five- or two-liter chemostat. The five-liter Point Mugu (PM-5L) chemostat operated with the influent media saturated with 1 mM PCE, as an electron acceptor, and 4 mM lactate, as a fermenting electron donor, while the two-liter PM chemostat (PM-2L) operated with media saturated with 1 mM PCE and 4 mM lactate plus sulfate fed as a competing electron acceptor to PCE (Berggren, 2013). The Evanite (EV) and Victoria (VS) five-liter chemostats (EV-5L and VS-5L) have an influent media of solution saturated with 10 mM TCE and formate (45 mM), as an electron donor, in excess of the amount needed to dechlorinate all the TCE to ethene. The EV and VS two-liter chemostats have an influent of the same TCE concentration (10 mM), but with a limited amount of formate (25 mM). The chemostats are maintained at room temperature between 20-23 °C. All the chemostats were stirred continuously with a 2 inch Teflon stir bar for complete mixing as shown in Figure 2. The chemostat reactors were fed at a rate to achieve a hydraulic and mean cell residence time of approximately 50 days.
Figure 2. The chemostat system used to grow anaerobic microorganisms. The continuous feed supports a steady population and the effluent can be examined to determine how the population is responding.

**PCE-to-Ethene Batch Rate Tests.**

The kinetic tests were conducted in batch reactors with cells harvested from the chemostats. One hundred and fifty six mL Borosilicate glass batch reactor bottles with screw on phenolic lids and a rubber septa were placed into an anaerobic glovebox (90% N₂, 10% H₂) overnight and then bottles were sealed and removed from the glovebox. Fifty milliliters of culture were harvested from each chemostat and placed into the 156 mL batch reactors that were constructed in triplicates. The harvesting was done by adding pressure to the chemostat with an inert gas line and injecting the culture into the bottles without exposing the culture to oxygen. The liquid in each bottle was purged for 10 minutes with an N₂/CO₂ gas mixture (75:25) to remove any residual chlorinated compounds and hydrogen. To each bottle, two milliliters of hydrogen, to be used as an electron donor, were added and the designated amount of neat PCE (99.9% spectrophotometric grade). Separate experiments were executed with PCE in high
amounts of (1.6 μL) and low amounts (0.5 μL). The batch reactor bottles were labeled and placed upside down on the shaker table that was operated at 200 rpm and 20 °C room for the entire experiment for complete mixing and to maintain gas/liquid equilibrium.

Chlorinated ethenes and ETH were quantified by gas chromatography with a HP-6890 gas chromatogram (GC), using a flame ionization detector (FID) and 30m long 0.53mm I.D. GS-Q column (J&W Scientific, Folsom, CA). Aqueous samples from the column were analyzed using the headspace method as described by Azizian et al., (2008). One hundred microliters of gas samples were collected with a Hamilton 100 mL gastight syringe (Leno, NV), and analyzed on the GC with a 15mL/min flow of helium carrier gas. The GC oven was programmed with an initial temperature of 150 °C, held for 2 min, increased to 220 °C at 45 °C/min, and held for 0.7 min at 220 °C. Hydrogen gas (H₂) was quantified on a HP 5890 GC with a thermal conductivity detector (TCD) and 15 ft and 1/8 in. I.D. Carbonex 1000 column (Supelco, Bellefonte, PA). Analyses were conducted at a 220 °C isotherm with an Argon carrier gas at 15mL/min. The detection limit for H₂ was 23nM (aqueous concentration). Aqueous, gas, and total CAH, ETH, and H₂ concentrations were determined from their respective Henry’s coefficients and the relationship $H_{CC} = C_G/C_L$ and mass balance $M = C_G V_G + C_L V_L$ (Azizian, Behrens, Sabalowsky, Dolan, & Semprini, 2008).

The experiment lasted until, ideally, all the PCE had transformed into ethene. The biomass added to the reactors was determined at the end of the experiment by filtering
the contents of the batch reactor onto a 0.45 μm filter, drying at 105 °C and measuring the sample weight.

**Modeling of Batch Data and Determination of Kinetic Parameters.**

The data from the gas chromatograph was converted into concentrations and molar amounts for each CAH in gas and liquid using Henry’s constant. Monod kinetics with competitive inhibition equation were applied to the experimental data to estimate a maximum reaction rate (k_mX) for each CAH transformation (Equation [2]).

\[
\frac{dM_z}{dt} = \frac{k_m,z \times X \times C_z \times V}{K_{s,z} \times \left(1 + \frac{C_y}{K_{I,y}}\right) + C_z} \tag{2}
\]

This was applied to each transformation step as shown in Equations [3], [4], [5], and [6] (Berggren, 2011). Berggren developed the functions to determine the maximum rates of transformation of each step of the dehalogenation reaction. The models were programmed into Excel so that Solver could be used to determine simultaneously the best fit maximum transformation rate of each step. The model equations used indicate the nature of each transformation step to inhibit the next, for example the presence of PCE can inhibit the rate of transformation of TCE as shown in Equation [4] (Yu, Dolan, & Semprini, 2005). In the model, the K_s value of the inhibited compound was used as the inhibition coefficient (K_I) as presented by Yu et al. (2005) and listed below the equations in Table 1. As Yu et al. (2005) and Cupples et al. (2004) determine, the K_I and K_S were
not statistically different and could be considered the same. Thus, these coefficients were held constant while $k_m X$ was changed.

\[
\frac{dC_{PCE}}{dt} = -\frac{k_{max,PCE} \cdot X \cdot C_{PCE}}{K_s, PCE + C_{PCE}} \quad [3]
\]

\[
\frac{dC_{TCE}}{dt} = \frac{-k_{max,TCE} \cdot X \cdot C_{TCE}}{K_s, TCE \cdot (1 + \frac{C_{PCE}}{K_i, PCE}) + C_{TCE}} + \frac{k_{max,PCE} \cdot X \cdot C_{PCE}}{K_s, PCE + C_{PCE}} \quad [4]
\]

\[
\frac{dC_{c-DCE}}{dt} = \frac{-k_{max,c-DCE} \cdot X \cdot C_{c-DCE}}{K_s, c-DCE \cdot (1 + \frac{C_{TCE}}{K_i, TCE}) + C_{c-DCE}} + \frac{k_{max,TCE} \cdot X \cdot C_{TCE}}{K_s, TCE \cdot (1 + \frac{C_{PCE}}{K_i, PCE}) + C_{TCE}} \quad [5]
\]

\[
\frac{dC_{VC}}{dt} = \frac{-k_{max,VC} \cdot X \cdot C_{VC}}{K_s, VC \cdot (1 + \frac{C_{TCE}}{K_i, TCE} + \frac{C_{c-DCE}}{K_i,c-DCE}) + C_{VC}} + \frac{k_{max,c-DCE} \cdot X \cdot C_{c-DCE}}{K_s, c-DCE \cdot (1 + \frac{C_{TCE}}{K_i, TCE}) + C_{c-DCE}} \quad [6]
\]

Table 1. The $K_s$ and $K_i$ values used in the equations. The $K_s$ and $K_i$ values were considered the same value as Yu et. al. (2005) discusses there is not a statistical difference in the values when determined experimentally.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$K_s$ and $K_i$ [umol/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCE</td>
<td>3.9</td>
</tr>
<tr>
<td>TCE</td>
<td>2.8</td>
</tr>
<tr>
<td>c-DCE</td>
<td>1.3</td>
</tr>
<tr>
<td>VC</td>
<td>8.5</td>
</tr>
</tbody>
</table>
Results

Chemostats

Trends of the effluent composition of two and five liters EV, VS, and PM chemostats are shown in Figures 3, 4, and 5, respectively, during the periods when batch cultures were taken from the chemostats for the kinetic tests. The CAHs and ethene concentrations in the effluents are constant throughout the time period and indicating that the reactors were operating under steady state conditions. The 5L EV, VS, and PM chemostats with excess electron donors transformed nearly all the influent PCE or TCE to ethene, while the 2L chemostats with limited amount of electron donors and a competing electron acceptor (sulfate) did not transform all the initial CAH to ethene. The acetate and hydrogen concentrations are also steady throughout the days shown. The fermentation of lactate produces acetate and hydrogen for the dechlorination process. Formate produces hydrogen, and hydrogen through the process of homoacetogenesis produces acetate. The acetate levels are higher in the 5L effluents than in the 2L effluents for all the cultures as expected due to higher concentrations of influent formate and lactate for the 5L chemostats.
CAHs and Ethene Concentration in Effluent

Acids and Other Compound Concentrations

Figure 3. The EV culture chemostat effluent compositions during the time of batch experiments. The CAHs and ethene in the effluent show the chemostats were operating at steady state. The 5L transforming all the influent TCE into ethene and the 2L chemostat had VC buildup.

Figure 4. The VS culture chemostat effluent during the batch reactor experimental period. The CAHs and ethene in the effluent show the chemostats were operating at steady state. The 5L transforming essentially the influent TCE into ethene and the 2L chemostat did not transform all the TCE into ethene, but had a large residual amount of VC.
**Batch Results**

The results of the PCE-to-ethene batch kinetic tests for EV, VS, and PM cultures and the corresponding model fits are shown in Figures 6, 7, and 8, respectively. The CAH mass profile of the triplicate experiments are captured well by the model simulation. The models assume constant total moles of CAHs, but in the experiment, the total mass balance did not remain the same due to possible absorption to the bottle cap (ex. High Concentration VS-5L). This can partially explain some of the error in the models. Both the EV and VS 5L cultures were able to transform the initial PCE into ethene completely in less than a day. The high concentration of starting PCE can be seen to take longer to fully transform the CAHs into ethene. The EV and VS 2L cultures had a buildup of VC. The PM culture showed similar trends but with a buildup of VC in all cultures and much
slower transformations. In all the 2L models, the VC does not start transforming into ethene until nearly all the PCE has been dechlorinated.

Figure 6. The model for EV-5L and -2L for high and low concentrations of starting PCE. The model follows the experimental values well.
Figure 7. The model for the VS culture for high and low PCE concentrations. The model is comparable to the experimental values.

Figure 8. The model for the PM-5L and -2L for high and low starting PCE concentrations. The model is comparable to the experimental values obtained.
Taking a closer look at the models a clear trend is that ethene does not start to be formed until all the PCE is removed from the system. This was expected as the model predicts the inhibition affect of the CAHs on the transformation of VC into ethene. The VC model shapes tend to all peak and then decrease for the 5L cultures. The 2L chemostats have VC concentrations that stay elevated and do not decrease like the 5L. The experimental duration over several days may have caused some important concentration shifts not to be caught and peaks to be missed. The PM culture was expected in have a c-DCE peak similar to the VC peaks, but due to the duration of the experiment it is possible that the peak was missed. The VS and EV -5L chemostats grown on excess TCE may have all the microorganisms or enzymes present that dechlorinate the TCE, c-DCE and VC contributing to the faster reactions. The EV and VS -2L chemostats had the buildup of VC in the effluent and may not have the enzymes/microorganisms present to dechlorinated the VC. This is evident in the -2L batch tests and model simulations when the VC is not transformed into ethene.

The average $k_mX$ values estimated from the model analysis of the kinetic tests are presented in Figures 9a, 9b, and 9c for cells harvested from the EV, VS and PM chemostats respectively. It is quite evident that the $k_mX$ of TCE is the highest and VC is the lowest for all cultures. This final step of transforming VC is the terminal electron acceptor and was most affected by the limited electron donor environments and competitive inhibition. Due to time limitations not all the batch reactors were able to be measured through VC transforming to ethene. This may have affected some of the model
k_mX values. As the models show, the cell harvested from the 2L EV, VS and PM (with limited formate or electron acceptor competitor sulfate) did not transform the VC into ethene as quickly as those from the 5L (excess formate or lactate). The VS and EV chemostats grown cells had similar rate magnitudes, but with VS-2L having much higher TCE rates. The VS and EV chemostats are in similar environments with the limited and excess donors.

Excluding PCE, each dechlorination step had a slower rate than the previous indicating each transformation step is slower as the ethene becomes less chlorianted. The decreasing sequential rates validate the buildup of some of the intermediates in the model. The EV

Figure 9. The different k_mX values that were determined from the models. Figure 9a is for the EV results, 9b for the VS results and 9c for the PM results. Note the different scale for EV and VS compared to PM.
culture with the higher starting concentration reported lower kmX values with the exception of c-DCE. The VS culture followed the same trend except with the 5L TCE kmX value being higher in the high concentration case. The PM culture models achieved all around lower kmX values than both other cultures as expected due to the lower influent feed concentration of 1 mM PCE compared to 10 mM TCE. They also followed the similar trend of the higher starting PCE concentration having smaller kmX values than the lower starting PCE concentration values, with the exception of c-DCE.

Discussion

The kmX values for several of the CAH transformations data were calculated and compared to published values. The values were extrapolated from published research and normalized to the protein amounts measured in the experiments. The EV culture had comparable kmX values for the CAHs when compared to Yu et. al. results, as shown in Table 2. The VC transformation rates seemed to be more affected in the limited electron donor chemostats (2L) compared to the batch experiment values reported by Yu et. al. (2005). The high PCE concentration in general had lower kmX values than lower concentration, likely due to the inhibition of each CAH on the following steps. The total transformation did not fully proceed to ethene and may have been affected by the VC rates and consequently the model may have predicted lower values.
Table 2. The EV culture kmX values determined using the model equations and Excel Solver to minimize the SEE.

<table>
<thead>
<tr>
<th>CAH</th>
<th>Experimental Values 5 L</th>
<th>Experimental Values 2 L</th>
<th>Yu's Published Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Conc. kmX</td>
<td>High Conc. kmX</td>
<td>Low Conc. kmX</td>
</tr>
<tr>
<td>PCE</td>
<td>647</td>
<td>499</td>
<td>116</td>
</tr>
<tr>
<td>TCE</td>
<td>5008</td>
<td>3426</td>
<td>3250</td>
</tr>
<tr>
<td>c-DCE</td>
<td>1424</td>
<td>1089</td>
<td>238</td>
</tr>
<tr>
<td>VC</td>
<td>365</td>
<td>388</td>
<td>3</td>
</tr>
</tbody>
</table>

The VS culture only had c-DCE and VC kmX values to compare with published data and similar kmX values for c-DCE were obtained values for both the 5-L and the 2-L as shown in Table 3. As the EV-2L, the VC-2L (limited electron donor) seemed to affect the kmX values for VC the most compared to values reported by Cupples et. al. (2004) published values. The values follow a similar rate patterns. A possible difference between experiments could be the difference in cultures grown in batch and in Cupples et. al. (2004) study.

Table 3. The VS culture kmX values determined using the model equations and Excel solver to minimize the SEE.

<table>
<thead>
<tr>
<th>CAH</th>
<th>Experimental Values 5 L</th>
<th>Experimental Values 2 L</th>
<th>Cupples's Published Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Conc. kmX</td>
<td>High Conc. kmX</td>
<td>Low Conc. kmX</td>
</tr>
<tr>
<td>PCE</td>
<td>919</td>
<td>689</td>
<td>850</td>
</tr>
<tr>
<td>TCE</td>
<td>2558</td>
<td>4780</td>
<td>5043</td>
</tr>
<tr>
<td>c-DCE</td>
<td>2487</td>
<td>1118</td>
<td>949</td>
</tr>
<tr>
<td>VC</td>
<td>628</td>
<td>648</td>
<td>18</td>
</tr>
</tbody>
</table>

The PM culture had some disparity from the published values of Berggren et. al. (2013) and Yu et. al. (2013) with the 2L and 5L values shown in Table 4 and Table 5. The kmX
values for the PM culture were much smaller than the rates of the EV and VS culture as expected since PCE was being fed to the PM chemostats at 1 mM compared to 10 mM TCE in the EV and VS chemostats. Also, the 2L culture was also being fed sulfate as a competing electron acceptor. The 2L values were comparable to Berggren’s et. al. (2013) published values and followed a similar rate pattern. The c-DCE and VC values were nearly the same, while the TCE and PCE values were lower (Table 4). The PM-5L values obtained were lower than the published values, but followed Berggren’s et. al. (2013) trends of TCE being the highest, and a decline in rates through VC. Berggren’s et. al. (2013) performed their experiments on the PM cultures before these experiments were performed and the culture may have changed.

Table 4. The PM 2L k_mX values for the high concentration and low concentration compared to Dusty Berggren's published values

<table>
<thead>
<tr>
<th>CAH</th>
<th>Experimental Values</th>
<th>Berggren’s Published Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Conc. kmX</td>
<td>High Conc. kmX</td>
</tr>
<tr>
<td>PCE</td>
<td>37</td>
<td>39</td>
</tr>
<tr>
<td>TCE</td>
<td>160</td>
<td>72</td>
</tr>
<tr>
<td>c-DCE</td>
<td>75</td>
<td>61</td>
</tr>
<tr>
<td>VC</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5. The PM 5L k_mX values for the high and low concentration compared to both Berggren's and Yu's published values.

<table>
<thead>
<tr>
<th>CAH</th>
<th>Experimental Values</th>
<th>Berggren’s Published Values</th>
<th>Yu’s Published Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Conc. kmX</td>
<td>High Conc. kmX</td>
<td>Low Conc. kmX</td>
</tr>
<tr>
<td>PCE</td>
<td>43</td>
<td>37</td>
<td>347</td>
</tr>
<tr>
<td>TCE</td>
<td>316</td>
<td>201</td>
<td>693</td>
</tr>
<tr>
<td>c-DCE</td>
<td>83</td>
<td>83</td>
<td>227</td>
</tr>
<tr>
<td>VC</td>
<td>22</td>
<td>19</td>
<td>194</td>
</tr>
</tbody>
</table>
Conclusions and Future Work

The models and kinetic parameters determined in this study can help to evaluate rate and CAH mass profiles of potential bioremediation microbial populations. The effects of the limited electron donors and high and low concentrations of PCE can help to understand boundary conditions of in-situ bioremediation. The model simulations can help assess the extent and potential use for in-situ bioremediation. The thesis determines the following conclusions:

- The rates determined were expected due to the chemostat performance. The VC rates were the slowest in the chemostats fed limited substrate. This is possibly due to the microorganisms required for this dechlorination step were not being grown effectively.

- Rates were lower in the PCE fed chemostat compared to TCE fed chemostat, which was expected due to the lower concentration of PCE in the influent limiting the growth of the microorganisms needed for the dechlorination steps.

- Rates compared fairly well to published data. EV and VS rates were comparable and PM rates varied, but may indicate a change in the culture.

- A buildup of intermediates occurs due to the sequentially lower transformation rates from TCE to ethene, especially in the chemostats fed limited substrate.

- The Monod inhibition models seem to accurately predict the experimental values and support the conclusion the more chlorinated ethenes inhibit less chlorinated ethenes. The models accurately predicting that ethene would not be formed until all the PCE is dechlorinated also contributes to the inhibition theory.
Further research should be performed on the reductive dechlorination by either different microorganisms or different enzymes in the culture. Determining the enzyme or microorganisms that specifically dechlorinates each CAH would benefit in the analysis of rates and affects of environments. Yu et. al. concludes that PCE does not inhibit c-DCE transformation and that supports the theory of different microorganisms responsible for each transformation. The PM culture findings support Berggerns conclusions on sulfate affects on the rates of dechlorination.

A limitation of the study shown is that the concentration of the dechlorinating microorganisms was not determined from the entire mix culture. This may explain some of the differences in previously published values and the experimental values obtained. Future research involving the microorganisms would benefit from determining the concentration of just the dechlorinating microorganisms in the culture using molecular methods. Rate coefficients provided here could be used to model the chemostat results and help to determine the difference between the batch results and the chemostats. The method of applying the model to the triplicates all at once should be compared to applying the model to each trial separately and comparing to the triplicate method. Model variations concerning the use of the each chlorinated ethene inhibition coefficient in the equations (especially the PCE affect on c-DCE as described above) should be investigated to tune the equations for more accurate models.
Bibliography


