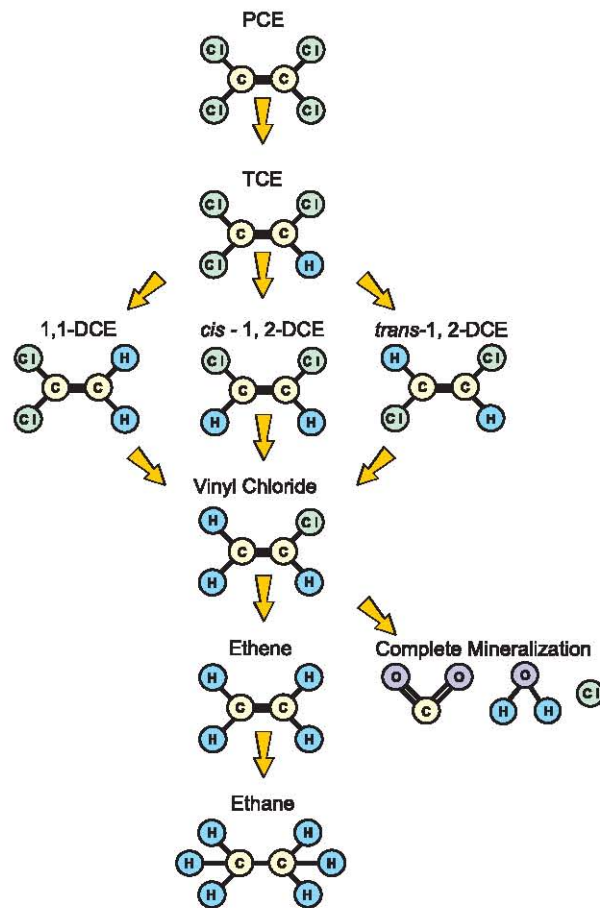


# Natural Attenuation of Chlorinated Solvents Performance and Cost Results From Multiple Air Force Demonstration Sites

## Technology Demonstration Technical Summary Report



October 1999



**Air Force Center  
for Environmental Excellence**

**NATURAL ATTENUATION OF CHLORINATED SOLVENTS  
PERFORMANCE AND COST RESULTS FROM MULTIPLE AIR FORCE  
DEMONSTRATION SITES**

**TECHNOLOGY DEMONSTRATION TECHNICAL SUMMARY REPORT**

**October 1999**

**Prepared For**

**Air Force Center for Environmental Excellence  
Technology Transfer Division  
Brooks Air Force Base, Texas 78235**

**Prepared By**

**Parsons Engineering Science, Inc.  
1700 Broadway, Suite 900  
Denver, Colorado 80290**

## EXECUTIVE SUMMARY

This technical memorandum summarizes the results of natural attenuation treatability studies (TSs) conducted at 14 United States (US) Air Force sites in the Continental US. In June 1993, the Air Force Center for Environmental Excellence, Technology Transfer Division (AFCEE/ERT), in cooperation with the US Environmental Protection Agency National Risk Management Research Laboratory, Subsurface Protection and Remediation Division, and Parsons Engineering Science, Inc. (Parsons ES), began a major initiative to evaluate the effectiveness of monitored natural attenuation (MNA) for remediation of groundwater contaminated with organic compounds. This study is nearing completion, and the results for sites contaminated with fuel hydrocarbons are summarized in *Natural Attenuation of Fuel Hydrocarbons – Performance and Cost Results from Multiple Air Force Demonstration Sites* (Parsons ES, 1999). The results of natural attenuation evaluations at sites contaminated with chlorinated solvents and their associated biodegradation daughter products (referred to as chlorinated aliphatic hydrocarbons [CAHs] in this document) or a mixture of CAHs and other contaminants (principally fuel hydrocarbons) are presented in this document.

The main emphasis of the work described herein was to evaluate the potential for naturally occurring degradation mechanisms to reduce the concentrations of CAHs dissolved in groundwater to levels that are protective of human health and the environment, and to limit the migration of CAH plumes in groundwater. The TSs were not intended to be contamination assessment reports or remedial action plans; rather, they were designed to provide a scientific evaluation of natural attenuation that could be used by individual Air Force bases and their prime environmental contractor(s) for future remedial decision making. Specific objectives included:

- Developing site characterization techniques to more accurately document *in situ* geochemistry and to maximize the quantity and quality of collected field data while reducing overall expenditures of money and time;
- Providing a consistent framework for documenting historical contaminant reductions and geochemical patterns consistent with biodegradation, and determining rates of contaminant degradation;
- Identifying those biological processes most responsible for contaminant attenuation in varied subsurface environments;
- Using analytical or numerical groundwater flow and solute fate and transport models to predict the effects of natural attenuation, both alone and in combination with engineered remedial technologies, on the future migration and persistence of dissolved CAHs;
- Evaluating strategies for using MNA as the sole remedial approach or in combination with other remedial techniques; and
- Developing long-term monitoring (LTM) strategies to verify the progress of natural attenuation over time until appropriate action levels are attained.

The following observations can be made based on the results of the TSs performed under this program:

- CAHs dissolved in groundwater are undergoing natural attenuation under all of the broad range of environmental conditions represented at the 14 Air Force test sites evaluated. Although intrinsic bioremediation (aerobic degradation and/or anaerobic reductive dechlorination) was found to be occurring to some degree at all of the sites studied under this program, the biodegradation of CAHs should not be considered universal. Sites were selected for study under this program only if it was suspected that biodegradation of CAHs was occurring at least in a limited fashion. Sites with no evidence of reductive dechlorination were excluded. This was done to facilitate an understanding of the biological mechanisms of natural CAH attenuation.
- The degree and rate of intrinsic bioremediation of CAHs is highly site specific, and is dependent upon the prevailing bio- and geochemistries of groundwater at a site (i.e., Type 1, Type 2, Type 3, or mixed environments described by USEPA [1998]).
- Eleven of the 14 sites studied exhibited some type of mixed behavior, with nine of the sites exhibiting Type 1 behavior coupled with either Type 2 behavior or Type 3 behavior. Two sites exhibited Type 2 behavior coupled with Type 3 behavior. The remaining three sites exhibited primarily Type 1 behavior. At least a portion of all of the sites were characterized by anaerobic conditions, and all except for F.E. Warren AFB LF-03 were either actively sulfate-reducing or methanogenic in at least a portion of the plume area. In all cases where petroleum hydrocarbons were commingled with CAHs the sites were actively methanogenic, and reductive dechlorination was occurring.
- Eight of the 14 sites had completed receptor exposure pathways.
- Three of the 14 sites appeared to have expanding plumes, six of the sites appeared to have plumes that are either stable or expanding slowly, and the remaining five plumes appeared to be either stable or receding.
- Field-scale biodegradation rate constants for two sites calculated using a conservative tracer (USEPA, 1998) were  $3.0 \times 10^{-4} \text{ day}^{-1}$  and  $7.4 \times 10^{-4} \text{ day}^{-1}$  (half-lives of 6.3 and 2.6 years, respectively).
- Field-scale biodegradation rate constants for the 11 sites with potentially stable plumes, calculated for trichloroethene (TCE), *cis*-1,2-dichloroethene (*cis*-1,2-DCE), vinyl chloride (VC), and total chlorinated ethenes using the method of Buscheck and Alcantar (1995), ranged from  $5.0 \times 10^{-5}$  per day ( $\text{day}^{-1}$ ) to  $1.3 \times 10^{-2} \text{ day}^{-1}$  (half-lives of 0.1 year to 38 years), with geometric mean and median values of  $4.2 \times 10^{-4} \text{ day}^{-1}$  (half-life of 4.5 years) and  $4.9 \times 10^{-4} \text{ day}^{-1}$  (half-life of 3.9 years), respectively. Where possible, field-scale reductive dechlorination rates also were computed using the method of Moutoux *et al.* (1996). These rates ranged from  $2.5 \times 10^{-3} \text{ day}^{-1}$  to  $4.0 \times 10^{-8} \text{ day}^{-1}$  (half-lives of 0.8 year to 47,000 years), with geometric mean and median values of  $8.8 \times 10^{-6} \text{ day}^{-1}$  (half-life of 221 years) and  $1.4 \times 10^{-5} \text{ day}^{-1}$  (half-life of 136 years), respectively.

- Some correlation was observed between field biodegradation rates and average groundwater velocities; maximum concentrations of dissolved hydrogen; minimum oxidation-reduction potentials (ORPs); minimum plume sulfate concentrations; plume “hotspot” total organic carbon concentrations; maximum concentrations of total benzene, toluene, ethylbenzene, and xylenes (BTEX); groundwater temperature; and plume length.
- Correlations between field biodegradation rates and maximum methane and CAH concentrations were not apparent.
- Recently developed contaminant fate and transport models are more sophisticated than models used for this initiative, and will allow more accurate simulation of the migration and persistence of CAHs dissolved in groundwater.
- Modeling results (obtained by simulating CAH degradation using first-order kinetics) suggest that, in many cases, conservative groundwater quality standards will not be uniformly achieved throughout the plumes within 100 years without the implementation of aggressive remedial programs that significantly reduce the contamination source and elevated concentrations of dissolved contaminants throughout the plume.
- The average cost per site for completing supplemental site characterization using existing monitoring wells and a Geoprobe®, laboratory analysis, data analysis, fate and transport modeling, and reporting was \$122,000. Slightly higher costs would be incurred at sites where conventional auger drilling is required.
- Of the 14 sites studied under this program, natural attenuation processes at two sites were sufficiently efficient to warrant the use of MNA in combination with institutional controls as the sole remedial alternative. In two cases, additional site characterization was recommended to facilitate assessment of the need for engineered remediation. In other cases, some form of engineered remediation was recommended in conjunction with MNA. However, MNA was recommended as the primary treatment alternative for at least a portion of the CAH plume at every site evaluated under this program.
- Recommended LTM programs for MNA included an average network of 17 wells and 3 surface water stations, and the projected average annual monitoring cost to implement MNA was \$22,800.

Because of the extremely site-specific nature of CAH biodegradation, quantifying intrinsic bioremediation is more difficult at sites contaminated with these compounds. For these reasons, remedial contractors working for the Department of Defense should critically evaluate the efficacy of MNA as a remedial option for dissolved CAHs. In all cases, engineered alternatives such as source reduction also should be evaluated to determine how they would limit plume migration and/or accelerate attainment of target cleanup levels.

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## LIST OF ACRONYMS AND ABBREVIATIONS

°C	degrees Celsius
µg	microgram(s)
2-D	2-dimensional
3-D	3-dimensional
AFB	Air Force Base
AFCEE/ERT	Air Force Center for Environmental Excellence, Technology Transfer Division
B301	Building 301
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
CAH	chlorinated aliphatic hydrocarbon
CO <sub>2</sub>	carbon dioxide
day <sup>-1</sup>	per day
DCE	dichloroethene
DO	dissolved oxygen
Fe(II)	ferrous iron
Fe(III)	ferric iron
ft/day	feet per day
ft/yr	feet per year
kg	kilogram(s)
L	liter(s)
LNAPL	light nonaqueous-phase liquid
LTM	long-term monitoring
MCL	maximum contaminant level
mg	milligram(s)
MNA	monitored natural attenuation
nM	nanomole
NRMRL	National Risk management Research Laboratory
ORP	oxidation/reduction potential
OSWER	Office of Solid Waste and Emergency Response
OU	operable unit
Parsons ES	Parsons Engineering Science, Inc.
PCE	tetrachloroethene
POC	point of compliance
ppb	part(s) per billion
redox	reduction/oxidation
SVE	soil vapor extraction
TARS	Tooele Army Rail Site
TCA	trichloroethane
TCE	trichloroethene
TMB	trimethylbenzene
TS	treatability study

US  
USACE  
USEPA  
UST  
VC

United States  
US Army Corps of Engineers  
US Environmental Protection Agency  
underground storage tank  
vinyl chloride

# SECTION 1

## INTRODUCTION

### 1.1 SCOPE

This technical memorandum summarizes the results of natural attenuation treatability studies (TSs) conducted at multiple United States (US) Air Force sites in the Continental US. In June 1993, the Air Force Center for Environmental Excellence, Technology Transfer Division (AFCEE/ERT), in cooperation with the US Environmental Protection Agency National Risk Management Research Laboratory (USEPA/NRMRL), Subsurface Protection and Remediation Division and Parsons Engineering Science, Inc. (Parsons ES), began a major initiative to evaluate the effectiveness of monitored natural attenuation (MNA) for remediation of groundwater contaminated with fuel hydrocarbons and chlorinated aliphatic hydrocarbons (CAHs). This study is nearing completion, and the results for fuel hydrocarbons are summarized in *Natural Attenuation of Fuel Hydrocarbons – Performance and Cost Results from Multiple Air Force Demonstration Sites* (Parsons ES, 1999). The results of natural attenuation evaluations at sites contaminated with CAHs or a mixture of CAHs and other contaminants (principally fuel hydrocarbons) are presented in this document.

### 1.2 OVERVIEW OF NATURAL ATTENUATION

Natural attenuation refers to the decrease in the concentration or mass of groundwater contaminants by natural physical, chemical, and biological processes. More recently, the term "monitored natural attenuation" (MNA) has been used to refer to the use of natural attenuation processes to aid in overall site remediation. The USEPA (1999) Office of Solid Waste and Emergency Response (OSWER) defines MNA as:

*...the reliance on natural attenuation processes (within the context of a carefully controlled and monitored cleanup approach) to achieve site-specific remediation objectives within a time frame that is reasonable compared to that offered by other more active methods. The "natural attenuation processes" that are at work in such a remediation approach include a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil and groundwater. These in-situ processes include biodegradation; dispersion; dilution; sorption; volatilization; radioactive decay; and chemical or biological stabilization, transformation, or destruction of contaminants.*

It should be noted that, when relying on natural attenuation processes for site remediation, the USEPA prefers those processes that degrade or destroy contaminants. In

addition, the USEPA generally expects that MNA will only be appropriate for sites that have a low potential for contaminant migration.

Scientific understanding of the microbial processes governing CAH degradation has significantly increased in the past 5 years. Until 1994, the microbial degradation of CAHs was thought to be primarily a cometabolic process (Holliger and Schumacher, 1994). Today, reductive dechlorination (during which CAHs are used as electron acceptors) is known to be the primary process for CAH biodegradation. In general, reductive dechlorination occurs in anaerobic, reducing environments by sequential dechlorination from the parent CAH (e.g., tetrachloroethene [PCE]) to successively less-chlorinated daughter products (e.g., trichloroethene [TCE], dichloroethene [DCE], vinyl chloride [VC], and ethene) (Figure 1.1). More recently, scientists have also discovered that less-chlorinated CAHs (e.g., DCE and VC) can be degraded aerobically through use as an electron donor (Bradley and Chapelle, 1998) (Figure 1.2). A full review of these microbial processes is beyond the scope of this document. The reader is referred to USEPA (1998) and Wiedemeier *et al.* (1999) for a more complete discussion.

MNA can provide nonintrusive groundwater remediation, and avoids the transfer of groundwater contaminants to another phase or location in the environment, as may occur with some conventional engineered treatment techniques. MNA generally is less costly than engineered remedial technologies, and may be equally protective of human health and the environment in some cases. However, it is important to note that natural attenuation may be less effective at many sites contaminated with CAHs than at sites contaminated with fuel hydrocarbons. Long-term monitoring (LTM) and land use control measures typically are required to ensure continuous protection of potential human and ecological receptors.

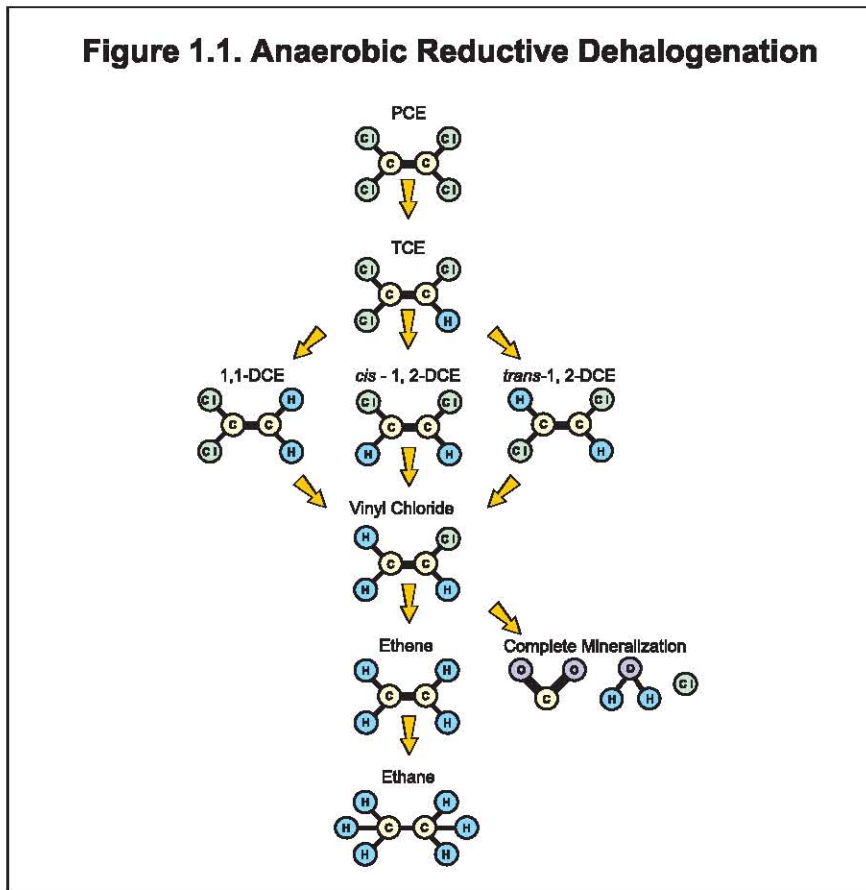
The intent of this portion of the Air Force natural attenuation initiative was to evaluate the effectiveness and potential applicability of MNA for dissolved CAH plumes at Air Force facilities. The procedures for documenting natural attenuation of dissolved CAHs were formalized in the *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water* (USEPA, 1998).

### **1.3 DEMONSTRATION SITE LOCATIONS**

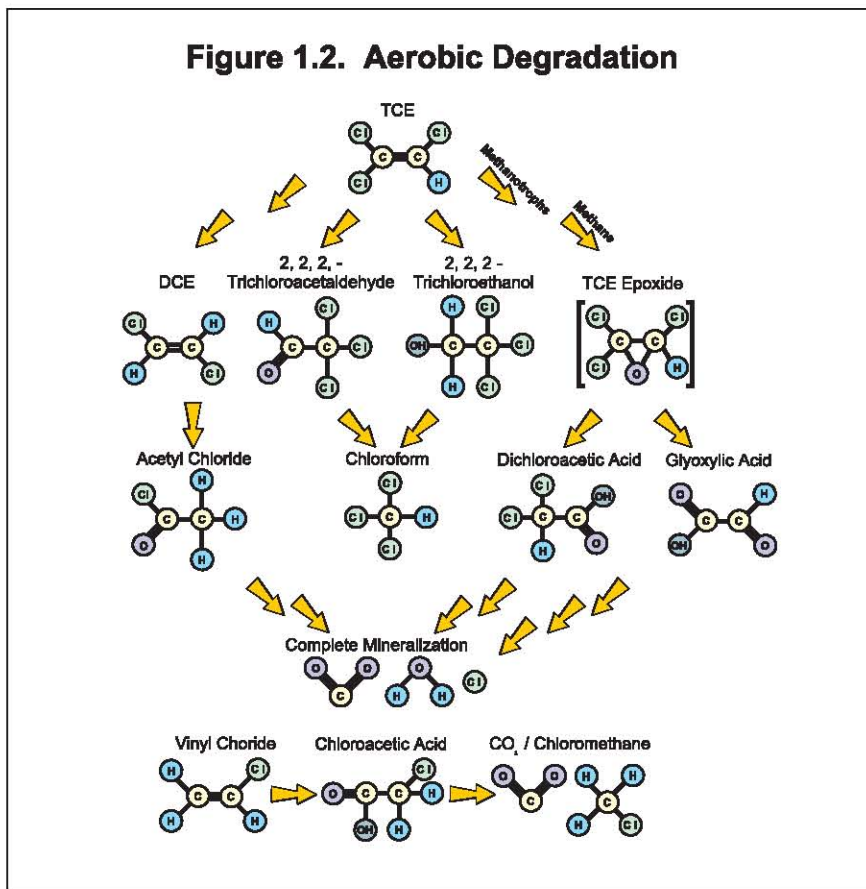
Between July 1993 and August 1999, natural attenuation TSs for CAHs in groundwater were completed at 14 Air Force sites at 11 Air Force installations in 10 states (Figure 1.3). Sites with a wide variety of environmental and contaminant conditions were investigated, including:

- Site locations ranging from California to upstate New York to Florida;
- Depths to groundwater ranging from 0 to 60 feet below ground surface (bgs);
- CAH plume areas ranging from 1.6 to 210 acres;

**Figure 1.1. Anaerobic Reductive Dehalogenation**



**Figure 1.2. Aerobic Degradation**



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**Figure 1.3. Air Force Natural Attenuation Initiative Locations for Chlorinated Aliphatic Hydrocarbons**



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■ CAH Natural Attenuation Site  
▲ Risk-Based Corrective Action Site

- Average groundwater temperatures ranging from 9.1 to 25.6 degrees Celsius (°C); and
- Aquifer matrices ranging from clays to coarse sand and gravel.

Dense non-aqueous phase liquid (DNAPL) was not identified at any of the TS sites, although the presence of DNAPL could not always be ruled out. CAH contamination at three of the sites had impacted both the shallow aquifer and a deeper aquifer.

All 14 sites were evaluated for evidence of natural attenuation reflected in chemical and geochemical trends according to the procedures outlined in the technical protocol (USEPA, 1998), as described in Section 2. One of the 14 sites (Travis AFB) was evaluated under the AFCEE risk-based remediation program that incorporates MNA into risk-based site closure strategies (Downey, 1998). Data from this site are included in this summary report to broaden the available database. Groundwater contamination is directly discharging to springs, streams, canals, or other surface water bodies to which receptors may be exposed at 8 of the 14 sites.



## **SECTION 2**

### **TREATABILITY STUDY PROTOCOL**

The six primary tasks described below were performed at each TS site. Parsons ES performed the majority of this work, with assistance from the USEPA/NRMRL (field data collection and laboratory analyses) and the US Army Corps of Engineers (USACE) (cone penetrometer and drilling support).

- Each TS was initiated with a site meeting and a MNA briefing among Base officials and concerned regulatory agencies. At that time, pertinent site-related documents and data files were identified.
- A site-specific work plan was prepared summarizing existing information and describing the TS methods and goals.
- Site investigation activities were performed to fill data gaps related to the nature and extent of soil, groundwater, and surface water contamination and to document groundwater geochemical conditions. In addition to standard monitoring well installation and sampling, rapid, low-cost soil and groundwater sampling was performed using a Geoprobe® to locate contaminant source areas and install small-diameter groundwater monitoring points.
- Groundwater monitoring wells and points were sampled for contaminant concentrations, and physical and geochemical biodegradation indicator parameters including pH, temperature, conductivity, oxidation/reduction potential (ORP), dissolved oxygen (DO), nitrate, nitrite, sulfate, sulfide, ferrous iron [Fe(II)], total iron, methane, ethene, ethane, carbon dioxide (CO<sub>2</sub>), alkalinity, chloride, and dissolved hydrogen). If necessary, surface water samples were collected to assess the impact of groundwater discharge on surface water quality.
- Groundwater levels were measured to establish groundwater flow directions and hydraulic gradients.
- Slug tests were performed to estimate aquifer hydraulic conductivity. In some cases, additional hydraulic conductivity data were available from previous investigations.
- Geochemical trends and biodegradation rates were evaluated to assess the impact of natural attenuation on contaminant fate and transport. Groundwater models were applied to predict future migration trends for contaminant plumes under the influence of natural attenuation processes, both alone and combined with engineered source reduction and/or hydraulic containment.

- The cost, effectiveness, and implementability of MNA, both alone and in combination with engineered remediation technologies, were assessed. In addition, an LTM plan was developed. At some sites, natural attenuation processes had stabilized the groundwater plumes, but engineered source remediation was recommended to reduce the duration and cost of LTM.

## SECTION 3

### TREATABILITY STUDY RESULTS

The results of the TSs indicated that natural attenuation, including intrinsic bioremediation, of CAHs was occurring to some degree at all of the sites studied under this program. However, the occurrence of significant biodegradation at some sites appeared to be very localized.

#### 3.1 PLUME BEHAVIOR

The most direct and convincing evidence for natural attenuation is historical groundwater data showing stabilization or decline of dissolved contaminant concentrations. At least two sets of groundwater quality data were available for 13 of the 14 MNA test sites. Based on historical groundwater quality data or model predictions, CAH plumes at three sites appeared to be expanding, the plumes at six sites appeared to be either stable or expanding slowly, and the remaining five plumes appeared to be stable or receding. The inference of plume stability will be confirmed with future LTM.

Plume areas for chlorinated ethenes observed at the 14 TS sites were as follow:

- TCE (13 sites): 1.6 to 175 acres;
- *cis*-1,2-DCE (13 sites): 3.2 to 210 acres;
- *trans*-1,2-DCE (3 sites): 1.4 to 42 acres;
- 1,1-DCE (2 sites): 2.4 to 15.8 acres;
- VC (8 sites): 3.3 to 83 acres; and
- Ethene (5 sites): 1.4 to 20 acres.

Based on these plume areas, TCE was the most pervasive chlorinated ethene at most of the TS sites, followed by its primary reductive dechlorination daughter product, *cis*-1,2-DCE.

#### 3.2 GEOCHEMISTRY AND BIODEGRADATION

Contaminant biodegradation causes geochemical changes in the groundwater system as a result of native or anthropogenic carbon being utilized as an electron donor for microbial metabolism. Electron acceptors common to most groundwater systems include DO, nitrate, ferric iron [Fe(III)], sulfate, and CO<sub>2</sub>. CAHs dissolved in groundwater also can be used as electron acceptors under favorable geochemical conditions. Most electron

acceptors (including CAHs) can easily be detected in groundwater, and their depletion, coupled with the accumulation of reaction byproducts (e.g., Fe [II], methane, and PCE/TCE daughter products), provides evidence regarding the preferred metabolic pathways for microbial contaminant biodegradation. For instance, high background DO, nitrate, and sulfate concentrations upgradient from a contaminant plume and low DO, nitrate, and sulfate concentrations in the plume interior indicate that aerobic biodegradation, denitrification, and sulfate reduction have occurred at the site. Conversely, low background Fe(II) and methane concentrations upgradient from a contaminant plume and high Fe(II) and methane concentrations in the plume interior indicate that Fe(III) reduction and methanogenesis have occurred.

The degree and rate of biodegradation of CAHs is dependent upon the prevailing biochemistry and geochemistry of the site. Type 1, Type 2, Type 3, or mixed environments of USEPA (1998) describe four types of plume behavior that are dependent on local phreatic site conditions. These plume types are described below:

- Type 1 behavior occurs under anaerobic groundwater conditions where the primary microbial substrate (electron donor) is anthropogenic carbon (e.g., BTEX or landfill leachate), which drives reductive dechlorination of CAHs, which serve as electron acceptors. Type 1 behavior results in the rapid and extensive degradation of the highly to moderately chlorinated solvents such as PCE, TCE, and DCE.
- Type 2 behavior dominates in areas that are characterized by anaerobic conditions and relatively high concentrations of biologically available native organic carbon, which serves as the electron donor in reductive CAH dechlorination. Type 2 behavior generally results in slower biodegradation of the highly chlorinated solvents than Type 1 behavior, but under the right conditions (e.g., areas with high natural organic carbon contents), this type of behavior also can result in rapid degradation of these compounds.
- Type 3 behavior dominates in areas that are characterized by low concentrations of native and/or anthropogenic carbon, and concentrations of DO that are greater than 1.0 milligram per liter (mg/L). Under these aerobic conditions, reductive dechlorination will not occur or will occur at very low rates. Thus there is little or no removal of PCE and TCE. Biodegradation may proceed via the much slower process of cometabolism, but will be limited by the low concentrations of native or anthropogenic carbon. The most significant attenuation mechanisms for the highly chlorinated CAHs in Type 3 plumes will be advection, dispersion, and sorption. However, VC can be rapidly oxidized under these conditions, DCE may be oxidized, and cometabolism also may occur.
- Mixed behavior occurs when different portions of a plume exhibit different types of behavior.

Eleven of the 14 sites studied exhibited some type of mixed behavior, with 9 of the 14 sites exhibiting Type 1 behavior coupled with either Type 2 behavior or Type 3 behavior. Two sites exhibited Type 2 behavior coupled with Type 3 behavior. The remaining 3 sites exhibited primarily Type 1 behavior. At least a portion of the plumes at all of the sites were characterized by anaerobic, reducing conditions, and all of the anaerobic zones except for F.E. Warren Air Force Base (AFB) LF-03 were either actively sulfate-reducing

or methanogenic. Plumes at 9 of the sites exhibited some Type 3 behavior; the occurrence of reductive dechlorination was inhibited in these areas, and conditions were more conducive to aerobic biodegradation of less-chlorinated CAHs. At all sites where petroleum hydrocarbons were commingled with the CAHs, the plumes were actively methanogenic, and reductive dechlorination was occurring.

According to USEPA (1998), the occurrence of reductive dechlorination may be inhibited if dissolved nitrate and sulfate concentrations exceed 1 mg/L and 20 mg/L, respectively. At higher concentrations, these compounds compete with CAHs for use as electron acceptors. Conversely, the presence of ferrous iron and methane concentrations that exceed 1 mg/L and 0.5 mg/L, respectively, in the contaminated zone indicates that reducing conditions favorable for reductive dechlorination are present (USEPA, 1998).

The minimum nitrate concentrations in the plume areas were less than 1 mg/L at all 14 sites. However, the minimum sulfate concentrations in the plume areas were less than 20 mg/L at only 8 sites (primarily those exhibiting Type 1 conditions), indicating that unless an adequate anthropogenic carbon source is present, sulfate concentrations may be sufficiently elevated to inhibit reductive dechlorination. Maximum ferrous iron concentrations in the CAH plumes exceeded 1 mg/L at 9 of the 14 sites; each of these 9 sites evidenced Type 1 conditions in at least a portion of the plume area. Maximum methane concentrations exceeded 0.5 mg/L at 11 sites. In summary, geochemical conditions favorable to the occurrence of reductive dechlorination were present at least locally at most of the TS sites. The presence of Type 1 conditions (where anthropogenic carbon such as fuel hydrocarbons serves as the electron donor) generally indicates that geochemical conditions are favorable for reductive degradation of CAHs.

Each terminal electron-accepting process has a characteristic associated dissolved hydrogen concentration; therefore, concentrations of dissolved hydrogen also can be used to evaluate reduction/oxidation (redox) processes in groundwater systems (Lovely and Goodwin, 1988; Lovely *et al.*, 1994; Chapelle *et al.*, 1995). Higher hydrogen concentrations are indicative of more reducing environments and vice versa. Maximum dissolved hydrogen concentrations, measured at 8 of the 14 TS sites, ranged from 1.4 to 19 nanomoles per liter (nM/L), with mean and median values of 6.4 nM/L and 5.5 nM/L, respectively. These values indicate the presence of moderately to strongly reducing conditions (dominant electron-accepting processes are sulfate reduction and methanogenesis) that are conducive to reductive dechlorination of CAHs. Dissolved hydrogen concentrations are related to calculated biodegradation rates in Section 3.3.

### **3.3 FIELD BIODEGRADATION RATE ESTIMATES**

Estimation of field-scale biodegradation rate constants is necessary to predict the fate and transport of CAHs dissolved in groundwater. Use of first-order kinetics can be appropriate to estimate field-scale biodegradation rates for CAHs where the rate of biodegradation is assumed to be controlled solely by the concentration of the contaminant. In order to calculate first-order field biodegradation rate constants, the apparent degradation rate must be normalized for the effects of dilution, sorption, and volatilization. Several methods were used to estimate first-order biodegradation rates in the TSs. The methods used for this analysis included:

- Use of a biologically recalcitrant compound, which acts as a conservative tracer (AFCEE, 1995 and USEPA, 1998). This method was used to compute decay rates for two sites (Hill AFB OU 1 and Tinker AFB Area A). The tracer used at both sites was trimethylbenzene (TMB). TMB isomers are recalcitrant to biological degradation under anaerobic conditions, but can be aerobically degraded.
- Use of the one-dimensional (1-D), steady-state analytical solution to the advection-dispersion equation presented by Bear (1979) (Buscheck & Alcantar, 1995). The Buscheck and Alcantar (1995) method assumes that the plume is in steady-state equilibrium, and yields total destructive attenuation rates that account for chemical (abiotic) decay and biological (aerobic and anaerobic) decay. For an expanding plume, this first-order approximation can be viewed as an upper bound on the destructive attenuation rate.
- Computation of field-scale reductive dechlorination rates using the method of Moutoux *et al.* (1996). This method provides an average total dechlorination rate for all dechlorination steps, including the rapid TCE-to-DCE rate and the slower VC-to-ethene rate. Because abiotic reactions and aerobic biodegradation reactions that involve CAHs in the role of an electron donor are not included in this rate, the rate should be considered a lower bound on the destructive attenuation rate. Consequently, these rates are often more than an order of magnitude lower than the rates computed for the same site using the Buscheck and Alcantar (1995) or conservative tracer method.

The results of field biodegradation rate estimates for chlorinated ethenes at the TS sites are summarized below, on Figures 3.1 and 3.2, and in Appendix A. In cases where rates were computed for multiple migration pathways, the rate corresponding to the longest pathway (traversing most or all of the plume in the direction of groundwater flow) is presented. In cases where rates were computed for multiple shorter pathways (e.g., upgradient and downgradient portions of the plume), the geometric mean of these rates is presented.

- Rates computed using a conservative tracer were  $3.0 \times 10^{-4}$  (for *cis*-1,2-DCE) and  $7.4 \times 10^{-4} \text{ day}^{-1}$  (for TCE) (equivalent to half-lives of 6.3 and 2.6 years, respectively). These rates were calculated using data collected from commingled fuel and solvent plumes, and are probably indicative primarily of reductive dechlorination rates in anaerobic, reducing environments.
- Total destructive attenuation rates for the 11 potentially steady-state CAH plumes (see Appendix A), calculated using the Buscheck and Alcantar (1995) method, ranged over three orders of magnitude, from  $5.0 \times 10^{-5} \text{ day}^{-1}$  to  $1.3 \times 10^{-2} \text{ day}^{-1}$  (equivalent to half-lives of 0.1 to 38 years) (Figures 3.1 and 3.2). The geometric mean and median total destructive attenuation rates for these 11 sites are summarized in Table 3.1. These rates are similar to those computed using the conservative tracer method (described above). It should be noted that, in many cases, decay rates were computed separately for different regions of the plumes.

Figure 3.1. Estimated Attenuation Rates for Trichloroethene, Dichloroethene, and Vinyl Chloride

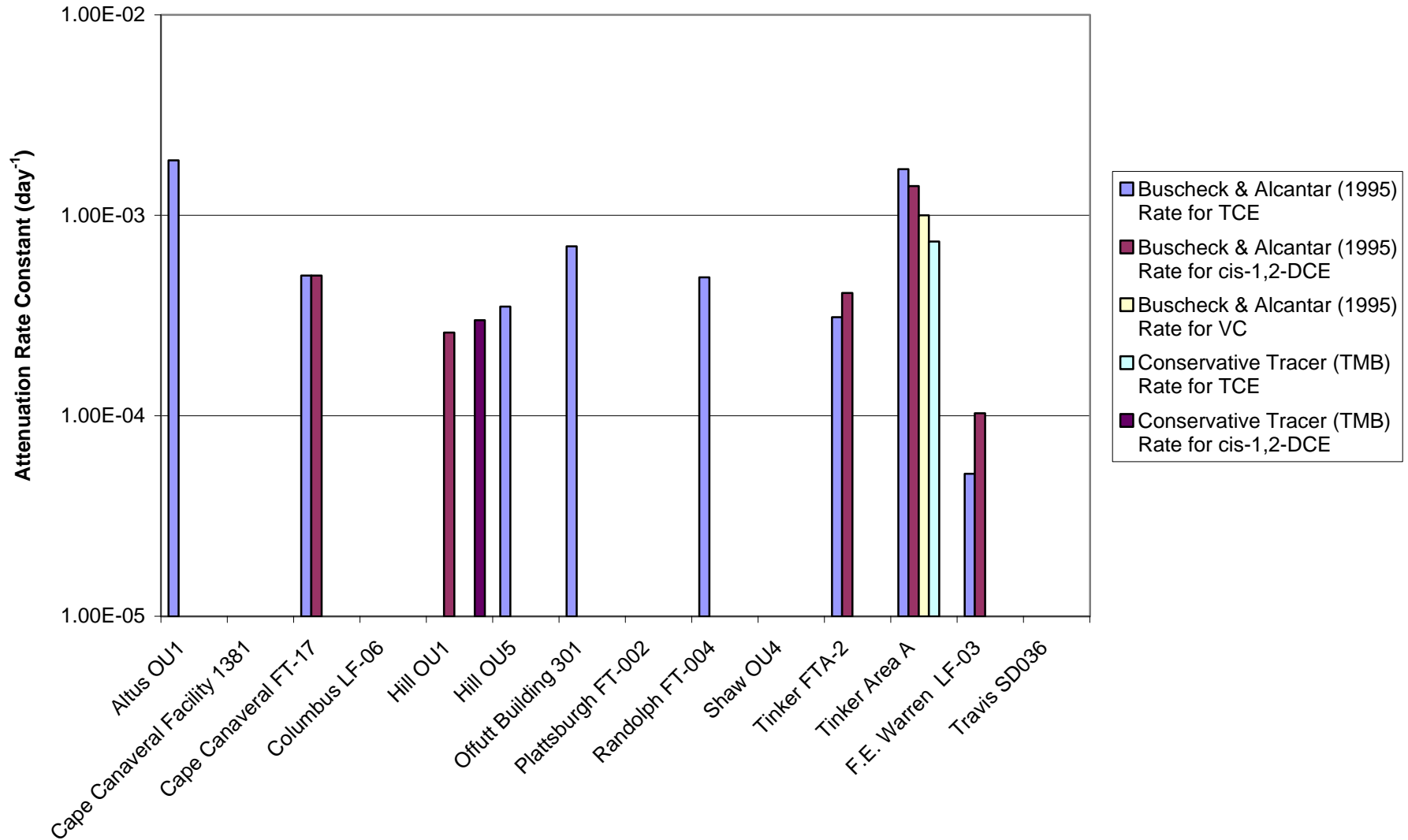
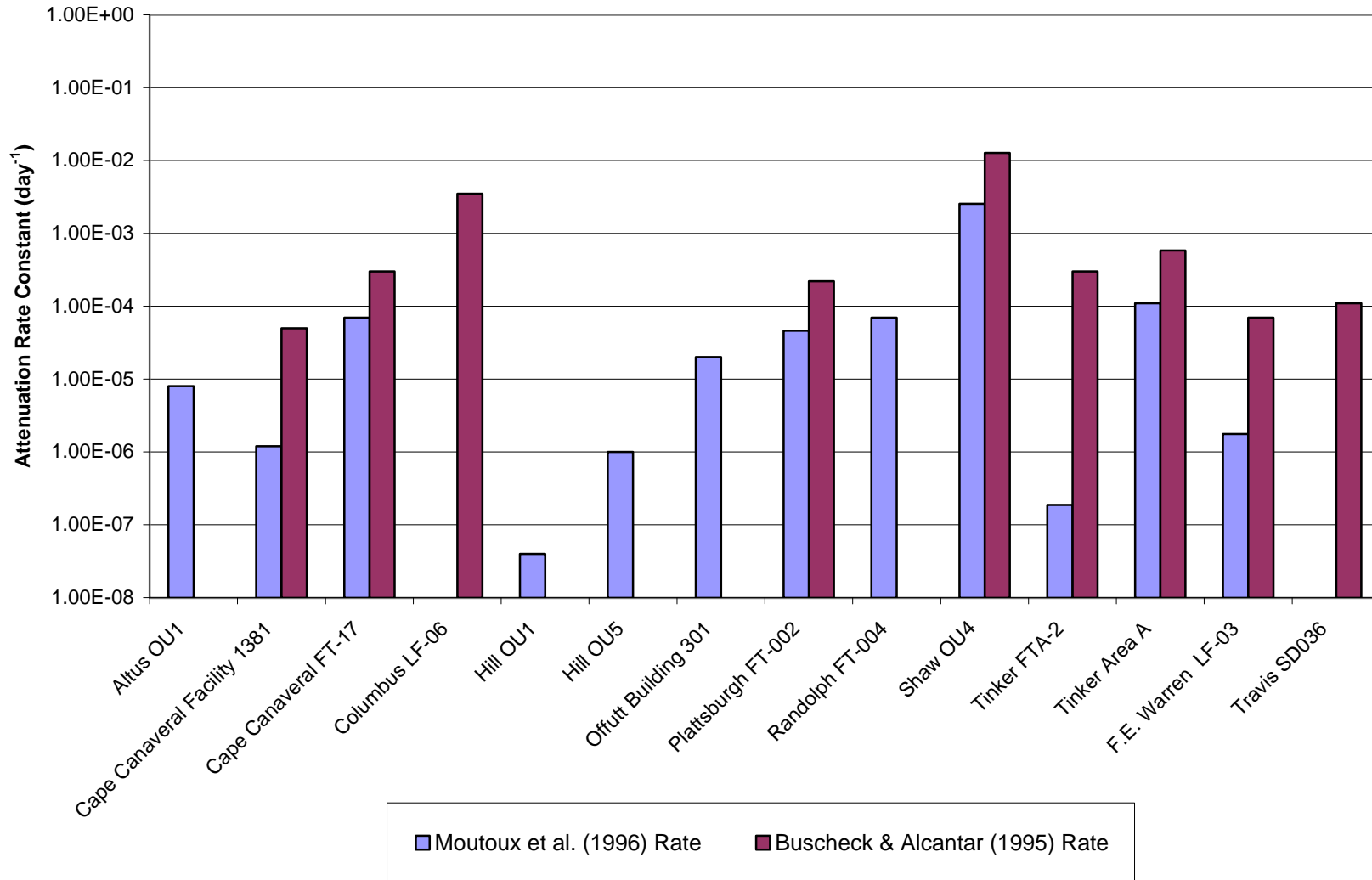


Figure 3.2. Estimated Attenuation Rates for Total Chlorinated Ethenes





The rates used to compute the geometric mean and median values are representative of the longest flowpath, and therefore are average rates representative of the entire plume.

**TABLE 3.1**  
**SUMMARY OF TOTAL DESTRUCTIVE ATTENUATION RATES FOR**  
**POTENTIALLY STEADY-STATE PLUMES<sup>a/</sup>**

Compound(s)	No. of Rates	Geometric Mean (day <sup>-1</sup> )	Half-Life (yr)	Median (day <sup>-1</sup> )	Half-Life (yr)
Total Chlorinated Ethenes	8	4.0 x 10 <sup>-4</sup>	4.7	2.6 x 10 <sup>-4</sup>	7.3
Trichloroethene	5	5.2 x 10 <sup>-4</sup>	3.7	5.0 x 10 <sup>-4</sup>	3.8
<i>cis</i> -1,2-Dichloroethene	4	3.7 x 10 <sup>-4</sup>	5.1	3.8 x 10 <sup>-4</sup>	5.0
Vinyl Chloride	1	1.0 x 10 <sup>-3</sup>	1.9	1.0 x 10 <sup>-3</sup>	1.9

<sup>a/</sup> Rates computed using the method of Buscheck and Alcantar (1995).

- The total CAH reductive dechlorination rates computed using the method of Moutoux *et al.* (1996) ranged from 2.5 x 10<sup>-3</sup> day<sup>-1</sup> to 4.0 x 10<sup>-8</sup> day<sup>-1</sup> (half-lives of 0.8 year to 47,000 years), with geometric mean and median values of 8.8 x 10<sup>-6</sup> day<sup>-1</sup> (half-life of 221 years) and 1.4 x 10<sup>-5</sup> day<sup>-1</sup> (half-life of 136 years), respectively (Figure 3.1). These rates generally are substantially lower than the rates computed using the conservative tracer and Buscheck and Alcantar (1995) methods for the reasons described above. The lowest rate (4 x 10<sup>-8</sup> day<sup>-1</sup>) was computed for Hill AFB OU1 in a predominantly aerobic environment downgradient from the source area that evidenced almost no signs of reductive dechlorination. The highest rate (2.5 x 10<sup>-3</sup> day<sup>-1</sup>) was calculated for a mixed CAH and fuel hydrocarbon plume at Shaw AFB.

Total destructive attenuation rates computed for TCE, *cis*-1,2-DCE, and total chlorinated ethenes using the method of Buscheck and Alcantar (1995) were plotted against selected variables to enable assessment of correlations. These variables include groundwater temperature, average and maximum groundwater velocity, minimum sulfate concentration, maximum methane concentration, minimum ORP, maximum CAH concentration, maximum dissolved hydrogen concentration, the total organic carbon concentration in the plume “hotspot”, maximum dissolved BTEX concentration, and plume length. In addition, CAH reductive dechlorination rates computed using the method of Moutoux *et al.* (1996) were plotted against maximum dissolved hydrogen and BTEX concentrations. The best-fit trend lines plotted on the graphs generally are those that give the highest correlation coefficients (R<sup>2</sup> values). The results of these comparisons are summarized in the following paragraphs. Graphs not included as figures in the text are contained in Appendix B.

Minimum ORPs are plotted versus total destructive attenuation rates for TCE and *cis*-1,2-DCE, computed using the method of Buscheck and Alcantar (1995), on Figures 3.3 and 3.4. These figures indicate an inverse relationship between ORP and attenuation rate, with low ORPs correlating to high attenuation rates. This correlation stems from the fact that reductive dehalogenation of CAHs occurs most readily in highly reducing environments.

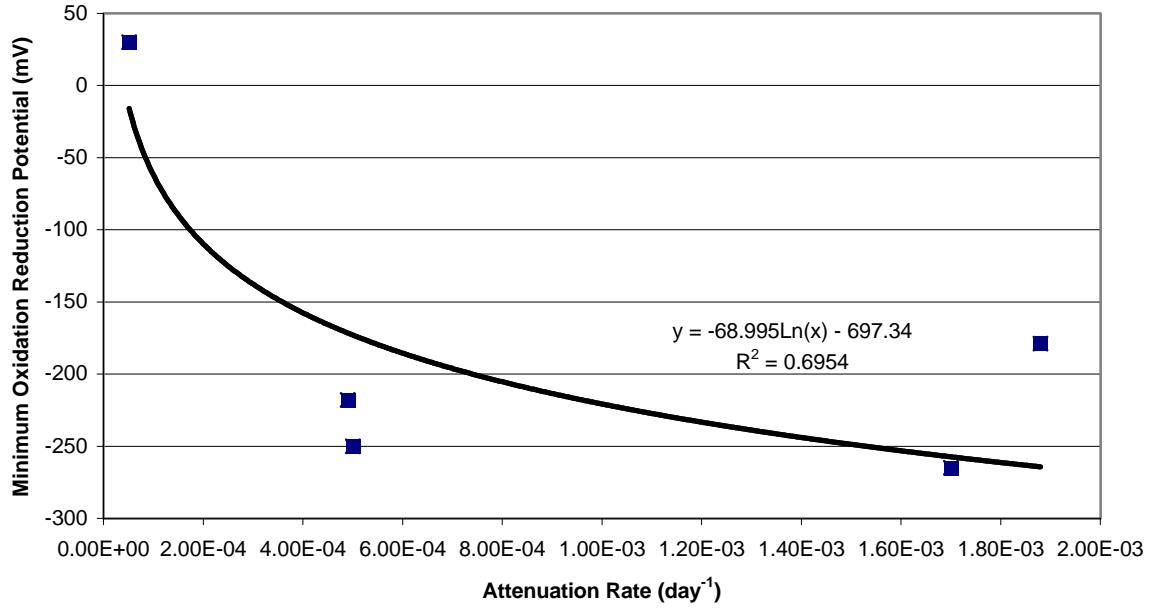
Dissolved hydrogen concentrations also indicate the prevailing redox environment. Figure 3.5 plots dissolved hydrogen concentrations versus total destructive attenuation rates for total chlorinated ethenes. This figure indicates that there is some correlation between hydrogen concentrations and average biodegradation rates (correlation coefficient [ $R^2$ ] = 0.94). However, the data are very limited and conclusions regarding correlations are therefore preliminary. Figure 3.6 plots dissolved hydrogen concentrations versus reductive dechlorination rates computed using the method of Moutoux *et al.* (1996). Some correlation also is indicated by these data ( $R^2 = 0.78$ ), supporting the observation that biodegradation rates vary proportionately with groundwater ORPs. Similar correlations between dissolved hydrogen concentrations and total destructive attenuation rates for TCE and *cis*-1,2-DCE were not observed; however, the number of data points available for these comparisons was relatively small. These graphs are contained in Appendix B.

Some correlation also was observed between total destructive attenuation rates for TCE and *cis*-1,2-DCE (computed using the method of Buscheck and Alcantar [1995]) and maximum dissolved BTEX concentrations (Figures 3.7 and 3.8), and between average reductive dechlorination rates (computed using the method of Moutoux *et al.* [1996]) and maximum dissolved BTEX concentrations (Figure 3.9). The presence of elevated organic carbon (e.g., fuel hydrocarbon) concentrations dissolved in groundwater creates anaerobic, reducing conditions that are conducive to the occurrence of reductive dechlorination. This observation also explains the correlation between total organic carbon concentrations and total destructive TCE attenuation rates suggested on Figure 3.10.

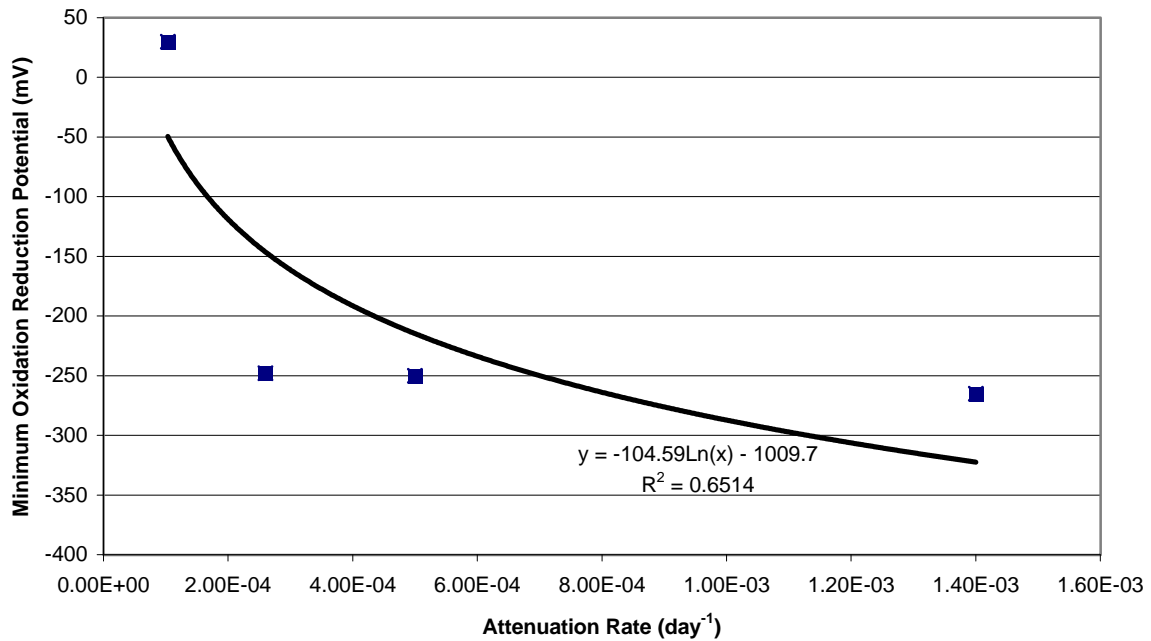
Figure 3.11 suggests a correlation between average groundwater velocity and total destructive attenuation rate. At sites with higher groundwater velocities, electron-acceptor-enriched groundwater sweeps through the plume at a relatively rapid rate, contributing to the aerobic biodegradation of less-chlorinated CAHs such as DCE and VC. It should be noted that data from Hill AFB OU1 are not included on Figures 3.9 and 3.11. The reductive dechlorination rate computed for this site ( $4 \times 10^{-8} \text{ day}^{-1}$ ) was heavily influenced by the aerobic environment downgradient from the source area, and therefore did not correlate well with the presence of elevated BTEX concentrations in the source area. In addition, the anomalously high average groundwater velocity was heavily influenced by conditions occurring in one limited portion of the site.

In laboratory experiments, rates of microbial production have been shown to increase by a factor of two for every  $10^\circ\text{C}$  increase in temperature (Atlas, 1988). This trend was not observed for TCE or total chlorinated ethenes at the 14 test sites, where average groundwater temperatures ranged from  $9^\circ\text{C}$  to  $26^\circ\text{C}$  (see graphs in Appendix B). The lack of correlation between these field biodegradation rates and groundwater temperature supports a similar observation at fuel hydrocarbon sites (Parsons ES, 1999). Each site appears to have a microbial community adapted to degrade CAHs at

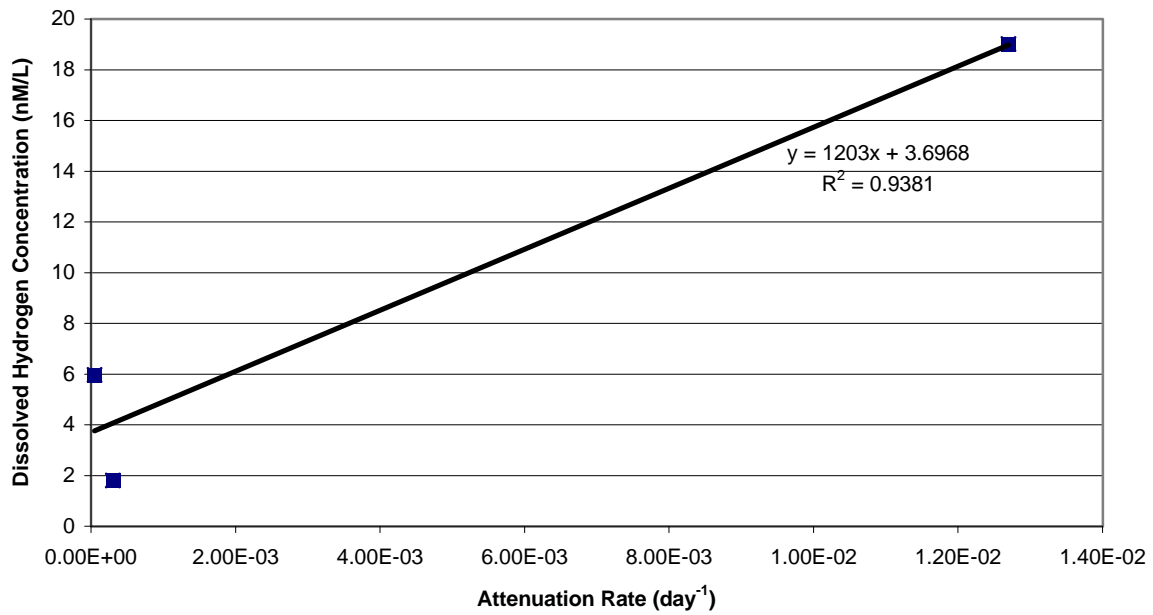
**Figure 3.3. Minimum Oxidation Reduction Potential versus Total Destructive TCE Attenuation Rate**



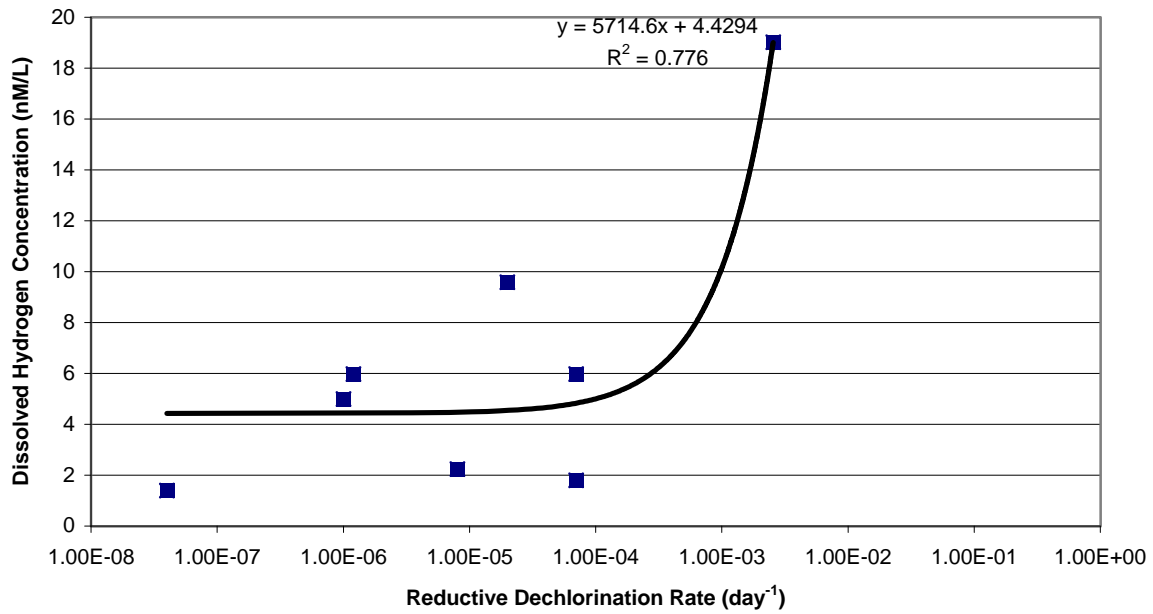
**Figure 3.4. Minimum Oxidation Reduction Potential versus Total Destructive *cis*-1,2-DCE Attenuation Rate**



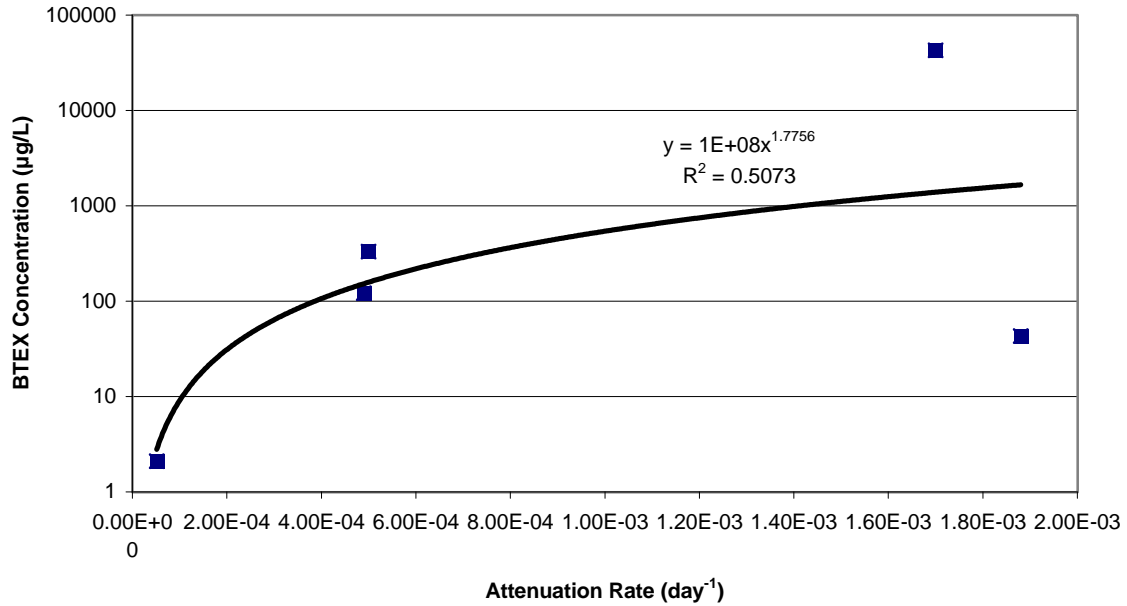
**Figure 3.5. Dissolved Hydrogen Concentration versus Total Destructive Chlorinated Ethenes Attenuation Rate**



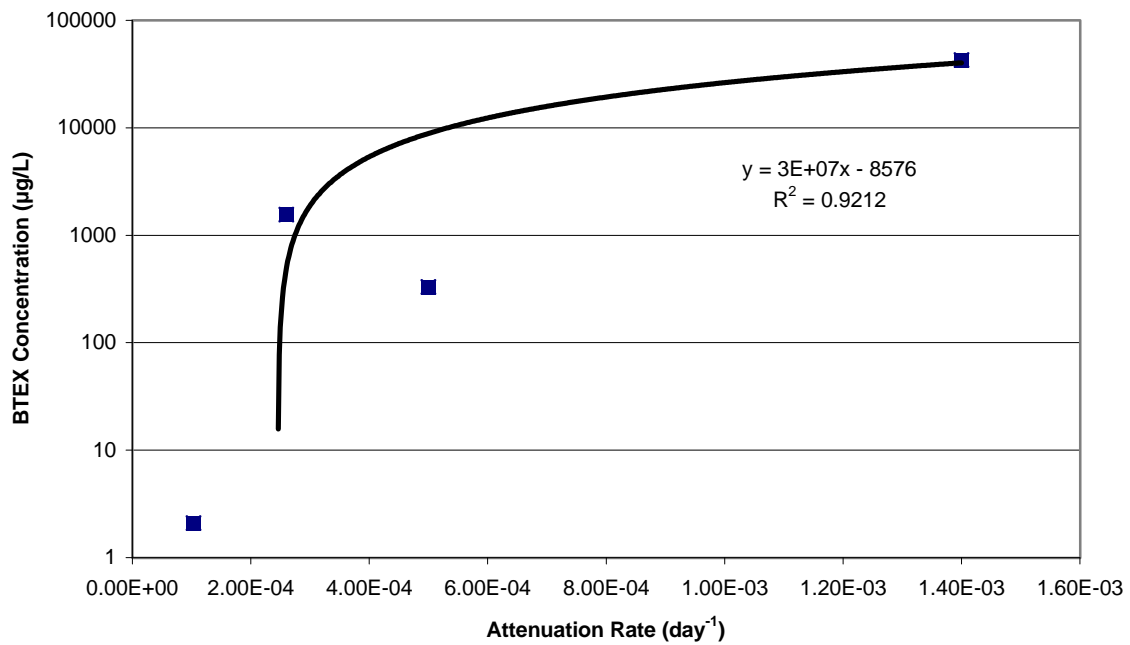
**Figure 3.6. Dissolved Hydrogen Concentration versus CAH Reductive Dechlorination Rate**



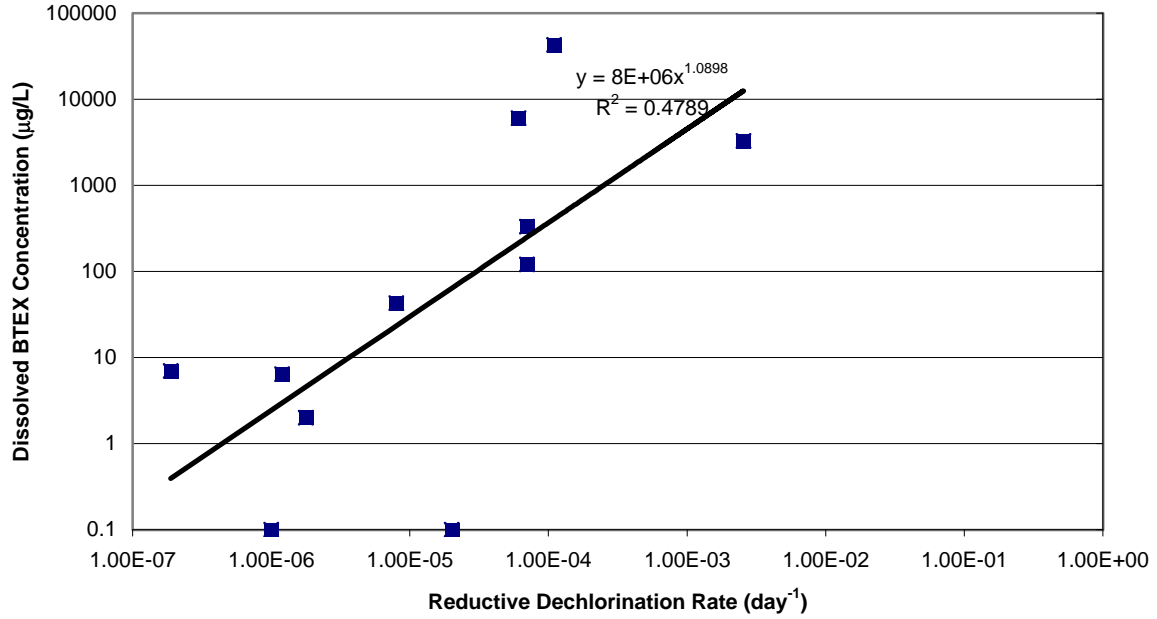
**Figure 3.7. Maximum BTEX Concentration versus Total Destructive TCE Attenuation Rate**



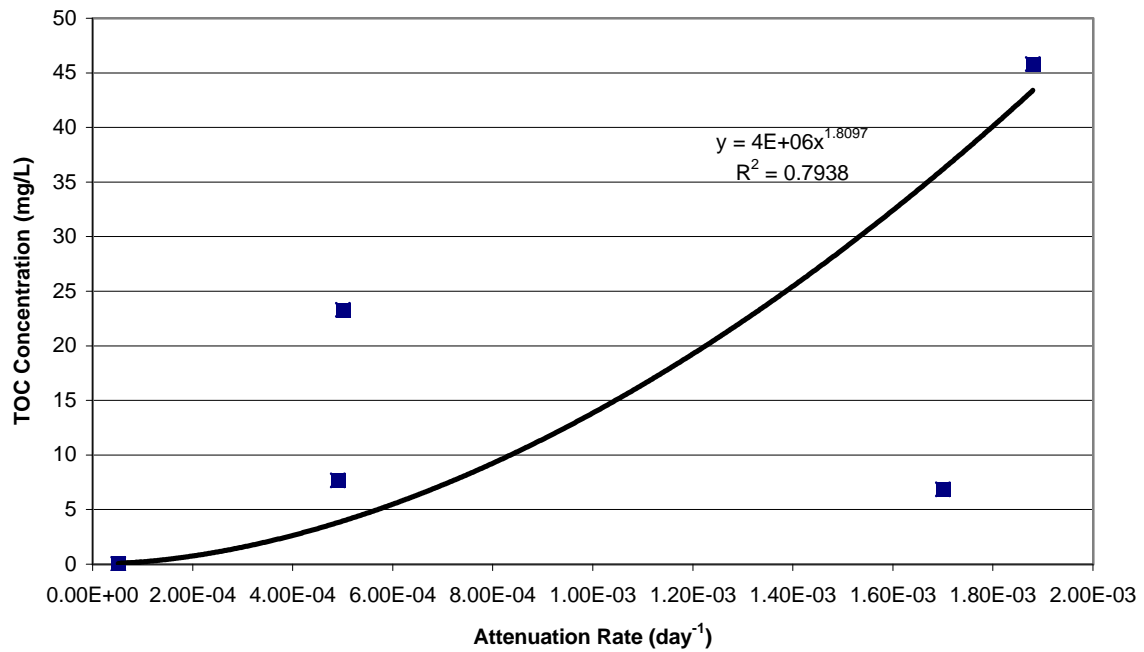
**Figure 3.8. Maximum BTEX Concentration versus Total Destructive *cis*-1,2-DCE Attenuation Rate**



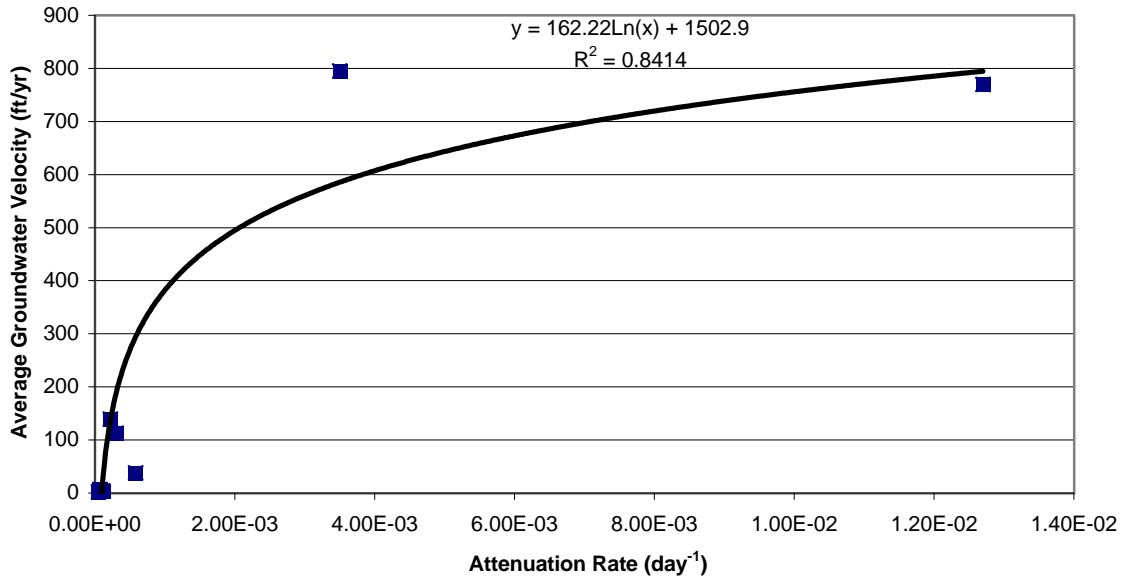
**Figure 3.9. Maximum BTEX Concentration versus CAH Reductive Dechlorination Rate**



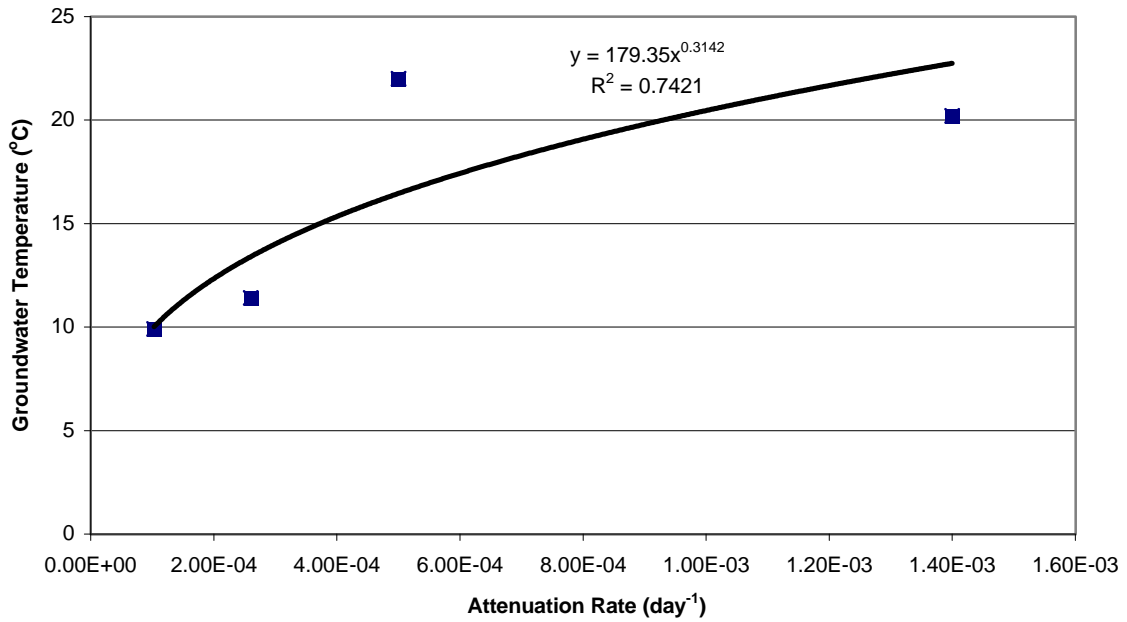
**Figure 3.10. Total Organic Carbon Concentration versus Total Destructive TCE Attenuation Rate**



**Figure 3.11. Average Groundwater Velocity versus Total Destructive Chlorinated Ethenes Attenuation Rate**



**Figure 3.12. Groundwater Temperature versus Total Destructive *cis*-1,2-DCE Attenuation Rate**



the site-specific temperature range. However, some correlation between groundwater temperature and the total destructive *cis*-1,2-DCE attenuation rate is indicated on Figure 3.12. Additional data are needed to assess the existence of such a correlation.

According to USEPA (1998), the presence of elevated sulfate concentrations (i.e., greater than 20 mg/L) may inhibit reductive dechlorination of CAHs, because sulfate competes with CAHs for use as electron acceptors in microbially-mediated redox reactions. This observation is supported by the relationships between total destructive attenuation rates for TCE and total chlorinated ethenes and minimum sulfate concentrations in the CAH plumes shown on Figures 3.13 and 3.14, respectively. However, a similar relationship was not observed for *cis*-1,2-DCE (Appendix B).

Total destructive attenuation rates for TCE and *cis*-1,2-DCE also were plotted against plume length for these compounds. No correlation was observed for TCE (Appendix B). With the exception of data for Hill AFB OU1 (plume length = 4,600 feet), shorter plume lengths appear to correlate well with higher *cis*-1,2-DCE attenuation rates (Figure 3.15).

Correlations between field biodegradation rates for CAHs and maximum methane and CAH concentrations were not apparent (see graphs in Appendix B). This lack of correlation may be due, at least in part, to the fact that in many cases the computed degradation rates used for comparison purposes are representative of average conditions across most or all of the dissolved plume. In reality, degradation rates can vary substantially across the plume, as evidenced by the fact that mixed plume behavior was observed for most of the plumes studied during this project. For example, the estimated CAH decay rates for the source area at Cape Canaveral Facility 1381, where the CAH plume was commingled with a fuel hydrocarbon plume, were approximately one order of magnitude higher than the average rate for the entire plume.

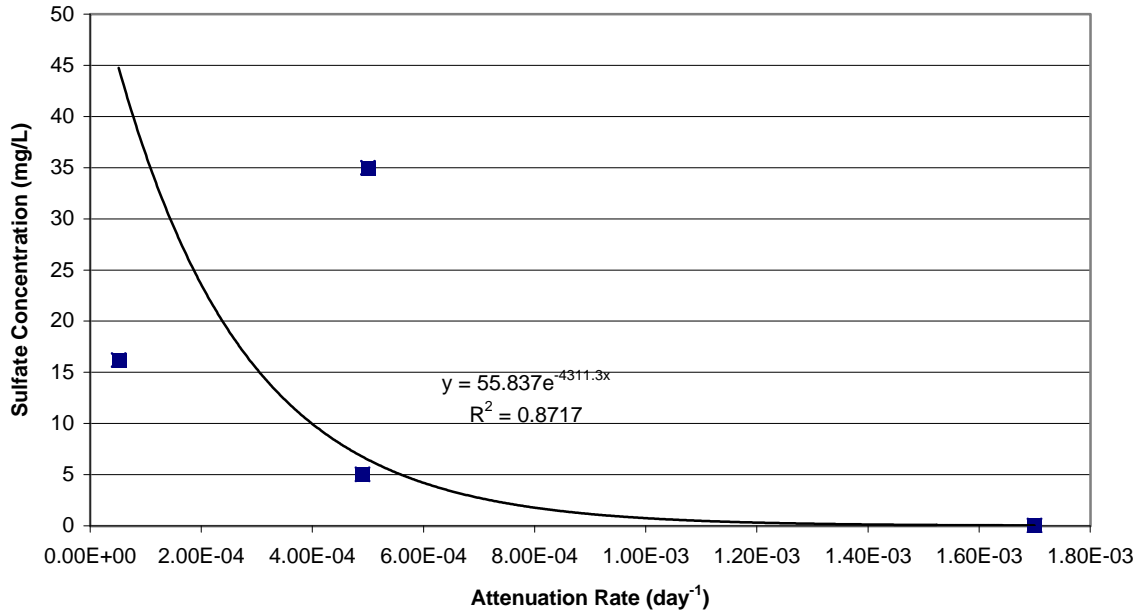
### 3.4 MODELING RESULTS

Groundwater flow and solute fate and transport modeling was performed for all 14 of the TS sites. The migration and persistence of one or more dissolved CAHs at 13 of the 14 study sites were simulated to predict natural attenuation trends and support development of LTM plans. For Plattsburgh AFB, only the fuel hydrocarbons were modeled. The three-dimensional (3-D) numerical model MODFLOW (McDonald & Harbaugh, 1988) coupled with MT3D (S.S. Papadopoulos & Associates, Inc., 1996) was used to simulate fate and transport at 12 of the study sites. The analytical solution presented by van Genuchten and Alves (1982) was used for the remaining site.

Four of the 13 modeled CAH plumes were discharging to a surface water body that constituted a hydraulic barrier to plume migration, therefore, the model did not predict future downgradient migration of these plumes. Future plume expansion under the influence of natural attenuation only was predicted for seven sites (Columbus AFB LF-06, Hill AFB OU5, Offutt AFB B301, Tinker AFB FTA-2, F.E. Warren AFB LF-03, Travis AFB SD036, and Altus AFB OU1); the simulated expansion distances ranged from 250 feet to 9,500 feet. The largest predicted expansion distance (Hill AFB OU5) corresponded with the inferred presence of Type 3 conditions and very little biodegradation of the principal CAH (TCE). The smallest predicted expansion distance



**Figure 3.13. Sulfate Concentration versus Total Destructive TCE Attenuation Rate**



**Figure 3.14. Sulfate Concentration versus Total Destructive Chlorinated Ethenes Attenuation Rate**

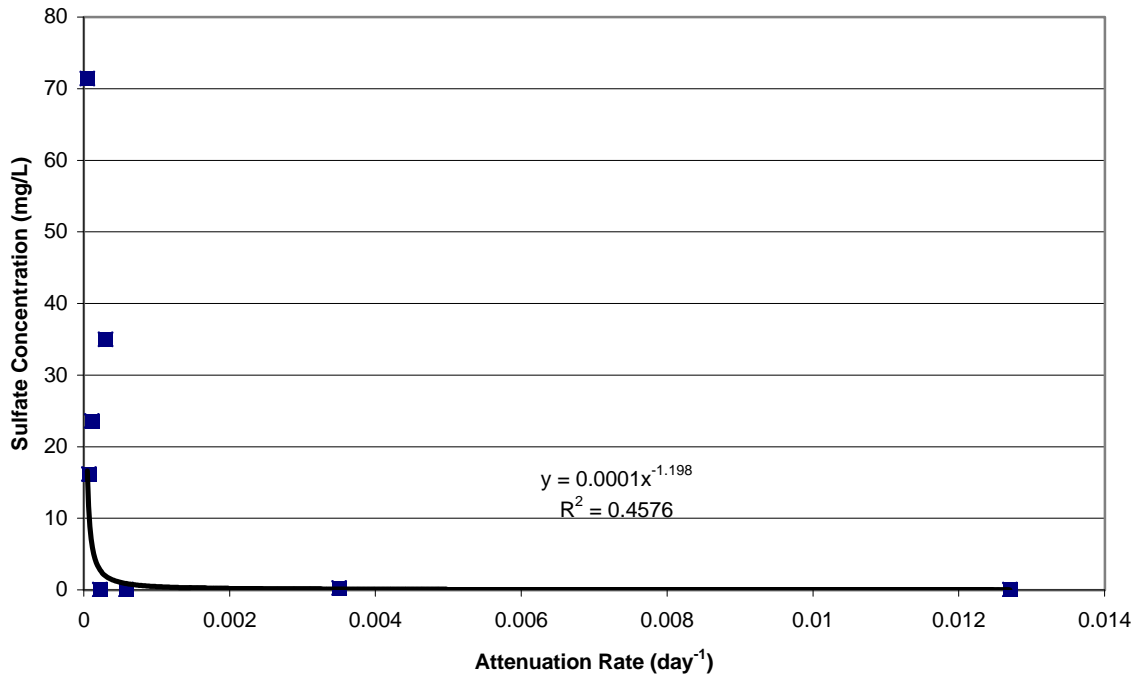
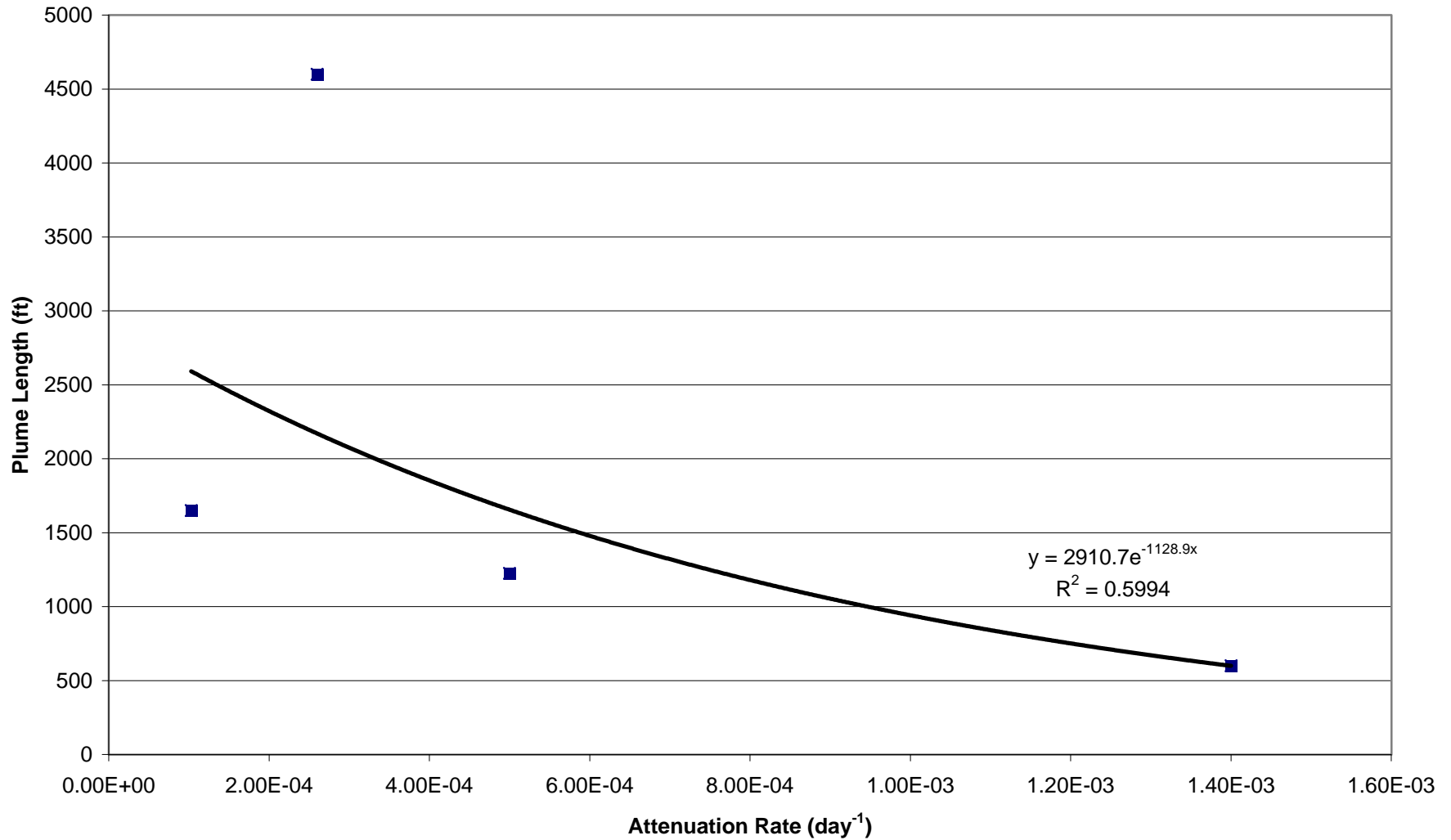


Figure 3.15. *cis*-1,2-DCE Plume Length versus Total Destructive *cis*-1,2-DCE Attenuation Rate



(F.E. Warren AFB) corresponded with the simulated interception of the plume by a downgradient creek, which was interpreted to be a hydraulic barrier. At one site (Altus AFB OU1), the modeling objective was to predict future CAH concentrations at the Base boundary, and the downgradient extent of the simulated plume under the influence of RNA alone was not determined. However, the model predicted that this plume would expand for approximately 125 years into the future. Only negligible downgradient expansion was predicted for the CAHs plumes at Tinker AFB Site Area A and Hill AFB OU1, indicating the presence of near-steady-state conditions. The model for Travis AFB SD036 indicated the presence of near-steady-state conditions throughout the majority of the plume, but predicted expansion along more-permeable sewer line corridors. These modeling results indicate that the extent of CAH plume migration can be significant unless migration is slowed by natural attenuation or interrupted by a hydraulic barrier (e.g., surface water body).

A number of significant characterization- and software-related limitations were encountered during the modeling activities that increased the uncertainty of model-generated predictions. These limitations included the following:

- For reductive dechlorination of CAHs, estimated first-order decay rates are not necessarily good representations of plume conditions because degradation of these compounds depends on concentrations both of electron donors (e.g., fuel hydrocarbons or native organic material) and of electron acceptors (including inorganic electron acceptors and CAHs) (Moutoux *et al.*, 1996). Therefore, second-order decay rates would allow more reliable modeling, but during the TSs, there were no readily available groundwater contaminant transport models that could utilize such rates as input. The recent introduction of new multi-species transport models such as RT3D (Clement, 1997) should reduce the uncertainty associated with simulation of CAH fate and transport.
- In most cases, only the effects of the contaminant source are measured; the detailed source characteristics and history are often unknown. The source must therefore be represented as a “black box” that produces appropriate contaminant concentrations or fluxes at selected points in the model domain. The source may be misrepresented under such a scenario, but there often is little choice in the matter. In addition, the future source weathering rate is often unknown, and must be conservatively simulated on the basis of available information.
- The fate and transport of multiple dissolved species (e.g., parent and daughter products) that may have a significant presence in groundwater could not be simulated simultaneously. Recently developed model codes, such as RT3D (Clement, 1997) and MT3D<sup>99</sup> (S.S. Papadopoulos & Associates, 1998) are intended to alleviate this concern.
- The modeling software used throughout much of the project does not allow spatial variability for certain input parameters (e.g., the first-order decay rate and the retardation coefficient). The inability to vary these parameters spatially required the use of average parameter values that compromised the simulation of hydrogeologic and geochemical heterogeneity (e.g., the presence of mixed plume behavior as

described in Section 3.2). More recently released software allows these parameters to be varied throughout the model domain.

Simulation results indicated that the models used are most sensitive to CAH biodegradation rates and hydraulic conductivity. Given the widespread acceptance of the effectiveness of natural attenuation for fuel hydrocarbons dissolved in groundwater, simple analytical models may be adequate to predict the future migration and persistence of BTEX contamination at many fuel-contaminated sites. However, because of the inherent complexity of CAH biodegradation, use of a 2- or 3-D numerical model often may be warranted. The analytical model BIOCHLOR (Aziz *et al.*, 1999), which is being developed for AFCEE, may increase the reliability (and therefore the regulatory acceptance) of analytical model results for CAH-contaminated sites.

### **3.5 PROPOSED REMEDIAL ALTERNATIVES**

Each of the 14 TSs included an evaluation of two or more remedial alternatives. Natural attenuation processes at 2 of the 14 sites were deemed sufficiently effective to warrant the use of MNA in combination with institutional controls as the site remedy. At a third site (Offutt AFB B301), MNA combined with attempts to locate and remediate the contaminant source were recommended, because remediation of the source could provide significant benefits in reducing the plume remediation time frame. At a fourth site (Randolph AFB FT004), the downgradient extent of the CAH plume was not defined; therefore, additional characterization was recommended to facilitate assessment of the need for engineered remediation of the CAH plume. At the remaining 10 sites, some type of engineered remedial action had either already been implemented to address at least a portion of the plume, was planned by the Base, or was recommended based on the results of the TS. These engineered remedial actions included dual-phase (i.e., aqueous- and vapor-phase) extraction, air sparging, soil excavation, soil washing, landfill cap repair, collection of discharge from surface springs, groundwater extraction, mobile light nonaqueous-phase liquid (LNAPL) recovery (for mixed fuel and CAH product), bioventing (for fuel hydrocarbons), and/or soil vapor extraction. Recommended engineered remedial actions for six sites focused on reducing contaminant concentrations in the source area alone; MNA with institutional controls was recommended for downgradient portions of the dissolved CAH plume. Recommended engineered remedial actions for the remaining four sites included some type of downgradient plume containment (e.g., via groundwater extraction or an air sparging curtain) to prevent or limit impacts to potential downgradient receptors.

The calibrated models developed for 13 of the 14 sites were used to simulate the effectiveness of one to three remedial alternatives for CAH-contaminated groundwater. However, plume persistence was evaluated for only 12 sites; the model for Columbus AFB LF-06 was only used to evaluate plume migration. For 11 of these 13 sites, Alternative 1 consisted of MNA with institutional controls. The estimated length of time required for natural attenuation alone to achieve federal or state groundwater quality standards for CAHs ranged from 17 to more than 200 years, based on conservative modeling assumptions. These estimated time frames exceeded 100 years for 6 of the 12 sites for which model predictions regarding plume persistence were developed.

The models constructed for 11 of the 13 sites also were used to evaluate the effectiveness of groundwater extraction in plume “hot spots” and/or engineered source

reduction using SVE, dual-phase extraction, mobile LNAPL recovery, or soil excavation (Alternative 2). The estimated time frames for dissolved CAH concentrations to decrease below groundwater quality standards in plumes at 6 of the 11 sites assuming some type of engineered remedial action, still exceeded the maximum lengths of the simulation periods (i.e., 35 to 200 years). For the remaining 5 sites, the projected compliance times for the MNA-only alternatives decreased by 0 percent to 90 percent (average 44 percent) for the engineered remediation alternatives. In some cases, once CAHs are in the groundwater, soil remediation has minimal impact on the total time frame required for MNA to achieve low parts-per-billion (ppb) cleanup values.

In cases where a third remedial alternative was simulated (typically hydraulic capture of the plume near the leading [downgradient] edge of the plume, or installation of a downgradient air sparging curtain), the predicted remediation times were not influenced because these alternatives focused on limiting plume migration rather than decreasing dissolved CAH concentrations within the plume. The simulation results described above suggest that in many cases, groundwater quality standards will not be uniformly achieved in CAH plumes within 100 years without the implementation of aggressive engineered remedial actions that can significantly reduce CAH concentrations in the source area and throughout the most concentrated portions of the plume.

### **3.6 LONG-TERM MONITORING**

A network of LTM and point-of-compliance (POC) wells was recommended at each TS site to monitor natural attenuation trends, verify model predictions, and protect downgradient receptors. The recommended number of LTM and POC wells ranged from 8 to 30 (average of 17). The recommended LTM plan for 9 of the sites also included collecting surface-water samples at up to 6 locations. Sampling frequencies recommended for these sites ranged from 1 to 2 years; annual sampling was recommended most frequently. In most cases, costs for no more than 30 years of LTM were presented in the TS reports, even in cases where projected remediation times exceeded 30 years, because substantially longer LTM periods may be administratively or regulatorily unacceptable. In many cases, collection of up to 30 years of groundwater quality data should be sufficient to document temporal trends and support either implementation of a more aggressive remedial alternative to speed compliance times, or a significant reduction in monitoring frequency accompanied by assignment of the site to a relatively inactive status.

## **SECTION 4**

### **NATURAL ATTENUATION CASE STUDIES**

The following case studies summarize site investigation methods, data analysis procedures, modeling results, and proposed remedial alternatives at representative sites characterized by a variety of hydrogeologic and chemical conditions. Detailed results for each site are available in the site-specific TS reports.

#### **4.1 HILL AIR FORCE BASE, UTAH, OPERABLE UNIT 5**

##### **4.1.1 Site Description**

The TS focused on the dissolved CAH plume emanating from the Tooele Army Rail Shop (TARS), located along the western boundary of the Base. The TARS was constructed in 1942, and was used to service and repair railroad engines. TCE was reportedly used at the rail shop from 1949 to 1964, and was discharged to a gravel leachfield, resulting in groundwater contamination. The off-Base area immediately west of (downgradient from) the TARS supports commercial and residential land uses. Downgradient from the plume toe, land uses are mixed residential, agricultural, and cattle rangeland. The unconfined, shallow aquifer beneath Operable Unit (OU) 5 consists primarily of fine- to medium-grained sand with occasional interbeds of coarser sand and gravel and thin seams of silt and clay. The advective groundwater flow velocity in the shallow aquifer is estimated to range from 0.005 ft/day to 22.5 ft/day, with average velocities ranging from 0.03 to 0.3 foot per day (ft/day). Potential downgradient receptor exposure points include Howard Slough, a wetland located approximately 2 miles west of the plume toe, and drainage ditches that are being constructed to lower the water table in the less-developed area between the plume toe and Howard Slough.

##### **4.1.2 Extent and Magnitude of Contamination**

TCE is the most widespread CAH detected in OU5 groundwater, and is also the CAH present at the highest concentrations. The maximum TCE concentration detected during the August 1996 TS was 259 micrograms per liter ( $\mu\text{g/L}$ ). The width of the TCE plume ranged up to approximately 1,300 feet, and the plume had migrated approximately 4,200 feet west of the TARS, beneath the residential area. The area of the TCE plume was approximately 126 acres. The vertical thickness of the TCE plume was not fully defined, but the highest concentrations were detected in the uppermost 35 feet of the shallow aquifer.

#### 4.1.3 Natural Attenuation Processes and Rates

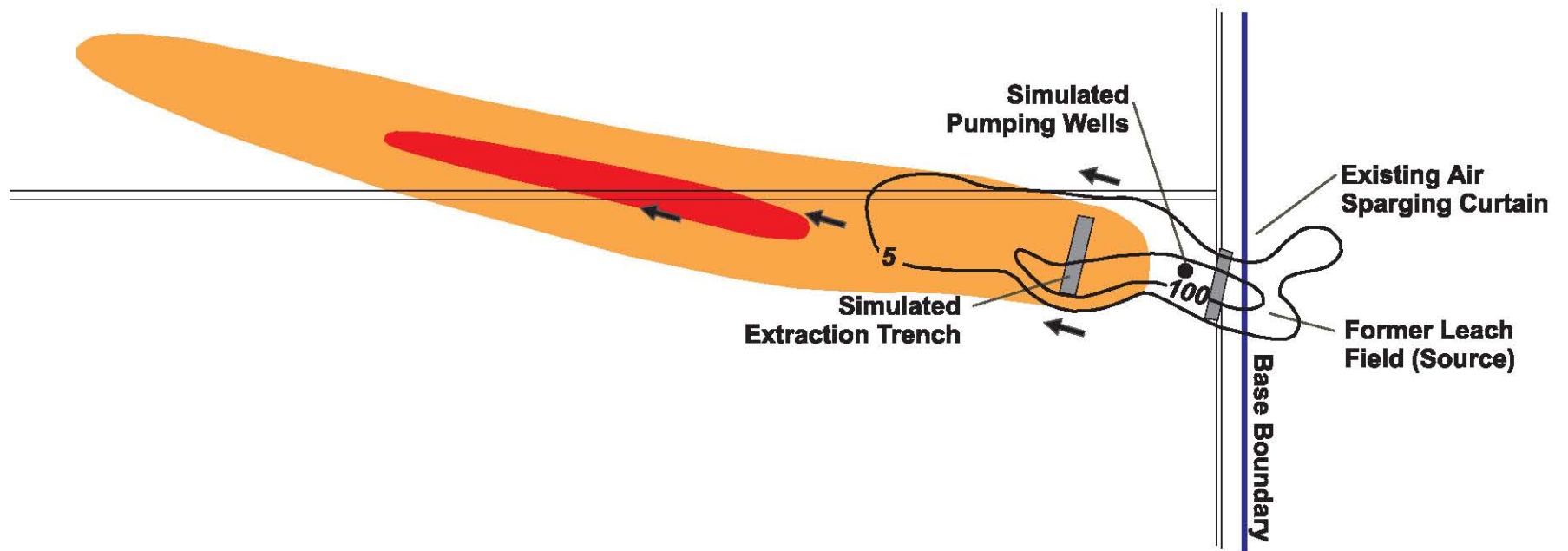
Limited biodegradation of the TCE plume was occurring, primarily by reductive dechlorination of TCE to *cis*-1,2-DCE. The TCE plume exhibited mixed behavior, with Type 2 behavior indicated in limited areas where DO concentrations and ORP were sufficiently low, and native organic carbon concentrations were sufficiently high to allow reductive dechlorination to proceed. In addition, Type 1 behavior appeared to have occurred in the source area in the past, perhaps driven by past leaching of petroleum hydrocarbons from source area soils. However, the aerobic nature of the groundwater throughout most of the plume area, combined with a marked lack of evidence that CAH biodegradation was occurring, indicated that Type 3 behavior was prevalent. In the 32 years since use of TCE at the site ended, only a small fraction of the TCE was being transformed to DCE, and the process was not sufficient to transform the parent CAHs and chlorinated daughter products to nonchlorinated end products such as ethene. The computed reductive dechlorination rates ranged from  $1 \times 10^{-7} \text{ day}^{-1}$  in the central portion of the plume to  $2 \times 10^{-5} \text{ day}^{-1}$  near the source area. The calibrated model used an anaerobic decay rate of  $6 \times 10^{-6} \text{ day}^{-1}$ , which corresponds to a TCE half-life of 316 years.

#### 4.1.4 Historical Trends and Modeling

Groundwater quality data collected from May 1993 through August 1996 indicated that TCE concentrations in and immediately downgradient from the source area were decreasing, suggesting that TCE in source areas soils is attenuating. However, TCE concentrations throughout the remainder of the plume were relatively uniform over time or have fluctuated.

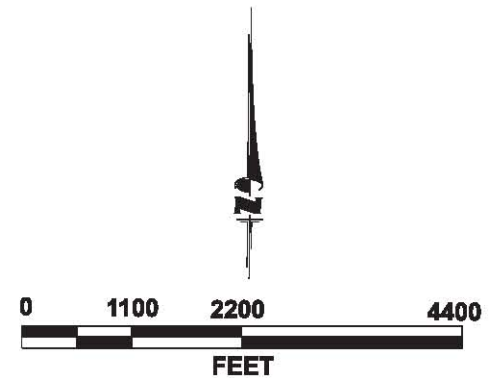
The calibrated numerical MODFLOW and MT3D models were used to evaluate the effectiveness of remedial actions that had been implemented by the Base, or that may be implemented in the future. These actions included a 400-foot-long air sparging curtain that was installed across the plume 450 feet downgradient from the source area, a proposed five-well groundwater extraction system in the off-Base plume hot spot, and a proposed 800-foot-long groundwater extraction trench approximately 2,200 feet downgradient from the source area. The simulation results suggested that, even with the existing sparge curtain and the implementation of all planned remedial actions, the dissolved TCE plume had the potential to migrate at least 10,000 feet beyond the August 1996 plume toe unless geochemical conditions are encountered along the plume flowpath that promote increased biodegradation rates and/or significant discharge of contaminated groundwater to surface water occurs (Figure 4.1). The predicted continuing migration is due primarily to the fact that substantial TCE concentrations had already migrated past the proposed location of the 800-foot-long extraction trench. In addition, the model results suggested that dissolved TCE concentrations in excess of  $5 \mu\text{g/L}$  (the federal maximum contaminant level [MCL]) had the potential to persist for more than 100 years.

Figure 4.1. Simulated OU5 TCE Plume (Year 2097) Assuming Air Sparging and Groundwater Extraction, Hill AFB, Utah



**LEGEND:**

- 5 Line of Equal TCE Concentration ( $\mu\text{g/L}$ ), August 1996
- Simulated TCE  $>50 \mu\text{g/L}$
- Simulated TCE  $5-50 \mu\text{g/L}$
- ← Inferred Groundwater Flow Direction





#### **4.1.5 Recommendations**

Based on the predicted migration and persistence of the TCE plume west of the proposed downgradient extraction trench, relocation of the extraction trench farther to the west (or installation of a second extraction system farther to the west) should be considered. Regular sampling of 14 existing and 5 new LTM wells was recommended to monitor the long-term migration and attenuation of the dissolved CAH plume. The plume should be tracked in the downgradient direction, and additional downgradient LTM wells and surface water sampling stations should be installed/sampled as required to allow assessment of whether additional engineering controls should be implemented, and to allow the model to be adjusted to reflect future conditions measured in the shallow aquifer. The estimated cost to perform 15 years of annual LTM (including 1 surface water station), followed by 15 years of biennial LTM (including 5 surface water stations), and to install up to 11 new LTM wells, was \$313,000.

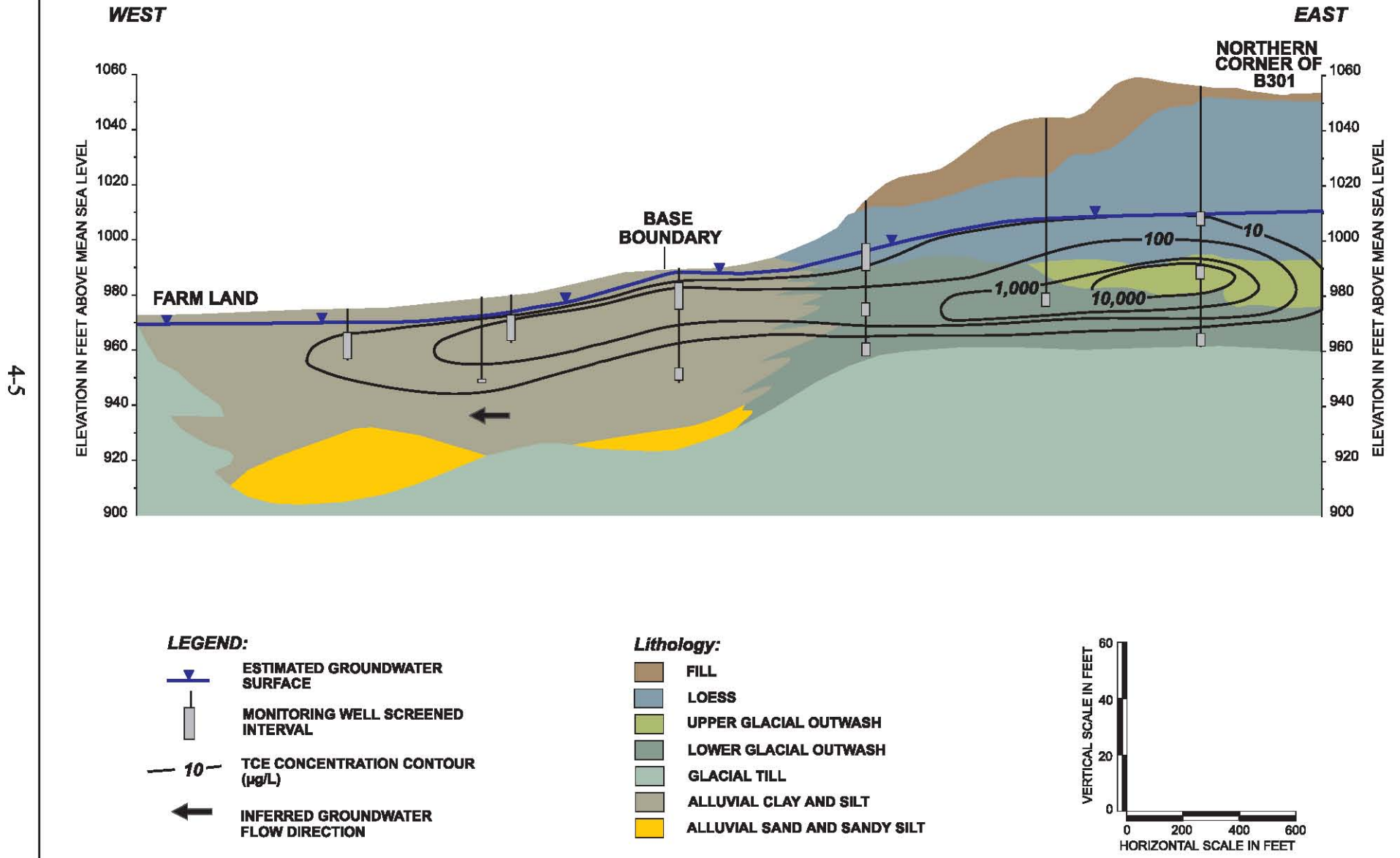
### **4.2 OFFUTT AIR FORCE BASE, NEBRASKA, BUILDING 301**

#### **4.2.1 Site Description**

The Building 301 (B301) complex was constructed in 1941 for the manufacture of bombers during World War II. Manufacturing operations ceased after the war, but were briefly resumed between 1959 and 1965 for the assembly of guided missiles. Solvents used during manufacturing operations are believed to be the source of groundwater contamination identified at the site. The specific source area for the B301 CAH plume has not been identified or characterized, and is presumed to be beneath the northwestern portion of the approximately 3.3-million-square-foot B301.

B301 is situated on a dissected Pleistocene alluvial terrace remnant of the Missouri River. To the west of B301, the ground surface slopes steeply downward into the primarily agricultural Papillion Creek alluvial valley. The uppermost water-bearing unit beneath the alluvial terrace is composed predominantly of well-sorted glaciofluvial sands and silty sands. The subsurface further west (downgradient) in the Papillion Creek valley consists mainly of clays and silts of alluvial origin, with intermittent sand lenses. The groundwater flow direction is westerly toward Papillion Creek. The depth to unconfined groundwater in the immediate vicinity of B301 is approximately 45 to 60 feet bgs, and decreases toward the west due to the steep decline in ground surface elevations (Figure 4.2). In the Papillion Creek valley, the depth to groundwater ranges from 3 to 10 feet bgs. Groundwater discharges to Papillion Creek and a drainage ditch in the valley west of the Base. The estimated groundwater velocity varies considerably across the site due to variations in hydraulic gradient and hydraulic conductivity, and ranges from less than 10 to nearly 2,000 feet per year (ft/yr). The primary remedial action objective for groundwater at and downgradient from B301 is limited plume expansion to prevent exposure of downgradient receptors to concentrations of CAHs in groundwater and surface water at levels that exceed regulatory levels of concern.

Figure 4.2. Cross-Section of B301 TCE Plume, 1996, Offutt AFB, Nebraska



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## 4.2.2 Extent and Magnitude of Contamination

TCE is the most prevalent CAH in both extent and concentration in groundwater at B301. A maximum TCE concentration of 25,000 µg/L was detected near the northwestern corner of B301, and the TCE plume extends westward approximately 2,800 feet from the suspected source area, terminating beneath a soybean field (Figure 4.2). The area of the TCE plume in July 1996 was approximately 73 acres. Vertical contaminant profiling indicates that the TCE migrates through the glacial outwash beneath the upland terrace, and through the alluvial clay and silt within the adjacent valley. In addition to TCE, lesser concentrations of PCE, DCE, and VC also were detected at maximum 1996 concentrations of 1.9 µg/L, 1,400 µg/L, and 1.3 µg/L, respectively. TCE also was detected in surface water samples from a drainage ditch at the edge of the Papillion Creek valley.

## 4.2.3 Natural Attenuation Processes and Rates

Limited biodegradation of TCE is occurring, primarily by reductive dechlorination to *cis*-1,2-DCE. The areas of most active reductive dechlorination appear to be characterized by Type 2 conditions and coincide with the Papillion Creek alluvial valley and possibly the source area. Between the source area and the Papillion Creek alluvial valley, Type 3 conditions prevail and may be accompanied by DCE oxidation. The inference that the most aggressive reductive dechlorination occurs within the alluvial valley is supported by observed depleted DO and nitrate concentrations, elevated ferrous iron and methane concentrations, a relatively low TCE-to-DCE ratio, and the presence of VC. Rates of CAH biodegradation estimated along the plume flowpath ranged from  $7 \times 10^{-4}$  to  $2 \times 10^{-5}$  day<sup>-1</sup>, corresponding to half-lives of 2.7 years to 95 years. Calculated decay rates for the downgradient portion of the plume in the Papillion Creek valley ranged from  $5 \times 10^{-4}$  to  $3 \times 10^{-5}$  day<sup>-1</sup> (half-lives of 3.8 years to 63 years).

## 4.2.4 Historical Trends and Modeling

Three sets of groundwater quality data collected between November 1991 and July 1996 indicated that TCE concentrations have been relatively uniform or have fluctuated erratically. Therefore, the available data did not indicate overall decreases in dissolved TCE concentrations during this period.

Numerical model simulations were made for three remedial alternatives. Alternative 1 was a baseline model that assumed that the contaminant source would not be removed. Because the source has not been characterized, and the presence of DNAPL could not be discounted, the continuing source term used to calibrate the model was left unchanged for the first 100 years of the model simulation to be conservative. Thereafter, TCE dissolution from the source was assumed to decrease at a rate of 1 percent per year (i.e., each year's TCE loading rate was 99 percent of the previous year's). Alternative 2 assumed that 10 years of dual-phase extraction would remove approximately 80 percent of the source TCE concentration, and the remaining source would weather at the rate of 1 percent per year. The model for Alternative 3 mimicked Alternative 2 in the source area; however, the effect of a hypothetical groundwater extraction trench that intercepted most of the TCE plume at the Base boundary also was simulated.

Because of the large range of possible TCE biodegradation rates in the alluvial silts and clays, two simulations for the alluvial portion of the plume were run for each of the three remedial scenarios: the first with a 24-year TCE half-life (intermediate between the upper- and lower-bound half-lives computed for the alluvium), and the second with a 4.5-year TCE half-life (best-case scenario). The TCE half-life assigned to the upgradient portion of the plume area for both simulations was 316 years (decay rate of  $6 \times 10^{-6} \text{ day}^{-1}$ ). This value was obtained during calibration of the fate and transport model, and is consistent with the evidence that significant biodegradation of TCE is not occurring between B301 and the Base boundary. Results of the 6 simulations are summarized in Table 4.1.

**TABLE 4.1**  
**SUMMARY RESULTS FROM MODEL SIMULATIONS FOR BUILDING 301**  
**OFFUTT AFB, NEBRASKA**

Simulation	TCE Half-Life in Alluvium (years)	Reduction in Source Strength	Maximum Downgradient Extent of TCE Plume
Alt.1 - MNA	24	0% after 100 years/ 63% after 200 years	Papillion Creek (8 µg/L at 200 years)
Alt.1 - MNA	4.5	0% after 100 years/ 63 % after 200 years	1,450 feet upgradient from Papillion Creek
Alt.2 - Dual-Phase Extraction (DPE)	24	80% after 10 years/ 97% after 200 years	Papillion Creek (4 µg/L at 200 years)
Alt.2 - DPE	4.5	80% after 10 years/ 97% after 200 years	1,500 feet upgradient from Papillion Creek
Alt.3 - DPE and Groundwater Extraction (GWE)	24	80% after 10 years/ 97% after 200 years	Papillion Creek (2 µg/L at 200 years)
Alt.3 - DPE and GWE	4.5	80% after 10 years/ 97% after 200 years	1,550 feet upgradient from Papillion Creek

#### 4.2.5 Recommendations

Alternative 1 (MNA with institutional controls) was recommended, at least for the short term. Available data indicate that the CAH plume is slowing and biodegrading west of the Base boundary, and is mostly contained within an easement area where land use is controlled by the Air Force. The degree to which natural attenuation will prevent further downgradient migration of the plume is uncertain, but should become more apparent as LTM events are performed, and contaminant decay rates and fate and transport predictions are refined. In addition, the shallow groundwater in the Papillion Creek valley near the plume is not being used as a drinking water or irrigation source, and may not represent a reliable groundwater source due to the low permeability of the alluvial deposits. To assess the effectiveness of naturally occurring processes at reducing contaminant mass and minimizing contaminant migration, groundwater and surface water sampling should continue on an annual basis for approximately 5 years, followed by less frequent sampling. The LTM plan should be periodically reevaluated and modified as

necessary on the basis of newly obtained data. If data collected at any time during the monitoring period indicate the need for additional remedial activities at the site, or if shortening of the LTM period is desired, then sampling frequency should be adjusted accordingly, and the appropriate remedial actions (e.g., dual-phase extraction and/or plume interruption at the Base boundary) should be implemented.

Source remediation was not recommended because the contaminant source has not been located or characterized. However, implementation of a source-reduction technology could provide significant benefits in reducing the overall remediation time frame. Therefore, if performance of source location activities beneath B301 is feasible, then a minimally intrusive soil gas survey beneath and adjacent to B301 should be considered to pinpoint subsurface TCE hot spots and facilitate design of a source-reduction system. The estimated present worth cost for the first 30 years of LTM (sampling 16 wells and 4 surface water stations annually for 5 years, followed by biennial sampling of 12 wells and 3 surface water stations for 25 years) was \$259,000.

### **4.3 CAPE CANAVERAL, FLORIDA FACILITY 1381 (SWMU 21)**

#### **4.3.1 Site Description**

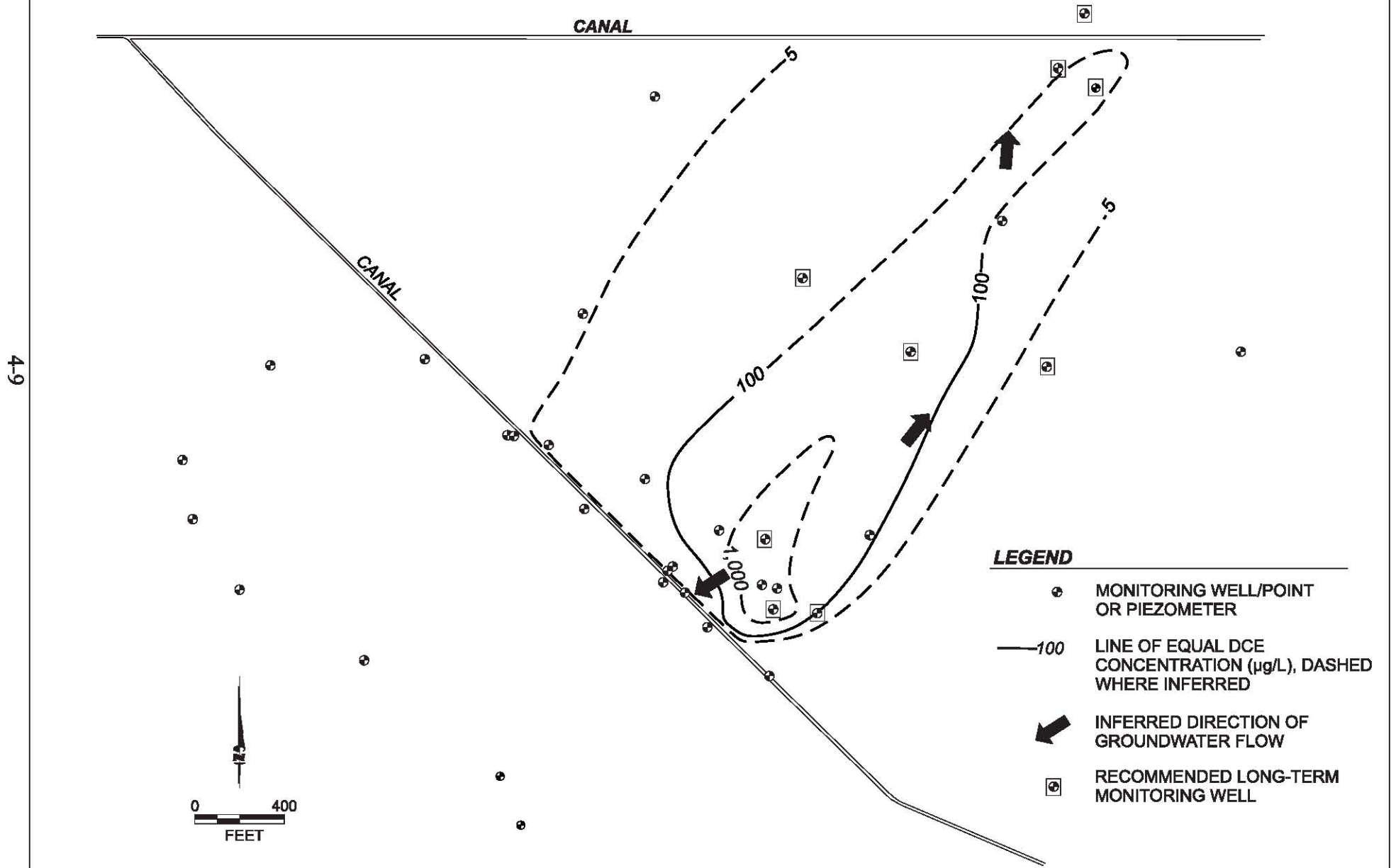
During the operation of an In-Place Precision Cleaning Lab (1968-1977), Facility 1381 housed acid and solvent dip tanks for cleaning metal components. Waste TCE was reportedly generated at a rate of approximately 3,300 gallons per year. Acids also were used, and were disposed of by discharging into a neutralization pit containing crushed limestone, which was located southwest of the building. CAH contamination is suspected to have resulted from accidental releases from past metal cleaning operations.

The topography of the site is relatively level, with ground elevations ranging from 5 to 8 feet above mean sea level. Drainage canals are located approximately 300 feet south/southwest and 2,500 feet north/northwest of the facility, and groundwater appears to discharge to the canals. The uppermost 35 feet of the subsurface consists of poorly sorted, coarse to fine sands and shell material. From 35 to 50 feet bgs, the grain size of the sands decreases, and the silt and clay content increases. Dissolved contaminants migrate primarily to the northeast, toward the northern drainage canal. The maximum advective groundwater velocity is estimated to be 77 ft/yr.

#### **4.3.2 Extent and Magnitude of Contamination**

TCE contamination was limited to a 200-foot radius from Facility 1381, and was detected at concentrations ranging up to 39,400 µg/L. DCE was the most widespread CAH detected in groundwater, comprising a plume approximately 3,100 feet in length and extending to the northern drainage canal (plume area of approximately 110 acres) (Figure 4.3). The maximum concentration of *cis*-1,2-DCE, which was the most prevalent DCE isomer, was 4,120 µg/L. DCE isomers detected at intermediate (25 to 30 feet bgs) and deep (45 to 50 feet bgs) monitoring well/point locations were limited to the source area at concentrations up to 1,360 µg/L. VC also is widespread at the site,

**Figure 4.3. Total DCE Concentrations Measured at Shallow Monitoring Wells/Points, September 1996  
 Facility 1381, Cape Canaveral Air Station, Florida**



and was detected in most groundwater samples, including those from wells adjacent to the northern drainage canal. The maximum detected VC concentration was 1,350 µg/L. Relatively low concentrations of 1,1,1-trichloroethane (TCA) (up to 130 µg/L) were detected south and southeast of Facility 1381. As of September 1996, CAH compounds had not been detected in surface water samples collected from the northern drainage canal.

### **4.3.3 Natural Attenuation Processes and Rates**

Reductive dechlorination of TCE to DCE appears to be occurring in Facility 1381 groundwater. DO concentrations below 0.5 mg/L throughout most of the plume area, substantial organic carbon concentrations, and the absence of significant anthropogenic carbon (e.g., petroleum hydrocarbons), indicated that Type 2 behavior was prevalent. All TCE concentrations were detected within 200 feet of the source area, indicating relatively rapid degradation to DCE. However, DCE and VC contamination extends from the source area to the northern canal, suggesting that dechlorination of DCE and VC are slower processes. The presence of ethene indicates dechlorination of VC is occurring. However, the strongly anaerobic nature of site groundwater inhibits the decay of VC, which is more easily biodegraded through oxidative processes. Available evidence further suggests that Type 1 behavior may have occurred in the source area at one time, based on detections of low concentrations of petroleum hydrocarbons (anthropogenic organic carbon).

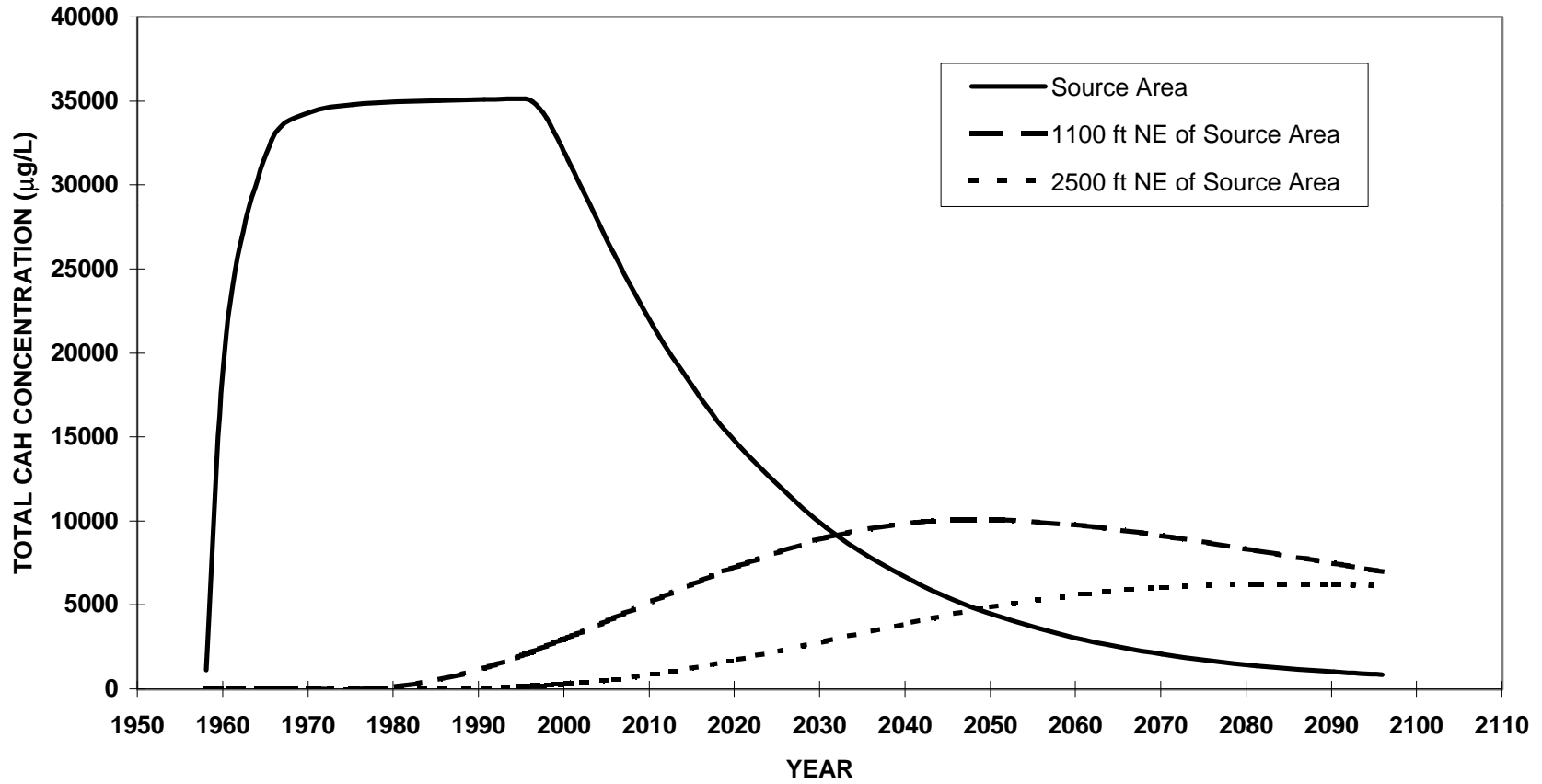
Estimated rates of CAH biodegradation range from  $3.21 \times 10^{-4}$  to  $1.0 \times 10^{-6}$  day<sup>-1</sup>, corresponding to half-lives ranging from 6 to 1,900 years, respectively. Higher decay rates predominate in the Facility 1381 source area, and lower decay rates appear to predominate in the downgradient portion of the plume. A conservative decay rate of  $1.1 \times 10^{-6}$  day<sup>-1</sup> was used in the calibrated fate and transport model.

### **4.3.4 Historical Trends and Modeling**

Despite the fact that the areal extent of TCE appears to have decreased from 1995 to 1997, TCE concentrations in nine wells that have historically exhibited TCE contamination have fluctuated erratically. Therefore, the available data do not conclusively indicate an overall trend in dissolved TCE concentrations during the time period for which analytical results are available.

A numerical model was used to simulate the fate and transport of total dissolved chlorinated ethenes. Model simulations indicated that, under the influence of natural attenuation alone (including natural source reduction at a rate of 4 percent per year), maximum DCE and VC concentrations will exceed state groundwater quality standards for more than 100 years, and CAH concentrations at downgradient monitoring wells will increase into the mid- to late 21<sup>st</sup> century (expanding plume, Figure 4.4).

**Figure 4.4. Simulated Future CAH Concentrations  
(4-Percent Source Reduction Per Year)  
Facility 1381, Cape Canaveral Air Station, Florida**





Additional simulations assumed that implementation of air sparging, dual-phase extraction, or a similar treatment technology would result in more rapid source reduction (25 to 50 percent per year). These simulations indicated that after 100 years, the groundwater plume would have approximately the same areal extent as the current plume, but would be substantially reduced in concentration (although concentrations above state groundwater quality standards would persist along the plume centerline). The benefits of source reduction would not be realized in the downgradient portion of the plume for decades because of the expanding nature of the plume and the low migration velocities.

#### **4.3.5 Recommendations**

Although the northern drainage canal could potentially receive the majority of groundwater contamination, the relatively slow groundwater velocities at the site indicate that contaminant mass flux into the stream also will be slow. The lack of CAH detections in surface water indicate that groundwater discharge does not currently pose a significant risk to surface water receptors. However, total CAH mass entering the creek may increase in the future because groundwater CAH concentrations are predicted to increase at downgradient wells. MNA is a viable alternative for treatment of the northward-migrating CAH-contaminated groundwater in the vicinity of Facility 1381. However, MNA may not be the sole remedy, as several source removal technologies will be evaluated as part of a corrective measures study. Annual sampling of groundwater at nine locations and of surface water at three locations is recommended for at least 20 years. Should LTM data suggest that MNA is not effective in reducing CAH concentrations, additional (engineered) remedial action may be necessary (e.g., an air sparging network or reactive wall designed to intercept and remove groundwater CAH contamination before it discharges to the northern canal).

### **4.4 SHAW AIR FORCE BASE, SOUTH CAROLINA, OPERABLE UNIT 4**

#### **4.4.1 Site Description**

OU4 encompasses the area impacted by activities at former Fire Training Area 1 on the eastern edge of Shaw AFB. The fire training area was used for weekly fire-fighting training exercises from 1941 through 1969. A variety of combustible wastes were burned during the training exercises, including jet fuel, waste oils, hydraulic fluids, spent solvents, contaminated fuels, and napalm. Waste materials were hauled to the site in drums and poured into unlined burn pits for ignition.

The shallow aquifer at OU4 is characterized by mostly medium to very coarse sands with gravelly layers, all containing interstitial fine sands and clays. A clay layer referred to as the "100-foot clay" separates the shallow aquifer from the underlying Lower Black Creek Aquifer. The average groundwater velocity in the shallow aquifer is estimated to be 2.1 ft/day. The nearest receptor exposure points for groundwater contamination are Long Branch Creek, which borders the downgradient edge of the site, and Booths Pond, into which Long Branch Creek discharges. Groundwater contamination appears to be discharging to Long Branch Creek. The areas beyond Long Branch Creek and off-Base are largely rural/residential, and the land is used primarily for agricultural purposes.

#### 4.4.2 Extent and Magnitude of Contamination

Three contaminant sources were identified that contained LNAPL floating on the water table or residual contamination sorbed to soils. The majority of the dissolved CAH contamination appears to be sourced at a suspected former fire training pit. The CAHs 1,1,1-TCA, 1,1-DCA, 1,2-DCA, PCE, TCE, *cis*- and *trans*-1,2-DCE, 1,1-DCE, and VC were detected in groundwater. 1,1,1-TCA, *cis*-1,2-DCE, and 1,1-DCA constituted approximately 94 percent of the contaminant mass in the groundwater CAH plume, with maximum concentrations of 23,000 µg/L, 4,590 µg/L, and 8,700 µg/L, respectively. The multiple sources have created a dual-lobed plume with a maximum lobe length of 650 feet and a maximum plume area (both lobes combined) of 8.2 acres (Figure 4.5). Groundwater contamination predominantly resides in the upper 35 feet of the shallow aquifer.

#### 4.4.3 Natural Attenuation Processes and Rates

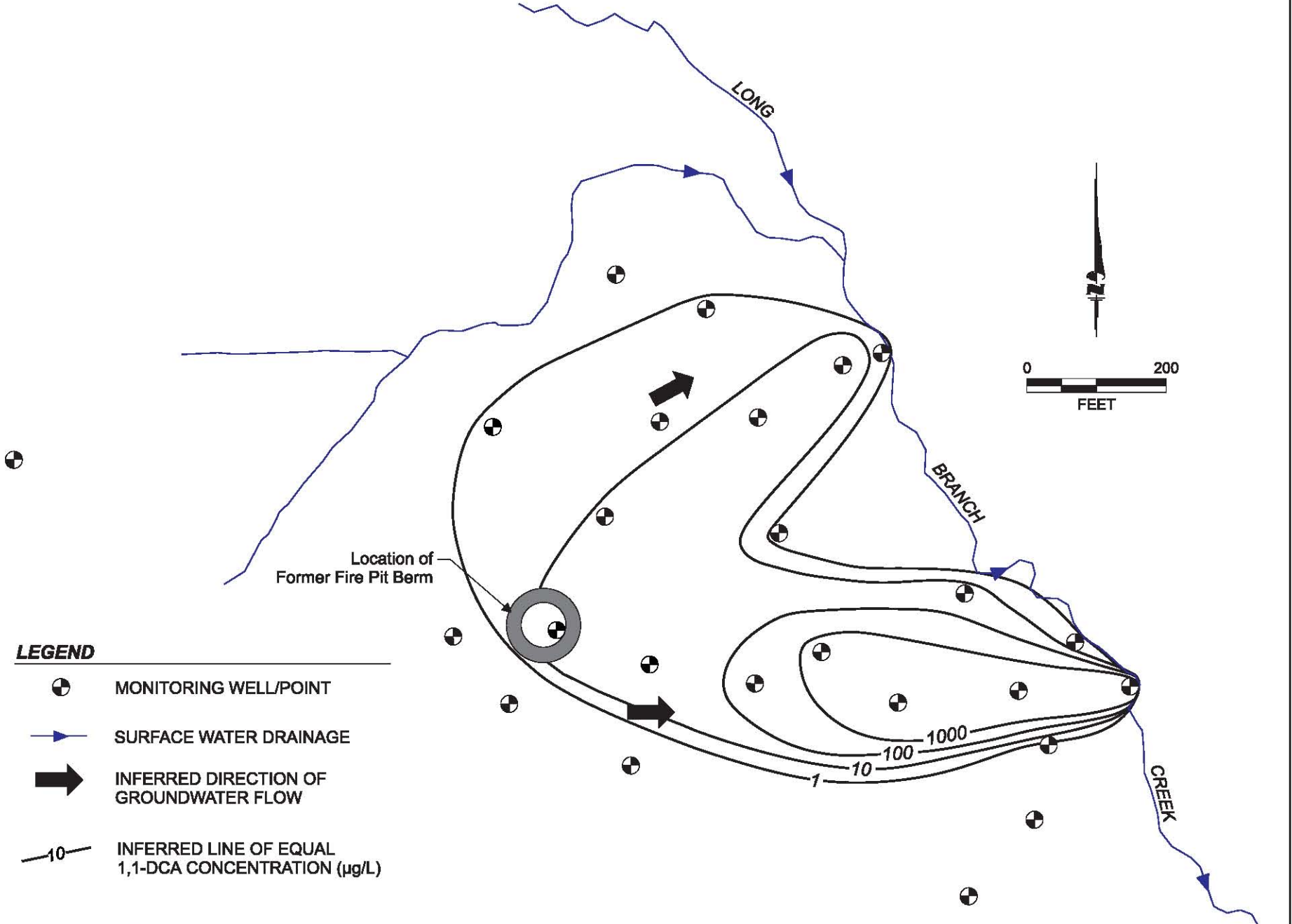
Site data indicate that CAH contaminants at OU4 are being biodegraded, either as substrates (electron donors) or electron acceptors. The presence of DCE (primarily *cis*-1,2-DCE which is not a commonly used solvent) and VC provides the primary line of chemical evidence for reductive dechlorination of chlorinated ethenes. The presence of 1,1-DCA suggests that 1,1,1-TCA also is being reductively dechlorinated. Low levels of ethane and ethene in the southern plume lobe indicate that groundwater conditions in that area are sufficiently reducing for dechlorination processes to proceed to completion. Relatively high 1,1-DCE concentrations coincide with significant 1,1,1-TCA concentrations, but TCE concentrations (potential parent product of 1,1-DCE under dechlorinating conditions) are relatively low at these same locations. It therefore appears that 1,1,1-TCA may be both reductively dechlorinated to 1,1-DCA and abiotically transformed to 1,1-DCE. The dissolved CAH plume at OU4 exhibits Type 1 behavior in the cores of the plume lobes, based on the presence of dissolved fuel constituents. Oxygenated waters near Long Branch Creek create a narrow zone of Type 3 conditions that are conducive to the oxidation of VC, and possibly also of DCE and DCA.

#### 4.4.4 Historical Trends and Modeling

A comparison of groundwater data sets from March through May 1993 and March 1997 indicated that CAH concentrations at individual monitoring wells generally have fluctuated over time, with no clear trends of increasing or decreasing concentrations within the primary source areas. The Visual MODFLOW and MT3D<sup>96</sup>® codes were used to simulate the effectiveness of three remedial actions that may be implemented by the Base: 1) MNA with no source removal; 2) installation of a soil vapor extraction (SVE) system to remediate the primary source area; and 3) groundwater extraction and treatment to limit contaminant discharge to Long Branch Creek. 1,1,1-TCA is the CAH exhibiting the highest concentrations in groundwater, and without source removal, concentrations of this analyte are not predicted to drop below the site-specific

Figure 4.5. 1,1-DCA in OU4 Groundwater, Shaw AFB, South Carolina

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groundwater cleanup goal (1,000 µg/L) for approximately 100 years unless abiotic degradation (hydrolysis) of this compound speeds the compliance time frame. The use of SVE is anticipated to expedite groundwater remediation by at least 10 years, but is dependent on the successful remediation of relatively thin zones of LNAPL contamination. Groundwater extraction rates in excess of 20 gallons per minute (gpm) near the primary source area would promote the retreat of the groundwater plume toward the source area and future stabilization of a smaller, less concentrated plume.

#### **4.4.5 Recommendations**

Model results suggest that the USEPA drinking water standard (200 µg/L) and the aquatic life criterion for 1,1,1-TCA will not be exceeded in Long Branch Creek at any time in the future because natural attenuation, volatilization, and stream dilution sufficiently reduce contaminant concentrations. However, implementation of engineered source reduction is most acceptable to the public and regulatory agencies because without concurrent source reduction, LTM or any planned groundwater extraction and treatment may have to be performed indefinitely. Source treatment through SVE has the potential to accelerate groundwater remediation time, possibly more rapidly than predicted by the computer model. If future LTM data indicate that 1,1,1-TCA is discharging into Long Branch Creek at levels of concern, then additional groundwater treatment in the form of an air sparging curtain or groundwater pump-and-treat system may need to be implemented. Conversely, if LTM results demonstrate that the plume is stable or receding, and surface water standards continue to be met, then the frequency of LTM could potentially be reduced. The estimated cost to perform 20 years of annual LTM (12 wells and 6 surface water stations), maintain institutional controls, install four new LTM wells, and install and operate an SVE system for 5 years, was \$594,000, compared to \$232,000 for MNA and institutional controls alone.

## SECTION 5

### COST ANALYSIS

The cost of each natural attenuation TS included the performance of an initial site visit and presentation, work plan development, field sampling/testing, data review, groundwater modeling, report preparation, and presenting the TS results to the Air Force and regulators at a final meeting. Groundwater samples were analyzed in the field for a suite of physical and geochemical biodegradation indicator parameters, and at a fixed-base laboratory for contaminants and geochemical parameters that could not be analyzed in the field. Soil sampling probes were advanced, and small-diameter groundwater monitoring points were installed using a Geoprobe® or cone penetrometer. The finite-difference models MODFLOW and MT3D generally were used to calibrate the groundwater model, perform sensitivity analyses, and to predict the future fate and transport of the dissolved CAH plume. These model predictions were used to assess the effectiveness of natural attenuation processes either alone or in conjunction with existing or potential future engineered remedial technologies. A conceptual engineering design of remedial alternatives was performed, and an LTM plan was developed.

Based on TS costs for the 14 natural attenuation evaluation sites, the average cost for a CAH natural attenuation TS as described above was approximately \$122,000 per site (Table 5.1). This estimate includes installation of an average of 9 new monitoring wells to augment the existing well networks and delineate the horizontal and vertical extents of the dissolved CAH plumes.

The first remedial alternative evaluated for 11 of the sites consisted solely of MNA with institutional controls. The average present worth cost to implement this alternative over a monitoring period ranging from 10 to 49 years (average 26 years) with an average LTM network of 17 wells and 3 surface water station was estimated to be \$480,000. The addition of engineered remediation in the source area (e.g., SVE or dual-phase extraction) increased the estimated average remedial cost to \$876,000 per site but did not always significantly reduce the time to achieve groundwater MCLs. At Shaw AFB Site OU-4, the similarity in remediation time frames stemmed from the fact that the simulated source reduction rate for Alternative 2 (SVE) was only 5 to 8 percent per year, compared to 3 percent per year for Alternative 1 (MNA). The overall effectiveness of SVE at remediating the thin free product layer at that site was predicted to be low. At Randolph AFB Site FT004, the model predicted that the maximum dissolved CAH concentrations had migrated downgradient from the source area to an uncharacterized, off-Base area. The model also predicted that installation of an on-Base pump and treat system (remedial alternative 2) would not remediate the off-Base portion of the plume more rapidly than natural attenuation (remedial alternative 1).

**Table 5.1  
Typical Natural Attenuation Treatability Study Costs**

Task	Geoprobe®/Cone Penetrometer
Site Visit/Technical Support <sup>a/</sup>	\$9,010
Work Plan/Regulatory Approval <sup>b/</sup>	\$20,300
Field Work Labor	\$9,760
Field Work Other Direct Costs (ODCs)	
Survey/Supplies/Per Diem	\$6,150
Geoprobe®/Cone Penetrometer Operation	\$878
Data Analysis/Analytical	\$18,200
Total Field Work ODCs	\$25,300
Modeling	\$19,400
Treatability Study Report <sup>c/</sup>	\$38,100
<b>Total Project:</b>	\$122,000

<sup>a/</sup> Includes kickoff meeting, post-reporting meeting, and regulatory support.

<sup>b/</sup> Includes draft and final versions, and gathering/analyzing available site data.

<sup>c/</sup> Includes draft and final versions, with formal written responses to review comments on the draft report.

The average cost for more aggressive site remediation approaches employing a combination of natural attenuation, source treatment, and plume containment via hot spot pumping downgradient groundwater extraction or installation of a downgradient air sparging curtain was estimated to be approximately \$1.8 million based on estimates for two sites. Although these more aggressive approaches were designed to be more protective of downgradient receptors, the addition of downgradient plume containment did not accelerate remediation times.

## **SECTION 6**

### **LESSONS LEARNED**

Lessons learned regarding site characterization, fate and transport modeling, the effectiveness of natural attenuation of CAHs, and the implementation of the MNA remedial alternative are summarized in this section.

#### **6.1 SITE CHARACTERIZATION**

- Successful documentation of natural attenuation of CAHs in the subsurface involves combining multiple lines of evidence, including geochemical evidence and documented loss of contaminant mass at the field scale. In addition, delineation of the magnitude and extent of the dissolved contaminant plume and the source area(s) is necessary. Therefore, rapid, low-cost collection of adequate field data is desirable. Use of a Geoprobe® or cone penetrometer to collect soil samples, investigate subsurface stratigraphy, and install small-diameter groundwater monitoring points proved advantageous except where the water table was relatively deep (greater than 20 feet bgs) or where subsurface obstructions (e.g., gravel/cobbles) were present.
- Time-sensitive geochemical indicators such as DO, ORP, pH, and temperature should be analyzed for in the field during well purging. The use of a continuous-flow apparatus to protect extracted groundwater from interference by reoxygenation is recommended for best results. Analysis for other geochemical parameters, including alkalinity, Fe (II), and sulfate, also can be performed quickly and inexpensively in the field. Nitrate tests performed in the field are susceptible to chemical interference and analysis error; therefore, they generally should be performed at a fixed-base laboratory.

#### **6.2 NATURAL ATTENUATION SCREENING**

Before investing in a detailed study of natural attenuation at a site, an accurate assessment of the potential for natural biodegradation of chlorinated compounds should be made. It should be determined if natural bioattenuation of CAHs is likely to be a remedial alternative before time and money are expended for a more active form of remediation. The bioattenuation screening process described in USEPA (1998) and Wiedemeier *et al.*, (1999) is designed to recognize geochemical environments where reductive dechlorination is possible. Solute transport models such as the BIOCHLOR natural attenuation model (Aziz *et al.*, 1999) can be used during the screening process to evaluate whether the efficiency of natural attenuation is sufficient to prevent contaminant transport to sensitive receptors.

### 6.3 FATE AND TRANSPORT MODELING

- At sites with relatively simple hydrogeology, 1-D analytical models (e.g., BIOCHLOR) may be sufficient to determine the persistence and migration potential of the dissolved CAH plume. However, the ability of such models to simulate spatial heterogeneities in the aquifer or the contaminant source, and the effects of weathering and engineered source reduction is limited. In addition, the effects of other types of remedial systems such as air sparging curtains or groundwater extraction systems cannot be simulated. Therefore, more sophisticated (2- or 3-D) numerical groundwater models are recommended for more complex sites or where more precise simulation of the effects of engineered treatment is desired.
- Reasonably conservative input parameters should be used for groundwater models so that the simulated persistence and migration potential of the dissolved plume are not likely to exceed that predicted by the model.
- Accurate prediction of contaminant fate and transport often is hindered by incomplete characterization of the contaminant source and inability to predict the natural source weathering rate.
- Use of software codes that have the following simulation capabilities is desirable:
  - Biological decay using higher-order kinetic models;
  - Multi-species chemical fate and transport (e.g., parent and daughter products); and
  - Spatial variability of input parameters that affect contaminant fate and transport.

### 6.4 EFFECTIVENESS OF NATURAL ATTENUATION

- The mechanisms of CAH biodegradation have been widely documented in the literature. Therefore, laboratory microcosm studies generally are not necessary to document the site-specific biodegradation potential or the presence of a native CAH-degrading microbial population. However, microcosm studies may be useful for determining site-specific biodegradation potential for less studied compounds. At most sites, two important questions must be answered regarding natural chemical attenuation:
  1. Are historical data available to show a stabilized or receding plume?
  2. Is there evidence in the form of biodegradation daughter products or altered geochemical trends at the site that supports the occurrence of biological attenuation?
- The degree and rate of intrinsic bioremediation of CAHs is site-specific and is dependent on the prevailing biochemistry and geochemistry of the site (i.e., Type 1, Type 2, Type 3, or mixed environments [Wiedemeier *et al.*, 1996 and 1998]).
- Dissolved CAH plumes can migrate long distances (i.e., more than 1 mile) in the subsurface, and interact with varying hydrogeologic and geochemical environments.



- Biodegradation rates can vary substantially within a single plume. Total destructive CAH attenuation rates computed for TCE, *cis*-1,2-DCE, and total chlorinated ethenes using the method of Buscheck and Alcantar (1995) ranged from  $5.0 \times 10^{-5} \text{ day}^{-1}$  to  $1.3 \times 10^{-2} \text{ day}^{-1}$ , with geometric mean and median values of  $4.2 \times 10^{-4} \text{ day}^{-1}$  and  $4.9 \times 10^{-4} \text{ day}^{-1}$ , respectively. These rates are similar to biodegradation rates computed using a conservative tracer, which ranged from  $3.0 \times 10^{-4} \text{ day}^{-1}$  to  $7.4 \times 10^{-4} \text{ day}^{-1}$ . Total CAH reductive dechlorination rates computed using the method of Moutoux *et al.* (1996) ranged from  $4.0 \times 10^{-8} \text{ day}^{-1}$  to  $2.5 \times 10^{-3} \text{ day}^{-1}$ , with geometric mean and median values of  $8.8 \times 10^{-6} \text{ day}^{-1}$  and  $1.4 \times 10^{-5} \text{ day}^{-1}$ , respectively.
- Some correlation was observed between field biodegradation rates and the following parameters: minimum ORPs and plume sulfate concentrations, plume "hotspot" TOC concentrations, groundwater temperature, plume length, maximum dissolved hydrogen and BTEX concentrations, and average groundwater velocities.
- Correlations between field biodegradation rates and maximum methane and CAH concentrations were not apparent.
- Although MNA with institutional controls alone was recommended at only two of the 14 sites, the recommendation for the remaining sites included remediation of at least a portion of the plume via MNA. Typically, source-reduction measures were recommended at these sites, and downgradient plume cutoff also was recommended for several sites to protect downgradient receptors and/or prevent off-Base migration.
- Model simulation results indicate that, in many cases, conservative groundwater quality standards (i.e., drinking water standards) will not be uniformly achieved within 100 years without the implementation of an aggressive and costly remedial program to significantly reduce elevated concentrations of CAHs in the source area and throughout the plume.

## 6.5 GENERAL IMPLEMENTATION

- Most states are now receptive to the use of MNA for dissolved BTEX plumes, and some have published guidance regarding performance of natural attenuation studies. The acceptance of MNA for CAHs is not as pervasive. Early coordination with concerned regulatory agencies is important. The burden of proof is on the investigator to adequately document the effectiveness of natural attenuation at stabilizing groundwater contamination and protecting human health and the environment. Important factors to consider when proposing MNA are the required level of groundwater modeling, the proximity of downgradient receptor exposure points, and the potential value of source reduction technologies in reducing LTM time frames and obtaining regulatory acceptance of a site closure strategy.
- The average cost of a natural attenuation TS was \$122,000. The average present worth cost to implement MNA with institutional controls over an average monitoring period of 26 years was estimated to be \$480,000. The addition of engineered remedial actions increases this cost substantially, but may not result in compliance with groundwater MCLs within an acceptable timeframe.

- This AFCEE initiative, combined with other state and USEPA natural attenuation studies, has laid the groundwork for increasing regulatory acceptance of natural attenuation as a valuable component of a remediation strategy for dissolved CAH plumes.

## SECTION 7

### RECOMMENDATIONS

The “lessons learned” from this initiative suggest that MNA will be a viable option for at least a portion of the dissolved CAH plumes at many sites. In most cases, some type of source reduction may be necessary to accelerate attainment of target cleanup levels and to restrict plume migration. In some cases, hot spot pumping and/or downgradient plume interception also may be required to achieve remedial action objectives. It should be noted that hot spot pumping may result in aerobic groundwater conditions and diminish the effectiveness of reductive dechlorination. Therefore, this approach is not recommended where significant anaerobic degradation is occurring, including destruction of DCE and VC. In cases where engineered remediation is required to reduce the remediation time frame or to protect potential receptors, low-cost, *in situ* source reduction techniques (e.g., SVE, air sparging) should be considered to speed the remediation process. If air sparging is considered, the effects of oxygen addition on biodegradation rates should be considered. More costly remediation techniques (e.g., reactive barriers and groundwater extraction and treatment) should be implemented only if the plume poses an imminent threat to human health or the environment (e.g., the plume is impacting or will shortly impact a receptor exposure point such as a drinking water well or an ecologically sensitive area).

Recent advances in modeling software will enhance the confidence in fate and transport predictions for dissolved CAHs. Where appropriate, state-of-the-art modeling software should be used to obtain the most realistic results and facilitate development of remedial alternatives.

Implementation of MNA is aided by the fact that many sites already have an established monitoring well network, and the need for installation of additional LTM wells is typically minimal. LTM programs generally are simple to implement and involve only periodic groundwater sampling and project oversight with respect to reporting contaminant trends, maintaining institutional controls until remedial standards are achieved, and public education. In summary, the results of this study support an Air Force requirement to evaluate natural attenuation as a potential remedy for solvent-contaminated groundwater before considering other more costly alternatives.

Enhanced reductive dechlorination of CAHs via addition of carbon or hydrogen are potentially promising remedial alternatives that should be tested further. The objective of carbon addition is to create the redox and electron donor conditions necessary to promote microbial reductive dechlorination of CAHs. During biologically mediated reductive dechlorination, hydrogen is used directly as an electron donor. Hydrogen is produced in the subsurface by the fermentation of a wide variety of organic compounds, including petroleum hydrocarbons, lactate, and natural organic carbon. Because of its importance in

the metabolism of the microbial organisms, the relative supply of dissolved hydrogen precursors compared to the amount of CAHs that must be degraded is an important consideration (Wiedemeier *et al.*, 1999).

## SECTION 8

### REFERENCES CITED AND LIST OF RNA TS REPORTS

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**APPENDIX A**

**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION  
OF CHLORINATED SOLVENTS AT MULTIPLE AIR FORCE  
DEMONSTRATION SITES**

**TABLE A.1**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		STATUS		CONTAMINANT		ASSISTANCE
Air Force Facility	Site	DRAFT REPORT DATE	FINAL REPORT DATE	CAHs	Fuels	USEPA or USACE Involvement? <sup>b/</sup>
Altus AFB, OK	OU1	Nov-97	Nov-99	X	X	USEPA
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	Oct-97	Nov-99	X	X	USEPA/USACE
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	May-97	-- <sup>a/</sup>	X	X	USEPA/USACE
Columbus AFB, MS	LF-06	Aug-97	--	X	X	None
Hill AFB, UT	OU1	Feb-98	Sep-99	X	X	USEPA
Hill AFB, UT	OU5	Dec-97	Dec-97	X	--	USEPA
Offutt AFB, NE	Building 301	Jun-97	Oct-97	X	--	USEPA/USACE
Plattsburgh AFB, NY	FT-002	Apr-95	Apr-95	X	X	USEPA/USACE
Randolph AFB, TX	FT004	May-98	--	X	X	USEPA/USACE
Shaw AFB, SC	Site OU-4	May-98	Sep-99	X	X	USEPA/USACE
Tinker AFB, OK	FTA-2	Apr-99	Nov-99	X	X	USEPA
Tinker AFB, OK	Area A	Apr-99	Nov-99	X	X	USEPA
F.E. Warren AFB, WY	LF-03	Aug-99	Nov-99	X	--	USEPA
Travis AFB, CA	SD036	Apr-98	Nov-99	X	X	None

<sup>a/</sup> "--" = Not applicable or not available.

<sup>b/</sup> USEPA = US Environmental Protection Agency.

USACE = US Army Corps of Engineers.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		SAMPLING EVENTS	PLUME DIMENSIONS							
Air Force Facility	Site	At Least 2 Parsons Field Mobilizations?	BTEX Plume Length (feet)	BTEX Plume Width (feet)	BTEX Plume Thickness (feet)	BTEX Plume Area (acres)	VC Plume Length (feet)	VC Plume Width (feet)	VC Plume Area (acres)	cis-1,2-DCE Plume Length (feet)
Altus AFB, OK	OU1	No	2750	500	-- <sup>a/</sup>	19.3	--	--	--	3125
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	Yes	2400	1800	--	90.9	3000	1400	83	3100 <sup>b/</sup>
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	Yes	1550	350	--	10.5	1225	500	15	1225
Columbus AFB, MS	LF-06	No	1000	750	--	13.5	1500	375	15	625
Hill AFB, UT	OU1	No	600	3180	--	45	2400	1600	71	4600
Hill AFB, UT	OU5	No	--	--	--	--	--	--	--	1750
Offutt AFB, NE	Building 301	No	--	--	--	--	--	--	--	1680/1110 <sup>c/</sup>
Plattsburgh AFB, NY	FT-002	No	2800	500	400	47.3	2000	500	27	--
Randolph AFB, TX	FT004	No	450	425	25	3.5	--	--	--	1800
Shaw AFB, SC	Site OU-4	Yes	625	875	--	9.5	600	300	3.3	600
Tinker AFB, OK	FTA-2	No	300	100	--	--	350	200	--	1450/1500 <sup>c/</sup>
Tinker AFB, OK	Area A	No	750	300	--	4.1	600	350	3.2	600
F.E. Warren AFB, WY	LF-03	No	--	--	--	--	--	--	--	1650
Travis AFB, CA	SD036	Yes	--	--	--	--	230	125	0.5	600

<sup>a/</sup> "--" = Not applicable or not available.

<sup>b/</sup> Total DCE.

<sup>c/</sup> Values given for two hydrostratigraphic units.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		PLUME DIMENSIONS							
Air Force Facility	Site	cis-1,2-DCE Plume Width (feet)	cis-1,2-DCE Plume Area (acres)	1,1-DCE Plume Length (feet)	1,1-DCE Plume Width (feet)	1,1-DCE Plume Area (acres)	trans-1,2-DCE Plume Length (feet)	trans-1,2-DCE Plume Width (feet)	trans-1,2-DCE Plume Area (acres)
Altus AFB, OK	OU1	1000	67	1500	500	15.8	2750	875	42
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	1650 <sup>a/</sup>	110 <sup>a/</sup>	-- <sup>b/</sup>	--	--	--	--	--
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	500	17.1	--	--	--	--	--	--
Columbus AFB, MS	LF-06	550	7.5	--	--	--	--	--	--
Hill AFB, UT	OU1	2240	210	--	--	--	--	--	--
Hill AFB, UT	OU5	350	15	--	--	--	--	--	--
Offutt AFB, NE	Building 301	600/325 <sup>c/</sup>	22/6.8 <sup>c/</sup>	--	--	--	--	--	--
Plattsburgh AFB, NY	FT-002	--	--	-- <sup>d/</sup>	-- <sup>d/</sup>	-- <sup>d/</sup>	-- <sup>d/</sup>	-- <sup>d/</sup>	-- <sup>d/</sup>
Randolph AFB, TX	FT004	450	19	--	--	--	--	--	--
Shaw AFB, SC	Site OU-4	600	6.5	600	275	2.4	--	--	--
Tinker AFB, OK	FTA-2	500/700 <sup>c/</sup>	12/20 <sup>c/</sup>	--	--	--	900/900 <sup>c/</sup>	525/300 <sup>c/</sup>	7.8/4.6 <sup>c/</sup>
Tinker AFB, OK	Area A	350	3.2	--	--	--	--	--	--
F.E. Warren AFB, WY	LF-03	600	7	--	--	--	--	--	--
Travis AFB, CA	SD036	315	3.7	--	--	--	350	210	1.4

<sup>a/</sup> Total DCE.

<sup>b/</sup> "--" = Not applicable or not available.

<sup>c/</sup> Values given for two hydrostratigraphic units.

<sup>d/</sup> DCE detected but not mapped.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		PLUME DIMENSIONS								
Air Force Facility	Site	Chlorobenzene Plume Length (feet)	Chlorobenzene Plume Width (feet)	Chlorobenzene Plume Area (acres)	Ethene Plume Length (feet)	Ethene Plume Width (feet)	Ethene Plume Area (acres)	TCE Plume Length (feet)	TCE Plume Width (feet)	TCE Plume Area (acres)
Altus AFB, OK	OU1	-- <sup>a/</sup>	--	--	--	--	--	4750	1250	118
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	--	--	--	1550	400	13	200	350	1.6
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	--	--	--	1250	375	11	1225	385	11.7
Columbus AFB, MS	LF-06	1375	600	15.48	--	--	--	--	--	--
Hill AFB, UT	OU1	--	--	--	300	2500	20	900/700 <sup>b/</sup>	300/800 <sup>b/</sup>	10.5/10.5 <sup>b/</sup>
Hill AFB, UT	OU5	--	--	--	--	--	--	5250	1300	126
Offutt AFB, NE	Building 301	--	--	--	--	--	--	3500	850	73
Plattsburgh AFB, NY	FT-002	--	--	--	--	--	--	4700	2000	175
Randolph AFB, TX	FT004	--	--	--	--	--	--	1230	300	8.9
Shaw AFB, SC	Site OU-4	450	150	1.37	575	125	1.4	650	550	5.2
Tinker AFB, OK	FTA-2	1000	600	--	--	--	--	1700/1500 <sup>b/</sup>	550/850 <sup>b/</sup>	17/24 <sup>b/</sup>
Tinker AFB, OK	Area A	--	--	--	650	300	4.4	650	150	1.8
F.E. Warren AFB, WY	LF-03	--	--	--	--	--	--	1860	750	21
Travis AFB, CA	SD036	--	--	--	--	--	--	700	600	6

<sup>a/</sup> "--" = Not applicable or not available.

<sup>b/</sup> Values given for two hydrostratigraphic units.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		CHEMICAL DATA							
Air Force Facility	Site	Plume Type (I,II,III)	Maximum Observed CAHs (mg/L)	Maximum Observed PCE (mg/L)	Maximum Observed TCE (mg/L)	Maximum Observed 1,1-DCE (mg/L)	Maximum Observed cis 1,2-DCE (mg/L)	Maximum Observed trans 1,2-DCE (mg/L)	Maximum Observed VC (mg/L)
Altus AFB, OK	OU1	I	13800	ND	12700	4.3	1340	33.3	-- <sup>a/</sup>
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	I & II	44182	3.3	39400	238	4120	145	1350
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	I & II	118756	56	15800	200	98500	389	6520
Columbus AFB, MS	LF-06	I & III	47.54	--	7.4	2.7	15	ND <sup>b/</sup>	10
Hill AFB, UT	OU1	I & III	9486	3	490	12.7	7083	63.4	469
Hill AFB, UT	OU5	II & III	361.4	253	355	2.3	15.6	< 1.0	ND
Offutt AFB, NE	Building 301	II & III	18737	1.9	17500	28.6	1230	9.4	1.3
Plattsburgh AFB, NY	FT-002	I & III	30325	--	1330	--	10900	3.3	2080
Randolph AFB, TX	FT004	I & III	675.4	3	54.4	ND	224	< 1	13.1
Shaw AFB, SC	Site OU-4	I & III	30238	90.7	718	748	4590	2.1	416
Tinker AFB, OK	FTA-2	I & III	10627	52	9440	9.5	1200	77	6.6
Tinker AFB, OK	Area A	I	2619	5.2	1120	3.1	1680	126	787
F.E. Warren AFB, WY	LF-03	I & III	--	ND	93.1	ND	50	5.7	ND
Travis AFB, CA	SD036	I	4520	114	2930	5.8	3820	112	315

<sup>a/</sup> "--" = Not applicable or not available.

<sup>b/</sup> ND = Not detected.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		CHEMICAL DATA				GEOCHEMICAL DATA			
Air Force Facility	Site	Maximum Observed 1,1,1-TCA (mg/L)	Maximum Observed CB (mg/L)	Maximum Observed 1,1-DCA (mg/L)	Maximum Observed Total BTEX (mg/L)	Maximum Dissolved Hydrogen (nM/L)	Minimum Dissolved Oxygen Plume (mg/L)	Average Dissolved Oxygen Background (mg/L)	Minimum Nitrate Plume (mg/L)
Altus AFB, OK	OU1	-- <sup>a/</sup>	--	--	43	2.24	< 0.1	1.18	<0.05
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	130	--	26.4	6.4	5.97	< 0.1	1.14	< 0.05
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	258	--	443	331	1.8	0.1	1	< 0.05
Columbus AFB, MS	LF-06	3.8	23	1.2	48	--	0.15	3.38	0.1
Hill AFB, UT	OU1	257	3465	187	1557	1.4	< 0.1	9.05	< 0.05
Hill AFB, UT	OU5	64	ND <sup>b/</sup>	5.6	ND	5	0.3	4.5	0.17
Offutt AFB, NE	Building 301	ND	--	1	ND	9.58	0.2	5.35	<.05
Plattsburgh AFB, NY	FT-002	--	--	--	6010	--	0.1	10	< 0.06
Randolph AFB, TX	FT004	--	--	--	121	5.97	0.2	5.46	<0.05
Shaw AFB, SC	Site OU-4	23000	9.2	8700	3290	19.02	< 0.1	6	< 0.05
Tinker AFB, OK	FTA-2	ND	117	4.6	7.2	--	0.2	3.5	0.27
Tinker AFB, OK	Area A	ND	ND	3.5	42739	--	0.1	2.2	< 0.05
F.E. Warren AFB, WY	LF-03	ND	--	ND	2.1	--	1.04	7.5	0.98
Travis AFB, CA	SD036	--	--	--	--	--	< 0.2	4.0	0.09

<sup>a/</sup> "--" = Not applicable or not available.

<sup>b/</sup> ND = Not detected.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		GEOCHEMICAL DATA								
Air Force Facility	Site	Average Nitrate Background (mg/L)	Max. Iron (II) Plume (mg/L)	Average Iron (II) Background (mg/L)	Min. Sulfate Plume (mg/L)	Average Sulfate Background (mg/L)	Maximum Methane Plume (mg/L)	Average Methane Background (mg/L)	ORP Min. (mV)	ORP Max. (mV)
Altus AFB, OK	OU1	4.6	< 0.05	< 0.05	1440	2056	0.078	< 0.001	-179	220
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	0.15	8.5	< 0.23	71.4	14.2	32.6	9.35	-340	277
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	0.14	10.3	0.35	35	270	6.97	0.004	-250	101
Columbus AFB, MS	LF-06	1.3	94	1.4	0.27	23.27	6.5 <sup>a/</sup> /2.7	< 0.012	-300	284
Hill AFB, UT	OU1	2.3	34.8	< 0.05	< 0.1	56.27	10.36	< 0.001	-248	262
Hill AFB, UT	OU5	3.1	0.2	ND <sup>b/</sup>	14.6	28.2	0.428	ND	-170	216
Offutt AFB, NE	Building 301	1.75	<.05	<.05	40.1	24.82	12.29	<.001	-98	312
Plattsburgh AFB, NY	FT-002	0.44	10.7	< 0.05	< 0.08	21.35	0.512	ND	-188	149
Randolph AFB, TX	FT004	0.1	13.5	< 0.05	5.05	17.6	3.63	ND	-218	490
Shaw AFB, SC	Site OU-4	1	7	0.44	< 0.1	9.49	6.95	ND	-201	319
Tinker AFB, OK	FTA-2	2.5	0.8	< 0.01	30	30	1.05	< 0.001	-105	139
Tinker AFB, OK	Area A	3.8	7.4	< 0.05	< 0.5	141	4.75	< 0.001	-265	465
F.E. Warren AFB, WY	LF-03	9.12	< 0.1	< 0.1	19.6	47.4	0.003	< 0.001	30	276
Travis AFB, CA	SD036	4.52	1.02	0.19	23.6	105	18	11	-1.4	417

<sup>a/</sup> Value from perched aquifer.

<sup>b/</sup> ND = Not detected.



**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		GEOCHEMICAL DATA							HYDROGEOLOGIC DATA	
		Alk. <sup>a/</sup> Min (mg/L)	Alk. <sup>a/</sup> Max (mg/L)	pH Avg.	pH Min	pH Max	Temp. Avg (°C)	Total Organic Carbon (mg/L)	General Soil Type S=Sand, G=Gravel ST=Silt, C=Clay	Transport Soil Type <sup>b/</sup> S=Sand, G=Gravel ST=Silt, C=Clay
Air Force Facility	Site									
Altus AFB, OK	OU1	157	504	7	6.8	8.1	15.7	45.8	ST/S, C, ST, Shale, S	Shale, C, S
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	178	960	7.5	7.2	8.3	25.6	9	S, ST/S, ST/C, S/C, C	S
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	213	527	7.3	6.7	7.8	22	23.3	S,ST,C	S
Columbus AFB, MS	LF-06	0	425	6.8	4.3	6.8	18.9	4.6	ST/C, C/ST, S, G, ST	G, S, ST/C
Hill AFB, UT	OU1	190	825	7.2	6.7	8.5	11.4	122	S, ST, C, S/G, ST/C	S, ST/C, S/G
Hill AFB, UT	OU5	70	> 500	7.3	6.8	7.9	17.4	2.4	ST/C, ST/S, S	ST/S, S, ST/C
Offutt AFB, NE	Building 301	129	488	7.2	6.8	8.2	16.4	1.1	S, S/ST, G, ST, ST/C, C, C/CS	S/G, ST/S, C/S, ST/C
Plattsburgh AFB, NY	FT-002	-- <sup>c/</sup>	--	7.7	5.2	12.1	9.1	37.4	S, C, ST, G	S
Randolph AFB, TX	FT004	40	520	7.2	6.9	8.1	21.9	5.8	ST, C, G, S	ST, C, G
Shaw AFB, SC	Site OU-4	10	250	5.2	4.3	6.4	18.1	7.7	S, ST, C, S/C	S, S/C
Tinker AFB, OK	FTA-2	190	560	7.2	6.8	7.75	19	3.3	ST/C, C/ST, ST, S/ST, S	S, ST/C, S/ST
Tinker AFB, OK	Area A	184	678	7.2	6.9	7.4	20.2	5.5	S, C, ST	S, ST
F.E. Warren AFB, WY	LF-03	120	300	7.3	6.8	8.14	9.9	7.8	C, ST/S, S, ST	S,ST,G
Travis AFB, CA	SD036	246	598	7	6.6	7.5	22.4	4.4	ST/C, C, ST	ST/S,S,ST

<sup>a/</sup> Alk. = Alkalinity as calcium carbonate.

<sup>b/</sup> Soil type along plume flowpath.

<sup>c/</sup> "--" = Not applicable or not available.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		HYDROGEOLOGIC DATA						
Air Force Facility	Site	Depth to Groundwater		Number of Slug Tests Performed During TS Field Work	Groundwater Flow Velocity		Average Groundwater Flow Velocity ft/year	Average Soil Fraction Organic Carbon
		Minimum (Feet)	Maximum (Feet)		Max ft/year	Min ft/year		
Altus AFB, OK	OU1	0	13	4	1898	182	1040	0.0015
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	0	7	4	77	0.04	2.4	0.0028
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	0	7	0	255	16.4	113	0.00184
Columbus AFB, MS	LF-06	5	21	6	1911	128	795	< 0.006
Hill AFB, UT	OU1	0	30	0	9125	620	2263	0.00065
Hill AFB, UT	OU5	0	58.7	0	8212	2	60.5	0.00079
Offutt AFB, NE	Building 301	2	60	6	1971	0.2	175/85*	0.036
Plattsburgh AFB, NY	FT-002	0	45	0	1102	0.7	139	0.0055
Randolph AFB, TX	FT004	16.3	27.3	2	11755	12	438	0.0029
Shaw AFB, SC	Site OU-4	0.25	20	2	827	184	770	0.00024
Tinker AFB, OK	FTA-2	8.3/53	20.2/61.5 <sup>a/</sup>	7	71/9.8 <sup>a/</sup>	227/476 <sup>a/</sup>	152/166 <sup>a/</sup>	0.00813
Tinker AFB, OK	Area A	4.4	18	0	99/11 <sup>a/</sup>	1.1/2.9 <sup>a/</sup>	38/8.4 <sup>a/</sup>	0.00063
F.E. Warren AFB, WY	LF-03	1.59	39.7	7	200	0.7	6.9	0.027
Travis AFB, CA	SD036	7	12	3	56	2.7	29	--- <sup>b/</sup>

<sup>a/</sup> Values given for two hydrostratigraphic units.

<sup>b/</sup> "---" = not applicable or not available.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		BIODEGRADATION RATES					
Air Force Facility	Site	Estimated Effective Porosity	Average Contam. Velocity ft/year	Avg. TMB <sup>a/</sup> 1/day	Average Buscheck & Alcantar (1995) Total Chlorinated Ethenes 1/day	Buscheck & Alcantar (1995) Specific Compounds 1/day	Avg. Other <sup>b/</sup> 1/day
Altus AFB, OK	OU1	0.05	224	-- <sup>c/</sup>	--	1.88E-3 (TCE)	8.00E-06
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	0.25	2.0	--	5.00E-05	--	1.20E-06
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	0.2	54	--	3.00E-04	5.00E-4 (TCE) / 5.00E-4 (DCE) <sup>d/</sup>	7.00E-05
Columbus AFB, MS	LF-06	0.25	630	--	3.50E-03	--	--
Hill AFB, UT	OU1	0.2-0.25	1968	3.00E-04 (DCE) <sup>d/</sup>	--	2.60E-4 (DCE) <sup>d/</sup>	4.00E-08
Hill AFB, UT	OU5	0.2	38	--	--	3.50E-4 (TCE)	1.00E-06
Offutt AFB, NE	Building 301	0.15-0.25 <sup>e/</sup>	50/75 <sup>e/</sup>	--	--	7.00E-4 (TCE)	2.00E-05
Plattsburgh AFB, NY	FT-002	0.3	13.4	--	2.20E-04	--	6.10E+00
Randolph AFB, TX	FT004	0.25	398	--	--	4.90E-4 (TCE)	7.00E-05
Shaw AFB, SC	Site OU-4	0.25	687	--	1.27E-02	--	2.55E-03
Tinker AFB, OK	FTA-2	0.2	27	--	3.00E-04	3.10E-4 (TCE) / 4.10E-4 (DCE) <sup>d/</sup>	1.88E-07
Tinker AFB, OK	Area A	0.2	24	7.04E-04 (TCE)	5.80E-04	1.70E-3 (TCE) / 1.40E-3 (DCE) <sup>d/</sup> / 1.00E-3 (VC)	1.10E-04
F.E. Warren AFB, WY	LF-03	0.2	--	--	6.96E-05	5.14E-5 (TCE) / 1.03E-4 (DCE) <sup>d/</sup>	1.77E-06
Travis AFB, CA	SD036	0.2	--	--	1.10E-04	--	--

<sup>a/</sup> TMB = trimethylbenzene.

<sup>b/</sup> Other = Rate computed using the method of Moutoux *et al.* (1996).

<sup>c</sup> "--" = Not applicable or not available.

<sup>d/</sup> DCE = cis-1,2-DCE

<sup>e/</sup> Values given for two hydrostratigraphic units.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		MONITORING WELL DATA			PROPOSED REMEDIAL ALTERNATIVE DATA	
Air Force Facility	Site	Recommended Number of LTM Wells	Recommended Number of LTM Surface Water Stations	Recommended LTM Sampling Frequency (years)	Remedial Alternative Selected	Specific Proposed Remedial Alternative (s) <sup>a/</sup>
Altus AFB, OK	OU1	11	5	1	Alt. 2	DPE + MNA+ IC
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	9	3	1	-- <sup>b/</sup>	AS + MNA + IC
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	8	5	1	--	MNA + AS + EXC + SW
Columbus AFB, MS	LF-06	10	0	1	Alt. 1	MNA + IC
Hill AFB, UT	OU1	-- <sup>c/</sup>	-- <sup>c/</sup>	2	--	MNA + IC + GE + FPR + LCR
Hill AFB, UT	OU5	25	5	1	--	MNA+ IC + AS + GE
Offutt AFB, NE	Building 301	19	4	1	Alt. 1	MNA, LTM, IC, ASC
Plattsburgh AFB, NY	FT-002	18	0	1	Alt. 3	MNA + IC + BV + FPR + AS
Randolph AFB, TX	FT004	-- <sup>c/</sup>	-- <sup>c/</sup>	1	Alt. 1	BV+ ASC + IC +MNA
Shaw AFB, SC	Site OU-4	12	6	1	Alt. 2	SVE + MNA + IC
Tinker AFB, OK	FTA-2	30	2	1	Alt. 1	MNA + IC + EXC + ASC
Tinker AFB, OK	Area A	17	0	2	Alt. 2	DPE + LTM + IC
F.E. Warren AFB, WY	LF-03	29	2	1	Alt. 2	MNA, LTM, IC, EXC
Travis AFB, CA	SD036	12	4	1	Alt. 3	SVE, NA, LTM, IC, GE

<sup>a/</sup> DPE = dual-phase extraction, MNA = monitored natural attenuation, IC = institutional controls, AS = air sparging, GE = groundwater extraction, BV = bioventing (for fuel hydrocarbons), SVE = soil vapor extraction, ASC = additional site characterization, EXC = soil excavation,

<sup>b/</sup> "--" = Not applicable or not available.

<sup>c/</sup> LTM plan not prepared.

SW = soil washing, FPR = free product recovery, LCR = landfill cap repair.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		PROPOSED REMEDIAL ALTERNATIVE DATA					
Air Force Facility	Site	Completed Exposure Pathway <sup>a/</sup>	Model Used	Historic Data to Show Attenuation Trends?	Receding (R) Steady-State (S) or Expanding (E) Plume	Estimated Alt. 1 Costs	Estimated Time Until Compliance with MCLs (yr) Alt.1
Altus AFB, OK	OU1	Yes	MODFLOW / MT3D	Yes	S, E	\$253,400	>150
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	Yes	MODFLOW / MT3D	Yes	S, E	-- <sup>b/</sup>	>100
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	Yes	MODFLOW / MT3D	Yes	S, E	--	50
Columbus AFB, MS	LF-06	No	vanGenuchten & Alves	No, only 1 date	S, R	\$179,516	--
Hill AFB, UT	OU1	Yes	MODFLOW / MT3D	Yes	S, R	--	>100
Hill AFB, UT	OU5	Yes	MODFLOW / MT3D	Yes	E	\$313,360	>100
Offutt AFB, NE	Building 301	Yes	MODFLOW / MT3D	Yes	E	\$258,562	>200
Plattsburgh AFB, NY	FT-002	No	BIOPLUME II	Yes	S, R	--	--
Randolph AFB, TX	FT004	No	MODFLOW / MT3D	Yes	S, R	\$31,175	17
Shaw AFB, SC	Site OU-4	Yes	MODFLOW / MT3D	Yes	S, E	\$232,110	98
Tinker AFB, OK	FTA-2	No	MODFLOW / MT3D	Yes	E	\$521,213	>100
Tinker AFB, OK	Area A	No	MODFLOW / MT3D	Yes	S, R	\$505,194	50
F.E. Warren AFB, WY	LF-03	No	MODFLOW / MT3D	Yes	S, E	\$1,500,000	30
Travis AFB, CA	SD036	Yes	MODFLOW / MT3D	Yes	S, E	\$426,000	26

<sup>a/</sup> Plume discharges to surface water body or spring/seep.

<sup>b/</sup> "--" = Not applicable or not available.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

SITE		PROPOSED REMEDIAL ALTERNATIVE DATA		
Air Force Facility	Site	Costed LTM Period with Alt. 1	Estimated Alt. 2 Costs	Estimated Time Until Compliance with MCLs (yr) Alt.2
Altus AFB, OK	OU1	30	\$568,200	>150
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	20	-- <sup>a/</sup>	>100
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	15-20	--	25
Columbus AFB, MS	LF-06	10	\$814,505	--
Hill AFB, UT	OU1	--	--	>100
Hill AFB, UT	OU5	30	--	>100
Offutt AFB, NE	Building 301	30	\$1,069,947	>200
Plattsburgh AFB, NY	FT-002	--	--	--
Randolph AFB, TX	FT004	20	\$240,493	17
Shaw AFB, SC	Site OU-4	20	\$593,590	93
Tinker AFB, OK	FTA-2	35	\$1,057,850	>35
Tinker AFB, OK	Area A	49	>\$950,000	5
F.E. Warren AFB, WY	LF-03	30	\$1,891,200	30
Travis AFB, CA	SD036	27	\$463,600	10

<sup>a/</sup> "--" = Not applicable or not available.

**TABLE A.1 (Continued)**  
**SUMMARY DATA TABLE FOR THE NATURAL ATTENUATION OF CHLORINATED SOLVENTS**  
**AT MULTIPLE AIR FORCE DEMONSTRATION SITES**  
**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE**  
**BROOKS AIR FORCE BASE, TEXAS**

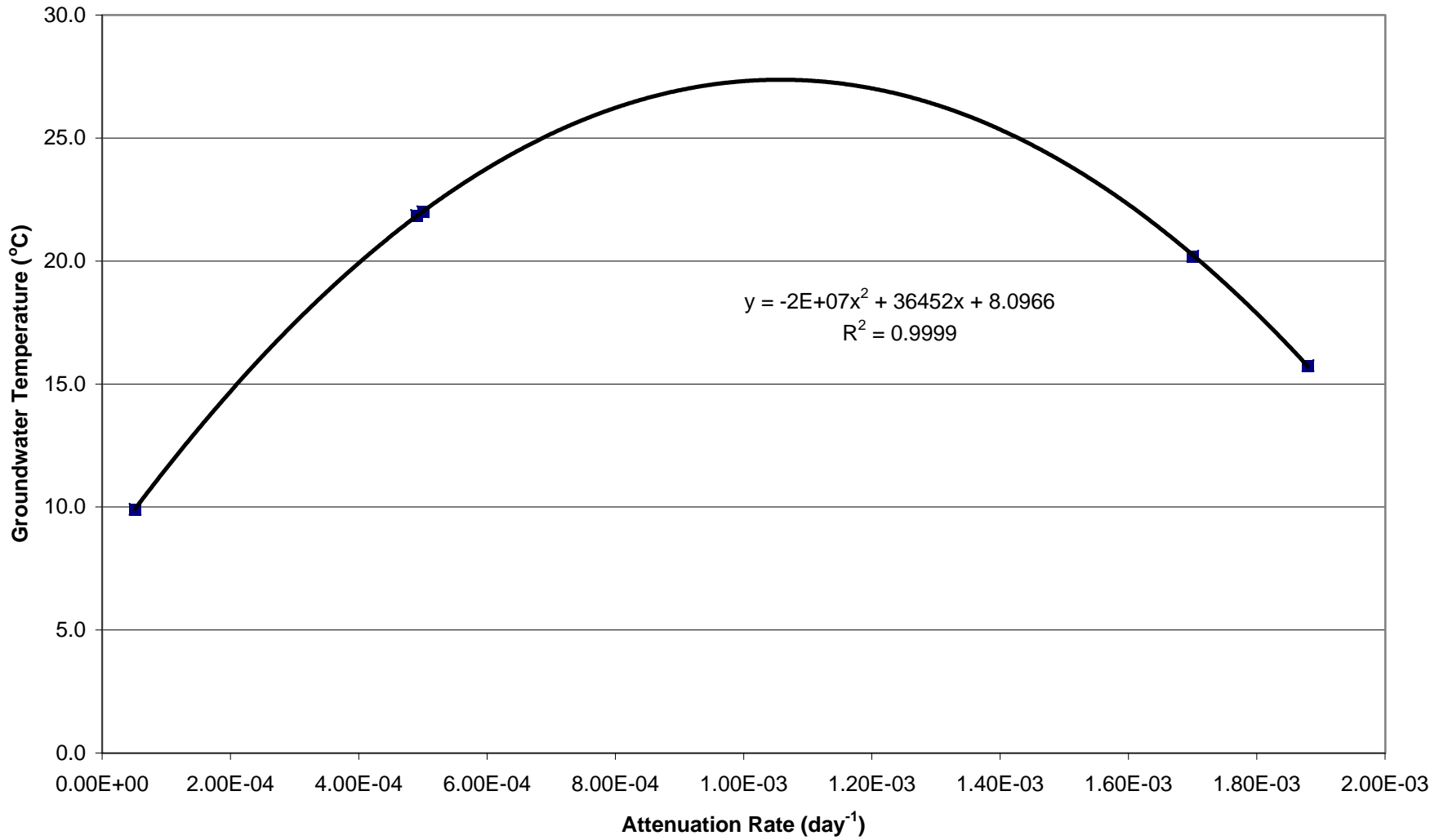
SITE		Long-Term Monitoring			
Air Force Facility	Site	Costed LTM Period with Alt. 2	Estimated Alt. 3 Costs	Estimated Time Until Compliance with MCLs (yr) Alt.3	Costed LTM Period with Alt. 3
Altus AFB, OK	OU1	30	-- <sup>a/</sup>	--	--
Cape Canaveral Air Station, FL	Facility 1381 (SWMU 21)	20	--	--	--
Cape Canaveral Air Station, FL	Site CCFTA-2 (FT-17)	15-20	--	--	--
Columbus AFB, MS	LF-06	10	\$846,229	--	10
Hill AFB, UT	OU1	--	--	>100	--
Hill AFB, UT	OU5	--	--	--	--
Offutt AFB, NE	Building 301	30	\$1,647,312	7200	30
Plattsburgh AFB, NY	FT-002	--	--	--	--
Randolph AFB, TX	FT004	20	--	--	--
Shaw AFB, SC	Site OU-4	20	--	--	--
Tinker AFB, OK	FTA-2	35	\$2,155,800	--	35
Tinker AFB, OK	Area A	5	--	--	--
F.E. Warren AFB, WY	LF-03	30	--	--	--
Travis AFB, CA	SD036	22	\$444,900	10	22

<sup>a/</sup> "--" = Not applicable or not available.

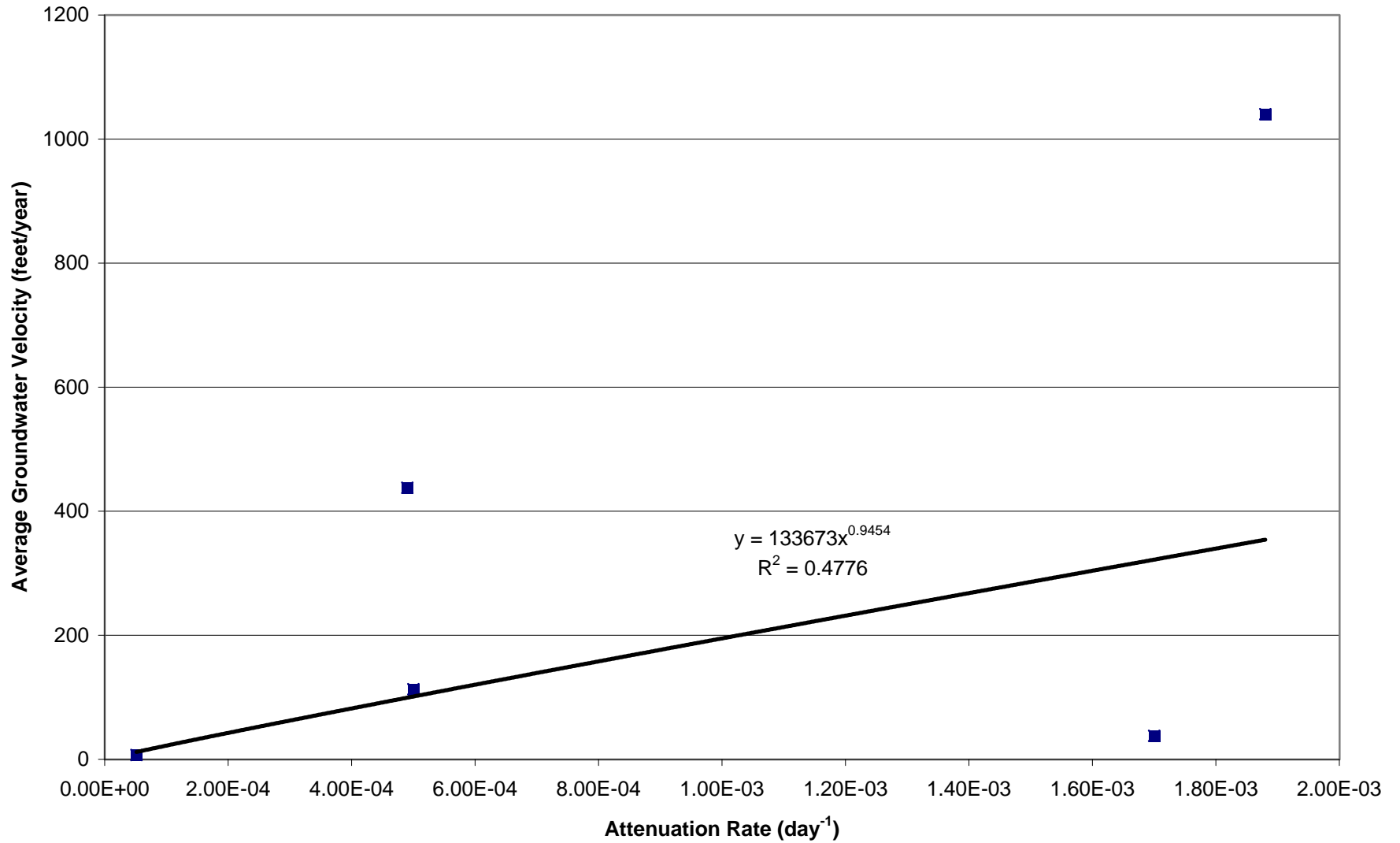
**APPENDIX B**  
**ATTENUATION RATE GRAPHS**



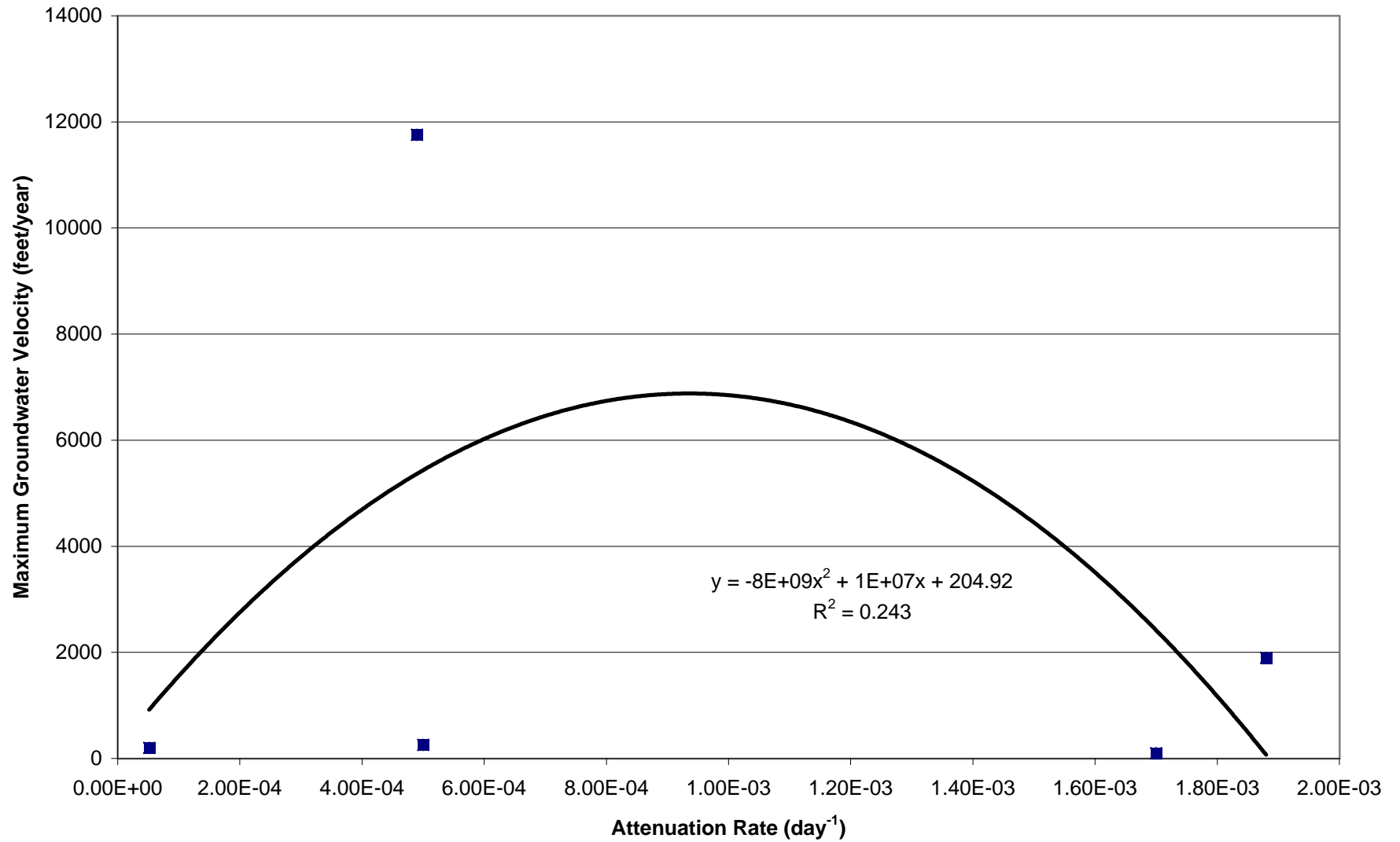
Groundwater Temperature versus Total Destructive TCE Attenuation Rate



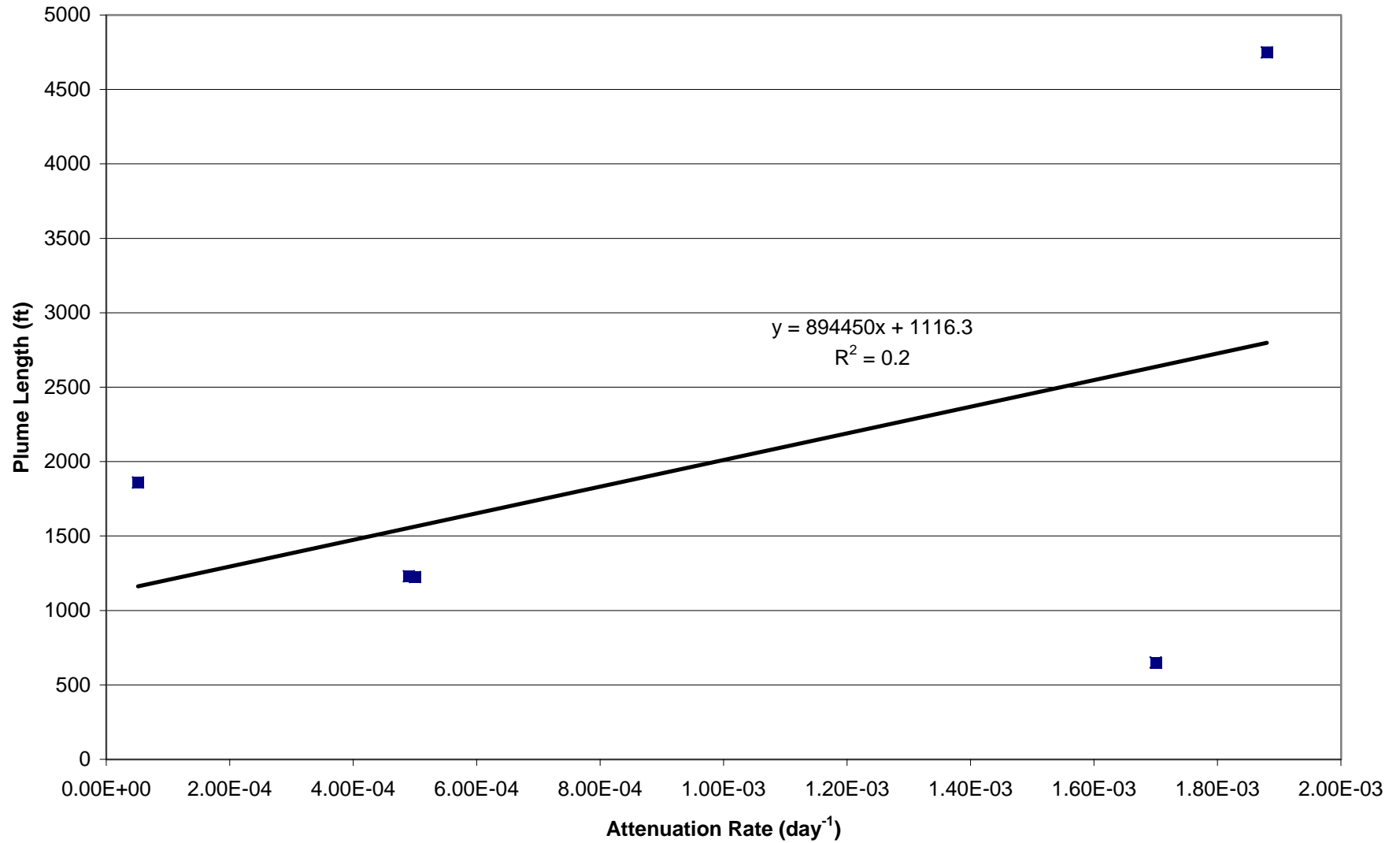
Average Groundwater Velocity versus Total Destructive TCE Attenuation Rate



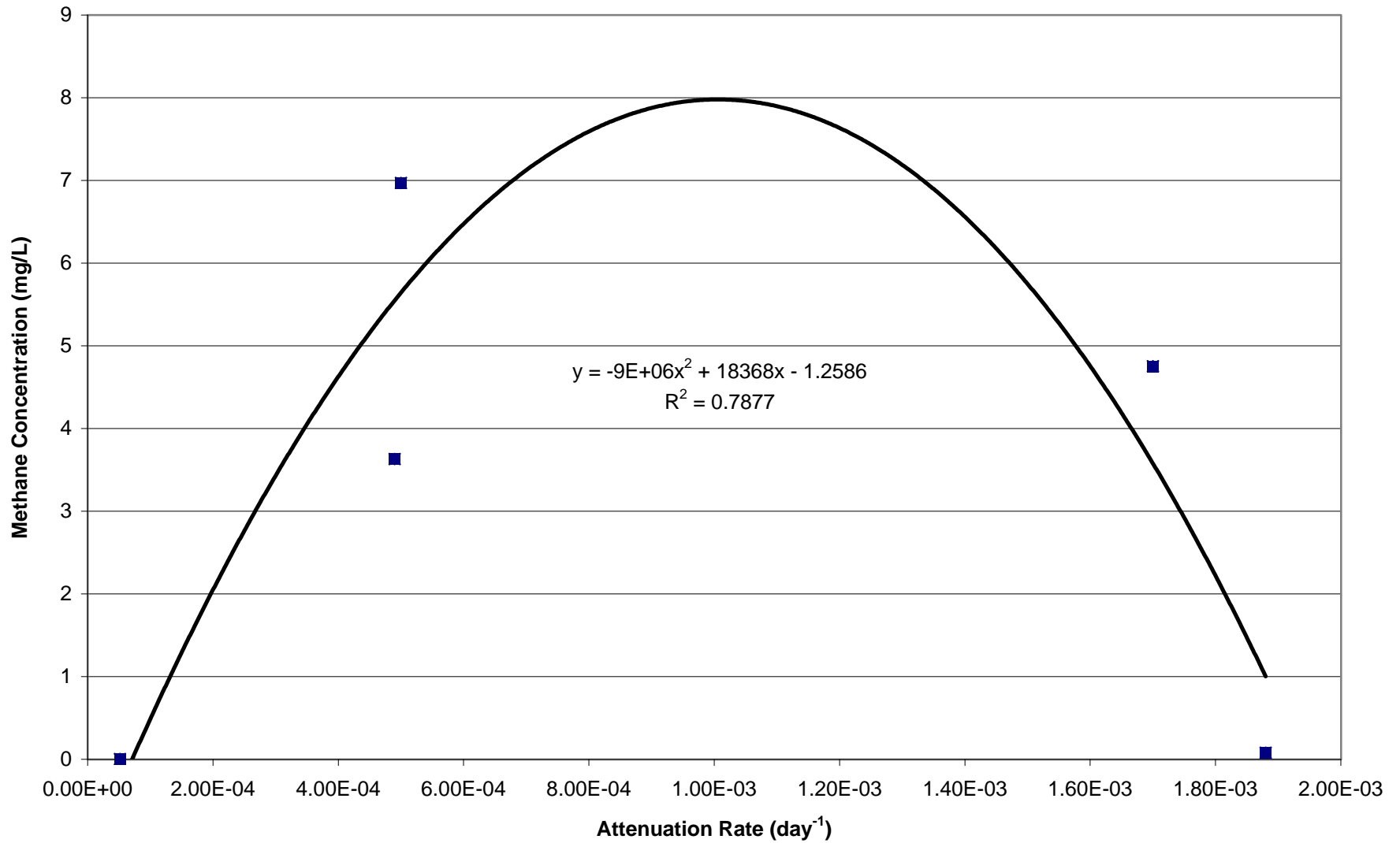
Maximum Groundwater Velocity versus Total Destructive TCE Attenuation Rate



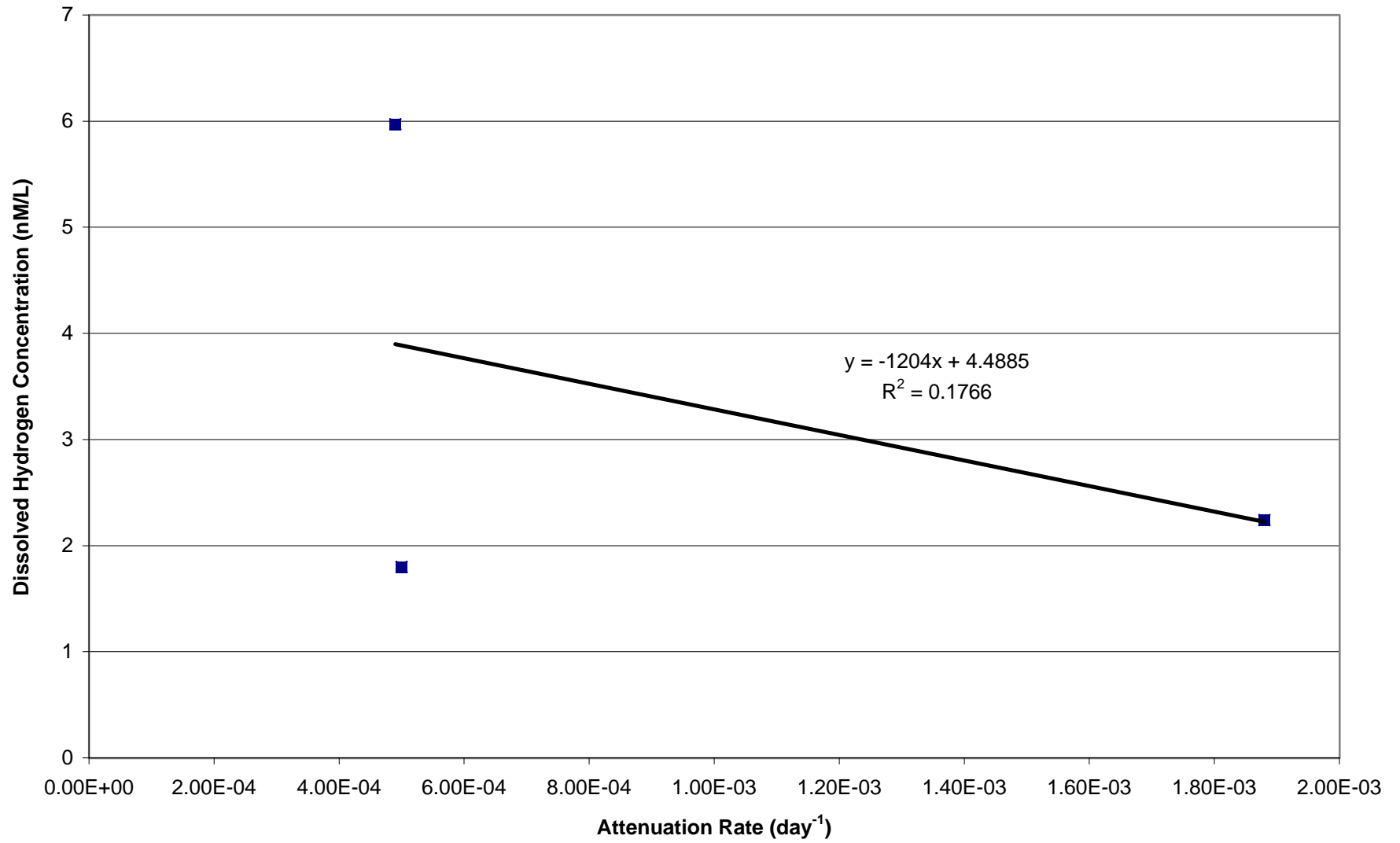
### TCE Plume Length versus Total Destructive TCE Attenuation Rate



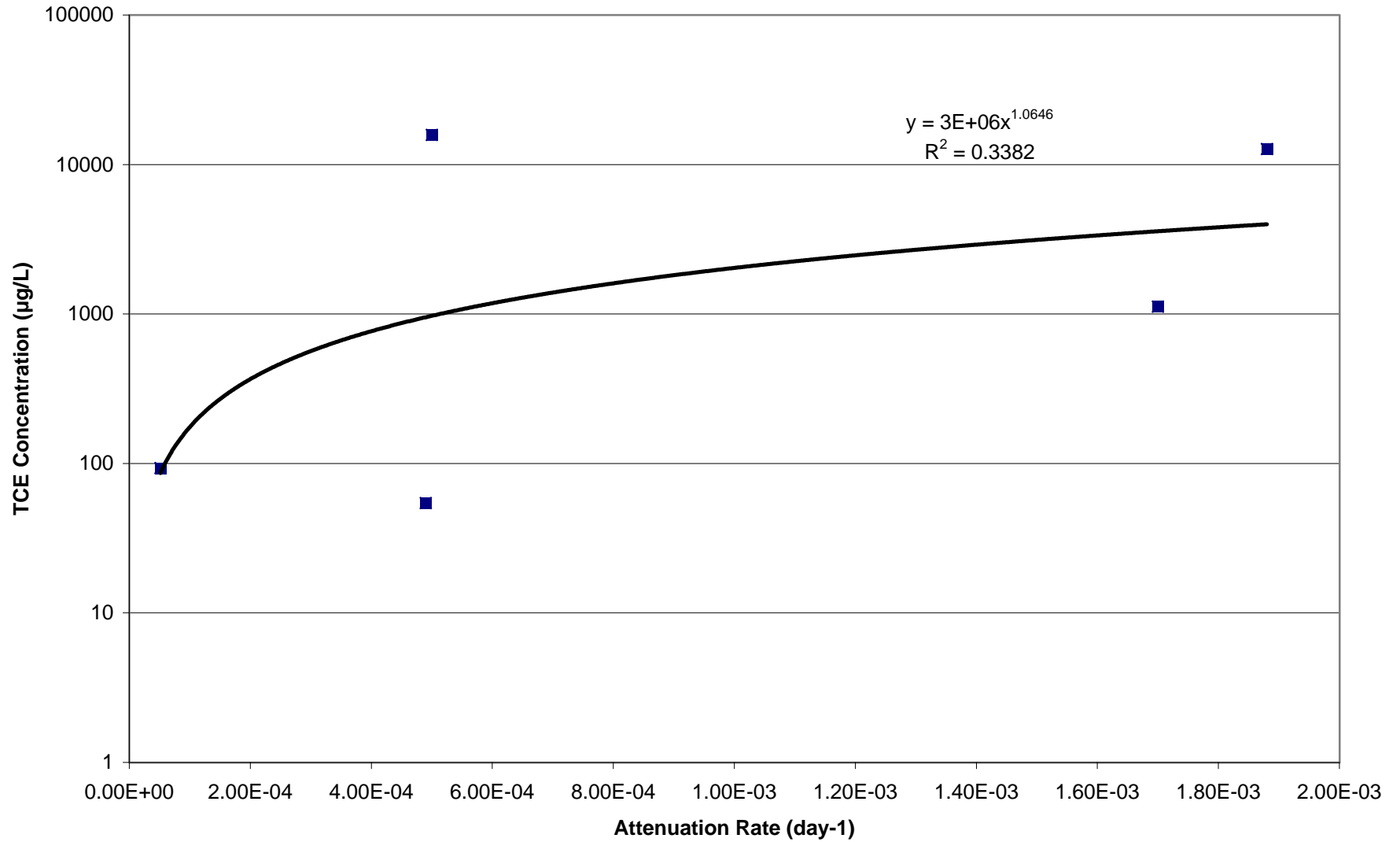
Methane Concentration versus Total Destructive TCE Attenuation Rate



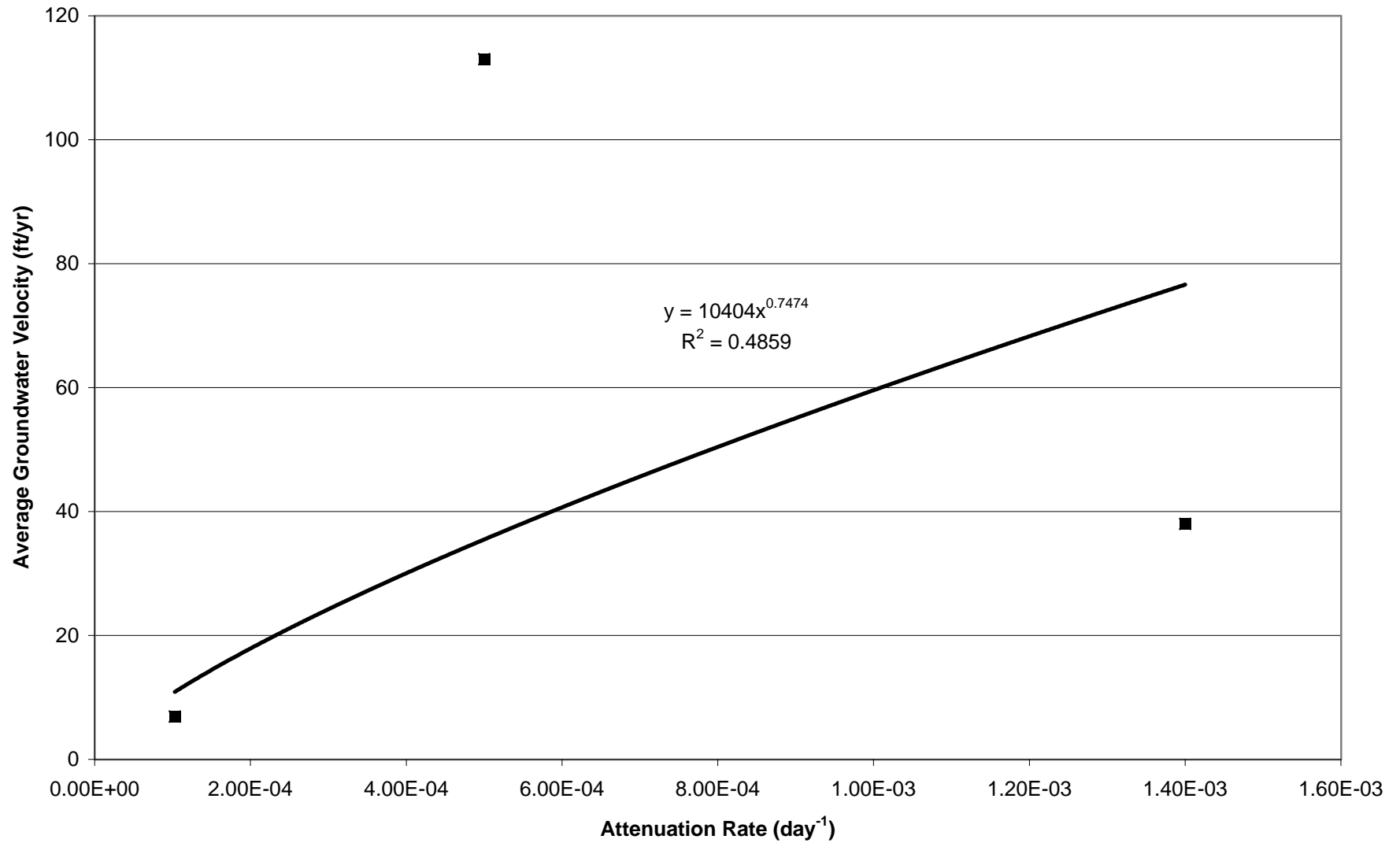
Maximum Dissolved Hydrogen versus Total Destructive TCE Attenuation Rate



Maximum TCE Concentration versus Total Destructive TCE Attenuation Rate

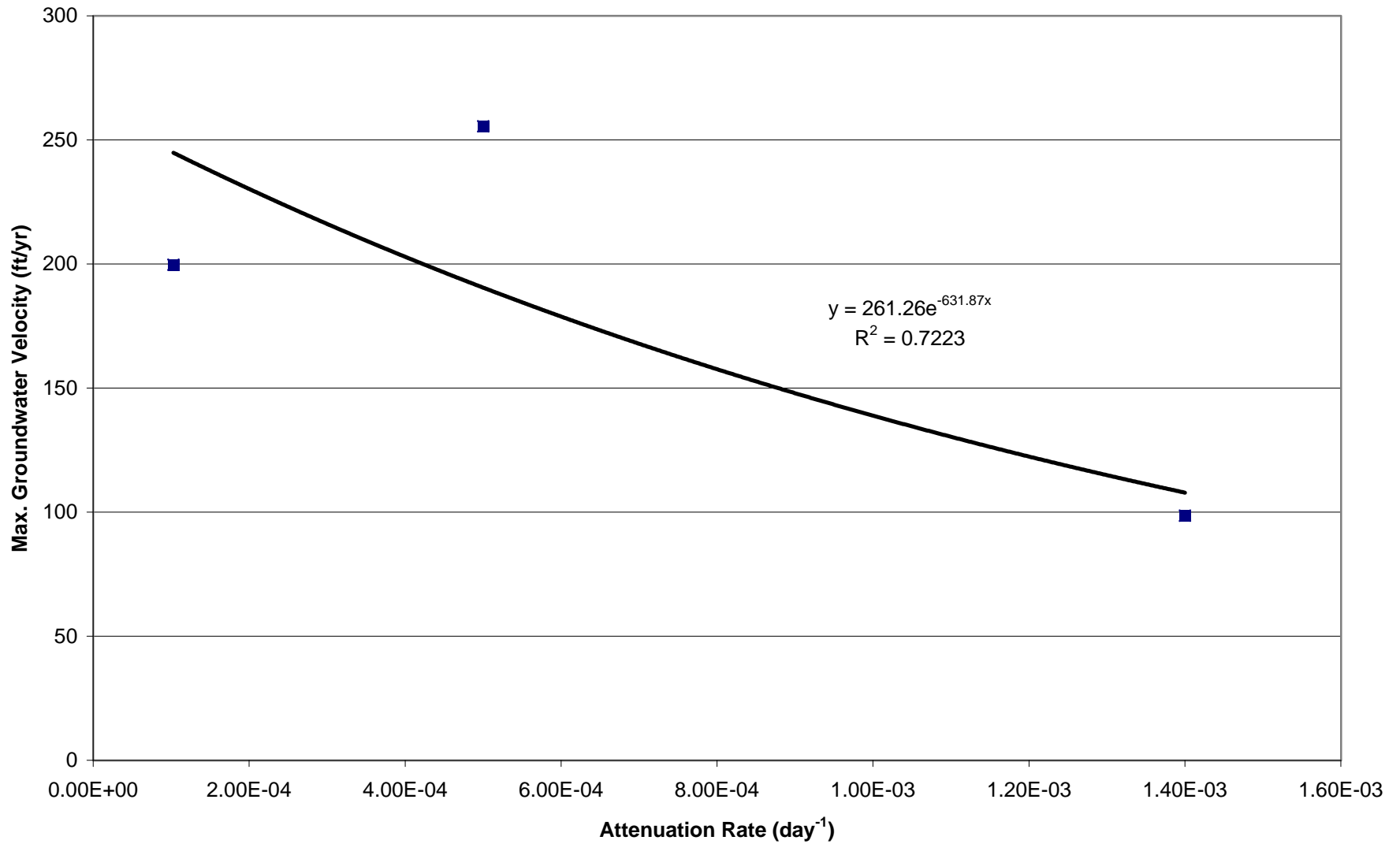


Average Groundwater Velocity versus Total Destructive *cis*-1,2-DCE Attenuation Rate

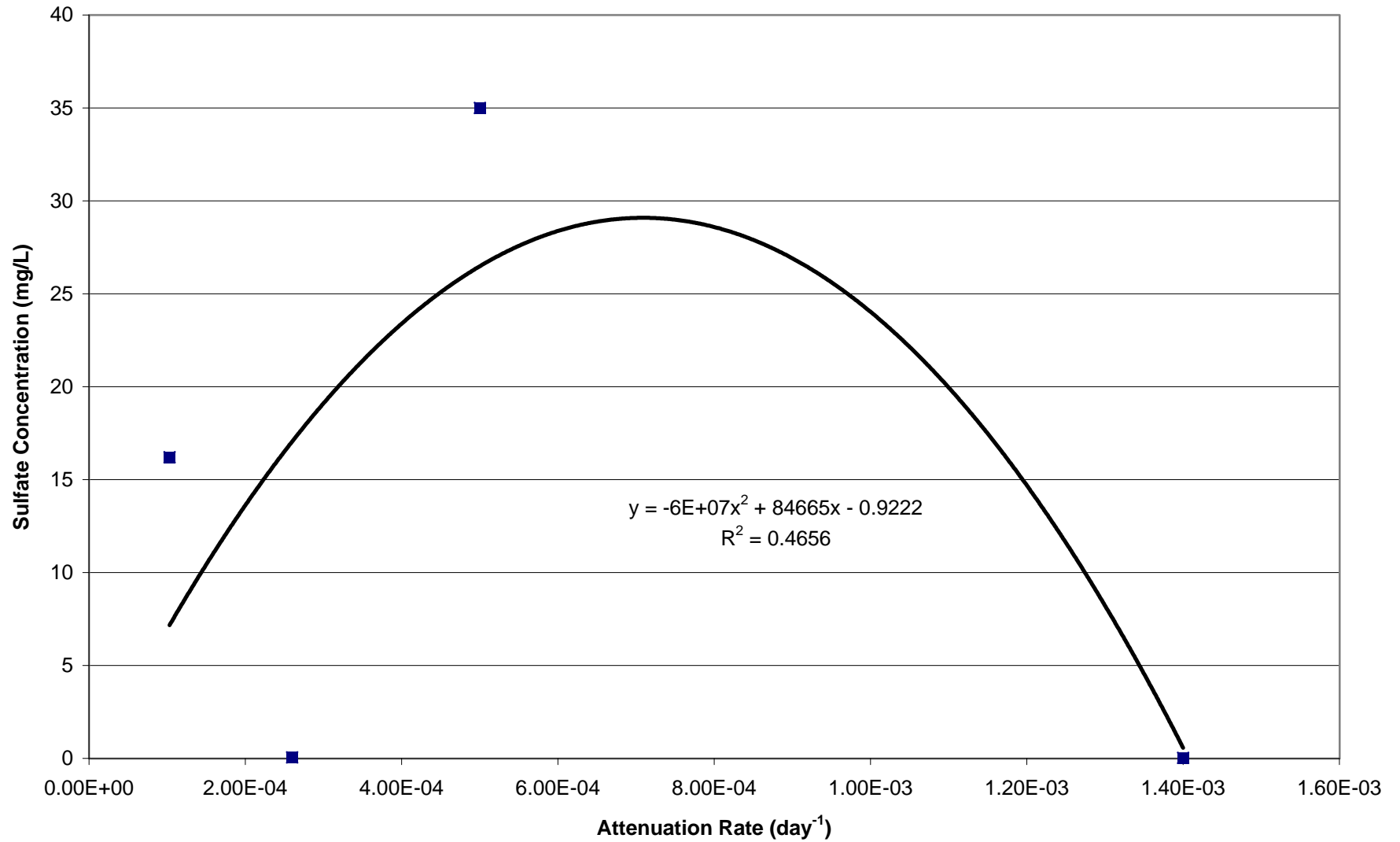




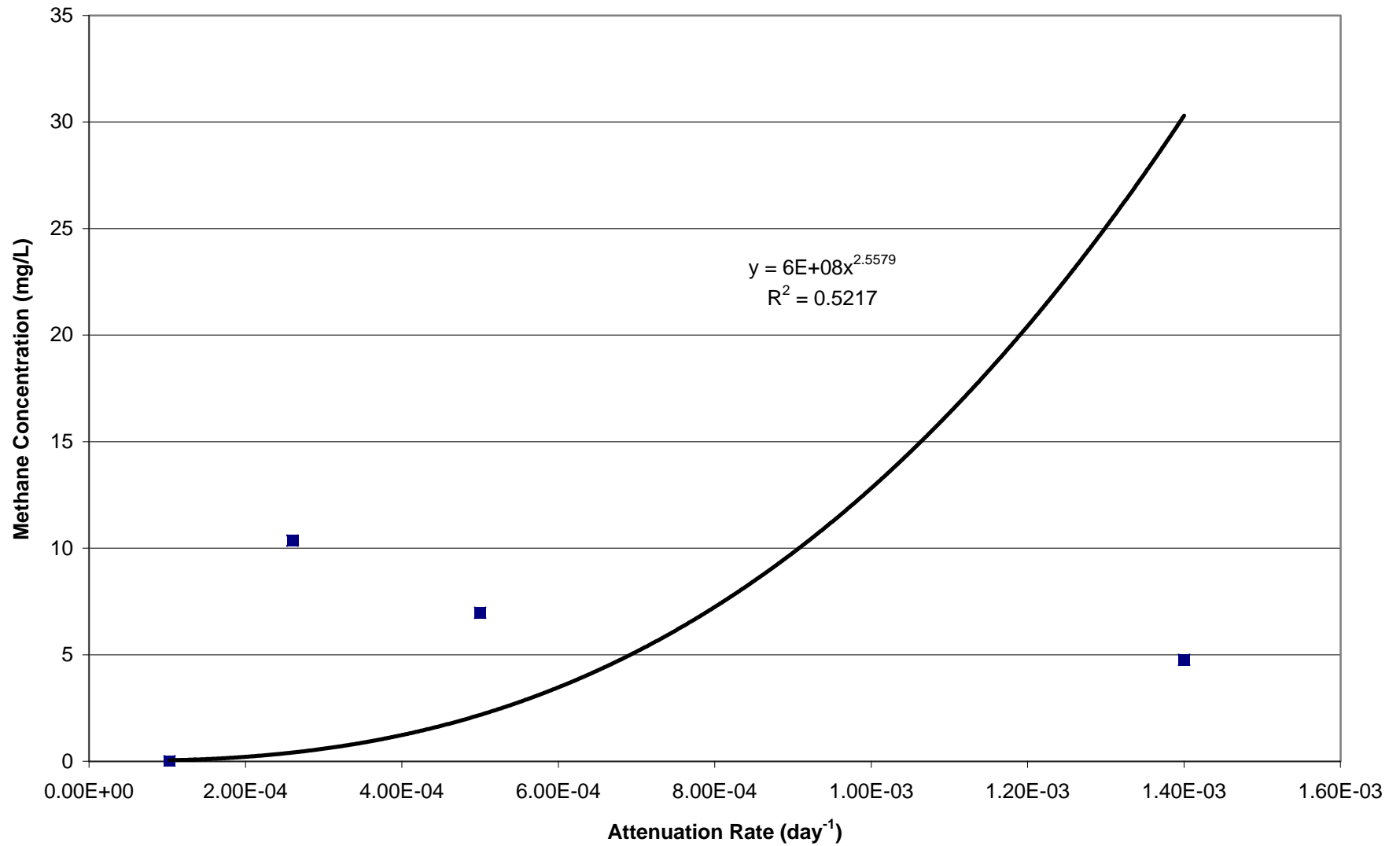
Maximum Groundwater Velocity versus Total Destructive *cis*-1,2-DCE Attenuation Rate



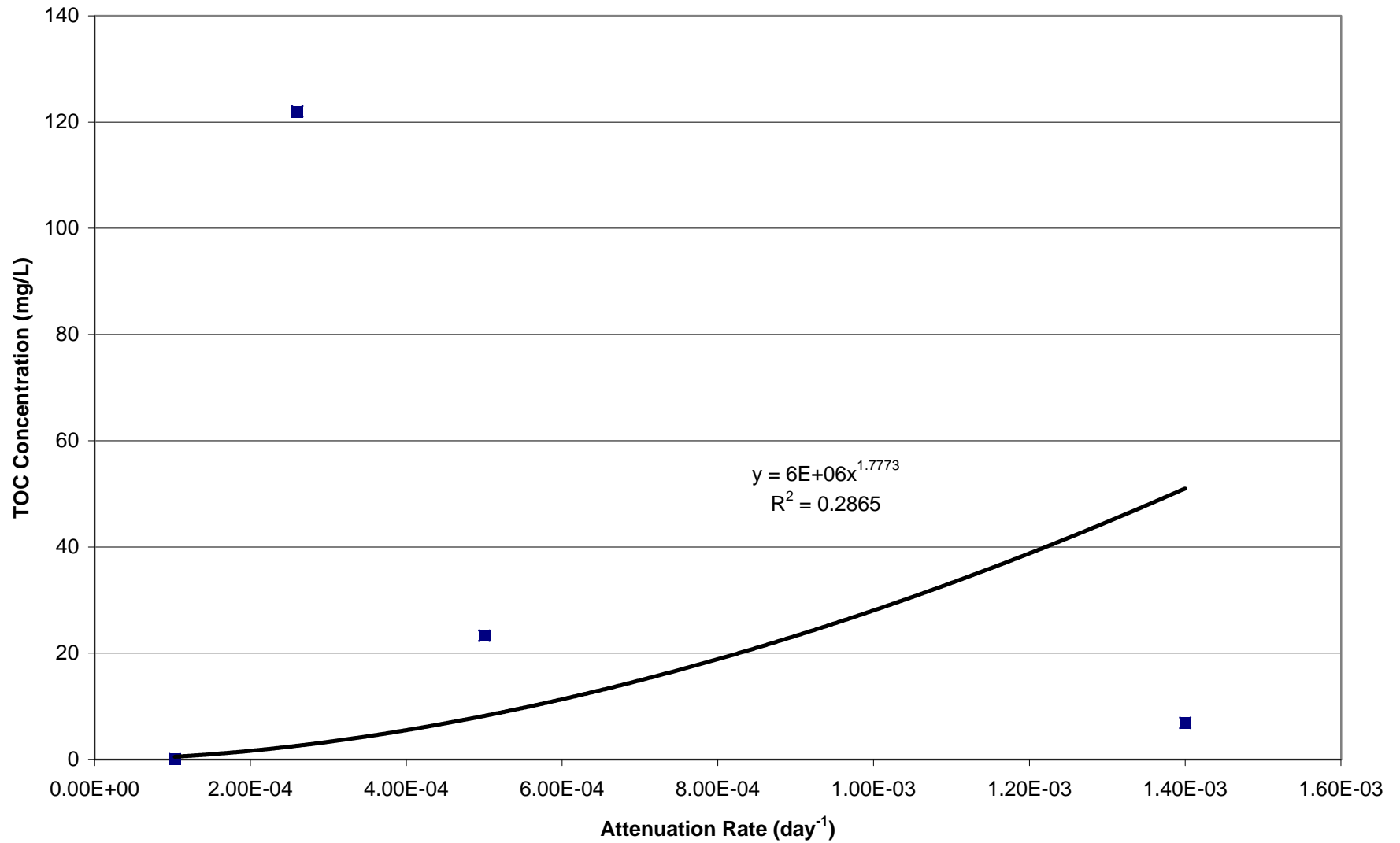
Sulfate Concentration versus Total Destructive *cis*-1,2-DCE Attenuation Rate



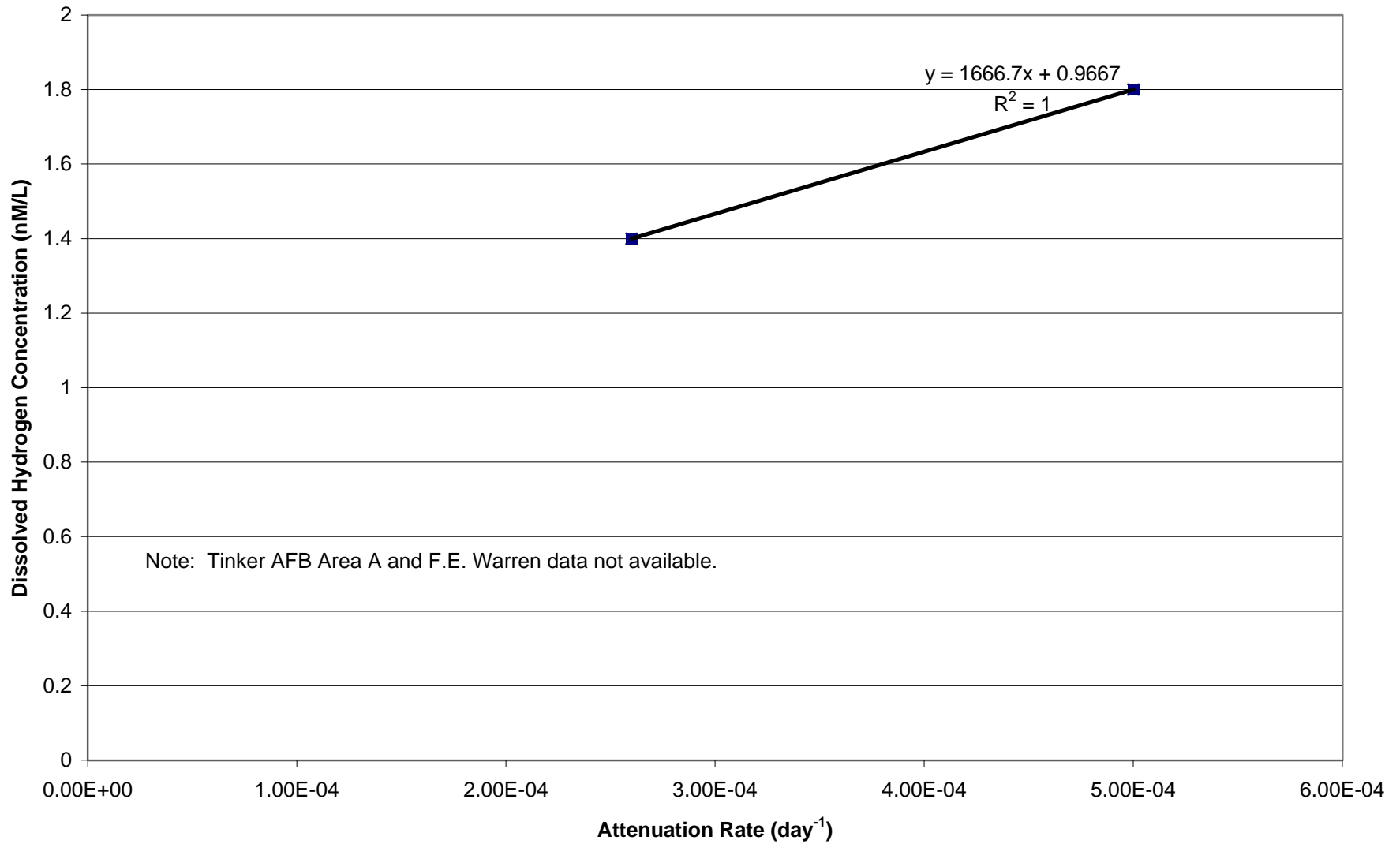
Methane Concentration versus Total Destructive *cis*-1,2-DCE Attenuation Rate



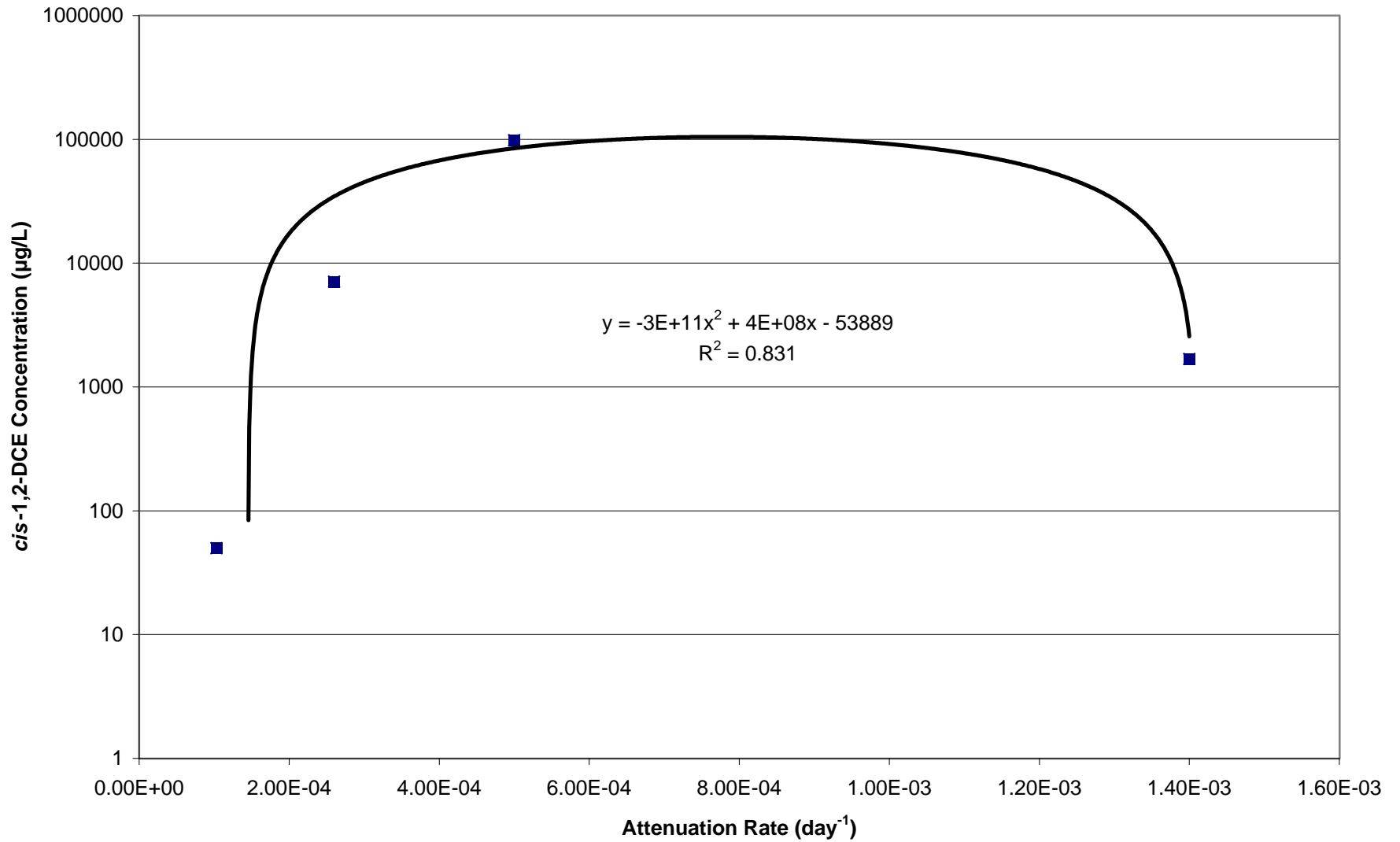
Total Organic Carbon Concentration versus Total Destructive *cis*-1,2-DCE Attenuation Rate



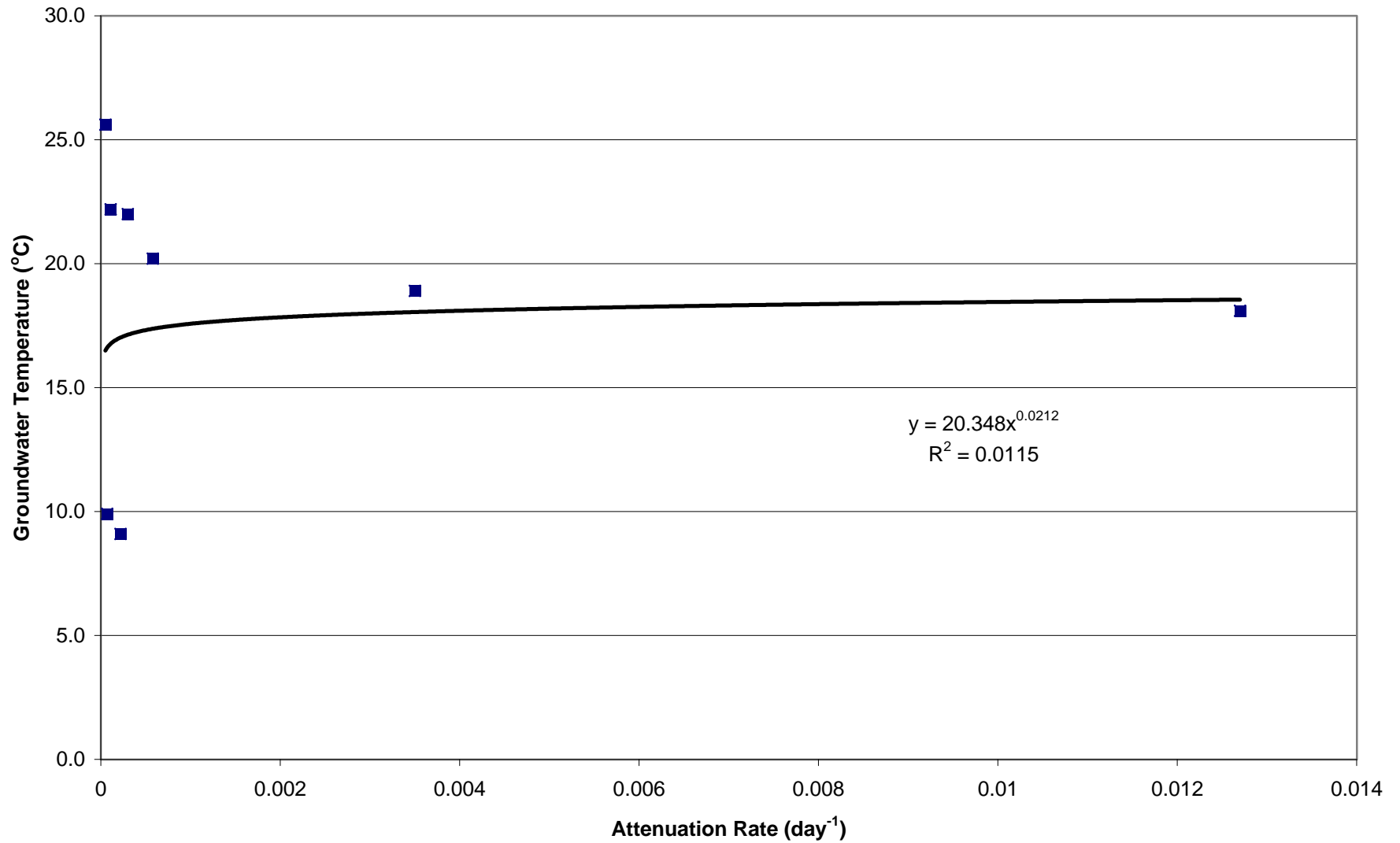
### Dissolved Hydrogen Concentration versus Total Destructive *cis*-1,2-DCE Attenuation Rate



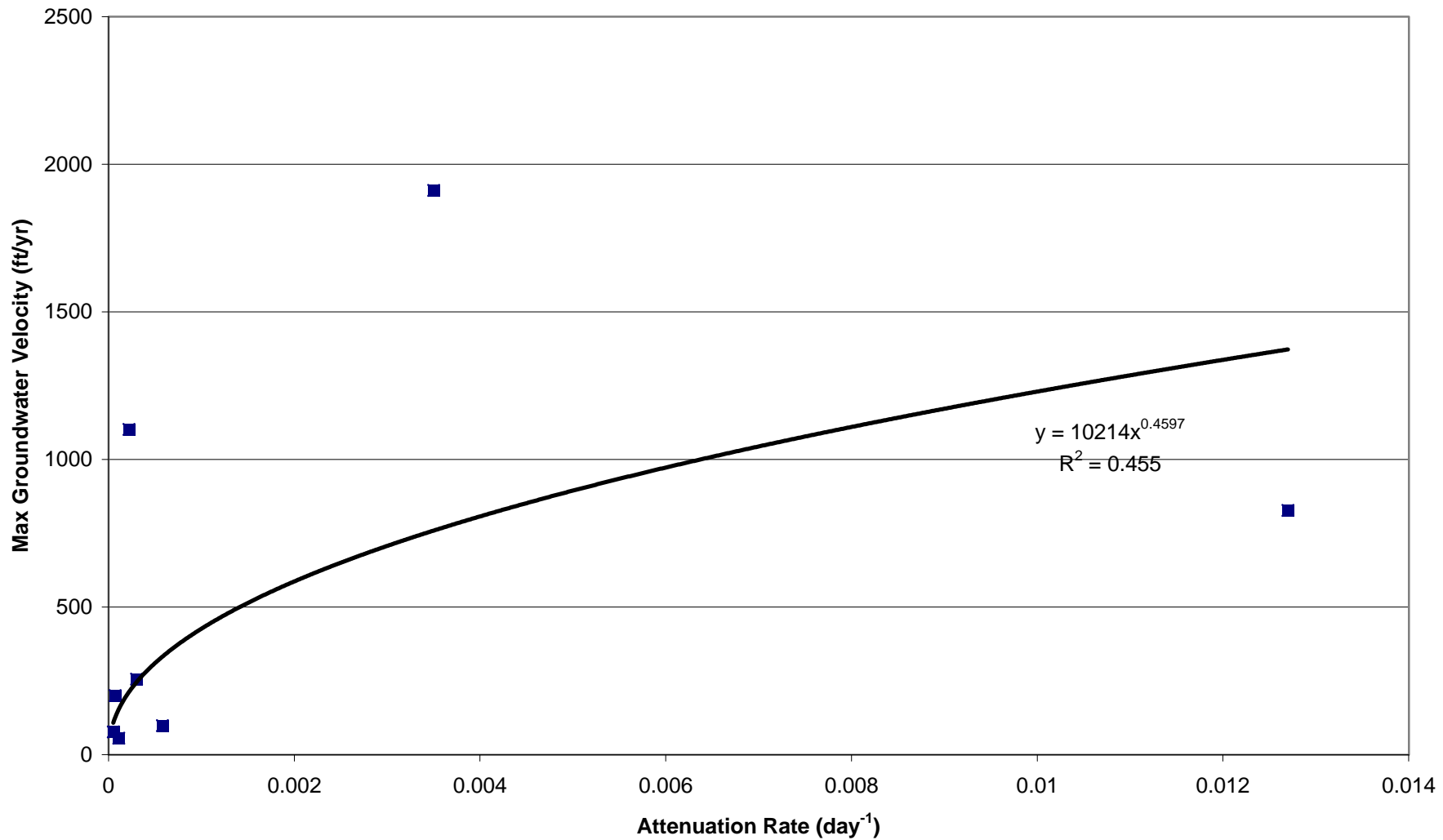
Maximum *cis*-1,2-DCE Concentration versus Total Destructive *cis*-1,2-DCE Attenuation Rate



Groundwater Temperature versus Total Destructive Chlorinated Ethenes Attenuation Rate

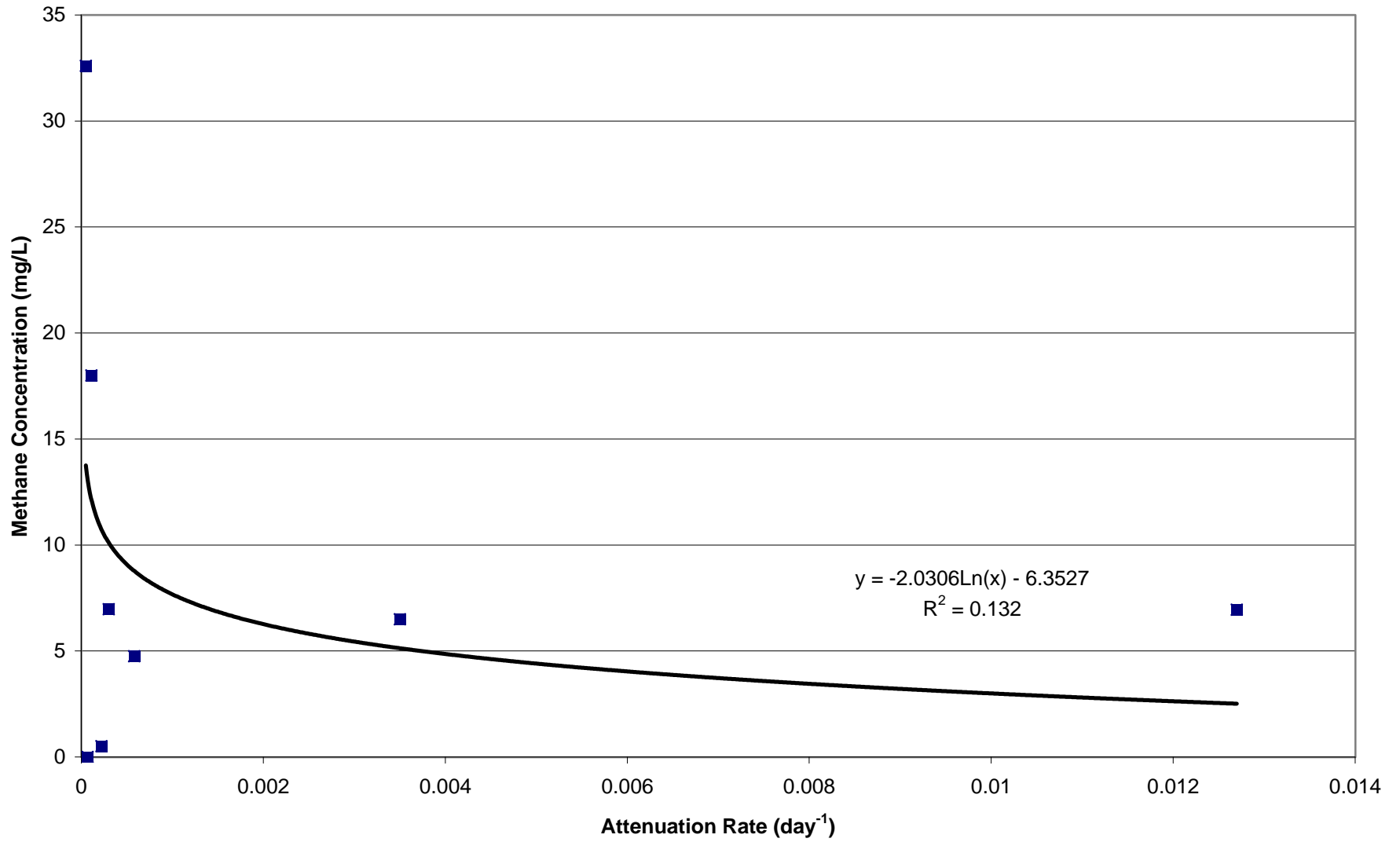


### Maximum Groundwater Velocity versus Total Destructive Chlorinated Ethenes Attenuation Rate

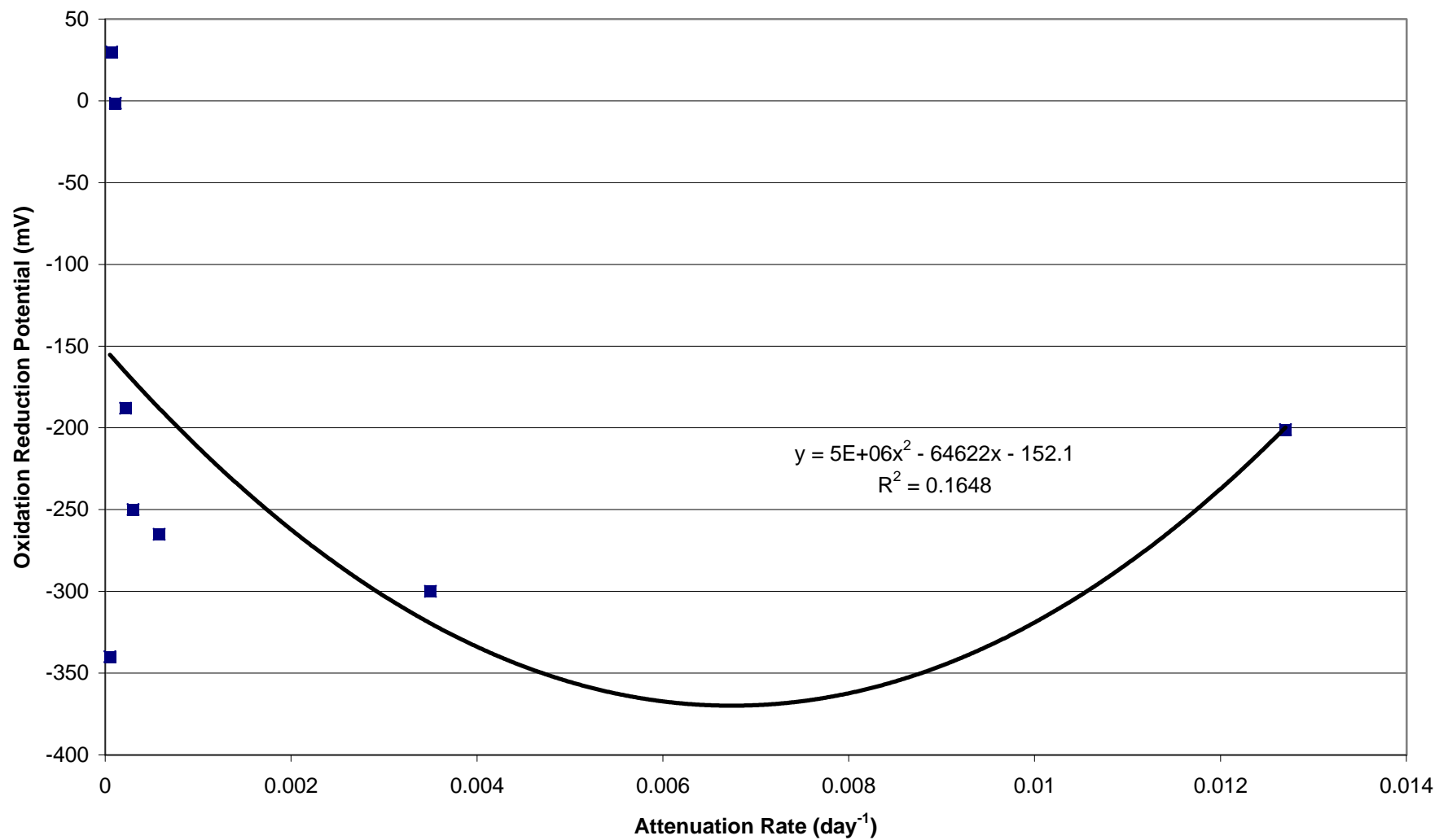




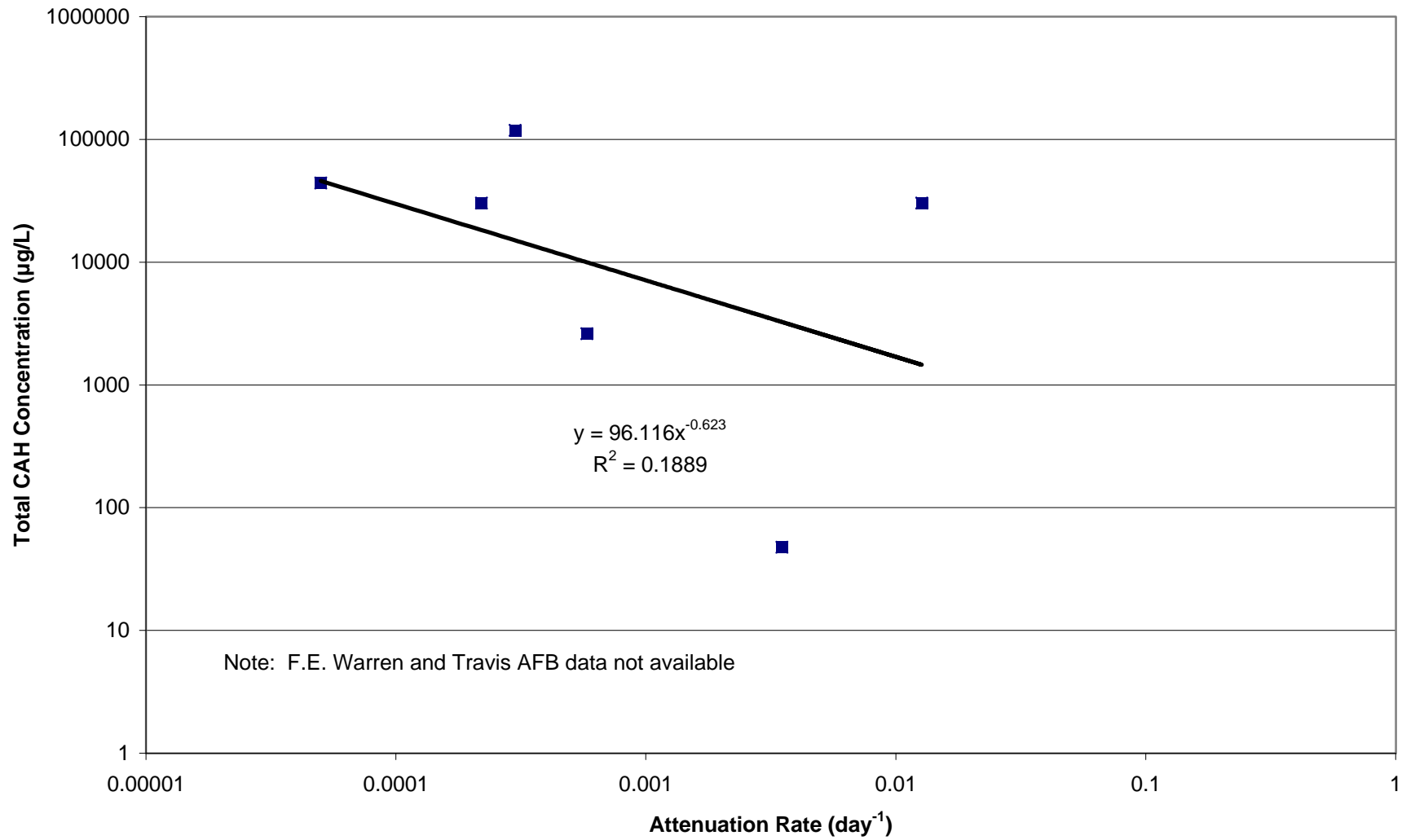
Methane Concentration versus Total Destructive Chlorinated Ethenes Attenuation Rate



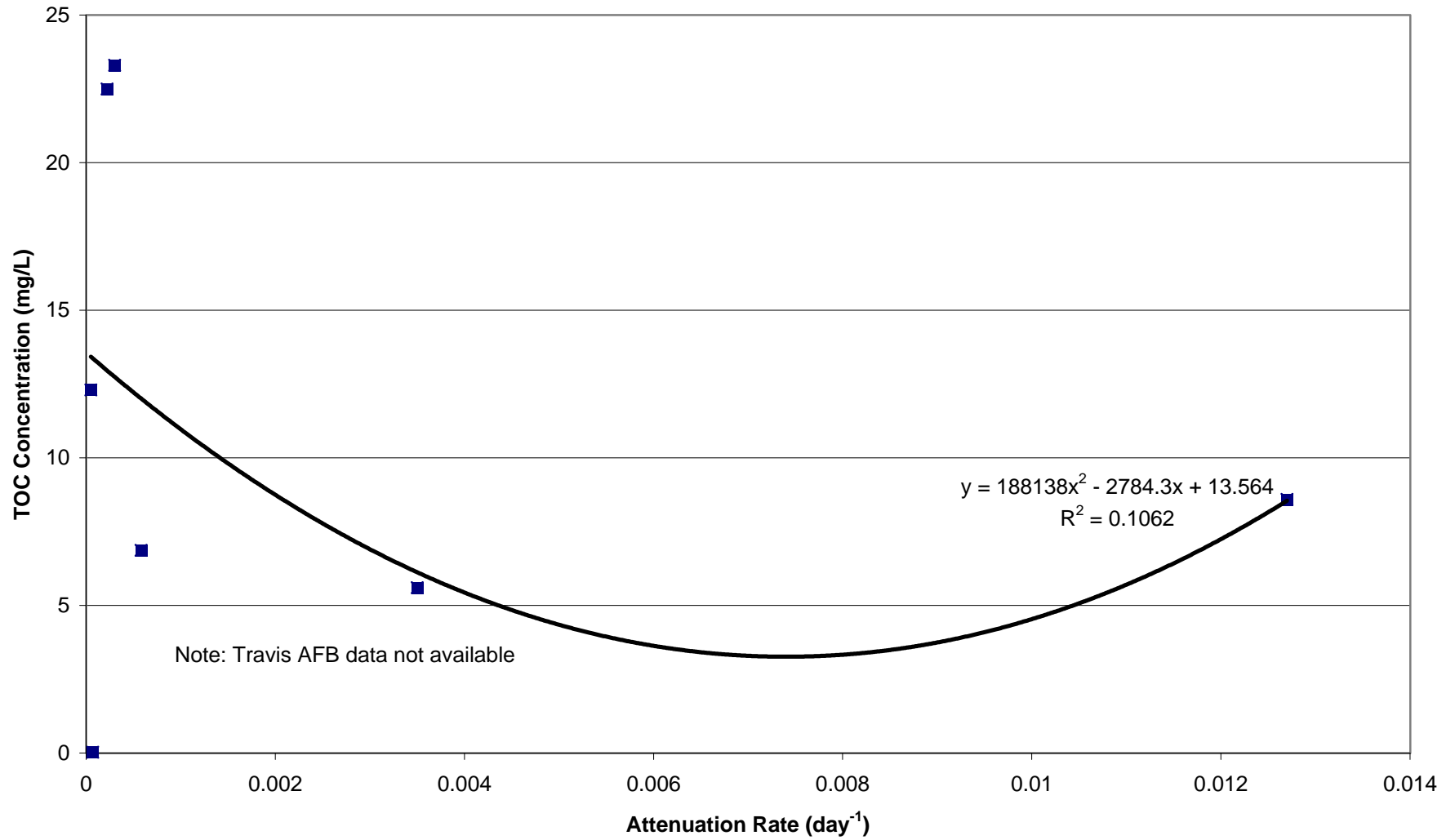
### Minimum Oxidation Reduction Potential versus Total Destructive Chlorinated Ethenes Attenuation Rate



### Maximum Total CAH Concentration versus Total Destructive Chlorinated Ethenes Attenuation Rate



### Total Organic Carbon Concentration versus Total Destructive Chlorinated Ethenes Attenuation Rate



Maximum BTEX Concentration versus Total Destructive Chlorinated Ethenes Attenuation Rate

